AN INTRODUCTION TO PREDICTIVE MAINTENANCE

Second Edition

AN INTRODUCTION TO PREDICTIVE MAINTENANCE

Second Edition

R. Keith Mobley

BUTTERWORTH HEINEMANN

Amsterdam London New York Oxford Paris Tokyo
Boston San Diego San Francisco Singapore Sydney

Butterworth-Heinemann is an imprint of Elsevier Science.

∞ Recognizing the importance of preserving what has been written, Elsevier-Science prints its books on acid-free paper whenever possible.

Library of Congress Cataloging-in-Publication Data
Mobley, R. Keith, 1943–.
An introduction to predictive maintenance / R. Keith Mobley.—2nd ed.
p. cm.
Includes index.
ISBN 0-7506-7531-4 (alk. paper)
1. Plant maintenance—Management. I. Title.
TS192 .M624 2002
658.2′02—dc21
2001056670

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

The publisher offers special discounts on bulk orders of this book.
For information, please contact:

Manager of Special Sales
Elsevier Science
225 Wildwood Avenue
Woburn, MA 01801-2041
Tel: 781-904-2500
Fax: 781-904-2620

For information on all Butterworth-Heinemann publications available, contact our World Wide Web home page at: http://www.bh.com

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

1 Impact of Maintenance 1

1.1 Maintenance management methods 2

1.2 Optimizing predictive maintenance......... 10

2 Financial Implications and Cost Justification 23

2.1 Assessing the need for condition monitoring 24

2.2 Cost justification 25

2.3 Justifying predictive maintenance........... 29

2.4 Economics of preventive maintenance... 32

3 Role of Maintenance Organization 43

3.1 Maintenance mission.............................. 43

3.2 Evaluation of the maintenance organization 44

3.3 Designing a predictive maintenance program 50

4 Benefits of Predictive Maintenance....... 60

4.1 Primary uses of predictive maintenance 61

5 Machine-Train Monitoring Parameters.. 74

5.1 Drivers 75

5.2 Intermediate drives 78

5.3 Driven components................................ 86

6 Predictive Maintenance Techniques 99

6.1 Vibration monitoring................................ 99

6.2 Themography 105

6.3 Tribology 108
6.4 Visual inspections 111
6.5 Ultrasonics 111
6.6 Other techniques 112

7 Vibration Monitoring and Analysis 114
7.1 Vibration analysis applications 114
7.2 Vibration analysis overview 117
7.3 Vibration sources 122
7.4 Vibration theory 125
7.5 Machine dynamics 132
7.6 Vibration data types and formats 146
7.7 Data acquisition 152
7.8 Vibration analyses techniques 161
Appendix 7.1 Abbreviations 165
Appendix 7.2 Glossary 166
Appendix 7.3 References 171

8 Thermography 172
8.1 Infrared basics 172
8.2 Types of infrared instruments 174
8.3 Training.. 175
8.4 Basic infrared theory............................... 176
8.5 Infrared equipment 178
8.6 Infrared thermography safety 179
8.7 Infrared thermography procedures 179
8.8 Types of infrared problems 179
Appendix 8.1 Abbreviations 183

Appendix 8.2 Glossary 183
Appendix 8.3 Electrical terminology 187
Appendix 8.4 Materials list............................ 193

9 Tribology 202
9.1 Lubricating oil analysis 203
9.2 Setting up an effective program.............. 208

10 Process Parameters.............................. 217
10.1 Pumps 218
10.2 Fans, blowers, and fluidizers 225
10.3 Conveyors 229
10.4 Compressors 229
10.5 Mixers and agitators 240
10.6 Dust collectors 240
10.7 Process rolls 241
10.8 Gearboxes/reducers 242
10.9 Steam traps 249
10.10 Inverters.. 249
10.11 Control valves 249
10.12 Seals and packing 251

11 Ultrasonics... 256
11.1 Ultrasonic applications.......................... 256
11.2 Types of ultrasonic systems 257
11.3 Limitations 258

12 Visual Inspection.................................. 259
12.1 Visual inspection methods 260
12.2 Thresholds 263

13 Operating Dynamics Analysis 267

13.1 It's not predictive maintenance 267

14 Failure-Mode Analysis 285

14.1 Common general failure modes 286

14.2 Failure modes by machine-train component 301

15 Establishing A Predictive Maintenance Program 325

15.1 Goals, objectives, and benefits............. 325

15.2 Functional requirements 326

15.3 Selling predictive maintenance programs 330

15.4 Selecting a predictive maintenance system 334

15.5 Database development......................... 343

15.6 Getting started 348

16 A Total-Plant Predictive Maintenance Program................................ 352

16.1 The optimum predictive maintenance program 353

16.2 Predictive is not enough 356

17 Maintaining the Program 389

17.1 Trending techniques 389

17.2 Analysis techniques.............................. 390

17.4 Additional training 392

17.5 Technical support 393

17.6 Contract predictive maintenance programs 393

18 World-Class Maintenance 394

18.1 What is world-class maintenance? 394

18.2 Five fundamentals of world-class performance 395

18.3 Competitive advantage 396

18.4 Focus on quality 397

18.5 Focus on maintenance 398

18.6 Overall equimpment effectiveness 402

18.7 Elements of effective maintenance....... 406

18.8 Responsibilities.................................... 412

18.9 Three types of maintenance 413

18.10 Supervision... 419

18.11 Standard procedures 424

18.12 Workforce development...................... 426

Index 435

1

IMPACT OF MAINTENANCE

Maintenance costs are a major part of the total operating costs of all manufacturing or production plants. Depending on the specific industry, maintenance costs can represent between 15 and 60 percent of the cost of goods produced. For example, in food-related industries, average maintenance costs represent about 15 percent of the cost of goods produced, whereas maintenance costs for iron and steel, pulp and paper, and other heavy industries represent up to 60 percent of the total production costs.

These percentages may be misleading. In most American plants, reported maintenance costs include many nonmaintenance-related expenditures. For example, many plants include modifications to existing capital systems that are driven by market-related factors, such as new products. These expenses are not truly maintenance and should be allocated to nonmaintenance cost centers; however, true maintenance costs are substantial and do represent a short-term improvement that can directly impact plant profitability.

Recent surveys of maintenance management effectiveness indicate that one-third—33 cents out of every dollar—of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance. When you consider that U.S. industry spends more than $200 billion each year on maintenance of plant equipment and facilities, the impact on productivity and profit that is represented by the maintenance operation becomes clear.

The result of ineffective maintenance management represents a loss of more than $60 billion each year. Perhaps more important is the fact that ineffective maintenance management significantly affects the ability to manufacture quality products that are competitive in the world market. The losses of production time and product quality that result from poor or inadequate maintenance management have had a dramatic impact on U.S. industries' ability to compete with Japan and other countries that have implemented more advanced manufacturing and maintenance management philosophies.

The dominant reason for this ineffective management is the lack of factual data to quantify the actual need for repair or maintenance of plant machinery, equipment, and systems. Maintenance scheduling has been, and in many instances still is, predicated on statistical trend data or on the actual failure of plant equipment.

Until recently, middle- and corporate-level management have ignored the impact of the maintenance operation on product quality, production costs, and more important, on bottom-line profit. The general opinion has been "Maintenance is a necessary evil" or "Nothing can be done to improve maintenance costs." Perhaps these statements were true 10 or 20 years ago, but the development of microprocessor- or computer-based instrumentation that can be used to monitor the operating condition of plant equipment, machinery, and systems has provided the means to manage the maintenance operation. This instrumentation has provided the means to reduce or eliminate unnecessary repairs, prevent catastrophic machine failures, and reduce the negative impact of the maintenance operation on the profitability of manufacturing and production plants.

1.1 Maintenance Management Methods

To understand a predictive maintenance management program, traditional management techniques should first be considered. Industrial and process plants typically employ two types of maintenance management: run-to-failure or preventive maintenance.

1.1.1 Run-to-Failure Management

The logic of run-to-failure management is simple and straightforward: When a machine breaks down, fix it. The "If it ain't broke, don't fix it" method of maintaining plant machinery has been a major part of plant maintenance operations since the first manufacturing plant was built, and on the surface it sounds reasonable. A plant using run-to-failure management does not spend any money on maintenance until a machine or system fails to operate.

Run-to-failure is a reactive management technique that waits for machine or equipment failure before any maintenance action is taken; however, it is actually a "no-maintenance" approach of management. It is also the most expensive method of maintenance management. Few plants use a true run-to-failure management philosophy. In almost all instances, plants perform basic preventive tasks (i.e., lubrication, machine adjustments, and other adjustments), even in a run-to-failure environment. In this type of management, however, machines and other plant equipment are not rebuilt, nor are any major repairs made until the equipment fails to operate. The major expenses associated with this type of maintenance management are high spare parts inventory cost, high overtime labor costs, high machine downtime, and low production availability.

Because no attempt is made to anticipate maintenance requirements, a plant that uses true run-to-failure management must be able to react to all possible failures within the plant. This reactive method of management forces the maintenance department to maintain extensive spare parts inventories that include spare machines or at least all major components for all critical equipment in the plant. The alternative is to rely on equipment vendors that can provide immediate delivery of all required spare parts.

Even if the latter option is possible, premiums for expedited delivery substantially increase the costs of repair parts and downtime required to correct machine failures. To minimize the impact on production created by unexpected machine failures, maintenance personnel must also be able to react immediately to all machine failures. The net result of this reactive type of maintenance management is higher maintenance cost and lower availability of process machinery. Analysis of maintenance costs indicates that a repair performed in the reactive or run-to-failure mode will average about three times higher than the same repair made within a scheduled or preventive mode. Scheduling the repair minimizes the repair time and associated labor costs. It also reduces the negative impact of expedited shipments and lost production.

1.1.2 Preventive Maintenance

There are many definitions of preventive maintenance, but all preventive maintenance management programs are time-driven. In other words, maintenance tasks are based on elapsed time or hours of operation. Figure 1–1 illustrates an example of the statistical life of a machine-train. The mean-time-to-failure (MTTF) or bathtub curve indicates that a new machine has a high probability of failure because of installation problems during the first few weeks of operation. After this initial period, the probability of failure is relatively low for an extended period. After this normal machine life period, the probability of failure increases sharply with elapsed time. In preventive maintenance management, machine repairs or rebuilds are scheduled based on the MTTF statistic.

The actual implementation of preventive maintenance varies greatly. Some programs are extremely limited and consist of only lubrication and minor adjustments. Comprehensive preventive maintenance programs schedule repairs, lubrication, adjustments, and machine rebuilds for all critical plant machinery. The common denominator for all of these preventive maintenance programs is the scheduling guideline—time.

All preventive maintenance management programs assume that machines will degrade within a time frame typical of their particular classification. For example, a single-stage, horizontal split-case centrifugal pump will normally run 18 months before it must be rebuilt. Using preventive management techniques, the pump would be removed from service and rebuilt after 17 months of operation. The problem with this

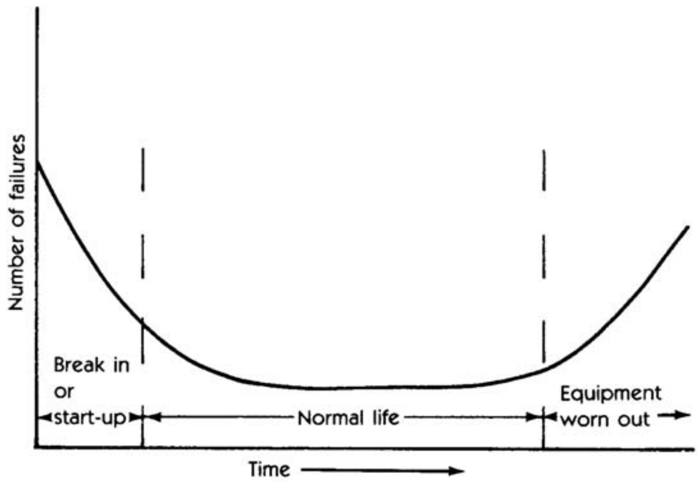


Figure 1–1 Typical bathtub curve.

approach is that the mode of operation and system or plant-specific variables directly affect the normal operating life of machinery. The mean-time-between-failures (MTBF) is not the same for a pump that handles water and one that handles abrasive slurries.

The normal result of using MTBF statistics to schedule maintenance is either unnecessary repairs or catastrophic failure. In the example, the pump may not need to be rebuilt after 17 months. Therefore, the labor and material used to make the repair was wasted. The second option using preventive maintenance is even more costly. If the pump fails before 17 months, it must be repaired using run-to-failure techniques. Analysis of maintenance costs has shown that repairs made in a reactive (i.e., after failure) mode are normally three times greater than the same repairs made on a scheduled basis.

1.1.3 Predictive Maintenance

Like preventive maintenance, predictive maintenance has many definitions. To some workers, predictive maintenance is monitoring the vibration of rotating machinery in an attempt to detect incipient problems and to prevent catastrophic failure. To others, it is monitoring the infrared image of electrical switchgear, motors, and other electrical equipment to detect developing problems. The common premise of predictive maintenance is that regular monitoring of the actual mechanical condition, operating efficiency, and other indicators of the operating condition of machine-trains and process systems will provide the data required to ensure the maximum interval between repairs and minimize the number and cost of unscheduled outages created by machine-train failures.

Predictive maintenance is much more, however. It is the means of improving productivity, product quality, and overall effectiveness of manufacturing and production plants. Predictive maintenance is not vibration monitoring or thermal imaging or lubricating oil analysis or any of the other nondestructive testing techniques that are being marketed as predictive maintenance tools.

Predictive maintenance is a philosophy or attitude that, simply stated, uses the actual operating condition of plant equipment and systems to optimize total plant operation. A comprehensive predictive maintenance management program uses the most cost-effective tools (e.g., vibration monitoring, thermography, tribology) to obtain the actual operating condition of critical plant systems and based on this actual data schedules all maintenance activities on an as-needed basis. Including predictive maintenance in a comprehensive maintenance management program optimizes the availability of process machinery and greatly reduces the cost of maintenance. It also improves the product quality, productivity, and profitability of manufacturing and production plants.

Predictive maintenance is a condition-driven preventive maintenance program. Instead of relying on industrial or in-plant average-life statistics (i.e., mean-time-to-failure) to schedule maintenance activities, predictive maintenance uses direct monitoring of the mechanical condition, system efficiency, and other indicators to determine the actual mean-time-to-failure or loss of efficiency for each machine-train and system in the plant. At best, traditional time-driven methods provide a guideline to "normal" machine-train life spans. The final decision in preventive or run-to-failure programs on repair or rebuild schedules must be made on the basis of intuition and the personal experience of the maintenance manager.

The addition of a comprehensive predictive maintenance program can and will provide factual data on the actual mechanical condition of each machine-train and the operating efficiency of each process system. This data provides the maintenance manager with actual data for scheduling maintenance activities. A predictive maintenance program can minimize unscheduled breakdowns of all mechanical equipment in the plant and ensure that repaired equipment is in acceptable mechanical condition. The program can also identify machine-train problems before they become serious. Most mechanical problems can be minimized if they are detected and repaired early. Normal mechanical failure modes degrade at a speed directly proportional to their severity. If the problem is detected early, major repairs can usually be prevented.

Predictive maintenance using vibration signature analysis is predicated on two basic facts: (1) all common failure modes have distinct vibration frequency components that can be isolated and identified, and (2) the amplitude of each distinct vibration component will remain constant unless the operating dynamics of the machine-train change. These facts, their impact on machinery, and methods that will identify and quantify the root cause of failure modes are developed in more detail in later chapters.

Predictive maintenance using process efficiency, heat loss, or other nondestructive techniques can quantify the operating efficiency of nonmechanical plant equipment or systems. These techniques used in conjunction with vibration analysis can provide maintenance managers and plant engineers with information that will enable them to achieve optimum reliability and availability from their plants.

Five nondestructive techniques are normally used for predictive maintenance management: vibration monitoring, process parameter monitoring, thermography, tribology, and visual inspection. Each technique has a unique data set that assists the maintenance manager in determining the actual need for maintenance.

How do you determine which technique or techniques are required in your plant? How do you determine the best method to implement each of the technologies? How do you separate the good from the bad? Most comprehensive predictive maintenance programs use vibration analysis as the primary tool. Because most normal plant equipment is mechanical, vibration monitoring provides the best tool for routine monitoring and identification of incipient problems; however, vibration analysis does not provide the data required on electrical equipment, areas of heat loss, condition of lubricating oil, or other parameters that should be included in your program.

1.1.4 Other Maintenance Improvement Methods

Over the past 10 years, a variety of management methods, such as total productive maintenance (TPM) and reliability-centered maintenance (RCM), have been developed and touted as the panacea for ineffective maintenance. Many domestic plants have partially adopted one of these quick-fix methods in an attempt to compensate for perceived maintenance shortcomings.

Total Productive Maintenance

Touted as the Japanese approach to effective maintenance management, the TPM concept was developed by Deming in the late 1950s. His concepts, as adapted by the Japanese, stress absolute adherence to the basics, such as lubrication, visual inspections, and universal use of best practices in all aspects of maintenance.

TPM is not a maintenance management program. Most of the activities associated with the Japanese management approach are directed at the production function and assume that maintenance will provide the basic tasks required to maintain critical production assets. All of the quantifiable benefits of TPM are couched in terms of capacity, product quality, and total production cost. Unfortunately, domestic advocates of TPM have tried to implement its concepts as maintenance-only activities. As a result, few of these attempts have been successful.

At the core of TPM is a new partnership among the manufacturing or production people, maintenance, engineering, and technical services to improve what is called *overall equipment effectiveness* (OEE). It is a program of zero breakdowns and zero defects aimed at improving or eliminating the following six crippling shop-floor losses:

- Equipment breakdowns
- Setup and adjustment slowdowns
- Idling and short-term stoppages
- Reduced capacity
- Quality-related losses
- Startup/restart losses

A concise definition of TPM is elusive, but improving equipment effectiveness comes close. The partnership idea is what makes it work. In the Japanese model for TPM are five pillars that help define how people work together in this partnership.

Five Pillars of TPM. Total productive maintenance stresses the basics of good business practices as they relate to the maintenance function. The five fundamentals of this approach include the following:

1. *Improving equipment effectiveness*. In other words, looking for the six big losses, finding out what causes your equipment to be ineffective, and making improvements.
2. *Involving operators in daily maintenance*. This does not necessarily mean actually performing maintenance. In many successful TPM programs, operators do not have to actively perform maintenance. They are involved in the maintenance activity—in the plan, in the program, and in the partnership—but not necessarily in the physical act of maintaining equipment.
3. *Improving maintenance efficiency and effectiveness*. In most TPM plans, though, the operator is directly involved in some level of maintenance. This effort involves better planning and scheduling better preventive maintenance, predictive maintenance, reliability-centered maintenance, spare parts equipment stores, and tool locations—the collective domain of the maintenance department and the maintenance technologies.
4. *Educating and training personnel*. This task is perhaps the most important in the TPM approach. It involves everyone in the company: Operators are taught how to operate their machines properly and maintenance personnel to maintain them properly. Because operators will be performing some of the inspections, routine machine adjustments, and other preventive tasks, training involves teaching operators how to do those inspections and how to work with maintenance in a partnership. Also involved is training supervisors on how to supervise in a TPM-type team environment.
5. *Designing and managing equipment for maintenance prevention*. Equipment is costly and should be viewed as a productive asset for its entire life. Designing equipment that is easier to operate and maintain than previous designs is a fundamental part of TPM. Suggestions from operators and maintenance technicians help engineers design, specify, and procure more effective equipment. By evaluating the costs of operating and maintaining

the new equipment throughout its life cycle, long-term costs will be minimized. Low purchase prices do not necessarily mean low life-cycle costs.

Overall equipment effectiveness (OEE) is the benchmark used for TPM programs. The OEE benchmark is established by measuring equipment performance. Measuring equipment effectiveness must go beyond just the availability or machine uptime. It must factor in all issues related to equipment performance. The formula for equipment effectiveness must look at the availability, the rate of performance, and the quality rate. This allows all departments to be involved in determining equipment effectiveness. The formula could be expressed as:

$$\text{Availability} \times \text{Performance Rate} \times \text{Quality Rate} = \text{OEE}$$

The availability is the required availability minus the downtime, divided by the required availability. Expressed as a formula, this would be:

$$\frac{\text{Required Availability} - \text{Downtime}}{\text{Required Availability}} \times 100 = \text{Availability}$$

The required availability is the time production is to operate the equipment, minus the miscellaneous planned downtime, such as breaks, scheduled lapses, meetings, and the like. The downtime is the actual time the equipment is down for repairs or changeover. This is also sometimes called breakdown downtime. The calculation gives the true availability of the equipment. This number should be used in the effectiveness formula. The goal for most Japanese companies is greater than 90 percent.

The performance rate is the ideal or design cycle time to produce the product multiplied by the output and divided by the operating time. This will give a performance rate percentage. The formula is:

$$\frac{\text{Design Cycle Time} \times \text{Output}}{\text{Operating Time}} \times 100 = \text{Performance Rate}$$

The design cycle time or production output is in a unit of production, such as parts per hour. The output is the total output for the given time period. The operating time is the availability value from the previous formula. The result is a percentage of performance. This formula is useful for spotting capacity reduction breakdowns. The goal for most Japanese companies is greater than 95 percent.

The quality rate is the production input into the process or equipment minus the volume or number of quality defects divided by the production input. The formula is:

$$\frac{\text{Production Input} - \text{Quality Defects}}{\text{Production Input}} \times 100 = \text{Quality Rate}$$

The production input is the unit of product being fed into the process or production cycle. The quality defects are the amount of product that is below quality standards (not rejected; there is a difference) after the process or production cycle is finished. The formula is useful in spotting production-quality problems, even when the customer accepts the poor-quality product. The goal for Japanese companies is higher than 99 percent.

Combining the total for the Japanese goals, it is seen that:

$$90\% \times 95\% \times 99\% = 85\%$$

To be able to compete for the national TPM prize in Japan, equipment effectiveness must be greater than 85 percent. Unfortunately, equipment effectiveness in most U.S. companies barely breaks 50 percent—little wonder that there is so much room for improvement in typical equipment maintenance management programs.

Reliability-Centered Maintenance

A basic premise of RCM is that all machines must fail and have a finite useful life, but neither of these assumptions is valid. If machinery and plant systems are properly designed, installed, operated, and maintained, they will not fail, and their useful life is almost infinite. Few, if any, catastrophic failures are random, and some outside influence, such as operator error or improper repair, causes all failures. With the exception of instantaneous failures caused by gross operator error or a totally abnormal outside influence, the operating dynamics analysis methodology can detect, isolate, and prevent system failures.

Because RCM is predicated on the belief that all machines will degrade and fail (P-F curve), most of the tasks, such as failure modes and effects analysis (FMEA) and Weibull distribution analysis, are used to anticipate when these failures will occur. Both of the theoretical methods are based on probability tables that assume proper design, installation, operation, and maintenance of plant machinery. Neither is able to adjust for abnormal deviations in any of these categories.

When the RCM approach was first developed in the 1960s, most production engineers believed that machinery had a finite life and required periodic major rebuilding to maintain acceptable levels of reliability. In his book *Reliability-Centered Maintenance* (1992), John Moubray states:

> The traditional approach to scheduled maintenance programs was based on the concept that every item on a piece of complex equipment has a *right age* at which complete overhaul is necessary to ensure safety and operating reliability. Through the years, however, it was discovered that many types of failures could not be prevented or effectively reduced by such maintenance activities, no matter how intensively they were performed. In response to this problem, airplane designers began to develop design features that mitigated failure consequences—that is, they learned how to

design airplanes that were *failure tolerant*. Practices such as the replication of system functions, the use of multiple engines, and the design of damage-tolerant structures greatly weakened the relationship between safety and reliability, although this relationship has not been eliminated altogether.

Mobray points to two examples of successful application of RCM in the commercial aircraft industry—the Douglas DC-10 and the Boeing 747. When his book was written, both of these aircraft were viewed as exceptionally reliable; however, history has changed this view. The DC-10 has the worst accident record of any aircraft used in commercial aviation; it has proven to be chronically unreliable. The Boeing 747 has faired better, but has had several accidents that were directly caused by reliability problems.

Not until the early 1980s did predictive maintenance technologies, such as microprocessor-based vibration analysis, provide an accurate means of early detection of incipient problems. With the advent of these new technologies, most of the founding premises of RCM disappeared. The ability to detect the slightest deviation from optimum operating condition of critical plant systems provides the means to prevent deterioration that ultimately results in failure of these systems. If prompt corrective action is taken, it effectively stops the degradation and prevents the failure that is the heart of the P-F curve.

1.2 Optimizing Predictive Maintenance

Too many of the predictive maintenance programs that have been implemented have failed to generate measurable benefits. These failures have not been caused by technology limitation, but rather by the failure to make the necessary changes in the workplace that would permit maximum utilization of these predictive tools. As a minimum, the following proactive steps can eliminate these restrictions and as a result help gain maximum benefits from the predictive maintenance program.

1.2.1 Culture Change

The first change that must take place is to change the perception that predictive technologies are exclusively a maintenance management or breakdown prevention tool. This change must take place at the corporate level and permeate throughout the plant organization. This task may sound simple, but changing corporate attitude toward or perception of maintenance and predictive maintenance is difficult. Because most corporate-level managers have little or no knowledge or understanding of maintenance—or even the need for maintenance—convincing them that a broader use of predictive technologies is necessary is extremely difficult. In their myopic view, breakdowns and unscheduled delays are solely a maintenance issue. They cannot understand that most of these failures are the result of nonmaintenance issues.

From studies of equipment reliability problems conducted over the past 30 years, maintenance is responsible for about 17 percent of production interruptions and quality problems. The remaining 83 percent are totally outside of the traditional maintenance function's responsibility. Inappropriate operating practices, poor design, nonspecification parts, and a myriad of other nonmaintenance reasons are the primary contributors to production and product-quality problems, not maintenance.

Predictive technologies should be used as a plant or process optimization tool. In this broader scope, they are used to detect, isolate, and provide solutions for all deviations from acceptable performance that result in lost capacity, poor quality, abnormal costs, or a threat to employee safety. These technologies have the power to fill this critical role, but that power is simply not being used. To accomplish this new role, the use of predictive technologies should be shifted from the maintenance department to a reliability group that is charged with the responsibility and is accountable for plant optimization. This group must have the authority to cross all functional boundaries and to implement changes that correct problems uncovered by their evaluations.

This approach is a radical departure from the traditional organization found in most plants. As a result, resistance will be met from all levels of the organization. With the exception of those few employees who understand the absolute need for a change to better, more effective practices, most of the workforce will not openly embrace or voluntarily accept this new functional group; however, the formation of a dedicated group of professionals that is absolutely and solely responsible for reliability improvement and optimization of all facets of plant operation is essential. It is the only way a plant or corporation can achieve and sustain world-class performance.

Staffing this new group will not be easy. The team must have a thorough knowledge of machine and process design, and be able to implement best practices in both operation and maintenance of all critical production systems in the plant. In addition, they must fully understand procurement and plant engineering methods that will provide best life-cycle cost for these systems. Finally, the team must understand the proper use of predictive technologies. Few plants have existing employees who have all of these fundamental requirements.

This problem can be resolved in two ways. The first approach would be to select personnel who have mastered one or more of these knowledge requirements. For example, the group might consist of the best operations, maintenance, engineering, and predictive personnel available from the current workforce. Care must be taken to ensure that each group member has a real knowledge of his or her specialty area. One common problem that plagues plants is that the superstars in the organization do not have a real, in-depth knowledge of their perceived specialty. In other words, the best operator may in fact be the worst contributor to reliability or performance problems. Although he or she can get more capacity through the unit than anyone else, the practices used may be the root-cause of chronic problems.

If this approach is followed, training for the reliability team must be the first priority. Few existing personnel will have all of the knowledge and skills required by this function, especially regarding application of predictive technologies. Therefore, the company must provide sufficient training to ensure maximum return on its investment. This training should focus on process or operating dynamics for each of the critical production systems in the plant. It should include comprehensive process design, operating envelope, operating methods, and process diagnostics training that will form the foundation for the reliability group's ability to optimize performance.

The second approach is to hire professional reliability engineers. This approach may sound easier, but it is not because there are very few fully qualified reliability professionals available, and they are very, very expensive. Most of these professionals prefer to offer their services as short-term consultants rather than become a long-term employee. If you try to hire rather than staff internally, use extreme caution. Résumés may sound great, but real knowledge is hard to find. For example, we recently interviewed 150 "qualified" predictive engineers but found only 5 with the basic knowledge we required. Even then, these five candidates required extensive training before they could provide acceptable levels of performance.

1.2.2 Proper Use of Predictive Technologies

System components, such as pumps, gearboxes, and so on, are an integral part of the system and must operate within their design envelope before the system can meet its designed performance levels. Why then, do most predictive programs treat these components as isolated machine-trains and not as part of an integrated system? Instead of evaluating a centrifugal pump or gearbox as part of the total machine, most predictive analysts limit technology use to simple diagnostics of the mechanical condition of that individual component. As a result, no effort is made to determine the influence of system variables, like load, speed, product, or instability on the individual component. These variations in process variables are often the root-cause of the observed mechanical problem in the pump or gearbox. Unless analysts consider these variables, they will not be able to determine the true root-cause. Instead, they will make recommendations to correct the symptom (e.g., damaged bearing, misalignment), rather than the real problem.

The converse is also true. When diagnostics are limited to individual components, system problems cannot be detected, isolated, and resolved. The system, not the individual components of that system, generates capacity, revenue, and bottom-line profit for the plant. Therefore, the system must be the primary focus of analysis.

When one thinks of predictive maintenance, vibration monitoring, thermography, or tribology is the normal vision. These are powerful tools, but they are not the panacea for plant problems. Used individually or in combination, these three cornerstones of predictive technologies cannot provide all of the diagnostics required to achieve and sustain world-class performance levels. To gain maximum benefit from predictive technologies, the following changes are needed: Process parameters, such as flow rates, retention time, temperatures, and others, are absolute requirements in all predictive maintenance and process optimization programs. These parameters define the operating envelope of the process and are essential requirements for system operation. In many cases, these data are readily available.

On systems that use computer-based or processor logic control (PLC), the parameters or variables that define their operating envelopes are automatically acquired and then used by the control logic to operate the system. The type and number of variables vary from system to system but are based on the actual design and mode of operation for that specific type of production system. It is a relatively simple matter to acquire these data from the Level I control system and use it as part of the predictive diagnostic logic. In most cases, these data combined with traditional predictive technologies provide all of the data an analyst needs to fully understand the system's performance.

Manually operated systems should not be ignored. Although the process data is more difficult to obtain, the reliability or predictive analyst can usually acquire enough data to permit full diagnostics of the system's performance or operating condition. Analog gauges, thermocouples, strip chart recorders, and other traditional plant instrumentation can be used. If plant instrumentation includes an analog or digital output, most microprocessor-based vibration meters can be used for direct data acquisition. These instruments can directly acquire most proportional signal outputs and automate the data acquisition and management that is required for this expanded scope of predictive technology.

Because most equipment used in domestic manufacturing, production, and process plants consists of electromechanical systems, our discussion begins with the best methods for this classification of equipment. Depending on the plant, these systems may range from simple machine-trains, such as drive couple pumps and electric motors, to complex continuous process lines. Regardless of the complexity, the methods that should be used are similar.

In all programs, the primary focus of the predictive maintenance program must be on the critical process systems or machine-trains that constitute the primary production activities of the plant. Although auxiliary equipment is important, the program must first address those systems on which the plant relies to produce revenue. In many cases, this approach is a radical departure from the currently used methods in traditional applications of predictive maintenance. In these programs, the focus is on simple rotating machinery and excludes the primary production processes.

Electromechanical Systems

Predictive maintenance for all electromechanical systems, regardless of their complexity, should use a combination of vibration monitoring, operating dynamics analysis, and infrared technologies. This combination is needed to ensure the ability to accurately determine the operating condition, to identify any deviation from acceptable operations, and to isolate the root-cause of these deviations.

Vibration Analysis. Single-channel vibration analysis, using microprocessor-based, portable instruments, is acceptable for routine monitoring of these critical production systems; however, the methods used must provide an accurate representation of the operating condition of the machine or system. The biggest change that must be made is in the parameters that are used to acquire vibration data.

When the first microprocessor-based vibration meter was developed in the early 1980s, the ability to acquire multiple blocks of raw data and then calculate an average vibration value was incorporated to eliminate the potential for spurious signals or bad data resulting from impacts or other transients that might distort the vibration signature. Generally, one to three blocks of data are adequate to acquire an accurate vibration signature. Today, most programs are set up to acquire 8 to 12 blocks of data from each measurement point. These data are then averaged and stored for analysis.

This methodology poses two problems. First, this approach distorts the data that will ultimately be used to determine whether corrective maintenance actions are necessary. When multiple blocks of data are used to create an average, transient events, such as impacts and periodic changes in the vibration profile, are excluded from the stored average that is the basis for analysis. As a result, the analyst is unable to evaluate the impact on operating condition that these transients may cause.

The second problem is time. Each block of data, depending on the speed of the machine, requires between 5 and 60 seconds of acquisition time. As a result, the time required for data acquisition is increased by orders of magnitude. For example, a data set, using 3 blocks, may take 15 seconds. The same data set using 12 blocks will then take 60 seconds. The difference of 45 seconds may not sound like much until you multiply it by the 400 measure points that are acquired in a typical day (5 labor hours per day) or 8,000 points in a typical month (100 labor hours per month).

Single-channel vibration instruments cannot provide all of the functions needed to evaluate the operating condition of critical production systems. Because these instruments are limited to steady-state analysis techniques, a successful predictive maintenance program must also include the ability to acquire and analyze both multichannel and transient vibration data. The ideal solution to this requirement is to include a multichannel *real-time analyzer*. These instruments are designed to acquire, store, and display real-time vibration data from multiple data points on the machine-train. These data provide the means for analysts to evaluate the dynamics of the machine and greatly improve their ability to detect incipient problems long before they become a potential problem.

Real-time analyzers are expensive, and some programs in smaller plants may not be able to justify the additional $50,000 to $100,000 cost. Although not as accurate as using a real-time analyzer, these programs can purchase a multichannel, digital tape recorder that can be used for real-time data acquisition. Several eight-channel digital recorders on the market range in price from $5,000 to $10,000 and have the dynamic range needed for accurate data acquisition. The tape-recorded data can be played back through most commercially available single-channel vibration instruments for analysis. Care must be taken to ensure that each channel of data is synchronized, but this methodology can be used effectively.

Operating Dynamics Analysis. Vibration data should never be used in a vacuum. Because the dynamic forces within the monitored machine and the system that it is a part of generate the vibration profile that is acquired and stored for analysis, both the data acquisition and analysis processes must always include all of the process variables, such as incoming materials, pressures, speeds, temperatures, and so on, that define the operating envelope of the system being evaluated.

Generally, the first five to ten measurement points defined for a machine-train should be process variables. Most of the microprocessor instruments that are used for vibration analysis are actually data loggers. They are capable of either directly acquiring a variety of process inputs, such as pressure, temperature, flow, and so on, or permitting manual input by the technician. These data are essential for accurate analysis of the resultant vibration signature. Unless analysts recognize the process variations, they cannot accurately evaluate the vibration profile. A simple example of this approach is a centrifugal compressor. If the load changes from 100 percent to 50 percent between data sets, the resultant vibration is increased by a factor of four. This is caused by a change in the spring constant of the rotor system. By design, the load on the compressor acts as a stabilizing force on the rotating element. At 100 percent load, the rotor is forced to turn at or near its true centerline. When the load is reduced to 50 percent, the stabilizing force is reduced by one-half; however, spring constant is a quadratic function, so a 50 percent reduction of the spring constant or stiffness results in an increase of vibration amplitude of 400 percent.

Infrared Technologies. Heat and/or heat distribution is also an essential tool that should be used for all electromechanical systems. In simple machine-trains, it may be limited to infrared thermometers that are used to acquire the temperature-related process variables needed to determine the machine or system's operating envelope. In more complex systems, full infrared scanning techniques may be needed to quantify the heat distribution of the production system. In the former technique, noncontact, infrared thermometers are used in conjunction with the vibration meter or data logger to acquire needed temperatures, such as bearings, liquids being transferred, and so on. In the latter method, fully functional infrared cameras may be needed to scan boilers, furnaces, electric motors, and a variety of other process systems where surface heat distribution indicates the system's operating condition.

The Total Package. The combination of these three technologies or methods is the minimum needed for an effective predictive maintenance program. In some instances, other techniques, such as ultrasonics, lubricating oil analysis, Meggering, and so on, may be needed to help analysts fully understand the operating dynamics of critical machines or systems within the plant. None of these technologies can provide all of the data needed for accurate evaluation of machine or system condition; however, when used in combination and further augmented with a practical knowledge of machine and system dynamics, these techniques can and will provide a predictive maintenance program that will virtually eliminate catastrophic failures and the need for corrective maintenance. These methods will also extend the useful life and minimize the life cycle cost of critical production systems.

Predictive Maintenance Is More Than Maintenance

Traditionally, predictive maintenance is used solely as a maintenance management tool. In most cases, this use is limited to preventing unscheduled downtime and/or catastrophic failures. Although this function is important, predictive maintenance can provide substantially more benefits by expanding the scope or mission of the program. As a maintenance management tool, predictive maintenance can and should be used as a maintenance optimization tool. The program's focus should be on eliminating unnecessary downtime, both scheduled and unscheduled; eliminating unnecessary preventive and corrective maintenance tasks; extending the useful life of critical systems; and reducing the total life-cycle cost of these systems.

Plant Optimization Tool. Predictive maintenance technologies can provide even more benefit when used as a plant optimization tool. For example, these technologies can be used to establish the *best* production procedures and practices for all critical production systems within a plant. Few of today's plants are operating within the original design limits of their production systems. Over time, the products that these lines produce have changed. Competitive and market pressure have demanded increasingly higher production rates. As a result, the operating procedures that were appropriate for the as-designed systems are no longer valid. Predictive technologies can be used to map the actual operating conditions of these critical systems and to provide the data needed to establish valid procedures that will meet the demand for higher production rates without a corresponding increase in maintenance cost and reduced useful life. Simply stated, these technologies permit plant personnel to quantify the cause-and-effect relationship of various modes of operation. This ability to actually measure the effect of different operating modes on the reliability and resultant maintenance costs should provide the means to make sound business decisions.

Reliability Improvement Tool. As a reliability improvement tool, predictive maintenance technologies cannot be beat. The ability to measure even slight deviations from normal operating parameters permits appropriate plant personnel (e.g., reliability engineers, maintenance planners) to plan and schedule minor adjustments that will prevent degradation of the machine or system, thereby eliminating the need for major rebuilds and associated downtime.

Predictive maintenance technologies are not limited to simple electromechanical machines. These technologies can be used effectively on almost every critical system or component within a typical plant. For example, time-domain vibration can be used to quantify the response characteristics of valves, cylinders, linear-motion machines, and complex systems, such as oscillators on continuous casters. In effect, this type of predictive maintenance can be used on any machine where timing is critical.

The same is true for thermography. In addition to its traditional use as a tool to survey roofs and building structures for leaks or heat loss, this tool can be used for a variety of reliability-related applications. It is ideal for any system where surface temperature indicates the system's operating condition. The applications are almost endless, but few plants even attempt to use infrared as a reliability tool.

The Difference. Other than the mission or intent of how predictive maintenance is used in your plant, the real difference between the limited benefits of a traditional predictive maintenance program and the maximum benefits that these technologies could provide is the diagnostic logic used. In traditional predictive maintenance applications, analysts typically receive between 5 and 15 days of formal instruction. This training is always limited to the particular technique (e.g., vibration, thermography) and excludes all other knowledge that might help them understand the true operating condition of the machine, equipment, or system they are attempting to analyze.

The obvious fallacy in this approach is that none of the predictive technologies can be used as stand-alone tools to accurately evaluate the operating condition of critical production systems. Therefore, analysts must use a variety of technologies to achieve anything more than simple prevention of catastrophic failures. At a minimum, analysts should have a practical knowledge of machine design, operating dynamics, and the use of at least the three major predictive technologies (i.e., vibration, thermography, and tribology). Without this minimum knowledge, they cannot be expected to provide accurate evaluations or cost-effective corrective actions.

In summary, there are two fundamental requirements of a truly successful predictive maintenance program: (1) a mission that focuses the program on total-plant optimization and (2) proper training for technicians and analysts. The mission or scope of the program must be driven by life-cycle cost, maximum reliability, and best practices from all functional organizations within the plant. If the program is properly structured, the second requirement is to give the personnel responsible for the program the tools and skills required for proper execution.

1.2.3 It Takes More Than Effective Maintenance

Plant performance requirements are basically the same for both small and large plants. Although some radical differences exist, the fundamental requirements are the same for both. Before we explore the differences, we need to understand the fundamental requirements in the following areas:

- Plant culture
- Sales and marketing
- Production
- Procurement
- Maintenance
- Information management
- Other plant functions

Plant Culture

The foremost requirement of world-class plant performance is a work environment that encourages and sustains optimum performance levels from the entire workforce. This plant culture must start with senior management and be inherent throughout the entire workforce. Without a positive work environment that encourages total employee involvement and continuous improvement, there is little chance of success.

Sales and Marketing

The sales and marketing group must provide a volume of new business that can sustain acceptable levels of production performance. Optimum equipment utilization cannot be achieved without a backlog that permits full use of the manufacturing, production, or process systems; however, volume is not the only criteria that must be satisfied by the sales and marketing group. They must also provide (1) a product mix that permits effective use of the production process, (2) order size that limits the number and frequency of setups, (3) delivery schedules that permit effective scheduling of the process, and (4) a sales price that provides a reasonable profit. The final requirement of the sales group is an accurate production forecast that permits long-range production and maintenance planning.

Production

Production management is the third criteria for acceptable plant performance. The production department must plan and schedule the production process to gain maximum use of their processes. Proper planning depends on several factors: good communication with the sales and marketing group, knowledge of unit production capabilities, adequate material control, and good equipment reliability. Production planning and effective use of production resources also depend on coordination with procurement, human resources, and maintenance functions within the plant. Unless these functions provide direct, coordinated support, the production planning function cannot achieve acceptable levels of performance from the plant.

In addition, the production department must execute the production plan effectively. Good operating procedures and practices are essential. Every manufacturing and production function must have, and use, standard operating procedures that support effective use of the production systems. These procedures must be constantly evaluated and upgraded to ensure proper use of critical plant equipment.

Equipment reliability is essential for acceptable production performance. Contrary to popular opinion, maintenance does not control equipment reliability; the production department has an equal responsibility. Operating practices and the skill level of production employees have a direct impact on equipment reliability; therefore, all facets of the production process, from planning to execution, must address this critical issue.

The final requirement of effective production is employee skills. All employees within the production group must have adequate job skills. Human resources or the training department must maintain an evaluation and training program that ensures that employee skill levels are maintained at acceptable levels.

Procurement

The procurement function must provide raw materials, production spares, and other consumables at the proper times to support effective production. In addition, these commodities must be of suitable quality and functionality to permit effective use of the process systems and finished product quality. The procurement function is critical to good performance of both production and maintenance. This group must coordinate its activities with both functions and provide acceptable levels of performance. In addition, they must implement and maintain standard procedures and practices that ensure optimum support for both the production and maintenance functions. At a minimum, these procedures should include vendor qualification, procurement specifications based on life-cycle costs, incoming inspection, inventory control, and material control.

Maintenance

The maintenance function must ensure that all production and manufacturing equipment is kept in optimum operating condition. The normal practice of quick response to failures must be replaced with maintenance practices that sustain optimum operating condition of all plant systems. It is not enough to have the production system operate. The equipment must reliably operate at or above nameplate capacity without creating abnormal levels of product-quality problems, preventive maintenance downtime, or delays. Maintenance prevention, not quick-fixes of breakdowns, should be the objective.

Maintenance planning and scheduling are essential parts of effective maintenance. Planners must develop and implement both preventive and corrective maintenance tasks that achieve maximum use of maintenance resources and the production capacity of plant systems. Good planning is not an option. Plants should adequately plan all maintenance activities, not just those performed during maintenance outages.

Standard procedures and practices are essential for effective use of maintenance resources. The practices should ensure proper interval of inspection, adjustment, or repair. In addition, these practices should ensure that each task is properly completed. Standard maintenance procedures (SMPs) should be written so that any qualified craftsman can successfully complete the task in the minimum required time and at minimum costs.

Adherence to SMPs is also essential. The workforce must have the training and skills required to effectively complete their assigned duties. In addition, maintenance management must ensure that all maintenance employees follow standard practices and fully support continuous improvement.

Information Management

Effective use of plant resources absolutely depends on good management decisions. Therefore, viable information management is critical to good plant performance. All plants have an absolute requirement for a system that collects, compiles, and interprets data that define the effectiveness of all critical plant functions. This system must be capable of providing timely, accurate performance indices that can be used to plan, schedule, and manage the plant.

Other Plant Functions

In medium and large plants, other plant functions play a key role in plant performance. Smaller plants either do not have these functions or they are combined within either the production or maintenance functions. These functions include human resources, plant engineering, labor relations, cost accounting, and environmental control. Each of these departments must coordinate its activities with sales, production, and maintenance to ensure acceptable levels of plant performance.

1.2.4 Small Plants

All plants must adhere to the basics discussed, but small plants face unique constraints. Their size precludes substantial investments in labor, tools, and training that are essential to effective asset management or to support continuous improvement. Many small plants are caught in a Catch-22. They are too small to support effective planning or to implement many of the tools, such as predictive maintenance and computer-based maintenance management systems (CMMS), that are required to improve performance levels. At the same time, they must improve to survive. In addition, the return on investment (ROI) generated by traditional continuous improvement programs is generally insufficient to warrant implementing these programs.

Predictive maintenance is a classic example of this Catch-22. Because of their size, many small plants cannot justify implementing predictive maintenance. Although the program will generate similar improvements to those achieved in larger plants, the change in actual financial improvement may not justify the initial and recurring costs associated with this tool. For example, a 1 percent improvement in availability in a large plant may represent an improvement of $1 million to $100 million. The same improvement in a small plant may be $1,000 to $10,000. Large plants can afford to invest the money and labor required to achieve these goals. In small plants, the cost required to establish and maintain the predictive program may exceed the total gain.

The same Catch-22 prohibits implementing formal planning, procurement, and training programs in many smaller plants. The perception is that the addition of nonrevenue-generating personnel to provide these functions would prohibit acceptable levels of financial performance. In other words, the bottom line would suffer. This view may be true to a point, but few plants can afford *not* to include the essentials of plant performance.

In many ways, small plants have a more difficult challenge than larger plants; however, with proper planning and implementation, small plants can improve their performance and gain enough additional market share to ensure both survival and long-term positive growth. They must exercise extreme caution and base their long-range plan on realistic goals.

Some plants attempt to implement continuous improvement programs that include too many tools. They assume that full, in-house implementation of predictive maintenance, CMMS, and other continuous improvement tools are essential requirements of continuous improvement. This is not true. Small plants can implement a continuous improvement program that achieves the increased performance levels needed without major investments. Judicious use of continuous improvement tools, including outside support and modification of in-house organizations, will permit dramatic improvement without being offset by increased costs.

Continuous improvement tools, such as CMMS, information management systems, and the like, are available for small plants. These systems are specifically designed for this application and provide all of the functionality required to improve performance, without the high costs of larger, more complex systems. The key to successful implementation of these tools is automation. Small plants cannot afford to add personnel whose sole function is to maintain continuous improvement systems or the predictive maintenance program. Therefore, these tools must provide the data required to improve plant effectiveness without additional personnel.

1.2.5 Large Plants

Because of the benefits generated by continuous improvement programs, large plants can justify implementation; however, this should not be used as justification for implementing expensive or excessive programs. A typical tendency is to implement multiple improvement programs, such as total productive maintenance, just-in-time manufacturing, and total quality control, which are often redundant or conflict with each other. Frankly, this shotgun approach is not justified. Each of these programs adds an overhead of personnel whose sole function is program management. This increase in indirect personnel cannot be justified. Continuous improvement should be limited to a single, holistic program that integrates all plant functions into a focused, unified effort.

Large plants must exercise more discipline than their smaller counterparts. Because of their size, the responsibilities and coordination of all plant functions must be clearly defined. Planning and scheduling must be formalized, and communication within and among functions is much more difficult.

An integrated, computer-based information management system is an absolute requirement in larger plants. At a minimum, this system should include cost accounting, sales, production planning, maintenance planning, procurement, inventory control, and environmental compliance data. These data should be universally available for each plan function and configured to provide accurate, timely management and planning data. Properly implemented, this system will also provide a means to effectively communicate and coordinate the integrated functions, such as sales, production, maintenance, and procurement, into an effective unit.

Large plants must also exercise caution. The tendency is to become excessive when implementing continuous improvement programs. Features are added to the information management system, predictive maintenance program, and other tools that are not needed by the program. For example, one plant added the ability to include video clips in its CMMS. Although this added feature may have been of some value, it was not worth the $12 million additional cost.

Continuous improvement is an absolute requirement in all plants, but these programs must be implemented logically. Your program must be designed for the unique requirements of your plant. It should be designed to minimize the costs required to implement and maintain the program and to achieve the best ROI. In my 30 years as a manager and consultant, I have not found a single plant that would not benefit from a continuous improvement program; however, I have also seen thousands of plants that failed in their attempt to improve. Most of these failures were the result of either (1) restricting the program to a single function, such as maintenance or production, or (2) inflated costs generated by adding unnecessary tools. Both of these types of failures are preventable. If you approach continuous improvement in a logical, plant-specific manner, you can be successful regardless of plant size.

2

FINANCIAL IMPLICATIONS AND COST JUSTIFICATION

The simple process of financial justification for an investment project would normally be to compare the initial and ongoing expenditure with the expected benefits, translated into cost savings and increased profits. If the capital can be paid off in a reasonable time, and concurrently earn more than an equivalent investment in secure stocks, then the project is probably a good financial investment.

The case for buying a new machine tool, or setting up an extra production line, can be assessed in this way and is the normal basis on which a business is set up or expanded. The purchase price plus installation, recruitment, and training costs must be paid off within a limited number of years and continue to show a substantial profit after deducting the amount of borrowed capital, operating cost, and so on; however, the benefits from an investment in a condition monitoring (CM) system are more difficult to assess, especially as a simple cost–benefit exercise, because, to put it simply, the variables are much more intuitive and less measurable than pure machine performance characteristics.

The ultimate justification for a CM system is where a bottleneck machine is totally dependent on a single component such as a bearing or gearbox, and failure of this component would create a prolonged, unscheduled stoppage affecting large areas of the plant. The cost of such an event could well be in the six-figure bracket, and the effect on sales and customer satisfaction beyond quantification. Yet a convincing financial case depends largely on knowing how often this sort of disaster is likely to happen and having a precise knowledge of the nonquantifiable factors referred to earlier. At best, whatever the cost, if it were likely to happen, it would be foolish not to install some method of predicting it, so that the appropriate preventive action could be taken.

2.1 Assessing the Need for Condition Monitoring

Any maintenance engineer's assessment of plant condition is influenced by a variety of practical observations and analyses of machine performance data, such as the following:

- Frequency of breakdowns
- Randomness of breakdowns
- Need for repetitive repairs
- Number of defective products produced
- Potential dangers linked to poor performance
- Any excessive fuel consumption during operation
- Any reduced throughput during operation

These, and many more pointers, may suggest that a particular item of plant requires either careful monitoring, routine planned preventive maintenance, better emergency repair procedures, or some combination of all these approaches to ensure a reasonable level of operational availability. The engineering symptoms can, however, rarely be quantified accurately in terms of financial loss. Very few companies can put an accurate figure on the cost of downtime per hour. Many have no reliable records of their aggregate downtime at all, even if they could put a value per hour on it.

Thus, although a maintenance engineer may decide that a particular machine with a history of random bearing failures requires CM, if problems are to be anticipated, and the plant should be taken out of use before a catastrophic in-service failure occurs, how can he or she justify the expenditure of, say, $10,000 on the appropriate monitoring equipment, when plant and production records may be too vague to show what time and expense could be saved, and what this savings represents in terms of profit and loss to the company? This dilemma can be a daily occurrence for engineering and maintenance staffs in large and small companies throughout the country.

As if the practical problems of quantifying both the potential losses and gains were not difficult enough, the status of maintenance engineering in many organizations is such that any financial justification, however accurate, can be meaningless. The maintenance department in most companies is usually classified as a cost overhead. This means that a fixed sum is allocated to maintenance each year as a budget, which covers the cost of staff wages, spare parts, consumable items, and so on. The maintenance department is then judged for performance, financially or on its ability to work within its budget. Overspending is classified as "bad," and may result in restricting the department's resources even further in future years, whereas underspending is classified as "good," in that it contributes directly to company profits, even if equipment maintenance is neglected and manufacturing quality or throughput suffers as a result.

Let us suppose that a forward-looking engineer succeeds in persuading his or her financial director—who knows nothing about CM and would rather invest the money anyway—to part with the capital needed to buy the necessary CM equipment. What happens then? Our hero, by using CM, succeeds in reducing unscheduled machine stoppages drastically, but which department gets the credit? Usually production because they have not needed to work overtime to make up for any lost production or have fewer rejects. Alternately, the sales department may receive the credit because of improved product quality or reduced manufacturing cost, which has given them an advantage over the firm's competitors. The maintenance engineer is rarely recognized as having added to the organization's improved cash flow by his or her actions.

Thus, a company that does not have a system of standard value costing cannot hope to isolate the benefits of efficient plant engineering and persuade the board of directors to invest in an effective arrangement for equipment purchasing and maintenance. This presents a bleak picture for the person who has to make out a good financial case for installing a particular CM technique. Yet my company has seen this familiar situation repeatedly. This scenario occurs in most organizations, where we have received initial inquiries regarding installation of our software.

The expense of a computer system, for example, to collect and analyze plant data, without which an accurate cost justification is impossible, is often treated as nonproductive overhead. This is a classic Catch-22 situation, which has been stated in the past as: "We need the computer system to calculate whether we need the computer system, even though we know that it is essential before we start."

So, in order to justify the cost of a particular CM project, the appropriate person in the financial control hierarchy needs to be persuaded that the CM system should be treated as a capital investment charge in its own right, and not as an item of expenditure from the maintenance department's annual budget. Obviously, this will place the project in competition with other capital investment projects for the organization's limited resources. Accordingly, the case for justifying any CM equipment must be good and show a tangible return in a short period.

2.2 Cost Justification

To produce a good case for financial investment in CM equipment, it is therefore important to obtain reliable past performance data for the plant under review. In addition, information relating to other equipment, whose operations may be improved by better performance from the plant whose failures we hope to prevent, must also be gathered. It is also essential to establish an effective financial record of actual CM achievement. This is especially true after the installation of any original equipment, so that it is possible to build on the success of an initial project.

The performance data relating to CM must therefore be quantified financially, which in effect can mean persuading the managers for all departments involved to estimate the cost of the various factors that fall within their responsibility. Many managers, who may have criticized maintenance engineering in the past for poor production plant performance, by statements such as: "It is costing the company a fortune," can sud-

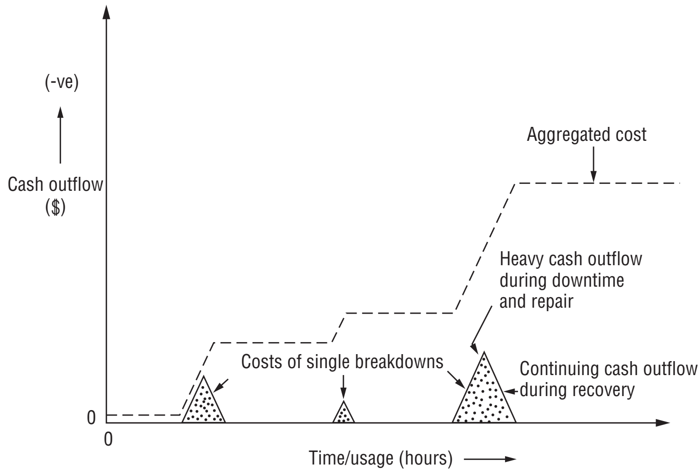


Figure 2–1 Typical cash flow diagram illustrating the cost of lost production.

denly become reluctant to put an actual cost value on the loss, particularly when asked for precise data. It is in their interest to try, however, because without financial data there can be no satisfactory cost justification for CM, and hence no will or investment to improve the maintenance situation. Ultimately, their department and the company will be the losers if poor maintenance leads to an uncompetitive marketplace position.

Some of the factors relevant to maintenance engineering that can have an adverse effect on the company's cash flow are as follows: Lost production and the need to work overtime to make up any shortfall in output; some organizations will find this factor relatively easy to quantify. For example, an unscheduled stoppage of 3 hours could mean 500 components not made, plus another 200 damaged during machine stoppage and restart. The production line would perhaps have to work an extra half shift of overtime to make up the loss, and thereby incur all the associated labor, heating, and other facility support costs involved. Alternately, the cost of a subcontract outside the company to make good the lost production is usually obtainable as a precise figure. This figure is normally easy to obtain and in real expenditure terms, as opposed to the internal cost of working overtime, which may not be so precisely calculated.

Other costs may also be difficult to quantify accurately, such as the sales department's need to put a value on the cost of customer dissatisfaction if a delivery is delayed, or the cost of changing the production schedule to correct the loss in production if the particular product involved has a high priority. The cost of lost production is a random set of peaks in the cash flow diagram, as shown in Figure 2–1. If treated independently, this cost can appear as a minor problem, but if aggregated the result can be quite startling. Even if we are able to accurately calculate the cost of lost production, however, we are still left with estimating the frequency and duration of future breakdowns, before we can come up with a cash flow statement.

Accordingly, it is important to have good past records if we are to do any better than guess at a value. If breakdowns are purely random occurrences, then past records are not going to give us the ability to predict precise savings for inclusion in a sound financial case. They may, however, give a feel for the likely cost when a breakdown happens. At best, we could say, for example, the likely cost of a stoppage is $8,000 per hour, and likely breakdown duration is going to be two shifts at a minimum. The question senior management then has to face is: "Are you willing to spend $10,000 on this condition monitoring device or not?"

2.2.1 Poor-Quality Product as Plant Performance Deteriorates

As a machine's bearings wear out, its lubricants decay, or its flow rates fluctuate, the product being manufactured may suffer damage. This can lead to an increase in the level of rejects or to growing customer dissatisfaction regarding product quality. Financial quantification here is similar to that outlined previously but can be even less precise because the total effect of poor quality may be unknown. In a severe case, the loss of ISO-9000 certification may take place, which can have financial implications well beyond any caused by increased rejection rates.

2.2.2 Increased Cost of Fuel and Other Consumables as the Plant Condition Deteriorates

A useful example of this point is the increased fuel consumption as boilers approach their time for servicing. The cost associated with servicing can be quantified precisely from past statistics or a service supplier's data. The damaging effects of a vibrating bearing or gearbox are, however, less easy to quantify directly and even more so as one realizes that they can have further consequential effects that compound the total cost. For example, the vibration in a faulty gearbox could in turn lead to rapid wear on clutch plates, brake linings, transmission bushes, or conveyor belt fabric. Thus, the component replacement costs rise, but maintenance records will not necessarily relate this situation to the original gearbox defect. Figure 2–2 shows how the cost of deterioration in plant condition rises as the equipment decays, with the occasional sudden or gradual increases as the consequential effects add to overall costs.

2.2.3 Cost of Current Maintenance Strategy

The cost of a maintenance engineering department as a whole should be fairly clearly documented, including wages, spares, overheads, and so on; however, it is usually difficult to break this cost down into individual plant items and virtually impossible to allocate an accurate proportion of this total cost to a single component's maintenance. In addition, overall costs will rise steadily in respect to routine plant maintenance as the equipment deteriorates with age and needs more careful attention to keep it running smoothly. Figure 2–3 outlines the cost of a current planned preventive maintenance strategy and shows it to be a steady outflow of cash for labor and spares, increasing as the plant ages.

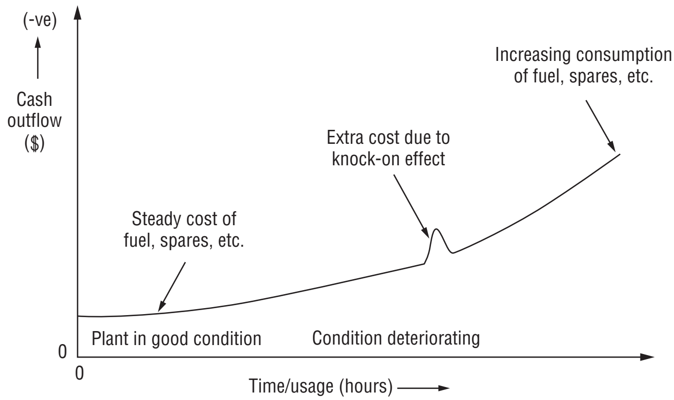


Figure 2–2 Typical cost of deterioration in plant condition.

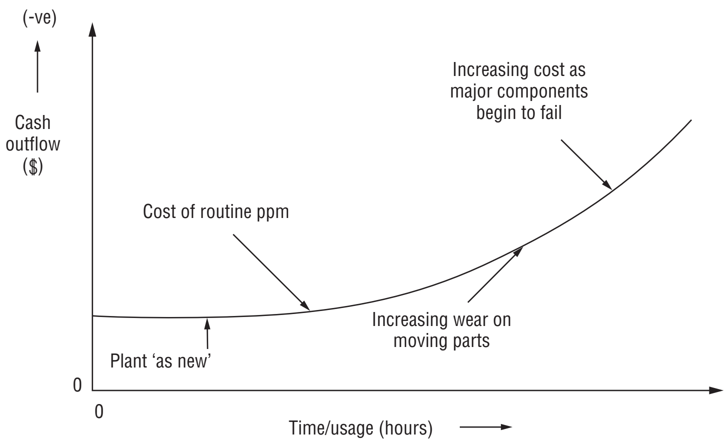


Figure 2–3 Typical cost of a preventive maintenance strategy.

If CM is to replace planned preventive maintenance, considerable savings may be realized in the spares and labor requirement for the plant, which may be found to be over-maintained. This is more common than one might expect because maintenance has always believed that regular prevention is much less costly than a serious breakdown in service. Unit replacement at weekends or during a stop period is not reflected in lost production figures, and the cost of stripping and refurbishing the plant is often lost in the maintenance department's wage budget for the year. In other words, the cost of planned preventive maintenance on plant and equipment can be a constant drain on resources that goes undetected. Accordingly, it should really be made available for comparison with the cost of monitoring the unit's condition on a regular basis and applying corrective measures only when needed.

2.3 Justifying Predictive Maintenance

In general, the cost of any current maintenance position is largely vague and unpredictable. This is true even if enough data are available to estimate past expenditure and allocate this precisely to a particular plant item. Thus, if we are to make any sense of financial justification, we must somehow overcome this impasse. The reduced cost of maintenance is usually the first factor that a financial manager looks at when we present our case, even though the real but intangible savings come from reduced downtime. Ideally, past worksheets should give the aggregated maintenance hours spent on the plant. These can then be pro-rated against total labor costs. Similarly, the spares consumption recorded on the worksheets can be multiplied by unit costs. The cost of the maintenance strategy for the plant will then be the labor cost plus the spares cost plus an overhead element.

Unfortunately, the nearest we are likely to get to a value for maintenance overheads will be to take the total maintenance department's overhead value and multiply it by the plant's maintenance labor cost, divided by the total maintenance labor cost. Even if we manage to arrive at a satisfactory figure, its justification will be queried if we cannot show it as a tangible savings, either resulting from reduced staffing levels in the maintenance department or through reduced spares consumption, which would also be acceptable as a real savings. The estimates will need to be aggregated and grouped according to how they can be allocated (e.g., whether they are downtime-based, total cost per hour the plant is stopped, frequency-based, recovery cost per breakdown, or general cost of regaining customer orders and confidence after failure to deliver). By using these estimates, plus the performance data that have been collected, it should then be possible to estimate the cost of machine failure and poor performance during the past few years or months. In addition, it should also be possible to allocate a probable savings if machine performance is improved by a realistic amount.

It may even be possible to create a traditional cash flow diagram showing expenses against savings and the final breakeven point, although its apparent precision is much less than the quality of the data would suggest. If we aggregate the graphs for the cost of the current maintenance situation, and plot that alongside the expected costs after installing CM, as shown in Figure 2–4, then the area between the two represents the potential savings. Figure 2–5, conversely, shows how the cost of installing CM equipment is high at first, until the capital has been paid off, and then the operating cost becomes fairly low but steady during the life of the CM equipment.

Put against the savings, there will be both the capital and running costs of introducing a CM project to be considered, which are outlined as follows.

2.3.1 Installation Cost

Some of the capital cost will be clearly defined by the equipment price and any specialist installation cost. There may also be preliminary alterations required, such as

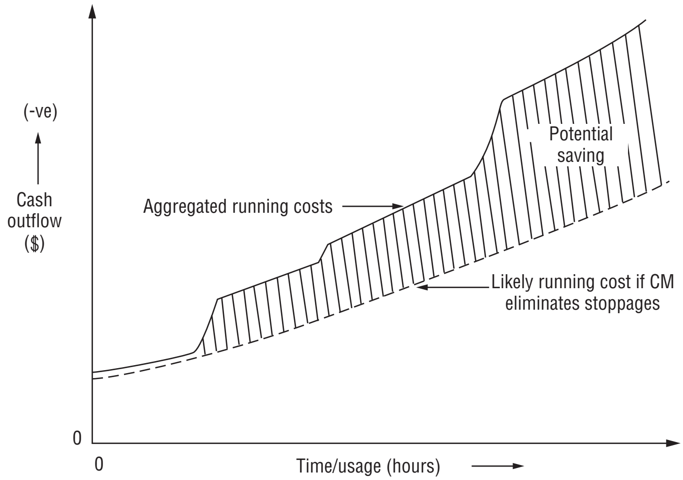


Figure 2–4 Typical potential savings produced by use of condition monitoring.

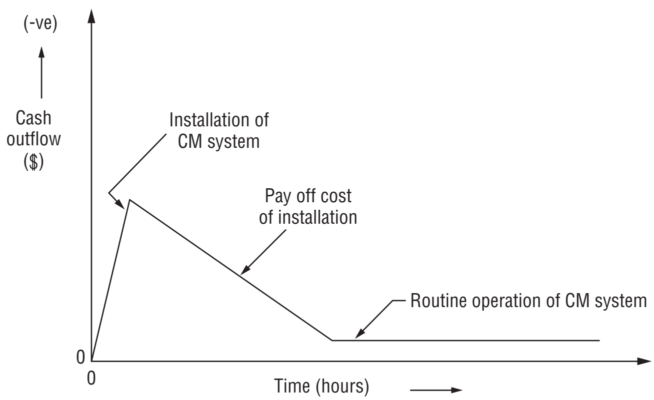


Figure 2–5 Typical cost of condition monitoring installation and operation.

creating access, installing foundations, covering or protection, power supply, service access, and so on. Some or all may be subject to development grants or other financial inducement, as may the cost of consultancy before, during, or after the installation. This could well include the cost of producing a financial project justification. The cost of lost production during installation may be avoided if the equipment is installed during normal product changes or shutdown periods; however, in a continuous process this may be another overhead to be added to the initial capital investment. Finally, it may be necessary to send staff to a training course, which has not been included in the equipment price. The cost of staff time and the course itself may be offset by training grants in some areas, which should be investigated. It is also possible that the vendor will offer rental terms on the CM equipment, in which case the cost becomes part of the operating rather than the capital budget.

2.3.2 Operating Cost

Once the unit has been installed and commissioned, the major cost is likely to be its staffing requirement. If the existing engineering staff has sufficient skill and training, and the improved plant performance reduces their workload sufficiently, then operating the equipment and monitoring its results may be absorbed without additional cost. In our experience, this time-saving factor has often been ignored in justifying the case for improved maintenance techniques. In retrospect, however, it has proved to be one of the main benefits of installing a computer-based monitoring system.

For example, a cable maker found that his company had increased its plant capacity by 50 percent during the year after the introduction of computer-based maintenance. Yet the level of maintenance staff needed to look after the plant had remained unchanged. This amounted to a 60 percent improvement in overall productivity. Another example of this effect was a drinks manufacturer who used a computerized scheduler to change from time-based to usage-based maintenance. This was done because demands on production fluctuated rapidly with changes in the weather. As a result, the workload on the maintenance trades fell so far that they were able to maintain an additional production line without any staffing increase at all.

If these savings can be made by better scheduling, how much more improvement in labor availability would there be if maintenance could be related to a measurable plant condition, and the servicing planned to coincide with a period of low activity in the production or maintenance schedule? So, the ongoing cost of labor needed to run the CM project must be assessed carefully and balanced against the potential labor savings as performance improves. Other continuing costs must also be considered, such as the fuel or consumables needed by the unit; however, these costs are normally small, and recent trends have shown that consumable costs tend to decrease as more companies turn to this type of equipment.

Combining the aforementioned initial costs and savings should result in an early outflow of cash investment in equipment and training, but this soon crosses the breakeven point within an acceptable period. It should then level off into a steady profit, which represents a satisfying return on the initial investment, as reduced maintenance costs, plus improved equipment performance, are realized as overall financial gains. Figure 2–6 indicates how the cash flow from investment in CM moves through the breakeven point into a region of steady positive financial gain.

2.3.3 Conclusions

In conclusion, it is possible to say that the financial justification for installation of any item of CM equipment should based on a firm business plan, where investment cost is offset by quantified financial benefits; however, the vagueness of the factors avail-

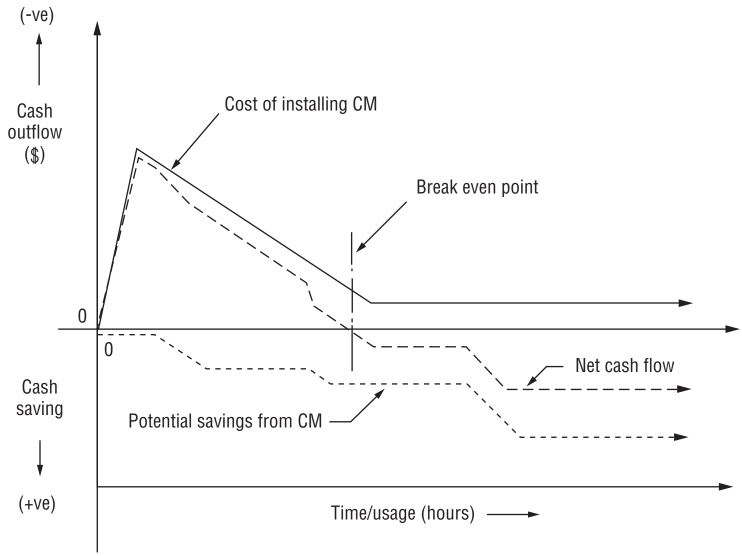


Figure 2–6 Typical overall cash flow from an investment in predictive maintenance.

able for quantification, the lack of firm tangible benefits, and the financial environment in which maintenance engineers operate all conspire to make the construction of such a plan difficult.

Until the engineer is given the facilities to collect and analyze performance data accurately and consistently; until the engineering and manufacturing departments are integrated under a precise standard value-costing system; and until the maintenance engineering function is given the status of a profit center, then financial justification will never become the precise science it should be. Instead, the more normal process is one in which an engineer makes a decision to install a CM system and then backs it up with precise-looking figures based on imprecise data. Fortunately, once the improved system has been approved, its performance is only rarely monitored against that estimated in the original business plan. This is largely because the financial values or benefits achieved are even more difficult to extract and quantify in a post-installation audit than those in the original business plan.

2.4 Economics of Preventive Maintenance

Maintenance is, and should be, managed like a business; however, few maintenance managers have the basic skill and experience needed to understand the economics of an effective business enterprise. This section provides a basic understanding of maintenance economics.

2.4.1 Benefits versus Costs

Preventive maintenance is an investment. Like anything in which we invest money and resources, we expect to receive benefits from preventive maintenance that are greater than our investment. The following financial overview is intended to provide enough knowledge to know what method is best and what the financial experts will need to know to provide assistance.

Making preventive investment trade-offs requires consideration of the time-value of money. Whether the organization is profit-driven, not-for-profit, private, public, or government, all resources cost money. The three dimensions of payback analysis are (1) the money involved in the flow, (2) the period over which the flow occurs, and (3) the appropriate cost of money expected over that period.

Preventive maintenance analysis is usually either "Yes/No" or choosing one of several alternatives. With any financial inflation, which is the time we live in, the time-value of money means that a dollar in your pocket today is worth more than that same dollar a year from now. Another consideration is that forecasting potential outcomes is much more accurate in the short term than it is in the long term, which may be several years away. Decision-making methods include the following:

- Payback
- Percent rate of return (PRR)
- Average return on investment (ROI)
- Internal rate of return (IRR)
- Net present value (NPV)
- Cost–benefit ratio (CBR)

The corporate controller often sets the financial rules to be used in justifying capital projects. Companies have rules like, "Return on investment must be at least 20 percent before we will even consider a project" or "Any proposal must pay back within 18 months." Preventive maintenance evaluations should normally use the same set of rules for consistency and to help achieve management support. It is also important to realize that the political or treasury drivers behind those rules may not be entirely logical for your level of working decision.

Payback

Payback simply determines the number of years that are required to recover the original investment. Thus, if you pay $50,000 for a test instrument that saves downtime and increases production worth $25,000 a year, then the payback is:

$$\frac{\$50,000}{\$25,000} = 2 \text{ years}$$

This concept is easy to understand. Unfortunately, it disregards the fact that the $25,000 gained the second year may be worth less than the $25,000 gained this year because of inflation. It also assumes a uniform stream of payback, and it ignores any returns after the two years. Why two years instead of any other number? There may be no good reason except "The controller says so." It should also be noted that if simple payback is negative, then you probably do not want to make the investment.

Percent Rate of Return (PRR)

Percent rate of return is a close relation of payback that is the reciprocal of the payback period. In our case above:

$$\frac{\$25,000}{\$50,000} = .05 = 50\% \text{ rate of return}$$

This is often called the naive rate of return because, like payback, it ignores the cost of money over time, compounding effect, and logic for setting a finite time period for payback.

Return on Investment (ROI)

Return on investment is a step better because it considers depreciation and salvage expenses and all benefit periods. If we acquire a test instrument for $80,000 that we project to have a five-year life, at which time it will be worth $5,000, then the cost calculation, excluding depreciation, is:

$$\frac{(\$80,000 - \$50,000)}{5 \text{ years}} = \$15,000 \text{ per year}$$

If we can benefit a total of $135,000 over that same five years, then the average increment is:

$$\$135,000 - \$75,000 = \frac{\$60,000}{5 \text{ years}} = \$12,000 \text{ per year}$$

The average annual ROI is:

$$\frac{\$75,000}{\$135,000} = .55 = 55\%$$

Ask your accounting firm how they handle depreciation because that expense can make a major difference in the calculation.

Internal Rate of Return (IRR)

Internal rate of return is more accurate than the preceding methods because it includes all periods of the subject life, considers the costs of money, and accounts for differing streams of cost and/or return over life. Unfortunately, the calculation requires a computer spreadsheet macro or a financial calculator. Ask your controller to run the numbers.

Net Present Value (NPV)

Net present value has the advantages of IRR and is easier to apply. We decide what the benefit stream should be by a future period in financial terms. Then we decide what the cost of capital is likely to be over the same time and discount the benefit stream by the cost of capital. The term *net* is used because the original investment cost is subtracted from the resulting present value for the benefit. If the NPV is positive, you should do the project. If the NPV is negative, then the costs outweigh the benefits.

Cost–Benefit Ratio (CBR)

The cost–benefit ratio takes the present value (initial project cost + NPV) divided by the initial project cost. For example, if the project will cost \$250,000 and the NPV is \$350,000, then:

$$\frac{\$250,000 + \$350,000}{\$250,000} = 2.4$$

It may appear that the CBR is merely a mirror of the NPV. The valuable addition is that CBR considers the size of the financial investment required. For example, two competing projects could have the same NPV, but if one required \$1 million and the other required only \$250,000, that absolute amount might influence the choice. Compare the previous example with the \$1 million example:

$$\frac{\$1,000,000 + \$350,000}{\$1,000,000} = 1.35$$

There should be little question that you would take the \$250,000 project instead of the \$1 million choice. Tables 2–1 through 2–5 provide the factors necessary for evaluating how much an investment today must earn over the next three years in order to achieve a target ROI. This calculation requires that we make a management judgment on what the inflation/interest rate will be for the payback time and what the pattern of those paybacks will be.

For example, if we spend \$5,000 today to modify a machine in order to reduce breakdowns, the payback will come from improved production revenues, reduced maintenance labor, having the right parts, tools, and information to do the complete job, and certainly less confusion.

The intention of this brief discussion of financial evaluation is to identify factors that should be considered and to recognize when to ask for help from accounting, control,

Table 2–1 Future Value

$$Future\ Value = \text{Principal}(1 + \text{Interest})^n$$

Periods	Interest 1%	2%	4%	10%	15%	20%
1	1.010	1.020	1.040	1.100	1.150	1.200
2	1.020	1.040	1.082	1.210	1.322	1.440
3	1.030	1.061	1.125	1.331	1.521	1.728
4	1.041	1.082	1.170	1.464	1.749	2.074
5	1.051	1.104	1.217	1.610	2.011	2.488
6	1.062	1.126	1.265	1.772	2.313	2.986
7	1.072	1.149	1.316	1.316	2.660	3.583
8	1.083	1.172	1.369	1.369	3.059	4.300
9	1.094	1.195	1.423	1.423	3.518	5.160
10	1.105	1.219	1.480	1.480	4.046	6.192
11	1.116	1.243	1.539	1.539	4.652	7.430
12	1.127	1.268	1.601	1.601	5.350	8.916
18	1.196	1.428	2.026	2.026	12.359	26.623
24	1.270	1.608	2.563	2.563		
36	1.431	2.040	4.104	4.104		
48	1.612	2.587	6.571	6.571		
60	1.817	3.281	10.520	10.520		

Table 2–2 Present Value

$$PV = S\frac{1}{(1+i)^n}$$

Periods	Interest 1%	2%	4%	10%	15%	20%
1	.990	.980	.962	.909	.870	.833
2	.980	.961	.925	.826	.756	.694
3	.971	.942	.889	.751	.658	.579
4	.961	.924	.855	.683	.572	.482
5	.951	.906	.822	.621	.497	.402
6	.942	.888	.790	.564	.432	.335
7	.933	.871	.760	.513	.376	.279
8	.923	.853	.731	.467	.327	.233
9	.914	.837	.703	.424	.284	.194
10	.905	.820	.676	.386	.247	.162
11	.896	.804	.650	.350	.215	.135
12	.887	.788	.625	.319	.187	.112
18	.836	.700	.494	.180	.081	.038
24	.788	.622	.390	.102	.035	.013
36	.699	.490	.244	.032		
48	.620	.387	.152			
60	.550	.305	.096			

Table 2–3 Future Value of Annuity in Arrears, Value of a Uniform Series of Payments

$$USCA = P\left(\frac{(1+i)^n - 1}{i}\right)$$

Periods	1%	2%	Interest 4%	10%	15%	20%
1	1.000	1.000	1.000	1.000	1.000	1.000
2	2.010	2.020	2.040	2.100	2.150	2.200
3	2.030	3.060	3.122	3.310	3.472	3.640
4	4.060	4.122	4.246	4.641	4.993	5.368
5	5.101	5.204	5.416	6.105	6.742	7.442
6	6.152	6.308	6.633	7.716	8.754	9.930
7	7.214	7.434	7.898	9.487	11.067	12.916
8	8.286	8.583	9.214	11.436	13.727	16.499
9	9.369	9.755	10.583	13.579	16.786	20.799
10	10.462	10.950	12.006	15.937	20.304	25.959
11	11.567	12.169	13.486	18.531	24.349	32.150
12	12.683	13.412	15.026	21.384	29.002	39.580
18	19.615	21.412	25.645	45.599	75.836	128.117
24	26.973	30.422	39.083	88.497	184.168	392.484
36	43.077	51.994	77.598	299.127	*	*
48	61.223	79.354	139.263	960.172	*	*
60	81.670	114.052	237.991	*	*	*

* Over 1,000.

Table 2–4 Present Value of Annuity in Arrears, Uniform Series Worth Factor

$$PVA_n = S\frac{(1+i)^n - 1}{i(1+i)^n}$$

Period	1%	2%	Interest 4%	10%	15%	20%
1	.990	.980	.962	.909	.870	.833
2	1.970	1.942	1.886	1.736	1.626	1.528
3	2.941	2.884	2.775	2.487	2.283	2.106
4	3.902	3.808	3.630	3.170	2.855	2.589
5	4.853	4.713	4.452	3.791	3.352	2.991
6	5.795	5.601	5.242	4.355	3.784	3.326
7	6.728	6.472	6.002	4.868	4.160	3.605
8	7.652	7.325	6.733	5.335	4.487	3.837
9	8.566	8.162	7.435	5.759	4.772	4.031
10	9.471	8.983	8.111	6.145	5.019	4.193
11	10.368	9.787	8.760	6.495	5.239	4.327
12	11.255	10.575	9.385	6.814	5.421	4.439
18	16.398	14.992	12.659	8.201	6.128	4.812
24	21.243	18.914	15.247	8.985	6.434	4.937
36	30.118	25.489	18.908	9.677	6.623	4.993
48	37.974	30.673	21.195	9.897	4.999	4.999
60	44.955	34.761	22.623	9.967	6.665	5.000

Table 2–5 Capital Recovery, Uniform Series with Present Value $1

$$CP = P\left(\frac{i(1+i)^n}{(1+i)^n - 1}\right)$$

			Interest			
Periods	**1%**	**2%**	**4%**	**10%**	**15%**	**20%**
1	1.010	1.020	1.040	1.100	1.150	1.200
2	.508	.515	.530	.576	.615	.654
3	.340	.347	.360	.402	.438	.475
4	.256	.263	.275	.315	.350	.386
5	.206	.212	.225	.264	.298	.334
6	.173	.179	.191	.230	.264	.301
7	.149	.155	.167	.205	.240	.277
8	.131	.137	.149	.187	.223	.261
9	.117	.122	.135	.174	.210	.248
10	.106	.111	.123	.163	.199	.239
11	.096	.102	.114	.154	.191	.231
12	.089	.095	.107	.147	.184	.225
18	.061	.067	.079	.120	.163	.208
24	.047	.053	.066	.111	.155	.203
36	.0033	.038	.051	.094	.151	.200
48	.026	.032	.045	.092	.150	.200
60	.022	.028	.043	.091	.150	.200

and finance experts. Financial evaluation of preventive maintenance is divided generally into either single transactions or multiple transactions. If payment or cost reductions are multiple, they may be either uniform or varied. Uniform series are the easiest to calculate. Nonuniform transactions are treated as single events that are then summed together.

Tables 2–1 through 2–5 are done in periods and interest rates that are most applicable to maintenance and service managers. The small interest rates will normally be applicable to monthly events, such as 1 percent per month for 24 months. The larger interest rates are useful for annual calculations. The factors are shown only to three decimal places because the data available for calculation are rarely even that accurate. The intent is to provide practical, applicable factors that avoid overkill. If factors that are more detailed, or different periods or interest rates, are needed, they can be found in most economics and finance texts or automatically calculated by the macros in computerized spreadsheets. The future value factors (Tables 2–1 and 2–3) are larger than 1, as are present values for a stream of future payments (Table 2–4). On the other hand, present value of a single future payment (Table 2–2) and capital recovery (Table 2–5 after the first year) result in factors of less than 1.000. The money involved to give the answer multiplies the table factor. Many programmable calculators can also work out these formulas. If, for example, interest rates are 15 percent per year and the total amount is to be repaid at the end of three years, refer to Table 2–1 on future value. Find the factor 1.521 at the intersection of three years and 15 percent. If our example cost is $35,000, it is multiplied by the factor to give:

$$\$35,000 \times 1.521 = \$53,235 \text{ due at the end of the term}$$

Present values from Table 2–2 are useful to determine how much we can afford to pay now to recover, say, $44,000 in expense reductions over the next two years. If the interest rates are expected to be lower than 15 percent, then:

$$\$44,000 \times 0.75\% = \$33,264$$

Note that a dollar today is worth more than a dollar received in the future. The annuity tables are for uniform streams of either payments or recovery. Table 2–3 is used to determine the value of a uniform series of payments. If we start to save now for a future project that will start in three years, and save $800 per month through reduction of one person, and the cost of money is 1 percent per month, then $34,462 should be in your bank account at the end of 36 months.

$$\$800 \times 43.077 = \$34,462$$

The factor 43.077 came from 36 periods at 1 percent. The first month's $800 earns interest for 36 months. The second month's savings earns for 35 months, and so on. The use of factors is much easier than using single-payment tables and adding the amount for $800 earning interest for 36 periods ($1,114.80), plus $800 for 35 periods ($1,134.07), and continuing for 34, 33, and so on, through one. If I sign a purchase order for new equipment to be rented at $500 per month over five years at 1 percent per month, then:

$$\$500 \times 44.955 = \$22,478$$

Note that five years is 60 months in the period column of Table 2–4. Capital recovery Table 2–5 gives the factors for uniform payments, such as mortgages or loans that repay both principal and interest. To repay $75,000 at 15 percent annual interest over five years, the annual payments would be:

$$\$75,000 \times 0.298 = \$22,350$$

Note that over the five years, total payments will equal $111,750 (5 × $22,350), which includes the principal $75,000 plus interest of $36,750. Also note that a large difference is made by whether payments are due in advance or in arrears.

A maintenance service manager should understand enough about these factors to do rough calculations and then get help from financial experts for fine-tuning. Even more important than the techniques used is the confidence in the assumptions. Control and finance personnel should be educated in your activities so they will know what items are sensitive and how accurate (or best judgment) the inputs are, and will be able to support your operations.

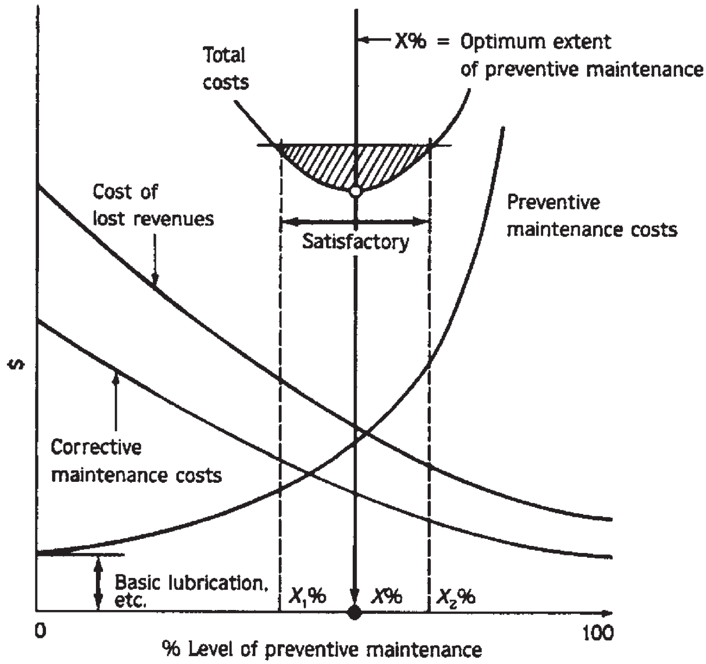


Figure 2–7 The relationship between cost and amount of preventive maintenance.

Trading Preventive for Corrective and Downtime

Figure 2–7 illustrates the relationships between preventive maintenance, corrective maintenance, and lost production revenues. The vertical scale is dollars. The horizontal scale is the percentage of total maintenance devoted to preventive maintenance. The percentage of preventive maintenance ranges from zero (no PMs) at the lower left intersection to nearly 100 percent preventive at the far right. Note that the curve does not go to 100 percent preventive maintenance because experience shows there will always be some failures that require corrective maintenance. Naturally, the more of any kind of maintenance that is done, the more it will cost to do those activities. The trade-off, however, is that doing more preventive maintenance should reduce both corrective maintenance and downtime costs. Note that the downtime cost in this illustration is greater than either preventive or corrective maintenance. Nuclear power-generating stations and many production lines have downtime costs exceeding $10,000 per hour. At that rate, the downtime cost far exceeds any amount of maintenance, labor, or even materials that we can apply to the job. The most important effort is to get the equipment back up without much concern for overtime or expense budget. Normally, as more preventive tasks are done, there will be fewer breakdowns and therefore lower corrective maintenance and downtime costs. The challenge is to find the optimum balance point.

	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Total
PM													
Labor	32	65	96	94	94	90	72						
Parts	23	38	49	56	68	65	54						
Total	55	103	145	150	162	155	126						
CM													
Labor	503	370	293	164	201	193	142						
Parts	231	213	181	185	199	196	157						
Total	734	583	474	349	400	389	299						
Lost revenues	407	397	320	290	330	320	362						
Total	1,196	1,083	939	789	82	864	787						

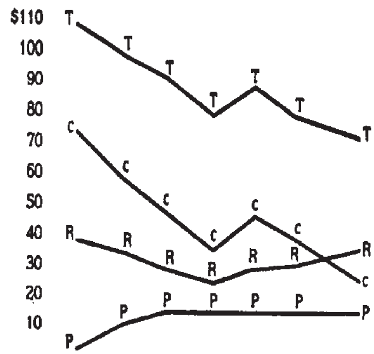


Figure 2–8 Preventive maintenance, condition monitoring, and lost revenue cost, $000.

As shown in Figure 2–7, it is better to operate in a satisfactory region than to try for a precise optimum point. Graphically, every point on the total-cost curve represents the sum of the preventive costs plus corrective maintenance costs plus lost revenues costs.

If you presently do no preventive maintenance tasks at all, then each dollar of effort for preventive tasks will probably gain savings of at least $10 in reduced corrective maintenance costs and increased revenues. As the curve shows, increasing the investment in preventive maintenance will produce increasingly smaller returns as the breakeven point is approached. The total-cost curve bottoms out, and total costs begin to increase again beyond the breakeven point. You may wish to experiment by going past the minimum-cost point some distance toward more preventive tasks. Even though costs are gradually increasing, subjective measures, including reduced confusion, safety, and better management control, that do not show easily in the cost calculations are still being gained with the increased preventive maintenance. How do you track these costs? Figure 2–8 shows a simple record-keeping spreadsheet that helps keep data on a month-by-month basis.

It should be obvious that you must keep cost data for all maintenance efforts in order to evaluate financially the cost and benefits of preventive versus corrective maintenance and revenues. A computerized maintenance information system is best, but data can be maintained by hand for smaller organizations. One should not expect immediate results and should anticipate some initial variation. This delay could be caused by the momentum and resistance to change that is inherent in every electromechanical system, by delays in implementation through training and getting the word out to all personnel, by some personnel who continue to do things the old way, by statistical variations within any equipment and facility, and by data accuracy.

If you operate electromechanical equipment and presently do not have a preventive maintenance program, you are well advised to invest at least half of your maintenance budget for the next three months in preventive maintenance tasks. You are probably thinking: "How do I put money into preventive and still do the corrective maintenance?" The answer is that you can't spend the same money twice. At some point, you have to stand back and decide to invest in preventive maintenance that will stop the large number of failures and redirect attention toward doing the job right once. This will probably cost more money initially as the investment is made. Like any other investment, the return is expected to be much greater than the initial cost.

One other point: it is useless to develop a good inspection and preventive task schedule if you don't have the people to carry out that maintenance when required. Careful attention should be paid to the Mean Time to Preventive Maintenance (MTPM). Many people are familiar with Mean Time to Repair (MTTR), which is also the Mean Corrective Time ($\overline{M}$ ct). It is interesting that the term MTPM is not found in any textbooks the author has seen, or even in the author's own previous writings, although the term $\overline{M}$ pt is in use. It is easier simply to use Mean Corrective Time ($\overline{M}$ ct) and Mean Preventive Time ($\overline{M}$ pt).

PM Time/Number of preventive maintenance events calculates $\overline{M}$ pt. That equation may be expressed in words as the sum of all preventive maintenance time divided by the number of preventive activities done during that time. If, for example, five oil changes and lube jobs on earthmovers took 1.5, 1, 1.5, 2, and 1.5 hours, the total is 7.5 hours, which divided by the five events equals an average of 1.5 hours each. A few main points, however, should be emphasized here:

1. Mean Time Between Maintenance (MTBM) includes preventive and corrective maintenance tasks.
2. Mean Maintenance Time is the weighted average of preventive and corrective tasks and any other maintenance actions, including modifications and performance improvements.
3. Inherent Availability (A_i) considers only failure and $\overline{M}$ ct. Achieved availability (A_a) adds in PM, although in a perfect support environment. Operational Availability (A_0) includes all actions in a realistic environment.

3

ROLE OF MAINTENANCE ORGANIZATION

Too many maintenance functions continue to pride themselves on how fast they can react to a catastrophic failure or production interruption rather than on their ability to prevent these interruptions. Although few production engineers will admit their continued adherence to this breakdown mentality, most plants continue to operate in this mode.

3.1 Maintenance Mission

Contrary to popular opinion, the role of maintenance is not to "fix" breakdown in record time; rather, it is to prevent all losses that are caused by equipment or system-related problems. The mission of the maintenance department in a world-class organization is to achieve and sustain the following:

- Optimum availability
- Optimum operating conditions
- Maximum utilization of maintenance resources
- Optimum equipment life
- Minimum spares inventory
- Ability to react quickly

3.1.1 Optimum Availability

The production capacity of a plant is partly determined by the availability of production systems and their auxiliary equipment. The primary function of the maintenance organization is to ensure that all machinery, equipment, and systems within the plant are always online and in good operating condition.

3.1.2 Optimum Operating Condition

Availability of critical process machinery is not enough to ensure acceptable plant performance levels. The maintenance organization must maintain all direct and indirect manufacturing machinery, equipment, and systems so that they will continuously be in optimum operating condition. Minor problems, no matter how slight, can result in poor product quality, reduced production speeds, or other factors that limit overall plant performance.

3.1.3 Maximum Utilization of Maintenance Resources

The maintenance organization controls a substantial part of the total operating budget in most plants. In addition to an appreciable percentage of the total-plant labor budget, the maintenance manager often controls the spare parts inventory, authorizes the use of outside contract labor, and requisitions millions of dollars in repair parts or replacement equipment. Therefore, one goal of the maintenance organization should be effective use of these resources.

3.1.4 Optimum Equipment Life

One way to reduce maintenance cost is to extend the useful life of plant equipment. The maintenance organization should implement programs that will increase the useful life of all plant assets.

3.1.5 Minimum Spares Inventory

Reductions in spares inventory should be a major objective of the maintenance organization; however, the reduction cannot impair their ability to meet the first four goals. With the predictive maintenance technologies that are available today, maintenance can anticipate the need for specific equipment or parts far enough in advance to purchase them on an as-needed basis.

3.1.6 Ability to React Quickly

All catastrophic failures cannot be avoided; therefore, the maintenance organization must be able to react quickly to the unexpected failure.

3.2 Evaluation of the Maintenance Organization

One means to quantify the maintenance philosophy in your plant is to analyze the maintenance tasks that have occurred over the past two to three years. Attention should be given to the indices that define management philosophy.

One of the best indices of management attitude and the effectiveness of the maintenance function is the number of production interruptions caused by maintenance-related problems. If production delays represent more than 30 percent of total production hours, reactive or breakdown response is the dominant management philosophy. To be competitive in today's market, delays caused by maintenance-related problems should represent less than 1 percent of the total production hours.

Another indicator of management effectiveness is the amount of maintenance overtime required to maintain the plant. In a breakdown maintenance environment, overtime costs are a major, negative cost. If your maintenance department's overtime represents more than 10 percent of the total labor budget, you definitely qualify as a breakdown operation. Some overtime is, and always will be, required. Special projects and the 1 percent of delays caused by machine failures will force some expenditure of overtime premiums, but these abnormal costs should be a small percentage of the total labor costs.

Labor usage is another key to management effectiveness. Evaluate the percentage of maintenance labor, compared to total available labor hours that are expended on the actual repairs and maintenance prevention tasks. In reactive maintenance management, the percentage will be less than 50 percent. A well-managed maintenance organization should maintain consistent labor usage above 90 percent. In other words, at least 90 percent of the available maintenance labor hours should be effectively used to improve the reliability of critical plant systems, not spent waiting for something to break.

3.2.1 Three Types of Maintenance

There are three main types of maintenance and three major divisions of preventive maintenance, as illustrated in Figure 3–1:

- Maintenance improvement
- Corrective maintenance
- Preventive maintenance
  - Reactive
  - Condition monitoring
  - Scheduled

Maintenance Improvement

Picture these divisions as the five fingers on your hand. Maintenance improvement efforts to reduce or eliminate the need for maintenance are like the thumb, the first and most valuable digit. We are often so involved in maintaining that we forget to plan and eliminate the need at its source. Reliability engineering efforts should emphasize elimination of failures that require maintenance. This is an opportunity to *pre-act* instead of react.

For example, many equipment failures occur at inboard bearings that are located in dark, dirty, inaccessible locations. The oiler does not lubricate inaccessible bearings as often as those that are easy to reach. This is a natural tendency, but the need for

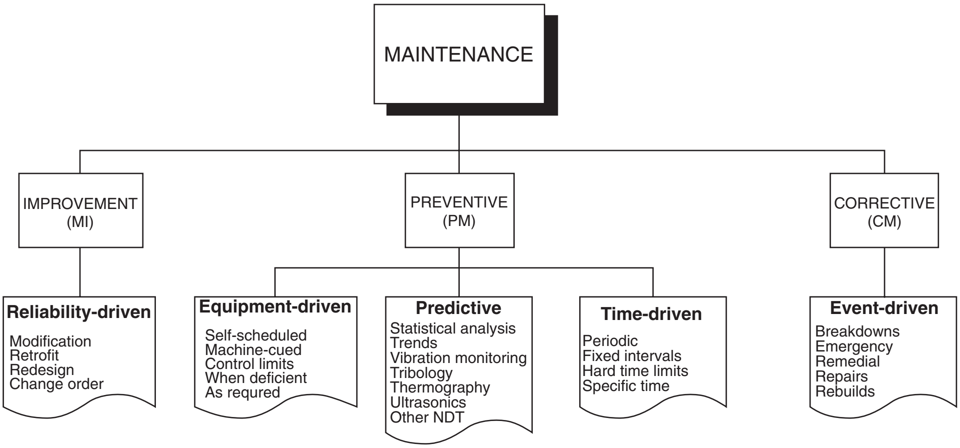


Figure 3–1 Structure of maintenance.

lubrication could be reduced by using permanently lubricated, long-life bearings. If that is not practical, at least an automatic oiler could be installed. A major selling point of new automobiles is the elimination of ignition points that require replacement and adjustment, introduction of self-adjusting brake shoes and clutches, and extension of oil-change intervals.

Corrective Maintenance

The little finger in our analogy to a human hand represents corrective maintenance (i.e., emergency, repair, remedial, unscheduled). At present, most maintenance is corrective. Repairs will always be needed. Better maintenance improvement and preventive maintenance, however, can reduce the need for emergency corrections. A shaft that is obviously broken into pieces is relatively easy to maintain because little human decision is involved. Troubleshooting and diagnostic fault detection and isolation are major time consumers in maintenance. When the problem is obvious, it can usually be corrected easily. Intermittent failures and hidden defects are more time-consuming, but with diagnostics, the causes can be isolated and then corrected. From a preventive maintenance perspective, the problems and causes that result in failures provide the targets for elimination by viable preventive maintenance. The challenge is to detect incipient problems before they lead to total failures and to correct the defects at the lowest possible cost. That leads us to the middle three fingers—the branches of preventive maintenance.

Preventive Maintenance

As the name implies, preventive maintenance tasks are intended to prevent unscheduled downtime and premature equipment damage that would result in corrective or repair activities. This maintenance management approach is predominantly a time-driven schedule or recurring tasks, such as lubrication and adjustments that are designed to maintain acceptable levels of reliability and availability.

Reactive. Reactive maintenance is done when equipment needs it. Inspection using human senses or instrumentation is necessary, with thresholds established to indicate when potential problems start. Human decisions are required to establish those standards in advance so that inspection or automatic detection can determine when the threshold limit has been exceeded. Obviously, a relatively slow deterioration before failure is detectable by condition monitoring, whereas rapid, catastrophic modes of failure may not be detected. Great advances in electronics and sensor technology are being made.

Also needed is a change in human thought process. Inspection and monitoring should disassemble equipment only when a problem is detected. The following are general rules for on-condition maintenance:

1. Inspect critical components.
2. Regard safety as paramount.
3. Repair defects.
4. If it works, don't fix it.

Condition Monitoring. Statistics and probability theory are the basis for condition-monitoring maintenance. Trend detection through data analysis often rewards the analyst with insight into the causes of failure and preventive actions that will help avoid future failures. For example, stadium lights burn out within a narrow period. If 10 percent of the lights have burned out, it may be accurately assumed that the rest will fail soon and should, most effectively, be replaced as a group rather than individually.

Scheduled. Scheduled, fixed-interval preventive maintenance tasks should generally be used only if failures that cannot be detected in advance can be reduced, or if dictated by production requirements. The distinction should be drawn between fixed-interval maintenance and fixed-interval inspection that may detect a threshold condition and initiate condition-monitoring tasks. Examples of fixed-interval tasks include 3,000-mile oil changes and 48,000-mile spark plug changes on a car, whether it needs the changes or not. This may be wasteful because all equipment and their operating environments are not alike. What is right for one situation may not be right for another.

The five-finger approach to maintenance emphasizes elimination and reduction of maintenance needs wherever possible, inspection and detection of pending failures before they happen, repair of defects, monitoring of performance conditions and failure causes, and accessing the equipment on a fixed-interval basis only if no better means exist.

Advantages and Disadvantages

Overall, preventive maintenance has many advantages. It is beneficial, however, to overview the advantages and disadvantages so that the positive may be increased and the negative reduced. Note that in most cases the advantages and disadvantages vary with the type of preventive maintenance tasks and techniques used. Use of on-condition or condition-monitoring techniques is usually better than fixed intervals.

Advantages. There are distinct advantages to preventive maintenance management. The predominant advantages include the following:

- *Management control*. Unlike repair maintenance, which must react to failures, preventive maintenance can be planned. This means "pre-active" instead of "reactive" management. Workloads may be scheduled so that equipment is available for preventive activities at reasonable times.
- *Overtime*. Overtime can be reduced or eliminated. Surprises are reduced. Work can be performed when convenient; however, proper distribution of the time-driven preventive maintenance tasks is required to ensure that all work is completed in a timely manner without excessive overtime.
- *Parts inventories*. Because the preventive maintenance approach permits planning of which parts are going to be required and when, those material requirements may be anticipated to be sure they are on hand for the event. A smaller stock of parts is required in organizations that emphasize preventive tasks compared to the stocks necessary to cover breakdowns that would occur when preventive maintenance is not emphasized.
- *Standby equipment*. With high demand for production and low equipment availability, reserve, standby equipment is often required in case of breakdowns. Some backup may still be required with preventive maintenance, but the need and investment will certainly be reduced.
- *Safety and pollution*. If no preventive inspections or built-in detection devices are used, equipment can deteriorate to a point where it is unsafe or may spew forth pollutants. Performance will generally follow a saw-tooth pattern, as shown in Figure 3–2, which does well after maintenance and then degrades until the failure is noticed and it is brought back up to a high level. A good detection system catches degrading performance before it reaches too low a level.
- *Quality*. For the same general reasons discussed previously, good preventive maintenance helps ensure quality output. Tolerances are maintained within control limits. Naturally, productivity is improved and the investment in preventive maintenance pays off with increased revenues.
- *Support to users*. If properly publicized, preventive tasks help show equipment operators, production managers, and other equipment users that the maintenance function is striving to provide a high level of support. Note here that an effective program must be published so that everyone involved understands the value of performed tasks, the investment required, and their own roles in the system.

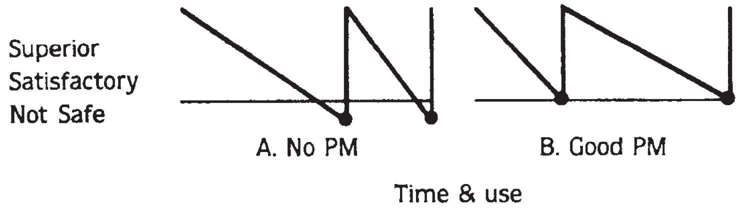


Figure 3–2 Preventive maintenance to keep acceptable performance.

- *Cost–benefit relationship*. Too often, organizations consider only costs without recognizing the benefit and profits that are the real goal. Preventive maintenance allows a three-way balance between corrective maintenance, preventive maintenance, and production revenues.

Disadvantages. Despite all the good reasons for doing preventive maintenance, several potential problems must be recognized and minimized:

- *Potential damage*. Every time a person touches a piece of equipment, damage can occur through neglect, ignorance, abuse, or incorrect procedures. Unfortunately, low-reliability people often service much high-reliability equipment. The *Challenger* space shuttle failure, the Three Mile Island nuclear power plant disaster, and many less-publicized accidents have been affected by inept preventive maintenance. Most of us have experienced car or home appliance problems that were caused by something that was done or not done at a previous service call. This situation gives rise to the slogan: “If it works, don’t fix it.”
- *Infant mortality*. New parts and consumables have a higher probability of being defective or failing than exists with the materials that are already in use. Replacement parts are too often not subjected to the same quality assurance and reliability tests as parts that are put into new equipment.
- *Parts use*. Replacing parts at preplanned preventive maintenance intervals, rather than waiting until a failure occurs, will obviously terminate that part’s useful life before failure and therefore require more parts. This is part of the trade-off among parts, labor, and downtime, of which the cost of parts will usually be the smallest component. It must, however, be controlled.
- *Initial costs*. Given the time-value of money and inflation that causes a dollar spent today to be worth more than a dollar spent or received tomorrow, it should be recognized that the investment in preventive maintenance is made earlier than when those costs would be incurred if equipment were run until failure. Even though the cost will be incurred earlier—and may even be larger than corrective maintenance costs would be—the benefits in terms of equipment availability should be substantially greater from doing preventive tasks.
- *Access to equipment*. One of the major challenges when production is at a high rate is for maintenance to gain access to equipment in order to perform

preventive maintenance tasks. This access will be required more often than it is with breakdown-driven maintenance. A good program requires the support of production, with immediate notification of any potential problems and willingness to coordinate equipment availability for inspections and necessary tasks.

The reasons for and against doing preventive maintenance are summarized in the following list. The disadvantages are most pronounced with fixed-interval maintenance tasks. Reactive and condition-monitoring tasks both emphasize the positive and reduce the negatives.

Advantages

- Performed when convenient
- Increases equipment uptime
- Creates maximum production revenue
- Standardizes procedures, times, and costs
- Minimizes parts inventory
- Cuts overtime
- Balances workload
- Reduces need for standby equipment
- Improves safety and pollution control
- Facilitates packaging tasks and contracts
- Schedules resources on hand
- Stimulates pre-action instead of reaction
- Indicates support to user
- Assures consistent quality
- Promotes benefit/cost optimization

Disadvantages

- Exposes equipment to possible damage
- Failures in new parts
- Uses more parts
- Increases initial costs
- Requires more frequent access to equipment

3.3 Designing a Predictive Maintenance Program

An effective predictive maintenance program must include both condition-driven and time-driven tasks. These tasks are determined by the specific equipment and systems that constitute the plant. At a minimum, each plant should evalute:

- Failure data
- Improving equipment reliability
- Improvement process

- Failures that can be prevented
- Maintenance to prevent failures
- Personnel
- Service Teams

3.3.1 Failure Data

Valid failure data provide the intelligence for an effective preventive maintenance program. After all, the objective is to prevent those failures from recurring. A failure reporting system should identify the problem, cause, and corrective action for every call. An action group, prophetically called the Failure Review and Corrective Actions Task Force (FRACAS), can be effective for involving responsible organizations in both detailed identification of problems and causes, and assignment of both short- and long-term corrective action. The following are typical factory and field problems and codes that shorten the computer data entry to four or fewer characters:

NOOP	Not Operable	OTHR	Other
BELR	Below rate	PM	Preventive task
INTR	Intermittent	QUAL	Quality
LEAK	Leak	SAFE	Safety
MOD	Modification	WEAT	Weather
NOIS	Noise	NPF	No problem found

The following are typical cause codes:

1.	Not applicable	60.	Program
10.	Controls	70.	Materials
20.	Power	71.	Normal wear
21.	External input power	72.	Damaged
22.	Main power supply	80.	Operator
30.	Motors	90.	Environment
40.	Drivers	99.	No cause found
50.	Transports	PM.	Preventive maintenance

The typical action codes are:

A/A	Adjust/align	REF	Refurbish
CAL	Calibrate	REB	Rebuild
CONS	Consumables	LUBE	Lubricate
DIAG	Diagnose	MOD	Modify
REMV	Remove	PM	Preventive task
R/R	Remove and replace	RPR	Repair
R/RE	Remove and reinstall	TRN	Train
INST	Install	NC	Not complete
INSP	Inspect	NK	Not known

These parameters and their codes should be established to fit the needs of the specific organization. For example, an organization with many pneumatic and optical instruments would have sticky dials and dirty optics that would not concern an electronically oriented organization. Note also that the code letters are the same, whenever possible, as the commonly used word's first letters. Preventive maintenance activities are recorded simply as PM/PM/PM. The cause codes, which may be more detailed, can use numbers and subsets of major groups, such as all power will be 20s, with external input power = 21, main power supply = 22, and so on.

It is possible, of course, to write out the complete words; however, analysis—whether done by computer or manually—requires standard terms. Short letter and number codes strike a balance that aids short reports and rapid data entry.

Use of the equipment at every failure should also be recorded. A key to condition-monitoring preventive maintenance effectiveness is knowing how many hours, miles, gallons, activations, or other kind of use have occurred before an item failed. This requires hour meters and similar instrumentation on major equipment. Use on related equipment may often be determined by its relationship to the parent. For example, it may be determined that if a specific production line is operating for seven hours, then the input feeder operates five hours (5/7), the mixer two hours (2/7), and the packaging machine four hours (4/7).

It is also important to determine the valid relationship between the cause of the problem and the recording measurement. For example, failures of an automotive starter are directly related to the number of times the car engine is started and only indirectly to odometer miles. If startup or a particular activity stresses the equipment different from normal use, then those special activities should be recorded.

Figure 3–3 is a combination work order and completion form. This form is printed by the computer on plain paper with the details of the work order on the top, space in the center for labor and materials for work orders that take a day or less, and a completion blank at the bottom to show when the work was started, when it was completed, the problem/cause/action codes, and meter reading. Labor on work orders that take more than one day is added daily from time reports and accumulated against the work order. Figure 3–4 shows the computer input screen for a simple service call report form that gathers the minimum information necessary for field reporting. Those forms may be used as input for a computer system, when a direct-entry system is not available.

3.3.2 Improving Equipment Reliability

Total-plant performance management (TPPM) and similar quality programs promote a holistic approach that includes equipment performance as a major enhancement to productivity. To reinforce the five-fingered approach to effective maintenance outlined previously, the fundamental thumb is elimination of failures. Uptime of equipment is what counts. Maintainability and maintenance are most successful if we do not have failures to fix.

WORK ORDER							
ORDER#: 1926	**PAD#: 45524**	**TYPE: A**			**PRI: 9**		
REQUESTED BY: Larry Smith	**DEPARTMENT** Maint. Planning	**TELEPHONE#** EXT. 356	**TGT START** 5/30/00		**TGT COMPLETE** 6/1/00		
DESCRIPTION			**EQUIPMENT**				
PM-A Recharge Freon in A/C 44			**ID:**	44			
			NAME:	BENDIX AIR CONDITIONER			
			LOC:	CPTR RM 16			
SPECIAL EQUIPMENT		**ASSIGNED EMPLOYEE**		**PRECAUTIONS**			
Charger Kit		23445	**ID:**	PRD-PROD PERMT			
		Jones, Joe	**NAME:**				
DOC: A/C 544		**ACCOUNTING:**	123-555	100%			
LABOR USED (ONLY FOR SINGLE-DAY JOBS)							
DATE:	**PERSON OR EQUIPMENT**		**TOTAL HOURS-MINUTES**				
			WORK	**TVL**	**DELAY**	**OT**	**$**
DATE:	**MATERIAL POSTING**						
	PART#	**DESCRIPTION**		**QTY.**	**$ UNIT**	**$ TOTAL**	
5/30/00	603552	Freon, A/C Charge Kit		1	$12.75	$12.75	
TOTAL MATERIAL COST:						$12.75	
COMPLETION							
	DATE	**TIME**			**CODES:**	CURR	
STARTED:					**PBM:**	METER	
COMPLETED:					**CAU:**	READ:	
					ACT:		
SIGNATURE:			**DATE:**				

Figure 3–3 Combination work order and completion form.

1 T CLOSE SERVICE CALL

CALL #: 2521 CUST ACCT #: 4543 NAME: KODAK-PARK CENTRAL FACILITIES
EMPL #: 2179 NAME: FELDMANN

STATUS (CMP=1)(CAN=2)(CNT=3): 1 ARR: 3/16/99 1030 CPLT: 3/17/99 1430

EQUIP ID#: C5 DESC: COMPRESSOR,10T,I-R METER: 5250

HOURS-MINUTES				$	$	$	$	CODES		
WORK	TVL	DELAY	OT	MI	MEALS	PH	DIEM	PBM	CAU	ACT
8-50	1-10	1-00	-	4.00	7.50	.80		MOD	40	MOD

DESC: REPLACED WORN GEAR & INSTALLED STABILIZING BRACKET.

PART #	DESCRIPTION		UNIT CST	QTY	EXTD CST	RPR	RSP?
621112	GEAR	,STNLS,HELI,18T	161.60	1	161.60	Y	Y
232240	OIL	,GEAR,600W,QT	.66	6	3.96		Y
*		,BRACKET,DWG 244	150.00	1	150.00		N

OTHER EQUIPMENT WORKED ON? N

TOTAL CALL:	HOURS	LABOR	MATERIALS	TOTAL
	11-00	206.25	315.56	521.81

Figure 3–4 Simple call report.

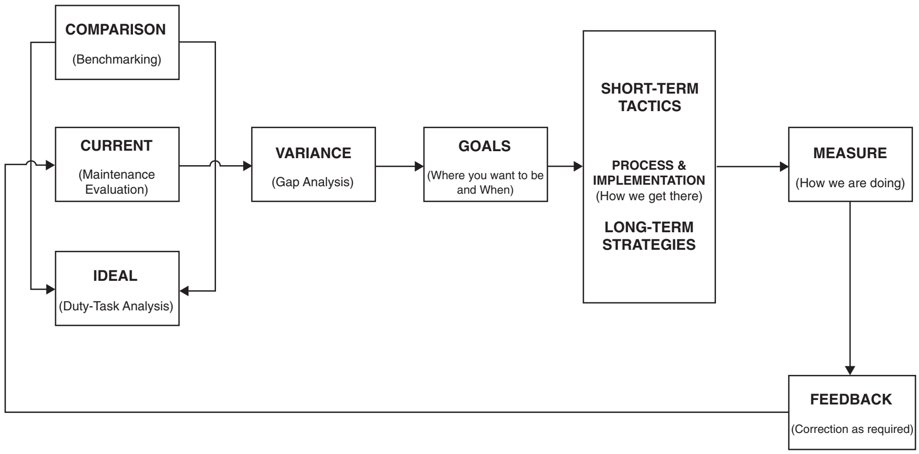


Figure 3–5 Business improvement process.

Successful maintenance organizations spend more time identifying trends and eliminating problems than they spend fixing repetitive breakdowns. Computerized maintenance management systems provide a tool to gather data and provide analysis that can lead to improvement.

3.3.3 Improvement Process

Figure 3–5 diagrams a business improvement process. A maintenance organization should start by measuring its own performance. For example, just a breakout of a typical day in the life of a maintenance person is revealing. Many groups are chagrined to discover that maintenance staff actually works less than 30 percent of the time. Benchmark comparisons with similar organizations provide a basis for analyzing performance both on metrics and processes. The third step in goal setting is to identify realistic ideal levels of performance. These goals should have the following characteristics:

- Written
- Measurable
- Understandable
- Challenging
- Achievable

The goals will have firm times, dollars, percentages, and dates. Everyone who will be challenged to meet the goals should be involved in their establishment. This may seem like a bureaucratic, warm-fuzzy approach, but the time it takes to achieve buy-in is earned back many times during accomplishment. Once the goals are set, any gaps between where performance is now versus where it needs to be can be identified. Then both short-term plans and long-term strategies can be implemented to reach the goals.

Frequent measurement and feedback will revise performance to achieve the desired levels.

3.3.4 Failures That Can Be Prevented

Failure modes, effects, and criticality analysis (FMECA) provide a method for determining which failures can be prevented. Necessary inputs are the frequency of occurrence for each problem and cause combination and what happens if a failure occurs. Criticality of the failure is considered for establishing priority of effort. FMECA is a bottom-up approach that looks at every component in the equipment and asks: "Will it fail? And if so, how and why?" Preventive maintenance investigators are interested in how a component will fail so that the mechanism for failure can be reduced or eliminated. For example, heat is the most common cause of failure for electromechanical components. Friction causes heat in assemblies moving relative to each other, often accompanied by material wear, and leads to many failures. Any moving component is likely to fail at a relatively high rate and is a fine candidate for preventive maintenance. The following are common causes of failure:

Abrasion	Friction
Abuse	Operator negligence
Age deterioration	Puncture
Bond separation	Shock
Consumable depletion	Stress
Contamination	Temperature extremes
Corrosion	Vibration
Dirt	Wear
Fatigue	

3.3.5 Maintenance to Prevent Failures

Cleanliness is the watchword of preventive maintenance. Metal filings, fluids in the wrong places, ozone and other gases that deteriorate rubber components—all are capable of damaging equipment and causing it to fail. A machine shop, for example, that contains many electromechanical lathes, mills, grinders, and boring machines should have established procedures for ensuring that the equipment is frequently cleaned and properly lubricated. In most plants, the best tactic is to assign responsibility for cleaning and lubrication to the machine's operator. There should be proper lubricants in grease guns and oilcans, and cleaning materials at every workstation. Every operator should be trained on proper operator preventive tasks. A checklist should be kept on the equipment for the operator to initial every time the lubrication is done.

It is especially important that lubrication be done cleanly. Grease fittings, for example, should be cleaned with waste material both before and after the grease gun is used. Grease attracts and holds particles of dirt. If the fittings are not clean, the grease gun could force contaminants between the moving parts, which is precisely what should be avoided. This is one example of how preventive maintenance done poorly can be worse than no maintenance at all.

3.3.6 Personnel

Another tactic for ensuring thorough lubrication is to have an oiler who can do all of the lubrication at the beginning of each shift. This may be better than having the operators do lubrication if the task is complicated or if the operators are not sufficiently skilled.

Whether operators will do their own equipment lubrication, rather than an oiler, is determined by the following criteria:

- The complexity of the task
- The motivation and ability of the operator
- The extent of pending failures that might be detected by the oiler but overlooked by operators

If operators can properly do the lubrication, then it should be made a part of their total responsibility, just as car drivers ensure that they have adequate gasoline in their vehicles. It is best if the operators are capable of doing their own preventive maintenance. Like many tasks, preventive maintenance should be delegated to the lowest possible level consistent with adequate knowledge and ability. If, however, operators may cause damage through negligence, willful neglect, or lack of ability, then a maintenance specialist should do lubrication. The tasks should be clearly defined. Operators may be able to do some items, whereas maintenance personnel will be required for others. Examples of how the work can be parceled out will be described later.

Preventive tasks are often assigned to the newest maintenance trainee. In most cases, management is just asking for trouble if maintenance is regarded as low-status, undesirable work. If management believes in preventive maintenance, they should assign well-qualified personnel. Education and experience make a big difference in maintenance. Most organizations have at least one skilled maintenance person who can step onto the factory floor and sense—through sight, sound, smell, vibration, and temperature—the conditions in the factory. This person can tell in an instant that "The feeder on number 2 is hanging up a little this morning, so we'd better look at it." This person should be encouraged to take a walk around the factory floor at the beginning of every shift to sense what is going on and inspect any questionable events. The human senses of an experienced person are the best detection systems available today.

3.3.7 Service Teams

A concept that is successfully applied in both factory and field service organizations is teams of three or four persons. This type of organization can be especially effective if equipment must have high uptime but requires lengthy maintenance time at

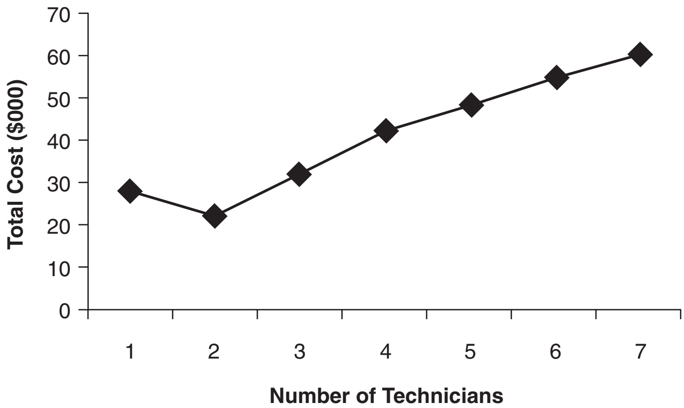


Figure 3–6 Total maintenance costs for varied number of technicans.

failures or preventive maintenance activities. If individual technicians were assigned to specific equipment, the person might well be busy on a lengthy project when a call comes to fix another machine. In an individual situation where a single person is responsible for specific machines, either the down machine would have to wait until the technician completes the first job and gets to the second or if the second machine has greater priority, the first machine may be left inoperable. The technician then interrupts his or her task to take care of the second problem and must return later to complete the first, thus wasting time and effort. The optimum number of people can be calculated for any scenario, time, and effort. Figure 3–6 illustrates one situation in which two was the best team size.

A good technique for teamwork is to rotate the preventive maintenance responsibility. The first week, Adam performs all the required tasks, while Brad, Chuck, and Donna make modifications and repairs. It may also help to assign Brad the short "do-it-now" (DIN) tasks for the same week. The next week, Brad does preventive, and Donna handles DIN, while Chuck and Adam attend to emergencies. Rotating preventive maintenance tasks has the following advantages:

- Responsibility is shared equally by all.
- Doing a good preventive job one week should reduce the breakdown emergency repairs in following weeks; thus a technician can benefit from the results of his or her own preventive efforts.
- Technicians' skills and interests vary, so that what one person fails to notice during his or her week will probably be picked up by another person the next week.

The time to start is now. Don't let any more failures occur or information be lost. There is probably a lot of effort ahead, so get started implementing your program now.

	Yes	No	Comments
1. Standardization			
a. Is equipment already in use that provides the desired function?			
b. Is this the same as existing equipment?			
c. Are there problems with existing equipment?			
d. Can we maintain this equipment with existing personnel?			
e. Are maintenance requirements compatible with our current procedures?			
2. Reliability and Maintainability			
a. Can vendor prove the equipment will operate at least to our specifications?			
b. Warranty of all parts and labor for 90+ days?			
c. Is design fault-tolerant?			
d. Are tests go/no go?			
3. Service Parts			
a. Is recommended replacement list provided?			
b. Is the dollar total of spares less than 10% of equipment cost?			
c. Do we already have usable parts?			
d. Can parts be purchased from other vendors?			
e. Are any especially high quality or expensive parts required?			
4. Training			
a. Is special technician training required?			
b. Will manufacturer provide training?			
1. At no additional cost for first year?			
2. At our location as required?			

	Yes	No	Comments
5. Documentation			
a. All technical manuals provided?			
1. Installation			
2. Operation			
3. Corrective and preventive maintenance			
4. Parts			
6. Special Tools and Test Equipment			
a. Do we already have all required tools and test equipment?			
b. Can at least 95% of all faults be detected by use of proposed equipment?			
c. Are calibration procedures minimum and clear?			
7. Safety			
a. Are all UL/SCA, OSHA, EPA and other applicable requirements met?			
b. Are any special precautions required?			
c. Can one person do all maintenance?			

Figure 3–7 Maintenance considerations checklist for purchasing agents and facilities engineers.

3.3.8 How to Start

The necessary items for establishing an effective preventive maintenance program are as follows:

- Every piece of equipment uniquely identified by prominent ID number or serial number and product type

- Accurate equipment history records
- Failure information by problem, cause, and action
- Experience data from similar equipment
- Manufacturer's interval and procedure recommendations
- Service manuals
- Consumables and replaceable parts
- Skilled personnel
- Proper test instruments and tools
- Clear instructions with a checklist to be signed off
- User cooperation
- Management support

A typical initial challenge is to get proper documentation for all equipment. When a new building or plant is constructed, the architects and construction engineers should be required to provide complete documentation on all facilities and the equipment installed in them. Any major equipment that is installed after that should have complete documentation. Figure 3–7 is a checklist that should be given to anyone who purchases facilities and equipment that must be maintained. One of the items on this list is ensuring availability of complete documentation and preventive maintenance recommendations.

Purchasing agents and facilities engineers are usually pleased to have such a checklist and will be cooperative if reminded occasionally about their major influence on life-cycle costs. This brings us back again to the principle of avoiding or minimizing the need for maintenance. Buying the right equipment in the beginning is the way to start. The best maintainability is eliminating the need for maintenance.

If you are in the captive service business or concerned with designing equipment that can be well maintained, you should recognize that the preceding recommendation was aimed more at factory maintenance; but after all, that is an environment in which your equipment will often be used. It helps to view the program from the operator and serviceperson's eyes to ensure that everyone's needs are satisfied.

4

BENEFITS OF PREDICTIVE MAINTENANCE

Predictive maintenance is not a substitute for the more traditional maintenance management methods. It is, however, a valuable addition to a comprehensive, total-plant maintenance program. Where traditional maintenance management programs rely on routine servicing of all machinery and fast response to unexpected failures, a predictive maintenance program schedules specific maintenance tasks as they are actually required by plant equipment. It cannot eliminate the continued need for either or both of the traditional maintenance programs (i.e., run-to-failure and preventive). Predictive maintenance can, however, reduce the number of unexpected failures and provide a more reliable scheduling tool for routine preventive maintenance tasks.

The premise of predictive maintenance is that regular monitoring of the actual mechanical condition of machine-trains and operating efficiency of process systems will ensure the maximum interval between repairs; minimize the number and cost of unscheduled outages created by machine-train failures; and improve the overall availability of operating plants. Including predictive maintenance in a total-plant management program will optimize the availability of process machinery and greatly reduce the cost of maintenance. In reality, predictive maintenance is a condition-driven preventive maintenance program.

The benefits that are derived from using predictive maintenance technologies depend on the way the program is implemented. If the predictive maintenance program is limited to preventing catastrophic failures of select plant systems, then that is the result that will be derived; however, exclusive focus on preventing failures may result in a substantial increase in maintenance costs. For example, a large integrated steel mill was able to reduce unscheduled machine failures by more than 30 percent, but a review of maintenance costs disclosed a 60 percent increase.

4.1 Primary Uses of Predictive Maintenance

When used properly, predictive maintenance can provide almost unlimited benefits; however, when the scope of the program is artificially limited by the scope or work or restrictions imposed by the plant, the benefits may be substantially reduced. Typically, predictive maintenance is implemented for one of the following reasons:

- As a maintenance management tool
- As a plant optimization tool
- As a reliability improvement tool

4.1.1 As a Maintenance Management Tool

Traditionally, predictive maintenance is used solely as a maintenance management tool. In most cases, this use is limited to preventing unscheduled downtime and/or catastrophic failures. Although this goal is important, predictive maintenance can provide substantially more benefits by expanding the scope or mission of the program. As a maintenance management tool, predictive maintenance can and should be used as a maintenance optimization tool. The program's focus should be on eliminating unnecessary downtime, both scheduled and unscheduled; eliminating unnecessary preventive and corrective maintenance tasks; extending the useful life of critical systems; and reducing the total life-cycle cost of these systems.

Benefits Derived from Maintenance-Only Use

A survey of 1,500 plants that had implemented predictive maintenance programs solely as a maintenance management tool indicated a substantial reduction in potential benefits. Results of the survey disclosed that 85.9 percent of the plants are currently using one or more of the traditional predictive maintenance technologies as an active part of their maintenance management activities and that the remaining 14.1 percent planned to start a program within the next three years. Five years ago, the reverse was true, with only 15 percent of surveyed plants using these technologies. One can conclude from this statistic that most plants have recognized the potential of predictive maintenance and have made an attempt to incorporate it into their maintenance management program.

Reasons for Implementation

The reason that plants implement predictive maintenance programs is also changing. In earlier surveys, the dominant reasons for which predictive maintenance was implemented focused on traditional maintenance issues, such as lower maintenance costs and reductions in unscheduled downtime caused by catastrophic machine failure. Although the companies polled in our May 2000 survey continue to cite these two factors as primary considerations, several nonmaintenance reasons have been added.

Product Quality. Almost 77 percent (76.7%) of the respondents cited improved product quality as a dominant reason their program was implemented. A few years ago, few plants recognized the ability of predictive technology to detect and correct product-quality problems.

Asset Protection. More than 60 percent (60.8%) of those interviewed included asset protection as the reason for implementation. Although asset management and protection is partially a maintenance issue, its inclusion as justification for a predictive maintenance program is a radical change from just a few years ago.

ISO Certification. Almost 36 percent (35.8%) included ISO certification as a reason for implementing predictive maintenance. The primary focus of ISO 9000 is product quality. As a result, the certification process includes criteria that seek to ensure equipment reliability and consistent production of first-quality products. Predictive maintenance helps maintain consistent quality performance levels of critical plant production systems. Although ISO certification does not include specific requirements for predictive maintenance, its inclusion in the plant program will greatly improve the probability of certification and will ensure long-term compliance with ISO program requirements.

Management Directive. Almost one-third (30.7 percent) of respondents stated that the primary reason for implementation was top management directives. More senior-level managers have recognized the absolute need for a tool to improve the overall reliability of critical plant systems. Many recognize the ability of predictive maintenance technologies as this critical management tool.

Lower Insurance Rates. Insurance considerations were cited by 25 percent of those interviewed. Most plants have insurance policies that protect them against interruptions in production. These policies are primarily intended to protect the plant against losses caused by fire, flood, breakdowns, or other prolonged interruptions in the plant's ability to operate. Over the past 10 years, insurance companies have begun to recognize the ability of predictive maintenance technology to reduce the frequency and severity of machine- and process-related production interruptions. As a result, the more progressive insurance companies now offer a substantially lower premium for production interruption insurance to plants that have a viable predictive maintenance program.

Predictive Maintenance Costs

The average maintenance budget of the plants interviewed was $12,053,000, but included those with budgets ranging from less than $100,000 to more than $100 million. The average plant invests 15.8 percent of its annual maintenance budget in predictive maintenance programs, but one-third (33%) of the plants interviewed in our May 2000 survey allocate less than 10 percent to predictive maintenance.

According to the survey, the average cost of a predictive maintenance program is $1.9 million annually. This cost includes procuring instrumentation but consists primarily of the recurring labor cost required to sustain these programs. The burdened cost—

including fringe benefits, overhead, taxes, and other nonpayroll costs—of labor varies depending on the location and type of plant. For example, the annual cost of an entry-level predictive analyst in a Chicago steel mill is about $70,000 per employee. The same analyst in a small food processing plant located in the South may be as low as $30,000.

In the survey, the full range of predictive maintenance program costs varied from a low of $72,318 to a high of almost $4 million ($3.98 million) and included plants with total maintenance budgets from less than $100,000 to more than $100 million annually. This range of costs is to be expected because the survey included a variety of industries, ranging from food and kindred products that would tend to have fewer personnel assigned to predictive maintenance to large, integrated process plants that require substantially more personnel.

The real message this measurement provides is that the recurring cost associated with data collection and analyses of a predictive maintenance program can be substantial and that the savings or improvements generated by the program must, at a minimum, offset these costs.

Contract Predictive Maintenance Costs

The survey indicates that most programs use a combination of in-house and contract personnel to sustain their predictive maintenance program. A series of questions designed to quantify the use of outside contractors was included in the survey and provided the following results.

The average plant spends $386,500 each year for contract predictive maintenance services. Obviously, the actual expenditure varies with size and management commitment of each individual plant. According to the survey, annual expenditures ranged from nothing to more than $1 million. The types of contract services include the following:

Vibration Monitoring. The results of our survey shows that 67.4 percent of the vibration monitoring programs are staffed with in-house personnel, and an additional 10.4 percent use a combination of plant personnel and outside contractors. The remaining 22.2 percent of these programs are outsourced to contract vibration-monitoring vendors.

In part, the decision to outsource may be justified. In smaller plants the labor requirements for a full-plant predictive maintenance program may not be enough to warrant a full-time, in-house analyst. In this situation outsourcing is often a viable option. Other plants that can justify full-time, in-house personnel elect to use outside contractors in the belief that a cost saving is gained by this approach. Although the plant can eliminate the burden, such as retirement benefits, taxes, and overhead, associated with in-house labor, this approach is questionable. If the contractual agreement with the vendor guarantees the same quality, commitment, and continuity that is typical of an in-house program, this approach can work; however, this is often not the case. Turnover and inconsistent results are too often the norm for contract predictive maintenance programs. There are good, well-qualified vendors, but there are also many contract predictive maintenance vendors who are totally unqualified to provide even minimum levels of performance.

Lube Oil Analysis. The ratio is reversed for lubricating oils analysis. Sixty-eight percent of these programs are staffed with contractors, and only 15.1 percent use only in-plant personnel. An additional 17 percent of these programs use a combination of personnel. This statistic is a little surprising both in the number of users and approach taken.

Until recently, lube oil analysis was limited to manual laboratory techniques that would normally preclude the use of in-house staff. As a result, most of the analysis required for this type of program was contracted to a material-testing laboratory. With this type of arrangement, we would have expected the survey to show a higher ratio of in-plant personnel involved in the program. Typically, in-house personnel are responsible for regular collections of lubricating oil samples, which are then sent to outside laboratories for analysis. This assumption is supported by the labor distribution of the tribology programs included in this survey. The mix includes 36 percent in-house and 56 percent outside services. One would assume from these statistics that in-house personnel acquire samples and rely on the outside laboratories for wear particle, ferrographic, or spectrographic analyses.

In the purely technical sense, lubricating oils analysis is not a predictive maintenance tool. Rather, it is a positive means of selecting and using lubricants in various plant applications. This technique evaluates the condition of the lubricants, not the condition of a machine or mechanical system. Although the sample may indicate that a defect or problem exists in a mechanical system, it does little to isolate the root-cause of the problem. One could conclude from the survey results that too many plants are using lubricating oils analysis incorrectly.

Thermography. Thermography programs are almost equally divided between in-house and contract programs. In-house personnel staff 45.9 percent, outside contractors provide 42.5 percent, and a combination of personnel account for 11.6 percent. The higher-than-expected reliance on outside contractors may be caused by the high initial investment cost of state-of-the-art infrared scanning systems. A typical full-color system will cost about $60,000 and may be prohibitive in smaller plants.

Derived Benefits

Our survey attempted to quantify the benefits that have been derived from predictive maintenance programs. Almost 91 percent (90.9%) of participants reported measurable savings as a result of their predictive maintenance program. On average, reductions in maintenance costs and downtime have recovered 113 percent of the total cost invested in these programs. Based on these statistics, the typical program will generate a net improvement of 13 percent. When compared to the average maintenance budget of survey participants ($12,053,000), the average annual savings are about $1.6 million.

A successful predictive maintenance program, according to most publications, should generate a return on investment of between 10:1 and 12:1. In other words, the plant should save $10 to $12 for every dollar invested. The survey results clearly indicate that this is not the case. Based on the statistics, the average return on investment was only 1.13:1, slightly better than breakeven. If this statistic were true, few financial managers would authorize an investment in predictive maintenance.

The statistics generated by the survey may be misleading. If you look carefully at the responses, you will see that 26.2 percent of respondents indicated that their programs recovered invested costs; 13 percent did not know; and 50.8 percent did not recover costs. From these statistics, one would have to question the worth of predictive technology; however, before you judge its worth, consider the remaining 10 percent. These plants not only recovered costs but also generated additional savings that increased bottom-line plant profitability. Almost half of these plants generated a profit five times greater than their total incurred cost, a return on investment of 5:1. Although this return is well below the reported norm of successful predictive maintenance programs, it does have a substantial, positive effect on profitability.

The statistics also confirm our belief that few plants are taking full advantage of predictive maintenance capabilities. When fully utilized, these technologies can generate a return on investment well above 100:1 or $100 for every dollar invested. As we have stated many times, the technology is available, but it must be used properly to gain maximum benefits. The survey results clearly show that this is not yet occurring for many companies.

Which Technology Is Most Beneficial

Each of the participants was asked to rank each of the traditional predictive maintenance technologies based on its benefits to improved performance. Vibration analysis was selected as the most beneficial by 54.6 percent of respondents. This statistic is not surprising for two reasons. First, most of the equipment, machines, and systems that constitute a typical plant are mechanical and well suited for vibration monitoring. The second reason has two parts. First, vibration-monitoring technology and instruments have evolved much faster than some of the other technologies. In the past 10 years, data collection instrumentation and its associated software packages have evolved to a point that almost anyone can use this technology effectively. The same is not true of predictive technologies, which still require manual collection and analysis.

The second part is that most users view vibration monitoring as being relatively easy. Simply follow the data collection route displayed on a portable data collector; download acquired data to a PC; print an exception report; and repeat the process a few weeks or months later. Don't laugh. This is exactly the way many vibration-monitoring programs are done. Will this approach reduce the number and frequency of unscheduled delays? Yes, it will, but it will do little or nothing to reduce costs, improve availability, or increase bottom-line profits. The unfortunate part is that too many programs are judged solely on the number of measurement points acquired each month, how many points are in alarm, or the number of unscheduled delays. As a result, a program is viewed as being successful even though it is actually increasing costs.

What Would You Change?

Perhaps the most interesting results of the survey were the responses to questions pertaining to improvements or changes that should be made to these existing programs. The responses included the following:

Do More Often. One of the favorite ploys used by upper management to reduce the perceived cost of predictive maintenance is to reduce the frequency of use. Instead of monitoring equipment on a frequency equal to its criticality, they elect to limit the frequency to quarterly, semi-annually, or even less. This approach will ensure failure or at best restrict the benefits of the program. To be effective, predictive maintenance technologies must be used. Limiting the evaluation cycle to abnormally long intervals destroys the program's ability to detect minor changes in critical plant equipments' operating condition.

The proper monitoring frequency varies depending on the specific technology used and the criticality of the plant system. For example, plant systems that are essential for continued plant operation should be monitored continuously. Systems with lesser importance may require monthly or annual evaluation frequencies.

When vibration monitoring is used, the maximum effective frequency is every 30 days. If the frequency is greater, the program effectiveness will be reduced in direct proportion to the analysis interval. In most cases, programs that use a monitoring frequency greater than 30 days for noncritical plant systems will never recover the recurring costs generated by the program. Thirty days is the maximum interval recommended for this program type. As the criticality of the plant system increases, so should the monitoring frequency.

Some applications for thermography, such as roof surveys, should have an interval of 12 to 36 months. Nothing is gained by increasing the survey frequency in these types of applications; however, other applications, such as monitoring electrical equipment and other critical plant systems, should follow a much more frequent schedule. Similar to vibration monitoring, the monitoring frequency for thermographic programs should be based on the criticality of the system. Normal intervals range from weekly on essential systems to bimonthly on less critical equipment.

Lubricating oil analysis, when used properly, does not require the same frequency as other predictive maintenance technologies. Because this technique is used solely to evaluate the operating condition of lubricants, a quarterly or semi-annual evaluation is often sufficient. Too many programs use a monthly sampling frequency in the mistaken belief that lube oil analysis will detect machine problems. If it were the only technology used, this belief may have some validity; however, other techniques, such as vibration monitoring, will provide a much more cost-effective means of early detection. Lube oil analysis is not an effective machinery diagnostic tool. Although some failure mechanisms will release detectable contaminants, such as bearing Babbitt, into the lubricant, this analysis technique cannot isolate the root-cause of the problem.

Nothing. Almost 13 percent of those interviewed stated that their predictive maintenance program did not require any change. This response is a little frightening. When one considers that only 10 percent of the surveyed programs generated a positive contribution to plant performance and more than 50 percent failed to recover the actual cost of their programs, it is difficult to believe that the programs do not need to be improved.

This response probably partly results from an indication that too many plant personnel do not fully understand predictive maintenance technology. In one of my columns, I used the example of a program that was judged to be highly successful by plant personnel, including senior management. After 6 years of a total-plant vibration-monitoring program, unscheduled delays had been reduced by about 30 percent. Based exclusively on this statistic, the program was deemed successful, but when evaluated from a standpoint of the frequency of scheduled downtime and annual procurement of maintenance spares, another story emerged. Scheduled downtime for maintenance increased by almost 40 percent and annual cost of replacement parts by more than 80 percent. As an example, before implementing the predictive maintenance program, the plant purchased about $4.1 million of bearings each year. In the sixth year of the program, annual bearing replacement costs exceeded $14 million. Clearly the program was not successful in all respects.

Don't Know. Almost 9 percent of those interviewed could not answer this question. Coupled with the previous response, this can probably be attributed to a lack of viable program evaluation tools. How do you measure the success of a predictive maintenance program? Is it the number of points monitored? Or the change in the overall vibration level of monitored machinery? Both of these criteria are too often the only measurement of a program's effectiveness.

The true measure of success is capacity. An effective program will result in a positive increase in first-time-through capacity—this is the only true measure of success. The converse of the increase in capacity is program cost. This criterion should include all incremental cost caused by the program, not just the labor required to maintain the program. For example, the frequency of scheduled or planned repairs may increase as a result of the program. This increase will generate additional or incremental charges that must be added to the program cost.

The problem that most programs face is that existing performance tracking programs do not provide an accurate means of evaluation. Plant data are too often fragmented, distorted, or conflicting and are not usable as a measurement of program success. This problem is not limited to effective measurement of predictive maintenance programs, but severely restricts the ability to manage all plant functions.

The ability to effectively use predictive maintenance technologies strictly depends on your ability to measure change. Therefore, it is essential that the plant implements and maintains an effective plant performance evaluation program. Universal use of a viable set of measurement criteria is essential.

More Management Involvement. Only 1 percent of the survey participants stated that more management involvement was needed. Of all the survey responses, this is the greatest surprise. Lack of management commitment and involvement is the primary reason that most predictive maintenance programs fail. Based on the other responses, this view may be a result of the respondents' failure to recognize the real reason for ineffective programs. Most of the responses, including increasing the monitoring frequency, have their roots in a lack of management involvement. Why else would the frequency be too great?

When you consider that 30.7 percent of these programs were implemented because of management directives, one would conclude that management commitment is automatic. Unfortunately, this is too often not the case. Like most of those interviewed, plant management does not have a complete understanding of predictive maintenance. They do not understand the absolute necessity of regular, timely monitoring cycles; the labor required to gain maximum benefits; or the need to fully use the information generated by the program. As a result, too many programs are only partially implemented. Staffing, training, and universal use of data are restricted in a misguided attempt to minimize cost.

Conclusions

The survey revealed many positive changes in the application and use of predictive maintenance technology. More participants are beginning to understand that this tool offers more than just the ability to prevent catastrophic failure of plant machinery. In addition, more plants are adopting these technologies and either have or plan to implement them in their plants. Apparently, few question the merit of these technologies as a tool to improve product quality, increase capacity, and reduce costs. These are all positive indications that predictive maintenance has gained credibility and will continue to be used by a growing number of plants.

The bad news is that too many plants are not fully utilizing predictive maintenance. Many of you have heard about or read my adamant opinion that predictive maintenance is not working. The survey results confirm this viewpoint. When fewer than 10 percent of the programs generate a positive return on investment, it would be difficult to disagree with this point. Is this a failure of the technology or are we doing something wrong?

In my opinion, the latter is the sole reason that predictive maintenance has failed to consistently achieve its full potential. The technology is real, and the evolution of microprocessor-based instrumentation and dedicated software programs has simplified the use of these technologies to a point that almost anyone can effectively use them. The failure is not because of technology limitations. We simply are not using the tools effectively.

In most cases, the reason for failure is a lack of planning and preparation before implementing the program. Many predictive maintenance system vendors suggest that implementing a predictive maintenance program is easy and requires little effort to set up. Nothing could be further from the truth. There are no easy solutions to the high costs of maintenance. The amount of time and effort required to select predictive methods that will provide the most cost-effective means to (1) evaluate the operating condition of critical plant systems; (2) establish a program plan; (3) create a viable database; and (4) establish a baseline value is substantial. The actual time and labor required will vary depending on plant size and the complexity of process systems. For a small company, the time required to develop a viable program will be about three person-months. For large, integrated process plants, this initial effort may be as much as 15 person-years. Are the benefits worth this level of effort? In almost every instance, the answer is an absolute yes.

4.1.2 As a Plant Optimization Tool

Predictive maintenance technologies can provide even more benefit when used as a plant optimization tool. For example, these technologies can be used to establish the *best* production procedures and practices for all critical production systems within a plant. Few of today's plants are operating within the original design limits of their production systems. Over time, the products that these lines produce have changed. Competitive and market pressure have demanded increasingly higher production rates. As a result, the operating procedures that were appropriate for the as-designed systems are no longer valid. Predictive technologies can be used to map the actual operating conditions of these critical systems and to provide the data needed to establish valid procedures that will meet the demand for higher production rates without a corresponding increase in maintenance cost and reduced useful life. Simply stated, these technologies permit plant personnel to quantify the cause-and-effect relationship of various modes of operation. This ability to actually measure the effect of different operating modes on the reliability and resultant maintenance costs should provide the means to make sound business decisions.

4.1.3 As a Reliability Improvement Tool

As a reliability improvement tool, predictive maintenance technologies cannot be beat. The ability to measure even slight deviations from normal operating parameters permits appropriate plant personnel (e.g., reliability engineers, maintenance planners) to plan and schedule minor adjustments to prevent degradation of the machine or system, thereby eliminating the need for major rebuilds and the associated downtime.

Predictive maintenance technologies are not limited to simple electromechanical machines. These technologies can be used effectively on almost every critical system or component within a typical plant. For example, time-domain vibration can be used to quantify the response characteristics of valves, cylinders, linear-motion machines, and complex systems, such as oscillators on continuous casters. In effect, this type of predictive maintenance can be used on any machine where timing is critical.

The same is true for thermography. In addition to its traditional use as a tool to survey roofs and building structures for leaks or heat loss, this tool can be used for a variety of reliability-related applications. It is ideal for any system where surface temperature indicates the system's operating condition. The applications are almost endless, but few plants even attempt to use infrared as a reliability tool.

4.1.4 The Difference

Other than the mission or intent of how predictive maintenance is used in your plant, the real difference between the limited benefits of a traditional predictive maintenance program and the maximum benefits that these technologies could provide is the diagnostic logic that is used. In traditional predictive maintenance applications, analysts typically receive between 5 and 15 days of formal instruction. This training is always limited to the particular technique (e.g., vibration, thermography) and excludes all other knowledge that might help them understand the true operating condition of the machine, equipment, or system they are attempting to analyze.

The obvious fallacy in this is that none of the predictive technologies can be used as stand-alone tools to accurately evaluate the operating condition of critical production systems. Therefore, analysts must use a variety of technologies to achieve anything more than simple prevention of catastrophic failures. At a minimum, analysts should have a practical knowledge of machine design, operating dynamics, and the use of at least the three major predictive technologies (i.e., vibration, thermography, and tribology). Without this minimum knowledge, they cannot be expected to provide accurate evaluations or cost-effective corrective actions.

In summary, there are two fundamental requirements of a truly successful predictive maintenance program: (1) a mission that focuses the program on total-plant optimization and (2) proper training for technicians and analysts. The mission or scope of the program must be driven by life-cycle cost, maximum reliability, and best practices from all functional organizations within the plant. If the program is properly structured, the second requirement is to give the personnel responsible for the program the tools and skills required for proper execution.

4.1.5 Benefits of a Total-Plant Predictive Program

A survey of 500 plants that have implemented predictive maintenance methods indicates substantial improvements in reliability, availability, and operating costs. The successful programs included in the survey include a cross-section of industries and provide an overview of the types of improvements that can be expected. Based on the survey results, major improvements can be achieved in maintenance costs, unscheduled machine failures, repair downtime, spare parts inventory, and both direct and indirect overtime premiums. In addition, the survey indicated a dramatic improvement in machine life, production, operator safety, product quality, and overall profitability.

Based on the survey, the actual costs normally associated with the maintenance operation were reduced by more than 50 percent. The comparison of maintenance costs included the actual labor and overhead of the maintenance department. It also included the actual materials cost of repair parts, tools, and other equipment required to maintain plant equipment. The analysis did not include lost production time, variances in direct labor, or other costs that should be directly attributed to inefficient maintenance practices.

The addition of regular monitoring of the actual condition of process machinery and systems reduced the number of catastrophic, unexpected machine failures by an average of 55 percent. The comparison used the frequency of unexpected machine failures before implementing the predictive maintenance program to the failure rate during the two-year period following the addition of condition monitoring to the program. Projections of the survey results indicate that reductions of 90 percent can be achieved using regular monitoring of the actual machine condition.

Predictive maintenance was shown to reduce the actual time required to repair or rebuild plant equipment. The average improvement in mean-time-to-repair (MTTR) was a reduction of 60 percent. To determine the average improvement, actual repair times before the predictive maintenance program were compared to the actual time to repair after one year of operation using predictive maintenance management techniques. The regular monitoring and analysis of machine condition identified the specific failed component(s) in each machine and enabled the maintenance staff to plan each repair. The ability to predetermine the specific repair parts, tools, and labor skills required provided the dramatic reduction in both repair time and costs.

The ability to predict machine-train and equipment failures and the specific failure mode provided the means to reduce spare parts inventories by more than 30 percent. Rather than carry repair parts in inventory, the surveyed plants had sufficient lead time to order repair or replacement parts as needed. The comparison included the actual cost of spare parts and the inventory carrying costs for each plant.

Prevention of catastrophic failures and early detection of incipient machine and systems problems increased the useful operating life of plant machinery by an average of 30 percent. The increase in machine life was a projection based on five years of operation after implementation of a predictive maintenance program. The calculation included frequency of repairs, severity of machine damage, and actual condition of machinery after repair. A condition-based predictive maintenance program prevents serious damage to machinery and other plant systems. This reduction in damage severity increases the operating life of plant equipment.

A side benefit of predictive maintenance is the automatic ability to monitor the mean-time-between-failures (MTBF). These data provide the means to determine the most cost-effective time to replace machinery rather than continue to absorb high maintenance costs. The MTBF of plant equipment is reduced each time a major repair or rebuild occurs. Predictive maintenance will automatically display the reduction of MTBF over the life of the machine. When the MTBF reaches the point that continued operation and maintenance costs exceed replacement cost, the machine should be replaced.

In each of the surveyed plants, the availability of process systems was increased after implementation of a condition-based predictive maintenance program. The average increase in the 500 plants was 30 percent. The reported improvement was based strictly on machine availability and did not include improved process efficiency; however, a full predictive program that includes process parameters monitoring can also improve the operating efficiency and therefore productivity of manufacturing and process plants. One example of this type of improvement is a food manufacturing plant that decided to build additional plants to meet peak demands. An analysis of existing plants, using predictive maintenance techniques, indicated that a 50 percent increase in production output could be achieved simply by increasing the operating efficiency of the existing production process.

The survey determined that advanced notice of machine-train and systems problems had reduced the potential for destructive failure, which could cause personal injury or death. The determination was based on catastrophic failures where personal injury would most likely occur. Several insurance companies are offering premium reductions to plants that have a condition-based predictive maintenance program in effect. Several other benefits can be derived from a viable predictive maintenance management program: verification of new equipment condition, verification of repairs and rebuild work, and product quality improvement.

Predictive maintenance techniques can be used during site acceptance testing to determine the installed condition of machinery, equipment, and plant systems. This provides the means to verify the purchased condition of new equipment before acceptance. Problems detected before acceptance can be resolved while the vendor has a reason—that is, the invoice has not been paid—to correct any deficiencies. Many industries are now requiring that all new equipment include a reference vibration signature provided with purchase. The reference signature is then compared with the baseline taken during site acceptance testing. Any abnormal deviation from the reference signature is grounds for rejection, without penalty of the new equipment. Under this agreement, the vendor is required to correct or replace the rejected equipment. These techniques can also be used to verify the repairs or rebuilds on existing plant machinery.

Vibration analysis, a key predictive maintenance tool, can be used to determine whether the repairs corrected existing problems and/or created additional abnormal behavior before the system is restarted. This ability eliminates the need for the second outage that is often required to correct improper or incomplete repairs.

Data acquired as part of a predictive maintenance program can be used to schedule and plan plant outages. Many industries attempt to correct major problems or schedule preventive maintenance rebuilds during annual maintenance outages. Predictive data can provide the information required to plan the specific repairs and other activities during the outage. One example of this benefit is a maintenance outage scheduled to rebuild a ball mill in an aluminum foundry. The normal outage, before predictive maintenance techniques were implemented in the plant, to completely rebuild the ball mill was three weeks, and the repair cost averaged $300,000.

The addition of predictive maintenance techniques as an outage-scheduling tool reduced the outage to five days and resulted in a total savings of $200,000. The predictive maintenance data eliminated the need for many of the repairs that would normally have been included in the maintenance outage. Based on the ball mill's actual condition, these repairs were not needed. The additional ability to schedule the required repairs, gather required tools, and plan the work reduced the time required from three weeks to five days.

The overall benefits of predictive maintenance management have proven to substantially improve the overall operation of both manufacturing and processing plants. In all surveyed cases, the benefits derived from using condition-based management have offset the capital equipment costs required to implement the program within the first three months. Use of microprocessor-based predictive maintenance techniques has further reduced the annual operating cost of predictive maintenance methods so that any plant can achieve cost-effective implementation of this type of maintenance management program.

5

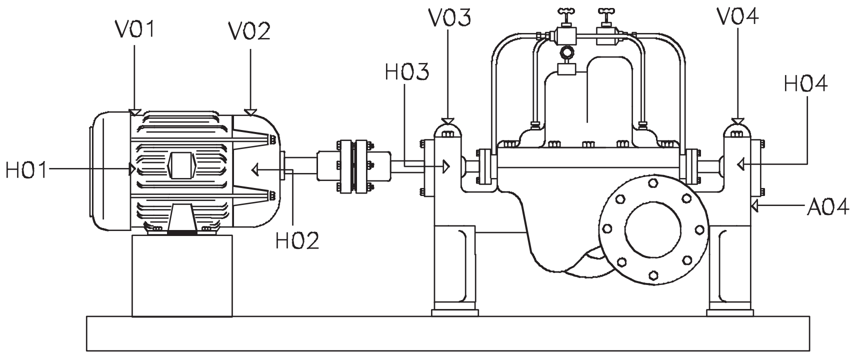
MACHINE-TRAIN MONITORING PARAMETERS

This chapter discusses normal failure modes, monitoring techniques that can prevent premature failures, and the measurement points required for monitoring common machine-train components. Understanding the specific location and orientation of each measurement point is critical to diagnosing incipient problems.

The frequency-domain, or FFT, signature acquired at each measurement point is an actual representation of the individual machine-train component's motion at that point on the machine. Without knowing the specific location and orientation, it is difficult—if not impossible—to correctly identify incipient problems. In simple terms, the FFT signature is a photograph of the mechanical motion of a machine-train in a specific direction and at a specific point and time.

The vibration-monitoring process requires a large quantity of data to be collected, temporarily stored, and downloaded to a more powerful computer for permanent storage and analysis. In addition, there are many aspects to collecting meaningful data. Data collection generally is accomplished using microprocessor-based data collection equipment referred to as *vibration analyzers*; however, before analyzers can be used, it is necessary to set up a database with the data collection and analysis parameters. The term *narrowband* refers to a specific frequency window that is monitored because of the knowledge that potential problems may occur as a result of known machine components or characteristics in this frequency range.

The orientation of each measurement point is an important consideration during the database setup and analysis. Each measurement point on every machine-train in a predictive maintenance program has an optimum orientation. For example, a helical gear set creates specific force vectors during normal operation. As the gear set degrades, these force vectors transmit the maximum vibration components. If only one radial



AO = Axial Orientation, HO = Horizontal Orientation, VO = Vertical Orientation

Figure 5–1 Recommended measurement point logic.

reading is acquired for each bearing housing, it should be oriented in the plane that provides the greatest vibration amplitude.

For continuity, each machine-train should be set up on a "common-shaft" with the outboard driver bearing designated as the first data point. Measurement points should be numbered sequentially, starting with the outboard driver bearing and ending with the outboard bearing of the final driven component. This point is illustrated in Figure 5–1. Any numbering convention may be used, but it should be consistent, which provides two benefits:

1. Immediate identification of the location of a particular data point during the analysis/diagnostic phase.
2. Grouping the data points by "common shaft" enables the analyst to evaluate all parameters affecting each component of a machine-train.

5.1 Drivers

All machines require some form of motive power, which is referred to as a *driver*. This section includes the monitoring parameters for the two most common drivers: electric motors and steam turbines.

5.1.1 Electric Motors

Electric motors are the most common source of motive power for machine-trains. As a result, more of them are evaluated using microprocessor-based vibration-monitoring systems than any other driver. The vibration frequencies of the following parameters are monitored to evaluate operating condition. This information is used to establish a database.

- Bearing frequencies
- Imbalance

- Line frequency
- Loose rotor bars
- Running speed
- Slip frequency
- V-belt intermediate drives

Bearing Frequencies

Electric motors may incorporate either sleeve or rolling-element bearings. A narrowband window should be established to monitor both the normal rotational and defect frequencies associated with the type of bearing used for each application.

Imbalance

Electric motors are susceptible to a variety of forcing functions that cause instability or imbalance. The narrowbands established to monitor the fundamental and other harmonics of actual running speed are useful in identifying mechanical imbalance, but other indices should also be used.

One such index is line frequency, which provides indications of instability. Modulations, or harmonics, of line frequency may indicate the motor's inability to find and hold magnetic center. Variations in line frequency also increase the amplitude of the fundamental and other harmonics of running speed.

Axial movement and the resulting presence of a third harmonic of running speed is another indication of instability or imbalance within the motor. The third harmonic is present whenever axial thrusting of a rotating element occurs.

Line Frequency

Many electrical problems—or problems associated with the quality of the incoming power and internal to the motor—can be isolated by monitoring the line frequency. Line frequency refers to the frequency of the alternating current being supplied to the motor. In the case of 60-cycle power, the fundamental or first harmonic (60 Hz), second harmonic (120 Hz), and third harmonic (180 Hz) should be monitored.

Loose Rotor Bars

Loose rotor bars are a common failure mode of electric motors. Two methods can be used to identify them. The first method uses high-frequency vibration components that result from oscillating rotor bars. Typically, these frequencies are well above the normal maximum frequency used to establish the broadband signature. If this is the case, a high-pass filter such as high-frequency domain can be used to monitor the condition of the rotor bars.

The second method uses the slip frequency to monitor for loose rotor bars. The passing frequency created by this failure mode energizes modulations associated with slip. This method is preferred because these frequency components are within the normal bandwidth used for vibration analysis.

Running Speed

The running speed of electric motors, both alternating current (AC) and direct current (DC), varies. Therefore, for monitoring purposes, these motors should be classified as variable-speed machines. A narrowband window should be established to track the true running speed.

Slip Frequency

Slip frequency is the difference between synchronous speed and actual running speed of the motor. A narrowband filter should be established to monitor electrical line frequency. The window should have enough resolution to clearly identify the frequency and the modulations, or sidebands that represent slip frequency. Normally, these modulations are spaced at the difference between synchronous and actual speed, and the number of sidebands is equal to the number of poles in the motor.

V-Belt Intermediate Drives

Electric motors with V-belt intermediate drive display the same failure modes as those described previously; however, the unique V-belt frequencies should be monitored to determine if improper belt tension or misalignment is evident.

In addition, electric motors used with V-belt intermediate drive assemblies are susceptible to premature wear on the bearings. Typically, electric motors are not designed to compensate for the sideloads associated with V-belt drives. In this type of application, special attention should be paid to monitoring motor bearings.

The primary data-measurement point on the inboard bearing housing should be located in the plane opposing the induced load (sideload), with the secondary point at 90 degrees. The outboard primary data-measurement point should be in a plane opposite the inboard bearing, with the secondary at 90 degrees.

5.1.2 Steam Turbines

There are wide variations in the size of steam turbines, which range from large utility units to small package units designed as drivers for pumps, and so on. The following section describes in general terms the monitoring guidelines. Parameters that should be monitored are bearings, blade pass, mode shape (shaft deflection), and speed (both running and critical).

Bearings

Turbines use both rolling-element and Babbitt bearings. Narrowbands should be established to monitor both the normal rotational frequencies and failure modes of the specific bearings used in each turbine.

Blade Pass

Turbine rotors consist of a series of vanes or blades mounted on individual wheels. Each of the wheel units, which are referred to as a *stage of compression*, has a different number of blades. Narrowbands should be established to monitor the blade-pass frequency of each wheel. Loss of a blade or flexing of blades or wheels is detected by these narrowbands.

Mode Shape (Shaft Deflection)

Most turbines have relatively long bearing spans and highly flexible shafts. These factors, coupled with variations in process flow conditions, make turbine rotors highly susceptible to shaft deflection during normal operation. Typically, turbines operate in either the second or third mode and should have narrowbands at the second (2X) and third (3X) harmonics of shaft speed to monitor for mode shape.

Speed

All turbines are variable-speed drivers and operate near or above one of the rotor's critical speeds. Narrowbands should be established that track each of the critical speeds defined for the turbine's rotor. In most applications, steam turbines operate above the first critical speed and in some cases above the second. A movable narrowband window should be established to track the fundamental (1X), second (2X), and third (3X) harmonics of actual shaft speed. The best method is to use orders analysis and a tachometer to adjust the window location.

Normally, the critical speeds are determined by the mechanical design and should not change; however, changes in the rotor configuration or a buildup of calcium or other foreign materials on the rotor will affect them. The narrowbands should be wide enough to permit some increase or decrease.

5.2 Intermediate Drives

Intermediate drives transmit power from the primary driver to a driven unit or units. Included in this classification are chains, couplings, gearboxes, and V-belts.

5.2.1 Chains

In terms of its vibration characteristics, a chain-drive assembly is much like a gear set. The meshing of the sprocket teeth and chain links generates a vibration profile that is almost identical to that of a gear set. The major difference between these two machine-train components is that the looseness or slack in the chain tends to modulate and amplify the tooth-mesh energy. Most of the forcing functions generated by a chain-drive assembly can be attributed to the forces generated by tooth-mesh. The typical frequencies associated with chain-drive assembly monitoring are those of running speed, tooth-mesh, and chain speed.

Running Speed

Chain-drives normally are used to provide positive power transmission between a driver and driven unit where direct coupling cannot be accomplished. Chain-drives generally have two distinct running speeds: driver or input speed and driven or output speed. Each of the shaft speeds is clearly visible in the vibration profile, and a discrete narrowband window should be established to monitor each of the running speeds.

These speeds can be calculated using the ratio of the drive to driven sprocket. For example, where the drive sprocket has a circumference of 10 inches and the driven sprocket a circumference of 5 inches, the output speed will be two times the input speed. Tooth-mesh narrowband windows should be created for both the drive and driven tooth-meshing frequencies. The windows should be broad enough to capture the sidebands or modulations that this type of passing frequency generates. The frequency of the sprocket-teeth meshing with the chain links, or passing frequency, is calculated by the following formula:

$$\text{Tooth} - \text{Mesh Frequency} = \text{Number of Sprocket Teeth} \times \text{Shaft Speed}$$

Unlike gear sets, a chain-drive system can have two distinctive tooth-mesh frequencies. Because the drive and driven sprockets do not directly mesh, the meshing frequency generated by each sprocket is visible in the vibration profile.

Chain Speed

The chain acts much like a driven gear and has a speed that is unique to its length. The chain speed is calculated by the following equation:

$$\text{Chain Speed} = \frac{\text{Number of Drive Sprocket Teeth} \times \text{Shaft Speed}}{\text{Number of Links in Chain}}$$

For example:

$$\text{Chain Speed} = \frac{25\ \text{teeth} \times 100\,\text{rpm}}{250\ \text{links}} = \frac{2500}{250} = 10\,\text{cpm} = 10\,\text{rpm}$$

5.2.2 Couplings

Couplings cannot be monitored directly, but they generate forcing functions that affect the vibration profile of both the driver and driven machine-train component. Each coupling should be evaluated to determine the specific mechanical forces and failure modes they generate. This section discusses flexible couplings, gear couplings, jackshafts, and universal joints.

Flexible Couplings

Most flexible couplings use an elastomer or spring-steel device to provide power transmission from the driver to the driven unit. Both coupling types create unique mechanical forces that directly affect the dynamics and vibration profile of the machine-train.

The most obvious force with flexible couplings is endplay or movement in the axial plane. Both the elastomer and spring-steel devices have memory, which forces the axial position of both the drive and driven shafts to a neutral position. Because of their flexibility, these devices cause the shaft to move constantly in the axial plane. This is exhibited as harmonics of shaft speed. In most cases, the resultant profile is a signature that contains the fundamental (1X) frequency and second (2X) and third (3X) harmonics.

Gear Couplings

When properly installed and maintained, gear-type couplings do not generate a unique forcing function or vibration profile; however, excessive wear, variations in speed or torque, or overlubrication results in a forcing function.

Excessive wear or speed variation generates a gear-mesh profile that corresponds to the number of teeth in the gear coupling multiplied by the rotational speed of the driver. Because these couplings use a mating gear to provide power transmission, variations in speed or excessive clearance permit excitation of the gear-mesh profile.

Jackshafts

Some machine-trains use an extended or spacer shaft, called a *jackshaft*, to connect the driver and a driven unit. This type of shaft may use any combination of flexible coupling, universal joint, or splined coupling to provide the flexibility required to make the connection. Typically, this type of intermediate drive is used either to absorb torsional variations during speed changes or to accommodate misalignment between the two machine-train components.

Because of the length of these shafts and the flexible couplings or joints used to transmit torsional power, jackshafts tend to flex during normal operation. Flexing results in a unique vibration profile that defines its operating mode shape.

In relatively low-speed applications, the shaft tends to operate in the first mode or with a bow between the two joints. This mode of operation generates an elevated vibration frequency at the fundamental (1X) turning speed of the jackshaft. In higher-speed applications, or where the flexibility of the jackshaft increases, it deflects into an "S" shape between the two joints. This "S" or second-mode shape generates an elevated frequency at both the fundamental (1X) frequency and the second harmonic (2X) of turning speed. In extreme cases, the jackshaft deflects further and operates in the third mode. When this happens, it generates distinct frequencies at the fundamental (1X), second harmonic (2X), and third harmonic (3X) of turning speed.

As a rule, narrowband windows should be established to monitor at least these three distinct frequencies (i.e., 1X, 2X, and 3X). In addition, narrowbands should be established to monitor the discrete frequencies generated by the couplings or joints used to connect the jackshaft to the driver and driven unit.

Universal Joints

A variety of universal joints is used to transmit torsional power. In most cases, this type of intermediate drive is used when some misalignment between the drive and driven unit is necessary. Because of the misalignment, the universal's pivot points generate a unique forcing function that influences both the dynamics and vibration profile generated by a machine-train.

Figure 5–2 illustrates a typical double-pivot universal joint. This type of joint, which is similar to those used in automobiles, generates a unique frequency at four times (4X) the rotational speed of the shaft. Each of the pivot-point bearings generates a passing frequency each time the shaft completes a revolution.

5.2.3 Gearboxes

Gear sets are used to change speed or rotating direction of the primary driver. The basic monitoring parameters for all gearboxes include bearings, gear-mesh frequencies, and running speeds.

Bearings

A variety of bearing types is used in gearboxes. Narrowband windows should be established to monitor the rotational and defect frequencies generated by the specific type of bearing used in each application.

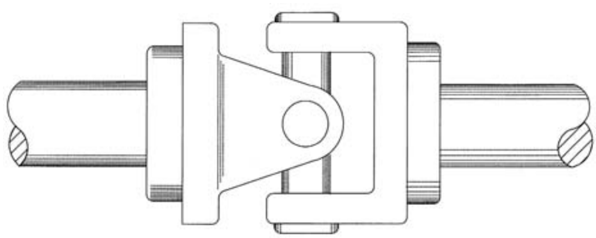


Figure 5–2 Typical double-pivot universal joint.

Special attention should be given to the thrust bearings, which are used in conjunction with helical gears. Because helical gears generate a relatively strong axial force, each gear shaft must have a thrust bearing located on the backside of the gear to absorb the thrust load. Therefore, all helical gear sets should be monitored for shaft run-out.

The thrust, or positioning, bearing of a herringbone or double-helical gear has little or no normal axial loading; however, a coupling lockup can cause severe damage to the thrust bearing. Double-helical gears usually have only one thrust bearing, typically on the bullgear. Therefore, the thrust-bearing rotor should be monitored with at least one axial data-measurement point.

The gear mesh should be in a plane opposing the preload, creating the primary data-measurement point on each shaft. A secondary data-measurement point should be located at 90 degrees to the primary point.

Gear-Mesh Frequencies

Each gear set generates a unique profile of frequency components that should be monitored. The fundamental gear-mesh frequency is equal to the number of teeth in the pinion or drive gear multiplied by the rotational shaft speed. In addition, each gear set generates a series of modulations, or sidebands, that surround the fundamental gear-mesh frequency. In a normal gear set, these modulations are spaced at the same frequency as the rotational shaft speed and appear on both sides of the fundamental gear mesh.

A narrowband window should be established to monitor the fundamental gear-mesh profile. The lower and upper limits of the narrowband should include the modulations generated by the gear set. The number of sidebands will vary depending on the resolution used to acquire data. In most cases, the narrowband limits should be about 10 percent above and below the fundamental gear-mesh frequency.

A second narrowband window should be established to monitor the second harmonic (2X) of gear mesh. Gear misalignment and abnormal meshing of gear sets result in multiple harmonics of the fundamental gear-mesh profile. This second window provides the ability to detect potential alignment or wear problems in the gear set.

Running Speeds

A narrowband window should be established to monitor each of the running speeds generated by the gear sets within the gearbox. The actual number of running speeds varies depending on the number of gear sets. For example, a single-reduction gearbox has two speeds: input and output. A double-reduction gearbox has three speeds: input, intermediate, and output. Intermediate and output speeds are determined by calculations based on input speed and the ratio of each gear set. Figure 5–3 illustrates a typical double-reduction gearbox.

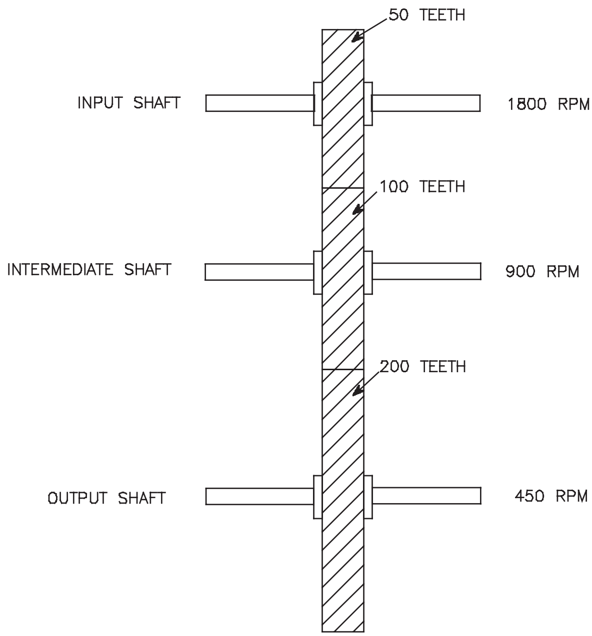


Figure 5–3 Double-reduction gearbox.

If the input speed is 1,800 rotations per minute (rpm), then the intermediate and output speeds are calculated using the following:

$$\text{Intermediate Speed} = \frac{\text{Input Speed} \times \text{Number of Input Gear Teeth}}{\text{Number of Intermedia Gear Teeth}}$$

$$\text{Output Speed} = \frac{\text{Intermediate Speed} \times \text{Number of Intermediate Gear Teeth}}{\text{Number of Output Gear Teeth}}$$

5.2.4 V-Belts

V-belts are common intermediate drives for fans, blowers, and other types of machinery. Unlike some other power-transmission mechanisms, V-belts generate unique forcing functions that must be understood and evaluated as part of a vibration analysis. The key monitoring parameters for V-belt–driven machinery are fault frequency and running speed.

Most of the forcing functions generated by V-belt drives can be attributed to the elastic or rubberband effect of the belt material. This elasticity is needed to provide the traction required to transmit power from the drive sheave (i.e., pulley) to the driven sheave. Elasticity causes belts to act like springs, increasing vibration in the direction of belt wrap, but damping it in the opposite direction. As a result,

Table 5–1 Belt-Drive Failure: Symptoms, Causes, and Corrective Actions

Symptom	Cause	Corrective Action
High 1X rotational frequency in radial direction.	Unbalanced or eccentric sheave.	Balance or replace sheave.
High 1X belt frequency with harmonics. Impacting at belt frequency in waveform.	Defects in belt.	Replace belt.
High 1X belt frequency. Sinusoidal waveform with period of belt frequency.	Unbalanced belt.	Replace belt.
High 1X rotational frequency in axial plane. 1X and possibly 2X radial.	Loose, misaligned, or mismatched belts.	Align sheaves, retension or replace belts as needed.

Source: Integrated Systems, Inc.

belt elasticity tends to accelerate wear and the failure rate of both the driver and driven unit.

Fault Frequencies

Belt-drive fault frequencies are the frequencies of the driver, the driven unit, and the belt. In particular, frequencies at one times the respective shaft speeds indicate faults with the balance, concentricity, and alignment of the sheaves. The belt frequency and its harmonics indicate problems with the belt. Table 5–1 summarizes the symptoms and causes of belt-drive failures, as well as corrective actions.

Running Speeds

Belt-drive ratios may be calculated if the pitch diameters (see Figure 5–5) of the sheaves are known. This coefficient, which is used to determine the driven speed given the drive speed, is obtained by dividing the pitch diameter of the drive sheave by the pitch diameter of the driven sheave. These relationships are expressed by the following equations:

$$\text{Drive Reduction} = \frac{\text{Drive Sheave Diameter}}{\text{Driven Sheave Diameter}}$$

$$\text{Drive Speed, rpm} = \text{Driven Speed, rpm} \times \left(\frac{\text{Driven Sheave Diameter}}{\text{Drive Sheave Diameter}}\right)$$

Using these relationships, the sheave rotational speeds can be determined; however, obtaining the other component speeds requires a bit more effort. The rotational speed of the belt cannot directly be determined using the information presented so far. To calculate belt rotational speed (rpm), the linear belt speed must first be determined by finding the linear speed (in./min.) of the sheave at its pitch diameter. In other words, multiply the pitch circumference (PC) by the rotational speed of the sheave, where:

$$\text{Pitch Circumference (in)} = \pi \times \text{Pitch Diameter (in)}$$

$$\text{Linear Speed (in/min)} = \text{Pitch Circumference (in)} \times \text{Sheave Speed (rpm)}$$

To find the exact rotational speed of the belt (rpm), divide the linear speed by the length of the belt:

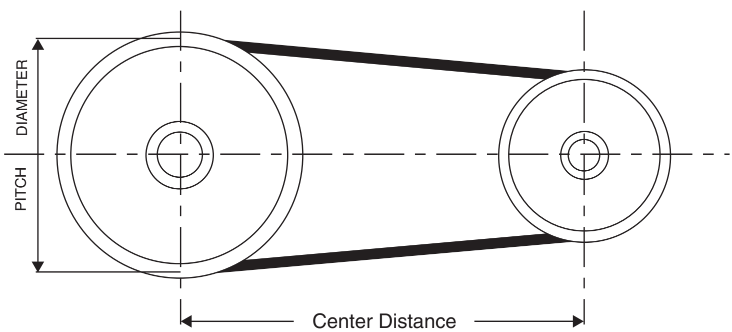
$$\text{Belt Rotational Speed (rpm)} = \frac{\text{Linear Speed (in/min)}}{\text{Belt Length (in)}}$$

To approximate the rotational speed of the belt, the linear speed may be calculated using the pitch diameters and the center-to-center distance (see Figure 5–4) between the sheaves. This method is accurate only if there is no belt sag. Otherwise, the belt rotational speed obtained using this method is slightly higher than the actual value.

In the special case where the drive and driven sheaves have the same diameter, the formula for determining the belt length is as follows:

The following equation is used to approximate the belt length where the sheaves have different diameters:

$$\text{Belt Length} = \frac{\text{Drive PC} + \text{Driven PC}}{2} + (2 \times \text{Center Distance})$$



Belt Length = Pitch Circumference + (2 × Center Distance)

Figure 5–4 Pitch diameter and center-to-center distance between belt sheaves.

5.3 Driven Components

This module cannot effectively discuss all possible combinations of driven components that may be found in a plant; however, the guidelines provided in this section can be used to evaluate most of the machine-trains and process systems that are typically included in a microprocessor-based vibration-monitoring program.

5.3.1 Compressors

There are two basic types of compressors: centrifugal and positive displacement. Both of these major classifications can be further divided into subtypes, depending on their operating characteristics. This section provides an overview of the more common centrifugal and positive-displacement compressors.

Centrifugal

There are two types of commonly used centrifugal compressors: inline and bullgear.

Inline. The inline centrifugal compressor functions in exactly the same manner as a centrifugal pump. The only difference between the pump and the compressor is that the compressor has smaller clearances between the rotor and casing. Therefore, inline centrifugal compressors should be monitored and evaluated in the same manner as centrifugal pumps and fans. As with these driven components, the inline centrifugal compressor consists of a single shaft with one or more impeller(s) mounted on the shaft. All components generate simple rotating forces that can be monitored and evaluated with ease. Figure 5–5 shows a typical inline centrifugal compressor.

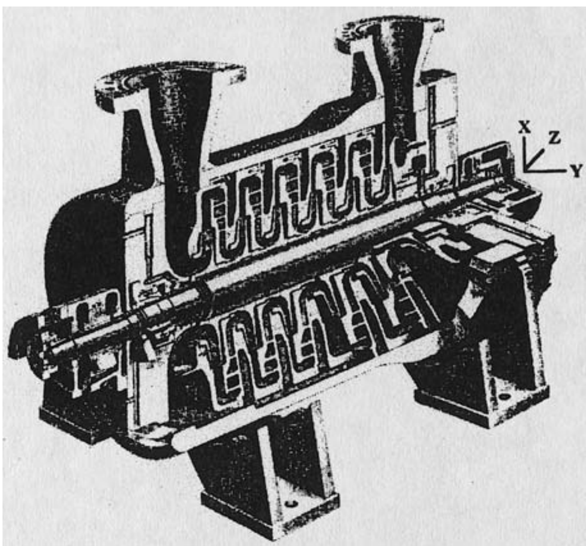


Figure 5–5 Typical inline centrifugal compressor.

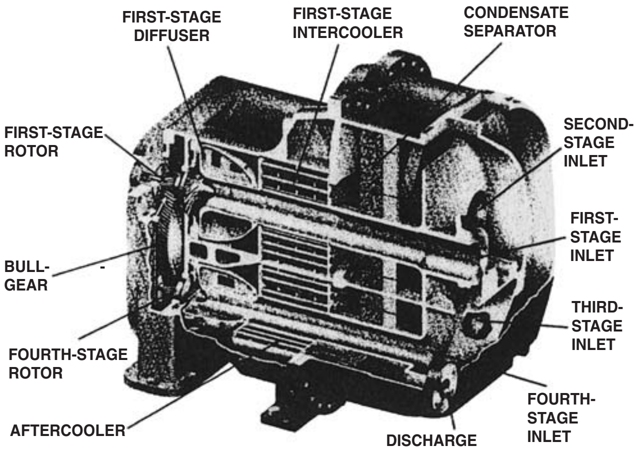


Figure 5–6 Cutaway of bullgear centrifugal compressor.

Bullgear. The bullgear centrifugal compressor (Figure 5–6) is a multistage unit that uses a large helical gear mounted onto the compressor's driven shaft and two or more pinion gears, which drive the impellers. These impellers act in series, whereby compressed air or gas from the first-stage impeller discharge is directed by flow channels within the compressor's housing to the second-stage inlet. The discharge of the second stage is channeled to the inlet of the third stage. This channeling occurs until the air or gas exits the final stage of the compressor.

Generally, the driver and bullgear speed is 3,600 rpm or less, and the pinion speeds are as high as 60,000 rpm (see Figure 5–7). These machines are produced as a package, with the entire machine-train mounted on a common foundation that also includes a panel with control and monitoring instrumentation.

Positive Displacement

Positive-displacement compressors, also referred to as *dynamic-type compressors*, confine successive volumes of fluid within a closed space. The pressure of the fluid increases as the volume of the closed space decreases. Positive-displacement compressors can be reciprocating or screw-type.

Reciprocating. Reciprocating compressors are positive-displacement types having one or more cylinders. Each cylinder is fitted with a piston driven by a crankshaft through a connecting rod. As the name implies, compressors within this classification displace a fixed volume of air or gas with each complete cycle of the compressor.

Reciprocating compressors have unique operating dynamics that directly affect their vibration profiles. Unlike most centrifugal machinery, reciprocating machines combine rotating and linear motions that generate complex vibration signatures.

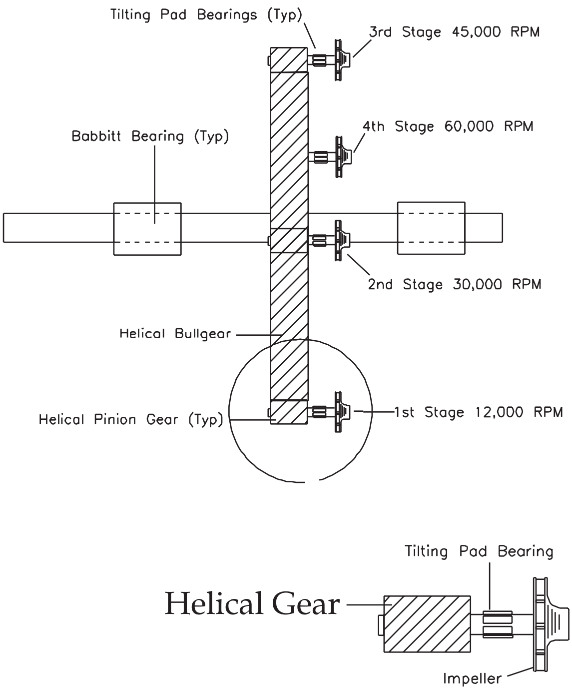


Figure 5–7 Internal bullgear drive's pinion gears at each stage.

Crankshaft frequencies. All reciprocating compressors have one or more crankshaft(s) that provide the motive power to a series of pistons, which are attached by piston arms. These crankshafts rotate in the same manner as the shaft in a centrifugal machine; however, their dynamics are somewhat different. The crankshafts generate all of the normal frequencies of a rotating shaft (i.e., running speed, harmonics of running speed, and bearing frequencies), but the amplitudes are much higher.

In addition, the relationship of the fundamental (1X) frequency and its harmonics changes. In a normal rotating machine, the 1X frequency normally contains between 60 and 70 percent of the overall, or broadband, energy generated by the machine-train. In reciprocating machines, however, this profile changes. Two-cycle reciprocating machines, such as single-action compressors, generate a high second harmonic (2X) and multiples of the second harmonic. While the fundamental (1X) is clearly present, it is at a much lower level.

Frequency shift caused by pistons. The shift in vibration profile is the result of the linear motion of the pistons used to provide compression of the air or gas. As each piston moves through a complete cycle, it must change direction two times. This reversal of direction generates the higher second harmonic (2X) frequency component.

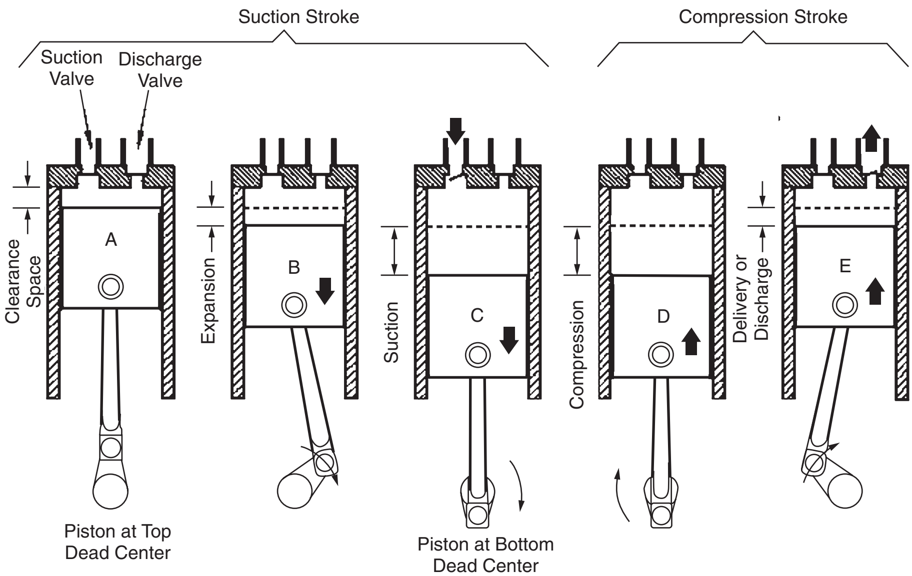


Figure 5–8 Two-cycle, or single-action, air compressor cylinders.

In a two-cycle machine, all pistons complete a full cycle each time the crankshaft completes one revolution. Figure 5–8 illustrates the normal action of a two-cycle, or single-action, compressor. Inlet and discharge valves are located in the clearance space and connected through ports in the cylinder head to the inlet and discharge connections.

During the suction stroke, the compressor piston starts its downward stroke and the air under pressure in the clearance space rapidly expands until the pressure falls below that on the opposite side of the inlet valve (Point B). This difference in pressure causes the inlet valve to open into the cylinder until the piston reaches the bottom of its stroke (Point C).

During the compression stroke, the piston starts upward, compression begins, and at Point D has reached the same pressure as the compressor intake. The spring-loaded inlet valve then closes. As the piston continues upward, air is compressed until the pressure in the cylinder becomes great enough to open the discharge valve against the pressure of the valve springs and the pressure of the discharge line (Point E). From this point, to the end of the stroke (Point E to Point A), the air compressed within the cylinder is discharged at practically constant pressure.

The impact energy generated by each piston as it changes direction is clearly visible in the vibration profile. Because all pistons complete a full cycle each time the crankshaft completes one full revolution, the total energy of all pistons is displayed at the fundamental (1X) and second harmonic (2X) locations. In a four-cycle machine, two complete revolutions (720 degrees) are required for all cylinders to complete a full cycle.

Piston orientations. Crankshafts on positive-displacement reciprocating compressors have offsets from the shaft centerline that provide the stroke length for each piston. The orientation of the offsets has a direct effect on the dynamics and vibration amplitudes of the compressor. In an opposed-piston compressor where pistons are 180 degrees apart, the impact forces as the pistons change directions are reduced. As one piston reaches top dead center, the opposing piston also is at top dead center. The impact forces, which are 180 degrees out-of-phase, tend to cancel out or balance each other as the two pistons change directions.

Another configuration, called an *unbalanced design*, has piston orientations that are neither in-phase nor 180 degrees out-of-phase. In these configurations, the impact forces generated as each piston changes direction are not balanced by an equal and opposite force. As a result, the impact energy and the vibration amplitude are greatly increased.

Horizontal reciprocating compressors (see Figure 5–9) should have X-Y data points on both the inboard and outboard main crankshaft bearings, if possible, to monitor the connecting rod or plunger frequencies and forces.

Screw. Screw compressors have two rotors with interlocking lobes and act as positive-displacement compressors (see Figure 5–10). This type of compressor is designed for baseload, or steady-state, operation and is subject to extreme instability if either the inlet or discharge conditions change. Two helical gears mounted on the outboard ends of the male and female shafts synchronize the two rotor lobes.

Analysis parameters should be established to monitor the key indices of the compressor's dynamics and failure modes. These indices should include bearings, gear mesh, rotor passing frequencies, and running speed; however, because of its sensitivity to process instability and the normal tendency to thrust, the most critical monitoring parameter is axial movement of the male and female rotors.

Bearings. Screw compressors use both Babbitt and rolling-element bearings. Because of the thrust created by process instability and the normal dynamics of the two rotors, all screw compressors use heavy-duty thrust bearings. In most cases, they are located on the outboard end of the two rotors, but some designs place them on the inboard end. The actual location of the thrust bearings must be known and used as a primary measurement-point location.

Gear mesh. The helical timing gears generate a meshing frequency equal to the number of teeth on the male shaft multiplied by the actual shaft speed. A narrowband window should be created to monitor the actual gear mesh and its modulations. The limits of the window should be broad enough to compensate for a variation in speed between full load and no load.

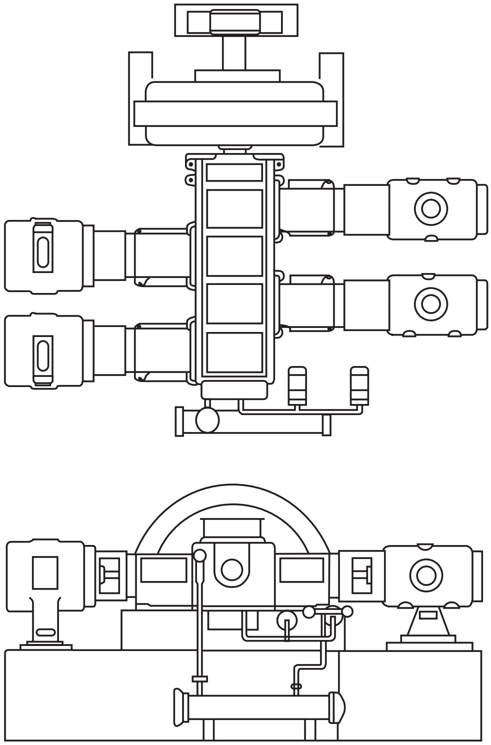


Figure 5–9 Horizontal, reciprocating compressor.

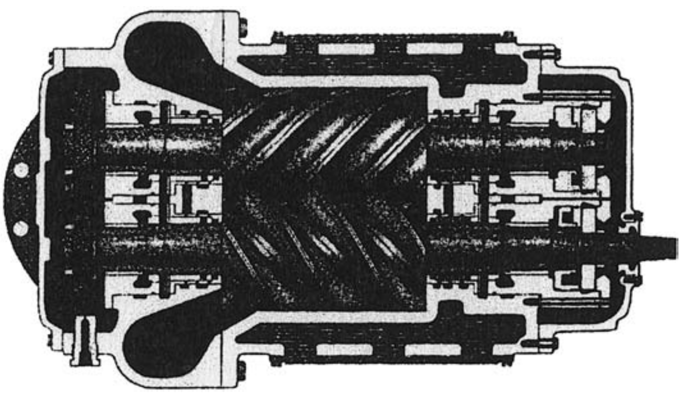


Figure 5–10 Screw compressor—steady-state applications only.

The gear set should be monitored for axial thrusting. Because of the compressor's sensitivity to process instability, the gears are subjected to extreme variations in induced axial loading. Coupled with the helical gear's normal tendency to thrust, the change in axial vibration is an early indicator of incipient problems.

Rotor passing. The male and female rotors act much like any bladed or gear unit. The number of lobes on the male rotor multiplied by the actual male shaft speed determines the rotor-passing frequency. In most cases, there are more lobes on the female than on the male. To ensure inclusion of all passing frequencies, the rotor-passing frequency of the female shaft also should be calculated. The passing frequency is equal to the number of lobes on the female rotor multiplied by the actual female shaft speed.

Running speeds. The input, or male, rotor in screw compressors generally rotates at a no-load speed of either 1,800 or 3,600 rpm. The female, or driven, rotor operates at higher no-load speeds ranging between 3,600 to 9,000 rpm. Narrowband windows should be established to monitor the actual running speed of the male and female rotors. The windows should have an upper limit equal to the no-load design speed and a lower limit that captures the slowest, or fully loaded, speed. Generally, the lower limits are between 15 and 20 percent lower than no-load.

5.3.2 Fans

Fans have many different industrial applications and designs vary; however, all fans fall into two major categories: centerline and cantilever. The centerline configuration has the rotating element located at the midpoint between two rigidly supported bearings. The cantilever or overhung fan has the rotating element located outboard of two fixed bearings. Figure 5–11 illustrates the difference between the two fan classifications.

The following parameters are monitored in a typical predictive maintenance program for fans: aerodynamic instability, running speeds, and shaft mode shape, or shaft deflection.

Aerodynamic Instability

Fans are designed to operate in a relatively steady-state condition. The effective control range is typically 15 to 30 percent of their full range. Operation outside of the

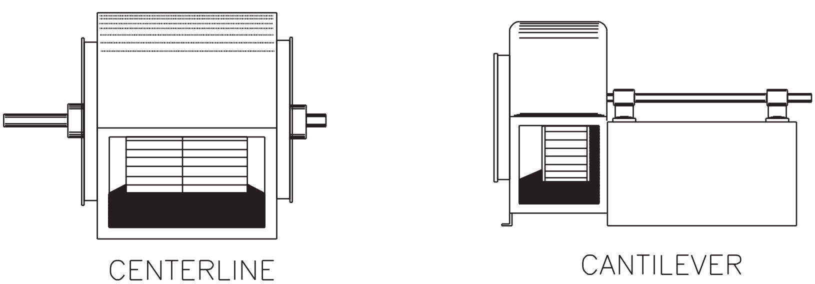


Figure 5–11 Major fan classifications.

effective control range results in extreme turbulence within the fan, which causes a significant increase in vibration. In addition, turbulent flow caused by restricted inlet airflow, leaks, and a variety of other factors increases rotor instability and the overall vibration generated by a fan.

Both of these abnormal forcing functions (i.e., turbulent flow and operation outside of the effective control range) increase the level of vibration; however, when the instability is relatively minor, the resultant vibration occurs at the vane-pass frequency. As it become more severe, the broadband energy also increases significantly.

A narrowband window should be created to monitor the vane-pass frequency of each fan. The vane-pass frequency is equal to the number of vanes or blades on the fan's rotor multiplied by the actual running speed of the shaft. The lower and upper limits of the narrowband should be set about 10 percent above and below (±10%) the calculated vane-pass frequency. This compensates for speed variations and includes the broadband energy generated by instability.

Running Speeds

Fan running speed varies with load. If fixed filters are used to establish the bandwidth and narrowband windows, the running speed upper limit should be set to the synchronous speed of the motor, and the lower limit set at the full-load speed of the motor. This setting provides the full range of actual running speeds that should be observed in a routine monitoring program.

Shaft Mode Shape (Shaft Deflection)

The bearing-support structure is often inadequate for proper shaft support because of its span and stiffness. As a result, most fans tend to operate with a shaft that deflects from its true centerline. Typically, this deflection results in a vibration frequency at the second (2X) or third (3X) harmonic of shaft speed.

A narrowband window should be established to monitor the fundamental (1X), second (2X), and third (3X) harmonic of shaft speed. With these windows, the energy associated with shaft deflection, or mode shape, can be monitored.

5.3.3 Generators

As with electric-motor rotors, generator rotors always seek the magnetic center of their casings. As a result, they tend to thrust in the axial direction. In almost all cases, this axial movement, or endplay, generates a vibration profile that includes the fundamental (1X), second (2X), and third (3X) harmonic of running speed. Key monitoring parameters for generators include bearings, casing and shaft, line frequency, and running speed.

Bearings

Large generators typically use Babbitt bearings, which are nonrotating, lined metal sleeves (also referred to as *fluid-film bearings*) that depend on a lubricating film to prevent wear; however, these bearings are subjected to abnormal wear each time a generator is shut off or started. In these situations, the entire weight of the rotating element rests directly on the lower half of the bearings. When the generator is started, the shaft climbs the Babbitt liner until gravity forces the shaft to drop to the bottom of the bearing. This alternating action of climb and fall is repeated until the shaft speed increases to the point that a fluid-film is created between the shaft and Babbitt liner.

Subharmonic frequencies (i.e., less than the actual shaft speed) are the primary evaluation tool for fluid-film bearings, and they must be monitored closely. A narrowband window that captures the full range of vibration frequency components between electronic noise and running speed is an absolute necessity.

Casing and Shaft

Most generators have relatively soft support structures. Therefore, they require shaft vibration-monitoring measurement points in addition to standard casing measurement points. This requires the addition of permanently mounted proximity, or displacement, transducers that can measure actual shaft movement.

The third (3X) harmonic of running speed is a critical monitoring parameter. Most, if not all, generators tend to move in the axial plane as part of their normal dynamics. Increases in axial movement, which appear in the third harmonic, are early indicators of problems.

Line Frequency

Many electrical problems cause an increase in the amplitude of line frequency, typically 60 Hz, and its harmonics. Therefore, a narrowband should be established to monitor the 60, 120, and 180 Hz frequency components.

Running Speed

Actual running speed remains relatively constant on most generators. While load changes create slight variations in actual speed, the change in speed is minor. Generally, a narrowband window with lower and upper limits of ±10 percent of design speed is sufficient.

5.3.4 Process Rolls

Process rolls are commonly found in paper machines and other continuous process applications. Process rolls generate few unique vibration frequencies. In most cases, the only vibration frequencies generated are running speed and bearing rotational frequencies; however, rolls are highly prone to loads induced by the process. In most cases, rolls carry some form of product or a mechanism that, in turn, carries a product. For example, a simple conveyor has rolls that carry a belt, which carries product from one location to another. The primary monitoring parameters for process rolls include bearings, load distribution, and misalignment.

Bearings

Both nonuniform loading and roll misalignment change the bearing load zones. In general, either of these failure modes results in an increase in outer-race loading. This is caused by the failure mode forcing the full load onto one quadrant of the bearing's outer race. Therefore, the ball-pass outer-race frequency should be monitored closely on all process rolls. Any increase in this unique frequency is a prime indication of a load, tension, or misaligned roll problem.

Load Distribution

By design, process rolls should be uniformly loaded across their entire bearing span (see Figure 5–12). Improper tracking and/or tension of the belt, or product carried by the rolls, will change the loading characteristics.

The loads induced by the belt increase the pressure on the loaded bearing and decrease the pressure on the unloaded bearing. An evaluation of process rolls should include a cross-comparison of the overall vibration levels and the vibration signature of each roll's inboard and outboard bearing.

Misalignment

Misalignment of process rolls is a common problem. On a continuous process line, most rolls are mounted in several levels. The distance between the rolls and the change in elevation make it extremely difficult to maintain proper alignment. In a vibration analysis, roll misalignment generates a signature similar to classical parallel misalignment. It generates dominant frequencies at the fundamental (1X) and second (2X) harmonic of running speed.

5.3.5 Pumps

A wide variety of pumps is used by industry, which can be grouped into two types: centrifugal and positive displacement. Pumps are highly susceptible to process-induced or installation-induced loads. Some pump designs are more likely to have axial- or thrust-induced load problems. Induced loads created by hydraulic forces also are a serious problem in most pump applications. Recommended monitoring for each type of pump is essentially the same, regardless of specific design or manufacturer; however, process variables such as flow, pressure, load, and so on must be taken into account.

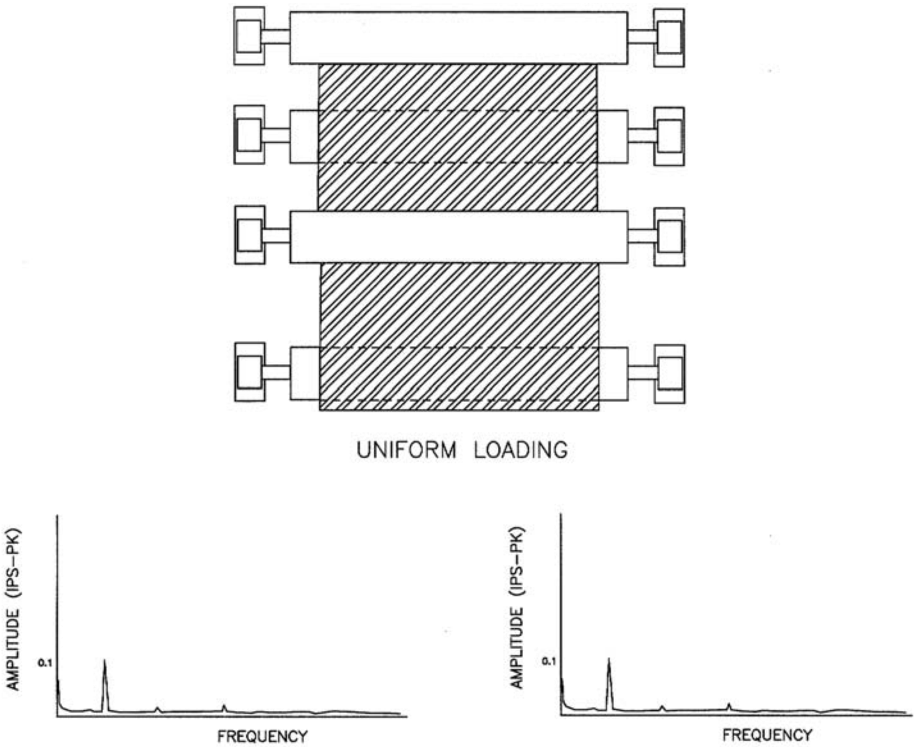


Figure 5–12 Rolls should be uniformly loaded.

Centrifugal

Centrifugal pumps can be divided into two basic types: end-suction and horizontal split-case. These two major classifications can be further broken down into single-stage and multistage. Each of these classifications has common monitoring parameters, but each also has unique features that alter their forcing functions and the resultant vibration profile. The common monitoring parameters for all centrifugal pumps include axial thrusting, vane-pass, and running speed.

Axial Thrusting. End-suction and multistage pumps with inline impellers are prone to excessive axial thrusting. In the end-suction pump, the centerline axial inlet configuration is the primary source of thrust. Restrictions in the suction piping, or low suction pressures, create a strong imbalance that forces the rotating element toward the inlet.

Multistage pumps with inline impellers generate a strong axial force on the outboard end of the pump. Most of these pumps have oversized thrust bearings (e.g., Kingsbury bearings) that restrict the amount of axial movement; however, bearing wear caused by constant rotor thrusting is a dominant failure mode. The axial movement of the shaft should be monitored when possible.

Hydraulic Instability (Vane Pass). Hydraulic or flow instability is common in centrifugal pumps. In addition to the restrictions of the suction and discharge discussed previously, the piping configuration in many applications creates instability. Although flow through the pump should be laminar, sharp turns or other restrictions in the inlet piping can create turbulent flow conditions. Forcing functions such as these results in hydraulic instability, which displaces the rotating element within the pump.

In a vibration analysis, hydraulic instability is displayed at the vane-pass frequency of the pump's impeller. Vane-pass frequency is equal to the number of vanes in the impeller multiplied by the actual running speed of the shaft. Therefore, a narrowband window should be established to monitor the vane-pass frequency of all centrifugal pumps.

Running Speed. Most pumps are considered constant speed, but the true speed changes with variations in suction pressure and back-pressure caused by restrictions in the discharge piping. The narrowband should have lower and upper limits sufficient to compensate for these speed variations. Generally, the limits should be set at speeds equal to the full-load and no-load ratings of the driver.

There is a potential for unstable flow through pumps, which is created by both the design-flow pattern and the radial deflection caused by back-pressure in the discharge piping. Pumps tend to operate at their second-mode shape or deflection pattern. This operation mode generates a unique vibration frequency at the second harmonic (2X) of running speed. In extreme cases, the shaft may be deflected further and operate in its third (3X) mode shape. Therefore, both of these frequencies should be monitored.

Positive Displacement

A variety of positive-displacement pumps is commonly used in industrial applications. Each type has unique characteristics that must be understood and monitored; however, most of the major types have common parameters that should be monitored.

With the exception of piston-type pumps, most of the common positive-displacement pumps use rotating elements to provide a constant-volume, constant-pressure output. As a result, these pumps can be monitored with the following parameters: hydraulic instability, passing frequencies, and running speed.

Hydraulic Instability (Vane Pass). Positive-displacement pumps are subject to flow instability, which is created either by process restrictions or by the internal pumping process. Increases in amplitude at the passing frequencies, as well as harmonics of both shafts' running speed and the passing frequencies, typically result from instability.

Passing Frequencies. With the exception of piston-type pumps, all positive-displacement pumps have one or more passing frequencies generated by the gears, lobes, vanes, or wobble-plates used in different designs to increase the pressure of the pumped liquid. These passing frequencies can be calculated in the same manner as the blade or vane-passing frequencies in centrifugal pumps (i.e., multiplying the number of gears, lobes, vanes, or wobble plates times the actual running speed of the shaft).

Running Speeds. All positive-displacement pumps have one or more rotating shafts that provide power transmission from the primary driver. Narrowband windows should be established to monitor the actual shaft speeds, which are in most cases essentially constant. Upper and lower limits set at ±10 percent of the actual shaft speed are usually sufficient.

6

PREDICTIVE MAINTENANCE TECHNIQUES

A variety of technologies can, and should be, used as part of a comprehensive predictive maintenance program. Because mechanical systems or machines account for most plant equipment, vibration monitoring is generally the key component of most predictive maintenance programs; however, vibration monitoring cannot provide all of the information required for a successful predictive maintenance program. This technique is limited to monitoring the mechanical condition and not other critical parameters required to maintain reliability and efficiency of machinery. It is a very limited tool for monitoring critical process and machinery efficiencies and other parameters that can severely limit productivity and product quality.

Therefore, a comprehensive predictive maintenance program must include other monitoring and diagnostic techniques. These techniques include vibration monitoring, thermography, tribology, process parameters, visual inspection, ultrasonics, and other nondestructive testing techniques. This chapter provides a brief description of each of the techniques that should be included in a full-capabilities predictive maintenance program for typical plants. Subsequent chapters provide a more detailed description of these techniques and how they should be used as part of an effective maintenance management tool.

6.1 Vibration Monitoring

Because most plants consist of electromechanical systems, vibration monitoring is the primary predictive maintenance tool. Over the past 10 years, most of these programs have adopted the use of microprocessor-based, single-channel data collectors and Windows®-based software to acquire, manage, trend, and evaluate the vibration energy created by these electromechanical systems. Although this approach is a valuable predictive maintenance methodology, these systems' limitations may restrict potential benefits.

6.1.1 Technology Limitations

Computer-based systems have several limitations. In addition, some system characteristics, particularly simplified data acquisition and analysis, provide both advantages and disadvantages.

Simplified Data Acquisition and Analysis

While providing many advantages, simplified data acquisition and analysis can also be a liability. If the database is improperly configured, the automated capabilities of these analyzers will yield faulty diagnostics that can allow catastrophic failure of critical plant machinery.

Because technician involvement is reduced to a minimum, the normal tendency is to use untrained or partially trained personnel for this repetitive function. Unfortunately, the lack of training results in less awareness and knowledge of visual and audible clues that can, and should be, an integral part of the monitoring program.

Single-Channel Data

Most of the microprocessor-based vibration-monitoring systems collect single-channel, steady-state data that cannot be used for all applications. Single-channel data are limited to the analysis of simple machinery that operates at relatively constant speed.

Although most microprocessor-based instruments are limited to a single input channel, in some cases, a second channel is incorporated in the analyzer; however, this second channel generally is limited to input from a tachometer, or a once-per-revolution input signal. This second channel cannot be used for vibration data capture.

This limitation prohibits the use of most microprocessor-based vibration analyzers for complex machinery or machines with variable speeds. Single-channel data acquisition technology assumes the vibration profile generated by a machine-train remains constant throughout the data acquisition process. This is generally true in applications where machine speed remains relatively constant (i.e., within 5 to 10 rpm). In this case, its use does not severely limit diagnostic accuracy and can be effectively used in a predictive maintenance program.

Steady-State Data

Most of the microprocessor-based instruments are designed to handle steady-state vibration data. Few have the ability to reliably capture transient events such as rapid speed or load changes. As a result, their use is limited in situations where these changes occur.

In addition, vibration data collected with a microprocessor-based analyzer are filtered and conditioned to eliminate nonrecurring events and their associated vibra-

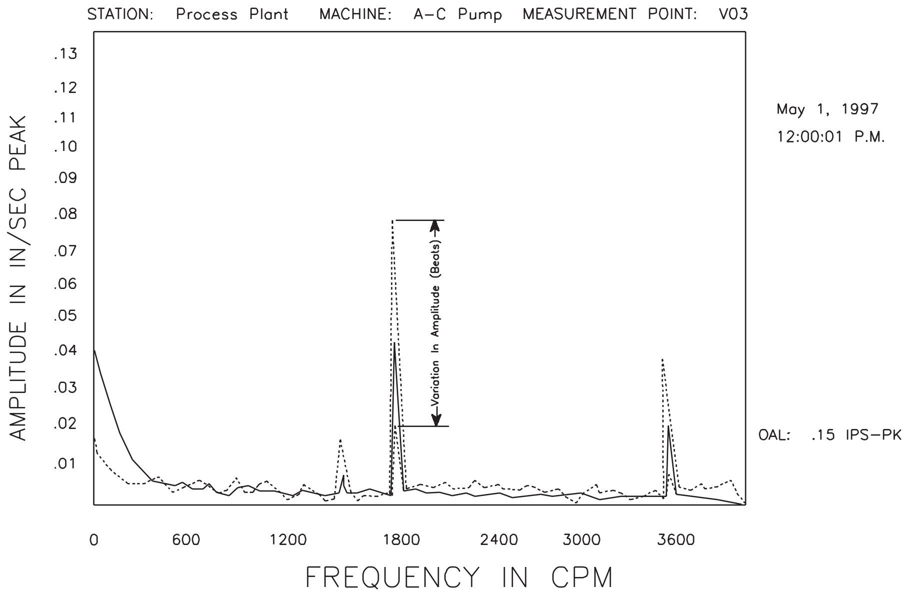


Figure 6–1 Vibration is dynamic and amplitudes constantly change.

tion profiles. Anti-aliasing filters are incorporated into the analyzers specifically to remove spurious signals such as impacts or transients. Although the intent behind the use of anti-aliasing filters is valid, their use can distort a machine's vibration profile.

Because vibration data are dynamic and the amplitudes constantly change, as shown in Figure 6–1, most predictive maintenance system vendors strongly recommend averaging the data. They typically recommend acquiring 3 to 12 samples of the vibration profile and averaging the individual profiles into a composite signature. This approach eliminates the variation in vibration amplitude of the individual frequency components that make up the machine's signature; however, these variations, referred to as *beats*, can be a valuable diagnostic tool. Unfortunately, they are not available from microprocessor-based instruments because of averaging and other system limitations.

The most serious limitations created by averaging and the anti-aliasing filters are the inability to detect and record impacts that often occur within machinery. These impacts generally are indications of abnormal behavior and are often the key to detecting and identifying incipient problems.

Frequency-Domain Data

Most predictive maintenance programs rely almost exclusively on frequency-domain vibration data. The microprocessor-based analyzers gather time-domain data and automatically convert it using Fast Fourier Transform (FFT) to frequency-domain data. A frequency-domain signature shows the machine's individual frequency components, or peaks.

While frequency-domain data analysis is much easier to learn than time-domain data analysis, it cannot isolate and identify all incipient problems within the machine or its installed system. Because of this limitation, additional techniques (e.g., time-domain, multichannel, and real-time analysis) must be used in conjunction with frequency-domain data analysis to obtain a complete diagnostic picture.

Low-Frequency Response

Many of the microprocessor-based vibration-monitoring analyzers cannot capture accurate data from low-speed machinery or machinery that generates low-frequency vibration. Specifically, some of the commercially available analyzers cannot be used where frequency components are below 600 cycles per minute (cpm) or 10 Hz.

Two major problems restricting the ability to acquire accurate vibration data at low frequencies are electronic noise and the response characteristics of the transducer. The electronic noise of the monitored machine and the "noise floor" of the electronics within the vibration analyzer tend to override the actual vibration components found in low-speed machinery.

Analyzers especially equipped to handle noise are required for most industrial applications. At least three commercially available microprocessor-based analyzers are capable of acquiring data below 600 cpm. These systems use special filters and data acquisition techniques to separate real vibration frequencies from electronic noise. In addition, transducers with the required low-frequency response must be used.

Averaging

All machine-trains are subject to random, nonrecurring vibrations as well as periodic vibrations. Therefore, it is advisable to acquire several sets of data and average them to eliminate the spurious signals. Averaging also improves the repeatability of the data because only the continuous signals are retained.

Typically, a minimum of three samples should be collected for an average; however, the factor that determines the actual number is time. One sample takes 3 to 5 seconds, a four-sample average takes 12 to 20 seconds, and a 1,000-sample average takes 50 to 80 minutes to acquire. Therefore, the final determination is the amount of time that can be spent at each measurement point. In general, three to four samples are acceptable for good statistical averaging and keeping the time required per measurement point within reason. Exceptions to this recommendation include low-speed machinery, transient-event capture, and synchronous averaging.

Overlap Averaging

Many of the microprocessor-based vibration-monitoring systems offer the ability to increase their data acquisition speed. This option is referred to as *overlap averaging*. Although this approach increases speed, it is not generally recommended for vibration analysis. Overlap averaging reduces the data accuracy and must be used with caution. Its use should be avoided except where fast transients or other unique machine-train characteristics require an artificial means of reducing the data acquisition and processing time.

When sampling time is limited, a better approach is to reduce or eliminate averaging altogether in favor of acquiring a single data block, or sample. This reduces the acquisition time to its absolute minimum. In most cases, the single-sample time interval is less than the minimum time required to obtain two or more data blocks using the maximum overlap-averaging sampling technique. In addition, single-sample data are more accurate.

Table 6–1 describes overlap-averaging options. Note that the approach described in this table assumes that the vibration profile of monitored machines is constant.

Excluding Machine Dynamics

Perhaps the most serious diagnostic error made by typical vibration-monitoring programs is the exclusive use of vibration-based failure modes as the diagnostic logic.

Table 6–1 Overlap Averaging Options

Overlap, %	Description
0	No overlap. Data trace update rate is the same as the block-processing rate. This rate is governed by the physical requirements that are internally driven by the frequency range of the requested data.
25	Terminates data acquisition when 75% of each block of new data is acquired. The last 25% of the previous sample (of the 75%) will be added to the new sample before processing is begun. Therefore, 75% of each sample is new. As a result, accuracy may be reduced by as much as 25% for each data set.
50	The last 50% of the previous block is added to a new 50% or half-block of data for each sample. When the required number of samples is acquired and processed, the analyzer averages the data set. Accuracy may be reduced to 50%.
75	Each block of data is limited to 25% new data and the last 75% of the previous block.
90	Each block contains 10% new data and the last 90% of the previous block. Accuracy of average data using 90% overlap is uncertain. Since each block used to create the average contains only 10% of actual data and 90% of a block that was extrapolated from a 10% sample, the result cannot be representative of the real vibration generated by the machine-train.

Source: Integrated Systems, Inc.

For example, most of the logic trees state that when the dominant energy contained in a vibration signature is at the fundamental running speed, then a state of unbalance exists. Although some forms of unbalance will create this profile, the rules of machine dynamics clearly indicate that all failure modes on a rotating machine will increase the amplitude of the fundamental or actual running speed.

Without a thorough understanding of machine dynamics, it is virtually impossible to accurately diagnose the operating condition of critical plant production systems. For example, gear manufacturers do not finish the backside (i.e., nondrive side) of gear teeth. Therefore, any vibration acquired from a gear set when it is braking will be an order of magnitude higher than when it is operating on the power side of the gear.

Another example is even more common. Most analysts ignore the effect of load on a rotating machine. If you were to acquire a vibration reading from a centrifugal compressor when it is operating at full load, it may generate an overall level of 0.1 ips-peak. The same measurement point will generate a reading in excess of 0.4 ips-peak when the compressor is operating at 50 percent load. The difference is the spring constant that is being applied to the rotating element. The spring constant or stiffness at 100 percent load is twice that of that when operating at 50 percent; however, spring constant is a quadratic function. A reduction of 50 percent in the spring constant will increase the vibration level by a factor of four.

To achieve maximum benefits from vibration monitoring, the analyst must understand the limitations of the instrumentation and the basic operating dynamics of machinery. Without this knowledge, the benefits will be dramatically reduced.

Application Limitations

The greatest mistake made by traditional application of vibration monitoring is in its application. Most programs limit the use of this predictive maintenance technology to simple rotating machinery and not to the critical production systems that produce the plant's capacity. As a result, the auxiliary equipment is kept in good operating condition, but the plant's throughput is unaffected.

Vibration monitoring is not limited to simple rotating equipment. The microprocessor-based systems used for vibration analysis can be used effectively on all electromechanical equipment—no matter how complex or what form the mechanical motion may take. For example, it can be used to analyze hydraulic and pneumatic cylinders that are purely linear motion. To accomplish this type of analysis, the analyst must use the time-domain function that is built into these instruments. Proper operation of cylinders is determined by the time it takes for the cylinder to finish one complete motion. The time required for the cylinder to extend is shorter than its return stroke. This is a function of the piston area and inlet pressure. By timing the transient from fully retracted or extended to the opposite position, the analyst can detect packing leakage, scored cylinder walls, and other failure modes.

Vibration monitoring must be focused on the critical production systems. Each of these systems must be evaluated as a single machine and not as individual components. For example, a paper machine, annealing line, or any other production system must be analyzed as a complete machine—not as individual gearboxes, rolls, or other components. This methodology permits the analyst to detect abnormal operation within the complex system. Problems such as tracking, tension, and product-quality deviations can be easily detected and corrected using this method.

When properly used, vibration monitoring and analysis is the most powerful predictive maintenance tool available. It must be focused on critical production systems, not simple rotating machinery. Diagnostic logic must be driven by the operating dynamics of machinery—not simplified vibration failure modes.

The proof is in the results. The survey conducted by Plant Services in July 1999 indicated that less than 50 percent of the vibration-monitoring programs generated enough quantifiable benefits to offset the recurring cost of the program. Only 3 percent generated a return on investment of 5 percent. When properly used, vibration-based predictive maintenance can generate return on investment of 100:1 or better.

6.2 Thermography

Thermography is a predictive maintenance technique that can be used to monitor the condition of plant machinery, structures, and systems, not just electrical equipment. It uses instrumentation designed to monitor the emission of infrared energy (i.e., surface temperature) to determine operating condition. By detecting thermal anomalies (i.e., areas that are hotter or colder than they should be), an experienced technician can locate and define a multitude of incipient problems within the plant.

Infrared technology is predicated on the fact that all objects having a temperature above absolute zero emit energy or radiation. Infrared radiation is one form of this emitted energy. Infrared emissions, or below red, are the shortest wavelengths of all radiated energy and are invisible without special instrumentation. The intensity of infrared radiation from an object is a function of its surface temperature; however, temperature measurement using infrared methods is complicated because three sources of thermal energy can be detected from any object: energy emitted from the object itself, energy reflected from the object, and energy transmitted by the object. Only the emitted energy is important in a predictive maintenance program. Reflected and transmitted energies will distort raw infrared data. Therefore, the reflected and transmitted energies must be filtered out of acquired data before a meaningful analysis can be completed.

Variations in surface condition, paint or other protective coatings, and many other variables can affect the actual emissivity factor for plant equipment. In addition to reflected and transmitted energy, the user of thermographic techniques must also consider the atmosphere between the object and the measurement instrument. Water vapor and other gases absorb infrared radiation. Airborne dust, some lighting, and other variables in the surrounding atmosphere can distort measured infrared radiation. Because the atmospheric environment is constantly changing, using thermographic techniques requires extreme care each time infrared data are acquired.

Most infrared-monitoring systems or instruments provide filters that can be used to avoid the negative effects of atmospheric attenuation of infrared data; however, the plant user must recognize the specific factors that affect the accuracy of the infrared data and apply the correct filters or other signal conditioning required to negate that specific attenuating factor or factors.

Collecting optics, radiation detectors, and some form of indicator are the basic elements of an industrial infrared instrument. The optical system collects radiant energy and focuses it on a detector, which converts it into an electrical signal. The instrument's electronics amplifies the output signal and processes it into a form that can be displayed.

6.2.1 Types of Thermographic Systems

Three types of instruments are generally used as part of an effective predictive maintenance program: infrared thermometers, line scanners, and infrared imaging systems.

Infrared Thermometers

Infrared thermometers or spot radiometers are designed to provide the actual surface temperature at a single, relatively small point on a machine or surface. Within a predictive maintenance program, the point-of-use infrared thermometer can be used in conjunction with many of the microprocessor-based vibration instruments to monitor the temperature at critical points on plant machinery or equipment. This technique is typically used to monitor bearing cap temperatures, motor winding temperatures, spot checks of process piping temperatures, and similar applications. It is limited in that the temperature represents a single point on the machine or structure; however, when used in conjunction with vibration data, point-of-use infrared data can be a valuable tool.

Line Scanners

This type of infrared instrument provides a one-dimensional scan or line of comparative radiation. Although this type of instrument provides a somewhat larger field of view (i.e., area of machine surface), it is limited in predictive maintenance applications.

Infrared Imaging

Unlike other infrared techniques, thermal or infrared imaging provides the means to scan the infrared emissions of complete machines, process, or equipment in a very short time. Most of the imaging systems function much like a video camera. The user can view the thermal emission profile of a wide area by simply looking through the instrument's optics.

A variety of thermal imaging instruments are on the market, ranging from relatively inexpensive, black-and-white scanners to full-color, microprocessor-based systems. Many of the less expensive units are designed strictly as scanners and cannot store and recall thermal images. This inability to store and recall previous thermal data will limit a long-term predictive maintenance program.

Point-of-use infrared thermometers are commercially available and relatively inexpensive. The typical cost for this type of infrared instrument is less than $1,000. Infrared imaging systems will have a price range between $8,000 for a black-and-white scanner without storage capability to over $60,000 for a microprocessor-based, color imaging system.

Training is critical with any of the imaging systems. The variables that can destroy the accuracy and repeatability of thermal data must be compensated for each time infrared data are acquired. In addition, interpretation of infrared data requires extensive training and experience.

Inclusion of thermography into a predictive maintenance program will enable you to monitor the thermal efficiency of critical process systems that rely on heat transfer or retention, electrical equipment, and other parameters that will improve both the reliability and efficiency of plant systems. Infrared techniques can be used to detect problems in a variety of plant systems and equipment, including electrical switchgear, gearboxes, electrical substations, transmissions, circuit breaker panels, motors, building envelopes, bearings, steam lines, and process systems that rely on heat retention or transfer.

6.2.2 Infrared Thermography Safety

Equipment included in an infrared thermography inspection is usually energized; therefore, a lot of attention must be given to safety. The following are basic rules for safety while performing an infrared inspection:

- Plant safety rules must be followed at all times.
- A safety person must be used at all times. Because proper use of infrared imaging systems requires the technician to use a viewfinder, similar to a video camera, to view the machinery to be scanned, he or she is blind to the surrounding environment. Therefore, a safety person is required to ensure safe completion.
- Notify area personnel before entering the area for scanning.
- A qualified electrician from the area should be assigned to open and close all electrical panels.
- Where safe and possible, all equipment to be scanned will be online and under normal load with a clear line of sight to the item.

- Equipment whose covers are interlocked without an interlock defect mechanism should be shut down when allowable. If safe, their control covers should be opened and equipment restarted.

When used correctly, thermography is a valuable predictive maintenance and/or reliability tool; however, the derived benefits are directly proportional to how it is used. If it is limited to annual surveys of roofs and/or quarterly inspections of electrical systems, the resultant benefits are limited. When used to regularly monitor all critical process or production systems where surface temperature or temperature distribution indicates reliability or operating condition, thermography can yield substantial benefits. To gain the maximum benefits from your investment in infrared systems, you must use its full power. Concentrate your program on those critical systems that generate capacity in your plant.

6.3 Tribology

Tribology is the general term that refers to design and operating dynamics of the bearing-lubrication-rotor support structure of machinery. Two primary techniques are being used for predictive maintenance: lubricating oil analysis and wear particle analysis.

6.3.1 Lube Oil Analysis

Lubricating oil analysis, as the name implies, is an analysis technique that determines the condition of lubricating oils used in mechanical and electrical equipment. It is not a tool for determining the operating condition of machinery or detecting potential failure modes. Too many plants are attempting to accomplish the latter and are disappointed in the benefits that are derived. Simply stated, lube oil analysis should be limited to a proactive program to conserve and extend the useful life of lubricants. Although some forms of lubricating oil analysis may provide an accurate quantitative breakdown of individual chemical elements—both oil additive and contaminants contained in the oil—the technology cannot be used to identify the specific failure mode or root-cause of incipient problems within the machines serviced by the lube oil system.

The primary applications for lubricating oil analysis are quality control, reduction of lubricating oil inventories, and determination of the most cost-effective interval for oil change. Lubricating, hydraulic, and dielectric oils can be periodically analyzed using these techniques to determine their condition. The results of this analysis can be used to determine if the oil meets the lubricating requirements of the machine or application. Based on the results of the analysis, lubricants can be changed or upgraded to meet the specific operating requirements.

In addition, detailed analysis of the chemical and physical properties of different oils used in the plant can, in some cases, allow consolidation or reduction of the number and types of lubricants required to maintain plant equipment. Elimination of unnecessary duplication can reduce required inventory levels and therefore maintenance costs.

As a predictive maintenance tool, lubricating oil analysis can be used to schedule oil change intervals based on the actual condition of the oil. In midsize to large plants, a reduction in the number of oil changes can amount to a considerable annual reduction in maintenance costs. Relatively inexpensive sampling and testing can show when the oil in a machine has reached a point that warrants change.

6.3.2 Wear Particle Analysis

Wear particle analysis is related to oil analysis only in that the particles to be studied are collected by drawing a sample of lubricating oil. Whereas lubricating oil analysis determines the actual condition of the oil sample, wear particle analysis provides direct information about the wearing condition of the machine-train. Particles in the lubricant of a machine can provide significant information about the machine's condition. This information is derived from the study of particle shape, composition, size, and quantity.

Analysis of Particulate Matter

Two methods are used to prepare samples of wear particles. The first method, called *spectroscopy* or *spectrographic analysis*, uses graduated filters to separate solids into sizes. Normal spectrographic analysis is limited to particulate contamination with a size of 10 microns or less. Larger contaminants are ignored. This fact can limit the benefits that can be derived from the technique. The second method, called *ferrographic analysis*, separates wear particles using a magnet. Obviously, the limitation to this approach is that only magnetic particles are removed for analysis. Nonmagnetic materials, such as copper, aluminum, and so on that make up many of the wear materials in typical machinery are therefore excluded from the sample.

Wear particle analysis is an excellent failure analysis tool and can be used to understand the root-cause of catastrophic failures. The unique wear patterns observed on failed parts, as well as those contained in the oil reservoir, provide a positive means of isolating the failure mode.

6.3.3 Limitations of Tribology

Three major limitations are associated with using tribology analysis in a predictive maintenance program: equipment costs, acquiring accurate oil samples, and interpretation of data.

Capital Cost

The capital cost of spectrographic analysis instrumentation is normally too high to justify in-plant testing. Typical cost for a microprocessor-based spectrographic system is between $30,000 and $60,000. Because of this, most predictive maintenance programs rely on third-party analysis of oil samples.

Recurring Cost

In addition to the labor cost associated with regular gathering of oil and grease samples, simple lubricating oil analysis by a testing laboratory will range from about $20 to $50 per sample. Standard analysis will normally include viscosity, flash point, total insolubles, total acid number (TAN), total base number (TBN), fuel content, and water content. More detailed analysis, using spectrographic, ferrographic, or wear particle techniques that include metal scans, particle distribution (size), and other data can cost more than $150 per sample.

Accurate Samples

A more severe limiting factor with any method of oil analysis is acquiring accurate samples of the true lubricating oil inventory in a machine. Sampling is not a matter of opening a port somewhere in the oil line and catching a pint sample. Extreme care must be taken to acquire samples that truly represent the lubricant that will pass through the machine's bearings. One recent example is an attempt to acquire oil samples from a bullgear compressor. The lubricating oil filter had a sample port on the clean (i.e., downstream) side; however, comparison of samples taken at this point and one taken directly from the compressor's oil reservoir indicated that more contaminants existed downstream from the filter than in the reservoir. Which location actually represented the oil's condition? Neither sample was truly representative of the oil's condition. The oil filter had removed most of the suspended solids (i.e., metals and other insolubles) and was therefore not representative of the actual condition. The reservoir sample was also not representative because most of the suspended solids had settled out in the sump.

Proper methods and frequency of sampling lubricating oil are critical to all predictive maintenance techniques that use lubricant samples. Sample points that are consistent with the objective of detecting large particles should be chosen. In a recirculating system, samples should be drawn as the lubricant returns to the reservoir and before any filtration occurs. Do not draw oil from the bottom of a sump where large quantities of material build up over time. Return lines are preferable to reservoir as the sample source, but good reservoir samples can be obtained if careful, consistent practices are used. Even equipment with high levels of filtration can be effectively monitored as long as samples are drawn before oil enters the filters. Sampling techniques involve taking samples under uniform operating conditions. Samples should not be taken more than 30 minutes after the equipment has been shut down.

Sample frequency is a function of the mean-time-to-failure (MTTF) from the onset of an abnormal wear mode to catastrophic failure. For machines in critical service, sampling every 25 hours of operation is appropriate. For most industrial equipment in continuous service, however, monthly sampling is adequate. The exception to monthly sampling is machines with extreme loads. In this instance, weekly sampling is recommended.

Understanding Results

Understanding the meaning of analysis results is perhaps the most serious limiting factor. Results are usually expressed in terms that are totally alien to plant engineers or technicians. Therefore, it is difficult for them to understand the true meaning, in terms of oil or machine condition. A good background in quantitative and qualitative chemistry is beneficial. At a minimum, plant staff will require training in basic chemistry and specific instruction on interpreting tribology results.

6.4 Visual Inspections

Visual inspection was the first method used for predictive maintenance. Almost from the beginning of the Industrial Revolution, maintenance technicians performed daily "walkdowns" of critical production and manufacturing systems in an attempt to identify potential failures or maintenance-related problems that could impact reliability, product quality, and production costs. A visual inspection is still a viable predictive maintenance tool and should be included in all total-plant maintenance management programs.

6.5 Ultrasonics

Ultrasonics, like vibration analysis, is a subset of noise analysis. The only difference in the two techniques is the frequency band they monitor. In the case of vibration analysis, the monitored range is between 1 Hertz (Hz) and 30,000 Hz; ultrasonics monitors noise frequencies above 30,000 Hz. These higher frequencies are useful for select applications, such as detecting leaks that generally create high-frequency noise caused by the expansion or compression of air, gases, or liquids as they flow through the orifice, or a leak in either pressure or vacuum vessels. These higher frequencies are also useful in measuring the ambient noise levels in various areas of the plant.

As it is being applied as part of a predictive maintenance program, many companies are attempting to replace what is perceived as an expensive tool (i.e., vibration analysis) with ultrasonics. For example, many plants are using ultrasonic meters to monitor the health of rolling-element bearings in the belief that this technology will provide accurate results. Unfortunately, this perception is invalid. Because this technology is limited to a broadband (i.e., 30 kHz to 1 MHz), ultrasonics does not provide the ability to diagnosis incipient bearing or machine problems. It certainly cannot define the root-cause of abnormal noise levels generated by either bearings or other machine-train components.

As part of a comprehensive predictive maintenance program, ultrasonics should be limited to the detection of abnormally high ambient noise levels and leaks. Attempting to replace vibration monitoring with ultrasonics simply will not work.

6.6 Other Techniques

Numerous other nondestructive techniques can be used to identify incipient problems in plant equipment or systems; however, these techniques either do not provide a broad enough application or are too expensive to support a predictive maintenance program. Therefore, these techniques are used as the means of confirming failure modes identified by the predictive maintenance techniques discussed in this chapter.

6.6.1 Electrical Testing

Traditional electrical testing methods must be used in conjunction with vibration analysis to prevent premature failure of electric motors. These tests should include:

- Resistance testing
- Megger testing
- HiPot testing
- Impedance testing
- Other techniques

Resistance Testing

Resistance is measured by using an ohmmeter. In reality, an ohmmeter does not directly measure resistance; it measures current instead. The scale of the meter is calibrated in ohms, but the meter movement responds to current. The amount of current supplied by the meter is very low, typically in the rage of 20 to 50 microamperes. The meter functions by applying its terminal voltage to the test subject and measuring the current in the circuit.

For practical purposes, although resistance testing is of limited value, some useful tests may be performed. A resistance test will indicate an open or closed circuit. This can tell us whether there is a break in a circuit or if there is a dead short to ground.

It is important to remember that inductive and capacitive elements in the circuit will distort the resistance measurements. Capacitive elements will appear initially as a short circuit and begin to open as they charge. They will appear as open circuits when they are fully charged. Inductive elements will appear initially as open circuits, and the resistance will decrease as they charge. In both cases, the actual charging time is tied to the actual resistance, capacitance, and inductance in the circuit in question. It still requires five time constants to charge capacitors and inductors. It is also important to remember that when disconnecting the meter from the circuit that there are now charged capacitive and inductive elements present, so due caution must be observed when disconnecting the test equipment.

Resistance testing is of limited value for testing coils. It will detect an open coil, or a coil shorted to ground. Resistance testing will most often not detect windings that are shorted together or weak insulation.

Megger Testing

In order to measure high resistances, a device known as a mega-ohmmeter can be used. This instrument differs from a normal ohmmeter in that instead of measuring current to determine resistance, it measures voltage. This mode of testing involves applying relatively high voltage (500 to 2,500 volts, depending on the unit) to the circuit and verifying that no breakdown is present. Generally, this is considered a non-destructive test, depending on the applied voltage and the rating of the insulation. This method of testing is used primarily to test the integrity of insulation. It will not detect shorts between windings, but it can detect higher-voltage–related problems with respect to ground.

HiPot Testing

HiPot (high potential) testing is a potentially destructive test used to determine the integrity of insulation. Voltage levels employed in this type of test are twice the rated voltage plus 1,000 volts. This method is used primarily by some equipment manufacturers and rebuilding facilities as a quality assurance tool. It is important to note that HiPot testing does some damage to insulation every time it is performed. HiPot testing can destroy insulation that is still serviceable, so this test is generally not recommended for field use.

Impedance Testing

Impedance has two components: a real (or resistive) component and a reactive (inductive or capacitive) component. This method of testing is useful because it can detect significant shorting in coils, either between turns or to ground. No other nonintrusive method exists to detect a coil that is shorted between turns.

Other Techniques

Other techniques that can support predictive maintenance include acoustic emissions, eddy-current, magnetic particle, residual stress, and most of the traditional nondestructive methods. If you need specific information on the techniques that are available, the American Society of Nondestructive Testing (ANST) has published a complete set of handbooks that provide a comprehensive database for most nondestructive testing techniques.

7

VIBRATION MONITORING AND ANALYSIS

All mechanical equipment in motion generates a vibration profile, or signature, that reflects its operating condition. This is true regardless of speed or whether the mode of operation is rotation, reciprocation, or linear motion. Vibration analysis is applicable to all mechanical equipment, although a common—yet invalid—assumption is that it is limited to simple rotating machinery with running speeds above 600 revolutions per minute (rpm). Vibration-profile analysis is a useful tool for predictive maintenance, diagnostics, and many other uses.

Predictive maintenance has become synonymous with monitoring vibration characteristics of rotating machinery to detect budding problems and to head off catastrophic failure; however, vibration analysis does not provide the data required for analyzing electrical equipment, areas of heat loss, the condition of lubricating oil, or other parameters typically evaluated in a maintenance management program. Therefore, a total-plant predictive maintenance program must include several techniques, each designed to provide specific information on plant equipment.

7.1 Vibration Analysis Applications

The use of vibration analysis is not restricted to predictive maintenance. This technique is useful for diagnostic applications as well. Vibration monitoring and analysis are the primary diagnostic tools for most mechanical systems that are used to manufacture products. When used properly, vibration data provide the means to maintain optimum operating conditions and efficiency of critical plant systems. Vibration analysis can be used to evaluate fluid flow through pipes or vessels, to detect leaks, and to perform a variety of nondestructive testing functions that improve the reliability and performance of critical plant systems.

Table 7–1 Equipment and Processes Typically Monitored by Vibration Analysis

Centrifugal	*Reciprocating*	*Continuous Process*
Pumps	Pumps	Continuous Casters
Compressors	Compressors	Hot and Cold Strip Lines
Blowers	Diesel Engines	Annealing Lines
Fans	Gasoline Engines	Plating Lines
Motor/Generators	Cylinders	Paper Machines
Ball Mills	Other Machines	Can Manufacturing Lines
Chillers		Pickle Lines
Product Rolls	*Machine-Trains*	Printing
Mixers	Boring Machines	Dyeing and Finishing
Gearboxes	Hobbing Machines	Roofing Manufacturing Lines
Centrifuges	Machining Centers	Chemical Production Lines
Transmissions	Temper Mills	Petroleum Production Lines
Turbines	Metal Working Machines	Neoprene Production Lines
Generators	Rolling Mills, and Most	Polyester Production Lines
Rotary Dryers	Machining Equipment	Nylon Production Lines
Electric Motors		Flooring Production Lines
All Rotating Machinery		Continuous Process Lines

Source: Integrated Systems, Inc.

Some of the applications that are discussed briefly in this section are predictive maintenance, acceptance testing, quality control, loose part detection, noise control, leak detection, aircraft engine analyzers, and machine design and engineering. Table 7–1 lists rotating, or centrifugal, and nonrotating equipment, machine-trains, and continuous processes typically monitored by vibration analysis.

7.1.1 Predictive Maintenance

The fact that vibration profiles can be obtained for all machinery having rotating or moving elements allows vibration-based analysis techniques to be used for predictive maintenance. Vibration analysis is one of several predictive maintenance techniques used to monitor and analyze critical machines, equipment, and systems in a typical plant. As indicated before, however, the use of vibration analysis to monitor rotating machinery to detect budding problems and to head off catastrophic failure is the dominant technique used with maintenance management programs.

7.1.2 Acceptance Testing

Vibration analysis is a proven means of verifying the actual performance versus design parameters of new mechanical, process, and manufacturing equipment. Preacceptance tests performed at the factory and immediately after installation can be used to ensure that new equipment performs at optimum efficiency and expected life-cycle cost. Design problems as well as possible damage during shipment or installation can be corrected before long-term damage and/or unexpected costs occur.

7.1.3 Quality Control

Production-line vibration checks are an effective method of ensuring product quality where machine tools are involved. Such checks can provide advanced warning that the surface finish on parts is nearing the rejection level. On continuous-process lines such as paper machines, steel-finishing lines, or rolling mills, vibration analysis can prevent abnormal oscillation of components that result in loss of product quality.

7.1.4 Loose or Foreign Parts Detection

Vibration analysis is useful as a diagnostic tool for locating loose or foreign objects in process lines or vessels. This technique has been used with great success by the nuclear power industry, and it offers the same benefits to nonnuclear industries.

7.1.5 Noise Control

Federal, state, and local regulations require that serious attention be paid to noise levels within the plant. Vibration analysis can be used to isolate the source of noise generated by plant equipment as well as background noises such as those generated by fluorescent lights and other less obvious sources. The ability to isolate the source of abnormal noises permits cost-effective corrective action.

7.1.6 Leak Detections

Leaks in process vessels and devices such as valves are a serious problem in many industries. A variation of vibration monitoring and analysis can be used to detect leakage and isolate its source. Leak-detection systems use an accelerometer attached to the exterior of a process pipe. This allows the vibration profile to be monitored in order to detect the unique frequencies generated by flow or leakage.

7.1.7 Aircraft Engine Analyzers

Adaptations of vibration-analysis techniques have been used for a variety of specialty instruments, in particular portable and continuous aircraft engine analyzers. Vibration-monitoring and analysis techniques are the basis of these analyzers, which are used to detect excessive vibration in turbo-prop and jet engines. These instruments incorporate logic modules that use existing vibration data to evaluate the engine condition. Portable units have diagnostic capabilities that allow a mechanic to determine the source of the problem while continuous sensors alert the pilot of any deviation from optimum operating condition.

7.1.8 Machine Design and Engineering

Vibration data have become a critical part of the design and engineering of new machines and process systems. Data derived from similar or existing machinery can be extrapolated to form the basis of a preliminary design. Prototype testing of new

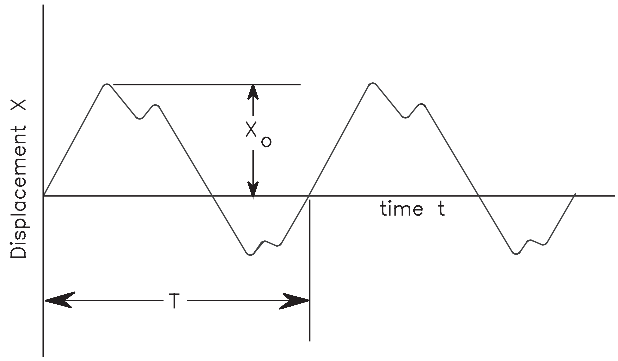


Figure 7–1 Periodic motion for bearing pedestal of a steam turbine.

machinery and systems allows these preliminary designs to be finalized, and the vibration data from the testing add to the design database.

7.2 Vibration Analysis Overview

Vibration theory and vibration profile, or signature, analyses are complex subjects that are the topic of many textbooks. This section provides enough theory to allow the concept of vibration profiles and their analysis to be understood before beginning the more in-depth discussions in the later sections of this book.

7.2.1 Theoretical Vibration Profiles

A vibration is a periodic motion or one that repeats itself after a certain interval. This interval is referred to as the period of the vibration, T. A plot, or profile, of a vibration is shown in Figure 7–1, which shows the period, T, and the maximum displacement or amplitude, X_0. The inverse of the period, $\frac{1}{T}$, is called the frequency, f, of the vibration, which can be expressed in units of cycles per second (cps) or Hertz (Hz). A harmonic function is the simplest type of periodic motion and is shown in Figure 7–2, which is the harmonic function for the small oscillations of a simple pendulum. Such a relationship can be expressed by the equation:

$$X = X_0 \sin(\omega t)$$

where:

X = Vibration displacement (thousandths of an inch, or mils)

X_0 = Maximum displacement or amplitude (mils)

ω = Circular frequency (radians per second)

t = Time (seconds)

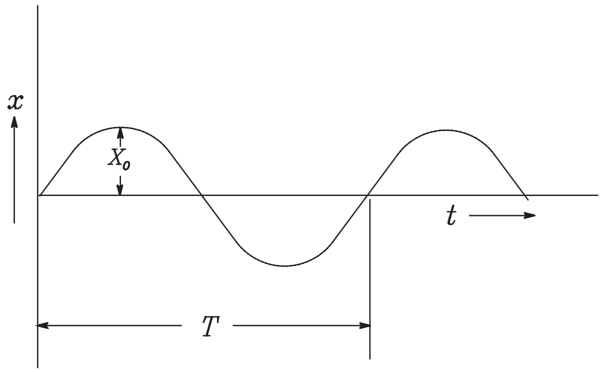


Figure 7–2 Small oscillations of a simple pendulum, harmonic function.

7.2.2 Actual Vibration Profiles

The process of vibration analysis requires gathering complex machine data and deciphering it. As opposed to the simple theoretical vibration curves shown in Figures 7–1 and 7–2, the profile for a piece of equipment is extremely complex because there are usually many sources of vibration. Each source generates its own curve, but these are essentially added together and displayed as a composite profile. These profiles can be displayed in two formats: time-domain and frequency-domain.

Time-Domain

Vibration data plotted as amplitude versus time is referred to as a time-domain data profile. Some simple examples are shown in Figures 7–1 and 7–2. An example of the complexity of this type of data for an actual piece of industrial machinery is shown in Figure 7–3.

Time-domain plots must be used for all linear and reciprocating motion machinery. They are useful in the overall analysis of machine-trains to study changes in operating conditions; however, time-domain data are difficult to use. Because all the vibration data in this type of plot are added together to represent the total displacement at any given time, it is difficult to directly see the contribution of any particular vibration source.

The French physicist and mathematician Jean Fourier determined that nonharmonic data functions such as the time-domain vibration profile are the mathematical sum of simple harmonic functions. The dashed-line curves in Figure 7–4 represent discrete harmonic components of the total, or summed, nonharmonic curve represented by the solid line.

This type of data, which is routinely taken over the life of a machine, is directly comparable to historical data taken at exactly the same running speed and load; however,

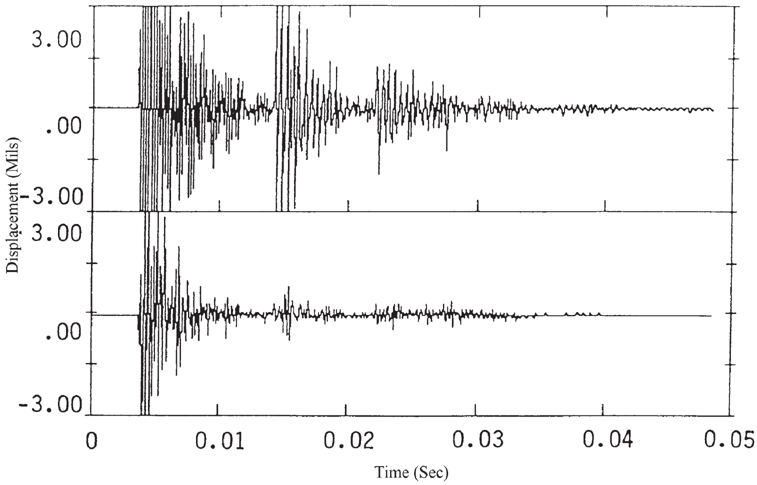


Figure 7–3 Example of a typical time-domain vibration profile for a piece of machinery.

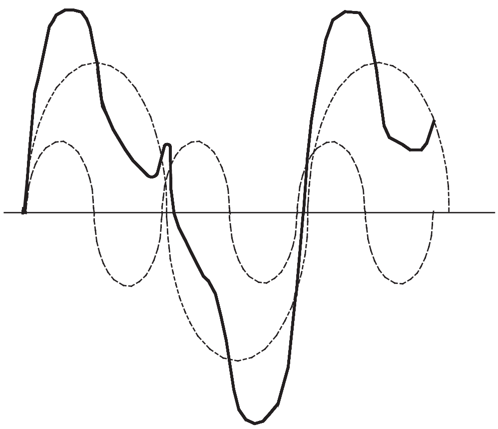


Figure 7–4 Discrete (harmonic) and total (nonharmonic) time-domain vibration curves.

this is not practical because of variations in day-to-day plant operations and changes in running speed. This significantly affects the profile and makes it impossible to compare historical data.

Frequency-Domain

From a practical standpoint, simple harmonic vibration functions are related to the circular frequencies of the rotating or moving components. Therefore, these frequencies are some multiple of the basic running speed of the machine-train, which is expressed

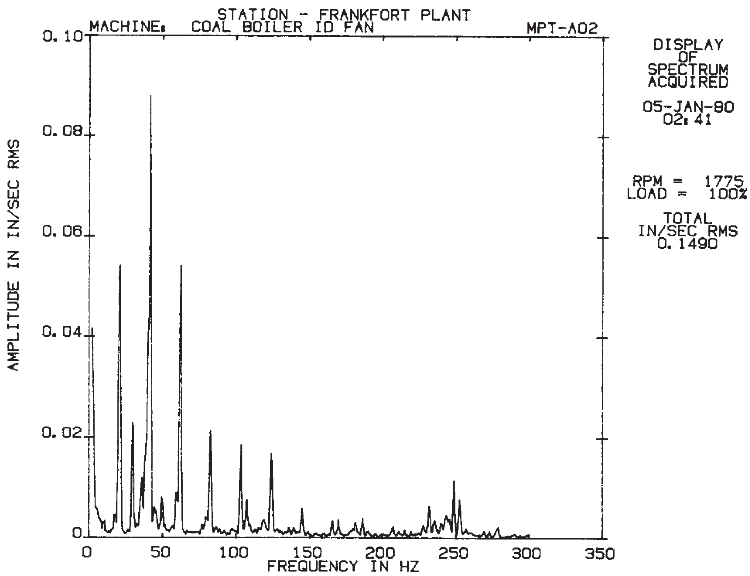


Figure 7–5 Typical frequency-domain vibration signature.

in revolutions per minute (rpm) or cycles per minute (cpm). Determining these frequencies is the first basic step in analyzing the operating condition of the machine-train.

Frequency-domain data are obtained by converting time-domain data using a mathematical technique referred to as Fast Fourier Transform (FFT). FFT allows each vibration component of a complex machine-train spectrum to be shown as a discrete frequency peak. The frequency-domain amplitude can be the displacement per unit time related to a particular frequency, which is plotted as the Y-axis against frequency as the X-axis. This is opposed to time-domain spectrums that sum the velocities of all frequencies and plot the sum as the Y-axis against time as the X-axis. An example of a frequency-domain plot or vibration signature is shown in Figure 7–5.

Frequency-domain data are required for equipment operating at more than one running speed and all rotating applications. Because the X-axis of the spectrum is frequency normalized to the running speed, a change in running speed will not affect the plot. A vibration component that is present at one running speed will still be found in the same location on the plot for another running speed after the normalization, although the amplitude may be different.

7.2.3 Interpretation of Vibration Data

The key to using vibration signature analysis for predictive maintenance, diagnostic, and other applications is the ability to differentiate between normal and abnormal vibration profiles. Many vibrations are normal for a piece of rotating or moving machinery. Examples of these are normal rotations of shafts and other rotors, contact with bearings, gear-mesh, and so on. Specific problems with machinery generate abnormal, yet identifiable, vibrations. Examples of these are loose bolts, misaligned shafts, worn bearings, leaks, and incipient metal fatigue.

Predictive maintenance using vibration signature analysis is based on the following facts, which form the basis of the methods used to identify and quantify the root causes of failure:

- All common machinery problems and failure modes have distinct vibration frequency components that can be isolated and identified.
- A frequency-domain vibration signature is generally used for analysis because it consists of discrete peaks, each representing a specific vibration source.
- There is a cause, referred to as a *forcing function*, for every frequency component in a machine-train's vibration signature.
- When the signature of a machine is compared over time, it will repeat until some event changes the vibration pattern (i.e., the amplitude of each distinct vibration component will remain constant until the operating dynamics of the machine-train change).

Although an increase or decrease in amplitude may indicate degradation of the machine-train, this is not always the case. Variations in load, operating practices, and a variety of other normal changes also change the amplitude of one or more frequency components within the vibration signature. In addition, it is important to note that a lower amplitude does not necessarily indicate an improvement in the mechanical condition of the machine-train. Therefore, it is important that the source of all amplitude variations be clearly understood.

7.2.4 Vibration-Measuring Equipment

Vibration data are obtained by the following procedure: (1) mounting a transducer onto the machinery at various locations, typically machine housing and bearing caps, and (2) using a portable data-gathering device, referred to as a *vibration monitor* or *analyzer*, to connect to the transducer to obtain vibration readings.

Transducers

The transducer most commonly used to obtain vibration measurements is an accelerometer. It incorporates piezoelectric (i.e., pressure-sensitive) films to convert mechanical energy into electrical signals. The device generally incorporates a weight suspended between two piezoelectric films. The weight moves in response to vibration and squeezes the piezoelectric films, which sends an electrical signal each time the weight squeezes it.

Portable Vibration Analyzers

The portable vibration analyzer incorporates a microprocessor that allows it to mathematically convert the electrical signal to acceleration per unit time, perform an FFT, and store the data. It can be programmed to generate alarms and displays of the data. The data stored by the analyzer can be downloaded to a PC or a more powerful computer to perform more sophisticated analyses, data storage and retrieval, and report generation.

7.3 Vibration Sources

All machinery with moving parts generates mechanical forces during normal operation. As the mechanical condition of the machine changes because of wear, changes in the operating environment, load variations, and so on, so do these forces. Understanding machinery dynamics and how forces create unique vibration frequency components is the key to understanding vibration sources.

Vibration does not just happen. There is a physical cause, referred to as a *forcing function*, and each component of a vibration signature has its own forcing function. The components that make up a signature are reflected as discrete peaks in the FFT or frequency-domain plot.

The vibration profile that results from motion is the result of a force imbalance. By definition, balance occurs in moving systems when all forces generated by, and acting on, the machine are in a state of equilibrium. In real-world applications, however, there is always some level of imbalance, and all machines vibrate to some extent. This section discusses the more common sources of vibration for rotating machinery, as well as for machinery undergoing reciprocating and/or linear motion.

7.3.1 Rotating Machinery

A rotating machine has one or more machine elements that turn with a shaft, such as rolling-element bearings, impellers, and other rotors. In a perfectly balanced machine, all rotors turn true on their centerline and all forces are equal. In industrial machinery, however, it is common for an imbalance of these forces to occur. In addition to imbalance generated by a rotating element, vibration may be caused by instability in the media flowing through the rotating machine.

Rotor Imbalance

Mechanical imbalance is not the only form of imbalance that affects rotating elements. It is the condition where more weight is on one side of a centerline of a rotor than on the other. In many cases, rotor imbalance is the result of an imbalance between centripetal forces generated by the rotation. The source of rotor vibration can also be an imbalance between the lift generated by the rotor and gravity.

Machines with rotating elements are designed to generate vertical lift of the rotating element when operating within normal parameters. This vertical lift must overcome gravity to properly center the rotating element in its bearing-support structure; however, because gravity and atmospheric pressure vary with altitude and barometric pressure, actual lift may not compensate for the downward forces of gravity in certain environments. When the deviation of actual lift from designed lift is significant, a rotor may not rotate on its true centerline. This offset rotation creates an imbalance and a measurable level of vibration.

Flow Instability and Operating Conditions

Rotating machines subject to imbalance caused by turbulent or unbalanced media flow include pumps, fans, and compressors. A good machine design for these units incorporates the dynamic forces of the gas or liquid in stabilizing the rotating element. The combination of these forces and the stiffness of the rotor-support system (i.e., bearing and bearing pedestals) determine the vibration level. Rotor-support stiffness is important because unbalanced forces resulting from flow instability can deflect rotating elements from their true centerline, and the stiffness resists the deflection.

Deviations from a machine's designed operating envelope can affect flow stability, which directly affects the vibration profile. For example, the vibration level of a centrifugal compressor is typically low when operating at 100 percent load with laminar airflow through the compressor; however, a radical change in vibration level can result from decreased load. Vibration resulting from operation at 50 percent load may increase by as much as 400 percent with no change in the mechanical condition of the compressor. In addition, a radical change in vibration level can result from turbulent flow caused by restrictions in either the inlet or discharge piping.

Turbulent or unbalanced media flow (i.e., aerodynamic or hydraulic instability) does not have the same quadratic impact on the vibration profile as that of load change, but it increases the overall vibration energy. This generates a unique profile that can be used to quantify the level of instability present in the machine. The profile generated by unbalanced flow is visible at the vane- or blade-pass frequency of the rotating element. In addition, the profile shows a marked increase in the random noise generated by the flow of gas or liquid through the machine.

Mechanical Motion and Forces

A clear understanding of the mechanical movement of machines and their components is an essential part of vibration analysis. This understanding, coupled with the forces applied by the process, is the foundation for diagnostic accuracy.

Almost every unique frequency contained in the vibration signature of a machine-train can be directly attributed to a corresponding mechanical motion within the machine. For example, the constant endplay or axial movement of the rotating element in a motor-generator set generates elevated amplitude at the fundamental (1X), second harmonic (2X), and third harmonic (3X) of the shaft's true running speed. In addition, this movement increases the axial amplitude of the fundamental (1X) frequency.

Forces resulting from air or liquid movement through a machine also generate unique frequency components within the machine's signature. In relatively stable or laminar-flow applications, the movement of product through the machine slightly increases the amplitude at the vane- or blade-pass frequency. In more severe, turbulent-flow applications, the flow of product generates a broadband, white-noise profile that can be directly attributed to the movement of product through the machine.

Other forces, such as the sideload created by V-belt drives, also generate unique frequencies or modify existing component frequencies. For example, excessive belt tension increases the sideload on the machine-train's shafts. This increase in sideload changes the load zone in the machine's bearings. The result of this change is a marked increase in the amplitude at the outer-race rotational frequency of the bearings.

Applied force or induced loads can also displace the shafts in a machine-train. As a result the machine's shaft will rotate off-center, which dramatically increases the amplitude at the fundamental (1X) frequency of the machine.

7.3.2 Reciprocating and/or Linear-Motion Machinery

This section describes machinery that exhibits reciprocating and/or linear motion(s) and discusses typical vibration behavior for these types of machines.

Machine Descriptions

Reciprocating linear-motion machines incorporate components that move linearly in a reciprocating fashion to perform work. Such reciprocating machines are bidirectional in that the linear movement reverses, returning to the initial position with each completed cycle of operation. Nonreciprocating linear-motion machines incorporate components that also generate work in a straight line but do not reverse direction within one complete cycle of operation.

Few machines involve linear reciprocating motion exclusively. Most incorporate a combination of rotating and reciprocating linear motions to produce work. One example of such a machine is a reciprocating compressor. This unit contains a rotating crankshaft that transmits power to one or more reciprocating pistons, which move linearly in performing the work required to compress the media.

Sources of Vibration

Like rotating machinery, the vibration profile generated by reciprocating and/or linear-motion machines is the result of mechanical movement and forces generated by the components that are part of the machine. Vibration profiles generated by most reciprocating and/or linear-motion machines reflect a combination of rotating and/or linear-motion forces; however, the intervals or frequencies generated by these machines are not always associated with one complete revolution of a shaft. In a two-cycle reciprocating engine, the pistons complete one cycle each time the crankshaft completes one 360-degree revolution. In a four-cycle engine, the crank must complete two complete revolutions, or 720 degrees, in order to complete a cycle of all pistons.

Because of the unique motion of reciprocating and linear-motion machines, the level of unbalanced forces generated by these machines is substantially higher than those generated by rotating machines. For example, a reciprocating compressor drives each of its pistons from bottom-center to top-center and returns to bottom-center in each complete operation of the cylinder. The mechanical forces generated by the reversal of direction at both top-center and bottom-center result in a sharp increase in the vibration energy of the machine. An instantaneous spike in the vibration profile repeats each time the piston reverses direction.

Linear-motion machines generate vibration profiles similar to those of reciprocating machines. The major difference is the impact that occurs at the change of direction with reciprocating machines. Typically, linear-motion-only machines do not reverse direction during each cycle of operation and, as a result, do not generate the spike of energy associated with direction reversal.

7.4 Vibration Theory

Mathematical techniques allow us to quantify total displacement caused by all vibrations, to convert the displacement measurements to velocity or acceleration, to separate this data into its components using FFT analysis, and to determine the amplitudes and phases of these functions. Such quantification is necessary if we are to isolate and correct abnormal vibrations in machinery.

7.4.1 Periodic Motion

Vibration is a periodic motion, or one that repeats itself after a certain interval of time called the period, T. Figure 7–6 illustrates the periodic-motion time-domain curve of a steam turbine bearing pedestal. Displacement is plotted on the vertical, or Y-axis, and time on the horizontal, or X-axis. The curve shown in Figure 7–6 is the sum of all vibration components generated by the rotating element and bearing-support structure of the turbine.

Harmonic Motion

The simplest kind of periodic motion or vibration, shown in Figure 7–7, is referred to as *harmonic*. Harmonic motions repeat each time the rotating element or machine component completes one complete cycle.

The relation between displacement and time for harmonic motion may be expressed by:

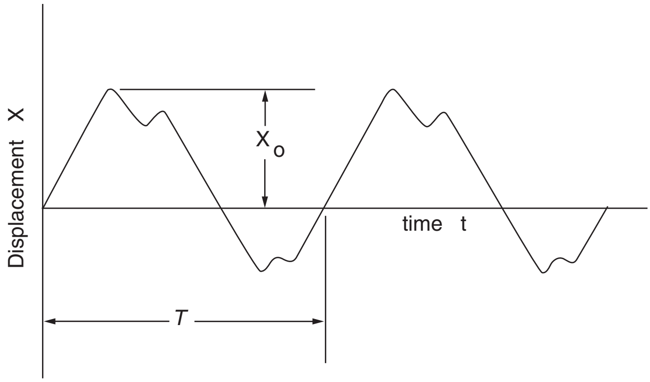


Figure 7–6 Typical periodic motion.

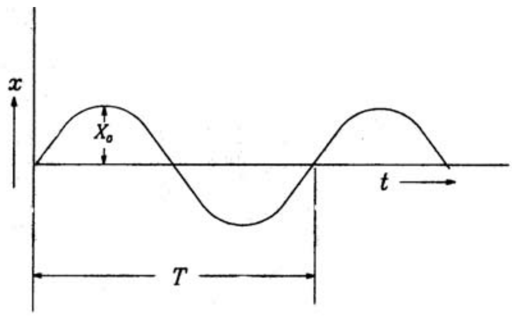


Figure 7–7 Simple harmonic motion.

$$X = X_0 \sin(\omega t)$$

The maximum value of the displacement is X_0, which is also called the *amplitude*. The period, T, is usually measured in seconds; its reciprocal is the frequency of the vibration, f, measured in cycles per second (cps) or Hertz (Hz).

$$f = \frac{1}{T}$$

Another measure of frequency is the circular frequency, ω, measured in radians per second. From Figure 7–8, it is clear that a full cycle of vibration (ωt) occurs after 360 degrees or 2π radians (i.e., one full revolution). At this point, the function begins a new cycle.

$$\omega = 2\pi f$$

For rotating machinery, the frequency is often expressed in vibrations per minute (vpm) or

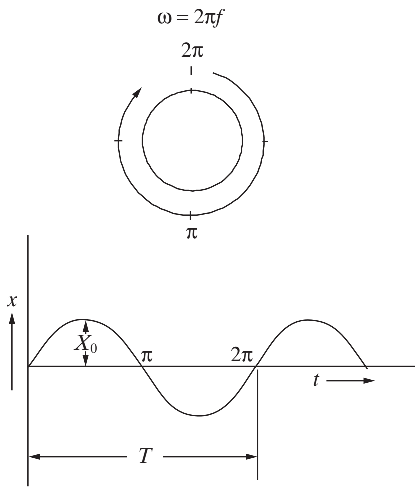


Figure 7–8 Illustration of vibration cycles.

$$VPM = \frac{\omega}{\pi}$$

By definition, velocity is the first derivative of displacement with respect to time. For a harmonic motion, the displacement equation is:

$$X = X_0 \sin(\omega t)$$

The first derivative of this equation gives us the equation for velocity:

$$v = \frac{dX}{dt} = \dot{X} = \omega X_0 \cos(\omega t)$$

This relationship tells us that the velocity is also harmonic if the displacement is harmonic and has a maximum value or amplitude of $-\omega X_0$.

By definition, acceleration is the second derivative of displacement (i.e., the first derivative of velocity) with respect to time:

$$a = \frac{d^2X}{dt^2} = \ddot{X} = \omega^2 X_0 \sin(\omega t)$$

This function is also harmonic with amplitude of $\omega^2 X_0$.

Consider two frequencies given by the expression $X_1 = a\sin(\omega t)$ and $X_2 = b\sin(\omega t + \phi)$, which are shown in Figure 7–9 plotted against ωt as the X-axis. The quantity, ϕ, in the equation for X_2 is known as the *phase angle* or *phase difference* between the

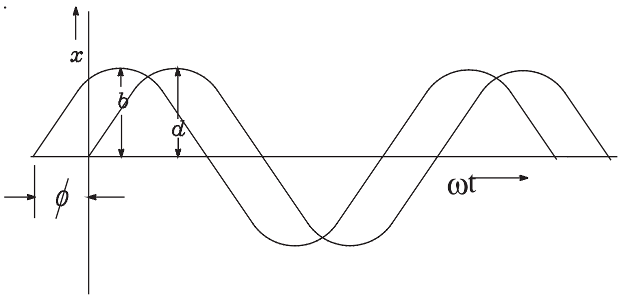


Figure 7–9 Two harmonic motions with a phase angle between them.

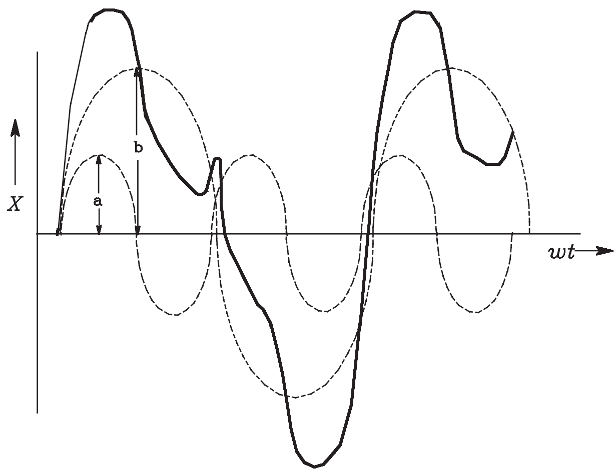


Figure 7–10 Nonharmonic periodic motion.

two vibrations. Because of ϕ, the two vibrations do not attain their maximum displacements at the same time. One is $\frac{\phi}{\omega}$ seconds behind the other. Note that these two motions have the same frequency, ω. A phase angle has meaning only for two motions of the same frequency.

Nonharmonic Motion

In most machinery, there are numerous sources of vibrations; therefore, most time-domain vibration profiles are nonharmonic (represented by the solid line in Figure 7–10). Although all harmonic motions are periodic, not every periodic motion is harmonic. In Figure 7–10, the dashed lines represent harmonic motions. Figure 7–10 is the superposition of two sine waves having different frequencies. These curves are represented by the following equations:

$$X_1 = a\sin(\omega_1 t)$$
$$X_2 = b\sin(\omega_2 t)$$

The total vibration represented by the solid line is the sum of the dashed lines. The following equation represents the total vibration:

$$X = X_1 + X_2 = a\sin(\omega_1 t) + b\sin(\omega_2 t)$$

Any periodic function can be represented as a series of sine functions having frequencies of ω, 2ω, 3ω, etc.:

$$f(t) = A_0 + A_1 \sin(\omega t + \phi_1) + A_2 \sin(2\omega t + \phi_2) + A_3 \sin(3\omega t + \phi_3) + \ldots$$

The previous equation is known as a Fourier Series, which is a function of time or $f(t)$. The amplitudes (A_1, A_2, etc.) of the various discrete vibrations and their phase angles (ϕ_1, ϕ_2, ϕ_3, . . .) can be determined mathematically when the value of function $f(t)$ is known. Note that these data are obtained using a transducer and a portable vibration analyzer.

The terms, 2ω, 3ω, etc., are referred to as the harmonics of the primary frequency, ω. In most vibration signatures, the primary frequency component is one of the running speeds of the machine-train (1X or 1ω). In addition, a signature may be expected to have one or more harmonics, for example, at two times (2X), three times (3X), and other multiples of the primary running speed.

7.4.2 Measurable Parameters

As shown previously, vibrations can be displayed graphically as plots, which are referred to as *vibration profiles* or *signatures*. These plots are based on measurable parameters (i.e., frequency and amplitude). [Note that the terms *profile* and *signature* are sometimes used interchangeably by industry. In this book, however, *profile* is used to refer either to time-domain (also may be called time trace or waveform) or frequency-domain plots. The term *signature* refers to a frequency-domain plot.]

Frequency

Frequency is defined as the number of repetitions of a specific forcing function or vibration component over a specific unit of time. Take for example a four-spoke wheel with an accelerometer attached. Every time the shaft completes one rotation, each of the four spokes passes the accelerometer once, which is referred to as four cycles per revolution. Therefore, if the shaft rotates at 100 rotations per minute (rpm), the frequency of the spokes passing the accelerometer is 400 cycles per minute (cpm). In addition to cpm, frequency is commonly expressed in cycles per second (cps) or Hertz (Hz).

Note that for simplicity, a machine element's vibration frequency is commonly expressed as a multiple of the shaft's rotation speed. In the previous example, the frequency would be indicated as 4X, or four times the running speed. In addition, because some malfunctions tend to occur at specific frequencies, it helps to segregate certain classes of malfunctions from others.

Note, however, that the frequency/malfunction relationship is not mutually exclusive, and a specific mechanical problem cannot definitely be attributed to a unique frequency. Although frequency is a very important piece of information with regard to isolating machinery malfunctions, it is only one part of the total picture. It is necessary to evaluate all data before arriving at a conclusion.

Amplitude

Amplitude refers to the maximum value of a motion or vibration. This value can be represented in terms of displacement (mils), velocity (inches per second), or acceleration (inches per second squared), each of which is discussed in more detail in the Maximum Vibration Measurement section that follows.

Amplitude can be measured as the sum of all the forces causing vibrations within a piece of machinery (broadband), as discrete measurements for the individual forces (component), or for individual user-selected forces (narrowband). Broadband, component, and narrowband are discussed in the Measurement Classifications section that follows. Also discussed in this section are the common curve elements: peak-to-peak, zero-to-peak, and root-mean-square.

Maximum Vibration Measurement. The maximum value of a vibration, or amplitude, is expressed as displacement, velocity, or acceleration. Most of the microprocessor-based, frequency-domain vibration systems will convert the acquired data to the desired form. Because industrial vibration-severity standards are typically expressed in one of these terms, it is necessary to have a clear understanding of their relationship.

Displacement. Displacement is the actual change in distance or position of an object relative to a reference point and is usually expressed in units of mils, 0.001 inch. For example, displacement is the actual radial or axial movement of the shaft in relation to the normal centerline, usually using the machine housing as the stationary reference. Vibration data, such as shaft displacement measurements acquired using a proximity probe or displacement transducer, should always be expressed in terms of mils, peak-to-peak.

Velocity. Velocity is defined as the time rate of change of displacement (i.e., the first derivative, $\frac{dX}{dt}$ or $\dot{X}$) and is usually expressed as inches per second (ips). In simple terms, velocity is a description of how fast a vibration component is moving rather than how far, which is described by displacement.

Used in conjunction with zero-to-peak (PK) terms, velocity is the best representation of the true energy generated by a machine when relative or bearing cap-data are used.

[Note: Most vibration-monitoring programs rely on data acquired from machine housing or bearing caps.] In most cases, peak velocity values are used with vibration data between 0 and 1,000 Hz. These data are acquired with microprocessor-based, frequency-domain systems.

Acceleration. Acceleration is defined as the time rate of change of velocity (i.e., second derivative of displacement, $\frac{d^2X}{dt^2}$ or $\ddot{X}$) and is expressed in units of inches per second squared (in/sec^2). Vibration frequencies above 1,000 Hz should always be expressed as acceleration.

Acceleration is commonly expressed in terms of the gravitational constant, g, which is 32.17 ft/sec^2. In vibration-analysis applications, acceleration is typically expressed in terms of g-RMS or g-PK. These are the best measures of the force generated by a machine, a group of components, or one of its components.

Measurement Classifications. There are at least three classifications of amplitude measurements used in vibration analysis: broadband, narrowband, and component.

Broadband or overall. The total energy of all vibration components generated by a machine is reflected by broadband, or overall, amplitude measurements. The normal convention for expressing the frequency range of broadband energy is a filtered range between 10 to 10,000 Hz, or 600 to 600,000 cpm. Because most vibration-severity charts are based on this filtered broadband, caution should be exercised to ensure that collected data are consistent with the charts.

Narrowband. Narrowband amplitude measurements refer to those that result from monitoring the energy generated by a user-selected group of vibration frequencies. Generally, this amplitude represents the energy generated by a filtered band of vibration components, failure mode, or forcing functions. For example, the total energy generated by flow instability can be captured using a filtered narrowband around the vane or blade-passing frequency.

Component. The energy generated by a unique machine component, motion, or other forcing function can yield its own amplitude measurement. For example, the energy generated by the rotational speed of a shaft, gear set meshing, or similar machine components produces discrete vibration components whose amplitude can be measured.

Common Elements of Curves. All vibration amplitude curves, which can represent displacement, velocity, or acceleration, have common elements that can be used to describe the function. These common elements are peak-to-peak, zero-to-peak, and root-mean-square, each of which are illustrated in Figure 7–11.

Peak-to-peak. As illustrated in Figure 7–11, the peak-to-peak amplitude (2A, where A is the zero-to-peak) reflects the total amplitude generated by a machine, a group of components, or one of its components. This depends on whether the data gathered are

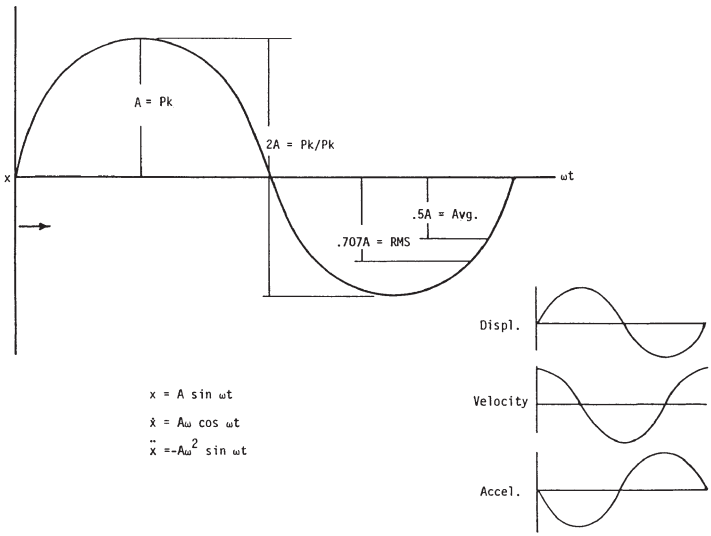


Figure 7–11 Relationship of vibration amplitude.

broadband, narrowband, or component. The unit of measurement is useful when the analyst needs to know the total displacement or maximum energy produced by the machine's vibration profile.

Technically, peak-to-peak values should be used in conjunction with actual shaft-displacement data, which are measured with a proximity or displacement transducer. Peak-to-peak terms should not be used for vibration data acquired using either relative vibration data from bearing caps or when using a velocity or acceleration transducer. The only exception is when vibration levels must be compared to vibration-severity charts based on peak-to-peak values.

Zero-to-peak. Zero-to-peak (A), or simply peak, values are equal to one half of the peak-to-peak value. In general, relative vibration data acquired using a velocity transducer are expressed in terms of peak.

Root-mean-square. Root-mean-square (RMS) is the statistical average value of the amplitude generated by a machine, one of its components, or a group of components. Referring to Figure 7–11, RMS is equal to 0.707 of the zero-to-peak value, A. Normally, RMS data are used in conjunction with relative vibration data acquired using an accelerometer or expressed in terms of acceleration.

7.5 Machine Dynamics

The primary reasons for vibration-profile variations are the dynamics of the machine, which are affected by mass, stiffness, damping, and degrees of freedom; however, care must be taken because the vibration profile and energy levels generated by a machine may vary depending on the location and orientation of the measurement.

7.5.1 Mass, Stiffness, and Damping

The three primary factors that determine the normal vibration energy levels and the resulting vibration profiles are mass, stiffness, and damping. Every machine-train is designed with a dynamic support system that is based on the following: the mass of the dynamic component(s), specific support system stiffness, and a specific amount of damping.

Mass

Mass is the property that describes how much material is present. Dynamically, the property describes how an unrestricted body resists the application of an external force. Simply stated, the greater the mass, the greater the force required to accelerate it. Mass is obtained by dividing the weight of a body (e.g., rotor assembly) by the local acceleration of gravity, g.

The English system of units is complicated compared to the metric system. In the English system, the units of mass are pounds-mass (lbm) and the units of weight are pounds-force (lbf). By definition, a weight (i.e., force) of one lbf equals the force produced by one lbm under the acceleration of gravity. Therefore, the constant, g_c, which has the same numerical value as g (32.17) and units of *lbm-ft/lbf-sec*^{2}, is used in the definition of weight:

$$\text{Weight} = \frac{\text{Mass} * g}{g_c}$$

Therefore,

$$\text{Mass} = \frac{\text{Weight} * g_c}{g}$$

Therefore,

$$\text{Mass} = \frac{\text{Weight} * g_c}{g} = \frac{\text{lbf}}{\frac{\text{ft}}{\text{sec}^2}} \times \frac{\text{lbm} * \text{ft}}{\text{lbf} * \text{sec}^2} = \text{lbm}$$

Stiffness

Stiffness is a spring-like property that describes the level of resisting force that results when a body changes in length. Units of stiffness are often given as pounds per inch (lbf/in). Machine-trains have three stiffness properties that must be considered in vibration analysis: shaft stiffness, vertical stiffness, and horizontal stiffness.

Shaft Stiffness. Most machine-trains used in industry have flexible shafts and relatively long spans between bearing-support points. As a result, these shafts tend to flex in normal operation. Three factors determine the amount of flex and mode shape that these shafts have in normal operation: shaft diameter, shaft material properties, and span length. A small-diameter shaft with a long span will obviously flex more than one with a larger diameter or shorter span.

Vertical Stiffness. The rotor-bearing support structure of a machine typically has more stiffness in the vertical plane than in the horizontal plane. Generally, the structural rigidity of a bearing-support structure is much greater in the vertical plane. The full weight of and the dynamic forces generated by the rotating element are fully supported by a pedestal cross-section that provides maximum stiffness.

In typical rotating machinery, the vibration profile generated by a normal machine contains lower amplitudes in the vertical plane. In most cases, this lower profile can be directly attributed to the difference in stiffness of the vertical plane when compared to the horizontal plane.

Horizontal Stiffness. Most bearing pedestals have more freedom in the horizontal direction than in the vertical. In most applications, the vertical height of the pedestal is much greater than the horizontal cross-section. As a result, the entire pedestal can flex in the horizontal plane as the machine rotates.

This lower stiffness generally results in higher vibration levels in the horizontal plane. This is especially true when the machine is subjected to abnormal modes of operation or when the machine is unbalanced or misaligned.

Damping

Damping is a means of reducing velocity through resistance to motion, in particular by forcing an object through a liquid or gas, or along another body. Units of damping are often given as pounds per inch per second (lbf/in/sec, which is also expressed as lbf-sec/in).

The boundary conditions established by the machine design determine the freedom of movement permitted within the machine-train. A basic understanding of this concept is essential for vibration analysis. Free vibration refers to the vibration of a damped (as well as undamped) system of masses with motion entirely influenced by their potential energy. Forced vibration occurs when motion is sustained or driven by an applied periodic force in either damped or undamped systems. The following sections discuss free and forced vibration for both damped and undamped systems.

Free Vibration—Undamped. To understand the interactions of mass and stiffness, consider the case of undamped free vibration of a single mass that only moves

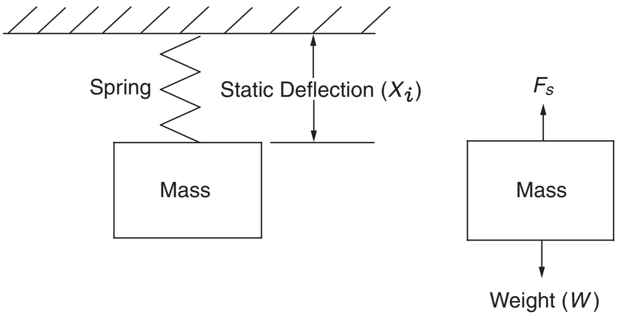


Figure 7–12 Undamped spring-mass system.

vertically, which is illustrated in Figure 7–12. In this figure, the mass "*M*" is supported by a spring that has a stiffness "K" (also referred to as the *spring constant*), which is defined as the number of pounds tension necessary to extend the spring one inch.

The force created by the static deflection, X_i, of the spring supports the weight, *W*, of the mass. Also included in Figure 7–12 is the free-body diagram that illustrates the two forces acting on the mass. These forces are the weight (also referred to as the *inertia force*) and an equal, yet opposite force that results from the spring (referred to as the *spring force*, F_s).

The relationship between the weight of mass, *M*, and the static deflection of the spring can be calculated using the following equation:

$$W = KX_i$$

If the spring is displaced downward some distance, X_0, from X_i and released, it will oscillate up and down. The force from the spring, F_s, can be written as follows, where "a" is the acceleration of the mass:

$$F_s = -KX = \frac{Ma}{g_c}$$

It is common practice to replace acceleration, a, with $\frac{d^2X}{dt^2}$, the second derivative of the displacement, *X*, of the mass with respect to time, *t*. Making this substitution, the equation that defines the motion of the mass can be expressed as:

$$\frac{M}{g_c}\frac{d^2X}{dt^2} = -KX \quad or \quad \frac{M}{g_c}\frac{d^2X}{dt^2} + KX = 0$$

Motion of the mass is known to be periodic. Therefore, the displacement can be described by the expression:

$$X = X_0 \cos(\omega t)$$

Where:

X = Displacement at time t

X_0 = Initial displacement of the mass

ω = Frequency of the oscillation (natural or resonant frequency)

t = Time

If this equation is differentiated and the result inserted into the equation that defines motion, the natural frequency of the mass can be calculated. The first derivative of the equation for motion yields the equation for velocity. The second derivative of the equation yields acceleration.

$$Velocity = \frac{dX}{dt} = \dot{X} = -\omega X_0 \sin(\omega t)$$

$$Acceleration = \frac{d^2X}{dt^2} = \ddot{X} = -\omega^2 X_0 \cos(\omega t)$$

Inserting the expression for acceleration, or $\frac{d^2X}{dt^2}$, into the equation for F_s yields the following:

$$\frac{M}{g_c}\frac{d^2X}{dt^2} + KX = 0$$

$$-\frac{M}{g_c}\omega^2 X_0 \cos(\omega t) + KX = 0$$

$$-\frac{M}{g_c}\omega^2 X + KX = -\frac{M}{g_c}\omega^2 + K = 0$$

Solving this expression for ω yields the equation:

$$w = \sqrt{\frac{Kg_c}{M}}$$

Where:

ω = Natural frequency of mass

K = Spring constant

M = Mass

Note that, theoretically, undamped free vibration persists forever; however, this never occurs in nature, and all free vibrations die down after time because of damping, which is discussed in the next section.

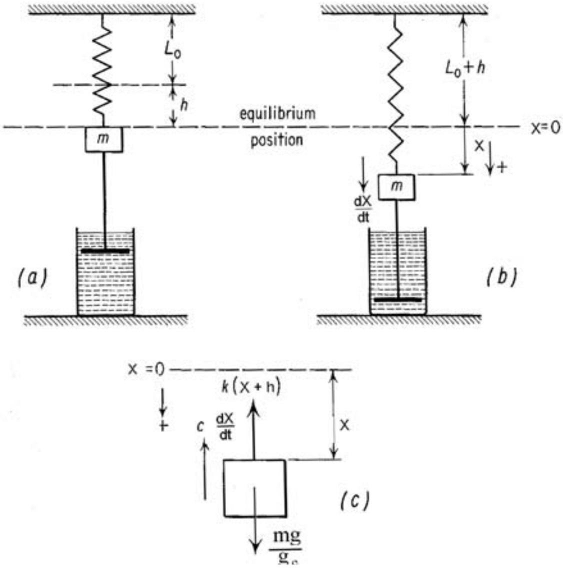


Figure 7–13 Damped spring-mass system.

Free Vibration—Damped. A slight increase in system complexity results when a damping element is added to the spring-mass system shown in Figure 7–13. This type of damping is referred to as *viscous damping*. Dynamically, this system is the same as the undamped system illustrated in Figure 7–12, except for the damper, which usually is an oil or air dashpot mechanism. A damper is used to continuously decrease the velocity and the resulting energy of a mass undergoing oscillatory motion.

The system consists of the inertia force caused by the mass and the spring force, but a new force is introduced. This force is referred to as the *damping force* and is proportional to the damping constant, or the coefficient of viscous damping, *c*. The damping force is also proportional to the velocity of the body and, as it is applied, it opposes the motion at each instant.

In Figure 7–13, the nonelongated length of the spring is "L_o" and the elongation caused by the weight of the mass is expressed by "*h*." Therefore, the weight of the mass is *Kh*. Part (a) of Figure 7–13 shows the mass in its position of stable equilibrium. Part (b) shows the mass displaced downward a distance X from the equilibrium position. Note that X is considered positive in the downward direction.

Part (c) of Figure 7–13 is a free-body diagram of the mass, which has three forces acting on it. The weight (Mg/g_c), which is directed downward, is always positive. The damping force $\left(c\dfrac{dX}{dt}\right)$, which is the damping constant times velocity, acts opposite to the direction of the velocity. The spring force, $K(X + h)$, acts in the direction opposite to the displacement. Using Newton's equation of motion, where $\Sigma F = Ma$, the sum of the forces acting on the mass can be represented by the following equation, remembering that X is positive in the downward direction:

$$\frac{M}{g_c}\frac{d^2X}{dt^2} = \frac{Mg}{g_c} - c\frac{dX}{dt} - K(X+h)$$
$$\frac{M}{g_c}\frac{d^2X}{dt^2} = Kh - c\frac{dX}{dt} - KX - Kh$$
$$\frac{M}{g_c}\frac{d^2X}{dt^2} = -c\frac{dX}{dt} - KX$$

Dividing by $\frac{M}{g_c}$:

$$\frac{d^2X}{dt^2} = -\frac{cg_c}{M}\frac{dX}{dt} - \frac{Kg_cX}{M}$$

In order to look up the solution to the above equation in a differential equations table (such as in *CRC Handbook of Chemistry and Physics*), it is necessary to change the form of this equation. This can be accomplished by defining the relationships, $cg_c/M = 2\mu$ and $Kg_c/M = \omega^2$, which converts the equation to the following form:

$$\frac{d^2X}{dt^2} = -2\mu\frac{dX}{dt} - \omega^2X$$

Note that for undamped free vibration, the damping constant, c, is zero and, therefore, μ is zero.

$$\frac{d^2X}{dt^2} = -\omega^2X$$
$$\frac{d^2X}{dt^2} = +\omega^2X = 0$$

The solution of this equation describes simple harmonic motion, which is given as follows:

$$X = A\ \cos(\omega t) + B\ \sin(\omega t)$$

Substituting at $t = 0$, then $X = X_0$ and $\frac{dX}{dt} = 0$, then

$$X = X_0\cos(\omega t)$$

This shows that free vibration is periodic and is the solution for X. For damped free vibration, however, the damping constant, c, is not zero.

$$\frac{d^2X}{dt^2} = -2\mu\frac{dX}{dt} - \omega^2 X$$

or

$$\frac{d^2X}{dt^2} + 2\mu\frac{dX}{dt} + \omega^2 X = 0$$

or

$$D^2 + 2\mu D + \omega^2 = 0$$

which has a solution of:

$$X = A\ e^{d^1 t} + B\ e^{d^2 t}$$

where:

$$d_1 = -\mu + \sqrt{\mu^2 - \omega^2}$$
$$d_2 = -\mu - \sqrt{\mu^2 - \omega^2}$$

There are different conditions of damping: critical, overdamping, and underdamping. Critical damping occurs when μ equals ω. Overdamping occurs when μ is greater than ω. Underdamping occurs when μ is less than ω.

The only condition that results in oscillatory motion and, therefore, represents a mechanical vibration is underdamping. The other two conditions result in periodic motions. When damping is less than critical ($\mu < \omega$), then the following equation applies:

$$X = \frac{X_0}{\alpha_1} e^{-\mu t}(\alpha_1 \cos \alpha_1 t + \mu \sin \alpha_1 t)$$

where:

$$\alpha_1 = \sqrt{\omega^2 - \mu^2}$$

Forced Vibration—Undamped. The simple systems described in the preceding two sections on free vibration are alike in that they are not forced to vibrate by any exciting force or motion. Their major contribution to the discussion of vibration fundamentals is that they illustrate how a system's natural or resonant frequency depends on the mass, stiffness, and damping characteristics.

The mass-stiffness-damping system also can be disturbed by a periodic variation of external forces applied to the mass at any frequency. The system shown in Figure 7–12 is increased in complexity by adding an external force, F_0, acting downward on the mass.

In undamped forced vibration, the only difference in the equation for undamped free vibration is that instead of the equation being equal to zero, it is equal to $F_0 \sin(\omega t)$:

$$\frac{M}{g_c}\frac{d^2X}{dt^2} + KX = F_0 \sin(\omega t)$$

Because the spring is not initially displaced and is "driven" by the function $F_0 \sin(\omega t)$, a particular solution, $X = X_0 \sin(\omega t)$, is logical. Substituting this solution into the above equation and performing mathematical manipulations yields the following equation for X:

$$X = C_1 \sin(\omega_n t) + C_2 \cos(\omega_n t) + \frac{X_{st}}{1-(\omega/\omega_n)^2}\sin(\omega t)$$

where:

X = Spring displacement at time, t

X_{st} = Static spring deflection under constant load, F_0

ω = Forced frequency

ω_n = Natural frequency of the oscillation

t = Time

C_1 and C_2 = Integration constants determined from specific boundary conditions

In the above equation, the first two terms are the undamped free vibration, whereas the third term is the undamped forced vibration. The solution, containing the sum of two sine waves of different frequencies, is not a harmonic motion.

Forced Vibration—Damped. In a damped forced vibration system such as the one shown in Figure 7–14, the motion of the mass "*M*" has two parts: (1) the damped free vibration at the damped natural frequency and (2) the steady-state harmonic motions at the forcing frequency. The damped natural frequency component decays quickly, but the steady-state harmonic associated with the external force remains as long as the energy force is present.

With damped forced vibration, the only difference in its equation and the equation for damped free vibration is that it is equal to $F_0 \sin(\omega t)$ as shown below instead of being equal to zero.

$$\frac{M}{g_c}\frac{d^2X}{dt^2} + c\frac{dX}{dt} + KX = F_0 \sin(\omega t)$$

With damped vibration, the damping constant, "c," is not equal to zero and the solution of the equation becomes complex assuming the function, $X = X_0 \sin(\omega t - \phi)$. In

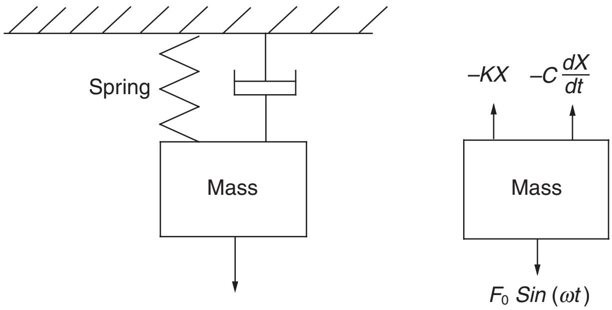


Figure 7–14 Damped forced vibration system.

this equation, ϕ is the phase angle, or the number of degrees that the external force, $F_0 \sin(\omega t)$, is ahead of the displacement, $X_0 \sin(\omega t - \phi)$. Using vector concepts, the following equations apply, which can be solved because there are two equations and two unknowns:

Vertical vector component: $KX_0 - \frac{M}{g_c}\omega^2 X_0 - F_0 \cos\phi = 0$

Horizontal vector component: $c\omega X_0 - F_0 \sin\phi = 0$

Solving these two equations for the unknowns X_0 and ϕ:

$$X_o = \frac{F_0}{\sqrt{(c\omega)^2 + \left(K - \frac{M}{g_c}\omega^2\right)^2}} = \frac{\frac{F_0}{K}}{\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\frac{c}{c_c} \times \frac{\omega}{\omega_n}\right)^2}}$$

$$\tan\phi = \frac{c\omega}{K - \frac{M}{g_c}\omega^2} = \frac{2\frac{c}{c_c} \times \frac{\omega}{\omega_n}}{1 - (\omega^2/\omega_n^2)}$$

Where:

c = Damping constant

$c_c = \text{Critical damping} = 2\frac{M}{g_c}\omega_n$

c/c_c = Damping ratio

F_0 = External force

F_0/K = Deflection of the spring under load, F_0 (also called static deflection, X_{st})

ω = Forced frequency

ω_n = Natural frequency of the oscillation

ω/ω_n = Frequency ratio

For damped forced vibrations, three different frequencies have to be distinguished: the undamped natural frequency, $\sqrt{Kg_c/M}$; the damped natural frequency, $q = \sqrt{\frac{Kg_c}{M} - \left(\frac{cg_c}{2M}\right)^2}$; and the frequency of maximum forced amplitude, sometimes referred to as the *resonant frequency*.

7.5.2 Degrees of Freedom

In a mechanical system, the degrees of freedom indicate how many numbers are required to express its geometrical position at any instant. In machine-trains, the relationship of mass, stiffness, and damping is not the same in all directions. As a result, the rotating or dynamic elements within the machine move more in one direction than in another. A clear understanding of the degrees of freedom is important because it has a direct impact on the vibration amplitudes generated by a machine or process system.

One Degree of Freedom

If the geometrical position of a mechanical system can be defined or expressed as a single value, the machine is said to have one degree of freedom. For example, the position of a piston moving in a cylinder can be specified at any point in time by measuring the distance from the cylinder end.

A single degree of freedom is not limited to simple mechanical systems such as the cylinder. For example, a 12-cylinder gasoline engine with a rigid crankshaft and a rigidly mounted cylinder block has only one degree of freedom. The position of all its moving parts (i.e., pistons, rods, valves, cam shafts) can be expressed by a single value. In this instance, the value would be the angle of the crankshaft; however, when mounted on flexible springs, this engine has multiple degrees of freedom. In addition to the movement of its internal parts in relationship to the crank, the entire engine can now move in any direction. As a result, the position of the engine and any of its internal parts requires more than one value to plot its actual position in space.

The definitions and relationships of mass, stiffness, and damping in the preceding section assumed a single degree of freedom. In other words, movement was limited to a single plane. Therefore, the formulas are applicable for all single-degree-of-freedom mechanical systems.

The calculation for torque is a primary example of a single degree of freedom in a mechanical system. Figure 7–15 represents a disk with a moment of inertia, I, that is attached to a shaft of torsional stiffness, *k*.

Torsional stiffness is defined as the externally applied torque, T, in inch-pounds needed to turn the disk one radian (57.3 degrees). Torque can be represented by the following equations:

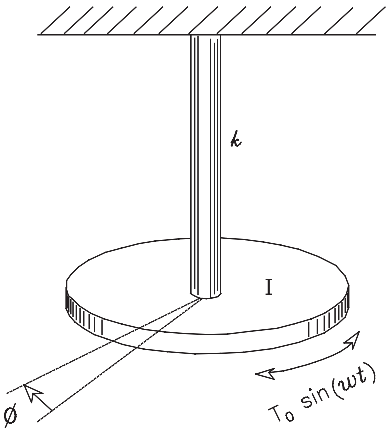


Figure 7–15 Torsional one-degree-of-freedom system.

$$\sum \text{Torque} = \text{Moment of intertia} \times \text{angular acceleration} = I\frac{d^2\phi}{dt^2} = I\ddot{\phi}$$

In this example, three torques are acting on the disk: the spring torque, the damping torque (caused by the viscosity of the air), and the external torque. The spring torque is minus (–) $k\phi$ where ϕ is measured in radians. The damping torque is minus (–) $c\phi$, where "c" is the damping constant. In this example, "c" is the damping torque on the disk caused by an angular speed of rotation of one radian per second. The external torque is T_0 sin (ωt).

$$I\ddot{\phi} = \sum Torque = -c\dot{\phi} - k\phi + T_0 \sin(\omega t)$$

or

$$I\ddot{\phi} + c\dot{\phi} + k\phi = T_0 \sin(\omega t)$$

Two Degrees of Freedom

The theory for a one-degree-of-freedom system is useful for determining resonant or natural frequencies that occur in all machine-trains and process systems; however, few machines have only one degree of freedom. Practically, most machines will have two or more degrees of freedom. This section provides a brief overview of the theories associated with two degrees of freedom. An undamped two-degree-of-freedom system is illustrated in Figure 7–16.

This diagram consists of two masses, M_1 and M_2, that are suspended from springs, K_1 and K_2. The two masses are tied together, or coupled, by spring, K_3, so that they are

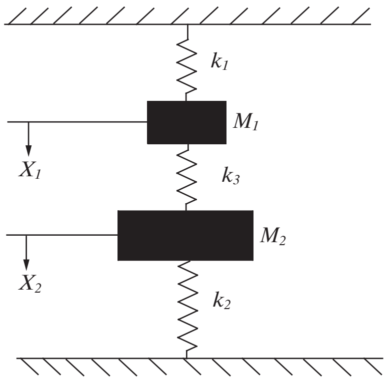


Figure 7–16 Undamped two-degrees-of-freedom system with a spring couple.

forced to act together. In this example, the movement of the two masses is limited to the vertical plane and, therefore, horizontal movement can be ignored. As in the single-degree-of-freedom examples, the absolute position of each mass is defined by its vertical position above or below the neutral, or reference, point. Because there are two coupled masses, two locations (i.e., one for M_1 and one for M_2) are required to locate the absolute position of the system.

To calculate the free or natural modes of vibration, note that two distinct forces are acting on mass, M_1: the force of the main spring, K_1, and that of the coupling spring, K_3. The main force acts upward and is defined as $-K_1X_1$. The shortening of the coupling spring is equal to the difference in the vertical position of the two masses, $X_1 - X_2$. Therefore, the compressive force of the coupling spring is $K_3(X_1 - X_2)$. The compressed coupling spring pushes the top mass, M_1, upward so that the force is negative.

Because these are the only tangible forces acting on M_1, the equation of motion for the top mass can be written as:

$$\frac{M_1}{g_c}\ddot{X}_1 = -K_1X_1 - K_3(X_1 - X_2)$$

or

$$\frac{M_1}{g_c}\ddot{X}_1 + (K_1 + K_3)X_1 - K_3X_2 = 0$$

The equation of motion for the second mass, M_2, is derived in the same manner. To make it easier to understand, turn the figure upside down and reverse the direction of X_1 and X_2. The equation then becomes:

$$\frac{M_2}{g_c}\ddot{X}_2 = -K_2 X_2 + K_3(X_1 - X_2)$$

or

$$\frac{M_2}{g_c}\ddot{X}_2 + (K_2 + K_3)X_2 - K_3 X_1 = 0$$

If we assume that the masses, M_1 and M_2, undergo harmonic motions with the same frequency, ω, and with different amplitudes, A_1 and A_2, their behavior can be represented as:

$$X_1 = A_1 \sin(\omega t)$$
$$X_2 = A_2 \sin(\omega t)$$

By substituting these into the differential equations, two equations for the amplitude ratio, $\frac{A_1}{A_2}$, can be found:

$$\frac{A_1}{A_2} = \frac{-K_3}{\frac{M_1}{g_c}\omega^2 - K_1 - K_3}$$

and

$$\frac{A_1}{A_2} = \frac{\frac{M_2}{g_c}\omega^2 - K_2 - K_3}{-K_3}$$

For a solution of the form we assumed to exist, these two equations must be equal:

$$\frac{-K_3}{\frac{M_1}{g_c}\omega^2 - K_1 - K_3} = \frac{\frac{M_2}{g_c}\omega^2 - K_2 - K_3}{-K_3}$$

or

$$\omega^4 - \omega^2\left\{\frac{K_1 + K_3}{M_1/g_c} + \frac{K_2 + K_3}{M_2/g_c}\right\} + \frac{K_1K_2 + K_2K_3 + K_1K_3}{\frac{M_1M_2}{g_c^2}} = 0$$

This equation, known as the *frequency equation*, has two solutions for ω^2. When substituted in either of the preceding equations, each one of these gives a definite value for $\frac{A_1}{A_2}$. This means that there are two solutions for this example, which are of the form $A_1 \sin(\omega t)$ and $A_2 \sin(\omega t)$. As with many such problems, the final answer is the superposition of the two solutions with the final amplitudes and frequencies determined by the boundary conditions.

Many Degrees of Freedom

When the number of degrees of freedom becomes greater than two, no critical new parameters enter into the problem. The dynamics of all machines can be understood by following the rules and guidelines established in the one- and two-degree(s)-of-freedom equations. There are as many natural frequencies and modes of motion as there are degrees of freedom.

7.6 Vibration Data Types and Formats

There are several options regarding the types of vibration data that can be gathered for machine-trains and systems and the formats in which the data can be collected. Selection of type and format depends on the specific application. There are two major data-type classifications: time-domain and frequency-domain. Each of these can be further divided into steady-state and dynamic data formats. In turn, each of these two formats can be further divided into single-channel and multichannel.

7.6.1 Data Types

Vibration profiles can be acquired and displayed in one of two data types: time-domain or frequency-domain.

Time-Domain

Most of the early vibration analysis was carried out using analog equipment, which necessitated the use of time-domain data, because it was difficult to convert time-domain data to frequency-domain data. Therefore, frequency-domain capability was not available until microprocessor-based analyzers incorporated a straightforward method (i.e., Fast Fourier Transform, FFT) of transforming the time-domain spectrum into its frequency components.

Actual time-domain vibration signatures are commonly referred to as *time traces* or *time plots* (see Figure 7–17). Theoretical vibration data are generally referred to as *waveforms* (see Figure 7–18).

Time-domain data are presented with amplitude as the vertical axis and elapsed time as the horizontal axis. Time-domain profiles are the sum of all vibration components (i.e., frequencies, impacts, and other transients) that are present in the machine-train and its installed system. Time traces include all frequency components,

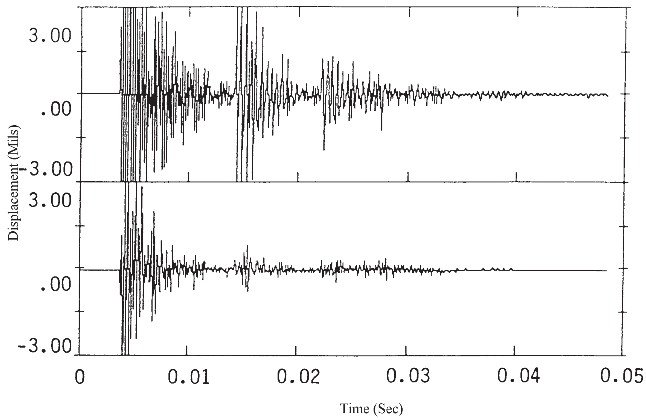


Figure 7–17 Typical time-domain signature.

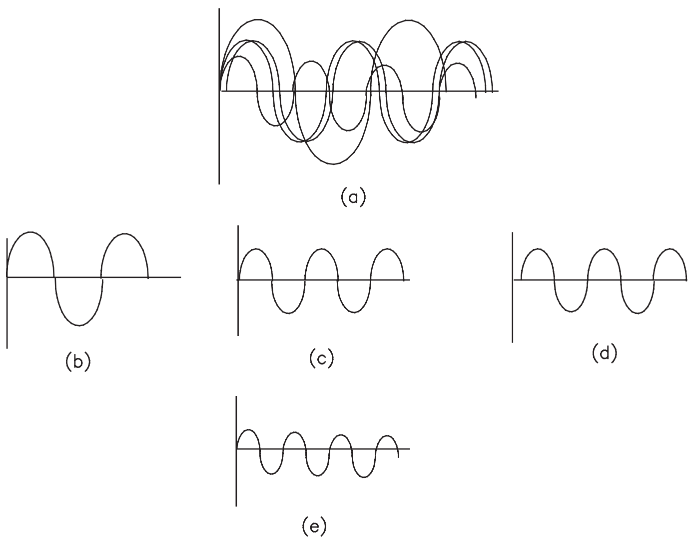


Figure 7–18 Theoretical time-domain waveforms.

but the individual components are more difficult to isolate than with frequency-domain data.

The profile shown in Figure 7–17 illustrates two different data acquisition points, one measured vertically and one measured horizontally, on the same machine and taken at the same time. Because they were obtained concurrently, these data points can be compared to determine the operating dynamics of the machine.

In this example, the data set contains an impact that occurred at 0.005 seconds. The impact is clearly visible in both the vertical (top) and horizontal (bottom) data set.

From these time traces, the vertical impact appears to be stronger than the horizontal. In addition, the impact repeated at 0.015 and 0.025 seconds. Two conclusions can be derived from this example: (1) the impact source is a vertical force, and (2) it impacts the machine-train at an interval of 0.010 seconds, or frequency of 1/0.010 seconds equals 100 Hz.

The waveform in Figure 7–18 illustrates theoretically the unique frequencies and transients that may be present in a machine's signature. Figure 7–18a illustrates the complexity of such a waveform by overlaying numerous frequencies. The discrete waveforms that make up Figure 7–18a are displayed individually in Figures 7–18b through 7–18e. Note that two of the frequencies (c and d) are identical but have a different phase angle (ϕ).

With time-domain data, the analyst must manually separate the individual frequencies and events that are contained in the complex waveform. This effort is complicated tremendously by the superposition of multiple frequencies. Note that, rather than overlaying each of the discrete frequencies as illustrated theoretically in Figure 7–18a, actual time-domain data represents the sum of these frequencies as was illustrated in Figure 7–17.

In order to analyze this type of plot, the analyst must manually change the time scale to obtain discrete frequency curve data. The time interval between the recurrences of each frequency can then be measured. In this way, it is possible to isolate each of the frequencies that make up the time-domain vibration signature.

For routine monitoring of machine vibration, however, this approach is not cost effective. The time required to manually isolate each of the frequency components and transient events contained in the waveform is prohibitive; however, time-domain data have a definite use in a total-plant predictive maintenance or reliability improvement program.

Machine-trains or process systems that have specific timing events (e.g., a pneumatic or hydraulic cylinder) must be analyzed using the time-domain data format. In addition, time-domain data must be used for linear and reciprocating motion machinery.

Frequency-Domain

Most rotating machine-train failures result at or near a frequency component associated with the running speed. Therefore, the ability to display and analyze the vibration spectrum as components of frequency is extremely important.

The frequency-domain format eliminates the manual effort required to isolate the components that make up a time trace. Frequency-domain techniques convert time-domain data into discrete frequency components using a mathematical process called Fast Fourier Transform (FFT). Simply stated, FFT mathematically converts a time-based

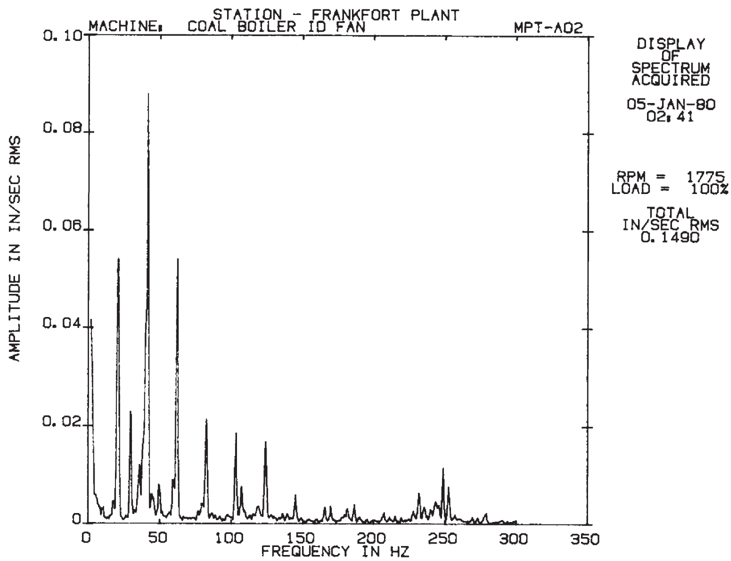


Figure 7–19 Typical frequency-domain signature.

trace into a series of discrete frequency components (see Figure 7–19). In a frequency-domain plot, the X-axis is frequency and the Y-axis is the amplitude of displacement, velocity, or acceleration.

With frequency-domain analysis, the average spectrum for a machine-train signature can be obtained. Recurring peaks can be normalized to present an accurate representation of the machine-train condition. Figure 7–20 illustrates a simplified relationship between time-domain and frequency-domain analysis.

The real advantage of frequency-domain analysis is the ability to normalize each vibration component so that a complex machine-train spectrum can be divided into discrete components. This ability simplifies isolation and analysis of mechanical degradation within the machine-train.

In addition, frequency-domain analysis can be used to determine the phase relationships for harmonic vibration components in a typical machine-train spectrum. Frequency-domain normalizes any or all running speeds, where time-domain analysis is limited to true running speed.

Mathematical theory shows that any periodic function of time, $f(t)$, can be represented as a series of sine functions having frequencies ω, 2ω, 3ω, 4ω, and so on. Function $f(t)$ is represented by the following equation, which is referred to as a Fourier Series:

$$f(t) = A_0 + A_1 \sin(\omega t + \phi_1) + A_2 \sin(2\omega t + \phi_2) + A_3 \sin(3\omega t + \phi_3) + \ldots$$

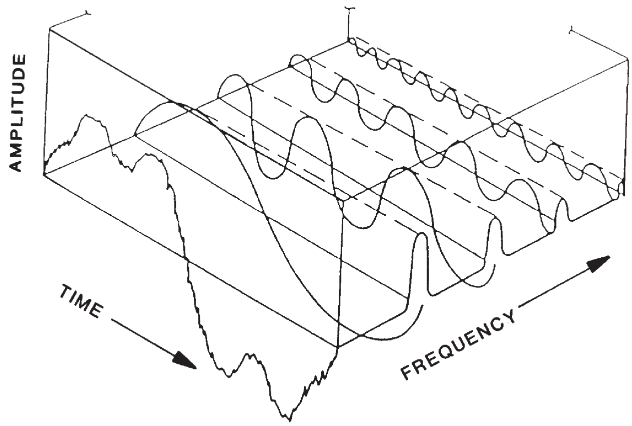


Figure 7–20 Relationship between time-domain and frequency-domain.

where:

A_x = Amplitude of each discrete sine wave

ωt = Frequency

ϕ_x = Phase angle of each discrete sine wave

Each of these sine functions represents a discrete component of the vibration signature discussed previously. The amplitudes of each discrete component and their phase angles can be determined by integral calculus when the function $f(t)$ is known. Because the subject of integral calculus is beyond the scope of this book, the math required to determine these integrals is not presented. A vibration analyzer and its associated software perform this determination using FFT.

7.6.2 Data Formats

Both time-domain and frequency-domain vibration data can be acquired and analyzed in two primary formats: steady-state or dynamic. Each of these formats has strengths and weaknesses that must be clearly understood for proper use. In addition, each of these formats can be obtained as single- or multichannel data.

Steady-State

Most vibration programs that use microprocessor-based analyzers are limited to steady-state data. Steady-state vibration data assumes that the machine-train or process system operates in a constant, or steady-state, condition. In other words, the machine is free of dynamic variables such as load, flow, and so on. This approach further assumes that all vibration frequencies are repeatable and maintain a constant relationship to the rotating speed of the machine's shaft.

Steady-state analysis techniques are based on acquiring vibration data when the machine or process system is operating at a fixed speed and specific operating parameters. For example, a variable-speed machine-train is evaluated at constant speed rather than over its speed range.

Steady-state analysis can be compared to a still photograph of the vibration profile generated by a machine or process system. Snapshots of the vibration profile are acquired by the vibration analyzer and stored for analysis. The snapshots can be used to evaluate the relative operating condition of simple machine-trains, but they do not provide a true picture of the dynamics of either the machine or its vibration profile.

Steady-state analysis totally ignores variations in the vibration level or vibration generated by transient events such as impacts and changes in speed or process parameters. Instruments used to obtain the profiles contain electronic circuitry, which are specifically designed to eliminate transient data.

In the normal acquisition process, the analyzer acquires multiple blocks of data. As part of the process, the microprocessor compares each data block as it is acquired. If a block contains a transient that is not included in subsequent blocks, the block containing the event is discarded and replaced with a transient-free block. As a result, steady-state analysis does not detect random events that may have a direct, negative effect on equipment reliability.

Dynamic

While steady-state data provides a snapshot of the machine, dynamic or real-time data provide a motion picture. This approach provides a better picture of the dynamics of both the machine-train and its vibration profile. Data acquired using steady-state methods would suggest that vibration profiles and amplitudes are constant, but this is not true. All dynamic forces, including running speed, vary constantly in all machine-trains. When real-time data acquisition methods are used, these variations are captured and displayed for analysis.

Single-Channel

Most microprocessor-based vibration-monitoring programs rely on single-channel vibration data format. Single-channel data acquisition and analysis techniques are acceptable for routine monitoring of simple, rotating machinery; however, it is important that single-channel analysis be augmented with multichannel and dynamic analysis. Total reliance on single-channel techniques severely limits the accuracy of analysis and the effectiveness of a predictive maintenance or reliability improvement program.

With the single-channel method, data are acquired in series or one channel at a time. Normally, a series of data points is established for each machine-train and data are acquired from each point in a measurement route. Although this approach is more than adequate for routine monitoring of relatively simple machines, it is based on the assumption that the machine's dynamics and the resultant vibration profile are constant throughout the entire data acquisition process. This approach hinders the ability to evaluate real-time relationships between measurement points on the machine-train and variations in process parameters such as speed, load, pressure, and so on.

Multichannel

Multichannel data provide the best picture of the relationship between measurement points on a machine-train. Data are acquired simultaneously from all measurement points on the machine-train. With this type of data, the analyst can establish the relationship between machine dynamics and vibration profile of the entire machine.

In most cases, a digital tape recorder is used to acquire data from the machine. Because all measurement points are recorded at the same time, the resultant data can be used to compare the tri-axial vibration profile of all measurement points. This capability greatly enhances the analyst's ability to isolate abnormal machine dynamics and to determine the root-cause of deviations.

7.7 Data Acquisition

It is important for predictive maintenance programs using vibration analysis to have accurate, repeatable data. In addition to the type and quality of the transducer, three key parameters affect data quality: the point of measurement, orientation, and transducer-mounting techniques.

In a predictive and reliability maintenance program, it is extremely important to keep good historical records of key parameters. How measurement point locations and orientation to the machine's shaft were selected should be kept as part of the database. It is important that every measurement taken throughout the life of the maintenance program be acquired at exactly the same point and orientation. In addition, the compressive load, or downward force, applied to the transducer should be exactly the same for each measurement.

7.7.1 Vibration Detectors: Transducers and Cables

A variety of monitoring, trending, and analysis techniques that can and should be used as part of a total-plant vibration-monitoring program. Initially, such a program depends on the use of historical trends to detect incipient problems. As the program matures, however, other techniques such as frequency-domain signature analysis, time-domain analysis, and operating dynamics analysis are typically added.

An analysis is only as good as the data; therefore, the equipment used to collect the data is critical and determines the success or failure of a predictive maintenance or reliability improvement program. The accuracy as well as proper use and mounting determine whether valid data are collected.

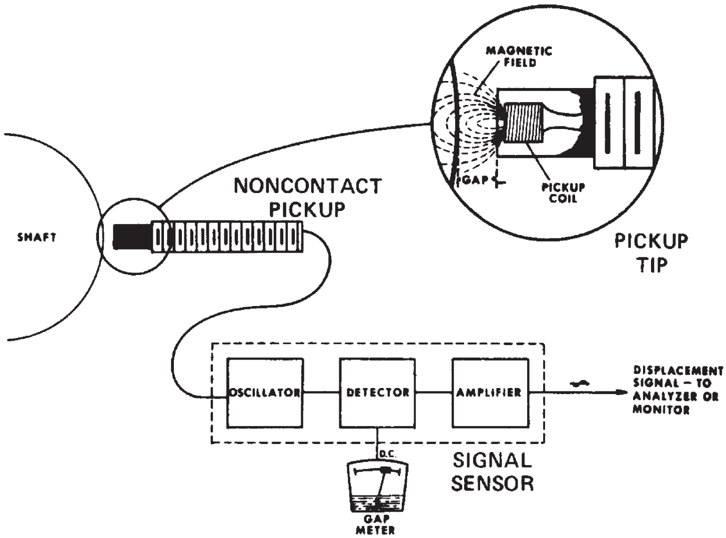


Figure 7–21 Displacement probe and signal conditioning system.

Three basic types of vibration transducers can be used for monitoring the mechanical condition of plant machinery: displacement probes, velocity transducers, and accelerometers. Each has limitations and specific applications for which its use is appropriate.

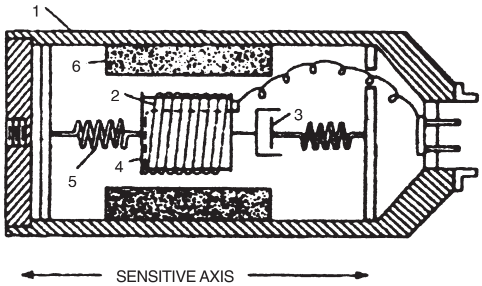
Displacement Probes

Displacement, or eddy-current, probes are designed to measure the actual movement, or displacement, of a machine's shaft relative to the probe. Data are normally recorded as peak-to-peak in mils, or thousandths of an inch. This value represents the maximum deflection or displacement from the true centerline of a machine's shaft. Such a device must be rigidly mounted to a stationary structure to obtain accurate, repeatable data. See Figure 7–21 for an illustration of a displacement probe and signal conditioning system.

Permanently mounted displacement probes provide the most accurate data on machines with a rotor weight that is low relative to the casing and support structure. Turbines, large compressors, and other types of plant equipment should have displacement transducers permanently mounted at key measurement locations.

The useful frequency range for displacement probes is from 10 to 1,000 Hz, or 600 to 60,000 rpm. Frequency components above or below this range are distorted and, therefore, unreliable for determining machine condition.

The major limitation with displacement or proximity probes is cost. The typical cost for installing a single probe, including a power supply, signal conditioning, and so on,



(1) Pickup case (2) Wire out (3) Damper (4) Mass (5) Spring (6) Magnet

Figure 7–22 Schematic diagram of velocity pickup.

averages $1,000. If each machine to be evaluated requires 10 measurements, the cost per machine is about $10,000. Using displacement transducers for all plant machinery dramatically increases the initial cost of the program. Therefore, key locations are generally instrumented first, and other measurement points are added later.

Velocity Transducers

Velocity transducers are electromechanical sensors designed to monitor casing, or relative, vibration. Unlike displacement probes, velocity transducers measure the rate of displacement rather than the distance of movement. Velocity is normally expressed in terms of inches per second (ips) peak, which is perhaps the best method of expressing the energy caused by machine vibration. Figure 7–22 is a schematic diagram of a velocity measurement device.

Like displacement probes, velocity transducers have an effective frequency range of about 10 to 1,000 Hz. They should not be used to monitor frequencies above or below this range.

The major limitation of velocity transducers is their sensitivity to mechanical and thermal damage. Normal use can cause a loss of calibration; therefore, a strict recalibration program is required to prevent data errors. At a minimum, velocity transducers should be recalibrated every six months. Even with periodic recalibration, however, velocity transducers are prone to distorting data as a result of loss of calibration.

Accelerometers

Acceleration is perhaps the best method of determining the force resulting from machine vibration. Accelerometers use piezoelectric crystals or films to convert mechanical energy into electrical signals. Figure 7–23 is a schematic of such a device. Data acquired with this type of transducer are relative acceleration expressed in terms of the gravitational constant, g, in inches/second/second.

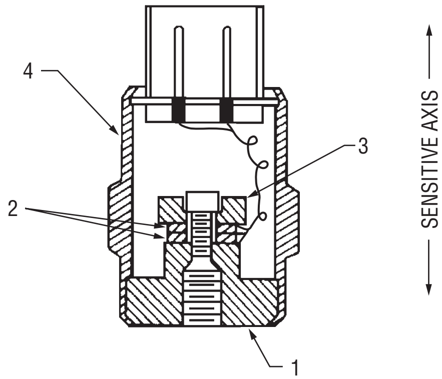


Figure 7–23 Schematic diagram of accelerometer. (1) Base, (2) Piezoelectric crystals, (3) Mass, (4) Case.

The effective range of general-purpose accelerometers is from about 1 Hz to 10,000 Hz. Ultrasonic accelerometers are available for frequencies up to 1 MHz. In general, vibration data above 1,000 Hz, or 60,000 cpm, should be taken and analyzed in acceleration or g's.

A benefit of the use of accelerometers is that they do not require a calibration program to ensure accuracy; however, they are susceptible to thermal damage. If sufficient heat radiates into the piezoelectric crystal, it can be damaged or destroyed, but thermal damage is rare because data acquisition time is relatively short (less than 30 seconds) using temporary mounting techniques.

Cables

Most portable vibration data collectors use a coiled cable to connect to the transducer (see Figure 7–24). The cable, much like a telephone cord, provides a relatively compact length when relaxed but will extend to reach distant measurement points. For general use, this type of cable is acceptable, but it cannot be used for all applications.

The coiled cable is not acceptable for low-speed (less than 300 rpm) applications or when there is a strong electromagnetic field. Because of its natural tendency to return to its relaxed length, the coiled cable generates a low-level frequency that corresponds to the oscillation rate of the cable. In low-speed applications, this oscillation frequency can mask real vibration that is generated by the machine. A strong electromagnetic field, such as that generated by large mill motors, accelerates cable oscillation. In these instances, the vibration generated by the cable will mask real machine vibration.

In these and other applications where the coiled cable distorts or interferes with the accuracy of acquired data, a shielded coaxial cable should be used. Although these

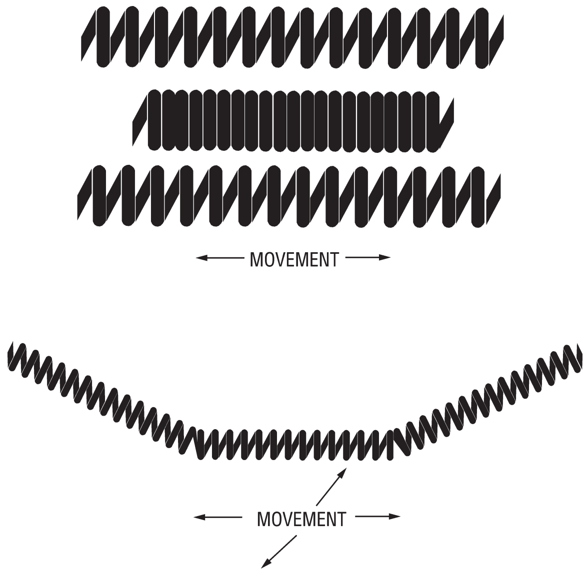


Figure 7–24 Types of coiled cables.

noncoiled cables can be more difficult to use in conjunction with a portable analyzer, they are essential for low-speed and electromagnetic field applications.

7.7.2 Data Measurements

Most vibration-monitoring programs rely on data acquired from the machine housing or bearing caps. The only exceptions are applications that require direct measurement of actual shaft displacement to obtain an accurate picture of the machine's dynamics. This section discusses the number and orientation of measurement points required to profile a machine's vibration characteristics.

The fact that both normal and abnormal machine dynamics tend to generate unbalanced forces in one or more directions increases the analyst's ability to determine the root-cause of deviations in the machine's operating condition. Therefore, measurements should be taken in both radial and axial orientations.

Radial Orientation

Radially oriented measurements permit the analyst to understand the relationship of vibration levels generated by machine components where the forces are perpendicular to the shaft's centerline. For example, mechanical imbalance generates radial forces in all directions, but misalignment generally results in a radial force in a single direction that corresponds with the misaligned direction. The ability to determine the actual displacement direction of the machine's shaft and other components greatly improves diagnostic accuracy.

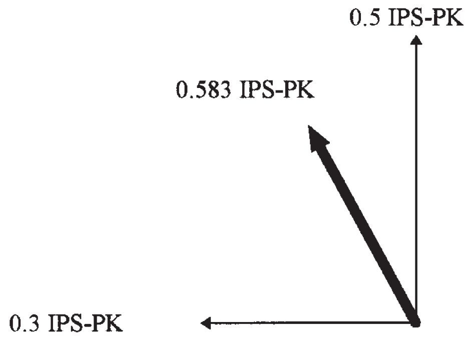


Figure 7–25 Resultant shaft velocity vector based on radial vibration measurements.

Two radial measurement points located 90 degrees apart are required at each bearing cap. The two points permit the analyst to calculate the actual direction and relative amplitude of any displacement that is present within the machine.

Figure 7–25 illustrates a simple vector analysis where the vertical and horizontal radial readings acquired from the outboard bearing cap indicate a relative vertical vibration velocity of 0.5 inches per second peak (IPS-PK) and a horizontal vibration velocity of 0.3 IPS-PK. Using simple geometry, the amplitude of vibration velocity (0.583 IPS-PK) in the actual direction of deflection can be calculated.

Axial Orientation

Axially oriented measurements are used to determine the lateral movement of a machine's shaft or dynamic mass. These measurement points are oriented in-line or parallel with the shaft or direction of movement.

At least one axial measurement is required for each shaft or dynamic movement. In the case of shafts with a combination of float and fixed bearings, readings should be taken from the fixed or stationary bearing to obtain the best data.

7.7.3 Transducer Mounting Techniques

For accuracy of data, a direct mechanical link between the transducer and the machine's casing or bearing cap is necessary. This makes the method used to mount the transducer crucial to obtaining accurate data. Slight deviations in this link will induce errors in the amplitude of vibration measurement and may create false frequency components that have nothing to do with the machine.

Permanent

The best method of ensuring that the point of measurement, its orientation, and the compressive load are exactly the same each time is to permanently or hard mount the

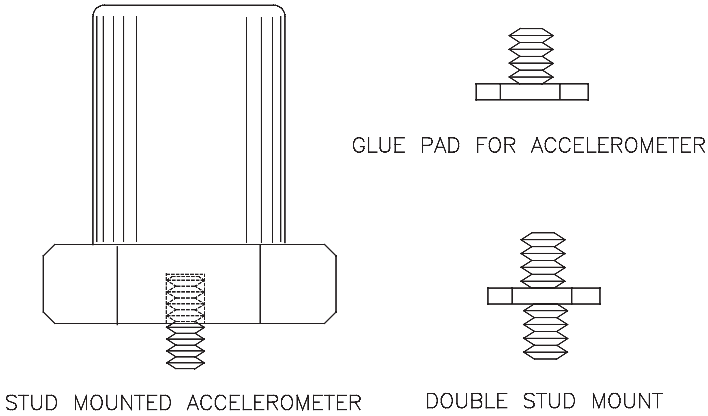


Figure 7–26 Permanent mounts provide best repeatability.

transducers, which is illustrated in Figure 7–26. This method guarantees accuracy and repeatability of acquired data, but it also increases the initial program cost. The average cost of installing a general-purpose accelerometer is about $300 per measurement point or $3,000 for a typical machine-train.

Quick Disconnect

To eliminate the capital cost associated with permanently mounting transducers, a well-designed quick-disconnect mounting can be used instead. With this technique, a quick-disconnect stud with an average cost of less than $5 is permanently mounted at each measurement point. A mating sleeve built into the transducer is used to connect with the stud. A well-designed quick-disconnect mounting technique provides almost the same accuracy and repeatability as the permanent mounting technique, but at a much lower cost.

Magnets

For general-purpose use below 1,000 Hz, a transducer can be attached to a machine by a magnetic base. Even though the resonant frequency of the transducer/magnet assembly may distort the data, this technique can be used with some success. Because the magnet can be placed anywhere on the machine, however, it is difficult to guarantee that the exact location and orientation is maintained with each measurement. Figure 7–27 shows common magnetic mounts for transducers.

Handheld

Another method used by some plants to acquire data is handheld transducers. This approach is not recommended if it is possible to use any other method. Handheld transducers do not provide the accuracy and repeatability required to gain

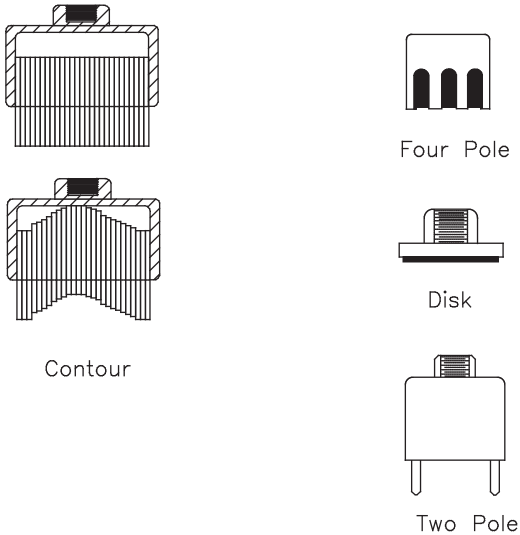
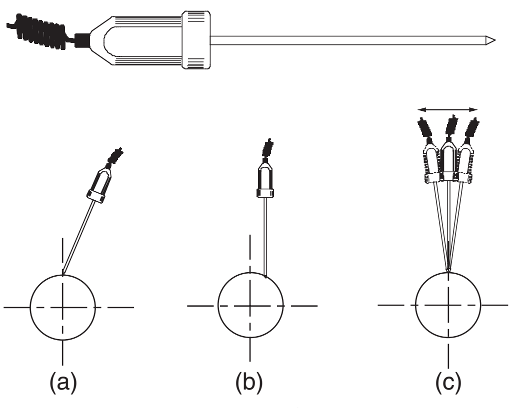


Figure 7–27 Common magnetic mounts for transducers.



a. Orientation is not 90° to shaft centerline.
b. Measurement-point location is not always consistent.
c. Compressive load varies and may induce faulty readings.

Figure 7–28 Handheld transducers should be avoided when possible.

maximum benefit from a predictive maintenance program. If this technique must be used, extreme care should be exercised to ensure that the same location, orientation, and compressive load are used for every measurement. Figure 7–28 illustrates a handheld device.

7.7.4 Acquiring Data

Three factors must be considered when acquiring vibration data: settling time, data verification, and additional data that may be required.

Settling Time

All vibration transducers require a power source that is used to convert mechanical motion or force to an electronic signal. In microprocessor-based analyzers, this power source is usually internal to the analyzer. When displacement probes are used, an external power source must be provided.

When the power source is turned on, there is a momentary surge of power into the transducer. This surge distorts the vibration profile generated by the machine. Therefore, the data acquisition sequence must include a time delay between powering up and acquiring data. The time delay will vary based on the specific transducer used and type of power source.

Some vibration analyzers include a user-selected time delay that can automatically be downloaded as part of the measurement route. If this feature is included, the delay can be preprogrammed for the specific transducer that will be used to acquire data. No further adjustment is required until the transducer type is changed.

In addition to the momentary surge created by energizing the power source, the mechanical action of placing the transducer on the machine creates a spike of energy that may distort the vibration profile. Therefore, the actual data acquisition sequence should include a 10- to 20-second delay to permit decay of the spike created by mounting the transducer.

Data Verification

Several equipment problems can result in bad or distorted data. In addition to the surge and spike discussed in the preceding section, damaged cables, transducers, power supplies, and other equipment failures can cause serious problems. Therefore, it is essential to verify all data throughout the acquisition process.

Most of the microprocessor-based vibration analyzers include features that facilitate verification of acquired data. For example, many include a low-level alert that automatically alerts the technician when acquired vibration levels are below a preselected limit. If these limits are properly set, the alert should be sufficient to detect this form of bad data.

Unfortunately, not all distortions of acquired data result in a low-level alert. Damaged or defective cables or transducers can result in a high level of low-frequency vibration. As a result, the low-level alert will not detect this form of bad data; however, the vibration signature will clearly display the abnormal profile that is associated with these problems.

In most cases, a defective cable or transducer generates a signature that contains a ski-slope profile, which begins at the lowest visible frequency and drops rapidly to the noise floor of the signature. If this profile is generated by defective components, it will not contain any of the normal rotational frequencies generated by the machine-train.

With the exception of mechanical rub, defective cables and transducers are the only sources of this ski-slope profile. When mechanical rub is present, the ski slope will also contain the normal rotational frequencies generated by the machine-train. In some cases, it is necessary to turn off the auto-scale function in order to see the rotational frequencies, but they will be evident. If no rotational components are present, the cable and transducer should be replaced.

Additional Data

Data obtained from a vibration analyzer are not all that are required to evaluate machine-train or system condition. Variables, such as load, have a direct effect on the vibration profile of machinery and must be considered. Therefore, additional data should be acquired to augment the vibration profiles.

Most microprocessor-based vibration analyzers are capable of directly acquiring process variables and other inputs. The software and firmware provided with these systems generally support preprogrammed routes that include almost any direct or manual data input. These routes should include all data required to effectively analyze the operating condition of each machine-train and its process system.

7.8 Vibration Analyses Techniques

Techniques used in vibration analysis are trending, both broadband and narrowband; comparative analysis; and signature analysis.

7.8.1 Trending

Most vibration-monitoring programs rely heavily on historical vibration-level amplitude trends as their dominant analysis tool. This approach is valid if the vibration data are normalized to remove the influence of variables, such as load, on the recorded vibration energy levels. Valid trend data provide an indication of change over time within the monitored machine. As stated in preceding sections, a change in vibration amplitude indicates a corresponding change in operating condition that can be a useful diagnostic tool.

Broadband

Broadband analysis techniques have been used to monitor the overall mechanical condition of machinery for more than 20 years. The technique is based on the overall vibration or energy from a frequency range of zero to the user-selected maximum frequency, $F_{MAX.}$ Broadband data are overall vibration measurements expressed in units such as velocity-PK, acceleration-RMS, and so on. This type of data, however, does not provide any indication of the specific frequency components that make up the machine's vibration signature. As a result, specific machine-train problems cannot be isolated and identified.

The only useful function of broadband analysis is long-term trending of the gross overall condition of machinery. Typically, sets of alert/alarm limits are established to monitor the overall condition of the machine-trains in a predictive maintenance program; however, this approach has limited value and, when used exclusively, severely limits the ability to achieve the full benefit of a comprehensive program.

Narrowband

Like broadband analysis, narrowband analysis also monitors the overall energy, but for a user-selected band of frequency components. The ability to select specific groups of frequencies, or narrowbands, increases the usefulness of the data. Using this technique can drastically reduce the labor required to monitor machine-trains and improve the accuracy of detecting incipient problems.

Unlike broadband data, narrowband data provide the ability to directly monitor, trend, and alarm specific machine-train components automatically by using a microprocessor for a window of frequencies unique to specific machine components. For example, a narrowband window can be established to directly monitor the energy of a gear set that consists of the primary gear-mesh frequency and corresponding sidebands.

7.8.2 Comparative Analysis

Comparative analysis directly compares two or more data sets in order to detect changes in the operating condition of mechanical or process systems. This type of analysis is limited to the direct comparison of the time-domain or frequency-domain signature generated by a machine. The method does not determine the actual dynamics of the system. Typically, the following data are used for this purpose: baseline data, known machine condition, or industrial reference data.

Note that great care must be taken when comparing machinery vibration data to industry standards or baseline data. The analyst must make sure the frequency and amplitude are expressed in units and running speeds that are consistent with the standard or baseline data. The use of a microprocessor-based system with software that automatically converts and displays the desired terms solves this problem.

Baseline Data

Reference or baseline data sets should be acquired for each machine-train or process system to be included in a predictive maintenance program when the machine is installed or after the first scheduled maintenance once the program is established. These data sets can be used as a reference or comparison data set for all future measurements; however, such data sets must represent the normal operating condition of each machine-train. Three criteria are critical to the proper use of baseline comparisons: reset after maintenance, proper identification, and process envelope.

Reset After Maintenance. The baseline data set must be updated each time the machine is repaired, rebuilt, or major maintenance is performed. Even when best practices are used, machinery cannot be restored to as-new condition when major maintenance is performed. Therefore, a new baseline or reference data set must be established following these events.

Proper Identification. Each reference or baseline data set must be clearly and completely identified. Most vibration-monitoring systems permit adding a label or unique identifier to any user-selected data set. This capability should be used to clearly identify each baseline data set. In addition, the data-set label should include all information that defines the data set. For example, any rework or repairs made to the machine should be identified. If a new baseline data set is selected after replacing a rotating element, this information should be included in the descriptive label.

Process Envelope. Because variations in process variables, such as load, have a direct effect on the vibration energy and the resulting signature generated by a machine-train, the actual operating envelope for each baseline data set must also be clearly identified. If this step is omitted, direct comparison of other data to the baseline will be meaningless. The label feature in most vibration-monitoring systems permits tagging the baseline data set with this additional information.

Known Machine Condition

Most microprocessor-based analyzers permit direct comparison to two machine-trains or components. The form of direct comparison, called *cross-machine comparison*, can be used to identify some types of failure modes.

When using this type of comparative analysis, the analyst compares the vibration energy and profile from a suspect machine to that of a machine with a known operating condition. For example, the suspect machine can be compared to the baseline reference taken from a similar machine within the plant. Or, a machine profile with a known defect, such as a defective gear, can be used as a reference to determine if the suspect machine has a similar profile and, therefore, a similar problem.

Industrial Reference Data

One form of comparative analysis is direct comparison of the acquired data to industrial standards or reference values. The International Standards Organization (ISO) established the vibration-severity standards presented in Table 7–2. These data are applicable for comparison with filtered narrowband data taken from machine-trains

Table 7–2 Vibration-Severity Standards

(Inches/Second-Peak)

	Machine Classes			
Condition	**I**	**II**	**III**	**IV**
Good Operating Condition	0.028	0.042	0.100	0.156
Alert Limit	0.010	0.156	0.255	0.396
Alarm Limit	0.156	0.396	0.396	0.622
Absolute Fault Limit	0.260	0.400	0.620	1.000

* Applicable to a machine with running speed between 600 to 12,000 rpm.
Narrowband setting: 0.3× to 3.0× running speed.
Machine Class Descriptions:

Class I Small machine-trains or individual components integrally connected with the complete machine in its normal operating condition (i.e., drivers up to 20 horsepower).
Class II Medium-sized machines (i.e., 20- to 100-horsepower drivers and 400-horsepower drivers on special foundations.
Class III Large prime movers (i.e., drivers greater than 100 horsepower) mounted on heavy, rigid foundations.
Class IV Large prime movers (i.e., drivers greater than 100 horsepower) mounted on relatively soft, light-weight structures.

Source: Derived by Integrated Systems, Inc. from ISO Standard #2372.

with true running speeds between 600 and 12,000 rpm. The values from the table include all vibration energy between a lower limit of 0.3× true running speed and an upper limit of 3.0×. For example, an 1,800-rpm machine would have a filtered narrowband between 540 (1,800 × 0.3) and 5,400 rpm (1,800 × 3.0). A 3,600-rpm machine would have a filtered narrowband between 1,080 (3,600 × 0.3) and 10,800 rpm (3,600 × 3.0).

7.8.3 Signature Analysis

The phrase "full Fast Fourier Transform (FFT) signature" is usually applied to the vibration spectrum that uniquely identifies a machine, component, system, or subsystem at a specific operating condition and time. It provides specific data on every frequency component within the overall frequency range of a machine-train. The typical frequency range can be from 0.1 to 30,000 Hz.

In microprocessor systems, the FFT signature is formed by breaking down the total frequency spectrum into unique components, or peaks. Each line or peak represents a specific frequency component that, in turn, represents one or more mechanical components within the machine-train. Typical microprocessor-based predictive maintenance systems can provide signature resolutions of at least 400 lines, and many provide 12,800 lines or more.

Full-signature spectra are an important analysis tool, but they require a tremendous amount of microprocessor memory. It is impractical to collect full, high-resolution spectra on all machine-trains on a routine basis. Data management and storage in the host computer is extremely difficult and costly. Full-range signatures should be collected only if a confirmed problem has been identified on a specific machine-train. This can be triggered automatically by exceeding a preset alarm limit in the historical amplitude trends.

Broadband and Full Signature

Systems that use either broadband or full-signature measurements have limitations that may hamper the program's usefulness. Broadband measurements usually do not have enough resolution at running speeds to be effective in early problem diagnostics. Full-signature measurement at every data point requires a massive data acquisition, handling, and storage system that greatly increases the capital and operating costs of the program.

Normally, a full-signature spectrum is needed only when an identified machine-train problem demands further investigation. Please note that although full signatures generate too much data for routine problem detection, they are essential for root-cause diagnostics. Therefore, the optimum system includes the capability to use all techniques. This ability optimizes the program's ability to trend, perform full root-cause failure analysis, and still maintain minimum data management and storage requirements.

Narrowband

Typically, a machine-train's vibration signature consists of vibration components with each component associated with one or more of the true running speeds within the machine-train. Because most machinery problems show up at or near one or more of the running speeds, the narrowband capability is beneficial in that high-resolution windows can be preset to monitor the running speeds; however, many of the microprocessor-based predictive maintenance systems available do not have narrowband capability. Therefore, care should be taken to ensure that the system used does have this capability.

Appendix 7.1 Abbreviations

A	Acceleration
A	Zero-to-peak amplitude
Cpm	Cycles per minute or cycles/minute
Cps	Cycles per second or cycles/second
e.g.,	For example
F	Frequency
$f(t)$	Function of time
F	Force
FFT	Fast Fourier Transform

F_{MAX}	Maximum frequency
F_{MIN}	Minimum frequency
F_0	External force
F_s	Spring force
G	Gravitational constant, 32.17 ft/sec^2
H	Elongation caused by the weight of the mass
Hz	Hertz
i.e.,	That is
in.	Inches
Ips	Inches per second or inches/second
ips-PK	Inches per second, zero-to-peak
K	Torsional stiffness
K	Spring constant or stiffness
Lbf	Pounds-force
Lbm	Pounds-mass
L_0	Unelongated spring length
M	Mass
MHz	Megahertz
PK	Zero-to-peak
RMS	Root-mean-square
Rpm	Revolutions per minute or revolutions/minute
sec^2	Seconds squared
T	Time
T	Period or Torque
T_0	External torque
VPM	Vibrations per minute or vibrations/minute
W	Weight
X	Displacement
X_i	Static displacement
X_0	Amount of displacement from X_i
1×, 2×, 3×	1 times, 2 times, 3 times

APPENDIX 7.2 Glossary

Acceleration The rate of change of velocity with respect to time (ft/sec^2) or (in/sec^2).

Accelerometer Transducer used to measure acceleration. Incorporates a piezoelectric crystal or film to convert mechanical energy into electrical signals.

Amplitude The magnitude or size of a quantity such as displacement, velocity, acceleration, etc., measured by a vibration analyzer in conjunction with a displacement probe, velocity transducer, or accelerometer.

Axial — Of, on, around, or along an axis (straight line about which an object rotates) or center of rotation.

Bearing cap — The protective structure that covers bearings.

Boundary condition — Mathematically defined as a requirement to be met by a solution to a set of differential equations on a specified set of values of the independent variables.

Displacement — The change in distance or position of an object relative to a reference point, usually measured in mils.

Dynamics, operating — Deals with the motion of a system under the influence of forces, especially those that originate outside the system under consideration.

Fast Fourier Transform (FFT) — A mathematical technique used to convert a time-domain plot into its unique frequency components.

Force — That influence on a body that causes it to accelerate. Quantitatively, it is a vector equal to the body's time rate of change of momentum.

Forcing function — The cause of each discrete frequency component in a machine-train's vibration signature.

Frequency — Frequency, f, is defined as the number of repetitions of a specific forcing function or vibration component over a specific unit of time. It is the inverse of the period, $\frac{1}{T}$, of the vibration and can be expressed in units of cycles per second (cps) or Hertz (Hz). For rotating machinery, the frequency is often expressed in vibrations per minute (vpm).

Frequency, circular — Another measure of frequency measured in radians ($\omega = 2\pi$ f).

Frequency, natural — All components have one or more natural frequencies that can be excited by an energy source that coincides with, or is in proximity to, that frequency. The result is a substantial increase in the amplitude of the natural frequency vibration component, which is referred to as *resonance*. Higher levels of input energy can cause catastrophic, near instantaneous failure of the machine or structure.

Frequency, primary The base frequency referred to in a vibration analysis that includes vibrations that are harmonics of the primary frequency.

Gravitational constant The constant of proportionality in the English system of units, g_c, which causes one pound of mass to produce one pound of force under the acceleration of gravity, equal to 32.17 lbm-ft/lbf-sec^2.

Harmonic motion A periodic motion or vibration that is a sinusoidal function of time, that is, motion along a line given by equation $x = a \cos(\omega t + \phi)$, where t is time, a and ω are constants, and ϕ is the phase angle. For example, $X = X_0 \sin(\omega t + \phi)$ where X is the displacement, X_0 is the amplitude, ω is the circular frequency, and ϕ is the phase angle.

Harmonics Multiples of the primary frequency (e.g., 2×, 3×).

Hertz Unit of frequency; a periodic oscillation has a frequency of *n* hertz if in one second it goes through *n* cycles.

Imbalance A condition that can result from a mechanical and/or a force imbalance. Mechanical imbalance is when there is more weight on one side of a centerline of a rotor than on the other. Force imbalance can result when there is an imbalance of the centripetal forces generated by rotation and/or when there is an imbalance between the lift generated by the rotor and gravity.

Machine element Rotating-machine components, such as rolling-element bearings, impellers, and other rotors, that turn with a shaft.

Machine-train A series of machines containing both driver and driven components.

Maintenance management program A comprehensive program that includes predictive maintenance techniques to monitor and analyze critical machines, equipment,

	and systems in a typical plant. Techniques include vibration analysis, ultrasonics, thermography, tribology, process monitoring, visual inspection, and other nondestructive analysis methods.
Maximum frequency	Broadband analysis techniques, which are used to monitor the overall mechanical condition of machinery, are based on the overall vibration or energy from a frequency range of zero to the user-selected maximum frequency (F_{MAX}).
Mil	One one-thousandth of an inch (0.001 inch).
Moment of inertia	The sum of the products formed by multiplying the mass of each element of a body by the square of its distance from a specified line. Also known as *rotational inertia*.
Oscillate	To move back and forth with a steady, uninterrupted rhythm.
Periodic motion	A motion that repeats after a certain interval.
Phase angle	The difference between the phase of a sinusoidally varying quantity and the phase of a second quantity that varies sinusoidally at the same frequency. Also known as *phase difference*.
Piezoelectric	Describes a crystal or film that can generate a voltage when mechanical force is applied or produce a mechanical force when a voltage is applied.
Predictive maintenance	The practice of using actual operating conditions of plant equipment and systems to optimize total plant operation. Relies on direct equipment monitoring to determine the actual mean-time-to-failure or loss of efficiency for each machine-train and system in a plant. This technique is used in place of traditional run-to-failure programs.
Profile	Refers to either time-domain (also may be called *time trace* or *waveform*) or frequency-domain vibration curves.
Quadratic	Any second-degree expression.

Radial	Extending from a point or center in the manner of rays (as the spokes of a wheel are radial).
Radian	The central angle of a circle determined by two radii and an arc joining them, all of the same length. A circle consists of 2π radians.
Reciprocation	The action of moving back and forth alternately.
Signature	A frequency-domain vibration curve.
Spring constant	The number of pounds tension necessary to extend the spring one inch. Also referred to as *stiffness* or *spring modulus*.
Thermography	Use of heat emissions of machinery or plant equipment as a monitoring and diagnostic predictive maintenance tool. For example, temperature differences on a coupling indicate misalignment and/or uneven mechanical forces.
Torque	A moment/force couple applied to a rotor such as a shaft in order to sustain acceleration/load requirements. A twisting load imparted to shafts as the result of induced loads/speeds.
Transducer	Any device or element that converts an input signal into an output signal of a different form.
Tribology	Science of rotor-bearing-support system design and operation. Predictive maintenance technique that uses spectrographic, wear particle, ferrography, and other measurements of the lubricating oil as a diagnostic tool.
Turbulent flow	Motion of fluids in which local velocities and pressures fluctuate irregularly and randomly.
Ultrasonic analysis	Predictive maintenance technique that uses principles similar to those of vibration analysis to monitor the noise generated by plant machinery or systems to determine their actual operating condition. Ultrasonics is used to monitor the higher frequencies (i.e., ultrasound) that range between 20,000 Hertz and 100 kiloHertz.

Vector A quantity that has both magnitude and direction, and whose components transform from one coordinate system to another in the same manner as the components of a displacement.

Velocity The time rate of change of position of a body. It is a vector quantity with direction as well as magnitude.

Vibration A continuing periodic change in a displacement with respect to a fixed reference. The motion will repeat after a certain interval.

Vibration analysis Vibration analysis monitors the noise or vibrations generated by plant machinery or systems to determine their actual operating condition. The normal monitoring range for vibration analysis is from less than 1 up to 20,000 Hertz.

Appendix 7.3 References

Hardenbergh, Donald E. 1963. *Introduction to Dynamics*. New York: Holt, Rinehart and Winston.

Higgins, Lindley, and R. Keith Mobley. 1995. *Maintenance Engineering Handbook*. New York: McGraw-Hill.

Mobley, R. Keith. 1989. *Advanced Diagnostics and Analysis.* Knoxville, TN: Technology for Energy Corp.

Mobley, R. Keith. 1990. *Introduction to Predictive Maintenance*. New York: Van Nostrand-Reinhold.

Mobley, R. Keith. 1999. *Vibration Fundamentals*. Boston: Butterworth–Heinemann.

8

THERMOGRAPHY

Thermography is a predictive maintenance technique that can be used to monitor the condition of plant machinery, structures, and systems. It uses instrumentation designed to monitor the emission of infrared energy (i.e., temperature) to determine operating condition. By detecting thermal anomalies (i.e., areas that are hotter or colder than they should be), an experienced surveyor can locate and define incipient problems within the plant.

8.1 Infrared Basics

Infrared technology is predicated on the fact that all objects with a temperature above absolute zero emit energy or radiation. Infrared radiation is one form of this emitted energy. Infrared emissions, or below red, are the shortest wavelengths of all radiated energy and are invisible without special instrumentation. The intensity of infrared radiation from an object is a function of its surface temperature; however, temperature measurement using infrared methods is complicated because three sources of thermal energy can be detected from any object: energy emitted from the object itself, energy reflected from the object, and energy transmitted by the object (Figure 8–1). Only the emitted energy is important in a predictive maintenance program. Reflected and transmitted energies will distort raw infrared data. Therefore, the reflected and transmitted energies must be filtered out of acquired data before a meaningful analysis can be completed.

The surface of an object influences the amount of emitted or reflected energy. A perfect emitting surface, Figure 8–2, is called a "blackbody" and has an emissivity equal to 1.0. These surfaces do not reflect. Instead, they absorb all external energy and re-emit it as infrared energy.

Surfaces that reflect infrared energy are called "graybodies" and have an emissivity less than 1.0 (Figure 8–3). Most plant equipment falls into this classification. Careful

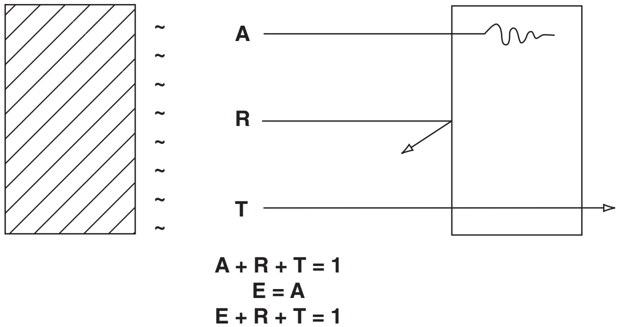


Figure 8–1 Energy emissions. All bodies emit energy within the infrared band. This provides the basis for infrared imaging or thermography. A = Absorbed energy. R = Reflected energy. T = Transmitted energy. E = Emitted energy.

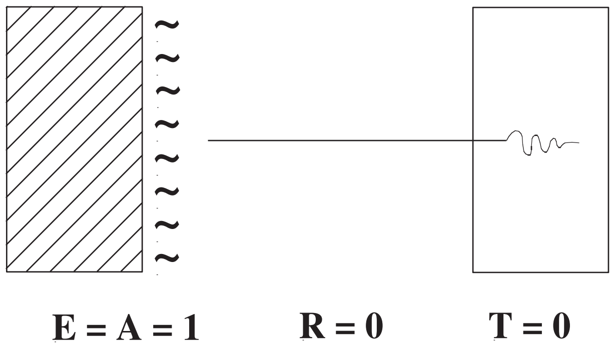


Figure 8–2 Blackbody emissions. A perfect or blackbody absorbs all infrared energy. A = Absorbed energy. R = Reflected energy. T = Transmitted energy. E = Emitted energy.

considerations of the actual emissivity of an object improve the accuracy of temperature measurements used for predictive maintenance. To help users determine emissivity, tables have been developed to serve as guidelines for most common materials; however, these guidelines are not absolute emissivity values for all machines or plant equipment.

Variations in surface condition, paint, or other protective coatings and many other variables can affect the actual emissivity factor for plant equipment. In addition to reflected and transmitted energy, the user of thermographic techniques must also consider the atmosphere between the object and the measurement instrument. Water vapor and other gases absorb infrared radiation. Airborne dust, some lighting, and other vari-

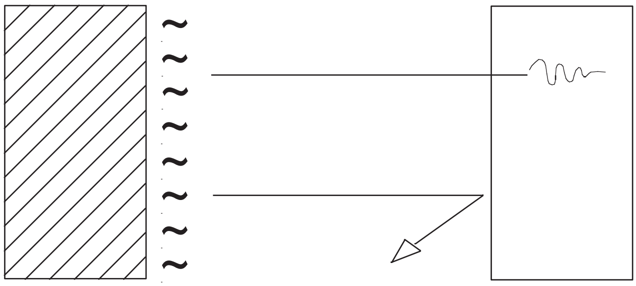


Figure 8–3 Graybody emissions. All bodies that are not blackbodies will emit some amount of infrared energy. The emissivity of each machine must be known before implementing a thermographic program. A = Absorbed energy. R = Reflected energy. T = Transmitted energy. E = Emitted energy.

ables in the surrounding atmosphere can distort measured infrared radiation. Because the atmospheric environment is constantly changing, using thermographic techniques requires extreme care each time infrared data are acquired.

8.2 Types of Infrared Instruments

Most infrared-monitoring systems or instruments provide special filters that can be used to avoid the negative effects of atmospheric attenuation of infrared data; however, the plant user must recognize the specific factors that will affect the accuracy of the infrared data and apply the correct filters or other signal conditioning required to negate that specific attenuating factor or factors.

Collecting optics, radiation detectors, and some form of indicator are the basic elements of an industrial infrared instrument. The optical system collects radiant energy and focuses it on a detector, which converts it into an electrical signal. The instrument's electronics amplifies the output signal and processes it into a form that can be displayed. Three general types of instruments can be used for predictive maintenance: infrared thermometers or spot radiometers, line scanners, and imaging systems.

8.2.1 Infrared Thermometers

Infrared thermometers or spot radiometers are designed to provide the actual surface temperature at a single, relatively small point on a machine or surface. Within a predictive maintenance program, the point-of-use infrared thermometer can be used in conjunction with many of the microprocessor-based vibration instruments to monitor the temperature at critical points on plant machinery or equipment. This technique is typically used to monitor bearing cap temperatures, motor winding temperatures, spot checks of process piping temperatures, and similar applications. It is limited in that the temperature represents a single point on the machine or structure. When used in conjunction with vibration data, however, point-of-use infrared data can be valuable.

8.2.2 Line Scanners

This type of infrared instrument provides a single-dimensional scan or line of comparative radiation. Although this type of instrument provides a somewhat larger field of view (i.e., area of machine surface), it is limited in predictive maintenance applications.

8.2.3 Infrared Imaging

Unlike other infrared techniques, thermal or infrared imaging provides the means to scan the infrared emissions of complete machines, process, or equipment in a very short time. Most of the imaging systems function much like a video camera. The user can view the thermal emission profile of a wide area by simply looking through the instrument's optics. A variety of thermal imaging instruments are on the market, ranging from relatively inexpensive, black-and-white scanners to full-color, microprocessor-based systems. Many of the less expensive units are designed strictly as scanners and cannot store and recall thermal images. The inability to store and recall previous thermal data limits a long-term predictive maintenance program.

Point-of-use infrared thermometers are commercially available and relatively inexpensive. The typical cost for this type of infrared instrument is less than $1,000. Infrared imaging systems have a price range from $8,000 for a black-and-white scanner without storage capability to more than $60,000 for a microprocessor-based, color imaging system.

8.3 Training

Training is critical with any of the imaging systems. The variables that can destroy the accuracy and repeatability of thermal data must be compensated for each time infrared data are acquired. In addition, interpretation of infrared data requires extensive training and experience.

Inclusion of thermography into a predictive maintenance program will enable you to monitor the thermal efficiency of critical process systems that rely on heat transfer or retention; electrical equipment; and other parameters that will improve both the reliability and efficiency of plant systems. Infrared techniques can be used to detect problems in a variety of plant systems and equipment, including electrical switchgear, gearboxes, electrical substations, transmissions, circuit breaker panels, motors, building envelopes, bearings, steam lines, and process systems that rely on heat retention or transfer.

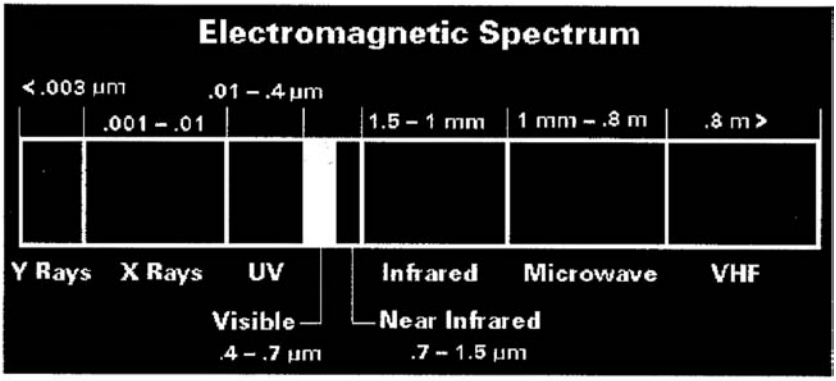


Figure 8–4 Electromagnetic spectrum.

8.4 Basic Infrared Theory

Infrared energy is light that functions outside the dynamic range of the human eye. Infrared imagers were developed to see and measure this heat. These data are transformed into digital data and processed into video images called *thermograms*. Each pixel of a thermogram has a temperature value, and the image's contrast is derived from the differences in surface temperature. An infrared inspection is a nondestructive technique for detecting thermal differences that indicate problems with equipment. Infrared surveys are conducted with the plant equipment in operation, so production need not be interrupted. The comprehensive information can then be used to prepare repair time/cost estimates, evaluate the scope of the problem, plan to have repair materials available, and perform repairs effectively.

8.4.1 Electromagnetic Spectrum

All objects emit electromagnetic energy when heated. The amount of energy is related to the temperature. The higher the temperature, the more electromagnetic energy it emits. The electromagnetic spectrum contains various forms of radiated energy, including X-ray, ultraviolet, infrared, and radio. Infrared energy covers the spectrum of 0.7 micron to 100 microns.

The electromagnetic spectrum is a continuum of all electromagnetic waves arranged according to frequency and wavelength. A wave has several characteristics (Figure 8–5). The highest point in the wave is called the *crest*. The lowest point in the wave is referred to as the *trough*. The distance from wavecrest to wavecrest is called a *wavelength*. *Frequency* is the number of wavecrests passing a given point per second. As the wave frequency increases, the wavelength decreases. The shorter the wavelength, the more energy contained; the longer the wavelength, the less energy.

For example, a steel slab exiting the furnace at the hot strip will have short wavelengths. You can feel the heat and see the red glow of the slab. The wavelengths have

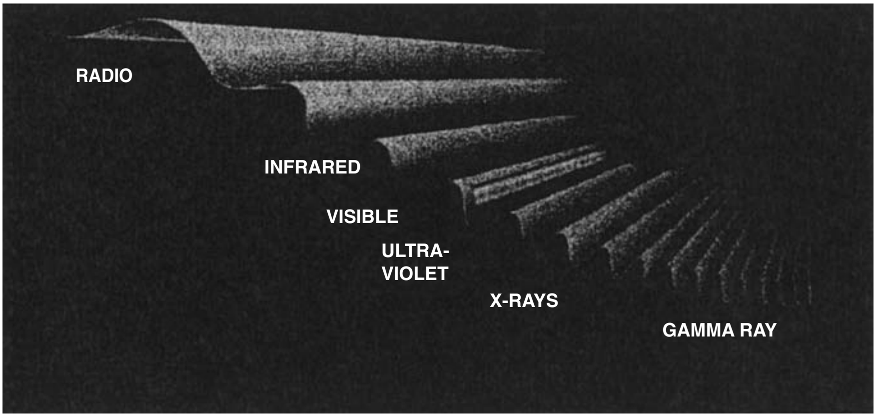


Figure 8–5 Wavelengths.

become shorter crest to crest and the energy being emitted has increased, entering the visible band on the spectrum. By contrast, (infrared energy) when the coil comes off of the coilers it has been cooled. Energy is lost. The wavelength have increased crest to crest and decreased in frequency.

8.4.2 Heat Transfer Concepts

Heat is a form of thermal energy. The first law of thermodynamics is that heat given up by one object must equal that taken up by another. The second law is that the transfer of heat takes place from the hotter system to the colder system. If the object is cold, it absorbs rather than emits energy. All objects emit thermal energy or infrared energy through three different types or modes: conduction, convection, and radiation. It is important to understand the differences among these three forms.

Conduction

Conduction is the transfer of energy through or between solid objects. A metal bar heated at one end will, in time, become hot at the other end. When a motor bearing is defective, the heat generated by the bearing is transferred to the motor casing. This is a form of conduction.

Convection

Convection is the transfer of energy through or between fluids or gases. If you took the same motor mentioned previously and placed a fan blowing directly on the hot bearing, the surface temperature would be different. This is convection cooling. It occurs on the surface of an object. An operator must be careful to identify the true cause and effect. In this case, the difference between good and bad source heating and the surface cooling is caused by convection.

Radiation

Radiation is the transfer of heat by wavelengths of electromagnetic energy. The most common cause of radiation is solar energy. Only radiated energy is detected by an infrared imager. If the aforementioned motor were sitting outside in the slab storage yard with slabs stacked around it, the electromagnetic energy from the sun and from the slabs would increase the temperature.

The purpose of the previous example was to make the thermographer aware that other causes of the thermal energy could be found or not found. In this case, was the motor hot because of a bad bearing or because of solar radiation? Was the motor missed and failed later because of the fan blowing on it and causing convection cooling? Conduction is the only mode that transfers thermal energy from location to location within a solid; however, at the surface of a solid or liquid, and in a gas, it is normal for all three modes to operate simultaneously.

Emissivity

Emissivity is the percentage of energy emitted by an object. Infrared energy hits an object; the energy is then transmitted, reflected, or absorbed. A common term used in infrared thermography is *blackbody*. A blackbody is a perfect thermal emitter. Its emissivity is 100 percent. It has no reflection or transmittance. The objects you will be scanning will each have a different emissivity value. A percentage of the total energy will be caused by reflection and transmittance; however, because most of your infrared inspection will be quantitative thermography, the emissivity value will not be as important now.

8.5 Infrared Equipment

Listed as follows are the criteria used to evaluate infrared equipment. It is important to determine which model best fits your needs before a purchase is made. Some of these points will be important to you and others will not. You will know more about your needs after you have finished reading this book.

- *Portability*. How much portability does your application require? Does weight and size of the instrument affect your data collection? What kind of equipment will you be scanning?
- *Ease of Use*. How much training is required to use the imager? Can it be used easily in your environment?
- *Qualitative or Quantitative*. Does it measure temperatures? If yes, what temperature range will be measured? Will you need more than one range?
- *Ambient or Quantitative Measurements*. What are the maximum upper and minimum lower ambient temperatures in which you will be scanning?
- *Short or Long Wavelengths*. Long-wavelength systems offer less solar reflection and operate in the 8- to 14-micron bandwidth. Short-wavelength systems offer smaller temperature errors when an incorrect emissivity value is entered. The operating bandwidth for a short-wave unit is 2 to 5.6 microns.

- *Batteries*. What is the weight and size of the batteries? How long will they last? Will you need additional batteries? How long do they take to charge?
- *Interchangeable Lenses*. Do the ones available fit your application? What are their costs?
- *Monitor, Eyepiece, or Both*. Will you need to show a live image to others while performing an inspection?
- *Analog or Digital*. How will you process the images? Does the imager have analog, digital, or both capabilities?
- *Software*. Can the software package produce quality reports and store and retrieve images? Do you require colonization and temperature editing?

8.6 Infrared Thermography Safety

Equipment included in an infrared thermography inspection is almost always energized. Therefore, a lot of attention must be given to safety. The following are basic rules for safety while performing an infrared inspection:

- Plant safety rules must be followed at all times.
- Notify area personnel before entering the area for scanning.
- A qualified electrician from the area should be assigned to open and close all panels.
- Where safe and possible, all equipment to be scanned will be online and under normal load with a clear line of sight to the item.
- Equipment whose covers are interlocked without an interlock defect mechanism should be shut down when allowable. If safe, their control covers should be opened and equipment restarted.

8.7 Infrared Scanning Procedures

The purpose of an infrared inspection is to identify and document problems in an electrical or mechanical system. The information provided by an inspection is presented in an easily and understandable form. A high percentage of problems occur in termination and connections, especially in copper-to-aluminum connections. A splice or a lug connector should not look warmer than its conductors if it has been sized properly. All problem connections should be dismantled, cleaned, reassembled, or replaced as necessary.

8.8 Types of Infrared Problems

There are three basic types of thermal problems:

- Mechanical looseness
- Load problems
- Component failure

8.8.1 Mechanical Looseness

Mechanical looseness occurs most often. A loose connection will result in thermal stress fatigue from overuse. Fuse clips are a good example because the constant heat-up and cooldown creates a poor connection. An accurate temperature measurement, or use of an isotherm, will identify a loose condition. When the isotherm is brought down to a single pixel, or temperature, it will identify the source of the loose condition.

8.8.2 Component Failure

Understanding the nomenclature of the problem can identify component failure. Specifically, the actual component will be the heat source. For example, a heat-stressed fuse in a three-phase assembly will appear hotter than the other two fusses.

8.8.3 Common Problems Found and What to Scan

Following are examples of what to scan while performing an infrared survey to easily detect common problems.

Motor Control and Distribution Centers

Have the switchgear panel covers opened or removed by qualified personnel before inspection. Scan cable, cable connections, fuse holders, fuse circuit breakers, and bus.

Main Secondary Switchgear

Have the switchgear panel covers opened or removed by qualified personnel before inspection. Scan cables, cables connections, circuit breakers (front and back), and bus.

Circuit Breaker Distribution Panels

Covers on small circuit breaker panels do not have to be removed for scanning. Circuit breakers and conductors are very close to the metal covers. Defective components are usually detectable by the heating of the cover in the area of the problem. If a problem exists, remove the panel cover to locate the problem. Only remove panel covers that can safely be removed.

Bus Duct

Electrical conductors are very close to the metal “skin” of the duct. Defective joints are usually detectable by the heating of the cover in the vicinity of the problem.

Motors

Do not scan motors less than 25 horsepower unless they are critical to production. On motors greater than 25 horsepower, scan the “T” boxes, visible conductors, connections, and rotors. Bearing problems can be found by comparing the surface temperature of like motors. Overheating conditions are documented as hot spots on the CRT and are usually found in comparing equipment, end bell and end bell (same type bearings), and stator to end bell.

Transformer—Oil-Filled

Scan transformer, transformer fins, cable connections, bushings, and tap changer. On all transformers, the oil level should be inspected during the survey. During the infrared survey, if a transformer appears exceptionally warm, the cooling radiators are near ambient temperature, and the transformer is above 50 percent of full load, the oil level is too low to circulate the oil and cooling is not taking place. Oil in the transformers is cooled by convection; as the load increases, the oil expands and the level increases until it then circulates in the cooling radiators. As a result of repeated oil samples and oil leaks, the reduced volume of oil causes the winding to overheat, thus reducing the life of the transformer. Plugged cooling heaters, isolated radiators, and plugged individual cooling fins can also be detected.

Transformers—Dry-Type

Scan transfers, cable connections, bushings, and tap changer. Enclosure covers on dry-type transformers should be removed only if there is safe clearance between the transformer connections and the enclosure panels. Some models, especially the newer ones, have screened openings for ventilation. Use these openings for your scanning survey.

The iron in these transformers is hot. It will heat the bus work and cause substantial infrared reflection. By increasing the temperature scale and adjusting the level control on the imager, you will be able to get uniform images, which will show hot spots in the secondary bus or the iron. A hot spot in the iron usually indicates a short. Make certain that reflection is not a factor.

Compare all windings. If temperatures are over a winding, but there is a difference in temperature of two windings, there may be an unbalanced load. A hot spot on a winding may point to a shorted turn.

Transformer Bushings

As a scanner moves upward on the transformer main tank and tap changer compartment, the bushings, lighting arresters, and their bus connections should be observed. This area is also critical because the integrity of the transformer, substation, or the complete system depends on proper installation and maintenance of each component. A survey of the transformer bushings, comparing one to the other, will reveal any loose connections or bushing problems. With the scanner, you can determine if the connection is loose internally or externally.

Capacitors

A capacitor has two conductive surfaces, which are separated by a dielectric barrier. Capacitors usually function as power factor correctors. When energized, all units should have the same temperature if the size is the same. A high uniform temperature is normal. A cold capacitor usually indicates a blown fuse or bad cell. Isolated spots showing a high temperature on a surface of the capacitor may indicate a bad capacitor.

High-Voltage Switchgear

Scan lighting arresters, insulators, cables, cables connections, bussing, circuit breakers, and disconnect switches.

Load Break Switches

In the switch, two metal surfaces act as conductors when they are brought into contact. Usually, problems are restricted to the contact surface. Poor contacts usually show up as hot spots.

Fuses

A fuse is a metal conductor, which is deliberately melted when an overload of current is forced on it. Major problems affected are loose mechanical stab clips that cause hot spots, corroded or oxidized external contact surfaces, and/or poor internal connections, which are bolted or soldered.

Circuit Breakers

Circuit breakers serve the same function as a fuse. It is a switching device that breaks an electrical circuit automatically. Problem areas are caused by corroded or oxidized contact surfaces, poor internal connections, poor control circuitry, and/or defective bushings.

Conductors

The melting points and current-carrying capacity of conductors are determined by the size and base material of the conductors. During a survey, compare between phases and between conductors and connections. An unbalanced load will account for some differences between conductors. Use metering devices already installed to check the differences.

The type of load will affect whether the load is balanced. Three-phase motor loads should be balanced; lighting and single-phase loads may be unbalanced.

Other Problems

- *Broken strands*. These hot spots are found at the support and at the cable termination.
- *Spiral heating*. This is found on stranded wire, which is heavily oxidized. The problem will show up as a hot spiral from one connection to another. There is a load imbalance between the strands, which results in a poor connection.
- *Ground conductor*. Usually there are no hot spots on a ground conductor. They do show up, however, as hot spots when there is abnormal leakage current to the ground. Be suspicious about such spots. Always point them out in the inspection report.
- *Parallel feeders*. A cold cable indicates a problem when parallel conductors are feeding the same load.

Appendix 8.1 Abbreviations

ΔT	Delta temperature. The delta notation represents the difference in two temperatures.
μ	Electrical units for ohms. Also used to describe microns in the infrared electromagnetic scale.
°C	Degrees Celsius
°F	Degrees Fahrenheit

Appendix 8.2 Glossary

A/D conversion	The conversion of continuous-type electrical signals varying in amplitude, frequency, or phase into proportional, discrete digital signals by means of an analog–digital converter.
Absorptivity	Ratio of the absorbed to incident electromagnetic radiation on a surface.
Ambient temperature	Ambient temperature is the temperature of the air in the immediate neighborhood of the equipment.
Analog data	Data represented in continuous form, as contrasted with digital data having discrete values.
Atmospheric absorption	The process whereby some or all of the energy of soundwaves or electromagnetic waves is transferred to the constituents of the atmosphere.

Atmospheric attenuation The process whereby some or all of the energy of the soundwaves or electromagnetic radiation is absorbed and/or scattered when traversing the atmosphere.

Atmospheric emission Electromagnetic radiation emitted by the atmosphere.

Atmospheric radiance The radiant flux per unit solid angle per unit of projected area of the source in the atmosphere.

Atmospheric reflectance Ratio of reflected radiation from the atmosphere to incident radiation.

Band A specification of a spectral range (say, from 0.4 to 0.5 microns) that is used for radiate measurements. The term *channel* is also in common use, with the same meaning as *band*. In the electromagnetic spectrum, the term *band* refers to a specific frequency range, designated as L-Band, S-Band, X-Band, and so on.

Bandwidth A certain range of frequencies within a band.

Conduction The transfer of heat through or between solids.

Convection The transfer of heat through or between fluids.

Corona The glow or brush discharge around conductors when air is stressed beyond its ionization point without developing flashover.

Electromagnetic spectrum Electromagnetic radiation is energy propagated through space between electrical and magnetic fields. The electromagnetic spectrum is the extent of that energy ranging from cosmic rays, gamma rays, and X-rays to ultraviolet, visible, and infrared radiation, including microwave energy.

Emissivity Consideration of the characteristics of materials, particularly with respect to the ability to absorb, transmit, or reflect infrared energy.

Emittance — Power radiated per unit area of a radiating surface.

Far-infrared — Infrared radiation extending approximately from 15 to 100 micrometers.

Gamma ray — A high-energy photon, especially as emitted by a nucleus in a transition between two energy levels.

Hot spot — An area of a negative or print revealing excessive light on that part of the subject.

Infrared band — The band of electromagnetic wavelengths lying between the extreme of the visible (approximately 0.70 micrometer) and the shortest microwaves (approximately 100 micrometers).

Infrared radiation — Electromagnetic radiation lying in the wavelength interval from 0.7 to 1,000 microns (or roughly between 1 micron and 1 millimeter wavelength). Its lower limit is bounded by visible radiation, and its upper limit by microwave radiation.

Isothermal mapping — Mapping of all regions with the same temperature.

Microwave band — The portion of the electromagnetic spectrum lying between the far-infrared and the conventional radio frequency portion. Although not bounded by definition, it is commonly regarded as extending from 0.1 cm (100 microns) to 30 cm in wavelength (1 to 100 gigaHertz frequency).

Mid-infrared — Infrared radiation extending approximately from 1.3 to 3.0 micrometers and being part of the reflective infrared. Often referred to as *short-wavelength infrared radiation* (SWIR).

Near-infrared — Infrared radiation extending approximately from 0.7 to 1.3 micrometers and being part of the radiative infrared.

Qualitative infrared thermography — The practice of gathering information about a system or process by observing images of infrared radiation and recording and presenting that information.

Quantitative infrared thermography	The practice of measuring temperatures of the observed patterns of infrared radiation.
Radar band	Frequency and designation with wavelengths within the range of approximately 100 microns to 2 meters.
Radiation	The emission and propagation of waves transmitting energy through space or through some medium.
Radio band	The range of wavelengths or frequencies of electromagnetic radiation designated as radio waves; approximately 4 to 9 Hz in frequency.
Reflectivity	The fraction of the incident radiant energy reflected by a surface that is exposed to uniform radiation from a source that fills its field of view.
Spectral band	An interval in the electromagnetic spectrum defined by two wavelengths, two frequencies, or two wave numbers.
Temperature gradient	Rate of change of temperature with distance.
Thermal emittance	Emittance of radiation by a body not at absolute zero because of the thermal agitation of its molecules.
Thermography	The recording of the thermal qualities of objects and surfaces by means of scanning equipment in which the infrared radiation or microwave radiation recorded can be converted into a thermal image.
Transmittance	The ratio of energy transmitted by a body to that incident on it.
Ultraviolet band	That portion of the electromagnetic spectrum ranging from just above the visible (about 4,000 ang.) to below 400 ang., on the border of the X-ray region.
Visible band	The band of the electromagnetic spectrum, which can be perceived by the naked eye. This band ranges from 7,500 ang. to 4,000 ang., being bordered by the infrared and ultraviolet bands.

X-ray	Electromagnetic waves of short wavelength from .00001 ang. to 3,000 ang.

APPENDIX 8.3 Electrical Terminology

Alternating current (AC)	Electrical current that reverses direction periodically, expressed in hertz (Hz) or cycles per second (cps).
Alternator	An AC generator that produces alternating current, which is internally rectified to direct current before being released.
Ampacity	A term used to describe the current-handling capacity of an electrical device.
Amperage	A term synonymous with current; used in describing electrical current. The total amount of current (amperes) flowing in a circuit.
Ampere	The quantitative unit measurement of electrical current.
Armature	The main power winding in a motor in which electromotive force is produced, usually the rotor of a DC motor or the stator of an AC motor.
Arrester	A device placed from phase to ground whose nonlinear impedance characteristics provide a path for high-amplitude transients.
Attenuator	A passive device used to reduce signal strength.
Brush	A piece of conducting material, which, when bearing against a commutator, slip ring, or the like will provide a passage for electrical current.
Capacitor	A discrete electrical device that has two electrodes and an intervening insulator, which is called the dielectric. A device used to store an electrical charge.
Circuit (closed)	An electrical circuit in which current flow is not interrupted.

Circuit (open) Any break or lack of contact in an electrical circuit either intentional (switch) or unintentional (bad connection).

Circuit (parallel) An electrical system in which all positive terminals are joined through one wire, and all negative terminals through another wire.

Circuit (series) An electrical system in which separate parts are connected end to end, to form a single path for current to flow through.

Circuit breaker A resettable device that responds to a preset level of excess current flow by opening the circuit, thereby preventing damage to circuit elements.

Circuit protector A circuit protector is a device that will open the circuit if it becomes overheated because of too much electricity flowing through it. Thus, it protects other components from damage if the circuit is accidentally grounded or overloaded. Fuses, fusible links, and circuit breakers are circuit protectors.

Coil A continuous winding arrangement of a conductor, which combines the separate magnetic fields of all the winding loops to produce a single, stronger field.

Current The flow of electricity in a circuit as expressed in amperes. Current refers to the quantity or intensity of electrical flow. Voltage, on the other hand, refers to the pressure or force causing the electrical flow.

Diode A device that permits current to flow in one direction only. Used to change alternating current to direct current. A rectifier.

Direct current (DC) Electrical current that flows consistently in one direction.

Distribution The way in which power is routed to various current-using sites or devices. Outside the building, distribution refers to the process of routing power from the power plant to the users. Inside the building, distribution is the process of using feeders and circuits to provide power to devices.

Electromagnetic interference (EMI) A term that describes electrically induced noise or transients.

Filter An electronic device that opposes the passage of a certain frequency band while allowing other frequencies to pass. Filters are designed to produce four different results: (1) a high-pass filter allows all signals above a given frequency to pass; (2) a low-pass filter allows only frequencies below a given frequency to pass; (3) a bandpass filter allows a given band of frequencies to pass while attenuating all others; and (4) a trap filter allows all frequencies to pass but acts as a high-impedance device to the tuned frequency of the filter.

Flashover Arcing that is caused by the breakdown of insulation between two conductors where a high current flow exists, with a high potential difference between the conductors.

Fuse A device that automatically self-destructs when the current passing through it exceeds the rated value of the fuse. A plug-in protector with a filament that melts or burns out when overloaded.

Ground A general term that refers to the point at which other portions of a circuit are referenced when making measurements. A power system's grounding is that point to which the neutral conductor, safety ground, and building ground are connected. This grounding electrode may be a water pipe, driven ground rod, or the steel frame of the building.

Harmonic A frequency that is a multiple of the fundamental frequency. For example, 120 Hz is the second harmonic of 60 Hz, 180 Hz is the third harmonic, and so forth.

Harmonic distortion Excessive harmonic content that distorts the normal sinusoidal waveform is harmonic distortion. This can cause overheating of circuit elements and might appear to a device as data-corrupting noise.

Hertz (Hz) A term describing the frequency of alternating current. The term *hertz* is synonymous with cycles per second.

Impedance (Z) Measured in ohms, impedance is the total opposition to current flow in a circuit in which alternating current is flowing. This includes inductive reactance, capacitive reactance, and resistance.

Inductance This term describes the electrical properties of a coil of wire and its resultant magnetic field when an alternating current is passed through it. This interaction offers impedance to current flow, thereby causing the current waveform to lag behind the voltage waveform. This results in what's known as a *lagging power factor*.

Inductor A discrete circuit element, which has the property of inductance. It should be noted that at very high radio frequencies, a straight wire or a path on a printed-circuit board can act as an inductor.

Insulator A nonconducting substance or body, such as porcelain, glass, or Bakelite, that is used for insulating wires in electrical circuits to prevent the undesired flow of electricity.

Inverter An inverter takes DC power and converts it into AC power.

Isolation The degree to which a device can separate the electrical environment of its input from its output, while allowing the desired transmission to pass across the separation.

Kilohertz (kHz) A term meaning 1,000 cycles per second (cps).

Kilovolt-Ampere (kVA) An electrical unit related to the power rating of a piece of equipment. It is calculated by multiplying the rated voltage of equipment by the current required (or produced). For resistive loads, 1 kilovolt-ampere equals 1 kilowatt.

Lightning arrester	A device used to pass large impulses to ground.
Mean time between failure (MTBF)	A statistical estimate of the time a component, subassembly, or operating unit will operate before failure will occur.
Megahertz (MHz)	A term for 1 million hertz (cycles per second).
Motor alternator	A device that consists of an AC generator mechanically linked to an electric motor, which is driven by utility power or by batteries. An alternator is an AC generator.
Motor generator	A motor generator consists of an AC motor coupled to a generator. The utility power energizes the motor to drive the generator, which powers the critical load. Motor generators provide protection against noise and spikes, and, if equipped with a heavy flywheel, they may also protect against sags and swells.
Neutral	One of the conductors of a three-phase wye system is the neutral conductor. Sometimes called the *return conductor*, it carries the entire current of a single-phase circuit and the resultant current in a three-phase system that is unbalanced. The neutral is bonded to ground on the output of a three-phase delta-wye transformer.
Ohm	The unit of measurement for electrical resistance.
Ohm's law	A law of electricity that states the relationship between voltage, amperes, and resistance. It takes a pressure of one volt to force one ampere of current through one ohm of resistance. Equation: Volts = amperes × ohms ($E = I \times R$).
Radiation	RF energy that is emitted or leaks from a distribution system and travels through space. These signals often cause interference with other communication services.
Rectifier	An electrical device containing diodes, used to convert AC to DC.

Relay An electromagnetic switching device using low current to open or close a high-current circuit.

Resistance (R) A term describing the opposition of elements of a circuit to alternating or direct current.

Resistor A device installed in an electrical circuit to permit a predetermined current to flow with a given voltage applied.

Rheostat A device for regulating a current by means of a variable resistance.

Rotor The part of the alternator that rotates inside the stator and produces an electrical current from induction by the electromagnetic fields of the stator windings.

SCR (semiconductor, or silicon, controlled rectifier) An electronic DC switch that can be triggered into conduction by a pulse to a gate electrode, but can only be cut off by reducing the main current below a predetermined level (usually zero).

Shielding Protective coating that helps eliminate electromagnetic and radio frequency interference.

Shunt A conductor joining two points in a circuit to form a parallel circuit, through which a portion of the current may pass, in order to regulate the amount of current flowing in the main circuit.

Sine wave A fundamental waveform produced by periodic oscillation that expresses the sine or cosine of a linear function of time or space, or both.

Single-phase That portion of a power source that represents only a single phase of the three phases that are available.

Solenoid A tubular coil containing a movable magnetic core, which moves when the coil is energized.

Stator The stationary winding of an alternator (the armature in a DC generator).

Switch A device used to open, close, or redirect current in an electrical circuit.

Three-phase An electrical system with three different voltage lines or legs, which carry sine-wave waveforms that are 120 degrees out of phases from one another.

Transformer A device used to change the voltage of an AC circuit and/or isolate a circuit from its power source.

Volt Electrical unit of measure (Current × Resistance).

Watt The unit for measuring electrical power or work. A watt is the mathematical product of amperes and volts (W = A × V).

APPENDIX 8.4 Materials List

	Material	°F	°C	Emissivity
Metals				
Alloys	20-Ni, 24-CR, 55-FE, Oxidized	392	200	0.9
	20-Ni, 24-CR, 55-FE, Oxidized	932	500	0.97
	60-Ni, 12-CR, 28-FE, Oxidized	518	270	0.89
	60-Ni, 12-CR, 28-FE, Oxidized	1040	560	0.82
	80-Ni, 20-CR, Oxidized	212	100	0.87
	80-Ni, 20-CR, Oxidized	1112	600	0.87
	80-Ni, 20-CR, Oxidized	2372	1300	0.89
Aluminum	Unoxidized	77	25	0.02
	Unoxidized	212	100	0.03
	Unoxidized	932	500	0.06
	Oxidized	390	199	0.11
	Oxidized	1110	599	0.19
	Oxidized at 599°C (1110°F)	390	199	0.11
	Oxidized at 599°C (1110°F)	1110	599	0.19
	Heavily Oxidized	200	93	0.2
	Heavily Oxidized	940	504	0.31
	Highly Polished	212	100	0.09
	Roughly Polished	212	100	0.18
	Commercial Sheet	212	100	0.09
	Highly Polished Plate	440	227	0.04
	Highly Polished Plate	1070	577	0.06
	Bright Rolled Plate	338	170	0.04

Material		°F	°C	Emissivity
	Bright Rolled Plate	932	500	0.05
	Alloy A3003, Oxidized	600	316	0.4
	Alloy A3003, Oxidized	900	482	0.4
	Alloy 1100-0	200–800	93–427	0.05
	Alloy 24ST	75	24	0.09
	Alloy 24ST, Polished	75	24	0.09
	Alloy 75ST	75	24	0.11
	Alloy 75ST, Polished	75	24	0.08
Bismuth	Bright	176	80	0.34
	Unoxidized	77	25	0.05
	Unoxidized	212	100	0.06
Brass	73% Cu, 27% Zn, Polished	476	247	0.03
	73% Cu, 27% Zn, Polished	674	357	0.03
	62% Cu, 37% Zn, Polished	494	257	0.03
	62% Cu, 37% Zn, Polished	710	377	0.04
	83% Cu, 17% Zn, Polished	530	277	0.03
	Matte	68	20	0.07
	Burnished to Brown Color	68	20	0.4
	Cu-Zn, Brass Oxidized	392	200	0.61
	Cu-Zn, Brass Oxidized	752	400	0.6
	Cu-Zn, Brass Oxidized	1112	600	0.61
	Unoxidized	77	25	0.04
	Unoxidized	212	100	0.04
Cadmium		77	25	0.02
Carbon	Lampblack	77	25	0.95
	Unoxidized	77	25	0.81
	Unoxidized	212	100	0.81
	Unoxidized	932	500	0.79
	Candle Soot	250	121	0.95
	Filament	500	260	0.95
	Graphitized	212	100	0.76
	Graphitized	572	300	0.75
	Graphitized	932	500	0.71
Chromium		100	38	0.08
Chromium		1000	538	0.26
Chromium, Polished		302	150	0.06
Cobalt, Unoxidized		932	500	0.13
Cobalt, Unoxidized		1832	1000	0.23
Columbium, Unoxidized		1500	816	0.19
Columbium, Unoxidized		2000	1093	0.24
Copper	Cuprous Oxide	100	38	0.87
	Cuprous Oxide	500	260	0.83
	Cuprous Oxide	1000	538	0.77
	Black, Oxidized	100	38	0.78

Material		°F	°C	Emissivity
	Etched	100	38	0.09
	Matte	100	38	0.22
	Roughly Polished	100	38	0.07
	Polished	100	38	0.03
	Highly Polished	100	38	0.02
	Rolled	100	38	0.64
	Rough	100	38	0.74
	Molten	1000	538	0.15
	Molten	1970	1077	0.16
	Molten	2230	1221	0.13
	Nickel Plated	100–500	38–260	0.37
Dow Metal		0.4–600	D18–316	0.15
Gold	Enamel	212	100	0.37
	Plate		0.0001	
	Plate on .0005 Silver	200–750	93–399	.11–.14
	Plate on .0005 Nickel	200–750	93–399	.07–.09
	Polished	100–500	38–260	0.02
	Polished	1000–2000	538–1093	0.03
Haynes Alloy C,	Oxidized	600–2000	316–1093	.90–.96
Haynes Alloy 25,	Oxidized	600–2000	316–1093	.86–.89
Haynes Alloy X,	Oxidized	600–2000	316–1093	.85–.88
Inconel Sheet	1000 (538)	1000	538	0.28
Inconel Sheet	1200 (649)	1200	649	0.42
Inconel Sheet	1400 (760)	1400	760	0.58
Inconel X, Polished	75 (24)	75	24	0.19
Inconel B, Polished	75 (24)	75	24	0.21
Iron	Oxidized	212	100	0.74
	Oxidized	930	499	0.84
	Oxidized	2190	1199	0.89
	Unoxidized	212	100	0.05
	Red Rust	77	25	0.7
	Rusted	77	25	0.65
	Liquid	2760–3220	1516–1771	.42–.45
Cast Iron	Oxidized	390	199	0.64
	Oxidized	1110	599	0.78
	Unoxidized	212	100	0.21
	Strong Oxidation	40	104	0.95
	Strong Oxidation	482	250	0.95
	Liquid	2795	1535	0.29
Wrought Iron				
	Dull	77	25	0.94
	Dull	660	349	0.94
	Smooth	100	38	0.35
	Polished	100	38	0.28
Lead	Polished	100–500	38–260	.06–.08
	Rough	100	38	0.43

Material		°F	°C	Emissivity
	Oxidized	100	38	0.43
	Oxidized at 1100¡F	100	38	0.63
	Gray Oxidized	100	38	0.28
Magnesium		100–500	38–260	.07–.13
Magnesium Oxide		1880–3140	1027–1727	.16–.20
Mercury		32	0	0.09
		77	25	0.1
		100	38	0.1
		212	100	0.12
Molybdenum		100	38	0.06
		500	260	0.08
		1000	538	0.11
		2000	1093	0.18
	Oxidized at 1000°F	600	316	0.8
	Oxidized at 1000°F	700	371	0.84
	Oxidized at 1000°F	800	427	0.84
	Oxidized at 1000°F	900	482	0.83
	Oxidized at 1000°F	1000	538	0.82
Monel, Ni-Cu		392	200	0.41
Monel, Ni-Cu		752	400	0.44
Monel, Ni-Cu		1112	600	0.46
Monel, Ni-Cu Oxidized		68	20	0.43
Monel, Ni-Cu Oxidized at 1110°F	1110 (599)	1110	599	0.46
Nickel	Polished	100	38	0.05
	Oxidized	100–500	38–260	.31–.46
	Unoxidized	77	25	0.05
	Unoxidized	212	100	0.06
	Unoxidized	932	500	0.12
	Unoxidized	1832	1000	0.19
	Electrolytic	100	38	0.04
	Electrolytic	500	260	0.06
	Electrolytic	1000	538	0.1
	Electrolytic	2000	1093	0.16
Nickel Oxide		1000–2000	538–1093	.59–.86
Palladium Plate	(.00005 on .0005 silver)	200–750	93–399	.16–.17
Platinum		100	38	0.05
		500	260	0.5
		1000	538	0.1
Platinum, Black		100	38	0.93
		500	260	0.96
		2000	1093	0.97
	Oxidized at 1100°F	500	260	0.07
		1000	538	0.11

Material		°F	°C	Emissivity
Rhodium Flash	(0.0002 on 0.0005 Ni)	200–700	93–371	.10–.18
Silver	Plate (0.0005 on Ni)	200–700	93–371	.06–.07
	Polished	100	38	0.01
		500	260	0.02
		1000	538	0.03
		2000	1093	0.03
Steel	Cold Rolled	200	93	.75–.85
	Ground Sheet	1720–2010	938–1099	.55–.61
	Polished Sheet	100	38	0.07
		500	260	0.1
		1000	538	0.14
	Mild Steel, Polished	75	24	0.1
	Mild Steel, Smooth	75	24	0.12
	ÊLiquid	2910–3270	1599–1793	0.28
	Steel, Unoxidized	212	100	0.08
	Steel, Oxidized	77	25	0.8
Steel Alloys	Type 301, Polished	75	24	0.27
	Type 301, Polished	450	232	0.57
	Type 301, Polished	1740	949	0.55
	Type 303, Oxidized	600–2000	316–1093	.74–.87
	Type 310, Rolled	1500–2100	816–1149	.56–.81
	Type 316, Polished	75	24	0.28
	Type 316, Polished	450	232	0.57
	Type 316, Polished	1740	949	0.66
	Type 321	200–800	93–427	.27–.32
	Type 321 Polished	300–1500	149–815	.18–.49
	Type 321 w/BK Oxide	200–800	93–427	.66–.76
	Type 347, Oxidized	600–2000	316–1093	.87–.91
	Type 350	200–800	93–427	.18–.27
	Type 350 Polished	300–1800	149–982	.11–.35
	Type 446, Polished	300–1500	149–815	.15–.37
	Type 17-7 PH	200–600	93–316	.44–.51
	ÊPolished	300–1500	149–815	.09–.16
	Oxidized	600–2000	316–1093	.87–.91
	Type PH-15-7 MO	300–1200	149–649	.07–.19
Stellite	Polished	68	20	0.18
Tantalum	Unoxidized	1340	727	0.14
		2000	1093	0.19
		3600	1982	0.26
		5306	2930	0.3
Tin, Unoxidized		77	25	0.04
		212	100	0.05
Tinned Iron, Bright		76	24	0.05
		212	100	0.08
Titanium, Alloy C110M	Polished	300–1200	149–649	.08–.19

Material		°F	°C	Emissivity
Tungsten	Unoxidized	77	25	0.02
	Unoxidized	212	100	0.03
	Unoxidized	932	500	0.07
	Unoxidized	1832	1000	0.15
	Unoxidized	2732	1500	0.23
	Unoxidized	3632	2000	0.28
	Filament (Aged)	100	38	0.03
	Filament (Aged)	1000	538	0.11
	Filament (Aged)	5000	2760	0.35
Uranium Oxide		1880	1027	0.79
Zinc	Bright, Galvanized	100	38	0.23
	Commercial 99.1%	500	260	0.05
	Galvanized	100	38	0.28
	Oxidized	500–1000	260–538	0.11
	Polished	100	38	0.02
	Polished	500	260	0.03
	Polished	1000	538	0.04
	Polished	2000	1093	0.06
Nonmetals				
Adobe	68 (20)			0.9
Asbestos	Board	100	38	0.96
	Cement	32–392	0–200	0.96
	Cement, Red	2500	1371	0.67
	Cement, White	2500	1371	0.65
	Cloth	199	93	0.9
	Paper	100–700	38–371	0.93
	Slate	68	20	0.97
Asphalt, pavement		100	38	0.93
Asphalt, tar paper		68	20	0.93
Basalt		68	20	0.72
Brick	Red, rough	70	21	0.93
	Gault Cream	2500–5000	1371–2760	.26–.30
	Fire Clay	2500	1371	0.75
	Light Buff	1000	538	0.8
	Lime Clay	2500	1371	0.43
	Fire Brick	1832	1000	.75–.80
	Magnesite, Refractory	1832	1000	0.38
	Grey Brick	2012	1100	0.75
	Silica, Glazed	2000	1093	0.88
	Silica, Unglazed	2000	1093	0.8
	Sandlime	2500–5000	1371–2760	.59–.63
Carborundum		1850	1010	0.92
Ceramic	Alumina on Inconel	800–2000	427–1093	.69–.45
	Earthenware, Glazed	70	21	0.9
	Earthenware, Matte	70	21	0.93

Nonmetals		°F	°C	Emissivity
	Greens No. 5210-2C	200–750	93–399	.89–.82
	Coating No. C20A	200–750	93–399	.73–.67
	Porcelain	72	22	0.92
	White Al2O3	200	93	0.9
	Zirconia on Inconel	800–2000	427–1093	.62–.45
Clay	68 (20)	0.39	0.39	
	Fired at	158	70	0.91
	Shale at	68	20	0.69
	Tiles, Light Red	2500–5000	1371–2760	.32–.34
	Tiles, Red	2500–5000	1371–2760	.40–.51
	Dark Purple	2500–5000	1371–2760	0.78
Concrete	Rough	32–2000	0–1093	0.94
	Tiles, Natural	2500–5000	1371–2760	.63–.62
	Tiles, Brown	2500–5000	1371–2760	.87–.83
	Tiles, Black	2500–5000	1371–2760	.94–.91
Cotton Cloth	68 (20)			0.77
Dolomite Lime	68 (20)			0.41
Emery Corundum	176 (80)			0.86
Glass	Convex D	212	100	0.8
	Convex D	600	316	0.8
	Convex D	932	500	0.76
	Nonex	212	100	0.82
	Nonex	600	316	0.82
	Nonex	932	500	0.78
	Smooth	32–200	0–93	.92–.94
Granite		70	21	0.45
Gravel		100	38	0.28
Gypsum		68	20	.80–.90
Ice, Smooth		32	0	0.97
Ice, Rough		32	0	0.98
Lacquer	Black	200	93	0.96
	Blue, on Al Foil	100	38	0.78
	Clear, on Al Foil (2 coats)	200	93	.08 (.09)
	Clear, on Bright Cu	200	93	0.66
	Clear, on Tarnished Cu	200	93	0.64
	Red, on Al Foil (2 coats)	100	38	.61 (.74)
	White	200	93	0.95
	White, on Al Foil (2 coats)	100	38	.69 (.88)
	Yellow, on Al Foil (2 coats)	100	38	.57 (.79)
Lime Mortar		100–500	38–260	.90–.92
Limestone		100	38	0.95
Marble, White		100	38	0.95
	Smooth, White	100	38	0.56
	Polished Gray	100	38	0.75
Mica		100	38	0.75

Nonmetals		°F	°C	Emissivity
Oil on Nickel	0.001 Film	72	22	0.27
	0.002 Film	72	22	0.46
	0.005 Film	72	22	0.72
	Thick Film	72	22	0.82
Oil, Linseed	On Al Foil, uncoated	250	121	0.09
	On Al Foil, 1 coat	250	121	0.56
	On Al Foil, 2 coats	250	121	0.51
	On Polished Iron, .001 Film	100	38	0.22
	On Polished Iron, .002 Film	100	38	0.45
	On Polished Iron, .004 Film	100	38	0.65
	On Polished Iron, Thick Film	100	38	0.83
Paints	Blue, Cu_2O_3	75	24	0.94
	Black, CuO	75	24	0.96
	Green, Cu_2O_3	75	24	0.92
	Red, Fe_2O_3	75	24	0.91
	White, Al_2O_3	75	24	0.94
	White, Y_2O_3	75	24	0.9
	White, ZnO	75	24	0.95
	White, $MgCO_3$	75	24	0.91
	White, ZrO_2	75	24	0.95
	White, ThO_2	75	24	0.9
	White, MgO	75	24	0.91
	White, $PbCO_3$	75	24	0.93
	Yellow, PbO	75	42	0.9
	Yellow, $PbCrO_4$	75	24	0.93
Paints, Aluminum	100 (38)	100	38	.27–.67
	10% Al	100	38	0.52
	26% Al	100	38	0.3
	Dow XP-310	200	93	0.22
Paints, Bronze	Low			.34–.80
	Gum Varnish (2 coats)	70	21	0.53
	Gum Varnish (3 coats)	70	21	0.5
	Cellulose Binder (2 coats)	70	21	0.34
Paints, Oil	All colors	200	93	.92–.96
	Black	200	93	0.92
	Black Gloss	70	21	0.9
	Camouflage Green	125	52	0.85
	Flat Black	80	27	0.88
	Flat White	80	27	0.91
	Gray-Green	70	21	0.95
	Green	200	93	0.95
	Lamp Black	209	98	0.96
	Red	200	93	0.95
	White	200	93	0.94

Nonmetals		°F	°C	Emissivity
Quartz, Rough,	Glass, 1.98 mm	540	282	0.9
Fused	Glass, 1.98 mm	1540	838	0.41
	Glass, 6.88 mm	540	282	0.93
	Glass, 6.88 mm	1540	838	0.47
	Opaque	570	299	0.92
	Opaque	1540	838	0.68
Red Lead		212	100	0.93
Rubber, Hard		74	23	0.94
Rubber, Soft, Gray		76	24	0.86
Sand		68	20	0.76
Sandstone		100	38	0.67
Sandstone, Red		100	38	.60–.83
Sawdust		68	20	0.75
Shale		68	20	0.69
Silica, Glazed		1832	1000	0.85
Silica, Unglazed		2012	1100	0.75
Silicon Carbide		300–1200	149–649	.83–.96
Silk Cloth		68	20	0.78
Slate		100	38	.67–.80
Snow, Fine Particles	20 (D7)			0.82
Snow, Granular	18 (D8)			0.89
Soil	Surface	100	38	0.38
	Black Loam	68	20	0.66
	Plowed Field	68	20	0.38
Soot	Acetylene	75	24	0.97
	Camphor	75	24	0.94
	Candle	250	121	0.95
	Coal	68	20	0.95
Stonework		100	38	0.93
Water	100 (38)	100	38	0.67
Waterglass	68 (20)	68	20	0.96
Wood	Low			.80–.90
	Beech, Planed	158	70	0.94
	Oak, Planed	100	38	0.91
	Spruce, Sanded	100	38	0.89

9

TRIBOLOGY

Tribology is the general term that refers to design and operating dynamics of the bearing-lubrication-rotor support structure of machinery. Several tribology techniques can be used for predictive maintenance: lubricating oil analysis, spectrographic analysis, ferrography, and wear particle analysis.

Lubricating oil analysis, as the name implies, is an analysis technique that determines the condition of lubricating oils used in mechanical and electrical equipment. It is not a tool for determining the operating condition of machinery. Some forms of lubricating oil analysis will provide an accurate quantitative breakdown of individual chemical elements, both oil additive and contaminates, contained in the oil. A comparison of the amount of trace metals in successive oil samples can indicate wear patterns of oil-wetted parts in plant equipment and will provide an indication of impending machine failure.

Until recently, tribology analysis has been a relatively slow and expensive process. Analyses were conducted using traditional laboratory techniques and required extensive, skilled labor. Microprocessor-based systems are now available that can automate most of the lubricating oil and spectrographic analysis, thus reducing the manual effort and cost of analysis.

The primary applications for spectrographic or lubricating oil analysis are quality control, reduction of lubricating oil inventories, and determination of the most cost-effective interval for oil change. Lubricating, hydraulic, and dielectric oils can be periodically analyzed using these techniques, to determine their condition. The results of this analysis can be used to determine if the oil meets the lubricating requirements of the machine or application. Based on the results of the analysis, lubricants can be changed or upgraded to meet the specific operating requirements.

In addition, detailed analysis of the chemical and physical properties of different oils used in the plant can, in some cases, allow consolidation or reduction of the number and types of lubricants required to maintain plant equipment. Elimination of unnecessary duplication can reduce required inventory levels and therefore maintenance costs.

As a predictive maintenance tool, lubricating oil and spectrographic analysis can be used to schedule oil change intervals based on the actual condition of the oil. In midsize to large plants, a reduction in the number of oil changes can amount to a considerable annual reduction in maintenance costs. Relatively inexpensive sampling and testing can show when the oil in a machine has reached a point that warrants change.

The full benefit of oil analysis can only be achieved by taking frequent samples and trending the data for each machine in the plant. It can provide a wealth of information on which to base maintenance decisions; however, major payback is rarely possible without a consistent program of sampling.

9.1 Lubricating Oil Analysis

Oil analysis has become an important aid to preventive maintenance. Laboratories recommend that samples of machine lubricant be taken at scheduled intervals to determine the condition of the lubricating film that is critical to machine-train operation.

9.1.1 Oil Analysis Tests

Typically, the following tests are conducted on lube oil samples:

Viscosity

Viscosity is one of the most important properties of lubricating oil. The actual viscosity of oil samples is compared to an unused sample to determine the thinning or thickening of the sample during use. Excessively low viscosity will reduce the oil film strength, weakening its ability to prevent metal-to-metal contact. Excessively high viscosity may impede the flow of oil to vital locations in the bearing support structure, reducing its ability to lubricate.

Contamination

Contamination of oil by water or coolant can cause major problems in a lubricating system. Many of the additives now used in formulating lubricants contain the same elements that are used in coolant additives. Therefore, the laboratory must have an accurate analysis of new oil for comparison.

Fuel Dilution

Dilution of oil in an engine, caused by fuel contamination, weakens the oil film strength, sealing ability, and detergency. Improper operation, fuel system leaks, ignition problems, improper timing, or other deficiencies may cause it. Fuel dilution is considered excessive when it reaches a level of 2.5 to 5 percent.

Solids Content

The amount of solids in the oil sample is a general test. All solid materials in the oil are measured as a percentage of the sample volume or weight. The presence of solids in a lubricating system can significantly increase the wear on lubricated parts. Any unexpected rise in reported solids is cause for concern.

Fuel Soot

Soot caused by the combustion of fuels is an important indicator for oil used in diesel engines and is always present to some extent. A test to measure fuel soot in diesel engine oil is important because it indicates the fuel-burning efficiency of the engine. Most tests for fuel soot are conducted by infrared analysis.

Oxidation

Oxidation of lubricating oil can result in lacquer deposits, metal corrosion, or oil thickening. Most lubricants contain oxidation inhibitors; however, when additives are used up, oxidation of the oil begins. The quantity of oxidation in an oil sample is measured by differential infrared analysis.

Nitration

Nitration results from fuel combustion in engines. The products formed are highly acidic, and they may leave deposits in combustion areas. Nitration will accelerate oil oxidation. Infrared analysis is used to detect and measure nitration products.

Total Acid Number (TAN)

The acidity of the oil is a measure of the amount of acid or acid-like material in the oil sample. Because new oils contain additives that affect the TAN, it is important to compare used oil samples with new, unused oil of the same type. Regular analysis at specific intervals is important to this evaluation.

Total Base Number (TBN)

The base number indicates the ability of oil to neutralize acidity. The higher the TBN, the greater its ability to neutralize acidity. Typical causes of low TBN include using the improper oil for an application, waiting too long between oil changes, overheating, and using high-sulfur fuel.

Particle Count

Particle count tests are important to anticipating potential system or machine problems. This is especially true in hydraulic systems. The particle count analysis made as a part of a normal lube oil analysis is different from wear particle analysis. In this test, high particle counts indicate that machinery may be wearing abnormally or that failures may occur because of temporarily or permanently blocked orifices. No attempt is made to determine the wear patterns, size, and other factors that would identify the failure mode within the machine.

Spectrographic Analysis

Spectrographic analysis allows accurate, rapid measurements of many of the elements present in lubricating oil. These elements are generally classified as wear metals, contaminants, or additives. Some elements can be listed in more than one of these classifications. Standard lubricating oil analysis does not attempt to determine the specific failure modes of developing machine-train problems. Therefore, additional techniques must be used as part of a comprehensive predictive maintenance program.

9.1.2 Wear Particle Analysis

Wear particle analysis is related to oil analysis only in that the particles to be studied are collected by drawing a sample of lubricating oil. Whereas lubricating oil analysis determines the actual condition of the oil sample, wear particle analysis provides direct information about the wearing condition of the machine-train. Particles in the lubricant of a machine can provide significant information about the machine's condition. This information is derived from the study of particle shape, composition, size, and quantity. Wear particle analysis is normally conducted in two stages.

The first method used for wear particle analysis is routine monitoring and trending of the solids content of machine lubricant. In simple terms, the quantity, composition, and size of particulate matter in the lubricating oil indicates the machine's mechanical condition. A normal machine will contain low levels of solids with a size less than 10 microns. As the machine's condition degrades, the number and size of particulate matter increases. The second wear particle method involves analysis of the particulate matter in each lubricating oil sample.

Types of Wear

Five basic types of wear can be identified according to the classification of particles: rubbing wear, cutting wear, rolling fatigue wear, combined rolling and sliding wear, and severe sliding wear. Only rubbing wear and early rolling fatigue mechanisms generate particles that are predominantly less than 15 microns in size.

Rubbing Wear. Rubbing wear is the result of normal sliding wear in a machine. During a normal break-in of a wear surface, a unique layer is formed at the surface. As long as this layer is stable, the surface wears normally. If the layer is removed faster than it is generated, the wear rate increases and the maximum particle size increases. Excessive quantities of contaminant in a lubrication system can increase rubbing wear by more than an order of magnitude without completely removing the shear mixed layer. Although catastrophic failure is unlikely, these machines can wear out rapidly. Impending trouble is indicated by a dramatic increase in wear particles.

Cutting Wear Particles. Cutting wear particles are generated when one surface penetrates another. These particles are produced when a misaligned or fractured hard surface produces an edge that cuts into a softer surface, or when abrasive contaminant becomes embedded in a soft surface and cuts an opposing surface. Cutting wear particles are abnormal and are always worthy of attention. If they are only a few microns long and a fraction of a micron wide, the cause is probably contamination. Increasing quantities of longer particles signals a potentially imminent component failure.

Rolling Fatigue. Rolling fatigue is associated primarily with rolling contact bearings and may produce three distinct particle types: fatigue spall particles, spherical particles, and laminar particles. *Fatigue spall particles* are the actual material removed when a pit or spall opens up on a bearing surface. An increase in the quantity or size of these particles is the first indication of an abnormality. Rolling fatigue does not always generate *spherical particles*, and they may be generated by other sources. Their presence is important in that they are detectable before any actual spalling occurs. *Laminar particles* are very thin and are formed by the passage of a wear particle through a rolling contact. They often have holes in them. Laminar particles may be generated throughout the life of a bearing, but at the onset of fatigue spalling the quantity increases.

Combined Rolling and Sliding Wear. Combined rolling and sliding wear results from the moving contact of surfaces in gear systems. These larger particles result from tensile stresses on the gear surface, causing the fatigue cracks to spread deeper into the gear tooth before pitting. Gear fatigue cracks do not generate spheres. Scuffing of gears is caused by too high a load or speed. The excessive heat generated by this condition breaks down the lubricating film and causes adhesion of the mating gear teeth. As the wear surfaces become rougher, the wear rate increases. Once started, scuffing usually affects each gear tooth.

Severe Sliding Wear. Excessive loads or heat causes severe sliding wear in a gear system. Under these conditions, large particles break away from the wear surfaces, causing an increase in the wear rate. If the stresses applied to the surface are increased further, a second transition point is reached. The surface breaks down, and catastrophic wear enses.

Normal spectrographic analysis is limited to particulate contamination with a size of 10 microns or less. Larger contaminants are ignored. This fact can limit the benefits derived from the technique.

9.1.3 Ferrography

This technique is similar to spectrography, but there are two major exceptions. First, ferrography separates particulate contamination by using a magnetic field rather than by burning a sample as in spectrographic analysis. Because a magnetic field is used to separate contaminants, this technique is primarily limited to ferrous or magnetic particles.

The second difference is that particulate contamination larger than 10 microns can be separated and analyzed. Normal ferrographic analysis will capture particles up to 100 microns in size and provides a better representation of the total oil contamination than spectrographic techniques.

9.1.4 Oil Analysis Costs and Uses

There are three major limitations with using tribology analysis in a predictive maintenance program: equipment costs, acquiring accurate oil samples, and interpretation of data.

The capital cost of spectrographic analysis instrumentation is normally too high to justify in-plant testing. The typical cost for a microprocessor-based spectrographic system is between $30,000 and $60,000; therefore, most predictive maintenance programs rely on third-party analysis of oil samples.

Simple lubricating oil analysis by a testing laboratory will range from about $20 to $50 per sample. Standard analysis normally includes viscosity, flash point, total insolubles, total acid number (TAN), total base number (TBN), fuel content, and water content. More detailed analysis, using spectrographic or ferrographic techniques, that includes metal scans, particle distribution (size), and other data can cost more than $150 per sample.

A more severe limiting factor with any method of oil analysis is acquiring accurate samples of the true lubricating oil inventory in a machine. Sampling is not a matter of opening a port somewhere in the oil line and catching a pint sample. Extreme care must be taken to acquire samples that truly represent the lubricant that will pass through the machine's bearings. One recent example is an attempt to acquire oil samples from a bullgear compressor. The lubricating oil filter had a sample port on the clean (i.e., downstream) side; however, comparison of samples taken at this point and one taken directly from the compressor's oil reservoir indicated that more contaminants existed downstream from the filter than in the reservoir. Which location actually represented the oil's condition? Neither sample was truly representative. The oil filter had removed most of the suspended solids (i.e., metals and other insolubles) and was therefore not representative of the actual condition. The reservoir sample was not representative because most of the suspended solids had settled out in the sump.

Proper methods and frequency of sampling lubricating oil are critical to all predictive maintenance techniques that use lubricant samples. Sample points that are consistent with the objective of detecting large particles should be chosen. In a recirculating system, samples should be drawn as the lubricant returns to the reservoir and before any filtration occurs. Do not draw oil from the bottom of a sump where large quantities of material build up over time. Return lines are preferable to reservoir as the sample source, but good reservoir samples can be obtained if careful, consistent practices are used. Even equipment with high levels of filtration can be effectively monitored as long as samples are drawn before oil enters the filters. Sampling techniques involve taking samples under uniform operating conditions. Samples should not be taken more than 30 minutes after the equipment has been shut down.

Sample frequency is a function of the mean time to failure from the onset of an abnormal wear mode to catastrophic failure. For machines in critical service, sampling every 25 hours of operation is appropriate; however, for most industrial equipment in continuous service, monthly sampling is adequate. The exception to monthly sampling is machines with extreme loads. In this instance, weekly sampling is recommended.

Understanding the meaning of analysis results is perhaps the most serious limiting factor. Results are usually expressed in terms that are totally foreign to plant engineers or technicians. Therefore, it is difficult for them to understand the true meaning of results, in terms of oil or machine condition. A good background in quantitative and qualitative chemistry is beneficial. At a minimum, plant staff will require training in basic chemistry and specific instruction on interpreting tribology results.

9.2 Setting Up an Effective Program

Many plants have implemented oil analysis programs to better manage their equipment and lubricant assets. Although some have received only marginal benefits, a few have reported substantial savings, cost reductions, and increased productivity. Success in an oil analysis program requires a dedicated commitment to understanding the equipment design, the lubricant, the operating environment, and the relationship between test results and the actions to be performed.

In North America, millions of dollars have been invested in oil analysis programs with little or no financial return. The analyses performed by original equipment manufacturers or lubricant manufacturers are often termed as "free." In many of these cases, the results from the testing have little or no effect on the maintenance, planning, and/or evaluated equipment's condition. The reason is not because this service is free, or the ability of the laboratory, or the effort of the lubricant supplier to provide value-added service. The reason is a lack of knowledge—a failure to understand the value lost when a sample is not representative of the system, and the inability to turn equipment and lubricant data into useful information that guides maintenance activities.

More important is the failure to understand the true requirements and operating characteristics of the equipment. This dilemma is not restricted to the companies receiving "free" analysis. In many cases, unsuccessful or ineffective oil analysis programs are in the same predicament. Conflicting information from equipment suppliers, laboratories, and lubricant manufacturers have clouded the true requirements of equipment to the maintenance personnel or individuals responsible for the program. The following steps provide a guideline to implementing an effective lubricating oil analysis program.

9.2.1 Equipment Audit

An equipment audit should be performed to obtain knowledge of the equipment, its internal design, the system design, and the present operating and environmental conditions. Failure to gain a full understanding of the equipment's operating needs and conditions undermines the technology. This information is used as a reference to set equipment targets and limits, while supplying direction for future maintenance tasks. The information should be stored under an equipment-specific listing and made accessible to other predictive technologies, such as vibration analysis.

Equipment Criticality

Safety, environmental concerns, historical problems, reliability, downtime costs, and repairs must all be considered when determining the equipment to be included in a viable lubricating oil analysis program. Criticality should also be the dominant factor used to determine the frequency and type of analyses that will be used to monitor plant equipment and systems.

Equipment Component and System Identification

Collecting, categorizing, and evaluating all design and operating manuals including schematics are required to understand the complexity of modern equipment. Original equipment manufacturers' assistance in identifying the original bearings, wear surfaces, and component metallurgy will take the guesswork out of setting targets and limits. This information, found in the operating and maintenance manuals furnished with each system, will aid in future troubleshooting. Equipment nameplate data with accurate model and serial numbers allow for easy identification by the manufacturer to aid in obtaining this information.

Care should be exercised in this part of the evaluation. In many cases, critical plant systems and equipment has been modified one or more times over their installed life. Information obtained from operating and maintenance manuals or directly from the original equipment manufacturer must be adjusted to reflect the actual installed equipment.

Operating Parameters

Equipment designers and operating manuals reflect the minimum requirements for operating the equipment. These include operating temperature, lubricant requirements, pressures, duty cycles, filtration requirements, and other parameters that directly or indirectly impact reliability and life-cycle cost. Operating outside these parameters will adversely impact equipment reliability and the lubricant's ability to provide adequate protection. It may also require modifications and/or additions to the system to allow the component to run within an acceptable range.

Operating Equipment Evaluation

A visual inspection of the equipment is required to examine and record the components used in the system, including filtration, breathers, coolers, heaters, and so on. This inspection should also record all operating temperatures and pressures, duty cycles, rotational direction, rotating speeds, filter indicators, and the like. Temperature reading of the major components is required to reflect the component operating system temperature. A noncontract, infrared scanner may be used to obtain accurate temperature readings.

Operating Environment

Hostile environments or environmental contamination is usually not considered when the original equipment manufacturer establishes equipment operating parameters. These conditions can influence lubricant degradation, eventually resulting in damaged equipment. All environmental conditions such as mean temperature, humidity, and all possible contaminants must be recorded.

Maintenance History

Reliable history relating to wear and lubrication-related failures can assist in the decision-making process of adjusting and tightening targets and limits. These targets should allow for advanced warnings of historical problems and possible root-cause detection.

Oil Sampling Location

A sampling location should be identified for each piece of equipment to allow for trouble-free, repetitive, and representative sampling of the health of the equipment and the lubricant. This sampling method should allow the equipment to be tested under its actual operating condition while being unobtrusive and safe for the technician.

New Oil Baseline

A sample of the new lubricant is required to provide a baseline or reference point for physical and chemical properties of the lubricant. Lubricants and additive packages can change over time, so adjusting lubrication targets and alarms should reflect these changes.

Cooling Water Baseline

A sample of the cooling water, when used, should be collected, tested, and analyzed to obtain its physical and chemical properties. These results are used to adjust the lubricant targets and to reflect and provide early warnings of leaks in the coolers.

Targets and Alarms

Original equipment manufacturing (OEM) operating specifications or the guidelines of a recognized governing body can be used in setting the minimum alarms. These alarms must be set considering all of the previously collected information. These settings must provide early detection of contaminants, lubricant deterioration, and present equipment health. These achievable targets should be set to supply an early warning of any anomalies that allow corrective actions to be planned, scheduled, and performed with little or no effect on production schedules.

Database Development

A database should be developed to organize equipment information and the collected data along with the equipment-specific targets and alarms. This database should be easy to use. The end user must have control of the targets and limits in order to reflect the true equipment-specific conditions within the plant.

In ideal circumstances, the database should be integrated into a larger predictive maintenance database that contains all information and data that are useful to the predictive maintenance analysts. Combining vibration, lubricating oil, infrared, and other predictive data into a single database will greatly enhance the analysts' ability to detect and correct incipient problems and will ensure that maximum benefits are obtained from the program.

9.2.2 Lubricant Audit Process

Equipment reliability requires a lubricant that meets and maintains specific physical, chemical, and cleanliness requirements. A detailed trail of a lubricant is required, beginning with the oil supplier and ending after disposal of spent lubricants. Sampling and testing of the lubricants are important to validate the lubricant condition throughout its life cycle.

Lubricant Requirements

Information from the equipment audit supplies the physical and chemical requirements of the lubricant to operate within the equipment. After ensuring that the correct type of lubricant is in use, the audit information ensures that the correct viscosity is used in relationship to the true operating temperature.

Lubricant Supplier

Quality control programs implemented by the lubricant manufacturer should be questioned and recorded when evaluating the supplier. Sampling and testing new lubricants before dispensing ensures that the vendor has supplied the correct lubricant.

Oil Storage

Correct labeling, including materials safety display system (MSDS), must be clearly installed to ensure proper use of the contents. Proper stock rotation and storage methods must be considered to prevent the possibility of the degradation of the physical, chemical, and cleanliness requirements of the lubricant throughout the storage and dispensing phase.

Handling and Dispensing

Handling and dispensing methods must ensure that the health and cleanliness of the lubricant meet the specifications required by the equipment. All opportunities for contamination must be eliminated. Prefiltering of all lubricants should be performed to meet the specific equipment requirements. Preventive maintenance activities involving oil drains, top-ups, sweetening, flushing, or reclaiming. Information should be recorded and forwarded to the individual responsible for the oil analysis program group in a timely manner. Record keeping of any activity involving lubricant consumption, lubricant replacement, and/or lubricant top-ups must be implemented and maintained.

Waste Oil

Oil deemed unfit for equipment usage must be disposed of in the correct storage container for that type of lubricant and properly marked and labeled. The lubricant must then be classified for the type of disposal and removed from the property without delay. Long storage times allow for the introduction of contaminants and could result in reclassification.

9.2.3 Baseline Signature

The baseline signature should be designed to gather and analyze all data required to determine the current health of the equipment and lubricant in relationship to the alarms and targets derived from the audit. The baseline signature or baseline reading requires a minimum of three consecutive, timely samples, preferably in a short duration (i.e., one per month) to effectively evaluate the present trend in the equipment condition.

Equipment Evaluation

Observing, recording, and trending operating equipment along with the environmental conditions, including equipment temperature readings, are required at the same time as the lubricant sample is obtained. This information is used in troubleshooting or detecting the root-cause of any anomalies discovered.

Sampling

A sampling method will be supplied to extract a sample for the equipment that will be repetitive and representative of the health of the equipment and the lubricant. Improper sampling methods or locations are the primary reason that many oil analysis programs fail to generate measurable benefits. Extreme care must be take to ensure that the correct location and best sampling practices are universally applied and followed.

Testing

Equipment-specific testing assigned during the audit stage will supply the required data to effectively report the health of the lubricant and equipment. This testing must be performed without delay.

Exception Testing

Sample data that report an abnormal condition or an alarm or target that has been exceeded requires exception testing. This will help pinpoint the root-cause of the anomaly. The oil analysis technician should authorize these tests, which are not to be considered as routine testing.

Data Entry

The recorded data should be installed into a system that allows for trending and future reference, along with report-generation opportunities.

Baseline Signature Review

After all tests are performed, the data are systematically reviewed. Combining the hard data gathered in the system audit with experience, the root-causes of potential failures can be pinpointed. A report should then be generated containing all test results, along with a list of recommendations. This report should include testing frequencies and any required improvements necessary to bring the present condition of the lubricant and/or the operating conditions to within the acceptable targets.

9.2.4 Monitoring

These activities are performed to collect and trend any early signs of deteriorating lubricant and equipment condition and/or any changes in the operating environment. This information should be used as a guide for the direction of any required maintenance activities, which will ensure safe, reliable, and cost-effective operation of the plant equipment.

Routine Monitoring

Routine monitoring is designed to collect the required data to competently inform the predictive maintenance analysts or maintenance group of the present condition of its lubricants and equipment. At this time, observations in the present operating and environmental conditions should be recorded. This schedule of the routine monitoring must remain timely and repetitive for effective trending.

Routes

A route is designed so that an oil sample can be collected in a safe, unobtrusive manner while the equipment is running at its typical full-load levels. These routes should allow enough time for the technician to collect, store, analyze, and report anomalies before starting another route. If the samples are sent to an outside laboratory, time should be allocated for analyzing and recording all information once the data are received.

Frequency of Monitoring

The frequency of the inspections should be based on the information obtained in the audit and baseline signature stages of program development. These frequencies are equipment specific and can be changed as the program matures or a degrading condition is observed.

Tests

Testing the current condition of critical plant equipment is the goal of the oil analysis program. Technicians who report alarms proceed into exception testing mode (i.e., troubleshooting) that pinpoints the root-cause of the anomaly. At this stage of interfacing, other predictive technologies should be implemented, if applicable. Testing by the maintenance group or the laboratory group requires a maximum of a 24-hour turnaround on exception tests. A 48-hour turnaround on routine tests supplied by the laboratory would be considered acceptable.

Post-Overhaul Testing

After completing an overhaul or replacement of a new component, certain oil analysis tests should be performed to ensure that the lubricant meets all equipment requirements. These tests become a quality check for maintenance activities required to perform the overhaul and supply an early warning of problem conditions.

Contractor Overhaul Templates

Components not overhauled in an in-house program should have a guideline or template of the overhaul procedures and required component replacement parts. These templates are a quality control measure to ensure that the information in the audit database is kept up-to-date but also to ensure compatibility of components and lubricants presently used.

Data Analysis

After all data are collected from the various inspections and tests, the alarms and targets should alert the technician to any anomalies. Instinct combined with sensory and inspection data should warrant further testing. Using the technicians' wealth of equipment knowledge along with the effects of the operating environment, is critical to the success of this program.

Root-Cause Analysis

Repetitive failures and/or problems that require a solution to alleviate the unknown cause require testing to identify the root-cause of the problem. All the data and information collected in the audit, baseline signature, and monitoring stages of the program will assist in identifying the underlying problem.

Reports

All completed routes, exception testing, and root-cause analysis require a report to be filed with the predictive maintenance specialist outlining the anomaly identified and the corrective actions required. These reports should be filed under specific equipment cataloging for easy, future reference. The reports should include:

- Specific equipment identification
- Data of sample
- Date of report
- Present condition of equipment and lubricant
- Recommendations
- Sample test result data
- Analyst's name

Use of a computerized system allows the reports to be designed as required and, in many cases, will provide an equipment condition overview report.

9.2.5 Program Evaluation

Predictive maintenance tasks are based on condition measurements and performance on the basis of defects before outright failure impacts safety and production. Well-managed predictive maintenance programs are capable of identifying and tracking anomalies. Success is often measured by factors such as number of machines monitored, problems recognized, number of saves, and other technical criteria. Few maintenance departments have successfully translated technical and operating results gained by predictive maintenance into a value and benefits in the financial terms necessary to ensure continued management support. Without credible financial links to the facility and organization's business objectives, technical criteria are essentially useless. As a result, many successful predictive maintenance programs are being curtailed or eliminated as a cost-savings measure. Dedication to an oil analysis program requires documenting all the obtained cost benefits associated with a properly implemented program.

10

PROCESS PARAMETERS

Many plants do not consider machine or systems efficiency as part of the maintenance responsibility; however, machinery that is not operating within acceptable efficiency parameters severely limits the productivity of many plants. Therefore, a comprehensive predictive maintenance program should include routine monitoring of process parameters. As an example of the importance of process parameters monitoring, consider a process pump that may be critical to plant operation. Vibration-based predictive maintenance will provide the mechanical condition of the pump, and infrared imaging will provide the condition of the electric motor and bearings. Neither provides any indication of the operating efficiency of the pump. Therefore, the pump can be operating at less than 50 percent efficiency and the predictive maintenance program would not detect the problem.

Process inefficiencies, like the example, are often the most serious limiting factor in a plant. Their negative impact on plant productivity and profitability is often greater than the total cost of the maintenance operation. Without regular monitoring of process parameters, however, many plants do not recognize this unfortunate fact. If your program included monitoring of the suction and discharge pressures and amp load of the pump, you could determine the operating efficiency. The brake-horsepower formula could be used to calculate operating efficiency of any pump in the program.

$$\text{BHP} = \frac{\text{Flow (GPM)} \times \text{Specific Gravity} \times \text{Total Dynamic Head (Feet)}}{3960 \times \text{Efficiency}}$$

By measuring the suction and discharge pressure, the total dynamic head (TDH) can be determined. Using this data, the pump curve will provide the flow and the amp load of the horsepower. With this measured data, the efficiency can be calculated.

Process parameters monitoring should include all machinery and systems in the plant process that can affect its production capacity. Typical systems include heat exchangers, pumps, filtration, boilers, fans, blowers, and other critical systems.

Inclusion of process parameters in a predictive maintenance program can be accomplished in two ways: manual or microprocessor-based systems. Both methods normally require installing instrumentation to measure the parameters that indicate the actual operating condition of plant systems. Even though most plants have installed pressure gauges, thermometers, and other instruments that should provide the information required for this type of program, many of them are no longer functioning. Therefore, including process parameters in your program will require an initial capital cost to install calibrated instrumentation.

Data from the installed instrumentation can be periodically recorded using either manual logging or with a microprocessor-based data logger. If the latter method is selected, many of the vibration-based microprocessor systems can also provide the means of acquiring process data. This should be considered when selecting the vibration-monitoring system that will be used in your program. In addition, some of the microprocessor-based predictive maintenance systems can calculate unknown process variables. For example, they can calculate the pump efficiency used in the example. This ability to calculate unknowns based on measured variables will enhance a total-plant predictive maintenance program without increasing the manual effort required. In addition, some of these systems include nonintrusive transducers that can measure temperatures, flows, and other process data without the necessity of installing permanent instrumentation. This technique further reduces the initial cost of including process parameters in your program.

10.1 Pumps

This section provides a general overview of the process parameters or failure modes that should be a part of a viable inspection program. Design, installation, and operation are the dominant factors that affect a pump's mode of failure. This section identifies common failures for centrifugal and positive-displacement pumps.

10.1.1 Centrifugal Pumps

Centrifugal pumps are especially sensitive to: (1) variations in liquid condition (i.e., viscosity, specific gravity, and temperature); (2) suction variations, such as pressure and availability of a continuous volume of fluid; and (3) variations in demand. Table 10–1 lists common failure modes for centrifugal pumps and their causes.

Mechanical failures may occur for several reasons. Some are induced by cavitation, hydraulic instability, or other system-related problems. Others are the direct result of improper maintenance. Maintenance-related problems include improper lubrication, misalignment, imbalance, seal leakage, and a variety of others that periodically affect machine reliability.

Table 10–1 Common Failure Modes of Centrifugal Pumps

THE CAUSES	THE PROBLEM: Insufficient Discharge Pressure	Intermittent Operation	Insufficient Capacity	No Liquid Delivery	High Bearing Temperatures	Short Bearing Life	Short Mechanical Seal Life	High Vibration	High Noise Levels	Power Demand Excessive	Motor Trips	Elevated Motor Temperature	Elevated Liquid Temperature
Bent Shaft					●	●	●	●		●			
Casing Distorted from Excessive Pipe Strain					●	●	●	●		●		●	
Cavitation	●	●	●	●	●		●	●	●				●
Clogged Impeller	●		●	●				●		●			
Driver Imbalance						●	●	●					
Electrical Problems (Driver)						●	●	●		●	●	●	
Entrained Air (Suction or Seal Leaks)	●	●	●					●	●			●	
Hydraulic Instability					●	●	●	●	●				
Impeller Installed Backward (Double-Suction Only)	●		●							●			
Improper Mechanical Seal							●						
Inlet Strainer Partially Clogged	●		●					●	●				●
Insufficient Flow through Pump													●
Insufficient Suction Pressure (NPSH)	●	●	●	●				●	●				
Insufficient Suction Volume	●	●	●	●	●			●	●				●
Internal Wear	●		●					●		●			
Leakage in Piping, Valves, Vessels	●		●	●									
Mechanical Defects, Worn, Rusted, Defective Bearings					●		●			●			
Misalignment					●	●	●	●		●		●	
Misalignment (Pump and Driver)								●		●	●		●
Mismatched Pumps in Series	●		●			●		●		●			
Noncondensables in Liquid	●	●	●					●	●			●	
Obstructions in Lines or Pump Housing	●		●	●				●				●	●
Rotor Imbalance						●	●	●					
Specific Gravity Too High	●									●		●	
Speed Too High										●	●		
Speed Too Low	●		●	●								●	
Total System Head Higher Than Design	●	●	●	●	●		●					●	●
Total System Head Lower Than Design					●		●	●	●	●			●
Unsuitable Pumps in Parallel Operation	●		●	●	●			●	●		●		●
Viscosity Too High	●		●							●		●	
Wrong Rotation	●			●						●		●	

Source: Integrated Systems, Inc.

Cavitation

Cavitation in a centrifugal pump, which has a significant, negative effect on performance, is the most common failure mode. Cavitation not only degrades a pump's performance but also greatly accelerates the wear rate of its internal components. There are three causes of cavitation in centrifugal pumps: change of phase, entrained air or gas, and turbulent flow.

Change of Phase. The formation or collapse of vapor bubbles in either the suction piping or inside the pump is one cause of cavitation. This failure mode normally occurs in applications, such as boiler feed, where the incoming liquid is at a temperature near its saturation point. In this situation, a slight change in suction pressure can cause the liquid to flash into its gaseous state. In the boiler-feed example, the water flashes into steam. The reverse process also can occur. A slight increase in suction pressure can force the entrained vapor to change phase to a liquid.

Cavitation caused by phase change seriously damages the pump's internal components. Visual evidence of operation with phase-change cavitation is an impeller surface finish like an orange peel. Prolonged operation causes small pits or holes on both the impeller shroud and vanes.

Entrained Air/Gas. Pumps are designed to handle gas-free liquids. If a centrifugal pump's suction supply contains any appreciable quantity of gas, the pump will cavitate. In the example of cavitation caused by entrainment, the liquid is reasonably stable, unlike with the change of phase described in the preceding section. Nevertheless, the entrained gas has a negative effect on pump performance. Although this form of cavitation does not seriously affect the pump's internal components, it severely restricts its output and efficiency.

The primary causes of cavitation resulting from entrained gas include two-phase suction supply, inadequate available net positive suction head ($NPSH_A$), and leakage in the suction-supply system. In some applications, the incoming liquid may contain moderate to high concentrations of air or gas. This may result from aeration or mixing of the liquid before reaching the pump or inadequate liquid levels in the supply reservoir. Regardless of the reason, the pump is forced to handle two-phase flow, which was not intended in its design.

Turbulent Flow. The effects of turbulent flow (not a true form of cavitation) on pump performance are almost identical to those described for entrained air or gas in the preceding section. Pumps are not designed to handle incoming liquids that do not have stable, laminar flow patterns. Therefore, if the flow is unstable, or turbulent, the symptoms are the same as for cavitation.

Symptoms

Noise (e.g., like a can of marbles being shaken) is one indication that a centrifugal pump is cavitating. Other indications are fluctuations of the pressure gauges, flowrate, and motor current, as well as changes in the vibration profile.

How to Eliminate

Several design or operational changes may be necessary to stop centrifugal pump cavitation. Increasing the available net positive suction head ($NPSH_A$) above that required ($NPSH_R$) is one way to stop it. The NPSH required to prevent cavitation is determined through testing by the pump manufacturer. It depends on several factors, including type of impeller inlet, impeller design, impeller rotational speed, pump flowrate, and the type of liquid being pumped. The manufacturer typically supplies curves of $NPSH_R$ as a function of flowrate for a particular liquid (usually water) in the pump's manual.

One way to increase the $NPSH_A$ is to increase the pump's suction pressure. If a pump is fed from an enclosed tank, either raising the level of the liquid in the tank or increasing the pressure in the gas space above the liquid can increase suction pressure. It is also possible to increase the $NPSH_A$ by decreasing the temperature of the liquid being pumped. This decreases the saturation pressure, which increases $NPSH_A$.

If the head losses in the suction piping can be reduced, the $NPSH_A$ will be increased. Methods for reducing head losses include increasing the pipe diameter; reducing the number of elbows, valves, and fittings in the pipe; and decreasing the pipe length.

It also may be possible to stop cavitation by reducing the pump's $NPSH_R$, which is not a constant for a given pump under all conditions. Typically, the $NPSH_R$ increases significantly as the pump's flowrate increases. Therefore, reducing the flowrate by throttling a discharge valve decreases $NPSH_R$. In addition to flowrate, $NPSH_R$ depends on pump speed. The faster the pump's impeller rotates, the greater the $NPSH_R$. Therefore, if the speed of a variable-speed centrifugal pump is reduced, the $NPSH_R$ of the pump is decreased.

Variations in Total System Head

Centrifugal pump performance follows its hydraulic curve (i.e., head versus flowrate). Therefore, any variation in the total back-pressure of the system causes a change in the pump's flow or output. Because pumps are designed to operate at their best efficiency point (BEP), they become more and more unstable as they are forced to operate at any other point because of changes in total system pressure, or head (TSH). This instability has a direct impact on centrifugal pump performance, reliability, operating costs, and required maintenance.

Symptoms of Changed Conditions

The symptoms of failure caused by variations in TSH include changes in motor speed and flowrate.

Motor Speed. The brake horsepower of the motor that drives a pump is load dependent. As the pump's operating point deviates from BEP, the amount of horsepower required also changes. This causes a change in the pump's rotating speed, which either increases or decreases depending on the amount of work the pump must perform.

Flowrate. The volume of liquid delivered by the pump varies with changes in TSH. An increase in the total system back-pressure results in decreased flow, whereas a back-pressure reduction increases the pump's output.

Correcting Problems

The best solution to problems caused by TSH variations is to prevent the variations. Although it is not possible to completely eliminate them, the operating practices for centrifugal pumps should limit operation to an acceptable range of system demand for flow and pressure. If system demand exceeds the pump's capabilities, it may be necessary to change the pump, the system requirements, or both. In many applications, the pump is either too small or too large. In these instances, it is necessary to replace the pump with one that is properly sized.

For applications where the TSH is too low and the pump is operating in run-out condition (i.e., maximum flow and minimum discharge pressure), the system demand can be corrected by restricting the discharge flow of the pump. This approach, called *false head*, changes the system's head by partially closing a discharge valve to increase the back-pressure on the pump. Because the pump must follow it's hydraulic curve, this forces the pump's performance back toward its BEP.

When the TSH is too great, there are two options: replace the pump or lower the system's back-pressure by eliminating line resistance caused by elbows, extra valves, and so on.

10.1.2 Positive-Displacement Pumps

Positive-displacement pumps are more tolerant to variations in system demands and pressures than are centrifugal pumps; however, they are still subject to a variety of common failure modes caused directly or indirectly by the process.

Rotary-Type

Rotary-type positive-displacement pumps share many common failure modes with centrifugal pumps. Both types of pumps are subject to process-induced failures caused by demands that exceed the pump's capabilities. Process-induced failures also are caused by operating methods that result in either radical changes in their operating envelope or instability in the process system.

Table 10–2 lists common failure modes for rotary-type positive-displacement pumps. The most common failure modes of these pumps are generally attributed to problems with the suction supply. They must have a constant volume of clean liquid in order to function properly.

Table 10–2 Common Failure Modes of Rotary-Type, Positive-Displacement Pumps

	THE PROBLEM										
THE CAUSES	No Liquid Delivery	Insufficient Discharge Pressure	Insufficient Capacity	Starts, But Loses Prime	Excessive Wear	Excessive Heat	Excessive Vibration and Noise	Excessive Power Demand	Motor Trips	Elevated Motor Temperature	Elevated Liquid Temperature
Air Leakage into Suction Piping or Shaft Seal		●	●				●			●	
Excessive Discharge Pressure			●		●		●	●	●		●
Excessive Suction Liquid Temperatures			●	●							
Insufficient Liquid Supply		●	●	●	●		●		●		
Internal Component Wear	●	●	●				●				
Liquid More Viscous Than Design								●	●	●	●
Liquid Vaporizing in Suction Line		●	●	●			●				●
Misaligned Coupling, Belt Drive, Chain Drive					●	●	●	●		●	
Motor or Driver Failure	●										
Pipe Strain on Pump Casing					●	●	●	●		●	
Pump Running Dry	●	●			●	●	●				
Relief Valve Stuck Open or Set Wrong		●	●								
Rotating Element Binding					●	●	●	●	●	●	
Solids or Dirt in Liquid					●						
Speed Too Low		●	●						●		
Suction Filter or Strainer Clogged	●	●	●				●			●	
Suction Piping Not Immersed in Liquid	●	●		●							
Wrong Direction of Rotation	●	●								●	

Source: Integrated Systems, Inc.

Reciprocating

Table 10–3 lists the common failure modes for reciprocating positive-displacement pumps. Reciprocating pumps can generally withstand more abuse and variations in system demand than any other type; however, they must have a consistent supply of relatively clean liquid in order to function properly.

The weak links in the reciprocating pump's design are the inlet and discharge valves used to control pumping action. These valves are the most common source of failure. In most cases, valve failure is caused by fatigue. The only positive way to prevent or minimize these failures is to ensure that proper maintenance is performed regularly on these components. It is important to follow the manufacturer's recommendations for valve maintenance and replacement.

Table 10–3 Common Failure Modes of Reciprocating Positive-Displacement Pumps

	THE PROBLEM								
THE CAUSES	No Liquid Delivery	Insufficient Capacity	Short Packing Life	Excessive Wear Liquid End	Excessive Wear Power End	Excessive Heat Power End	Excessive Vibration and Noise	Persistent Knocking	Motor Trips
Abrasives or Corrosives in Liquid			●	●					
Broken Valve Springs		●		●			●		
Cylinders Not Filling		●	●	●			●		
Drive-Train Problems							●		●
Excessive Suction Lift	●	●							
Gear Drive Problem							●	●	●
Improper Packing Selection			●						
Inadequate Lubrication						●	●		●
Liquid Entry into Power End of Pump						●			
Loose Cross-Head Pin or Crank Pin								●	
Loose Piston or Rod								●	
Low Volumetric Efficiency		●	●						
Misalignment of Rod or Packing			●						●
Non-Condensables (Air) in Liquid	●	●	●				●		●
Not Enough Suction Pressure	●	●							
Obstructions in Lines	●						●		●
One or More Cylinders Not Operating		●							
Other Mechanical Problems: Wear, Rusted, etc.					●	●	●	●	
Overloading					●				●
Pump Speed Incorrect		●				●			
Pump Valve(s) Stuck Open		●							
Relief or Bypass Valve(s) Leaking		●							
Scored Rod or Plunger		●							●
Supply Tank Empty	●								
Worn Cross-Head or Guides			●			●			
Worn Valves, Seats, Liners, Rods, or Plungers	●	●		●					

Source: Integrated Systems, Inc.

Because of the close tolerances between the pistons and the cylinder walls, reciprocating pumps cannot tolerate contaminated liquid in their suction-supply system. Many of the failure modes associated with this type of pump are caused by contamination (e.g., dirt, grit, and other solids) that enters the suction-side of the pump. This problem can be prevented by using well-maintained inlet strainers or filters.

10.2 Fans, Blowers, and Fluidizers

Tables 10–4 and 10–5 list the common failure modes for fans, blowers, and fluidizers. Typical problems with these devices include output below rating, vibration and noise, and overloaded driver bearings.

10.2.1 Centrifugal Fans

Centrifugal fans are extremely sensitive to variations in either suction or discharge conditions. In addition to variations in ambient conditions (e.g., temperature, humidity), control variables can have a direct effect on fan performance and reliability.

Most of the problems that limit fan performance and reliability are either directly or indirectly caused by improper application, installation, operation, or maintenance; however, the majority is caused by misapplication or poor operating practices. Table 10–4 lists failure modes of centrifugal fans and their causes. Some of the more common failures are aerodynamic instability, plate-out, speed changes, and lateral flexibility.

Aerodynamic Instability

Generally, the control range of centrifugal fans is about 15 percent above and 15 percent below its BEP. When fans are operated outside of this range, they tend to become progressively unstable, which causes the fan's rotor assembly and shaft to deflect from their true centerline. This deflection increases the vibration energy of the fan and accelerates the wear rate of bearings and other drive-train components.

Plate-Out

Dirt, moisture, and other contaminates tend to adhere to the fan's rotating element. This buildup, called *plate-out*, increases the mass of the rotor assembly and decreases its critical speed, the point where the phenomenon referred to as *resonance* occurs. This occurs because the additional mass affects the rotor's natural frequency. Even if the fan's speed does not change, the change in natural frequency may cause its critical speed (note that machines may have more than one) to coincide with the actual rotor speed. If this occurs, the fan will resonate, or experience severe vibration, and may catastrophically fail. The symptoms of plate-out are often confused with those of mechanical imbalance because both dramatically increase the vibration associated with the fan's running speed.

The problem of plate-out can be resolved by regularly cleaning the fan's rotating element and internal components. Removal of buildup lowers the rotor's mass and

Table 10–4 Common Failure Modes of Centrifugal Fans

THE CAUSES	THE PROBLEM									
	Insufficient Discharge Pressure	Intermittent Operation	Insufficient Capacity	Overheated Bearings	Short Bearing Life	Overload on Driver	High Vibration	High Noise Levels	Power Demand Excessive	Motor Trips
Abnormal End Thrust				●			●			
Aerodynamic Instability		●	●	●	●		●	●		
Air Leaks in System	●	●	●							
Bearings Improperly Lubricated						●	●	●		●
Bent Shaft				●	●	●	●		●	
Broken or Loose Bolts or Setscrews				●			●			
Damaged Motor							●			
Damaged Wheel	●		●	●						
Dampers or Variable-Inlet Not Properly Adjusted	●		●							
Dirt in Bearings				●			●			
Excessive Belt Tension				●			●			●
External Radiated Heat				●						
Fan Delivering More Than Rated Capacity						●	●			
Fan Wheel or Driver Imbalanced				●			●			
Foreign Material in Fan Causing Imbalance (Plate-Out)				●			●	●		
Incorrect Direction of Rotation	●		●			●	●			
Insufficient Belt Tension							●	●		
Loose Dampers or Variable-Inlet Vanes							●			
Misaligment of Bearings, Coupling, Wheel, or Belts				●		●	●	●	●	
Motor Improperly Wired						●	●	●		●
Packing Too Tight or Defective Stuffing Box						●	●		●	●
Poor Fan Inlet or Outlet Conditions	●		●							
Specific Gravity or Density Above Design						●	●		●	
Speed Too High		●		●	●	●	●			●
Speed Too Low	●	●	●					●		●
Too Much Grease in Ball Bearings				●						
Total System Head Greater Than Design	●		●	●		●			●	
Total System Head Less Than Design		●					●			●
Unstable Foundation		●		●			●	●		
Vibration Transmitted to Fan from Outside Sources				●			●	●		
Wheel Binding on Fan Housing				●		●	●	●		●
Wheel Mounted Backward on Shaft	●		●							
Worn Bearings							●	●		
Worn Coupling							●			
120-Cycle Magnetic Hum							●	●		

Source: Integrated Systems, Inc.

Table 10–5 Common Failure Modes of Blowers and Fluidizers

THE CAUSES	THE PROBLEM: No Air/Gas Delivery	Insufficient Discharge Pressure	Insufficient Capacity	Excessive Wear	Excessive Heat	Excessive Vibration and Noise	Excessive Power Demand	Motor Trips	Elevated Motor Temperature	Elevated Air/Gas Temperature
Air Leakage into Suction Piping or Shaft Seal		●	●			●				
Coupling Misaligned				●	●	●	●		●	
Excessive Discharge Pressure			●	●		●	●	●		●
Excessive Inlet Temperature/Moisture			●							
Insufficient Suction Air/Gas Supply		●	●	●		●		●		
Internal Component Wear	●	●	●							
Motor or Driver Failure	●									
Pipe Strain on Blower Casing				●	●	●	●		●	
Relief Valve Stuck Open or Set Wrong		●	●							
Rotating Element Binding				●	●	●	●	●	●	
Solids or Dirt in Inlet Air/Gas Supply				●						
Speed Too Low		●	●					●		
Suction Filter or Strainer Clogged	●	●	●			●			●	
Wrong Direction of Rotation	●	●							●	

Source: Integrated Systems, Inc.

returns its natural frequency to the initial, or design, point. In extremely dirty or dusty environments, it may be advisable to install an automatic cleaning system that uses high-pressure air or water to periodically remove any buildup that occurs.

Speed Changes

In applications where a measurable fan-speed change can occur (i.e., V-belt or variable-speed drives), care must be taken to ensure that the selected speed does not coincide with any of the fan's critical speeds. For general-purpose fans, the actual running speed is designed to be between 10 and 15 percent below the first critical speed of the rotating element. If the sheave ratio of a V-belt drive or the actual running speed is increased above the design value, it may coincide with a critical speed.

Some fans are designed to operate between critical speeds. In these applications, the fan must transition through the first critical point to reach its operating speed. These transitions must be made as quickly as possible to prevent damage. If the fan's speed remains at or near the critical speed for any extended period, serious damage can occur.

Lateral Flexibility

By design, the structural support of most general-purpose fans lacks the mass and rigidity needed to prevent flexing of the fan's housing and rotating assembly. This problem is more pronounced in the horizontal plane, but also is present in the vertical direction. If support-structure flexing is found to be the root-cause or a major contributing factor to the problem, it can be corrected by increasing the stiffness and/or mass of the structure; however, do not fill the structure with concrete. As it dries, concrete pulls away from the structure and does little to improve its rigidity.

10.2.2 Blowers or Positive-Displacement Fans

Blowers, or positive-displacement fans, have the same common failure modes as rotary pumps and compressors. Table 10–5 (see also Tables 10–2 and 10–9) lists the failure modes that most often affect blowers and fluidizers. In particular, blower failures occur because of process instability, caused by start/stop operation and demand variations, and mechanical failures caused by close tolerances.

Process Instability

Blowers are very sensitive to variations in their operating envelope. As little as a one psig change in downstream pressure can cause the blower to become extremely unstable. The probability of catastrophic failure or severe damage to blower components increases in direct proportion to the amount and speed of the variation in demand or downstream pressure.

Start/Stop Operation. The transients caused by frequent start/stop operation also have a negative effect on blower reliability. Conversely, blowers that operate constantly in a stable environment rarely exhibit problems. The major reason is the severe axial thrusting caused by the frequent variations in suction or discharge pressure caused by the start/stop operation.

Demand Variations. Variations in pressure and volume demands have a serious impact on blower reliability. Because blowers are positive-displacement devices, they generate a constant volume and a variable pressure that depends on the downstream system's back-pressure. If demand decreases, the blower's discharge pressure continues to increase until (1) a downstream component fails and reduces the back-pressure, or (2) the brake horsepower required to drive the blower is greater than the motor's locked rotor rating. Either of these outcomes will result in failure of the blower system. The former may result in a reportable release, whereas the latter will cause the motor to trip or burn out.

Frequent variations in demand greatly accelerate the wear rate of the thrust bearings in the blower. This can be directly attributed to the constant, instantaneous axial thrusting caused by variations in the discharge pressure required by the downstream system.

Mechanical Failures

Because of the extremely close clearances that must exist within the blower, the potential for serious mechanical damage or catastrophic failure is higher than with other rotating machinery. The primary failure points include thrust bearings, timing gears, and rotor assemblies.

In many cases, these mechanical failures are caused by the instability discussed in the preceding sections, but poor maintenance practices are another major cause. See the troubleshooting guide in Table 10–9 for rotary-type, positive-displacement compressors for more information.

10.3 Conveyors

Conveyor failure modes vary depending on the type of system. Two common types of conveyor systems used in chemical plants are pneumatic and chain-type mechanical.

10.3.1 Pneumatic

Table 10–6 lists common failure modes associated with pneumatic-conveyor systems; however, most common problems can be attributed to either conveyor piping plugging or problems with the prime mover (i.e., fan or fluidizer). For a centrifugal fan troubleshooting guide, refer to Table 10–4. For fluidizer and blower guides, refer to Table 10–5.

10.3.2 Chain-Type Mechanical

The Hefler-type chain conveyor is a common type of mechanical conveyor used in integrated chemical plants. Table 10–7 provides the more common failure modes of this type of conveyor. Most of the failure modes defined in the table can be directly attributed to operating practices, changes in incoming product quality (i.e., density or contamination), or maintenance practices.

10.4 Compressors

Compressors can be divided into three classifications: centrifugal, rotary, and reciprocating. This section identifies the common failure modes for each.

10.4.1 Centrifugal

The operating dynamics of centrifugal compressors are the same as for other centrifugal machine-trains. The dominant forces and vibration profiles are typically iden-

Table 10–6 Common Failure Modes of Pneumatic Conveyors

	THE PROBLEM						
THE CAUSES	Fails to Deliver Rated Capacity	Output Exceeds Rated Capacity	Frequent Fan/Blower Motor Trips	Product Contamination	Frequent System Blockage	Fan/Blower Failures	Fan/Blower Bearing Failures
Aerodynamic Imbalance			●			●	●
Blockage Caused By Compaction of Product	●		●			●	
Contamination in Incoming Product				●			
Excessive Moisture in Product/Piping	●		●	●	●	●	
Fan/Blower Too Small	●		●			●	
Foreign Object Blocking Piping	●		●		●		
Improper Lubrication						●	●
Mechanical Imbalance						●	●
Misalignment						●	●
Piping Configuration Unsuitable	●		●		●		
Piping Leakage	●			●			
Product Compaction During Downtime/Stoppage	●		●		●		
Product Density Too Great	●		●			●	
Product Density Too Low		●					
Rotor Binding or Contacting			●			●	●
Startup Torque Too Great			●				

Source: Integrated Systems, Inc.

tical to pumps or fans; however, the effects of variable load and other process variables (e.g., temperatures, inlet/discharge pressure) are more pronounced than in other rotating machines. Table 10–8 identifies the common failure modes for centrifugal compressors.

Aerodynamic instability is the most common failure mode for centrifugal compressors. Variable demand and restrictions of the inlet airflow are common sources of this instability. Even slight variations can cause dramatic changes in the operating stability of the compressor.

Entrained liquids and solids can also affect operating life. When dirty air must be handled, open-type impellers should be used. An open design provides the ability to handle a moderate amount of dirt or other solids in the inlet air supply; however, inlet

Table 10–7 Common Failure Modes of Hefler-Type Chain Conveyors

THE CAUSES	THE PROBLEM: Fails to Deliver Rated Capacity	Frequent Drive Motor Trips	Conveyor Blockage	Abnormal Wear on Drive Gears	Excessive Shear Pin Breakage	Excessive Bearing Failures/Wear	Motor Overheats	Excessive Noise
Blockage of Conveyor Ductwork	●	●					●	
Chain Misaligned			●		●	●	●	●
Conveyor Chain Binding on Ductwork								●
Conveyor Not Emptied Before Shutdown		●	●		●			
Conveyor Over-Filled When Idle		●	●		●			
Excessive Looseness on Drive Chains	●							
Excessive Moisture in Product	●	●	●					
Foreign Object Obstructing Chain	●	●				●	●	
Gear Set Center-to-Center Distance Incorrect				●				●
Gears Misaligned				●		●	●	●
Lack of Lubrication				●		●	●	●
Motor Speed Control Damaged or Not Calibrated	●							
Product Density Too High	●	●			●		●	
Too Much Volume/Load	●	●					●	

Source: Integrated Systems, Inc.

filters are recommended for all applications, and controlled liquid injection for cleaning and cooling should be considered during the design process.

10.4.2 Rotary-Type Positive Displacement

Table 10–9 lists the common failure modes of rotary-type positive-displacement compressors. This type of compressor can be grouped into two types: sliding vane and rotary screw.

Sliding Vane

Sliding-vane compressors have the same failure modes as vane-type pumps. The dominant components in their vibration profile are running speed, vane-pass frequency, and bearing-rotation frequencies. In normal operation, the dominate energy is at the shaft's running speed. The other frequency components are at much lower energy

Table 10–8 Common Failure Modes of Centrifugal Compressors

THE CAUSES	THE PROBLEM								
	Excessive Vibration	Compressor Surges	Loss of Discharge Pressure	Low Lube Oil Pressure	Excessive Bearing Oil Drain Temp.	Units Do Not Stay in Alignment	Persistent Unloading	Water in Lube Oil	Motor Trips
Bearing Lube Oil Orifice Missing or Plugged				●					
Bent Rotor (Caused by Uneven Heating and Cooling)	●						●		
Build-up of Deposits on Diffuser		●							
Build-up of Deposits on Rotor	●	●							
Change in System Resistance		●							●
Clogged Oil Strainer/Filter				●					
Compressor Not Up to Speed			●						
Condensate in Oil Reservoir								●	
Damaged Rotor	●								
Dry Gear Coupling	●								
Excessive Bearing Clearance	●								
Excessive Inlet Temperature			●						
Failure of Both Main and Auxiliary Oil Pumps				●					
Faulty Temperature Gauge or Switch				●	●				●
Improperly Assembled Parts	●						●		●
Incorrect Pressure Control Valve Setting				●					
Insufficient Flow		●							
Leak In Discharge Piping			●						
Leak In Lube Oil Cooler Tubes or Tube Sheet								●	
Leak in Oil Pump Suction Piping				●					
Liquid "Slugging"	●						●		
Loose or Broken Bolting	●								
Loose Rotor Parts	●								
Oil Leakage				●					
Oil Pump Suction Plugged				●					
Oil Reservoir Low Level				●					
Operating at Low Speed w/o Auxiliary Oil Pump				●					
Operating in Critical Speed Range	●								
Operating in Surge Region	●								
Piping Strain	●					●	●	●	●
Poor Oil Condition					●				
Relief Valve Improperly Set or Stuck Open				●					
Rotor Imbalance	●						●		
Rough Rotor Shaft Journal Surface					●		●		●
Shaft Misalignment	●					●			
Sympathetic Vibration	●						●	●	
Vibration					●				
Warped Foundation or Baseplate							●		●
Wiped or Damaged Bearings					●				●
Worn or Damaged Coupling	●								

Source: Integrated Systems, Inc.

Table 10–9 Common Failure Modes of Rotary-Type, Positive-Displacement Compressors

	THE PROBLEM									
THE CAUSES	No Air/Gas Delivery	Insufficient Discharge Pressure	Insufficient Capacity	Excessive Wear	Excessive Heat	Excessive Vibration and Noise	Excessive Power Demand	Motor Trips	Elevated Motor Temperature	Elevated Air/Gas Temperature
Air Leakage Into Suction Piping or Shaft Seal		●	●			●				
Coupling Misaligned				●	●	●	●		●	
Excessive Discharge Pressure			●	●		●	●	●		●
Excessive Inlet Temperature/Moisture			●							
Insufficient Suction Air/Gas Supply		●	●	●		●		●		
Internal Component Wear	●	●	●							
Motor or Driver Failure	●									
Pipe Strain on Compressor Casing				●	●	●	●		●	
Relief Valve Stuck Open or Set Wrong		●	●							
Rotating Element Binding				●	●	●	●	●	●	
Solids or Dirt in Inlet Air/Gas Supply				●						
Speed Too Low		●	●					●		
Suction Filter or Strainer Clogged	●	●	●			●			●	
Wrong Direction of Rotation	●	●							●	

Source: Integrated Systems, Inc.

levels. Common failures of this type of compressor occur with shaft seals, vanes, and bearings.

Shaft Seals. Leakage through the shaft's seals should be checked visually once a week or as part of every data acquisition route. Leakage may not be apparent from the outside of the gland. If the fluid is removed through a vent, the discharge should be configured for easy inspection. Generally, more leakage than normal is the signal to replace a seal. Under good conditions, they have a normal life of 10,000 to 15,000 hours and should routinely be replaced when this service life has been reached.

Vanes. Vanes wear continuously on their outer edges and, to some degree, on the faces that slide in and out of the slots. The vane material is affected somewhat by prolonged heat, which causes gradual deterioration. Typical life expectancy of vanes in 100 psig service is about 16,000 hours of operation. For low-pressure applications, life may reach 32,000 hours.

Replacing vanes before they break is extremely important. Breakage during operation can severely damage the compressor, which requires a complete overhaul and realignment of heads and clearances.

Bearings. In normal service, bearings have a relatively long life. Replacement after about six years of operation is generally recommended. Bearing defects are usually displayed in the same manner in a vibration profile as for any rotating machine-train. Inner- and outer-race defects are the dominant failure modes, but roller spin may also contribute to the failure.

Rotary Screw

The most common reason for compressor failure or component damage is process instability. Rotary-screw compressors are designed to deliver a constant volume and pressure of air or gas. These units are extremely susceptible to any change in either inlet or discharge conditions. A slight variation in pressure, temperature, or volume can result in instantaneous failure. The following are used as indices of instability and potential problems: rotor mesh, axial movement, thrust bearings, and gear mesh.

Rotor Mesh. In normal operation, the vibration energy generated by male and female rotor meshing is very low. As the process becomes unstable, the energy caused by the rotor-meshing frequency increases, with both the amplitude of the meshing frequency and the width of the peak increasing. In addition, the noise floor surrounding the meshing frequency becomes more pronounced. This white noise is similar to that observed in a cavitating pump or unstable fan.

Axial Movement. The normal tendency of the rotors and helical timing gears is to generate axial shaft movement, or thrusting; however, the extremely tight clearances between the male and female rotors do not tolerate any excessive axial movement and, therefore, axial movement should be a primary monitoring parameter. Axial measurements are needed from both rotor assemblies. If the vibration amplitude of these measurements increases at all, it is highly probable that the compressor will fail.

Thrust Bearings. Although process instability can affect both fixed and float bearings, thrust bearings are more likely to show early degradation as a result of process instability or abnormal compressor dynamics. Therefore, these bearings should be monitored closely, and any degradation or hint of excessive axial clearance should be corrected immediately.

Gear-Mesh. The gear-mesh vibration profile also indicates prolonged compressor instability. Deflection of the rotor shafts changes the wear pattern on the helical gear sets. This change in pattern increases the backlash in the gear mesh, results in higher vibration levels, and increases thrusting.

Table 10–10a Common Failure Modes of Reciprocating Compressors

THE CAUSES	THE PROBLEM																							
	Air Discharge Temperature Above Normal	Carbonaceous Deposits Abnormal	Compressor Fails to Start	Compressor Fails to Unload	Compressor Noisy or Knocks	Compressor Parts Overheat	Crankcase Oil Pressure Low	Crankcase Water Accumulation	Delivery Less Than Rated Capacity	Discharge Pressure Below Normal	Excessive Compressor Vibration	Interceder Pressure Above Normal	Interceder Pressure Below Normal	Intercooler Safety Valve Pops	Motor Over-Heating	Oil Pumping Excessive (Single-Acting Compressor)	Operating Cycle Abnormality Long	Outlet Water Temperature Above Normal	Piston Ring, Piston, Cylinder Wear Excessive	Piston Rod or Packing Wear Excessive	Receiver Pressure Above Normal	Receiver Safety Valve Pops	Starts Too Often	Valve Wear and Breakage Normal
Air Discharge Temperature Too High		●																●						
Air Fitter Defective		●																	●	●				●
Air Flow to Fan Blocked	●	●				●																		
Air Leak into Pump Suction							●																	
Ambient Temperature Too High	●	●				●									●									
Assembly Incorrect																								●
Bearings Need Adjustment or Renewal					●	●	●								●									
Belts Slipping					●				●	●														
Belts Too Tight			●			●									●									
Centrifugal Pilot Valve Leaks																●								
Check or Discharge Valve Defective						●																		
Control Air Filter, Strainer Clogged				●																				
Control Air Line Clogged																					●			
Control Air Pipe Leaks																					●	●		
Crankcase Oil Pressure Too High																●								
Crankshaft End Play Too Great					●																			
Cylinder, Head, Cooler Dirty	●	●																						
Cylinder, Head, Intercooler Dirty						●												●						
Cylinder (Piston) Worn or Scored	●	●			●	●		●	●	●		●*H*	●*L*	●*H*	●*L*	●	●		●*H*	●*H*				
Detergent Oil Being Used (*3*)								●																
Demand Too Steady (*2*)																							●	
Dirt, Rust Entering Cylinder		●																	●	●				●

10.4.3 Reciprocating Positive Displacement

Reciprocating compressors have a history of chronic failures that include valves, lubrication system, pulsation, and imbalance. Table 10–10a to e identifies common failure modes and causes for this type of compressor.

Like all reciprocating machines, reciprocating compressors normally generate higher levels of vibration than centrifugal machines. In part, the increased level of vibration is caused by the impact as each piston reaches top dead-center and bottom dead-center of its stroke. The energy levels are also influenced by the unbalanced forces generated by nonopposed pistons and looseness in the piston rods, wrist pins, and journals of the compressor. In most cases, the dominant vibration frequency is the second harmonic (2X) of the main crankshaft's rotating speed. Again, this results from the

Table 10–10b Common Failure Modes of Reciprocating Compressors

	THE PROBLEM																							
THE CAUSES	Air Discharge Temperature Above Normal	Carbonaceous Deposits Abnormal	Compressor Fails to Start	Compressor Fails to Unload	Compressor Noisy or Knocks	Compressor Parts Overheat	Crankcase Oil Pressure Low	Crankcase Water Accumulation	Delivery Less Than Rated Capacity	Discharge Pressure Below Normal	Excessive Compressor Vibration	Intercooler Pressure Above Normal	Intercooler Pressure Below Normal	Intercooler Safety Valve Pops	Motor Over-Heating	Oil Pumping Excessive (Single-Acting Compressor)	Operating Cycle Abnormally Long	Outlet Water Temperature Above Normal	Piston Ring, Piston, Cylinder Wear Excessive	Piston Rod or Packing Wear Excessive	Receiver Pressure Above Normal	Receiver Safety Valve Pops	Starts Too Often	Valve Wear and Breakage Normal
Discharge Line Restricted	●														●									
Discharge Pressure Above Rating	●	●			●	●			●		●	●		●	●		●	●	●	●	●	●		
Electrical Conditions Wrong			●												●									
Excessive Number of Starts															●									
Excitation Inadequate			●												●									
Foundation Bolts Loose					●						●													
Foundation Too Small											●													
Foundation Uneven–Unit Rocks					●						●													
Fuses Blown			●																					
Gaskets Leak	●	●			●	●			●	●		●*H*	●*L*	●*H*	●*L*		●		●*H*	●*H*				
Gauge Defective							●			●		●	●								●			
Gear Pump Worn/Defective							●																	
Grout, Improperly Placed											●													
Intake Filter Clogged	●				●	●			●	●			●		●	●	●							
Intake Pipe Restricted, Too Small, Too Long	●				●	●			●	●			●		●	●	●							
Intercooler, Drain More Often								●																
Intercooler Leaks													●											
Intercooler Passages Clogged												●		●										
Intercooler Pressure Too High																		●						
Intercooler Vibrating					●																			
Leveling Wedges Left Under Compressor											●													
Liquid Carry-Over					●			●											●	●				●

impact that occurs when each piston changes directions (i.e., two impacts occur during one complete crankshaft rotation).

Valves

Valve failure is the dominant failure mode for reciprocating compressors. Because of their high cyclic rate, which exceeds 80 million cycles per year, inlet and discharge valves tend to work hard and crack.

Lubrication System

Poor maintenance of lubrication system components, such as filters and strainers, typically causes premature failure. Such maintenance is crucial to reciprocating

Table 10–10c Common Failure Modes of Reciprocating Compressors

THE CAUSES	THE PROBLEM																							
	Air Discharge Temperature Above Normal	Carbonaceous Deposits Abnormal	Compressor Fails to Start	Compressor Fails to Unload	Compressor Noisy or Knocks	Compressor Parts Overheat	Crankcase Oil Pressure Low	Crankcase Water Accumulation	Delivery Less Than Rated Capacity	Discharge Pressure Below Normal	Excessive Compressor Vibration	Intercooler Pressure Above Normal	Intercooler Pressure Below Normal	Intercooler Safety Valve Pops	Motor Over-Heating	Oil Pumping Excessive (Single-Acting Compressor)	Operating Cycle Abnormality Long	Outlet Water Temperature Above Normal	Piston Ring, Piston, Cylinder Wear Excessive	Piston Rod or Packing Wear Excessive	Receiver Pressure Above Normal	Receiver Safety Valve Pops	Starts Too Often	Valve Wear and Breakage Normal
Location Too Humid and Damp								●																
Low Oil Pressure Relay Open			●																					
Lubrication Inadequate	●				●	●									●		●		●	●				●
Motor Overload Relay Tripped			●																					
Motor Rotor Loose on Shaft					●						●													
Motor Too Small			●												●									
New Valve on Worn Seat																								●
"Off" Time Insufficient	●	●				●																		
Oil Feed Excessive		●			●															●				●
Oil Filter or Strainer Clogged							●																	
Oil Level Too High	●	●			●	●										●								
Oil Level Too Low						●	●																	
Oil Relief Valve Defective							●																	
Oil Viscosity Incorrect		●			●	●	●								●	●			●	●				●
Oil Wrong Type																●								
Packing Rings Worn, Stuck, Broken																				●				
Piping Improperly Supported											●													
Piston or Piston Nut Loose					●																			
Piston or Ring Drain Hole Clogged																●								
Piston Ring Gaps Not Staggered																●								
Piston Rings Worn, Broken, or Stuck	●	●			●	●		●	●	●		●*H*	●*L*	●*H*	●*L*	●	●		●*H*	●*H*				
Piston-to-Head Clearance Too Small					●																			

compressors because they rely on the lubrication system to provide a uniform oil film between closely fitting parts (e.g., piston rings and the cylinder wall). Partial or complete failure of the lube system results in catastrophic failure of the compressor.

Pulsation

Reciprocating compressors generate pulses of compressed air or gas that are discharged into the piping that transports the air or gas to its point(s) of use. This pulsation often generates resonance in the piping system, and pulse impact (i.e., standing waves) can severely damage other machinery connected to the compressed-air system. Although this behavior does not cause the compressor to fail, it must be prevented to protect other plant equipment. Note, however, that most compressed-air systems do not use pulsation dampers.

Table 10–10d Common Failure Modes of Reciprocating Compressors

THE CAUSES	THE PROBLEM: Air Discharge Temperature Above Normal	Carbonaceous Deposits Abnormal	Compressor Fails to Start	Compressor Fails to Unload	Compressor Noisy or Knocks	Compressor Parts Overheat	Crankcase Oil Pressure Low	Crankcase Water Accumulation	Delivery Less Than Rated Capacity	Discharge Pressure Below Normal	Excessive Compressor Vibration	Intercooler Pressure Above Normal	Intercooler Pressure Below Normal	Intercooler Safety Valve Pops	Motor Over-Heating	Oil Pumping Excessive (Single-Acting Compressor)	Operating Cycle Abnormally Long	Outlet Water Temperature Above Normal	Piston Ring, Piston, Cylinder Wear Excessive	Piston Rod or Packing Wear Excessive	Receiver Pressure Above Normal	Receiver Safety Valve Pops	Starts Too Often	Valve Wear and Breakage Normal
Pulley or Flywheel Loose					●						●													
Receiver, Drain More Often																							●	
Receiver Too Small																							●	
Regulation Piping Clogged				●																				
Resonant Pulsation (Inlet or Discharge)												●	●	●	●									●
Rod Packing Leaks	●				●	●			●	●														
Rod Packing Too Tight						●																		
Rod Scored, Pitted, Worn																				●				
Rotation Wrong	●	●	●																					
Runs Too Little *(2)*								●																
Safety Valve Defective													●	●								●		
Safety Valve Leaks	●				●				●	●			●		●									
Safety Valve Set Too Low														●								●		
Speed Demands Exceed Rating																	●							
Speed Lower Than Rating									●	●														
Speed Too High	●	●				●					●				●			●						
Springs Broken																								●
System Demand Exceeds Rating	●				●				●	●			●		●		●							
System Leakage Excessive	●				●				●	●			●		●		●						●	
Tank Ringing Noise					●																			
Unloader Running Time Too Long *(1)*																●								
Unloader or Control Defective	●	●	●	●	●	●			●	●	●	●	●	●	●		●		●	●	●	●	●	●

Each time the compressor discharges compressed air, the air tends to act like a compression spring. Because it rapidly expands to fill the discharge piping's available volume, the pulse of high-pressure air can cause serious damage. The pulsation wavelength, λ, from a compressor with a double-acting piston design can be determined by:

$$\lambda = \frac{60a}{2n} = \frac{34,050}{n}$$

Where:

λ = Wavelength, feet

a = Speed of sound = 1,135 feet/second

n = Compressor speed, revolutions/minute

Table 10–10e Common Failure Modes of Reciprocating Compressors

THE CAUSES	Air Discharge Temperature Above Normal	Carbonaceous Deposits Abnormal	Compressor Fails to Start	Compressor Fails to Unload	Compressor Noisy or Knocks	Compressor Parts Overheat	Crankcase Oil Pressure Low	Crankcase Water Accumulation	Delivery Less Than Rated Capacity	Discharge Pressure Below Normal	Excessive Compressor Vibration	Intercooler Pressure Above Normal	Intercooler Pressure Below Normal	Intercooler Safety Valve Pops	Motor Over-Heating	Oil Pumping Excessive (Single-Acting Compressor)	Operating Cycle Abnormally Long	Outlet Water Temperature Above Normal	Piston Ring, Piston, Cylinder Wear Excessive	Piston Rod or Packing Wear Excessive	Receiver Pressure Above Normal	Receiver Safety Valve Pops	Starts Too Often	Valve Wear and Breakage Normal
Unloader Parts Worn or Dirty				●																				
Unloader Setting Incorrect	●	●	●		●	●			●	●		●	●	●	●		●		●	●	●	●	●	
V-Belt or Other Misalignment					●	●					●													
Valves Dirty	●	●				●						●	●											●
Valves Incorrectly Located	●	●			●	●			●	●		●*H*	●*L*	●*H*	●*L*		●		●*H*	●*H*				
Valves Not Seated in Cylinder	●	●			●	●			●	●		●*H*	●*L*	●*H*	●*L*		●		●*H*	●*H*				
Valves Worn or Broken	●	●			●	●			●	●		●*H*	●*L*	●*H*	●*L*		●*H*	●*H*	●*H*	●*H*				
Ventilation Poor	●	●				●									●									
Voltage Abnormally Low			●												●									
Water Inlet Temperature Too High	●	●				●			●			●						●						
Water Jacket or Cooler Dirty	●	●																						
Water Jackets or Intercooler Dirty						●						●						●						
Water Quantity Insufficient	●					●			●			●						●						
Wiring Incorrect			●																					
Worn Valve on Good Seat																								●
Wrong Oil Type		●																	●	●				
(1) Use Automatic Start/Stop Control																								
(2) Use Constant Speed Control																								
(3) Change to Non-Detergent Oil																								
H (in High Pressure Cylinder)																								
L (in Low Pressure Cylinder)																								

(Column group heading: THE PROBLEM)

For a double-acting piston design, a compressor running at 1,200 revolutions per minute (rpm) will generate a standing wave of 28.4 feet. In other words, a shock load equivalent to the discharge pressure will be transmitted to any piping or machine connected to the discharge piping and located within 28 feet of the compressor. Note that, for a single-acting cylinder, the wavelength will be twice as long.

Imbalance

Compressor inertial forces may have two effects on the operating dynamics of a reciprocating compressor, affecting its balance characteristics. The first effect is a force in the direction of the piston movement, which is displayed as impacts in a vibration profile as the piston reaches top and bottom dead-center of its stroke. The second effect is a couple, or moment, caused by an offset between the axes of two or more pistons on a common crankshaft. The interrelationship and magnitude of these two effects depend on such factors as number of cranks, longitudinal and angular arrangement, cylinder arrangement, and amount of counterbalancing possible. Two significant vibration periods result, the primary at the compressor's rotation speed (X) and the secondary at 2X.

Although the forces developed are sinusoidal, only the maximum (i.e., the amplitude) is considered in the analysis. Figure 10–1 shows relative values of the inertial forces for various compressor arrangements.

10.5. Mixers and Agitators

Table 10–11 identifies common failure modes and their causes for mixers and agitators. Most of the problems that affect performance and reliability are caused by improper installation or variations in the product's physical properties.

Proper installation of mixers and agitators is critical. The physical location of the vanes or propellers within the vessel is the dominant factor to consider. If the vanes are set too close to the side, corner, or bottom of the vessel, a stagnant zone will develop that causes both loss of mixing quality and premature damage to the equipment. If the vanes are set too close to the liquid level, vortexing can develop. This causes a loss of efficiency and accelerated component wear.

Variations in the product's physical properties, such as viscosity, also cause loss of mixing efficiency and premature wear of mixer components. Although the initial selection of the mixer or agitator may have addressed the full range of physical properties expected to be encountered, applications sometimes change. Such a change may result in the use of improper equipment for a particular application.

10.6 Dust Collectors

This section identifies common problems and their causes for baghouse and cyclonic separator dust-collection systems.

10.6.1 Baghouses

Table 10–12 lists the common failure modes for baghouses. This guide may be used for all such units that use fabric filter bags as the primary dust-collection media.

10.6.2 Cyclonic Separators

Table 10–13 identifies the failure modes and their causes for cyclonic separators. Because there are no moving parts within a cyclone, most of the problems associated with this type of system can be attributed to variations in process parameters, such as flowrate, dust load, dust composition (e.g., density, size), and ambient conditions (e.g., temperature, humidity).

CRANK ARRANGEMENTS	FORCES		COUPLES	
	PRIMARY	SECONDARY	PRIMARY	SECONDARY
SINGLE CRANK	F' WITHOUT COUNTERWTS. 0.5F' WITH COUNTERWTS.	F"	NONE	NONE
TWO CRANKS AT 180° IN LINE CYLINDERS	ZERO	2F"	F'D WITHOUT COUNTERWTS. $\frac{F'D}{2}$ WITH COUNTERWTS.	NONE
TWO CRANKS AT 180° OPPOSED CYLINDERS	ZERO	ZERO	NIL	NIL
TWO CRANKS AT 90°	1.41 F' WITHOUT COUNTERWTS. 0.707 F' WITH COUNTERWTS.	ZERO	.707F'D WITHOUT COUNTERWTS. 0.354 F'D WITH COUNTERWTS.	F"D
TWO CYLINDERS ON ONE CRANK CYLINDERS AT 90°	F' WITHOUT COUNTERWTS. ZERO WITH COUNTERWTS.	1.41 F"	NIL	NIL
TWO CYLINDERS ON ONE CRANK OPPOSED CYLINDERS	2F' WITHOUT COUNTERWTS. F' WITH COUNTERWTS.	ZERO	NONE	NIL
THREE CRANKS AT 120°	ZERO	ZERO	3.46F'D WITHOUT COUNTERWTS. 1.73F'D WITH COUNTERWTS.	3.46 F"D
FOUR CYLINDERS CRANKS AT 180°	ZERO	4F"	ZERO	ZERO
FOUR CYLINDERS CRANKS AT 90°	ZERO	ZERO	1.41F'D WITHOUT COUNTERWTS. 0.707 F'D WITH COUNTERWTS.	4.0 F"D
SIX CYLINDERS	ZERO	ZERO	ZERO	ZERO

F' = PRIMARY INERTIA FORCE IN LBS.
$F' = .0000284\ RN^2W$
F" = SECONDARY INERTIA FORCE IN LBS.
$F'' = \frac{R}{L}F'$
R = CRANK RADIUS, INCHES
N = R.P.M.
W = RECIPROCATING WEIGHT OF ONE CYLINDER, LBS
L = LENGTH OF CONNECTING ROD, INCHES
D = CYLINDER CENTER DISTANCE

Figure 10–1 Unbalanced inertial forces and couples for various reciprocating compressors.

10.7 Process Rolls

Most of the failures that cause reliability problems with process rolls can be attributed to either improper installation or abnormal induced loads. Table 10–14 identifies the common failure modes of process rolls and their causes.

Table 10–11 Common Failure Modes of Mixers And Agitators

	THE PROBLEM						
THE CAUSES	Surface Vortex Visible	Incomplete Mixing of Product	Excessive Vibration	Excessive Wear	Motor Overheats	Excessive Power Demand	Excessive Bearing Failures
Abrasives in Product				●			
Mixer/Agitator Setting Too Close to Side or Corner		●	●	●		●	●
Mixer/Agitator Setting Too High	●	●					
Mixer/Agitator Setting Too Low		●		●			
Mixer/Agitator Shaft Too Long							●
Product Temperature Too Low		●			●	●	
Rotating Element Imbalanced or Damaged		●	●		●	●	●
Speed Too High	●		●	●			
Speed Too Low		●					
Viscosity/Specific Gravity Too High		●			●	●	
Wrong Direction of Rotation		●			●		●

Source: Integrated Systems, Inc.

Installation problems are normally the result of misalignment where the roll is not perpendicular to the travel path of the belt or transported product. If process rolls are misaligned, either vertically or horizontally, the load imparted by the belt or carried product is not uniformly spread across the roll face or to the support bearings. As a result, both the roll face and bearings are subjected to abnormal wear and may prematurely fail.

Operating methods may cause induced loads that are outside the acceptable design limits of the roll or its support structure. Operating variables, such as belt or strip tension or tracking, may be the source of chronic reliability problems. As with misalignment, these variables apply an unequal load distribution across the roll face and bearing-support structure. These abnormal loads accelerate wear and may result in premature failure of the bearings or roll.

10.8 Gearboxes/Reducers

This section identifies common gearbox (also called a *reducer*) problems and their causes. Table 10–15 lists the more common gearbox failure modes. One of the primary causes of failure is the fact that, with few exceptions, gear sets are designed for oper-

Table 10–12 Common Failure Modes of Baghouses

THE CAUSES	THE PROBLEM: Continuous Release of Dust-Laden Air	Intermittent Release of Dust-Laden Air	Loss of Plant Air Pressure	Blow-Down Ineffective	Insufficient Capacity	Excessive Differential Pressure	Fan/Blower Motor Trips	Fan Has High Vibration	Premature Bag Failures	Differential Pressure Too Low	Chronic Plugging of Bags
Bag Material Incompatible for Application									●		●
Bag Plugged						●	●	●			
Bag Torn or Improperly Installed	●							●	●	●	
Baghouse Undersized					●		●				●
Blow-Down Cycle Interval Too Long						●	●				
Blow-Down Cycle Time Failed or Damaged						●	●				
Blow-Down Nozzles Plugged						●					
Blow-Down Pilot Valve Failed to Open (Solenoid Failure)			●			●					
Dust Load Exceeds Capacity											●
Excessive Demand			●								
Fan/Blower Not Operating Properly					●						
Improper or Inadequate Lubrication								●			
Leaks in Ductwork or Baghouse	●				●						
Misalignment of Fan and Motor								●			
Moisture Content Too High											●
Not Enough Blow-Down Air (Pressure and Volume)			●	●		●					
Not Enough Dust Layer on Filter Bags	●	●						●		●	
Piping/Valve Leaks			●								
Plate-Out (Dust Build-up on Fan's Rotor)								●			
Plenum Cracked or Seal Defective	●		●							●	
Rotor Imbalanced								●			
Ruptured Blow-Down Diaphrams			●	●		●					
Suction Ductwork Blocked or Plugged					●						

Source: Integrated Systems, Inc.

ation in one direction only. Failure is often caused by inappropriate bidirectional operation of the gearbox or backward installation of the gear set. Unless specifically manufactured for bidirectional operation, the "nonpower" side of the gear's teeth is not finished. Therefore, this side is rougher and does not provide the same tolerance as the finished "power" side.

Table 10–13 Common Failure Modes of Cyclonic Separators

	THE PROBLEM								
THE CAUSES	Continuous Release of Dust-Laden Air	Intermittent Release of Dust-Laden Air	Cyclone Plugs in Inlet Chamber	Cyclone Plugs in Dust Removal Section	Rotor-Lock Valve Fails to Turn	Excessive Differential Pressure	Differential Pressure Too Low	Rotor-Lock Valve Leaks	Fan Has High Vibration
Clearance Set Wrong								●	
Density and Size Distribution of Dust Too High				●	●	●			●
Density and Size Distribution of Dust Too Low	●	●							
Dust Load Exceeds Capacity	●	●			●				●
Excessive Moisture in Incoming Air			●						
Foreign Object Lodged in Valve					●				
Improper Drive-Train Adjustments					●				
Improper Lubrication					●				
Incoming Air Velocity Too High						●			
Incoming Air Velocity Too Low	●	●	●				●		
Internal Wear or Damage								●	
Large Contaminates in Incoming Air Stream			●		●				
Prime Mover (Fan, Blower) Malfunctioning	●	●				●	●		●
Rotor-Lock Valve Turning Too Slow	●	●		●					
Seals Damaged								●	

Source: Integrated Systems, Inc.

Note that it has become standard practice in some plants to reverse the pinion or bullgear in an effort to extend the gear set's useful life. Although this practice permits longer operation times, the torsional power generated by a reversed gear set is not as uniform and consistent as when the gears are properly installed.

Gear overload is another leading cause of failure. In some instances, the overload is constant, which is an indication that the gearbox is not suitable for the application. In other cases, the overload is intermittent and occurs only when the speed changes or when specific production demands cause a momentary spike in the torsional load requirement of the gearbox.

Misalignment, both real and induced, is also a primary root-cause of gear failure. The only way to ensure that gears are properly aligned is to hard blue the gears immedi-

Table 10–14 Common Failure Modes of Process Rolls

THE CAUSES	THE PROBLEM: Frequent Bearing Failures	Abnormal Roll Face Wear	Roll Neck Damage or Failure	Abnormal Product Tracking	Motor Overheats	Excessive Power Demand	High Vibration	Product Quality Poor
Defective or Damaged Roll Bearings								●
Excessive Product Tension	●	●	●	●	●	●		●
Excessive Load					●	●		
Misaligned Roll	●	●	●	●	●	●	●	●
Poor Roll Grinding Practices								●
Product Tension Too Loose								●
Product Tension/Tracking Problem		●		●				●
Roll Face Damage	●		●	●				●
Speed Coincides with Roll's Natural Frequency	●			●			●	●
Speed Coincides with Structural Natural Frequency		●		●			●	●

Source: Integrated Systems, Inc.

ately after installation. After the gears have run for a short time, their wear pattern should be visually inspected. If the pattern does not conform to vendor's specifications, alignment should be adjusted.

Poor maintenance practices are the primary source of real misalignment problems. Proper alignment of gear sets, especially large ones, is not an easy task. Gearbox manufacturers do not provide an easy, positive means to ensure that shafts are parallel and that the proper center-to-center distance is maintained.

Induced misalignment is also a common problem with gear drives. Most gearboxes are used to drive other system components, such as bridle or process rolls. If misalignment is present in the driven members (either real or process induced), it will also directly affect the gears. The change in load zone caused by the misaligned driven component will induce misalignment in the gear set. The effect is identical to real misalignment within the gearbox or between the gearbox and mated (i.e., driver and driven) components.

Visual inspection of gears provides a positive means to isolate the potential root-cause of gear damage or failures. The wear pattern or deformation of gear teeth provides clues about the most likely forcing function or cause. The following sections discuss the clues that can be obtained from visual inspection.

Table 10–15 Common Failure Modes of Gearboxes and Gear Sets

	THE PROBLEM								
THE CAUSES	Gear Failures	Variations in Torsional Power	Insufficient Power Output	Overheated Bearings	Short Bearing Life	Overload on Driver	High Vibration	High Noise Levels	Motor Trips
Bent Shaft				●	●	●	●		
Broken or Loose Bolts or Setscrews				●			●		
Damaged Motor						●	●		●
Eliptical Gears		●	●			●	●		
Exceeds Motor's Brake Horsepower Rating			●			●			
Excessive or Too Little Backlash	●	●							
Excessive Torsional Loading	●	●	●	●	●	●			●
Foreign Object in Gearbox	●						●	●	●
Gear Set Not Suitable for Application	●		●			●	●		
Gears Mounted Backward on Shafts			●				●	●	
Incorrect Center-to-Center Distance Between Shafts							●	●	
Incorrect Direction of Rotation			●			●	●		
Lack of or Improper Lubrication	●	●		●	●		●	●	●
Misalignment of Gears or Gearbox	●	●		●	●		●	●	
Overload	●		●	●	●	●			
Process Induced Misalignment	●	●		●	●				
Unstable Foundation		●		●			●	●	
Water or Chemicals in Gearbox	●								
Worn Bearings							●	●	
Worn Coupling							●		

Source: Integrated Systems, Inc.

10.8.1 Normal Wear

Figure 10–2 illustrates a gear that has a normal wear pattern. Note that the entire surface of each tooth is uniformly smooth above and below the pitch line.

10.8.2 Abnormal Wear

Figures 10–3 through 10–5 illustrate common abnormal wear patterns found in gear sets. Each of these wear patterns suggests one or more potential failure modes for the gearbox.

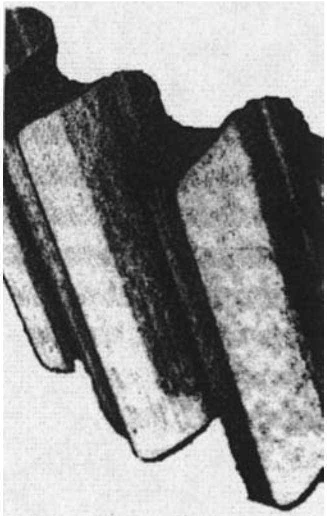


Figure 10–2 Normal wear pattern.

Figure 10–3 Wear pattern caused by abrasives in lubricating oil.

Abrasion

Abrasion creates unique wear patterns on the teeth. The pattern varies depending on the type of abrasion and its specific forcing function. Figure 10–3 illustrates severe abrasive wear caused by particulates in the lubricating oil. Note the score marks that run from the root to the tip of the gear teeth.

Chemical Attack or Corrosion

Water and other foreign substances in the lubricating oil supply also cause gear degradation and premature failure. Figure 10–4 illustrates a typical wear pattern on gears caused by this failure mode.

Figure 10–4 Pattern caused by corrosive attack on gear teeth.

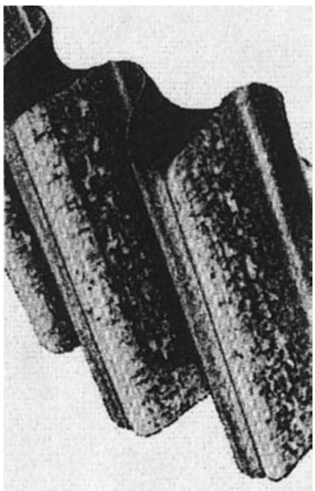


Figure 10–5 Pitting caused by gear overloading.

Overloading

The wear patterns generated by excessive gear loading vary, but all share similar components. Figure 10–5 illustrates pitting caused by excessive torsional loading. The pits are created by the implosion of lubricating oil. Other wear patterns, such as spalling and burning, can also help identify specific forcing functions or root-causes of gear failure.

10.9 Steam Traps

Most of the failure modes that affect steam traps can be attributed to variations in operating parameters or improper maintenance. Table 10–16 lists the more common causes of steam trap failures.

Operation outside the trap's design envelope results in loss of efficiency and may result in premature failure. In many cases, changes in the condensate load, steam pressure or temperature, and other related parameters are the root-cause of poor performance or reliability problems. Careful attention should be given to the actual versus design system parameters. Such deviations are often the root-causes of problems under investigation.

Poor maintenance practices or the lack of a regular inspection program may be the primary source of steam trap problems. It is important for steam traps to be routinely inspected and repaired to ensure proper operation.

10.10 Inverters

Table 10–17 lists the common symptoms and causes of inverter problems. Most of these problems can be attributed to improper selection for a particular application. Others are caused by improper operation. When evaluating inverter problems, careful attention should be given to recommendations found in the vendor's operations and maintenance manual. These recommendations are often extremely helpful in isolating the true root-cause of a problem.

10.11 Control Valves

Although there are limited common control valve failure modes, the dominant problems are usually related to leakage, speed of operation, or complete valve failure. Table 10–18 lists the more common causes of these failures.

Special attention should be given to the valve actuator when conducting a root-cause failure analysis. Many of the problems associated with both process and fluid-power control valves are really actuator problems. In particular, remotely controlled valves that use pneumatic, hydraulic, or electrical actuators are subject to actuator failure. In many cases, these failures are the reason a valve fails to properly open, close, or seal. Even with manually controlled valves, the true root-cause can be traced to an actuator problem. For example, when a manually operated process-control valve is jammed open or closed, it may cause failure of the valve mechanism. This overtorquing of the valve's sealing device may cause damage or failure of the seal, or it may freeze the valve stem. Either of these failure modes results in total valve failure.

Table 10–16 Common Failure Modes of Steam Traps

	THE PROBLEM							
THE CAUSES	Trap Will Not Discharge	Will Not Shut-off	Continuously Blows Steam	Capacity Suddenly Falls Off	Condensate Will Not Drain	Not Enough Steam Heat	Traps Freeze in Winter	Back Flow in Return Line
Back-Pressure Too High				●				
Boiler Foaming or Priming		●				●		
Boiler Gauge Reads Low	●							
Bypass Open or Leaking	●		●					
Condensate Load Greater Than Design		●						
Condensate Short-Circuits					●			
Defective Thermostatic Elements						●		
Dirt or Scale in Trap			●		●			
Discharge Line Has Long Horizontal Runs							●	
Flashing in Return Main				●				●
High-Pressure Traps Discharge into Low-Pressure Return								●
Incorrect Fittings or Connectors				●				●
Internal Parts of Trap Broken or Damaged	●	●	●		●			
Internal Parts of Trap Plugged	●				●			
Kettles or Other Units Increasing Condensate Load		●						
Leaky Steam Coils		●						
No Cooling Leg Ahead of Thermostatic Trap						●		●
Open By-Pass or Vent in Return Line				●				
Pressure Regulator Out of Order	●							
Process Load Greater Than Design		●						
Plugged Return Lines				●				
Plugged Strainer, Valve, or Fitting Ahead of Trap	●							
Scored or Out-of-Round Valve Seat in Trap						●		
Steam Pressure Too High	●							
System Is Air-Bound					●			
Trap and Piping Not Insulated							●	
Trap Below Return Main				●				●
Trap Blowing Steam into Return				●				
Trap Inlet Pressure Too Low				●	●			
Trap Too Small for Load		●						

Source: Integrated Systems, Inc.

Table 10–17 Common Failure Modes of Inverters

THE CAUSES	THE PROBLEM: Main Circuit Undervoltage	Control Circuit Undervoltage	Momentary Power Loss	Overcurrent	Ground Fault	Overvoltage	Load Short-Circuit	Heat-Sink Overheat	Motor/Inverter Overload	Frequent Speed Deviations
Accel/Decel Time Too Short				●						●
Acceleration Rate Too High									●	●
Ambient Temperature Too High								●		
Control Power Source Too Low			●							
Cooling Fan Failure or Improper Operation								●		
Deceleration Time Too Short						●				●
Excessive Braking Required						●				
Improper or Damaged Power Supply Wiring	●	●								
Improper or Damaged Wiring in Inverter-Motor					●					
Incorrect Line Voltage	●	●				●				
Main Circuit DC Voltage Too Low			●							
Motor Coil Resistance Too Low				●			●			
Motor Insulation Damage				●	●					
Pre-Charge Contactor Open			●							
Process Load Exceeds Motor Rating									●	●
Process Load Variations Exceed System Capabilities										●

Source: Integrated Systems, Inc.

10.12 Seals and Packing

Failure modes that affect shaft seals are normally limited to excessive leakage and premature failure of the mechanical seal or packing. Table 10–19 lists the common failure modes for both mechanical seals and packed boxes. As the table indicates, most of these failure modes can be directly attributed to misapplication, improper installation, or poor maintenance practices.

10.12.1 Mechanical Seals

By design, mechanical seals are the weakest link in a machine-train. If there is any misalignment or eccentric shaft rotation, the probability of a mechanical seal failure is extremely high. Most seal tolerances are limited to no more than 0.002 inches of total shaft deflection or misalignment. Any deviation outside of this limited range will cause catastrophic seal failure.

Table 10–18 Common Failure Modes of Control Valves

THE CAUSES		Valve Fails to Open	Valve Fails to Close	Leakage through Valve	Leakage Around Stem	Excessive Pressure Drop	Opens/Closes Too Fast	Open/Closes Too Slow
		THE PROBLEM						
Manually Actuated	Dirt/Debris Trapped in Valve Seat		●	●				
	Excessive Wear		●	●				
	Galling	●	●					
	Line Pressure Too High	●	●	●	●	●		
	Mechanical Damage	●	●					
	Not Packed Properly				●			
	Packed Box Too Loose				●			
	Packing Too Tight	●	●					
	Threads/Lever Damaged	●	●					
	Valve Stem Bound	●	●					
	Valve Undersized					●		●
Pilot Actuated	Dirt/Debris Trapped in Valve Seat	●	●	●				
	Galling	●	●					
	Mechanical Damage (Seals, Seat)	●	●	●				
	Pilot Port Blocked/Plugged	●	●	●				
	Pilot Pressure Too High		●				●	
	Pilot Pressure Too Low	●		●				●
Solenoid Actuated	Corrosion	●	●	●				
	Dirt/Debris Trapped in Valve Seat	●	●	●				
	Galling	●	●					
	Line Pressure Too High	●	●	●	●			●
	Mechanical Damage	●	●	●				
	Solenoid Failure	●	●					
	Solenoid Wiring Defective	●	●					
	Wrong Type of Valve (N-O, N-C)	●	●					

Source: Integrated Systems, Inc.

Misalignment

Physical misalignment of a shaft will either cause seal damage or permit some leakage through the seal, or it will result in total seal failure. Therefore, it is imperative that good alignment practices be followed for all shafts that have an installed mechanical seal.

Table 10–19 Common Failure Modes of Packing and Mechanical Seals

		THE CAUSES	THE PROBLEM: Excessive Leakage	Continuous Stream of Liquid	No Leakage	Shaft Hard to Turn	Shaft Damage Under Packing	Frequent Replacement Required	Bellows Spring Failure	Seal Face Failure
Packed Box	Nonrotating	Cut Ends of Packing Not Staggered	●	●				●		
		Line Pressure Too High	●							
		Not Packed Properly				●	●	●		
		Packed Box Too Loose	●	●						
		Packing Gland Too Loose	●	●						
		Packing Gland Too Tight	●	●		●	●	●		
	Rotating	Cut End of Packing Not Staggered		●						
		Line Pressure Too High	●							
		Mechanical Damage (Seals, Seat)	●	●	●			●		
		Noncompatible Packing	●	●			●			
		Packing Gland Too Loose	●							
		Packing Gland Too Tight			●		●	●		
Mechanical Seal	Internal Flush	Flush Flow/Pressure Too Low							●	●
		Flush Pressure Too High	●	●					●	●
		Improperly Installed	●						●	●
		Induced Misalignment	●							
		Internal Flush Line Plugged							●	●
		Line Pressure Too High							●	●
		Physical Shaft Misalignment	●							
		Seal Not Compatible with Application	●							
	External Flush	Contamination in Flush Liquid	●							●
		External Flush Line Plugged							●	●
		Flush Flow/Pressure Too Low							●	●
		Flush Pressure Too High	●	●					●	●
		Improperly Installed	●							●
		Induced Misalignment	●						●	●
		Line Pressure Too High							●	●
		Physical Shaft Misalignment	●						●	●
		Seal Not Compatible with Application	●							●

Source: Integrated Systems, Inc.

Process- and machine-induced shaft instability also create seal problems. Primary causes for this failure mode include aerodynamic or hydraulic instability, critical speeds, mechanical imbalance, process load changes, or radical speed changes. These problems can cause the shaft to deviate from its true centerline enough to result in seal damage.

Chemical Attack

Chemical attack (i.e., corrosion or chemical reaction with the liquid being sealed) is another primary source of mechanical seal problems. Generally, two primary factors cause chemical attack: misapplication or improper flushing of the seal.

Misapplication. Little attention is generally given to the selection of mechanical seals. Most plants rely on the vendor to provide a seal that is compatible with the application. Too often a serious breakdown in communications occurs between the end user and the vendor on this subject. Either the procurement specification does not provide the vendor with appropriate information or the vendor does not offer the option of custom ordering the seals. Regardless of the reason, mechanical seals are often improperly selected and used in inappropriate applications.

Seal Flushing. When installed in corrosive chemical applications, mechanical seals must have a clear-water flush system to prevent chemical attack. The flushing system must provide a positive flow of clean liquid to the seal and provide an enclosed drain line that removes the flushing liquid. The flowrate and pressure of the flushing liquid will vary depending on the specific type of seal but must be enough to ensure complete, continuous flushing.

12.12.2 Packed Boxes

Packing is used to seal shafts in a variety of applications. In equipment where the shaft is not continuously rotating (e.g., valves), packed boxes can be used successfully without any leakage around the shaft. In rotating applications, such as pump shafts, the application must be able to tolerate some leakage around the shaft.

Nonrotating Applications

In nonrotating applications, packing can be installed tight enough to prevent leakage around the shaft. As long as the packing is properly installed and the stuffing-box gland is properly tightened, seal failure is not likely to occur. This type of application does require periodic maintenance to ensure that the stuffing-box gland is properly tightened or that the packing is replaced when required.

Rotating Applications

In applications where a shaft continuously rotates, packing cannot be tight enough to prevent leakage. In fact, some leakage is required to provide both flushing and cooling of the packing. Properly installed and maintained packed boxes should not fail or contribute to equipment reliability problems. Proper installation is relatively easy, and routine maintenance is limited to periodic tightening of the stuffing-box gland.

11

ULTRASONICS

This predictive maintenance technique uses principles similar to vibration analysis. Both monitor the noise generated by plant machinery or systems to determine their actual operating condition. Unlike vibration monitoring, however, ultrasonics monitors the higher frequencies (i.e., ultrasound) produced by unique dynamics in process systems or machines. The normal monitoring range for vibration analysis is from less than 1 Hz to 30,000 Hz. Ultrasonics techniques monitor the frequency range between 20,000 Hz and 100 kHz.

11.1 Ultrasonic Applications

As part of a predictive maintenance program, ultrasonic instruments are used for three primary applications: airborne noise analysis, leak detection, or material testing.

11.1.1 Airborne Noise Analysis

All plants are required by Occupational Safety and Health Administration (OSHA) regulations to meet ambient noise levels throughout their facilities. These mandates have forced these plants to routinely monitor the noise levels within each area of the plant and to provide hearing protection in those areas where the ambient noise level is above acceptable levels.

Ultrasonic meters are the primary tool used to monitor the ambient noise levels and to ensure compliance with OSHA regulations. In addition, some plants use simple ultrasonic meters to survey noncritical plant equipment and systems for unusual noise emissions. This latter application is limited to a simple “go/no-go” measurement and has practically no ability to diagnose the root-cause of the abnormal noise.

11.1.2 Leak Detection

The principal application for ultrasonic monitoring is in leak detection. The turbulent flow of liquids and gases through a restricted orifice (i.e., leak) will produce a high-frequency signature that can easily be identified using ultrasonic techniques. Therefore, this technique is ideal for detecting leaks in valves, steam traps, piping, and other process systems.

11.1.3 Materials Testing

Ultrasonics has been, and continues to be, a primary test methodology for materials testing. Typical test frequencies start at 250 kiloHertz (kHz), or 250,000 cycles per second (cps), up to 25 MegaHertz (MHz), or 25 million cps.

Testing materials generally consist of introducing an energy source into the material to be tested and recording the response characteristics using ultrasonic instruments. These tests may be as simple as striking the material with a hammer and recording the results with an accelerometer and ultrasonic meter.

Ultrasonic testing relies on the measurement of time and amplitude or strength of a signal between emission and reception. Because of a mismatch of acoustic properties between materials, the sound will partly reflect at interfaces. The quality of reflected energy depends on the acoustic impedance ratio between two materials. For example, sound transmitted through steel reaching a steel/air boundary will cause 99.9 percent internal reflection, whereas a steel/water boundary would reflect only 88 percent within the material and transmit 12 percent into the water. If impedance ratios are widely different, such as an open crack with a steel/air interface, then adequate reflection will occur and permit detection of the flaw. Conversely, a small crack in a compressive stress field that does not have oxidized faces will yield a steel/steel boundary and cannot be detected using this method.

11.2 Types of Ultrasonic Systems

Two types of ultrasonic systems are available that can be used for predictive maintenance: structural and airborne. Both provide fast, accurate diagnosis of abnormal operation and leaks. Airborne ultrasonic detectors can be used in either a scanning or contact mode. As scanners, they are most often used to detect gas pressure leaks. Because these instruments are sensitive only to ultrasound, they are not limited to specific gases as are most other gas leak detectors. In addition, they are often used to locate various forms of vacuum leaks.

In the contact mode, a metal rod acts as a waveguide. When it touches a surface, it is stimulated by the high frequencies, ultrasound, on the opposite side of the surface. This technique is used to locate turbulent flow and/or flow restriction in process piping.

Some of the ultrasonic systems include ultrasonic transmitters that can be placed inside plant piping or vessels. In this mode, ultrasonic monitors can be used to detect areas of sonic penetration along the container's surface. This ultrasonic transmission method is useful in quick checks of tank seams, hatches, seals, caulking, gaskets, or building wall joints.

Most of the ultrasonic monitoring systems are strictly scanners that do not provide any long-term trending or data storage. They are in effect a point-of-use instrument that provides an indication of the overall amplitude of noise within the bandwidth of the instrument. Therefore, the cost for this type of instrument is relatively low. The normal cost of ultrasonic instruments will range from less than $1,000 to about $8,000. When used strictly for leak detection, little training is required to employ ultrasonic techniques. The combination of low capital cost, minimum training required to use the technique, and the potential impact of leaks on plant availability provide a positive cost benefit for including ultrasonic techniques in a total-plant predictive maintenance program.

11.3 Limitations

Care should be exercised in applying this technique in your program. Many ultrasonic systems are sold as a bearing condition monitor. Even though the natural frequencies of rolling-element bearings will fall within the bandwidth of ultrasonic instruments, this is not a valid technique for determining the condition of rolling-element bearings. In a typical machine, many other machine dynamics will also generate frequencies within the bandwidth covered by an ultrasonic instrument. Gear-meshing frequencies, blade-pass, and other machine components will also create energy or noise that cannot be separated from the bearing frequencies monitored by this type of instrument. The only reliable method of determining the condition of specific machine components, including bearings, is vibration analysis. The use of ultrasonics to monitor bearing condition is not recommended.

12

VISUAL INSPECTION

Regular visual inspection of the machinery and systems in a plant is a necessary part of any predictive maintenance program. In many cases, visual inspection will detect potential problems that will be missed using the other predictive maintenance techniques. Even with the predictive techniques discussed, many potentially serious problems can remain undetected. Routine visual inspection of all critical plant systems will augment the other techniques and ensure that potential problems are detected before serious damage can occur.

Most of the vibration-based predictive maintenance systems include the capability of recording visual observations as part of the routine data acquisition process. Because the incremental costs of these visual observations are small, this technique should be incorporated into all predictive maintenance programs.

All equipment and systems in the plant should be visually inspected on a regular basis. The additional information provided by visual inspection will augment the predictive maintenance program regardless of the primary techniques used.

As was pointed out previously, inspection is a key to detecting the need for preventive maintenance requirements. It should be nondestructive so that it will not harm the equipment. Some common methods of nondestructive testing (NDT) are outlined as follows:

1. ***Body Senses***
—Sight
—Smell
—Sound
—Taste
—Touch
2. ***Temperature***
—Thermistor
—Thermometer
—Crayons, stickers, paints
—Infrared
—Thermopile
—Heat flow
3. ***Vibration Wear***
—Accelerometer
—Stethoscope

—Stroboscope
—Ultrasonic listening
—Laser alignment

4. ***Materials Defects***
—Magnetics
—Penetrating dyes
—Eddy currents
—Radiographs
—Ultrasonics
—Rockwell hardness
—Sonic resonance
—Corona listener
—Fiberoptics bore scopes

5. ***Deposits, Corrosion, and Erosion***
—Ultrasonics
—Radiographs
—Cathodic potential
—Weight

6. ***Flow***
—Neon freon detector
—Smoke bomb
—Gas sensor
—Quick-disconnect gauges
—Manometer

7. ***Electrical***
—Cable fault detector
—Outlet checker
—HiPot
—VOM
—Oscilloscope
—Static meter gun
—Frequency recorder
—Phase angle meter
—Circuit-breaker tester
—Transient voltage

8. ***Chemical/Physical***
—Spectrographic oil analysis
—Humidity
—Water or antifreeze in gases/liquids
—O_2
—CO_2
—pH
—Viscosity
—Metals present

Tests may be made on functionally related components or on the output product. For example, most printing presses, copiers, and duplicators are intended to produce high-quality images on paper. Inspection of those output copies can show whether the process is working properly. Skips, smears, blurs, and wrinkles will show up on the copy. A good inspector can tell from a copy exactly what roll is wearing or what bearing is causing the skips. Careful inspection, which can be done without “tearing down” the machine, saves both technician time and exposure of the equipment to possible damage.

Rotating components find their own best relationship to surrounding components. For example, piston rings in an engine or compressor cylinder quickly wear to the cylinder wall configuration. If they are removed for inspection, the chances are that they will not easily fit back into the same pattern. As a result, additional wear will occur, and the rings will have to be replaced much sooner than if they were left intact and performance-tested for pressure produced and metal particles in the lubricating oil.

12.1 Visual Inspection Methods

Most of the visual inspections that are performed as part of a preventive maintenance program are ineffective. The primary reasons for this ineffectiveness is that the methods used are almost totally subjective. For example, a preventive task may read, "Check V-belt tension and correct as necessary." How should the technician check tension? Where should he or she measure? What tension levels are acceptable?

Effective visual inspection must be quantifiable, and all personnel must universally apply the methods used. The specific methods will vary from simple visual inspections, such as looking for leaks or reading a gauge, to requiring test instruments, such as vacuum gauges, dial indicators, and so on. In all cases, the methods used must clearly define exactly how the inspection is to be performed, the exact location that measurements or inspection is to be made, criteria for evaluation, and the acceptable range of performance.

Generally, visual inspection can be broken into two major classifications: those that can be conducted using only human senses and those that require the use of sensors or instrumentation.

12.1.1 Human Senses

Humans have a great capability for sensing unusual sights, sounds, smells, tastes, vibrations, and touches. Every maintenance manager should make a concerted effort to increase the sensitivity of his or her own and that of the personnel's human senses. Experience is generally the best teacher. Often, however, we experience things without knowing what we are experiencing. A few hours of training in what to look for could have high payoff.

Human senses are able to detect large differences but are generally not sensitive to small changes. Time tends to have a dulling effect. Have you ever tried to determine if one color was the same as another without having a sample of each to compare side by side? If you have, you will understand the need for standards. A standard is any example that can be compared to the existing situation as a measurement. Quantitative specifications, photographs, recordings, and actual samples should be provided. The critical parameters should be clearly marked on the samples with display as to what is good and what is bad. It is best if judgments can be reduced to "go/no-go." Figure 12–1 shows such a standard.

As the reliability-based preventive maintenance program develops, samples should be collected to help pinpoint with maximum accuracy how much wear can take place before problems will occur. A display where craftspeople gather can be effective. A framed four-foot by four-foot pegboard works well because shafts, bearings, gears, and other components can be easily wired to it or hung on hooks for display. An effective, but little used, display area where notices can be posted is above the urinal or on the inside of the toilet stall door. Those are frequently viewed locations and allow people to make dual use of their time.

12.1.2 Sensors

Because humans are not continually alert or sensitive to small changes and cannot get inside small spaces, especially when operating, it is necessary to use sensors that

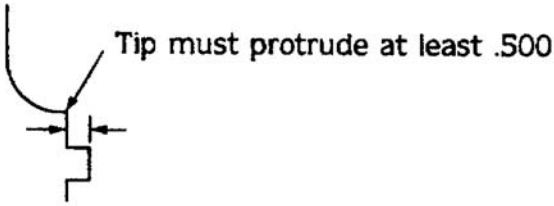


Figure 12–1 "Go/no-go" standards.

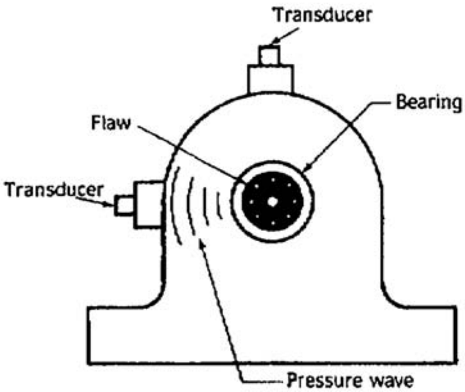


Figure 12–2 Accelerometer to measure vibration of rotating shaft.

measure conditions and transmit information to external indicators. Sensor technology is progressing rapidly; considerable improvements have been made in capability, accuracy, size, and cost. Pressure transducers, temperature thermocouples, electrical ammeters, revolution counters, and a liquid height-level float are examples found in most automobiles. Accelerometers, eddy-current proximity sensors, and velocity seismic transducers are enabling the techniques of motion, position, and expansion analysis to be increasingly applied to large numbers of rotating equipment. Motors, turbines, compressors, jet engines, and generators can use vibration analysis.

Figure 12–2 shows accelerometers placed on a rotating shaft. The accelerometers are usually permanently attached to equipment at two positions 90 degrees apart, perpendicular to the rotating axes. Measurement of their output may be taken by portable test meters and chart recorders or by permanently attached recorders, often with alarms that indicate when problem thresholds are exceeded. Such devices may automatically shut down equipment to prevent damage.

The normal pattern of operation, called its *signature*, is established by measuring the performance of equipment under known good conditions. Comparisons are made at routine intervals, such as every 30 days, to determine if any of the parameters are changing erratically, and further, what the effect of such changes may be.

12.1.3 Spectrometric Oil Analysis

The spectrometric oil analysis (SOA) process is useful for any mechanical moving device that uses oil for lubrication. It tests for presence of metals, water, glycol, fuel dilution, viscosity, and solid particles. Automotive engines, compressors, and turbines all benefit from oil analysis. Most major oil companies provide this service if you purchase lubricants from them. Experience indicates that the typical result is that less oil is used and costs are reduced from what they were before using SOA.

The major advantage of SOA is early detection of component wear. Not only does it evaluate when oil is no longer lubricating properly and should be replaced, but it also identifies and measures small quantities of metals that are wearing from the moving surfaces. The metallic elements found, and their quantity, can indicate what components are wearing and to what degree so that maintenance and overhaul can be carefully planned. For example, presence of chrome would indicate cylinder head wear; phosphor bronze would probably be from the main bearings; and stainless steel would point toward lifters. Experience with particular equipment naturally leads to improved diagnosis.

The Air Force and commercial airlines have been refining these techniques on jet aircraft for many years. They find that SOA, together with bore scopes to look inside an engine and vibration analysis, enables them to do a very good job of predicting when maintenance should be done. The aircraft maintenance techniques that required complete teardown of propeller-driven aircraft every 1,000 hours, whether they needed it or not, are rapidly vanishing in that industry. Many manufacturing plants can gain improvements through the same maintenance techniques.

12.2 Thresholds

Now that instrumentation is becoming available to measure equipment performance, it is still necessary to determine when that performance is “go” and when it is “no-go.” A human must establish the threshold point, which can then be controlled by manual, semiautomatic, or automatic means. First, let’s decide how the threshold is set and then discuss how to control it.

To set the threshold, one must gather information on what measurements can exist while equipment is running safely and what the measurements were just before or at the time of failure. Equipment manufacturers, and especially their experienced field representatives, are a good starting source of information. Most manufacturers will run equipment until failure in their laboratories as part of their tests to evaluate quality, reliability, maintainability, and maintenance procedures. Such data are necessary to determine how much stress can be put on a device under actual operating conditions before it will break. Many devices, such as nuclear reactors and airplanes, should not be taken to the breaking point under operating conditions, but they can be made to fail under secure test conditions so that knowledge can be used to keep them safe during actual use.

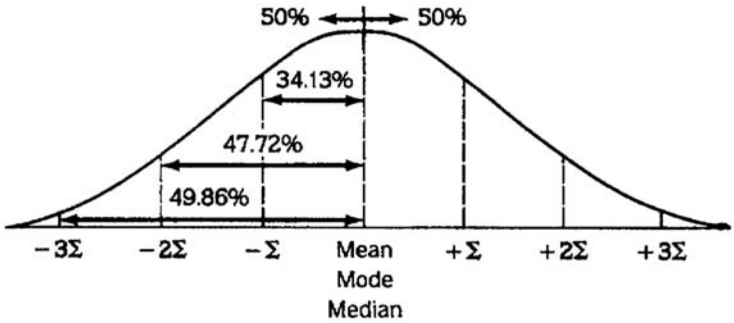


Figure 12–3 Normal distribution of failures.

Once the breaking point is determined, a margin of safety should be added to account for variations in individual components, environments, and operating conditions. Depending on the severity of failure, that safety margin could be anywhere from one to three standard deviations before the average failure point. As Figure 12–3 shows, one standard deviation on each side of the mean will include 68 percent of all variations, two standard deviations include 95 percent, and three standard deviations is 98.7 percent. When the mission is to prevent failures, however, only the left half of the distribution is applicable. This single-sided distribution also shows that we are dealing with probabilities and risk.

The earlier the threshold is set and effective preventive maintenance done, the greater the assurance that it will be done before failure. If the mean-time-between-failures (MTBF) is 9,000 miles with a standard deviation of 1,750 miles, then proper preventive maintenance at 5,500 miles could eliminate almost 98 percent of failures. Note the word *proper*, meaning that no new problems are injected. That also means, however, that costs will be higher than necessary because components will be replaced before the end of their useful life, and more labor is required.

Once the threshold set point has been determined, it should be monitored to detect when it is exceeded. The investment in monitoring depends on the period over which deterioration may occur, the means of detection, and the benefit value. Figure 12–4 illustrates the need for automatic monitoring.

If failure conditions build up quickly, a human may not easily detect the condition, and the relatively high cost of automatic instrumentation will be repaid.

The monitoring signal may be used to activate an annunciator that rings a bell or lights a red light. It may activate a feedback mechanism that reduces temperature or other parameters. A thermostat connected to a heating and air-conditioning system provides this feedback function to regulate temperature. The distinction between operational controls and maintenance controls is not important because the result is a reduced

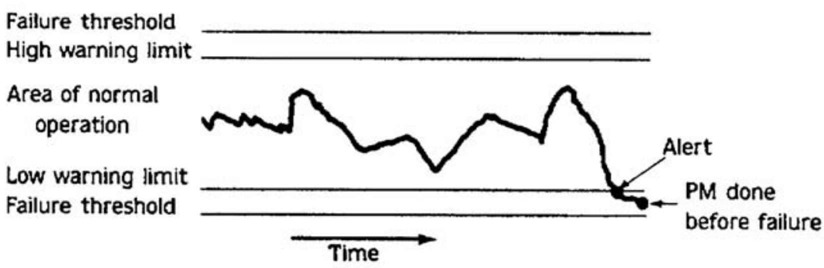


Figure 12–4 Control chart warning of possible failure before it occurs.

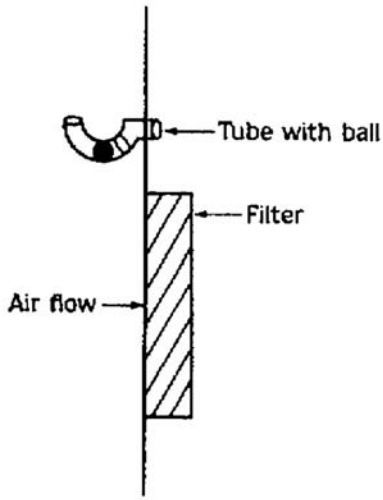


Figure 12–5 A simple manometer to warn of inadequate airflow.

need for maintenance and notification that a problem is building up to a point where maintenance should be scheduled when convenient. A simple threshold indicator is the manometer shown in Figure 12–5.

This simple device can be effective in air conditioners, computer cabinets, office copiers, and any devices that rely on airflow. A spring-loaded block can serve the same function in vacuum cleaners and other devices that must be moved and therefore cannot rely on the pull/push of air against gravity. The purpose of a filter is to remove contaminant materials so they will not clog coils, fans, electronic components, or optics. As the filter is doing its job, the caught contaminants reduce airflow. This will build to the point where equipment is straining to pull enough air, and temperatures will probably begin to rise. At such a point, the filter should be changed or cleaned, which will restore equipment to normal operating conditions. This buildup of dirt can be easily detected by a difference in the air pressure.

When the filter is operating efficiently, air pushing on the entry side will be only slightly impeded and will have about the same pressure on the exit side. A small colored ball that fits inside the clear manometer tube will rest in the bottom when the airflow is balanced. As the filter becomes restricted, pressure on the entry will be greater than on the exit and the ball will be pushed to the exit side of the tube. Colored bands around the tube can indicate the threshold of safety versus a need to replace the filter.

Because it will normally take at least several days and probably weeks for the filter to become clogged, the manometer can be checked on a routine inspection schedule and then maintenance can be performed as conditions require. This schedule is certainly less expensive for both labor and materials than either routinely replacing the filter, whether it needs it or not, or letting it build up until equipment fails and both temperatures and tempers rise. More sophisticated sensors are certainly required where humans cannot or will not notice them, as well as remote communications and alarm systems.

The decision to put or not to put a filter in the airflow is a good example of initial investment in preventive maintenance that will pay off over the equipment life. Equipment would operate just fine initially without any filter and would, of course, cost less without those components; however, when contaminants build up on an electronic circuit board, coil, or fan, extensive and expensive cleaning will have to be done to prevent the equipment from failing. Changing the filter is much easier than major equipment refurbishing, and the initial cost and replacement filters pay off through improved performance. As the automotive oil-filter advertising campaign said: “You can pay a little now, or a lot later.”

13

OPERATING DYNAMICS ANALYSIS

Effective performance of any manufacturing or process plant depends on reliability systems that continuously operate at their best design performance levels. To achieve and sustain this performance level, the plant must have an effective way to constantly monitor and evaluate these critical systems. Operating dynamics analysis provides a cost-effective means of accomplishing this fundamental requirement.

The focus of an operating dynamics analysis program is on the manufacturing process and production systems that generate plant capacity. It is not a maintenance management tool like traditional predictive maintenance programs. Because of perceived restrictions, such as low speed and machine complexity, of the technologies, most traditional predictive maintenance programs ignore or omit these critical systems. Although there may be some benefit in monitoring auxiliary equipment, maximum benefit can be achieved only when reliability of the plant's critical production systems is maintained. Within the operating dynamics concept, auxiliary equipment is not ignored, but the focus is on those systems that produce capacity and revenue for the plant.

13.1 It's Not Predictive Maintenance

Prevention of catastrophic failure, the primary focus of predictive maintenance, is important, but programs that are restricted to this one goal will not improve equipment reliability, nor will they provide sufficient benefits to justify their continuance. By shifting the focus to a plant optimization tool that concentrates on capacity and reliability improvements, an operating dynamics program can greatly improve benefits to the company.

Predictive maintenance technologies can, and should, be used as a total-plant performance tool. When used correctly, these tools can provide the means to eliminate most of the factors that limit plant performance. To achieve this expanded role, the predictive maintenance program must be developed with clear goals and objectives that permit maximum utilization of the technologies. The program must be able to cross organizational boundaries and not be limited to the maintenance function. Every function within the plant affects equipment reliability and performance, and the predictive maintenance program must address all of these influences.

Vibration monitoring and analysis is the most common of the predictive maintenance technologies. It is also the most underutilized of these tools. Most vibration-based predictive maintenance programs use less than 1 percent of the power this technology provides. The primary deficiencies of traditional predictive maintenance are:

- Technology limitations
- Limitation to maintenance issues
- Influence of process variables
- Training limitations
- Interpreting operating dynamics

13.1.1 Technology Limitations

Most predictive maintenance programs are severely restricted to a small population of plant equipment and systems. For example, vibration-based programs are generally restricted to simple, rotating machinery, such as fans, pumps, or compressors. Thermography is typically restricted to electrical switchgear and related electrical equipment. These restrictions are thought to be physical limitations of the predictive technologies. In truth, they are not.

Predictive instrumentation has the ability to effectively acquire accurate data from almost any manufacturing or process system. Restrictions, such as low speed, are purely artificial. Not only can many of the vibration meters record data at low speeds, but they can also be used to acquire most process variables, such as temperature, pressure, or flow. Because most have the ability to convert any proportional electrical signal into user-selected engineering units, they are in fact multimeters that can be used as part of a comprehensive process performance analysis program.

13.1.2 Limitation to Maintenance Issues

From its inception, predictive maintenance has been perceived as a maintenance improvement tool. Its sole purpose was, and is, to prevent catastrophic failure of plant equipment. Although it is capable of providing the diagnostic data required to meet this goal, limiting these technologies solely to this task will not improve overall plant performance.

When predictive programs are limited to the traditional maintenance function, they must ignore those issues or contributors that directly affect equipment reliability. Outside factors, such as poor operating practices, are totally ignored.

Many predictive maintenance programs are limited to simple trending of vibration, infrared, or lubricating oil data. The perception that a radical change in the relative values indicates a corresponding change in equipment condition is valid; however, this logic does not go far enough. The predictive analyst must understand the true meaning of a change in one or more of these relative values. If a compressor's vibration level doubles, what does the change really mean? It may mean that serious mechanical damage has occurred, but it could simply mean that the compressor's load was reduced.

A machine or process system is much like the human body. It generates a variety of signals, like a heartbeat, that define its physical condition. In a traditional predictive maintenance program, the analyst evaluates one or a few of these signals as part of his or her determination of condition. For example, the analyst may examine the vibration profile or heartbeat of the machine. Although this approach has some merit, it cannot provide a complete understanding of the machine or the system's true operating condition.

When a doctor evaluates a patient, he or she uses all of the body's signals to diagnose an illness. Instead of relying on the patient's heartbeat, the doctor also uses a variety of blood tests, temperature, urine composition, brainwave patterns, and a variety of other measurements of the body's condition. In other words, the doctor uses all of the measurable indices of the patient's condition. These data are then compared to the benchmark or normal profile for the human body.

Operating dynamics is much like the physician's approach. It uses all of the indices that quantify the operating condition of a machine-train or process system and evaluates them using a design benchmark that defines normal for the system.

13.1.3 Influence of Process Variables

In many cases, the vibration-monitoring program isolates each machine-train or a component of a machine-train and ignores its system. This approach results in two major limitations: it ignores (1) the efficiency or effectiveness of the machine-train and (2) the influence of variations in the process.

When the diagnostic logic is limited to common failure modes, such as imbalance, misalignment, and so on, the benefits derived from vibration analyses are severely restricted. Diagnostic logic should include the total operating effectiveness and efficiency of each machine-train as a part of its total system. For example, a centrifugal pump is installed as part of a larger system. Its function is to reliably deliver, with the lowest operating costs, a specific volume of liquid and a specific pressure to the larger system. Few programs consider this fundamental requirement of the pump. Instead, their total focus is on the mechanical condition of the pump and its driver.

The second limitation to many vibration programs is that the analyst ignores the influence of the system on a machine-train's vibration profile. All machine-trains are affected by system variations, no matter how simple or complex. For example, a comparison of vibration profiles acquired from a centrifugal compressor operating at 100 percent load and at 50 percent load will clearly be different. The amplitude of all rotational frequency components will increase by as much as four times at 50 percent load. Why? Simply because more freedom of movement occurs at the lower load. As part of the compressor design, load was used to stabilize the rotor. The designer balanced the centrifugal and centripetal forces within the compressor based on the design load (100 percent). When the compressor is operated at reduced or excessive loads, the rotor becomes unbalanced because the internal forces are no longer equal. In addition, the spring constant of the rotor-bearing support structure also changes with load: It becomes weaker as load is reduced and stronger as it is increased.

In more complex systems, such as paper mills other continuous process lines, the impact of the production process is much more severe. The variation in incoming product, line speeds, tensions, and a variety of other variables directly impacts the operating dynamics of the system and all of its components. The vibration profiles generated by these system components also vary with the change in the production variables. The vibration analyst must adjust for these changes before the technology can be truly beneficial as either a maintenance scheduling or plant improvement tool.

Because most predictive maintenance programs are established as maintenance tools, they ignore the impact of operating procedures and practices on the dynamics of system components. Variables such as ramp rate, startup and shutdown practices, and an infinite variety of other operator-controlled variables have a direct impact on both reliability and the vibration profiles generated by system components. It is difficult, if not impossible, to accurately detect, isolate, and identify incipient problems without clearly understanding these influences. The predictive maintenance program should evaluate existing operating practices; quantify their impact on equipment reliability, effectiveness, and costs; and provide recommended modifications to these practices that will improve overall performance of the production system.

13.1.4 Training Limitations

In general, predictive maintenance analysts receive between 5 and 25 days of training as part of the initial startup cost. This training is limited to three to five days of predictive system training by the system vendor and about five days of vibration or infrared technology training. In too many cases, little additional training is provided. Analysts are expected to teach themselves or network with other analysts to master their trade. This level of training is not enough to gain even minimal benefits from predictive maintenance.

Vendor training is usually limited to use of the system and provides little, if any, practical technology training. The technology courses that are currently available are of limited value. Most are limited to common failure modes and do not include any training in machine design or machine dynamics. Instead, analysts are taught to identify simple failure modes of generic machine-trains.

To be effective, predictive analysts must have a thorough knowledge of machine/system design and machine dynamics. This knowledge provides the minimum base required to effectively use predictive maintenance technologies. Typically, a graduate mechanical engineer can master this basic knowledge of machine design, machine dynamics, and proper use of predictive tools in about 13 weeks of classroom training. Nonengineers, with good mechanical aptitude, will need 26 or more weeks of formal training.

13.1.5 Understanding Machine Dynamics

It Starts with the Design

Every machine or process system is designed to perform a specific function or range of functions. To use operating dynamics analysis, one must first fully understand how machines and process systems perform their work. This understanding must start with a thorough design review that identifies the criteria that were used to design a machine and its installed system. In addition, the analyst must also understand the inherent weaknesses and potential failure modes of these systems. For example, consider the centrifugal pump.

Centrifugal pumps are highly susceptible to variations in process parameters, such as suction pressure, specific gravity of the pumped liquid, back-pressure induced by control valves, and changes in demand volume. Therefore, the dominant reasons for centrifugal pump failures are usually process related.

Several factors dominate pump performance and reliability: internal configuration, suction condition, total dynamic pressure or head, hydraulic curve, brake horsepower, installation, and operating methods. These factors must be understood and used to evaluate any centrifugal pump-related problem or event.

All centrifugal pumps are not alike. Variations in the internal configuration occur in the impeller type and orientation. These variations have a direct impact on a pump's stability, useful life, and performance characteristics.

There are a variety of impeller types used in centrifugal pumps. They range from simple radial-flow, open designs to complex variable-pitch, high-volume enclosed designs. Each of these types is designed to perform a specific function and should be selected with care. In relatively small, general-purpose pumps, the impellers are normally designed to provide radial flow, and the choices are limited to either enclosed or open design.

Enclosed impellers are cast with the vanes fully encased between two disks. This type of impeller is generally used for clean, solid-free liquids. It has a much higher efficiency than the open design. Open impellers have only one disk, and the opposite side of the vanes is open to the liquid. Because of its lower efficiency, this design is limited to applications where slurries or solids are an integral part of the liquid.

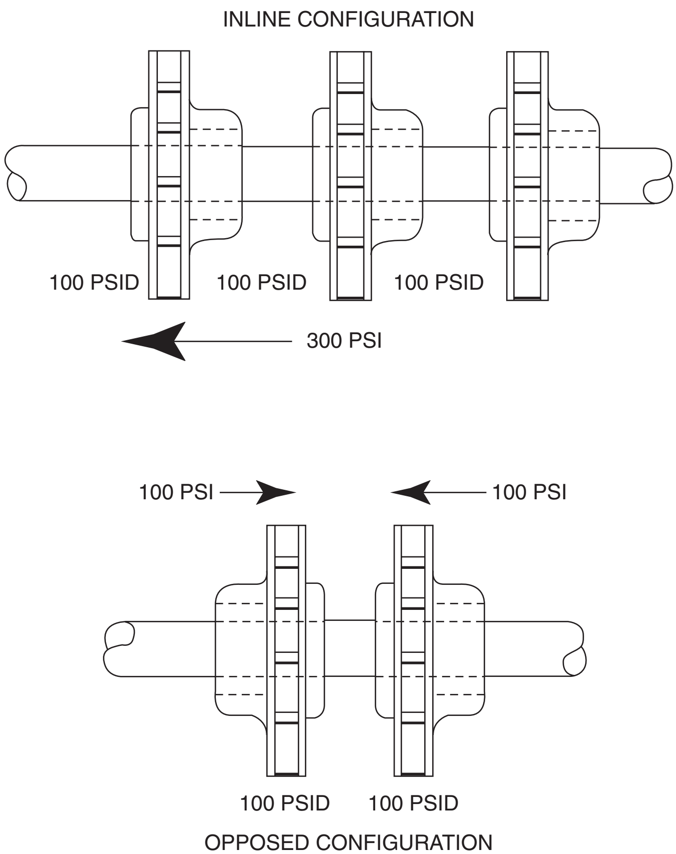


Figure 13–1 Impeller orientation.

In single-stage centrifugal pumps, impeller orientation is fixed and is not a factor in pump performance; however, it must be carefully considered in multistage pumps, which are available in two configurations: inline and opposed.

Inline configurations (see Figure 13–1) have all impellers facing in the same direction. As a result, the total differential pressure between the discharge and inlet is axially applied to the rotating element toward the outboard bearing. Because of this configuration, inline pumps are highly susceptible to changes in the operating envelope.

Because of the tremendous axial pressures that are created by the inline design, these pumps must have a positive means of limiting endplay, or axial movement, of the rotating element. Normally, one of two methods is used to fix or limit axial movement: (1) a large thrust bearing is installed at the outboard end of the pump to restrict movement, or (2) discharge pressure is vented to a piston mounted on the outboard end of the shaft.

Multistage pumps that use opposed impellers are much more stable and can tolerate a broader range of process variables than those with an inline configuration. In the opposed-impeller design, sets of impellers are mounted back-to-back on the shaft. As a result, the other cancels the thrust or axial force generated by one of the pairs. This design approach virtually eliminates axial forces. As a result, the pump does not require a massive thrust-bearing or balancing piston to fix the axial position of the shaft and rotating element.

Because the axial forces are balanced, this type of pump is much more tolerant of changes in flow and differential pressure than the inline design; however, it is not immune to process instability or to the transient forces caused by frequent radical changes in the operating envelope.

Factors that Determine Performance

Centrifugal pump performance is primarily controlled by two variables: suction conditions and total system pressure or head requirement. Total system pressure consist of the total vertical lift or elevation change, friction losses in the piping, and flow restrictions caused by the process. Other variables affecting performance include the pump's hydraulic curve and brake horsepower.

Suction Conditions. Factors affecting suction conditions are the net positive suction head, suction volume, and entrained air or gas. Suction pressure, called *net positive suction head* (NPSH), is one of the major factors governing pump performance. The variables affecting suction head are shown in Figure 13–2.

Centrifugal pumps must have a minimum amount of consistent and constant positive pressure at the eye of the impeller. If this suction pressure is not available, the pump will be unable to transfer liquid. The suction supply can be open and below the pump's centerline, but the atmospheric pressure must be greater than the pressure required to lift the liquid to the impeller eye and to provide the minimum NPSH required for proper pump operation.

At sea level, atmospheric pressure generates a pressure of 14.7 pounds per square inch (psi) to the surface of the supply liquid. This pressure minus vapor pressure, friction loss, velocity head, and static lift must be enough to provide the minimum NPSH requirements of the pump. These requirements vary with the volume of liquid transferred by the pump.

Most pump curves provide the minimum NPSH required for various flow conditions. This information, which is usually labeled $NPSH_R$, is generally presented as a rising curve located near the bottom of the hydraulic curve. The data are usually expressed in "feet of head" rather than psi.

The pump's supply system must provide a consistent volume of single-phase liquid equal to or greater than the volume delivered by the pump. To accomplish this, the

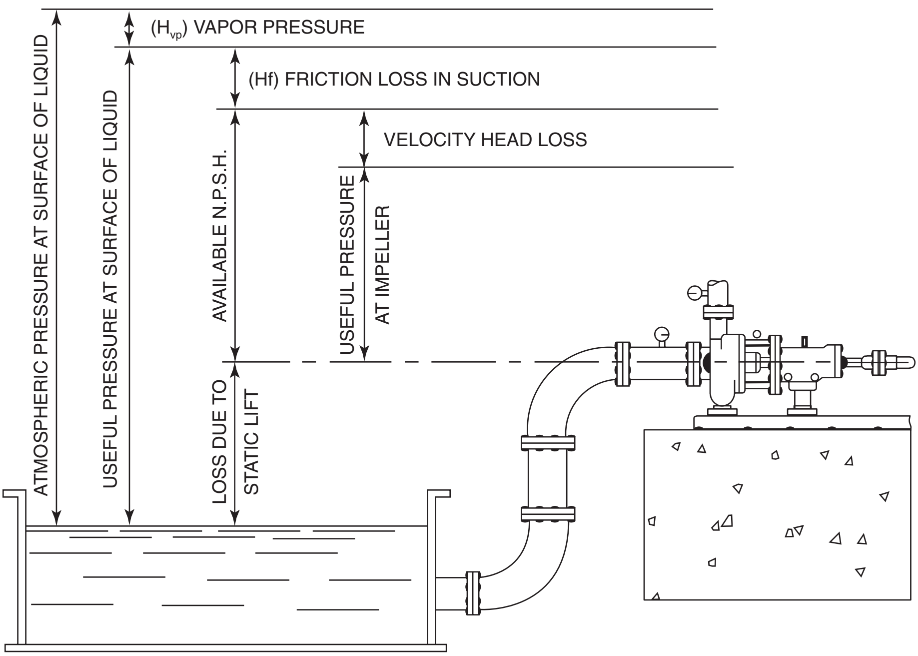


Figure 13–2 Net positive suction head requirements.

suction supply should have relatively constant volume and properties (e.g., pressure, temperature, specific gravity). Special attention must be paid to applications where the liquid has variable physical properties (e.g., specific gravity, density, viscosity). As the suction supply's properties vary, effective pump performance and reliability will be adversely affected.

In applications where two or more pumps operate within the same system, special attention must be given to the suction flow requirements. Generally, these applications can be divided into two classifications: pumps in series and pumps in parallel.

Most pumps are designed to handle single-phase liquids within a limited range of specific gravity or viscosity. Entrainment of gases, such as air or steam, has an adverse effect on both the pump's efficiency and its useful operating life. This is one form of cavitation, which is a common failure mode of centrifugal pumps. The typical causes of cavitation are leaks in suction piping and valves or a change of phase induced by liquid temperature or suction pressure deviations. For example, a one-pound suction pressure change in a boiler-feed application may permit the deaerator-supplied water to flash into steam. The introduction of a two-phase mixture of hot water and steam into the pump causes accelerated wear, instability, loss of pump performance, and chronic failure problems.

Total System Head. Centrifugal pump performance is controlled by the total system head (TSH) requirement, unlike positive-displacement pumps. TSH is defined as the

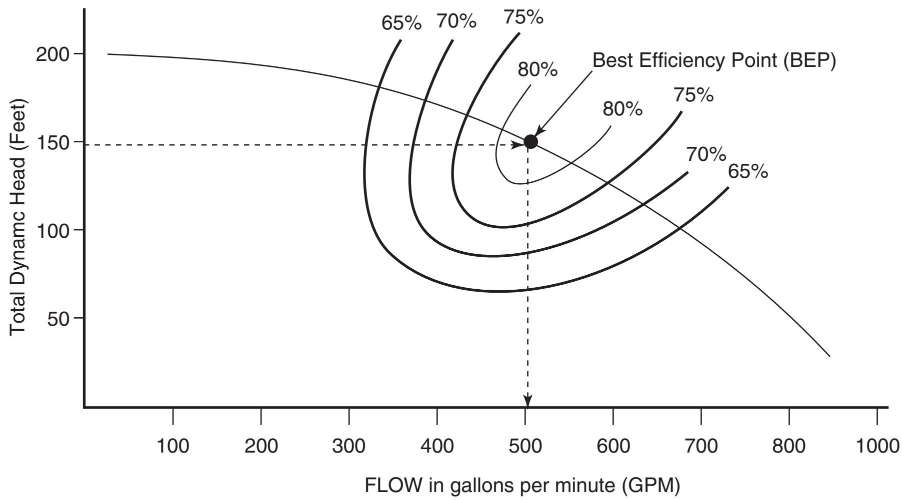


Figure 13–3 Simple hydraulic curve for centrifugal pump.

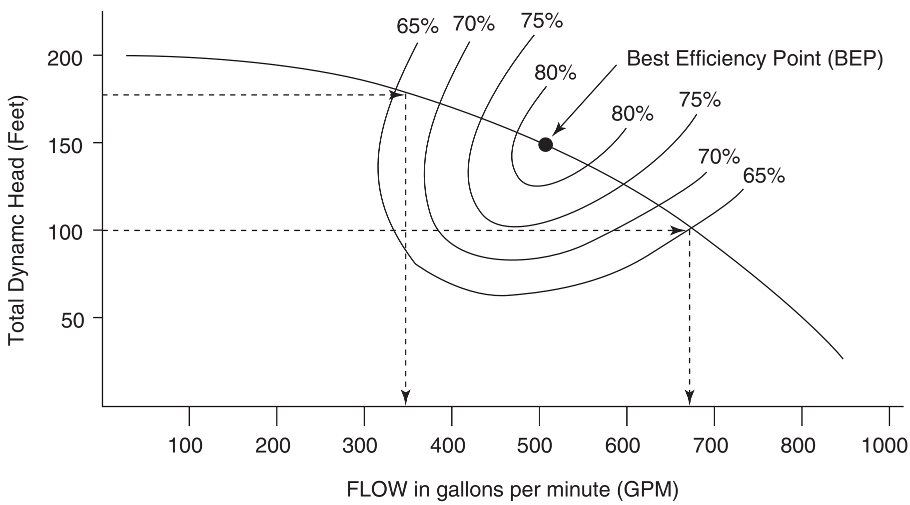


Figure 13–4 Actual centrifugal pump performance depends on total system head.

total pressure required to overcome all resistance at a given flow. This value includes all vertical lift, friction loss, and back-pressure generated by the entire system. It determines the efficiency, discharge volume, and stability of the pump.

Total Dynamic Head. Total dynamic head (TDH) is the difference between the discharge and suction pressure of a centrifugal pump. Pump manufacturers that generate hydraulic curves, such as those shown in Figures 13–3, 13–4, and 13–5, use this value. These curves represent the performance that can be expected for a particular pump

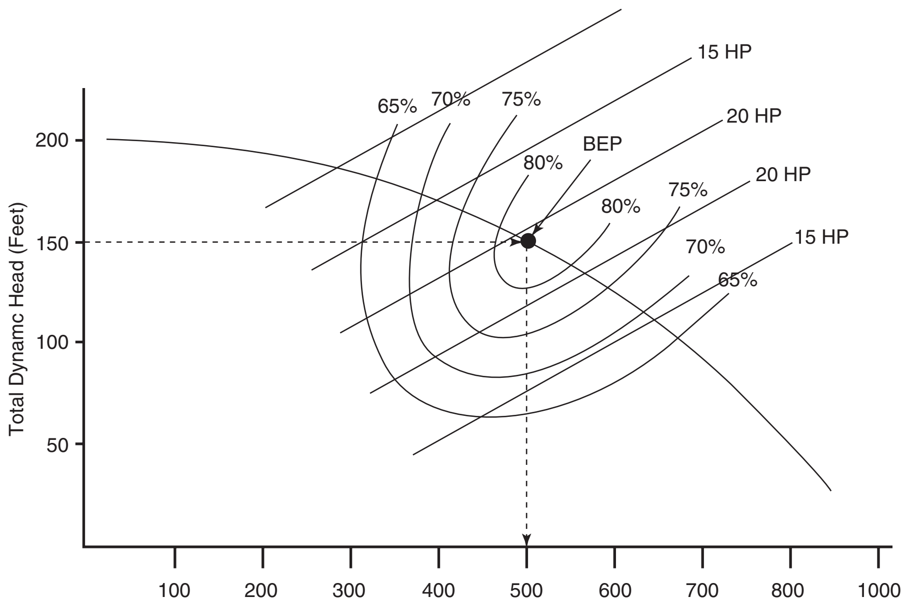


Figure 13–5 Brake horsepower needs to change with process parameters.

under specific operating conditions. For example, a pump with a discharge pressure of 100 psig and a positive pressure of 10 psig at the suction will have a TDH of 90 psig.

Most pump hydraulic curves define pressure to be TDH rather than actual discharge pressure. This consideration is important when evaluating pump problems. For example, a variation in suction pressure has a measurable impact on both discharge pressure and volume. Figure 13–3 is a simplified hydraulic curve for a single-stage centrifugal pump. The vertical axis is TDH, and the horizontal axis is discharge volume or flow.

The best operating point for any centrifugal pump is called the best efficiency point (BEP). This is the point on the curve where the pump delivers the best combination of pressure and flow. In addition, the BEP defines the point that provides the most stable pump operation with the lowest power consumption and longest maintenance-free service life.

In any installation, the pump will always operate at the point where its TDH equals the TSH. When selecting a pump, it is hoped that the BEP is near the required flow where the TDH equals TSH on the curve. If it is not, some operating-cost penalty will result from the pump's inefficiency. This is often unavoidable because pump selection is determined by choosing from what is available commercially as opposed to selecting one that would provide the best theoretical performance.

For the centrifugal pump illustrated in Figure 13–3, the BEP occurs at a flow of 500 gallons per minute with 150 feet TDH. If the TSH were increased to 175 feet, however, the pump's output would decrease to 350 gallons per minute. Conversely, a decrease in TSH would increase the pump's output. For example, a TSH of 100 feet would result in a discharge flow of almost 670 gallons per minute.

From an operating dynamic standpoint, a centrifugal pump becomes more and more unstable as the hydraulic point moves away from the BEP. As a result, the normal service life decreases and the potential for premature failure of the pump or its components increases. A centrifugal pump should not be operated outside the efficiency range shown by the bands on its hydraulic curve, or 65 percent for the example shown in Figure 13–3.

If the pump is operated to the left of the minimum recommended efficiency point, it may not discharge enough liquid to dissipate the heat generated by the pumping operation. This can result in a heat buildup within the pump that can result in catastrophic failure. This operating condition, which is called *shut-off*, is a leading cause of premature pump failure.

When the pump operates to the right of the last recommended efficiency point, it tends to overspeed and become extremely unstable. This operating condition, which is called *run-out*, can also result in accelerated wear and premature failure.

Brake horsepower (BHP) refers to the amount of motor horsepower required for proper pump operation. The hydraulic curve for each type of centrifugal pump reflects its performance (i.e., flow and head) at various BHPs. Figure 13–5 is an example of a simplified hydraulic curve that includes the BHP parameter.

Note the diagonal lines that indicate the BHP required for various process conditions. For example, the pump illustrated in Figure 13–2 requires 22.3 horsepower at its BEP. If the TSH required by the application increases from 150 feet to 175 feet, the horsepower required by the pump increases to 24.6. Conversely, when the TSH decreases, the required horsepower also decreases.

The brake horsepower required by a centrifugal pump can be easily calculated by:

$$\text{Brake Horsepower} = \frac{\text{Flow (GPM)} \times \text{Specific Gravity} \times \text{Total Dynamic Head (Feet)}}{3960 \times \text{Efficiency}}$$

With two exceptions, the certified hydraulic curve for any centrifugal pump provides the data required by calculating the actual brake horsepower. Those exceptions are specific gravity and TDH.

Specific gravity must be determined for the specific liquid being pumped. For example, water has a specific gravity of 1.0. Most other clear liquids have a specific gravity of less than 1.0. Slurries and other liquids that contain solids or are highly viscous materials generally have a higher specific gravity. Reference books, like Ingersoll Rand's *Cameron's Hydraulics Databook*, provide these values for many liquids.

The TDH can be directly measured for any application using two calibrated pressure gauges. Install one gauge in the suction inlet of the pump and the other on the discharge. The difference between these two readings is TDH.

With the actual TDH, flow can be determined directly from the hydraulic curve. Simply locate the measured pressure on the hydraulic curve by drawing a horizontal line from the vertical axis (i.e., TDH) to a point where it intersects the curve. From the intersect point, draw a vertical line downward to the horizontal axis (i.e., flow). This provides an accurate flowrate for the pump. The intersection point also provides the pump's efficiency for that specific point. Because the intersection may not fall exactly on one of the efficiency curves, some approximation may be required.

Installation

Centrifugal pump installation should follow Hydraulic Institute Standards, which provide specific guidelines to prevent distortion of the pump and its baseplate. Distortions can result in premature wear, loss of performance, or catastrophic failure. The following should be evaluated as part of a root-cause failure analysis: foundation, piping support, and inlet and discharge piping configurations.

Centrifugal pumps require a rigid foundation that prevents torsional or linear movement of the pump and its baseplate. In most cases, this type of pump is mounted on a concrete pad with enough mass to securely support the baseplate, which has a series of mounting holes. Depending on size, there may be three to six mounting points on each side.

The baseplate must be securely bolted to the concrete foundation at all of these points. One common installation error is to leave out the center baseplate lag bolts. This permits the baseplate to flex with the torsional load generated by the pump.

Pipe strain causes the pump casing to deform and results in premature wear and/or failure. Therefore, both suction and discharge piping must be adequately supported to prevent strain. In addition, flexible isolator connectors should be used on both suction and discharge pipes to ensure proper operation.

Centrifugal pumps are highly susceptible to turbulent flow. The Hydraulic Institute provides guidelines for piping configurations that are specifically designed to ensure laminar flow of the liquid as it enters the pump. As a general rule, the suction pipe should provide a straight, unrestricted run that is six times the inlet diameter of the pump.

Installations that have sharp turns, shut-off or flow-control valves, or undersized pipe on the suction side of the pump are prone to chronic performance problems. Such deviations from good engineering practices result in turbulent suction flow and cause hydraulic instability that severely restricts pump performance.

The restrictions on discharge piping are not as critical as for suction piping, but using good engineering practices ensures longer life and trouble-free operation of the pump. The primary considerations that govern discharge piping design are friction losses and total vertical lift or elevation change. The combination of these two factors is called TSH, which represents the total force that the pump must overcome to perform properly. If the system is designed properly, the discharge pressure of the pump will be slightly higher than the TSH at the desired flowrate.

In most applications, it is relatively straightforward to confirm the total elevation change of the pumped liquid. Measure all vertical rises and drops in the discharge piping, then calculate the total difference between the pump's centerline and the final delivery point.

Determining the total friction loss, however, is not as simple. Friction loss is caused by several factors, all of which depend on the flow velocity generated by the pump. The major sources of friction loss include:

- Friction between the pumped liquid and the sidewalls of the pipe
- Valves, elbows, and other mechanical flow restrictions
- Other flow restrictions, such as back-pressure created by the weight of liquid in the delivery storage tank or resistance within the system component that uses the pumped liquid

Several reference books, like Ingersoll-Rand's *Cameron's Hydraulics Databook*, provide the pipe-friction losses for common pipes under various flow conditions. Generally, data tables define the approximate losses in terms of specific pipe lengths or runs. Friction loss can be approximated by measuring the total run length of each pipe size used in the discharge system, dividing the total by the equivalent length used in the table, and multiplying the result by the friction loss given in the table.

Each time the flow is interrupted by a change of direction, a restriction caused by valving, or a change in pipe diameter, the flow resistance of the piping increases substantially. The actual amount of this increase depends on the nature of the restriction. For example, a short-radius elbow creates much more resistance than a long-radius elbow; a ball valve's resistance is much greater than a gate valve's; and the resistance from a pipe-size reduction of four inches will be greater than for a one-inch reduction. Reference tables are available in hydraulics handbooks that provide the relative values for each of the major sources of friction loss. As in the friction tables mentioned earlier, these tables often provide the friction loss as equivalent runs of straight pipe.

In some cases, friction losses are difficult to quantify. If the pumped liquid is delivered to an intermediate storage tank, the configuration of the tank's inlet determines if it adds to the system pressure. If the inlet is on or near the top, the tank will add no back-pressure; however, if the inlet is below the normal liquid level, the total height of liquid above the inlet must be added to the total system head.

In applications where the liquid is used directly by one or more system components, the contribution of these components to the total system head may be difficult to calculate. In some cases, the vendor's manual or the original design documentation will provide this information. If these data are not available, then the friction losses and back-pressure need to be measured or an overcapacity pump selected for service based on a conservative estimate.

Operating Methods

Normally, little consideration is given to operating practices for centrifugal pumps; however, some critical practices must be followed, such as using proper startup procedures, using proper bypass operations, and operating under stable conditions.

Startup Procedures. Centrifugal pumps should always be started with the discharge valve closed. As soon as the pump is activated, the valve should be slowly opened to its full-open position. The only exception to this rule is when there is positive back-pressure on the pump at startup. Without adequate back-pressure, the pump will absorb a substantial torsional load during the initial startup sequence. The normal tendency is to overspeed because there is no resistance on the impeller.

Bypass Operation. Many pump applications include a bypass loop intended to prevent deadheading (i.e., pumping against a closed discharge). Most bypass loops consist of a metered orifice inserted into the bypass piping to permit a minimal flow of liquid. In many cases, the flow permitted by these metered orifices is not sufficient to dissipate the heat generated by the pump or to permit stable pump operation.

If a bypass loop is used, it must provide sufficient flow to ensure reliable pump operation. The bypass should provide sufficient volume to permit the pump to operate within its designed operating envelope. This envelope is bound by the efficiency curves that are included on the pump's hydraulic curve, which provides the minimum flow needed to meet this requirement.

Stable Operating Conditions. Centrifugal pumps cannot absorb constant, rapid changes in operating environment. For example, frequent cycling between full-flow and no-flow ensures premature failure of any centrifugal pump. The radical surge of back-pressure generated by rapidly closing a discharge valve, referred to as *hydraulic hammer*, generates an instantaneous shock load that can literally tear the pump from its piping and foundation.

In applications where frequent changes in flow demand are required, the pump system must be protected from such transients. Two methods can be used to protect the system.

- *Slow down the transient*. Instead of instant valve closing, throttle the system over a longer interval. This will reduce the potential for hydraulic hammer and prolong pump life.
- *Install proportioning valves*. For applications where frequent radical flow swings are necessary, the best protection is to install a pair of proportioning valves that have inverse logic. The primary valve controls flow to the process. The second controls flow to a full-flow bypass. Because of their inverse logic, the second valve will open in direct proportion as the primary valve closes, keeping the flow from the pump nearly constant.

Design Limitations. Centrifugal pumps can be divided into two basic types: end-suction and horizontal split case. These two major classifications can be further broken into single-stage and multistage. Each of these classifications has common monitoring parameters, but each also has unique features that alter its forcing functions and the resultant vibration profile. The common monitoring parameters for all centrifugal pumps include axial thrusting, vane-pass, and running speed.

End-suction and multistage pumps with inline impellers are prone to excessive axial thrusting. In the end-suction pump, the centerline axial inlet configuration is the primary source of thrust. Restrictions in the suction piping, or low suction pressures, create a strong imbalance that forces the rotating element toward the inlet.

Multistage pumps with inline impellers generate a strong axial force on the outboard end of the pump. Most of these pumps have oversized thrust bearings (e.g., Kingsbury bearings) that restrict the amount of axial movement; however, bearing wear caused by constant rotor thrusting is a dominant failure mode. Monitoring the axial movement of the shaft should be done whenever possible.

Hydraulic or flow instability is common in centrifugal pumps. In addition to the restrictions of the suction and discharge discussed previously, the piping configuration in many applications creates instability. Although flow through the pump should be laminar, sharp turns or other restrictions in the inlet piping can create turbulent flow conditions. Forcing functions such as these result in hydraulic instability, which displaces the rotating element within the pump.

In a vibration analysis, hydraulic instability is displayed at the vane-pass frequency of the pump's impeller. Vane-pass frequency is equal to the number of vanes in the impeller multiplied by the actual running speed of the shaft. Therefore, a narrowband window should be established to monitor the vane-pass frequency of all centrifugal pumps.

13.1.6 Interpreting Operating Dynamics

Operating dynamics analysis must be based on the design and dynamics of the specific machine or system. Data must include all parameters that define the actual operating condition of that system. In most cases, these data will include full, high-resolution vibration data, incoming product characteristics, all pertinent process data, and actual operating control parameters.

Vibration Data

For steady-state operation, high-resolution, single-channel vibration data can be used to evaluate a system's operating dynamics. If the system is subject to variables, such as incoming production, operator control inputs, or changes in speed or load, multi-channel, real-time data may be required to properly evaluate the system. In addition, for systems that rely on timing or have components where response time or response characteristics are critical to the process, these data should be augmented with time-domain vibration data.

Data Normalization

In all cases, vibration data must be normalized to ensure proper interpretation. Without a clear understanding of the actual operating envelope that was present when the vibration data were acquired, it is nearly impossible to interpret the data. Normalization is required to eliminate the effects of process changes in the vibration profiles. At a minimum, each data set must be normalized for speed, load, and the other standard process variables. Normalization allows the use of trending techniques or the comparison of a series of profiles generated over time.

Regardless of the machine's operating conditions, the frequency components should occur at the same location when comparing normalized data for a machine. Normalization allows the location of frequency components to be expressed as an integer multiple of shaft running speed, although fractions sometimes result. For example, gear-mesh frequency locations are generally integer multiples (e.g., 5×, 10×), and bearing-frequency locations are generally noninteger multiples (e.g., 0.5×, 1.5×). Plotting the vibration signature in multiples of running speed quickly differentiates the unique frequencies that are generated by bearings from those generated by gears, blades, and other components that are integers of running speed. At a minimum, the vibration data must be normalized to correct for changes in speed, load, and other process variables.

Speed. When normalizing data for speed, all machines should be considered to be variable-speed—even those classified as constant-speed. Speed changes caused by load occur even with simple "constant-speed" machine-trains, such as electric-motor–driven centrifugal pumps. Generally, the change is relatively minor (between 5 to 15 percent), but it is enough to affect diagnostic accuracy. This variation in speed is enough to distort vibration signatures, which can lead to improper diagnosis.

With constant-speed machines, an analyst's normal tendency is to normalize speed to the default speed used in the database setup; however, this practice can introduce enough error to distort the results of the analysis because the default speed is usually an average value from the manufacturer. For example, a motor may have been assigned a speed of 1,780 revolutions per minute (rpm) during setup. The analyst then assumes that all data sets were acquired at this speed. In actual practice, however, the motor's speed could vary the full range between locked rotor speed (i.e., maximum load) to synchronous (i.e., no-load) speed. In this example, the range could be between 1,750 rpm and 1,800 rpm, a difference of 50 rpm. This variation is enough to distort data normalized to 1,780 rpm. Therefore, it is necessary to normalize each data set to the actual operating speed that occurs during data acquisition rather than using the default speed from the database.

Take care when using the vibration analysis software provided with most microprocessor-based systems to determine the machine speed to use for data normalization. In particular, do not obtain the machine speed value from a display-screen plot (i.e., on-screen or print-screen) generated by a microprocessor-based vibration analysis software program. Because the cursor position does not represent the true frequency of displayed peaks, it cannot be used. The displayed cursor position is an average value. The graphics packages in most of the programs use an average of four or five data points to plot each visible peak. This technique is acceptable for most data analysis purposes, but it can skew the results if used to normalize the data. The approximate machine speed obtained from such a plot is usually within 10 percent of the actual value, which is not accurate enough to be used for speed normalization. Instead, use the peak search algorithm and print out the actual peaks and associated speeds.

Load. Data also must be normalized for variations in load. Where speed variations result in a right or left shift of the frequency components, variations in load change the amplitude. For example, the vibration amplitude of a centrifugal compressor taken at 100 percent load is substantially lower than the vibration amplitude in the same compressor operating at 50 percent load.

In addition, the effect of load variation is not linear. In other words, the change in overall vibration energy does not change by 50 percent with a corresponding 50 percent load variation. Instead, it tends to follow more of a quadratic relationship. A 50 percent load variation can create a 200 percent, or a factor of four, change in vibration energy.

None of the comparative trending or diagnostic techniques used by traditional vibration analysis can be used on variable-load machine-trains without first normalizing the data. Again, since even machines classified as constant-load operate in a variable-load condition, it is good practice to normalize all data to compensate for load variations using the proper relationship for the application.

Other Process Variables. Other variations in a process or system have a direct effect on the operating dynamics and vibration profile of the machinery. In addition to changes in speed and load, other process variables affect the stability of the rotating elements, induce abnormal distribution of loads, and cause a variety of other abnormalities that directly impact diagnostics. Therefore, each acquired data set should include a full description of the machine-train and process system parameters. For example, abnormal strip tension or traction in a continuous-process line changes the load distribution on the process rolls that transport a strip through the line. This abnormal loading induces a form of misalignment that is visible in the roll and its drive-train's vibration profile.

Analysis of shaft deflection is a fundamental diagnostic tool. If the analyst can establish the specific direction and approximate severity of shaft displacement, it is much easier to isolate the forcing function. For example, when the discharge valve on an end-suction centrifugal pump is restricted, the pump's shaft is displaced in a direction opposite to the discharge volute. Such deflection is caused by the back-pressure generated by the partially closed valve. Most of the failure modes and abnormal operating dynamics that affect machine reliability force the shaft from its true centerline. By using common-shaft diagnostics, the analyst can detect deviations from normal operating condition and isolate the probable forcing function.

We have used centrifugal pumps to illustrate the basics of operating dynamics analysis, but these same concepts are applicable to all plant machinery, equipment, and systems. The same concepts can be used for both dynamic and static plant systems with equal results. In every case, the first step is a thorough understanding of the design precepts of the system, then understanding the installation and application. It is imperative that all deviations created by the installation, application, or mode of operation must be fully understood and used to analyze the dynamics of the system.

14

FAILURE-MODE ANALYSIS

All of the analysis techniques discussed to this point have been methods to determine if a potential problem exists within the machine-train or its associated systems. Failure-mode analysis is the next step required to specifically pinpoint the failure mode and identify which machine-train component is degrading.

Although failure-mode analysis identifies the number and symptoms of machine-train problems, it does not always identify the true root-cause of problems. Visual inspection, additional testing, or other techniques such as operating dynamics analysis must verify root-cause.

Failure-mode analysis is based on the assumption that certain failure modes are common to all machine-trains and all applications. It also assumes that the vibration patterns for each of these failure modes, when adjusted for process-system dynamics, are absolute and identifiable.

Two types of information are required to perform failure-mode analysis: (1) machine-train vibration signatures, both FFTs and time traces; and (2) practical knowledge of machine dynamics and failure modes. Several failure-mode charts are available that describe the symptoms or abnormal vibration profiles that indicate potential problems exist. An example is the following description of the imbalance failure mode, which was obtained from a failure-mode chart: Single-plane imbalance generates a dominant fundamental (1×) frequency component with no harmonics (2×, 3×, etc.). Note, however, that the failure-mode charts are simplistic because many other machine-train problems also excite, or increase the amplitude of, the fundamental (1×) frequency component. In a normal vibration signature, 60 to 70 percent of the total overall, or broadband, energy is contained in the 1× frequency component. Any deviation from a state of equilibrium increases the energy level at this fundamental shaft speed.

14.1 Common General Failure Modes

Many of the common causes of failure in machinery components can be identified by understanding their relationship to the true running speed of the shaft within the machine-train.

Table 14–1 is a vibration troubleshooting chart that identifies some of the common failure modes. This table provides general guidelines for interpreting the most common abnormal vibration profiles. These guidelines, however, do not provide positive verification or identification of machine-train problems. Verification requires an understanding of the failure mode and how it appears in the vibration signature.

The sections to follow describe the most common machine-train failure modes: critical speeds, imbalance, mechanical looseness, misalignment, modulations, process instability, and resonance.

14.1.1 Critical Speeds

All machine-trains have one or more critical speeds that can cause severe vibration and damage to the machine. Critical speeds result from the phenomenon known as *dynamic resonance*.

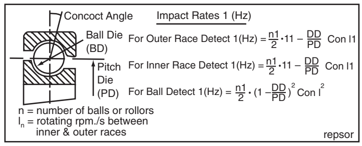
Critical speed is a function of the natural frequency of dynamic components such as a rotor assembly, bearings, and so on. All dynamic components have one or more natural frequencies that can be excited by an energy source that coincides with, or is in proximity to, that frequency. For example, a rotor assembly with a natural frequency of 1,800 rotations per minute (rpm) cannot be rotated at speeds between 1,782 and 1,818 rpm without exciting the rotor's natural frequency.

Critical speed should not be confused with the mode shape of a rotating shaft. Deflection of the shaft from its true centerline (i.e., mode shape) elevates the vibration amplitude and generates dominant vibration frequencies at the rotor's fundamental and harmonics of the running speed; however, the amplitude of these frequency components tends to be much lower than those caused by operating at a critical speed of the rotor assembly. Also, the excessive vibration amplitude generated by operating at a critical speed disappears when the speed is changed. Vibrations caused by mode shape tend to remain through a much wider speed range or may even be independent of speed.

The unique natural frequencies of dynamic machine components are determined by the mass, freedom of movement, support stiffness, and other factors. These factors define the response characteristics of the rotor assembly (i.e., rotor dynamics) at various operating conditions.

Each critical speed has a well-defined vibration pattern. The first critical excites the fundamental (1×) frequency component; the second critical excites the secondary (2×) component; and the third critical excites the third (3×) frequency component.

Table 14–1 Vibration Troubleshooting Chart

Nature of Fault	Frequency of Dominant Vibration (Hz = rpm. 60)	Direction	Remarks
Rotating Members Out of Balance	1 × rpm	Radial	A common cause of excess vibration in machinery
Misalignment & Bent Shaft	Usually 1 × rpm Often 2 × rpm Sometimes 3 & 4 × rpm	Radial & Axial	A common fault
Damaged Rolling Element Bearings (Ball, Roller, etc.)	Impact rates for the individual bearing components° Also vibrations at very high frequencies (20 to 60 kHz)	Radial & Axial	Uneven vibration levels, often with shocks. °Impact-Rates: 
Journal Bearings Loose in Housings	Sub-harmonics of shaft rpm, exactly 1/2 or 1/3 × rpm	Primarily Radial	Looseness may only develop at operating speed and temperature (e.g., turbomachines)
Oil Film Whirl or Whip in Journal Bearings	Slightly less than half shaft speed (42% to 48%)	Primarily Radial	Applicable to high-speed (e.g., turbo) machines
Hysteresis Whirl	Shaft critical speed	Primarily Radial	Vibrations excited when passing through critical shaft speed are maintained at higher shaft speeds. Can sometimes be cured by checking tightness of rotor components
Damaged or Worn Gears	Tooth meshing frequencies (shaft rpm × number of teeth) and harmonics	Radial & Axial	Sidebands around tooth meshing frequencies indicate modulation (e.g., eccentricity) at frequency corresponding to sideband spacings. Normally only detectable with very narrow-band analysis
Mechanical Looseness	2 × rpm		
Faulty Belt Drive	1, 2, 3 & 4 × rpm of belt	Radial	
Unbalanced Reciprocating Forces and Couples	1 × rpm and/or multiples for higher order unbalance	Primarily Radial	
Increased Turbulence	Blade & Vane passing frequencies and harmonics	Radial & Axial	Increasing levels indicate increasing turbulence
Electrically Induced Vibrations	1 × rpm or 1 or 2 times sychronous frequency	Radial & Axial	Should disappear when turning off the power

The best way to confirm a critical-speed problem is to change the operating speed of the machine-train. If the machine is operating at a critical speed, the amplitude of the vibration components (1×, 2×, or 3×) will immediately drop when the speed is changed. If the amplitude remains relatively constant when the speed is changed, the problem is not critical speed.

14.1.2 Imbalance

The term *balance* means that all forces generated by, or acting on, the rotating element of a machine-train are in a state of equilibrium. Any change in this state of equilibrium creates an imbalance. In the global sense, imbalance is one of the most common abnormal vibration profiles exhibited by all process machinery.

Theoretically, a perfectly balanced machine that has no friction in the bearings would experience no vibration and would have a perfect vibration profile—a perfectly flat, horizontal line—however, no perfectly balanced machines exist. All machine-trains exhibit some level of imbalance, which has a dominant frequency component at the fundamental running speed (1×) of each shaft.

An imbalance profile can be excited as a result of the combined factors of mechanical imbalance, lift/gravity differential effects, aerodynamic and hydraulic instabilities, process loading, and, in fact, all failure modes.

Mechanical

It is incorrect to assume that mechanical imbalance must exist to create an imbalance condition within the machine. Mechanical imbalance, however, is the only form of imbalance that is corrected by balancing the rotating element. When all failures are considered, the number of machine problems that are the result of actual mechanical rotor imbalance is relatively small.

Single-Plane. Single-plane mechanical imbalance excites the fundamental (1×) frequency component, which is typically the dominant amplitude in a signature. Because there is only one point of imbalance, only one high spot occurs as the rotor completes each revolution. The vibration signature may also contain lower-level frequencies reflecting bearing defects and passing frequencies. Figure 14–1 illustrates single-plane imbalance.

Because mechanical imbalance is multidirectional, it appears in both the vertical and horizontal directions at the machine's bearing pedestals. The actual amplitude of the 1× component generally is not identical in the vertical and horizontal directions and both generally contain elevated vibration levels at 1×.

The difference between the vertical and horizontal values is a function of the bearing-pedestal stiffness. In most cases, the horizontal plane has a greater freedom of movement and, therefore, contains higher amplitudes at 1× than the vertical plane.

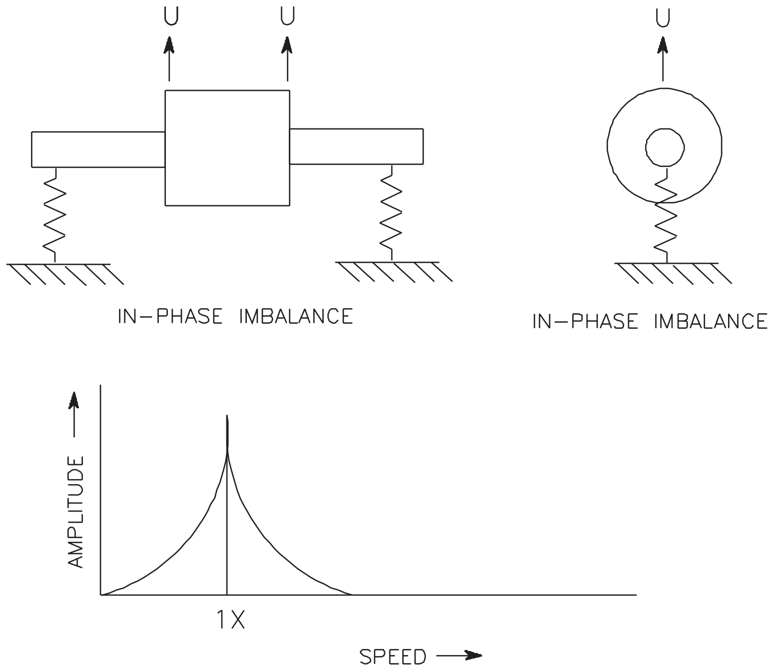


Figure 14–1 Single-plane imbalance.

Multiplane. Multiplane mechanical imbalance generates multiple harmonics of running speed. The actual number of harmonics depends on the number of imbalance points, the severity of imbalance, and the phase angle between imbalance points.

Figure 14–2 illustrates a case of multiplane imbalance in which there are four out-of-phase imbalance points. The resultant vibration profile contains dominant frequencies at 1×, 2×, 3×, and 4×. The actual amplitude of each of these components is determined by the amount of imbalance at each of the four points, but the 1× component should always be higher than any subsequent harmonics.

Lift/Gravity Differential

Lift, which is designed into a machine-train's rotating elements to compensate for the effects of gravity acting on the rotor, is another source of imbalance. Because lift does not always equal gravity, some imbalance always exists in machine-trains. The vibration component caused by the lift/gravity differential effect appears at the fundamental or 1× frequency.

Other

All failure modes create some form of imbalance in a machine, as do aerodynamic instability, hydraulic instability, and process loading. The process loading of most

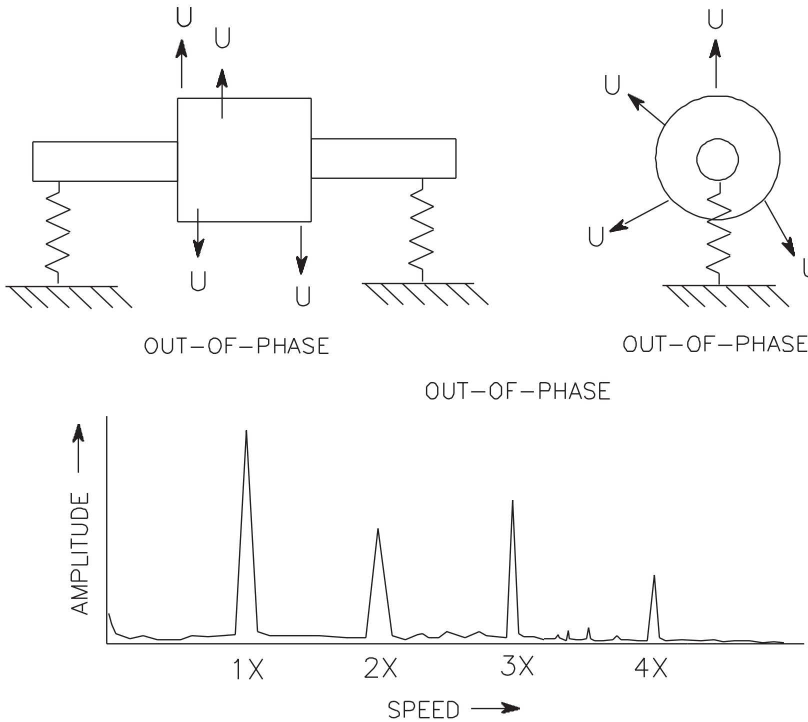


Figure 14–2 Multiplane imbalance generates multiple harmonics.

machine-trains varies, at least slightly, during normal operations. These vibration components appear at the 1× frequency.

14.1.3 Mechanical Looseness

Looseness, which can be present in both the vertical and horizontal planes, can create a variety of patterns in a vibration signature. In some cases, the fundamental (1×) frequency is excited. In others, a frequency component at one-half multiples of the shaft's running speed (e.g., 0.5×, 1.5×, 2.5×) is present. In almost all cases, there are multiple harmonics, both full and half.

Vertical

Mechanical looseness in the vertical plane generates a series of harmonic and half-harmonic frequency components. Figure 14–3 is a simple example of a vertical mechanical looseness signature.

In most cases, the half-harmonic components are about one-half of the amplitude of the harmonic components. They result from the machine-train lifting until stopped by the bolts. The impact as the machine reaches the upper limit of travel generates a fre-

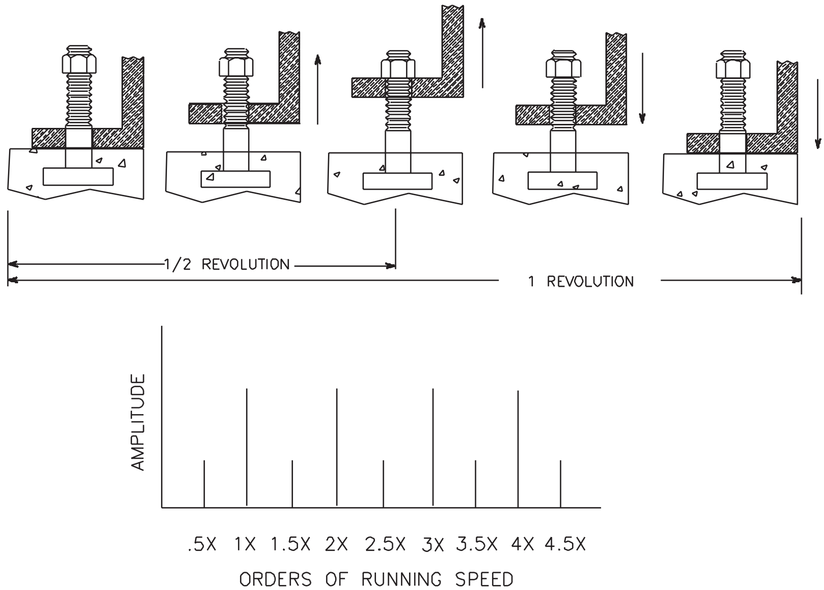


Figure 14–3 Vertical mechanical looseness has a unique vibration profile.

quency component at one-half multiples (i.e., orders) of running speed. As the machine returns to the bottom of its movement, its original position, a larger impact occurs that generates the full harmonics of running speed.

The difference in amplitude between the full harmonics and half-harmonics is caused by the effects of gravity. As the machine lifts to its limit of travel, gravity resists the lifting force. Therefore, the impact force that is generated as the machine foot contacts the mounting bolt is the difference between the lifting force and gravity. As the machine drops, the force of gravity combines with the force generated by imbalance. The impact force as the machine foot contacts the foundation is the sum of the force of gravity and the force resulting from imbalance.

Horizontal

Figure 14–4 illustrates horizontal mechanical looseness, which is also common to machine-trains. In this example, the machine's support legs flex in the horizontal plane. Unlike the vertical looseness illustrated in Figure 4–37, gravity is uniform at each leg and there is no increased impact energy as the leg's direction is reversed.

Horizontal mechanical looseness generates a combination of first (1×) and second (2×) harmonic vibrations. Because the energy source is the machine's rotating shaft, the timing of the flex is equal to one complete revolution of the shaft, or 1×. During this single rotation, the mounting legs flex to their maximum deflection on both sides of

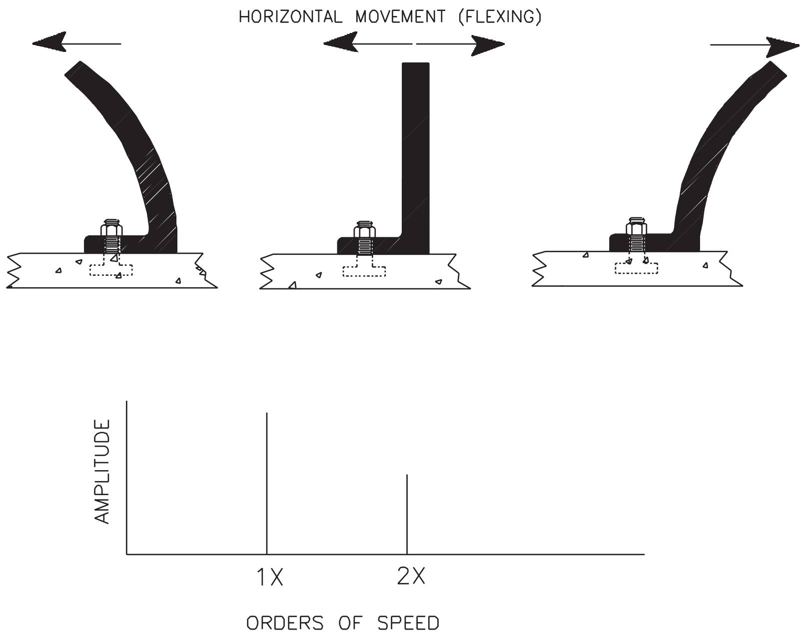


Figure 14–4 Horizontal looseness creates first and second harmonics.

neutral. The double change in direction as the leg first deflects to one side then the other generates a frequency at two times (2×) the shaft's rotating speed.

Other

Many other forms of mechanical looseness (besides vertical and horizontal movement of machine legs) are typical for manufacturing and process machinery. Most forms of pure mechanical looseness result in an increase in the vibration amplitude at the fundamental (1×) shaft speed. In addition, looseness generates one or more harmonics (i.e., 2×, 3×, 4×, or combinations of harmonics and half-harmonics); however, not all looseness generates this classic profile. For example, excessive bearing and gear clearances do not generate multiple harmonics. In these cases, the vibration profile contains unique frequencies that indicate looseness, but the profile varies depending on the nature and severity of the problem.

With sleeve or Babbitt bearings, looseness is displayed as an increase in subharmonic frequencies (i.e., less than the actual shaft speed, such as 0.5×). Rolling-element bearings display elevated frequencies at one or more of their rotational frequencies. Excessive gear clearance increases the amplitude at the gear-mesh frequency and its sidebands.

Other forms of mechanical looseness increase the noise floor across the entire bandwidth of the vibration signature. Although the signature does not contain a distinct

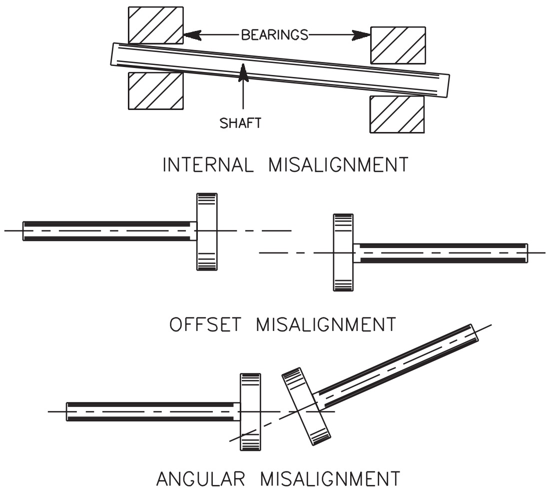


Figure 14–5 Three types of misalignment.

peak or series of peaks, the overall energy contained in the vibration signature is increased. Unfortunately, the increase in noise floor cannot always be used to detect mechanical looseness. Some vibration instruments lack sufficient dynamic range to detect changes in the signature's noise floor.

14.1.4 Misalignment

This condition is virtually always present in machine-trains. Generally, we assume that misalignment exists between shafts that are connected by a coupling, V-belt, or other intermediate drive; however, it can also exist between bearings of a solid shaft and at other points within the machine.

How misalignment appears in the vibration signature depends on the type of misalignment. Figure 14–5 illustrates three types of misalignment (i.e., internal, offset, and angular). These three types excite the fundamental (1×) frequency component because they create an apparent imbalance condition in the machine.

Internal (i.e., bearing) and offset misalignment also excites the second (2×) harmonic frequency. The shaft creates two high spots as it turns through one complete revolution. These two high spots create the first (1×) and second harmonic (2×) components.

Angular misalignment can take several signature forms and excites the fundamental (1×) and secondary (2×) components. It can excite the third (3×) harmonic frequency depending on the actual phase relationship of the angular misalignment. It also creates a strong axial vibration.

14.1.5 Modulations

Modulations are frequency components that appear in a vibration signature but cannot be attributed to any specific physical cause or forcing function. Although these frequencies are "ghosts" or artificial frequencies, they can result in significant damage to a machine-train. The presence of ghosts in a vibration signature often leads to misinterpretation of the data.

Ghosts are caused when two or more frequency components couple, or merge, to form another discrete frequency component in the vibration signature. This generally occurs with multiple-speed machines or a group of single-speed machines.

Note that the presence of modulation, or ghost peaks, is not an absolute indication of a problem within the machine-train. Couple effects may simply increase the amplitude of the fundamental running speed and do little damage to the machine-train; however, this increased amplitude will amplify any defects within the machine-train.

Coupling can have an additive effect on the modulation frequencies, as well as being reflected as a differential or multiplicative effect. These concepts are discussed in the sections to follow.

Take as an example the case of a 10-tooth pinion gear turning at 10 rpm while driving a 20-tooth bullgear with an output speed of 5 rpm. This gear set generates real frequencies at 5, 10, and 100 rpm (i.e., 10 teeth × 10 rpm). This same set can also generate a series of frequencies (i.e., sum and product modulations) at 15 rpm (i.e., 10 rpm + 5 rpm) and 150 rpm (i.e., 15 rpm × 10 teeth). In this example, the 10-rpm input speed coupled with the 5-rpm output speed to create ghost frequencies driven by this artificial fundamental speed (15 rpm).

Sum

This type of modulation, which is described in the previous example, generates a series of frequencies that include the fundamental shaft speeds, both input and output, and fundamental gear-mesh profile. The only difference between the real frequencies and the ghost is their location on the frequency scale. Instead of being at the actual shaft-speed frequency, the ghost appears at frequencies equal to the sum of the input and output shaft speeds. Figure 14–6 illustrates this for a speed-increaser gearbox.

Difference

In this case, the resultant ghost, or modulation, frequencies are generated by the difference between two or more speeds (see Figure 14–7). If we use the same example as before, the resultant ghost frequencies appear at 5 rpm (i.e., 10 rpm –5 rpm) and 50 rpm (i.e., 5 rpm × 10 teeth). Note that the 5-rpm couple frequency coincides with the real output speed of 5 rpm. This results in a dramatic increase in the amplitude of one real running-speed component and the addition of a false gear-mesh peak.

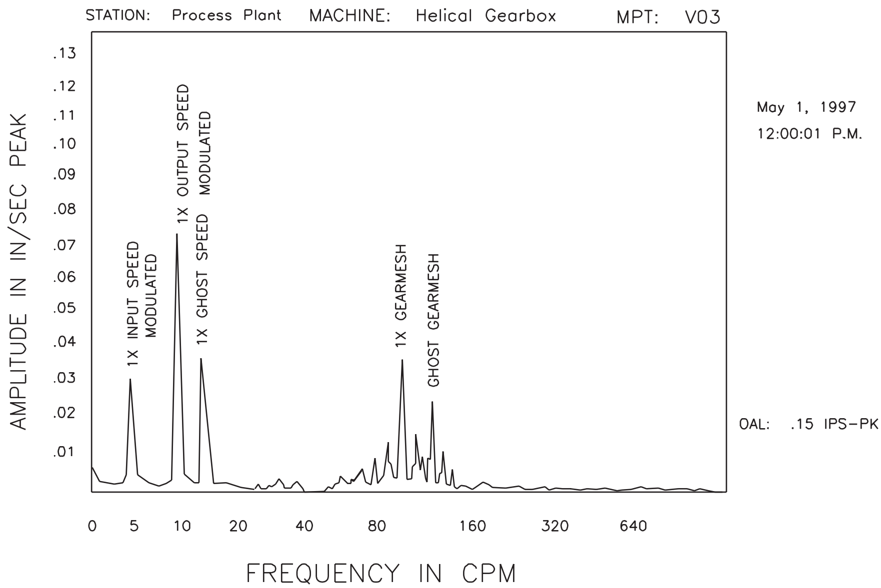


Figure 14–6 Sum modulation for a speed-increaser gearbox.

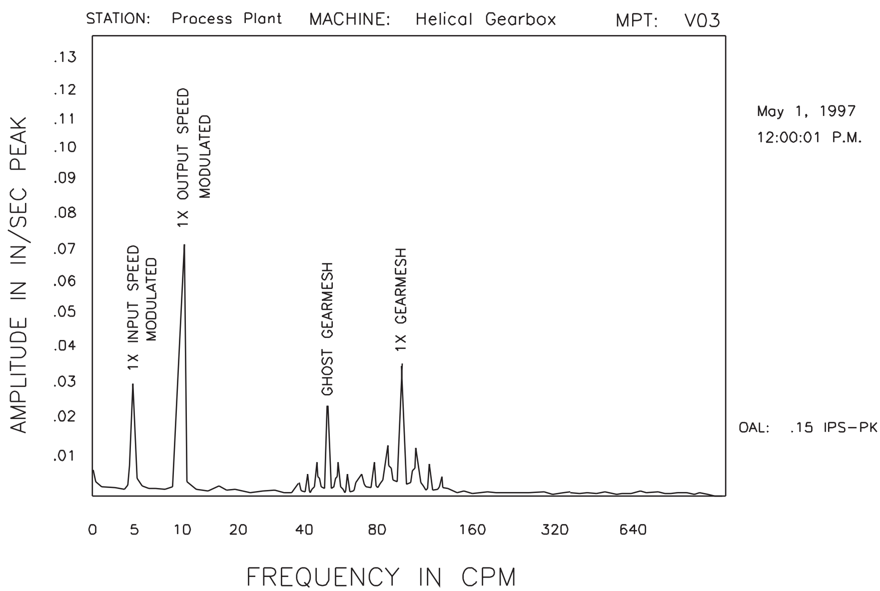


Figure 14–7 Difference modulation for a speed-increaser gearbox.

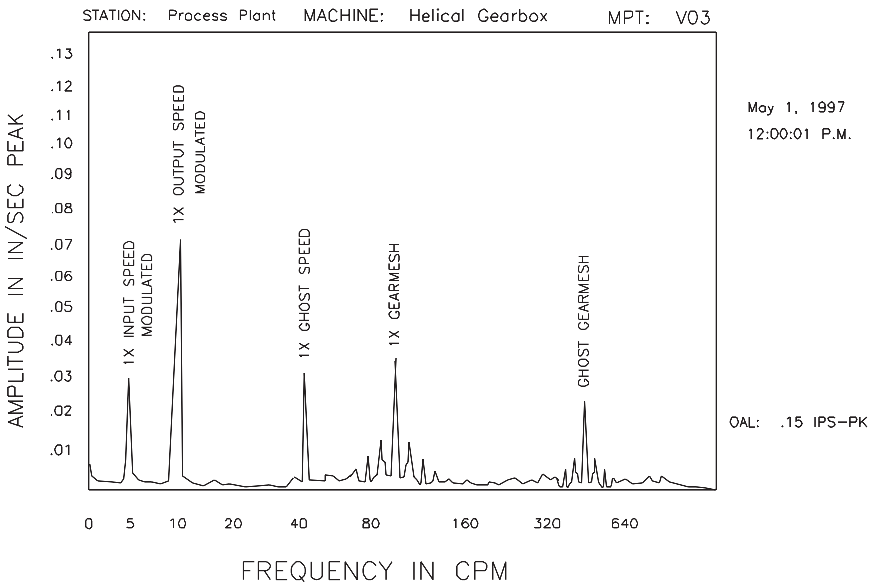


Figure 14–8 Product modulation for a speed-increaser gearbox.

This type of coupling effect is common in single-reduction/increase gearboxes or other machine-train components where multiple running or rotational speeds are relatively close together or even integer multiples of one another. It is more destructive than other forms of coupling in that it coincides with real vibration components and tends to amplify any defects within the machine-train.

Product

With product modulation, the two speeds couple in a multiplicative manner to create a set of artificial frequency components (see Figure 14–8). In the previous example, product modulations occur at 50 rpm (i.e., 10 rpm × 5 rpm) and 500 rpm (i.e., 50 rpm × 10 teeth).

Beware that this type of coupling may often go undetected in a normal vibration analysis. Because the ghost frequencies are relatively high compared to the expected real frequencies, they are often outside the monitored frequency range used for data acquisition and analysis.

14.1.6 Process Instability

Normally associated with bladed or vaned machinery such as fans and pumps, process instability creates an unbalanced condition within the machine. In most cases, it excites the fundamental (1×) and blade-pass/vane-pass frequency components. Unlike true mechanical imbalance, the blade-pass and vane-pass frequency components are broader and have more energy in the form of sideband frequencies.

In most cases, this failure mode also excites the third (3×) harmonic frequency and creates strong axial vibration. Depending on the severity of the instability and the design of the machine, process instability can also create a variety of shaft-mode shapes. In turn, this excites the 1×, 2×, and 3× radial vibration components.

14.1.7 Resonance

Resonance is defined as a large-amplitude vibration caused by a small periodic stimulus with the same, or nearly the same, period as the system's natural vibration. In other words, an energy source with the same, or nearly the same, frequency as the natural frequency of a machine-train or structure will excite that natural frequency. The result is a substantial increase in the amplitude of the natural frequency component.

The key point to remember is that a very low amplitude energy source can cause massive amplitudes when its frequency coincides with the natural frequency of a machine or structure. Higher levels of input energy can cause catastrophic, near instantaneous failure of the machine or structure. Every machine-train has one or more natural frequencies. If one of these frequencies is excited by some component of the normal operation of the system, the machine structure will amplify the energy, which can cause severe damage.

An example of resonance is a tuning fork. If you activate a tuning fork by striking it sharply, the fork vibrates rapidly. As long as it is held suspended, the vibration decays with time; however, if you place it on a desktop, the fork could potentially excite the natural frequency of the desk, which would dramatically amplify the vibration energy.

The same thing can occur if one or more of the running speeds of a machine excite the natural frequency of the machine or its support structure. Resonance is a destructive vibration and, in most cases, it will cause major damage to the machine or support structure.

Two major classifications of resonance are found in most manufacturing and process plants: static and dynamic. Both types exhibit a broad-based, high-amplitude frequency component when viewed in an FFT vibration signature. Unlike meshing or passing frequencies, the resonance frequency component does not have modulations or sidebands. Instead, resonance is displayed as a single, clearly defined peak.

As illustrated in Figure 14–9, a resonance peak represents a large amount of energy. This energy is the result of both the amplitude of the peak and the broad area under the peak. This combination of high peak amplitude and broad-based energy content is typical of most resonance problems. The damping system associated with a reso-

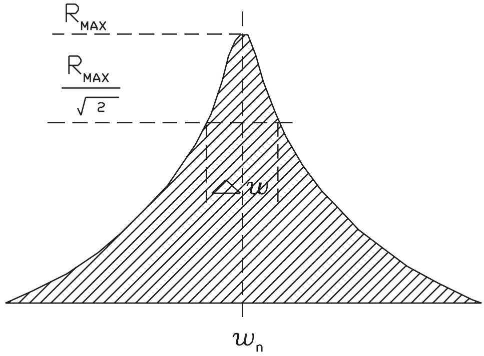


Figure 14–9 Resonance response.

nance frequency is indicated by the sharpness or width of the response curve, ω_n, when measured at the half-power point. R_{MAX} is the maximum resonance and $R_{MAX}/\sqrt{2}$ is the half-power point for a typical resonance-response curve.

Static

When the natural frequency of a stationary, or nondynamic, structure is energized, it will resonate. This type of resonance is classified as static resonance and is considered a nondynamic phenomenon. Nondynamic structures in a machine-train include casings, bearing-support pedestals, and structural members such as beams, piping, and the like.

Because static resonance is a nondynamic phenomenon, it is generally not associated with the primary running speed of any associated machinery. Rather, the source of static resonance can be any energy source that coincides with the natural frequency of any stationary component. For example, an I-beam support on a continuous annealing line may be energized by the running speed of a roll; however, it can also be made to resonate by a bearing frequency, overhead crane, or any of a multitude of other energy sources.

The actual resonant frequency depends on the mass, stiffness, and span of the excited member. In general terms, the natural frequency of a structural member is inversely proportional to the mass and stiffness of the member. In other words, a large turbocompressor's casing will have a lower natural frequency than that of a small end-suction centrifugal pump.

Figure 14–10 illustrates a typical structural-support system. The natural frequencies of all support structures, piping, and other components are functions of mass, span, and stiffness. Each of the arrows on Figure 14–10 indicates a structural member or stationary machine component with a unique natural frequency. Note that each time a structural span is broken or attached to another structure, the stiffness changes. As a result, the natural frequency of that segment also changes.

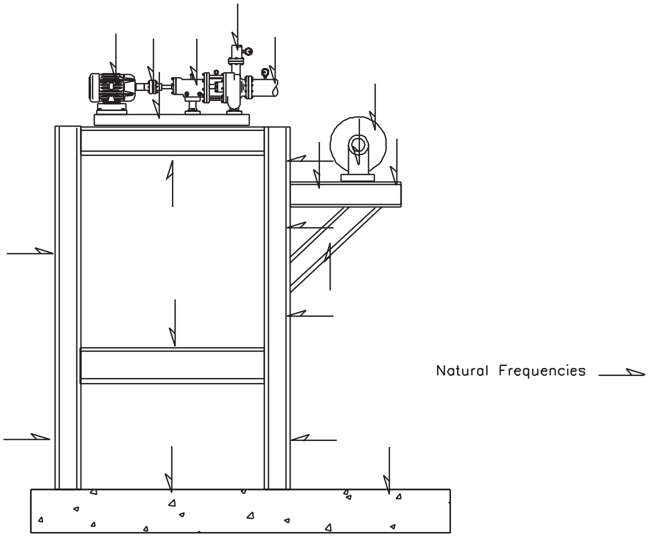


Figure 14–10 Typical discrete natural frequency locations in structural members.

Although most stationary machine components move during normal operation, they are not always resonant. Some degree of flexing or movement is common in most stationary machine-trains and structural members. The amount of movement depends on the spring constant or stiffness of the member; however, when an energy source coincides and couples with the natural frequency of a structure, excessive and extremely destructive vibration amplitudes result.

Dynamic

When the natural frequency of a rotating, or dynamic, structure (e.g., rotor assembly in a fan) is energized, the rotating element resonates. This phenomenon is classified as dynamic resonance, and the rotor speed at which it occurs is referred to as the *critical*.

In most cases, dynamic resonance appears at the fundamental running speed or one of the harmonics of the excited rotating element, but it can also occur at other frequencies. As in the case of static resonance, the actual natural frequencies of dynamic members depend on the mass, bearing span, shaft and bearing-support stiffness, as well as several other factors.

Confirmation Analysis. In most cases, the occurrence of dynamic resonance can be quickly confirmed. When monitoring phase and amplitude, resonance is indicated by a 180-degree phase shift as the rotor passes through the resonant zone. Figure 14–11 illustrates a dynamic resonance at 500 rpm, which shows a dramatic amplitude increase in the frequency-domain display. This is confirmed by the 180-degree phase

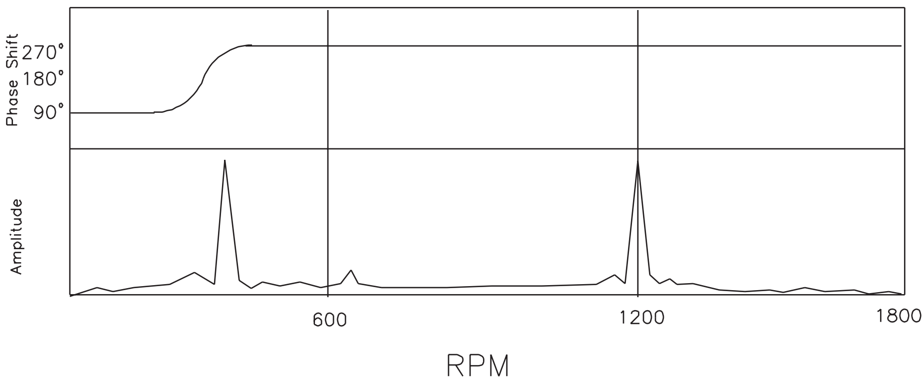


Figure 14–11 Dynamic resonance phase shift.

shift in the time-domain plot. Note that the peak at 1,200 rpm is not resonance. The absence of a phase shift, coupled with the apparent modulations in the FFT, discount the possibility that this peak is resonance-related.

Common Confusions. Vibration analysts often confuse resonance with other failure modes. Because many of the common failure modes tend to create abnormally high vibration levels that appear to be related to a speed change, analysts tend to miss the root-cause of these problems.

Dynamic resonance generates abnormal vibration profiles that tend to coincide with the fundamental (1×) running speed, or one or more of the harmonics, of a machine-train. This often leads the analyst to incorrectly diagnose the problem as imbalance or misalignment. The major difference is that dynamic resonance is the result of a relatively small energy source, such as the fundamental running speed, that results in a massive amplification of the natural frequency of the rotating element.

Function of Speed. The high amplitudes at the rotor's natural frequency are strictly speed dependent. If the energy source, in this case speed, changes to a frequency outside the resonant zone, the abnormal vibration will disappear.

In most cases, running speed is the forcing function that excites the natural frequency of the dynamic component. As a result, rotating equipment is designed to operate at primary rotor speeds that do not coincide with the rotor assembly's natural frequencies. Most low- to moderate-speed machines are designed to operate below the first critical speed of the rotor assembly.

Higher-speed machines may be designed to operate between the first and second, or second and third, critical speeds of the rotor assembly. As these machines accelerate through the resonant zones or critical speeds, their natural frequency is momentarily

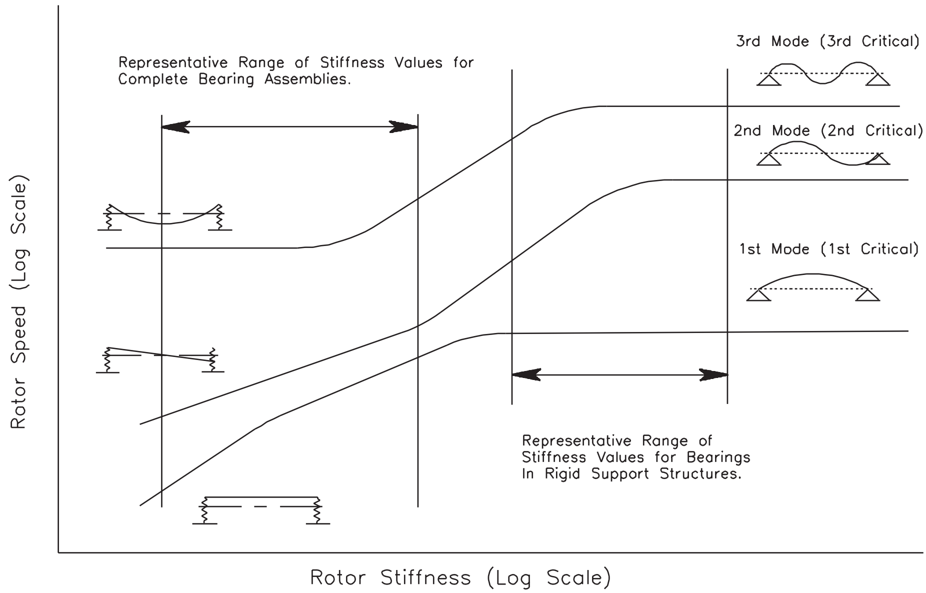


Figure 14–12 Dynamic resonance plot.

excited. As long as the ramp rate limits the duration of excitation, this mode of operation is acceptable; however, care must be taken to ensure that the transient time through the resonant zone is as short as possible.

Figure 14–12 illustrates a typical critical-speed or dynamic-resonance plot. This figure is a plot of the relationship between rotor-support stiffness (X-axis) and critical rotor speed (Y-axis). Rotor-support stiffness depends on the geometry of the rotating element (i.e., shaft and rotor) and the bearing-support structure. These two dominant factors determine the response characteristics of the rotor assembly.

14.2 Failure Modes by Machine-Train Component

In addition to identifying general failure modes that are common to many types of machine-train components, failure-mode analysis can be used to identify failure modes for specific components in a machine-train; however, care must be exercised when analyzing vibration profiles because the data may reflect induced problems. Induced problems affect the performance of a specific component but are not caused by that component. For example, an abnormal outer-race passing frequency may indicate a defective rolling-element bearing. It can also indicate that abnormal loading caused by misalignment, roll bending, process instability, and so on has changed the load zone within the bearing. In the latter case, replacing the bearing does not resolve the problem, and the abnormal profile will still be present after the bearing is changed.

14.2.1 Bearings: Rolling Element

Bearing defects are one of the most common faults identified by vibration-monitoring programs. Although bearings do wear out and fail, these defects are normally symptoms of other problems within the machine-train or process system. Therefore, extreme care must be exercised to ensure that the real problem is identified, not just the symptom. In a rolling-element, or anti-friction, bearing vibration profile, three distinct sets of frequencies can be found: natural, rotational, and defect.

Natural Frequency

Natural frequencies are generated by impacts of the internal parts of a rolling-element bearing. These impacts are normally the result of slight variations in load and imperfections in the machined bearing surfaces. As their name implies, these are natural frequencies and are present in a new bearing that is in perfect operating condition.

The natural frequencies of rolling-element bearings are normally well above the maximum frequency range, F_{MAX}, used for routine machine-train monitoring. As a result, predictive maintenance analysts rarely observe them. Generally, these frequencies are between 20 KHz and 1 MHz. Therefore, some vibration-monitoring programs use special high-frequency or ultrasonic monitoring techniques such as high-frequency domain (HFD). Note, however, that little is gained from monitoring natural frequencies. Even in cases of severe bearing damage, these high-frequency components add little to the analyst's ability to detect and isolate bad bearings.

Rotational Frequency

Four normal rotational frequencies are associated with rolling-element bearings: fundamental train frequency (FTF), ball/roller spin, ball-pass outer-race, and ball-pass inner-race. The following are definitions of abbreviations that are used in the discussion to follow:

BD = Ball or roller diameter

PD = Pitch diameter

β = Contact angle (for roller = 0)

n = Number of balls or rollers

f_r = Relative speed between the inner and outer race (rps)

Fundamental Train Frequency. The bearing cage generates the FTF as it rotates around the bearing races. The cage properly spaces the balls or rollers within the bearing races, in effect, by tying the rolling elements together and providing uniform support. Some friction exists between the rolling elements and the bearing races, even with perfect lubrication. This friction is transmitted to the cage, which causes it to rotate around the bearing races.

Because this is a friction-driven motion, the cage turns much slower than the inner race of the bearing. Generally, the rate of rotation is slightly less than one-half of the shaft speed. The FTF is calculated by the following equation:

$$FTF = \frac{1}{2} f_r \left[1 - \frac{BD}{PD} \right]$$

Ball-Spin Frequency. Each of the balls or rollers within a bearing rotates around its own axis as it rolls around the bearing races. This spinning motion is referred to as *ball spin*, which generates a ball-spin frequency (BSF) in a vibration signature. The speed of rotation is determined by the geometry of the bearing (i.e., diameter of the ball or roller, and bearing races) and is calculated by:

$$BSF = \frac{1}{2} \frac{PD}{BD} \times f_r \left[1 - \left(\frac{BD}{PD} \right)^2 \times \cos^2 \beta \right]$$

Ball-Pass Outer-Race. The ball or rollers passing the outer race generate the ball-pass outer-race frequency (BPFO), which is calculated by:

$$BPFO = \frac{n}{2} \times f_r \left(1 - \frac{BD}{PD} \times \cos \beta \right)$$

Ball-Pass Inner-Race. The speed of the ball/roller rotating relative to the inner race generates the ball-pass inner-race rotational frequency (BPFI). The inner race rotates at the same speed as the shaft, and the complete set of balls/rollers passes at a slower speed. They generate a passing frequency that is determined by:

$$BPFI = \frac{n}{2} \times f_r \left(1 + \frac{BD}{PD} \times \cos \beta \right)$$

Defect Frequencies

Rolling-element bearing defect frequencies are the same as their rotational frequencies, except for the BSF. If there is a defect on the inner race, the BPFI amplitude increases because the balls or rollers contact the defect as they rotate around the bearing. The BPFO is excited by defects in the outer race.

When one or more of the balls or rollers have a defect such as a spall (i.e., a missing chip of material), the defect impacts both the inner and outer race each time one revolution of the rolling element is made. Therefore, the defect vibration frequency is visible at two times (2×) the BSF rather than at its fundamental (1×) frequency.

14.2.2 Bearings: Sleeve (Babbitt)

In normal operation, a sleeve bearing provides a uniform oil film around the supported shaft. Because the shaft is centered in the bearing, all forces generated by the

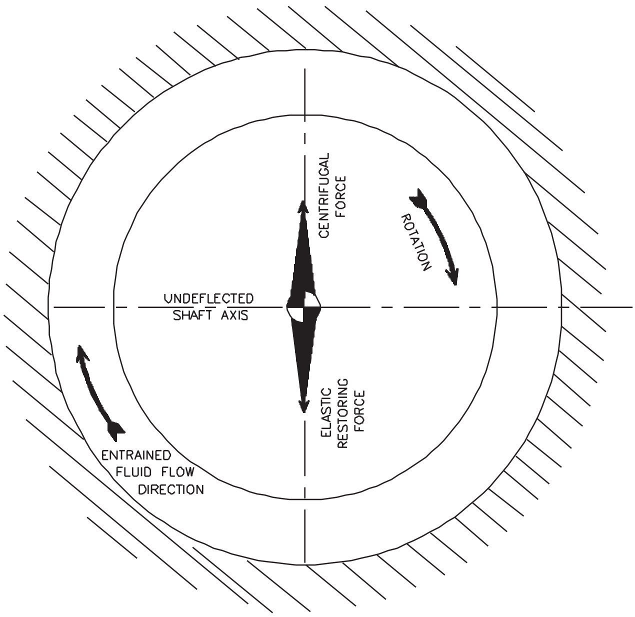


Figure 14–13 A normal Babbitt bearing has balanced forces.

rotating shaft, and all forces acting on the shaft, are equal. Figure 14–13 shows the balanced forces on a normal bearing.

Lubricating-film instability is the dominant failure mode for sleeve bearings. This instability is typically caused by eccentric, or off-center, rotation of the machine shaft resulting from imbalance, misalignment, or other machine or process-related problems. Figure 14–14 shows a Babbitt bearing that exhibits instability.

When oil-film instability or oil whirl occurs, frequency components at fractions (e.g., 1/4, 1/3, 3/8) of the fundamental (1×) shaft speed are excited. As the severity of the instability increases, the frequency components become more dominant in a band between 0.40 and 0.48 of the fundamental (1×) shaft speed. When the instability becomes severe enough to isolate within this band, it is called *oil whip*. Figure 14–15 shows the effect of increased velocity on a Babbitt bearing.

14.2.3 Chains and Sprockets

Chain drives function in essentially the same basic manner as belt drives; however, instead of tension, chains depend on the mechanical meshing of sprocket teeth with the chain links.

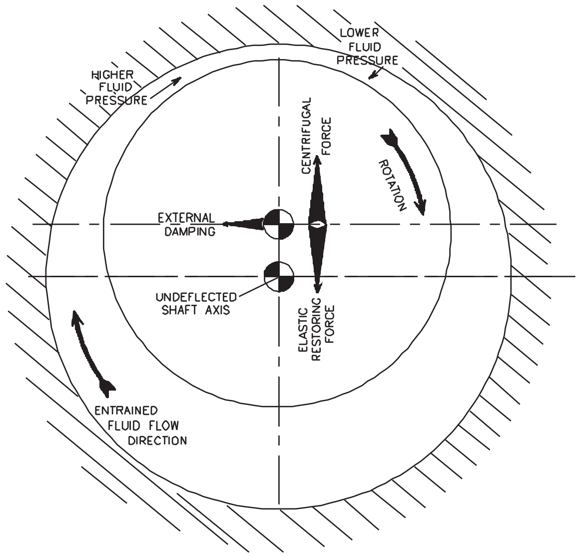


Figure 14–14 Dynamics of Babbitt bearing instability.

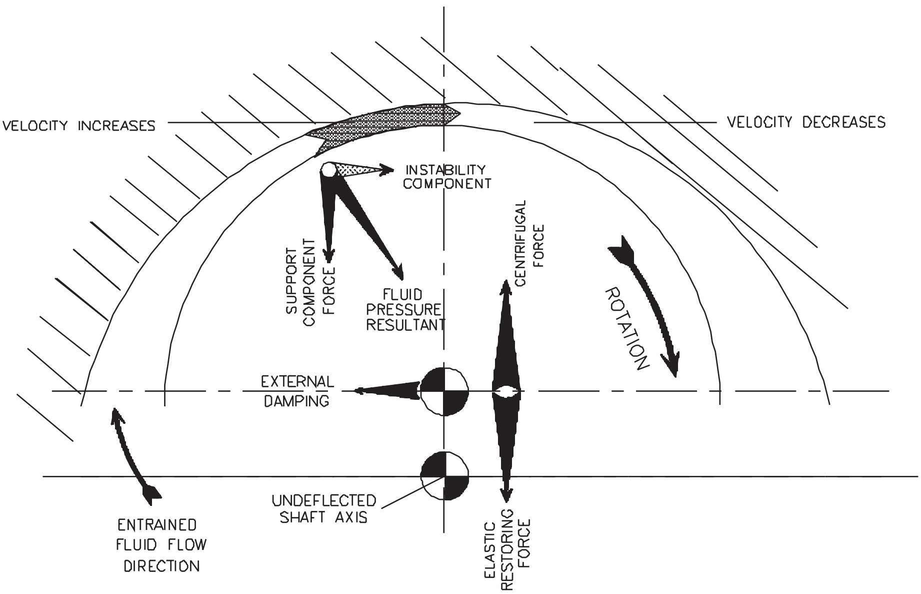


Figure 14–15 Increased velocity generates an unbalanced force.

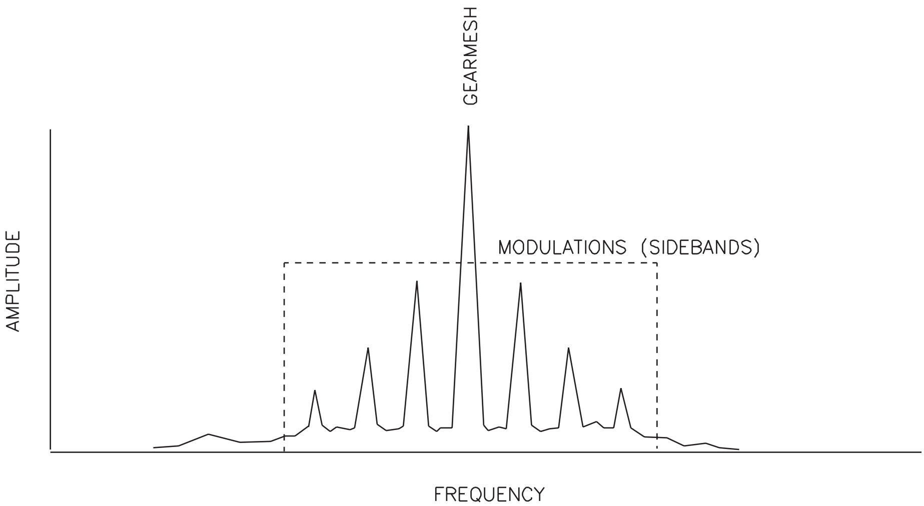


Figure 14–16 Normal gear set profile is symmetrical.

14.2.4 Gears

All gear sets create a frequency component referred to as *gear mesh*. The fundamental gear-mesh frequency is equal to the number of gear teeth times the running speed of the shaft. In addition, all gear sets create a series of sidebands or modulations that are visible on both sides of the primary gear-mesh frequency.

Normal Profile

In a normal gear set, each of the sidebands is spaced by exactly the 1× running speed of the input shaft, and the entire gear mesh is symmetrical as seen in Figure 14–16. In addition, the sidebands always occur in pairs, one below and one above the gear-mesh frequency, and the amplitude of each pair is identical.

If we split the gear-mesh profile for a normal gear by drawing a vertical line through the actual mesh (i.e., number of teeth times the input shaft speed), the two halves would be identical. Therefore, any deviation from a symmetrical profile indicates a gear problem; however, care must be exercised to ensure that the problem is internal to the gears and not induced by outside influences.

External misalignment, abnormal induced loads, and a variety of other outside influences destroy the symmetry of a gear-mesh profile. For example, a single-reduction gearbox used to transmit power to a mold-oscillator system on a continuous caster drives two eccentric cams. The eccentric rotation of these two cams is transmitted directly into the gearbox, creating the appearance of eccentric meshing of the gears; however, this abnormal induced load actually destroys the spacing and amplitude of the gear-mesh profile.

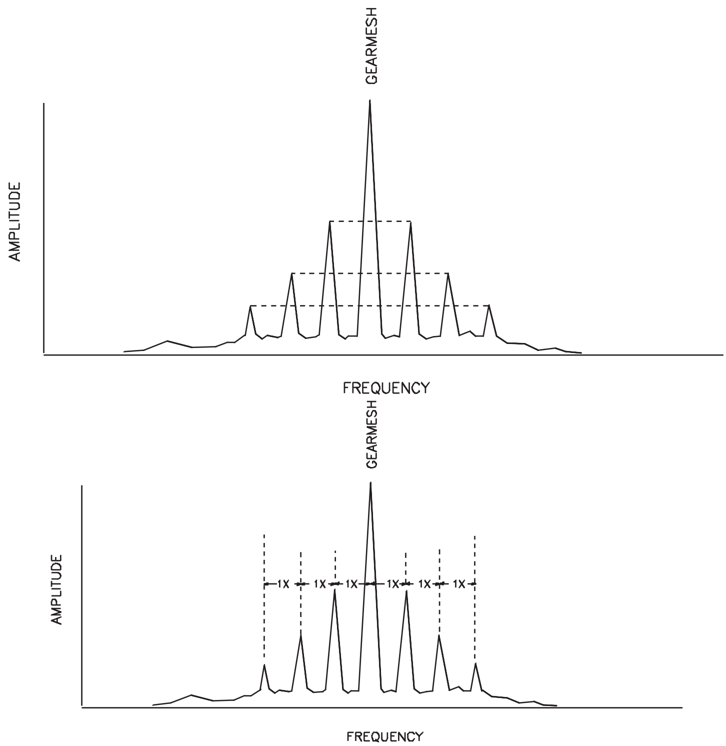


Figure 14–17 Sidebands are paired and equal.

Defective Gear Profiles

If the gear set develops problems, the amplitude of the gear-mesh frequency increases and the symmetry of the sidebands changes. The pattern illustrated in Figure 14–18 is typical of a defective gear set, where overall energy is the broadband, or total, energy. Note the asymmetrical relationship of the sidebands.

Excessive Wear. Figure 14–19 is the vibration profile of a worn gear set. Note that the spacing between the sidebands is erratic and is no longer evenly spaced by the input shaft speed frequency. The sidebands for a worn gear set tend to occur between the input and output speeds and are not evenly spaced.

Cracked or Broken Teeth. Figure 14–20 illustrates the profile of a gear set with a broken tooth. As the gear rotates, the space left by the chipped or broken tooth increases the mechanical clearance between the pinion and bullgear. The result is a low-amplitude sideband to the left of the actual gear-mesh frequency. When the next (i.e., undamaged) teeth mesh, the added clearance results in a higher-energy impact. The sideband to the right of the mesh frequency has much higher amplitude. As a result, the paired sidebands have nonsymmetrical amplitude, which is caused by the disproportional clearance and impact energy.

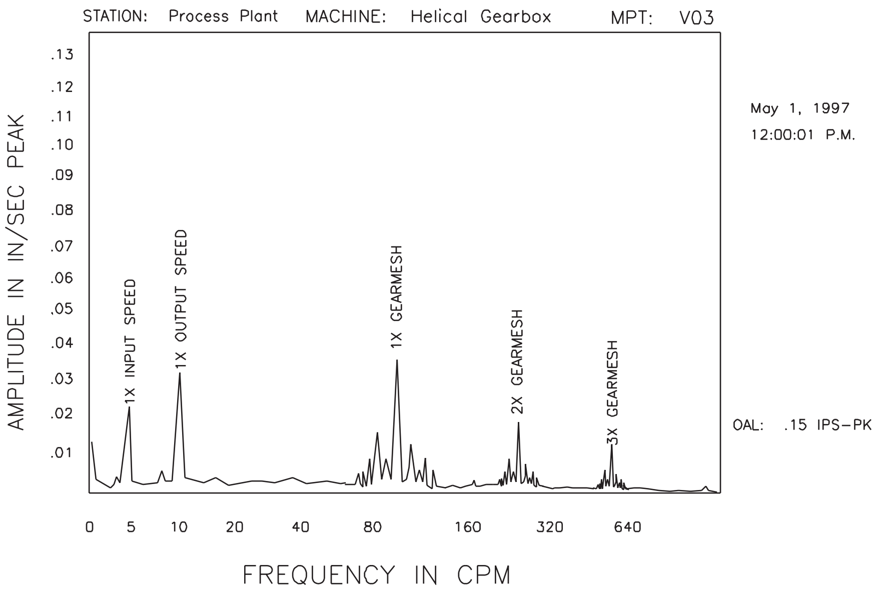


Figure 14–18 Typical defective gear-mesh signature.

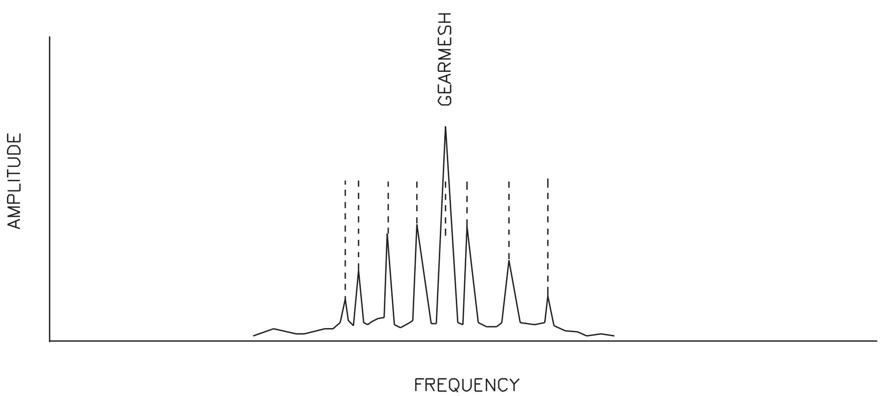


Figure 14–19 Wear or excessive clearance changes the sideband spacing.

Improper Shaft Spacing

In addition to gear-tooth wear, variations in the center-to-center distance between shafts create erratic spacing and amplitude in a vibration signature. If the shafts are too close together, the sideband spacing tends to be at input shaft speed, but the amplitude is significantly reduced. This condition causes the gears to be deeply meshed (i.e., below the normal pitch line), so the teeth maintain contact through the entire mesh. This loss of clearance results in lower amplitudes, but it exaggerates any tooth-profile defects that may be present.

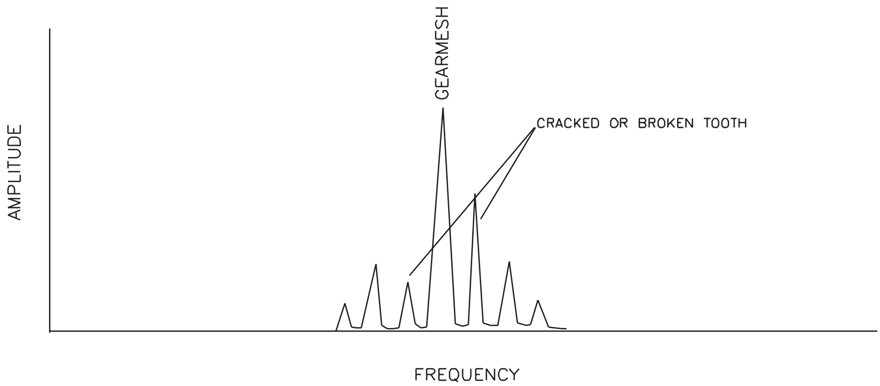


Figure 14–20 A broken tooth will produce an asymmetrical sideband profile.

If the shafts are too far apart, the teeth mesh above the pitch line, which increases the clearance between teeth and amplifies the energy of the actual gear-mesh frequency and all of its sidebands. In addition, the load-bearing characteristics of the gear teeth are greatly reduced. Because the force is focused on the tip of each tooth where there is less cross-section, the stress in each tooth is greatly increased. The potential for tooth failure increases in direct proportion to the amount of excess clearance between the shafts.

Load Changes

The energy and vibration profiles of gear sets change with load. When the gear is fully loaded, the profiles exhibit the amplitudes discussed previously. When the gear is unloaded, the same profiles are present, but the amplitude increases dramatically. The reason for this change is gear-tooth roughness. In normal practice, the backside of the gear tooth is not finished to the same smoothness as the power, or drive, side. Therefore, more looseness is present on the nonpower, or back, side of the gear. Figure 14–21 illustrates the relative change between a loaded and unloaded gear profile.

14.2.5 Jackshafts and Spindles

Another form of intermediate drive consists of a shaft with some form of universal connection on each end that directly links the prime mover to a driven unit (see Figures 14–22 and 14–23). Jackshafts and spindles are typically used in applications where the driver and driven unit are misaligned.

Most of the failure modes associated with jackshafts and spindles are the result of lubrication problems or fatigue failure resulting from overloading; however, the actual failure mode generally depends on the configuration of the flexible drive.

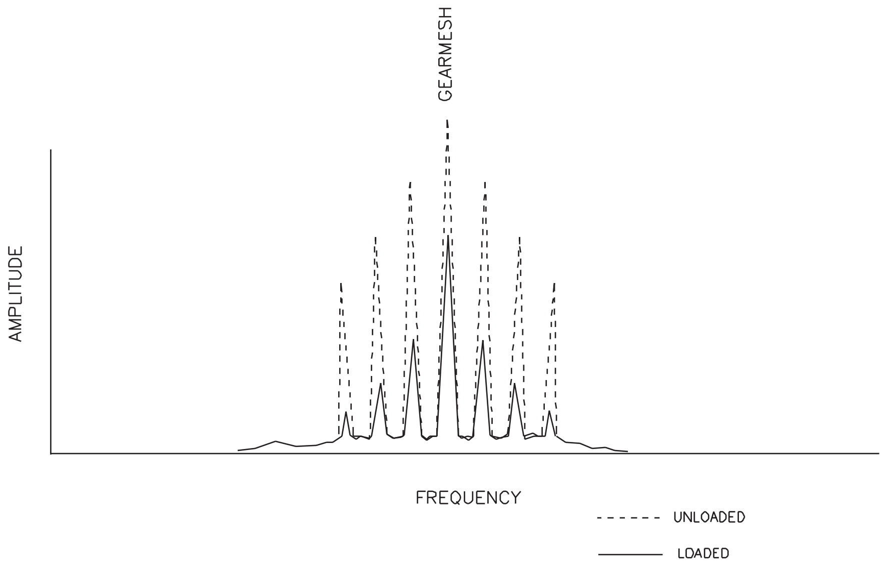


Figure 14–21 Unloaded gear has much higher vibration levels.

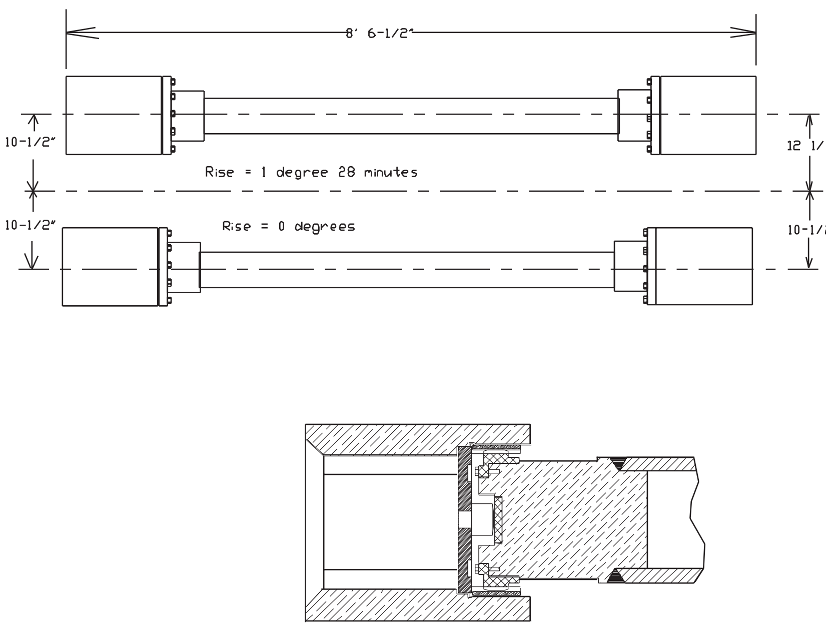


Figure 14–22 Typical gear-type spindles.

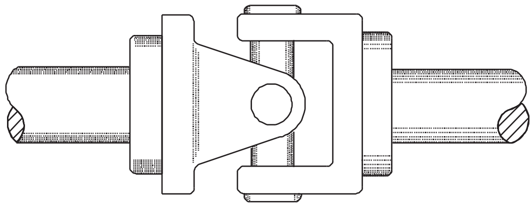


Figure 14–23 Typical universal-type jackshaft.

Lubrication Problems

Proper lubrication is essential for all jackshafts and spindles. A critical failure point for spindles (see Figure 14–22) is in the mounting pod that provides the connection between the driver and driven machine components. Mounting pods generally use either a spade-and-slipper or a splined mechanical connector. In both cases, regular application of suitable grease is essential for prolonged operation. Without proper lubrication, the mating points between the spindle's mounting pod and the machine-train components impact each time the torsional power varies between the primary driver and driven component of the machine-train. The resulting mechanical damage can cause these critical drive components to fail.

In universal-type jackshafts like the one illustrated in Figure 14–23, improper lubrication results in nonuniform power transmission. The absence of a uniform grease film causes the pivot points within the universal joints to bind and restrict smooth power transmission.

The typical result of poor lubrication, which results in an increase in mechanical looseness, is an increase of those vibration frequencies associated with the rotational speed. In the case of gear-type spindles (Figure 14–22), both the fundamental (1×) and second harmonic (2×) will increase. Because the resulting forces generated by the spindle are similar to angular misalignment, the axial energy generated by the spindle will also increase significantly.

The universal-coupling configuration used by jackshafts (Figure 14–23) generates an elevated vibration frequency at the fourth (4×) harmonic of its true rotational speed. The binding that occurs as the double pivot points move through a complete rotation causes this failure mode.

Fatigue

Spindles and jackshafts are designed to transmit torsional power between a driver and driven unit that are not in the same plane or that have a radical variation in torsional power. Typically, both conditions are present when these flexible drives are used.

Both the jackshaft and spindle are designed to absorb transient increases or decreases in torsional power caused by twisting. In effect, the shaft or tube used in these designs winds, much like a spring, as the torsional power increases. Normally, this torque and the resultant twist of the spindle are maintained until the torsional load is reduced. At that point, the spindle unwinds, releasing the stored energy that was generated by the initial transient.

Repeated twisting of the spindle's tube or the solid shaft used in jackshafts results in a reduction in the flexible drive's stiffness. When this occurs, the drive loses some of its ability to absorb torsional transients. As a result, the driven unit may be damaged.

Unfortunately, the limits of single-channel, frequency-domain data acquisition prevent accurate measurement of this failure mode. Most of the abnormal vibration that results from fatigue occurs in the relatively brief time interval associated with startup, when radical speed changes occur, or during shutdown of the machine-train. As a result, this type of data acquisition and analysis cannot adequately capture these transients; however, the loss of stiffness caused by fatigue increases the apparent mechanical looseness observed in the steady-state, frequency-domain vibration signature. In most cases, this is similar to the mechanical looseness.

14.2.6 Process Rolls

Process rolls commonly encounter problems or fail because of being subjected to induced (variable) loads and from misalignment.

Induced (Variable) Loads

Process rolls are subjected to variable loads that are induced by strip tension, tracking, and other process variables. In most cases, these loads are directional. They not only influence the vibration profile but also determine the location and orientation of data acquisition.

Strip Tension or Wrap. Figure 14–24 illustrates the wrap of the strip as it passes over a series of rolls in a continuous-process line. The orientation and contact area of this wrap determines the load zone on each roll.

In this example, the strip wrap is limited to one-quarter of the roll circumference. The load zone, or vector, on the two top rolls is on a 45-degree angle to the pass line. Therefore, the best location for the primary radial measurement is at 45 degrees opposite to the load vector. The secondary radial measurement should be 90 degrees to the primary. On the top-left roll, the secondary measurement point should be to the top left of the bearing cap; on the top-right roll, it should be at the top-right position.

The wrap on the bottom roll encompasses one-half of the roll circumferences. As a result, the load vector is directly upward, or 90 degrees, to the pass line. The best location for the primary radial-measurement point is in the vertical-downward position. The secondary radial measurement should be taken at 90 degrees to the primary.

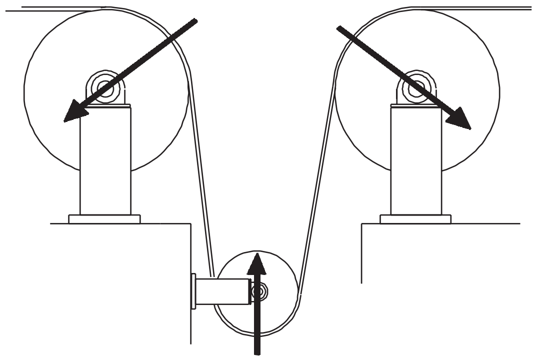


Figure 14–24 Load zones determined by wrap.

Because the strip tension is slightly forward (i.e., in the direction of strip movement), the secondary measurement should be taken on the recoiler side of the bearing cap.

Because strip tension loads the bearings in the direction of the force vector, it also tends to dampen the vibration levels in the opposite direction, or 180 degrees, of the force vector. In effect, the strip acts like a rubberband. Tension inhibits movement and vibration in the direction opposite the force vector and amplifies the movement in the direction of the force vector. Therefore, the recommended measurement-point locations provide the best representation of the roll's dynamics.

In normal operation, the force or load induced by the strip is uniform across the roll's entire face or body. As a result, the vibration profile in both the operator- and drive-side bearings should be nearly identical.

Strip Width and Tracking. Strip width has a direct effect on roll loading and how the load is transmitted to the roll and its bearing-support structures. Figure 14–25 illustrates a narrow strip that is tracking properly. Note that the load is concentrated on the center of the roll and is not uniform across the entire roll face.

The concentration of strip tension or load in the center of the roll tends to bend the roll. The degree of deflection depends on the following: roll diameter, roll construction, and strip tension. Regardless of these three factors, however, the vibration profile is modified. Roll bending, or deflection, increases the fundamental (1×) frequency component. The amount of increase is determined by the amount of deflection.

As long as the strip remains at the true centerline of the roll face, the vibration profile in both the operator- and drive-side bearing caps should remain nearly identical. The only exceptions are bearing rotational and defect frequencies. Figures 14–26 and 14–27 illustrate uneven loading and the resulting different vibration profiles of the operator- and drive-side bearing caps.

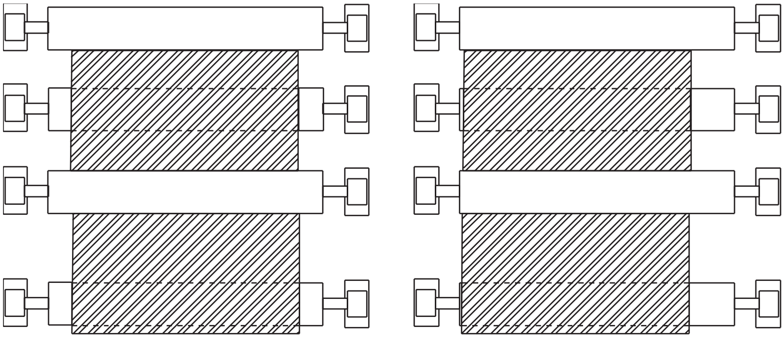


Figure 14–25 Load from narrow strip concentrated in center.

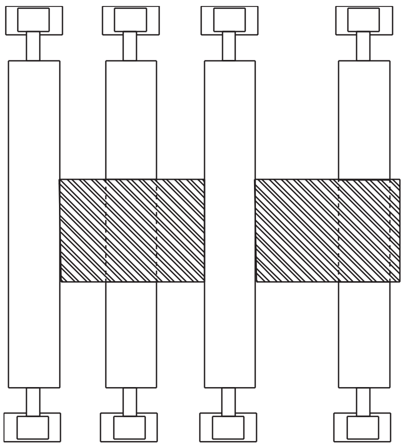


Figure 14–26 Roll loading.

This extremely important factor can be used to evaluate many of the failure modes of continuous process lines. For example, the vibration profile resulting from the transmission of strip tension to the roll and its bearings can be used to determine proper roll alignment, strip tracking, and proper strip tension.

Alignment

Process rolls must be properly aligned. The perception that they can be misaligned without causing poor quality, reduced capacity, and premature roll failure is incorrect. In the case of single rolls (e.g., bridle and furnace rolls), they must be perpendicular to the pass line and have the same elevation on both the operator and drive sides. Roll pairs such as scrubber/backup rolls must be parallel to each other.

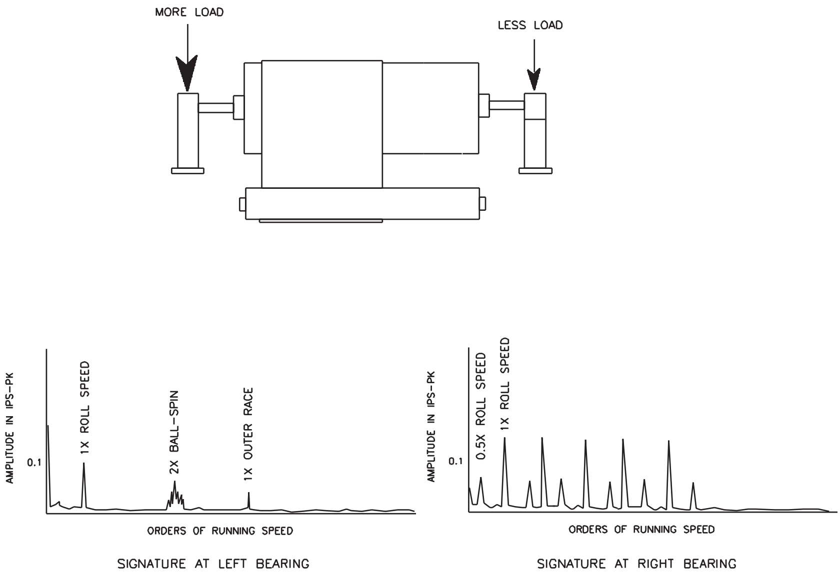


Figure 14–27 Typical vibration profile with uneven loading.

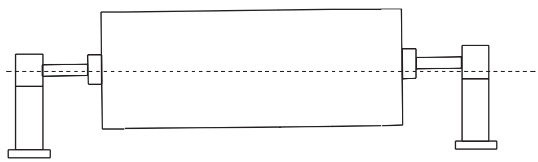


Figure 14–28 Vertically misaligned roll.

Single Rolls. With the exception of steering rolls, all single rolls in a continuous-process line must be perpendicular to the pass line and have the same elevation on both the operator and drive sides. Any horizontal or vertical misalignment influences the tracking of the strip and the vibration profile of the roll.

Figure 14–28 illustrates a roll that does not have the same elevation on both sides (i.e., vertical misalignment). With this type of misalignment, the strip has greater tension on the side of the roll with the higher elevation, which forces it to move toward the lower end. In effect, the roll becomes a steering roll, forcing the strip to one side of the centerline.

The vibration profile of a vertically misaligned roll is not uniform. Because the strip tension is greater on the high side of the roll, the vibration profile on the high-side bearing has lower broadband energy. This is the result of damping caused by the strip tension. Dominant frequencies in this vibration profile are roll speed (1×) and outer-

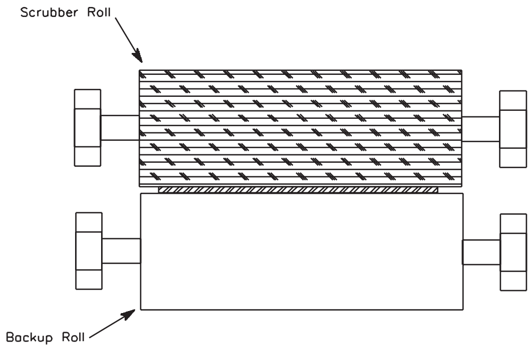


Figure 14–29 Scrubber roll set.

race defects. The low end of the roll has higher broadband vibration energy, and dominant frequencies include roll speed (1×) and multiple harmonics (i.e., the same as mechanical looseness).

Paired Rolls. Rolls that are designed to work in pairs (e.g., damming or scrubber rolls) also must be perpendicular to the pass line. In addition, they must be parallel to each other. Figure 14–29 illustrates a paired set of scrubber rolls. The strip is captured between the two rolls, and the counter-rotating brush roll cleans the strip surface.

Because of the designs of both the damming and scrubber roll sets, it is difficult to keep the rolls parallel. Most of these roll sets use a single pivot point to fix one end of the roll and a pneumatic cylinder to set the opposite end.

Other designs use two cylinders, one attached to each end of the roll. In these designs, the two cylinders are not mechanically linked and, therefore, the rolls do not maintain their parallel relationship. The result of nonparallel operation of these paired rolls is evident in roll life.

For example, the scrubber/backup roll set should provide extended service life; however, in actual practice, the brush rolls have a service life of only a few weeks. After this short time in use, the brush rolls will have a conical shape, much like a bottle brush (see Figure 14–30). This wear pattern is visual confirmation that the brush roll and its mating rubber-coated backup roll are not parallel.

Vibration profiles can be used to determine if the roll pairs are parallel and, in this instance, the rules for parallel misalignment apply. If the rolls are misaligned, the vibration signatures exhibit a pronounced fundamental (1×) and second harmonic (2×) of roll speed.

Multiple Pairs of Rolls. Because the strip transmits the vibration profile associated with roll misalignment, it is difficult to isolate misalignment for a continuous-process line by evaluating one single or two paired rolls. The only way to isolate such mis-

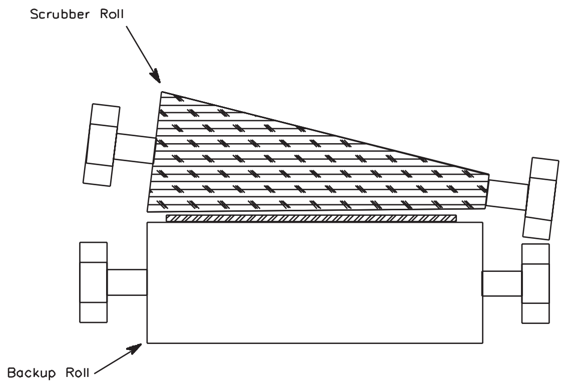


Figure 14–30 Result of misalignment or nonparallel operation on brush rolls.

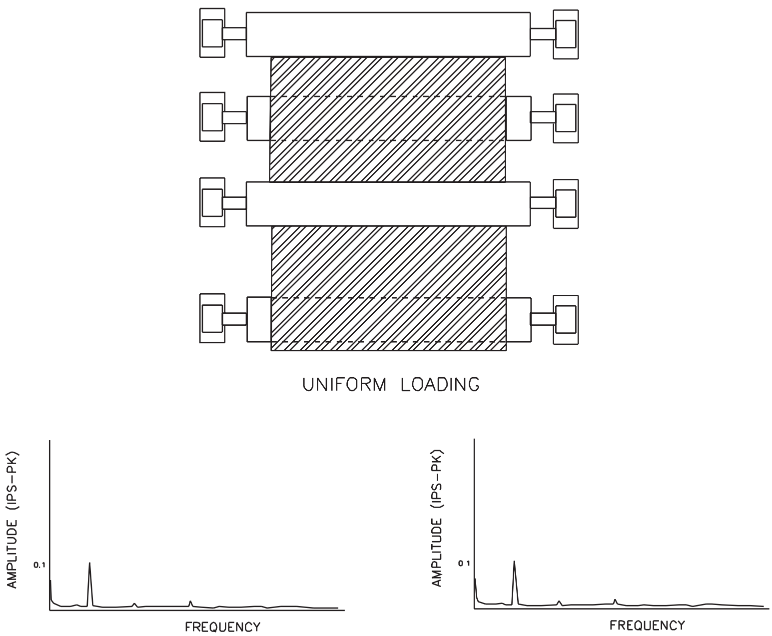


Figure 14–31 Rolls in series.

alignment is to analyze a series of rolls rather than individual (or a single pair of) rolls. This approach is consistent with good diagnostic practices and provides the means to isolate misaligned rolls and to verify strip tracking.

Strip tracking. Figure 14–31 illustrates two sets of rolls in series. The bottom set of rolls is properly aligned and has good strip tracking. In this case, the vibration profiles acquired from the operator- and drive-side bearing caps are nearly identical.

Unless there is a damaged bearing, all of the profiles contain low-level roll frequencies (1×) and bearing rotational frequencies.

The top roll set is also properly aligned, but the strip tracks to the bottom of the roll face. In this case, the vibration profile from all of the bottom bearing caps contain much lower-level broadband energy, and the top bearing caps have clear indications of mechanical looseness (i.e., multiple harmonics of rotating speed). The key to this type of analysis is the comparison of multiple rolls in the order that the strip connects them. This requires comparison of both top and bottom rolls in the order of strip pass. With proper tracking, all bearing caps should be nearly identical. If the strip tracks to one side of the roll face, all bearing caps on that side of the line will have similar profiles, but they will have radically different profiles compared to those on the opposite side.

Roll misalignment. Roll misalignment can be detected and isolated using this same method. A misaligned roll in the series being evaluated causes a change in the strip track at the offending roll. The vibration profiles of rolls upstream of the misaligned roll will be identical on both the operator and drive sides of the rolls; however, the profiles from the bearings of the misaligned roll will show a change. In most cases, they will show traditional misalignment (i.e., 1× and 2× components) but will also indicate a change in the uniform loading of the roll face. In other words, the overall or broadband vibration levels will be greater on one side than the other. The lower readings will be on the side with the higher strip tension, and the higher readings will be on the side with less tension.

The rolls following the misalignment also show a change in vibration pattern. Because the misaligned roll acts as a steering roll, the loading patterns on the subsequent rolls show different vibration levels when the operator and drive sides are compared. If the strip track was normal before the misaligned roll, the subsequent rolls will indicate off-center tracking. In those cases where the strip was already tracking off-center, a misaligned roll either improves or amplifies the tracking problem. If the misaligned roll forces the strip toward the centerline, tracking improves and the vibration profiles are more uniform on both sides. If the misaligned roll forces the strip farther off-center, the nonuniform vibration profiles will become even less uniform.

14.2.7 Shaft

A bent shaft creates an imbalance or a misaligned condition within a machine-train. Normally, this condition excites the fundamental (1×) and secondary (2×) running-speed components in the signature; however, it is difficult to determine the difference between a bent shaft, misalignment, and imbalance without a visual inspection. Figures 14–32 and 14–33 illustrate the normal types of bent shafts and the force profiles that result.

14.2.8 V-Belts

V-belt drives generate a series of dynamic forces, and vibrations result from these forces. Frequency components of such a drive can be attributed to belts and sheaves.

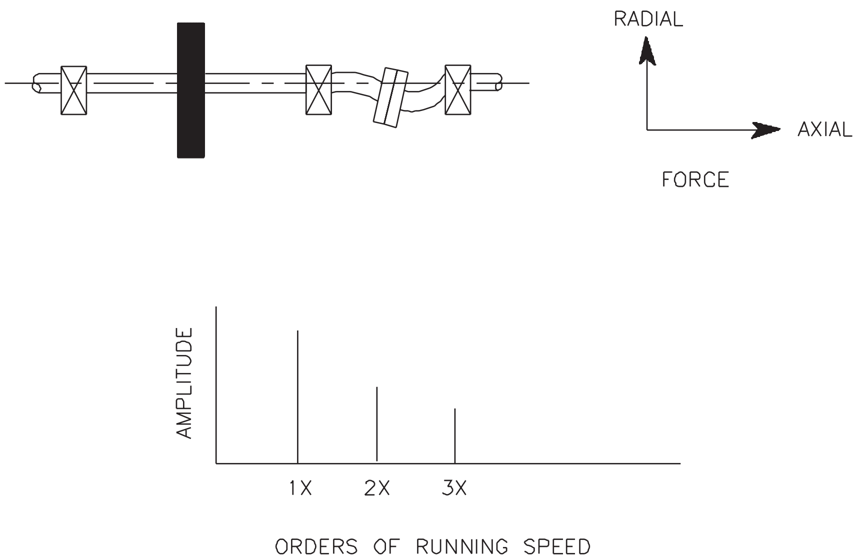


Figure 14–32 Bends that change shaft length generate axial thrust.

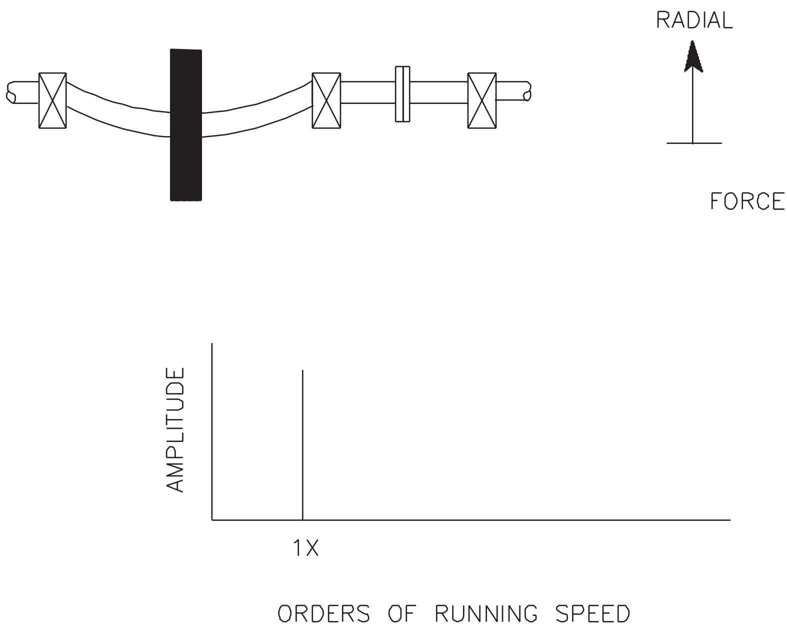


Figure 14–33 Bends that do not change shaft length generate radial forces only.

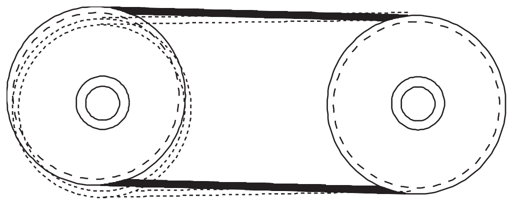


Figure 14–34 Eccentric sheaves.

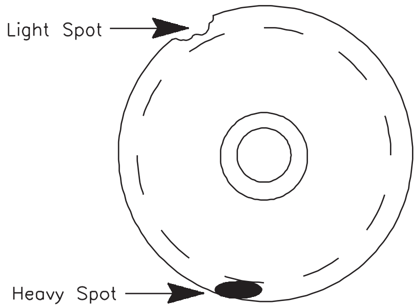


Figure 14–35 Light and heavy spots on an unbalanced sheave.

The elastic nature of belts can either amplify or damp vibrations that are generated by the attached machine-train components.

Sheaves

Even new sheaves are not perfect and may be the source of abnormal forces and vibration. The primary sources of induced vibration resulting from sheaves are eccentricity, imbalance, misalignment, and wear.

Eccentricity. Vibration caused by sheave eccentricity manifests itself as changes in load and rotational speed. As an eccentric drive sheave passes through its normal rotation, variations in the pitch diameter cause variations in the linear belt speed. An eccentric driven sheave causes variations in load to the drive. The rate at which such variations occur helps determine which is eccentric. An eccentric sheave may also appear to be unbalanced; however, performing a balancing operation will not correct the eccentricity.

Imbalance. Sheave imbalance may be caused by several factors, one of which may be that it was never balanced to begin with. The easiest problem to detect is an actual imbalance of the sheave itself. A less obvious cause of imbalance is damage that has resulted in loss of sheave material. Imbalance caused by material loss can be determined easily by visual inspection, either by removing the equipment from service or by using a strobe light while the equipment is running. Figure 14–35 illustrates light and heavy spots that result in sheave imbalance.

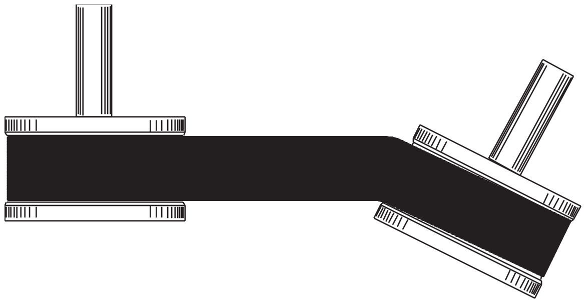


Figure 14–36 Angular sheave misalignment.

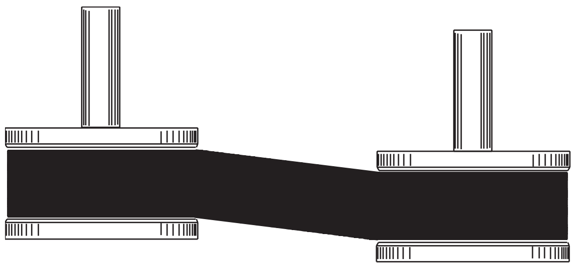


Figure 14–37 Parallel sheave misalignment.

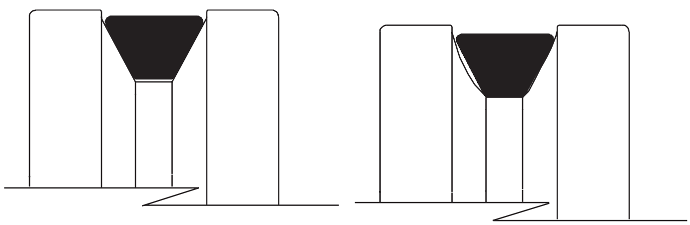


Figure 14–38 Normal and worn sheave grooves.

Misalignment. Sheave misalignment most often produces axial vibration at the shaft rotational frequency (1×) and radial vibration at one and two times the shaft rotational frequency (1× and 2×). This vibration profile is similar to coupling misalignment. Figure 14–36 illustrates angular sheave misalignment, and Figure 14–37 illustrates parallel misalignment.

Wear. Worn sheaves may also increase vibration at certain rotational frequencies; however, sheave wear is more often indicated by increased slippage and drive wear. Figure 14–38 illustrates both normal and worn sheave grooves.

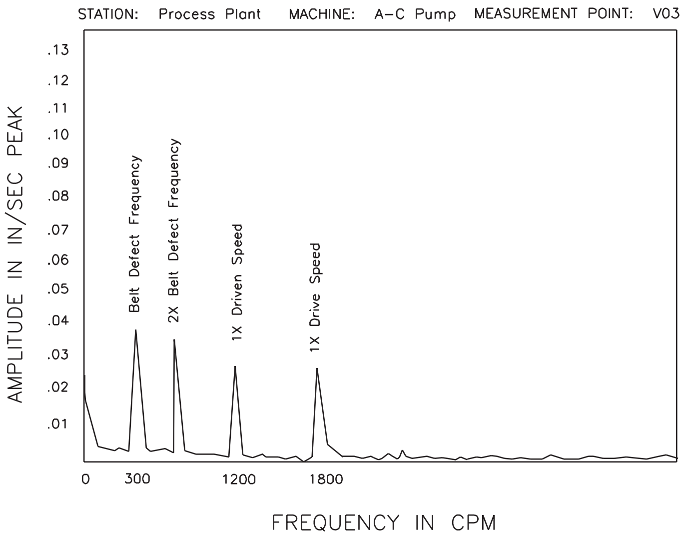


Figure 14–39 Typical spectral plot (i.e., vibration profile) of a defective belt.

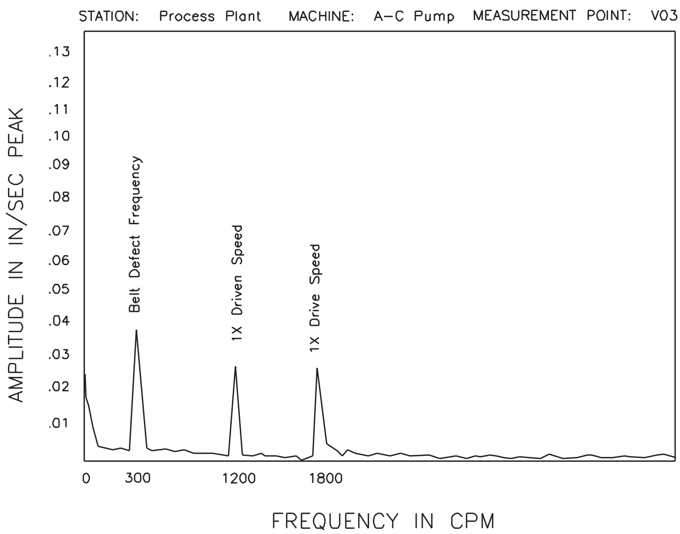


Figure 14–40 Spectral plot of shaft rotational and belt defect (i.e., imbalance) frequencies.

Belts

V-belt drives typically consist of multiple belts mated with sheaves to form a means of transmitting motive power. Individual belts, or an entire set of belts, can generate abnormal dynamic forces and vibration. The dominant sources of belt-induced vibrations are defects, imbalance, resonance, tension, and wear.

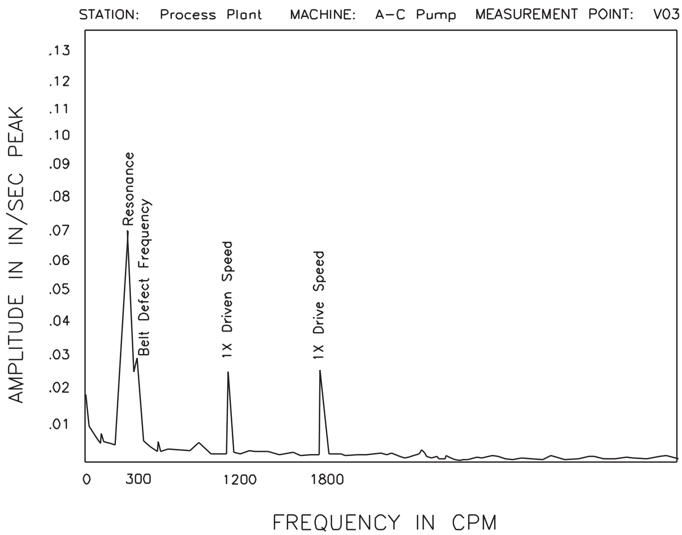


Figure 14–41 Spectral plot of resonance excited by belt-defect frequency.

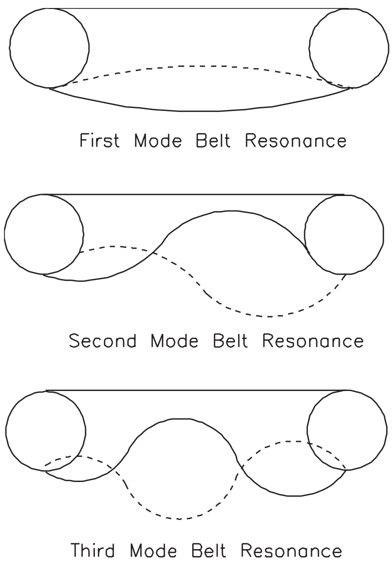


Figure 14–42 Examples of mode resonance in a belt span.

Defects. Belt defects appear in the vibration signature as subsynchronous peaks, often with harmonics. Figure 14–39 shows a typical spectral plot (i.e., vibration profile) for a defective belt.

Imbalance. An imbalanced belt produces vibration at its rotational frequency. If a belt's performance is initially acceptable and later develops an imbalance, the belt has most likely lost material and must be replaced. If imbalance occurs with a new belt, it is defective and must be replaced. Figure 14–40 shows a spectral plot of shaft rotational and belt defect (i.e., imbalance) frequencies.

Resonance. Belt resonance occurs primarily when the natural frequency of some length of the belt is excited by a frequency generated by the drive. Occasionally, a sheave may also be excited by some drive frequency. Figure 14–41 shows a spectral plot of resonance excited by belt-defect frequency.

Adjusting the span length, belt thickness, and belt tension can control belt resonance. Altering any of these parameters changes the resonance characteristics. In most applications, it is not practical to alter the shaft rotational speeds, which are also possible sources of the excitation frequency.

Resonant belts are readily observable visually as excessive deflection, or *belt whip*. It can occur in any resonant mode, so there may or may not be inflection points observed along the span. Figure 14–42 illustrates first-, second-, and third-mode resonance in a belt span.

Tension. Loose belts can increase the vibration of the drive, often in the axial plane. In the case of multiple V-belt drives, mismatched belts also aggravate this condition. Improper sheave alignment can also compromise tension in multiple-belt drives.

Wear. Worn belts slip, and the primary indication is speed change. If the speed of the driver increases and the speed of the driven unit decreases, then slippage is probably occurring. This condition may be accompanied by noise and smoke, causing belts to overheat and be glazed in appearance. It is important to replace worn belts.

15

ESTABLISHING A PREDICTIVE MAINTENANCE PROGRAM

The decision to establish a predictive maintenance program is the first step toward controlling maintenance costs and improving process efficiency in your plant. Now what do you do? Numerous predictive maintenance programs can serve as models for implementing a successful predictive maintenance program. Unfortunately, many programs were aborted within the first three years because a clear set of goals and objectives were not established before the program was implemented. Implementing a total-plant predictive maintenance program is expensive. After the initial capital cost of instrumentation and systems, a substantial annual labor cost is required to maintain the program.

To be successful, a predictive maintenance program must be able to quantify the cost–benefit generated by the program. This goal can be achieved if the program is properly established, uses the proper predictive maintenance techniques, and has measurable benefits. The amount of effort expended to initially establish the program is directly proportional to its success or failure.

15.1 Goals, Objectives, and Benefits

Constructive actions issue from a well-established purpose. It is important that the goals and objectives of a predictive maintenance program be fully developed and adopted by the personnel who perform the program and upper management of the plant. A predictive maintenance program is not an excuse to buy sophisticated, expensive equipment. Neither is the purpose of the program to keep people busy measuring and reviewing data from the various machines, equipment, and systems within the plant.

The purpose of predictive maintenance is to minimize unscheduled equipment failures, maintenance costs, and lost production. It is also intended to improve the production efficiency and product quality in the plant. This is accomplished by regular monitoring of the mechanical condition, machine and process efficiencies, and other parameters that define the operating condition of the plant. Using the data acquired from critical plant equipment, incipient problems are identified and corrective actions taken to improve the reliability, availability, and productivity of the plant.

Specific goals and objectives will vary from plant to plant; however, we will provide an example that illustrates the process. Before goals and objectives can be developed for your plant, you must determine the existing maintenance costs and other parameters that will establish a reference or baseline data set. Because most plants do not track the true cost of maintenance, this may be the most difficult part of establishing a predictive maintenance program.

At a minimum, your baseline data set should include the staffing, overhead, overtime premiums, and other payroll costs of the maintenance department. It should also include all maintenance-related contract services, excluding janitorial, and the total costs of spare parts inventories. The baseline should also include the percentage of unscheduled versus scheduled maintenance repairs, actual repair costs on critical plant equipment, and the annual availability of the plant.

This baseline should include the incremental costs of production created by catastrophic machine failures and other parameters. If they are available or can be obtained, they will help greatly in establishing a valid baseline. The long-term objectives of a predictive maintenance program are to:

- Eliminate unnecessary maintenance.
- Reduce lost production caused by failures.
- Reduce repair parts inventory.
- Increase process efficiency.
- Improve product quality.
- Extend the operating life of plant systems.
- Increase production capacity.
- Reduce overall maintenance costs.
- Increase overall profits.

Just stating these objectives, however, will not make them happen or provide the means of measuring the program's success. Establish specific objectives (e.g., reduce unscheduled maintenance by 20 percent or increase production capacity by 15 percent). In addition to quantifying the expected goals, define the methods that will be used to accomplish each objective and the means that can be used to measure the actual results.

15.2 Functional Requirements

Functional requirements will vary with the size and complexity of the plant, company, or corporation; however, minimal requirements must be met regardless of the variables. These requirements are management support, dedicated and accountable personnel, efficient data collection and analysis procedures, and a viable database.

15.2.1 Management Support

Implementing a predictive maintenance program will require an investment in both capital equipment and labor. If a program is to get started and survive to accomplish its intended goals, management must be willing to commit the necessary resources. Management must also insist on the adoption of vital record-keeping and information exchange procedures that are critical to program success and are outside the control of the maintenance department. In most aborted programs, management committed to the initial investment for capital equipment but did not invest the resources required for training, consulting support, and in-house staffing that are essential to success. Several programs have been aborted during the time between 18 and 24 months after implementation. They were not aborted because the program failed to achieve the desired results, but rather they failed because upper management did not clearly understand how the program worked.

During the first 12 months, most predictive maintenance programs identify numerous problems in plant machinery and systems. Therefore, the reports and recommendations for corrective actions generated by the predictive maintenance group are highly visible. After the initial 12 to 18 months, most of the serious plant problems have been resolved and the reports begin to show little need for corrective actions. Without a clear understanding of this normal cycle and the means of quantifying the achievements of the predictive maintenance program, upper management often concludes that the program is not providing sufficient benefits to justify the continued investment in staffing.

15.2.2 Dedicated and Accountable Personnel

All successful programs are built around a full-time predictive maintenance team. Some of these teams may cover multiple plants and some monitor only one; however, every successful program has a dedicated team that can concentrate its full attention on achieving the objectives established for the program. Even though a few successful programs have been structured around part-time personnel, this approach is not recommended. All too often, part-time personnel will not or cannot maintain the monitoring and analysis frequency that is critical to success.

The accountability expected of the predictive maintenance group is another critical factor to program effectiveness. If measures of program effectiveness are not established, neither management nor program personnel can determine if the program's potential is being achieved.

15.2.3 Efficient Data Collection and Analysis Procedures

Efficient procedures can be established if adequate instrumentation is available and the monitoring tasks are structured to emphasize program goals. A well-planned program should not be structured so that all machines and equipment in the plant receive the same scrutiny. Typical predictive maintenance programs monitor from 50 to 500 machine-trains in a given plant.

Some of the machine-trains are more critical to the continued, efficient operation of the plant than others. The predictive maintenance program should be set up to concentrate the program's efforts in the areas that will provide maximum results. The use of microprocessor- and PC-based predictive maintenance systems greatly improves the data collection and data management functions required for a successful program. These systems can also provide efficient data analysis; however, procedures that define the methods, schedule, and other parameter of data acquisition, analysis, and report generation must also be included in the program definition.

15.2.4 Viable Database

The methods and systems that you choose for your program and the initial program development will largely determine the success or failure of predictive maintenance in your plant. Proper implementation of a predictive maintenance program is not easy. It will require a great deal of thought and—perhaps for the first time—a complete understanding of the operation of the various systems and machinery in your plant.

The initial database development required to successfully implement a predictive maintenance program will require several staffing months of effort. The result of the extensive labor required to properly establish a predictive database often results in either a poor or incomplete database. In some cases, the program is discontinued because of staff limitations. If the extensive labor required to establish a database is not available in-house, consultants can provide the knowledge and labor required to accomplish this task.

The ideal situation would be to have the predictive systems vendor establish a viable database as part of the initial capital equipment purchase. This service is offered by a few of the systems vendors. Unfortunately, many predictive maintenance programs have failed because these important first critical steps were omitted or ignored. There are a variety of beneficial technologies and predictive maintenance systems. How do you decide which method and system to use?

A vibration-based predictive maintenance program is the most difficult to properly establish and requires much more effort than any of the other techniques. It will also provide the most return on investment. Too many of the vibration-based programs fail to use the full capability of the predictive maintenance tool. They ignore the automatic diagnostic power that is built into most of the microprocessor-based systems and rely instead on manual interpretation of all data.

The first step is to determine the types of plant equipment and systems that are to be included in your program. A plant survey of your process equipment should list every critical component within the plant and its impact on both production capacity and maintenance costs. A plant process layout is invaluable during this phase of program development. It is easy to omit critical machines or components during the audit; therefore, care should be taken to ensure that all components that can limit production capacity are included in your list.

The listing of plant equipment should be ordered into the following classes depending on the equipment's impact on production capacity or maintenance cost: Class I, essential; Class II, critical; Class III, serious; and Class IV, others.

> Class I, or essential, machinery or equipment must be online for continued plant operation. Loss of any one of these components will result in a plant outage and total loss of production. Plant equipment that has excessive repair costs or repair parts lead-time should also be included in the essential classification.
>
> Class II, or critical, machinery would severely limit production capacity. As a rule of thumb, loss of critical machinery would reduce production capacity by 30 percent or more. Also included in the critical classification are machines or systems with chronic maintenance histories or that have high repair or replacement costs.
>
> Class III, or serious, machinery includes major plant equipment that does not have a dramatic impact on production but that contributes to maintenance costs. An example of the serious classification would be a redundant system. Because the inline spare could maintain production, loss of one component would not affect production; however, the failure would have a direct impact on maintenance cost.
>
> Class IV machinery includes other plant equipment that has a proven history of impacting either production or maintenance costs. All equipment in this classification must be evaluated to determine whether routine monitoring is cost effective. In some cases, replacement costs are lower than the annual costs required to monitor machinery in this classification.

The completed list should include every machine, system, or other plant equipment that has or could have a serious impact on the availability and process efficiency of your plant. The next step is to determine the best method or technique for cost-effectively monitoring the operating condition of each item on the list. To select the best methods for regular monitoring, you should consider the dynamics of operation and normal failure modes of each machine or system to be included in the program. A clear understanding of the operating characteristics and failure modes will provide the answer to which predictive maintenance method should be used.

Most predictive maintenance programs use vibration monitoring as the principal technique. Visual inspection, process parameters, ultrasonics, and limited thermographic techniques should also be added to the in-house program. The initial cost of systems and advanced training required by full thermographic and tribology techniques prohibits their inclusion into in-house programs. Plants that require these techniques normally rely on outside contractors to provide the instrumentation and expertise required.

Because of the almost unlimited numbers and types of machinery and systems used in industry, it is impossible to cover every one in this book; however, Chapter 7 provides a cross-section that illustrates the process used to identify the monitoring parameters for plant equipment.

15.3 Selling Predictive Maintenance Programs

Justification of a predictive maintenance program to corporate management is difficult, but convincing the entire workforce to embrace improvement is almost impossible. Because few companies can afford to invest the financial resources and staffing required to improve the effectiveness of their plants, corporate management has a built-in resistance to change. Couple this resistance with the natural aversion to change that dominates most workforces, and selling improvement becomes very difficult. How do you convince corporate management and the workforce to invest in predictive maintenance improvement?

15.3.1 Six Keys to Success

There are six keys to successful justification and implementation of a continuous improvement program: (1) formulating a detailed program plan, (2) knowing your audience, (3) creating an implementation plan, (4) doing your homework, (5) taking a holistic view, and (6) getting absolute buy-in.

Formulating a Detailed Program Plan

Do not shortcut the program plan. It must be a concise, detailed document that provides clear direction for the program. Remember that the plan should be a living document. It should be upgraded or modified as the program matures.

Concise Goals and Objectives. Your justification package must include a clear, concise game plan. Corporate and plant management expect you to understand the problems that reduce plant effectiveness and to offer a well-defined plan to correct these problems.

The first step in reaching this understanding is conducting a comprehensive evaluation of your facility. Evaluation of your plant will be the most difficult part of your preparation. Cost-accounting and performance tracking systems are not set up to track all of the indices that define performance. At best, there will be some data for yield, unscheduled delays, and traditional costs, such as maintenance, labor, and material, but in most cases, the data will be extremely limited and may not provide a true picture.

Typically, the reports generated by these tracking programs are compartmentalized and will only disclose part of the true picture. For example, delays will be contained in several reports. Maintenance delays will be divided into at least two reports: unscheduled and planned downtime. Operating delays will be in another report or reports, and material control in yet another. To get a true picture of downtime, you must consolidate all nonproduction time into one report. The same is true of yield or product quality. At one client's facility, we found 57 different yield reports, none of which agreed. As you can imagine, developing a true picture of the yield for this plant was extremely difficult.

Do not use artificial limits; normalize data to the physical limits that bound plant performance. For example, a plant that operates continuously has a physical limit of 8,760 production hours in a calendar year. Capacity, availability, and all other performance indices should be based on this physical limit, not an arbitrary number of hours that are the common industry practice. Data should also be normalized to remove other variables, such as selling price and sales volume.

Self-evaluation is extremely difficult. Each of us has built-in perceptions that influence how we interpret data. These perceptions are deep-rooted and may prevent you from developing an honest evaluation of plant effectiveness. One of my favorite examples is maintenance planning. Most of my clients state absolutely that they plan at least 80 percent of their maintenance activities. Few, if any, actually plan 10 percent. At best, 80 percent of their maintenance tasks may be listed on a written schedule, but few are effectively planned.

How do you get around these perceptions? There is no easy answer. You must either make a commitment to honestly evaluate the effectiveness of each function and area within your plant or hire a qualified consultant to conduct the evaluation for you.

Accurate Cost Estimates. Many programs fail simply because costs, such as training, infrastructure, and required staffing, are underestimated. Make every effort to identify and quantify these costs as part of your justification.

Realistic Return-on-Investment Milestones. A clear set of project milestones will help ensure continuation of your program. If corporate executives can see measurable improvements, the probability of continuation and long-term success is greatly improved.

Tracking and Evaluation Plan. Selling the program is not finished when the justification package is approved. You must continue to sell the program for its entire life. A well-defined tracking and evaluation plan, coupled with clearly defined milestones, will greatly improve your chance of success. Remember: Never stop selling the program. Newsletters, video presentations, periodic reports, and personal contacts are essential to the continuation and success of your program.

Knowing Your Audience

There are at least five levels of selling that must be accomplished for a successful program: (1) corporate management, (2) plant management, (3) division management, (4) line supervision, and (5) the hourly workforce. Your justification package must address all five levels of approval. Benefits must address the unique concerns of each of these five groups.

Corporate Management. Corporate management must make the first commitment. Most improvement programs are expensive and will require corporate-level approval. Therefore, your initial justification package must be prepared for this critical audience.

A successful justification package must be couched in terms that these individuals will understand and accept. Remember that corporate managers are driven by one and only one thing—the bottom line. Your company's president is evaluated by the stockholders and board of directors based solely on the overall profitability of the corporation. Your justification package must presents the means to improve profitability.

Improvements in terms of staffing per unit produced, increased yields, and reduced overall costs are the key phrases that must be used to gain approval. Corporate-level executives are looking for ways to improve their perceived value. You must supply these means as part of your plan.

Plant Management. To a lesser degree, plant executives are driven by the same stimuli as those at corporate level. Although they tend to have a broader view of plant operations, plant-level managers want to see justification couched in terms of *total* plant.

One other factor is critical to success at this level. Most plant executives do not have a maintenance background. In fact, most have a built-in prejudice against the maintenance organization. Many are convinced that maintenance is the root-cause of the plant's poor performance. If your justification package and program plan are defined in maintenance terms or you limit improvements to traditional maintenance issues, your chances for approval will be severely limited.

Division Management. Total, absolute support of division managers is crucial. In most plants, the division manager controls all of the resources required to implement change. Regardless of the organizational structure, this level of management has control of the operating and maintenance budget as well as allocation of the workforce. Without this support, your program cannot succeed. If you can gain this support, you are well on your way to success.

Line Supervision. In many plants, first-line supervisors are the most resistant to change. In some cases, this resistance is driven by insecurity. Generally, this segment of the workforce is the first to be cut during reengineering or downsizing. As a result, their natural tendency is to resist any new program that is touted as a plant improvement program.

In other plants, supervisors have been conditioned by a long history of failed attempts to correct plant problems. The myriad "programs of the month," which have become the norm in our domestic plants, have resulted in widespread frustration throughout the workforce. This frustration is especially true of first-line supervisors.

Regardless of the reason for their resistance, first-line supervisors must be convinced to provide absolute, unconditional support. Your program plan must include the motivation and rationale that will convince this critical part of the workforce to get involved and to become a positive force that will ensure success.

Hourly Workforce. Most programs fail to address the final audience—the hourly workforce. This mistake is absolutely fatal. Without the total support and assistance of the hourly workers, nothing can change. Your program plan must include specific means of winning both initial and long-term support from the workers.

The best way to accomplish this key milestone is to include their representatives in the program development phase and continue their involvement throughout the program. Think like your audience. Include specific information and data that will be understood by your audience. Corporate executives will relate to staffing per ton, working ratios, and bottom-line profit. Hourly workers will relate to improved working conditions and higher incentives that result from improved yields. Think like your audience and your potential for approval will be improved.

Creating an Implementation Plan

A concise, detailed program plan is the most important part of your program. Without a good plan, most programs fail within the first year. The plan must include well-defined goals and objectives. Use extreme caution to ensure that goals are achievable within the prescribed timeline.

Few plants can afford to lay out major capital investments that are required by improvement programs. Therefore, your program should use a phased approach. Specific tasks should be defined in a logical sequence that minimizes investment and maximizes returns. Return on investment must be the driving force behind your timeline and implementation approach.

Make sure that all tasks required to accomplish your program are included in the program plan. Each task should include a clear definition, including a deliverable; assign responsibility to a specific individual; and indicate a start and end date. In addition, each task description should include all tools, skills, and support required.

Return on Investment. A viable continuous improvement program must be designed to pay for itself. Do not be misled; this is not an arbitrary management view. Your profit and loss statement clearly shows that the financial resources required to support an improvement program are simply not available. Every decision made must be driven by this single factor—return on investment. Unless your program can definitely pay for itself, it should not be implemented.

Frankly, most maintenance improvement programs will not pay for themselves. Traditional applications of predictive maintenance, reliability-centered maintenance, total productive maintenance, and a myriad of others are not capable of generating enough return to justify implementation. The only proven means of generating a positive return is to include the *total* plant in your program.

Do Not Overstate Benefits. The natural tendency is to define outlandish benefits that will be generated by the program. In some instances, these projections are based on data provided by consultants or vendors of improvement systems, like predictive maintenance, and are simply not valid. In other cases, you may overstate expected return-on-investment numbers to ensure approval. This is perhaps the greatest mistake that can be made. Remember that your justification will establish expectations that you must meet. If you overstate benefits, you will be expected to deliver. In conclusion, make sure that you prepare your justification and plan to assure success.

Doing Your Homework

An honest, in-depth evaluation of your plant is an absolute requirement. This evaluation provides two essential data sets: (1) it defines the specific areas that need to be improved, and (2) it provides a baseline or benchmark that can be used to measure the success of your program.

Taking a Holistic View

Do not limit your plant evaluation to a single plant function or deficiency. If you really want to improve the performance of your plant, look at every function or variable that has a direct or indirect impact on performance. Your evaluation should include these critical plant functions: sales, purchasing, engineering, production, maintenance, human resources, and management. Unless you take a holistic view, your program and its benefits will be limited.

Getting Absolute Buy-In

The total, absolute support of all employees within your plant is essential to success. You must gain their support or the program will fail. This task must be ongoing for the duration of your program. You must constantly reinforce this commitment or some portion of the workforce will lose interest and you will lose their support.

15.4 Selecting a Predictive Maintenance System

After developing the requirements for a comprehensive predictive maintenance program, the next step is to select the hardware and software system that will most cost-effectively support your program. Because most plants will require a combination of techniques (e.g., vibration, thermography, tribology), the system should be able to provide support for all of the required techniques. Because a single system that will support all of the predictive maintenance is not available, you must decide on the specific techniques that must be used to support your program. Some of the techniques may have to be eliminated to enable the use of a single predictive maintenance system. In most cases, though, two independent systems will be required to support the monitoring requirements in your plant.

Most plants can be cost-effectively monitored using a microprocessor-based system designed to use vibration, process parameters, visual inspection, and limited infrared temperature monitoring. Plants with large populations of heat transfer systems and electrical equipment will need to add a full thermal imaging system in order to meet the total-plant requirements for a full predictive maintenance program. Plants with fewer systems that require full infrared imaging may elect to contract this portion of the predictive maintenance program. This option will eliminate the need for an additional system. A typical microprocessor-based system will consist of four main components: a meter or data logger, a host computer, transducers, and a software program. Each component is important, but the total capability must be evaluated to achieve a system that will support a successful program.

15.4.1 Fundamental System Requirements

The first step in selecting the predictive maintenance system that will be used in your plant is to develop a list of the specific features or capabilities the system must have to support your program. At a minimum, the total system must have the following capabilities:

- User-friendly software and hardware
- Automated data acquisition
- Automated data management and trending
- Flexibility
- Reliability
- Accuracy
- Training and technical support

User-Friendly Software and Hardware

The premise of predictive maintenance is that existing plant staff must be able to understand the operation of both the data logger and the software program. Because plant staff normally has little, if any, computer or microprocessor background, the system must use simple, straightforward operation of both the data acquisition instrument and software. Complex systems, even if they provide advanced diagnostic capabilities, may not be accepted by plant staff and therefore will not provide the basis for a long-term predictive maintenance program.

Automated Data Acquisition

The object of using microprocessor-based systems is to remove any potential for human error, reduce staffing, and automate as much as possible the acquisition of vibration, process, and other data that will provide a viable predictive maintenance database. Therefore, the system must be able to automatically select and set monitoring parameters without user input. The ideal system would limit user input to a single operation, but this is not totally possible with today's technology.

Automated Data Management and Trending

The amount of data required to support a total-plant predictive maintenance program is massive and will continue to increase over the life of the program. The system must be able to store, trend, and recall the data in multiple formats that will enable the user to monitor, trend, and analyze the condition of all plant equipment included in the program. The system should be able to provide long-term trend data for the life of the program. Some of the microprocessor-based systems limit trends to a maximum of 26 data sets and will severely limit the decision-making capabilities of the predictive maintenance staff. Limiting trend data to a finite number of data sets eliminated the ability to determine the most cost-effective point to replace a machine rather than let it continue in operation.

Flexibility

Not all machines or plant equipment are the same, and neither are the best methods of monitoring their condition equal. Therefore, the selected system must be able to support as many of the different techniques as possible. At a minimum, the system should be capable of obtaining, storing, and presenting data acquired from all vibration and process transducers and provide an accurate interpretation of the measured values in user-friendly terms. The minimum requirement for vibration-monitoring systems must include the ability to acquire filter broadband, select narrowband, time traces, and high-resolution signature data using any commercially available transducer. Systems that are limited to broadband monitoring or to a single type of transducer cannot support the minimum requirements of a predictive maintenance program.

The added capability of calculating unknown values based on measured inputs will greatly enhance the system's capabilities. For example, neither fouling factor nor efficiency of a heat exchanger can be directly measured. A predictive maintenance system that can automatically calculate these values based on the measured flow, pressure, and temperature data would enable the program to automatically trend, log, and alarm deviations in these unknown, critical parameters.

Reliability

The selected hardware and software must be proven in actual field use to ensure their reliability. The introduction of microprocessor-based predictive maintenance systems is still relatively new, and it is important that you evaluate the field history of a system before purchase. Ask for a list of users and talk to the people who are already using the systems. This is a sure way to evaluate the strengths and weaknesses of a particular system before you make a capital investment.

Accuracy

Decisions on machine-train or plant system condition will be made based on the data acquired and reported by the predictive maintenance system. It must be accurate and repeatable. Errors can be input by the microprocessor and software as well as by the operators. The accuracy of commercially available predictive maintenance systems varies. Although most will provide at least minimum acceptable accuracy, some are well below the acceptable level.

It is extremely difficult for the typical plant user to determine the level of accuracy of the various instruments that are available for predictive maintenance. Vendor literature and salespeople will attempt to assure the potential user that their system is the best, most accurate, and so on. The best way to separate fact from fiction is to compare the various systems in your plant. Most vendors will provide a system on consignment for up to 30 days. This will provide sufficient time for your staff to evaluate each of the potential systems before purchase.

Training and Technical Support

Training and technical support are critical to the success of your predictive maintenance program. Regardless of the techniques or systems selected, your staff will have to be trained. This training will take two forms: system users' training and application knowledge for the specific techniques included in your program. Few, if any, of the existing staff will have the knowledge base required to implement the various predictive maintenance techniques discussed in the preceding chapters. None will understand the operation of the systems that are purchased to support your program.

Many of the predictive systems' manufacturers are strictly hardware and software oriented. Therefore, they offer minimal training and no application training or technical support. Few plants can achieve minimum benefits from predictive maintenance without training and some degree of technical support. It is therefore imperative that the selected system or system vendors provide a comprehensive support package that includes both training and technical support.

System Cost

Cost should not be the primary deciding factor in system selection. The capabilities of the various systems vary greatly, and so does the cost. Care should be taken to ensure a fair comparison of the total system capability and price before selecting your system. For example, vibration-based systems are relatively competitive in price. The general spread is less than $1,000 for a complete system; however, the capabilities of these systems are not comparable. A system that provides minimum capability for vibration monitoring will be about the same price as one that provides full vibration-monitoring capability and provides process parameter, visual inspection, and point-of-use thermography.

Operating Cost

The real cost of implementing and maintaining a predictive maintenance program is not the initial system cost. Rather, it is the annual labor and overhead costs associated with acquiring, storing, trending, and analyzing the data required to determine the operating condition of plant equipment. This is the area where predictive maintenance systems have the greatest variance in capability. Systems that fully automate data acquisition, storing, and so on will provide the lowest operating costs. Manual systems and many of the low-end microprocessor-based systems require substantially more labor to accomplish the minimum objectives required by predictive maintenance. The list of users will again help you determine the long-term cost of the various systems. Most users will share their experience, including a general indication of labor cost.

The Microprocessor

The data logger or microprocessor selected by your predictive maintenance program is critical to the program's success. A wide variety of systems are on the market, ranging from handheld overall value meters to advanced analyzers that can provide an almost unlimited amount of data. The key selection parameters for a data acquisition instrument should include the expertise required to operate, accuracy of data, type of data, and staffing required to meet the program demands.

Expertise Required to Operate. One of the objectives for using microprocessor-based predictive maintenance systems is to reduce the expertise required to acquire error-free, useful vibration and process data from a large population of machinery and systems within a plant. The system should not require user input to establish maximum amplitude, measurement bandwidths, filter settings, or allow free-form data input. All of these functions force the user to be a trained analyst and will increase the cost and time required to routinely acquire data from plant equipment. Many of the microprocessors on the market provide easy, menu-driven measurement routes that lead the user through the process of acquiring accurate data. The ideal system should require a single key input to automatically acquire, analyze, alarm, and store all pertinent data from plant equipment. This type of system would enable an unskilled user to quickly and accurately acquire all of the data required for predictive maintenance.

Accuracy of Data. The microprocessor should be able to automatically acquire accurate, repeatable data from equipment included in the program. The elimination of user input on filter settings, bandwidths, and other measurement parameters would greatly improve the accuracy of acquired data. The specific requirements that determine data accuracy will vary depending on the type of data. For example, a vibration instrument should be able to average data, reject spurious signals, auto-scale based on measured energy, and prevent aliasing.

The basis of frequency-domain vibration analysis assumes that we monitor the rotational frequency components of a machine-train. If a single block of data is acquired, nonrepetitive or spurious data can be introduced into the database. The microprocessor should be able to acquire multiple blocks of data, average the total, and store the averaged value. Basically, this approach enables the data acquisition unit to automatically reject any spurious data and provide reliable data for trending and analysis. Systems that rely on a single block of data will severely limit the accuracy and repeatability of acquired data. They will also limit the benefits that can be derived from the program.

The microprocessor should also have electronic circuitry that automatically checks each data set and block of data for accuracy and rejects any spurious data that may occur. Auto-rejection circuitry is available in several of the commercially available systems. Coupled with multiple block averaging, this auto-rejection circuitry ensures maximum accuracy and repeatability of acquired data. A few of the microprocessor-based systems require the user to input the maximum scale that is used to acquire data. This will severely limit the accuracy of data.

Setting the scale too high will prevent acquisition of factual machine data, whereas too low a setting will not capture any high-energy frequency components that may be generated by the machine-train. Therefore, the microprocessor should have auto-scaling capability to ensure accurate data. Vibration data can be distorted by high-frequency components that fold over into the lower frequencies of a machine's signature. Even though these aliased frequency components appear real, they do not exist in the machine. Low-frequency components can also distort the midrange signature of a machine in the same manner as high frequency. The microprocessor selected for vibration should include a full range of anti-aliasing filters to prevent distortion of machine signatures.

The features illustrated in the example also apply to nonvibration measurements. For example, pressure readings require the averaging capability to prevent spurious readings. Slight fluctuations in line or vessel pressure are normal in most plant systems. Without the averaging capability, the microprocessor cannot acquire an accurate reading of the true system pressure.

Alert and Alarm Limits. The microprocessor should include the ability to automatically alert the user to changes in machine, equipment, or system condition. Most of the predictive maintenance techniques rely on a change in the operating condition of plant equipment to identify an incipient problem. Therefore, the system should be able to analyze data and report any change in the monitoring parameters that were established as part of the database development.

Predictive maintenance systems use two methods to detect a change in the operating condition of plant equipment: static and dynamic. Static alert and alarm limits are preselected thresholds that are downloaded into the microprocessor. If the measurement parameters exceed the preset limit, an alarm is displayed. This type of monitoring does not consider the rate of change or historical trends of a machine and therefore cannot anticipate when the alarm will be reached.

The second method uses dynamic limits that monitor the rate of change in the measurement parameters. This type of monitoring can detect minor deviations in the rate that a machine or system is degrading and anticipate when an alarm will be reached. The use of dynamic limits will greatly enhance the automatic diagnostic capabilities of a predictive maintenance system and reduce the manual effort required to gain maximum benefits.

Data Storage. The microprocessor must be able to acquire and store large amounts of data. The memory capacities of the various predictive maintenance systems vary. At a minimum, the system must be able to store a full eight hours of data before transferring it to the host computer. The actual memory requirements will depend on the type of data acquired. For example, a system used to acquire vibration data would need enough memory to store about 1,000 overall readings or 400 full signatures. Process monitoring would require a minimum of 1,000 readings to meet the minimum requirements.

Data Transfer. The data acquisition unit will not be used for long-term data storage. Therefore, it must be able to reliably transfer data into the host computer. The actual time required to transfer the microprocessor's data into the host computer is the only nonproductive time of the data acquisition unit. It cannot be used to acquire additional data during the data transfer operation. Therefore, the transfer time should be kept to a minimum. Most of the available systems use an RS 232 communication protocol that allows data transfer at rates of up to 19,200 baud. The time required to dump the full memory of a typical microprocessor can be 30 minutes or more.

Some of the systems have incorporated an independent method of transferring data that eliminates the dead time altogether. These systems transfer stored data from the data logger into a battery-backed memory, bypassing the RS 232 link. Using this technique, data can be transferred at more than 350,000 baud and will reduce the nonproductive time to a few minutes.

The microprocessor should also be able to support modem communication with remote computers. This feature will enable multiple plant operation and direct access to third-party diagnostic and analysis support. Data can be transferred anywhere in the world using this technique. Not all predictive maintenance systems use a true RS 232 communications protocol or support modem communications. These systems can severely limit the capabilities of your program. The various predictive maintenance techniques will add other specifications for an acceptable data acquisition unit.

The Host Computer

The host computer provides all of the data management, storage, report generation, and analysis capabilities of the predictive maintenance program. Therefore, care should be exercised during the selection process. This is especially true if multiple technologies will be used within the predictive maintenance program. Each predictive maintenance system will have a unique host computer specification that will include hardware configuration, computer operating system, hard disk memory requirements, and many others. This can become a serious if not catastrophic problem. You may find that one system requires a special printer that is not compatible with other programs to provide hard copies of reports or graphic data. One program may be compatible with PC-DOS, whereas another requires a totally different operating program.

Therefore, you should develop a complete computer specification sheet for each of the predictive maintenance systems that will be used. A comparison of the list will provide a compatible computer configuration to support each of the techniques. If this is not possible, you may have to reconsider your choice of techniques. Computers, like plant equipment, sometimes fail. Therefore, the use of a commercially available computer is recommended. The critical considerations include availability of repair parts and local vendor support.

Most of the individual predictive maintenance techniques do not require a dedicated computer. Therefore, there is usually sufficient storage and computing capacity to handle several, if not all, of the required techniques and still leave room for other support programs (e.g., word processing, database management). Use of commercially available PCs provides the user with the option of including these auxiliary programs in the host computer. The actual configuration of the host computer will depend on the specific requirements of the predictive maintenance techniques that will be used. Therefore, we will not attempt to establish guidelines for selection.

The Software

The software program provided with each predictive maintenance system is the heart of a successful program. It is also the most difficult aspect to evaluate before purchase. The methodology used by vendors of predictive maintenance systems varies greatly. Many appear to have all of the capabilities required to meet the demands of a total-plant predictive maintenance program; however, on close inspection, usually after purchase, they are found to be lacking.

Software is also the biggest potential limiting factor of a program. Even though all vendors use some form of formal computer language (e.g., Fortran, Cobol, Basic), their programs are normally not interchangeable with other programs. The apparently simple task of having one computer program communicate with another can often be impossible. This lack of compatibility among various computer programs prohibits transferring a predictive maintenance database from one vendor's system into a system manufactured by another vendor. The result is that once a predictive maintenance program is started, a plant cannot change to another system without losing the data already developed in the initial program.

At a minimum, the software program should provide automatic database management, automatic trending, automatic report generation, and simplified diagnostics. As in the case of the microprocessor used to acquire data, the software must be user-friendly.

User-Friendly Operation. The software program should be menu-driven with clear online user instructions. The program should protect the user from distorting or deleting stored data. Some of the predictive maintenance systems are written in DBASE software shells. Even though these programs provide a knowledgeable user with the ability to modify or customize the structure of the program (e.g., report formats), they also provide the means to distort or destroy stored data. A single key entry can destroy years of stored data. Protection should be built into the program to limit the user's ability to modify or delete data and to prevent accidental database damage.

The program should have a clear, plain language user's manual that provides the logic and specific instructions required to set up and use the program.

Automatic Trending. The software program should be capable of automatically storing all acquired data and updating the trends of all variables. This capability should include multiple parameters, not just a broadband or single variable. This will enable the user to display trends of all variables that affect plant operations.

Automatic Report Generation. Report generation will be an important part of the predictive maintenance program. Maximum flexibility in format and detail is important to program success. The system should be able to automatically generate reports at multiple levels of detail. At a minimum, the system should be able to report:

- A listing of machine-trains or other plant equipment that has exceeded or is projected to exceed one or more alarm limits—The report should also provide a projection to probable failure based on the historical data and last measurement.
- A listing of missed measurement points, machines overdue for monitoring, and other program management information—These reports act as reminders to ensure that the program is maintained properly.
- A listing of visual observations—Most of the microprocessor-based systems support visual observations as part of their approach to predictive maintenance. This report provides hard copies of the visual observations as well as maintaining the information in the computer's database.
- Equipment history reports—These reports provide long-term data on the condition of plant equipment and are valuable for analysis.

Simplified Diagnostics. Identification of specific failure modes of plant equipment requires manual analysis of data stored in the computer's memory. The software program should be able to display, modify, and compare stored data in a manner that simplifies the analysis of the actual operating condition of the equipment. At a minimum, the program should be able to directly compare data from similar machines, normalize data into compatible units, and display changes in machine parameters (e.g., vibration, process).

Transducers

The final portion of a predictive maintenance system is the transducer that will be used to acquire data from plant equipment. Becaise we have assumed that a microprocessor-based system will be used, we will limit this discussion to those sensors that can be used with this type of system.

Acquiring accurate vibration and process data will require several types of transducers. Therefore, the system must be capable of accepting input from as many different types of transducers as possible. Any restriction of compatible transducers can become a serious limiting factor. This should eliminate systems that will accept inputs from a single type of transducer. Other systems are limited to a relatively small range of transducers that will also prohibit maximum utilization of the system. Selection of the specific transducers required to monitor the mechanical condition (e.g., vibration, flow, pressure) also deserves special consideration and will be discussed later.

15.5 Database Development

Each of the predictive maintenance technologies requires a logical method of acquiring, storing, evaluating, and trending massive amounts of data over an extended period. Therefore, a comprehensive database that is based on the actual requirements of critical plant systems must be developed for the predictive maintenance program. At a minimum, these databases should include the following capabilities:

- Establishing data acquisition frequency
- Setting up analysis parameters
- Setting boundaries for signature analysis
- Defining alert and alarm limits
- Selecting transducers

15.5.1 Establishing Data Acquisition Frequency

During the implementation stage of a predictive maintenance program, all classes of machinery should be monitored to establish a valid baseline data set. Full vibration signatures should be acquired to verify the accuracy of the database setup and determine the initial operating condition of the machinery. Because a comprehensive program will include trending and projected time-to-failure, multiple readings are required on all machinery to provide sufficient data for the microprocessor to develop trend statistics. During this phase, measurements are usually acquired every two weeks.

After the initial or baseline evaluation of the machinery, the frequency of data collection will vary depending on the classification of the machine-trains. Class I machines should be monitored on a two- to three-week cycle; Class II on a three- to four-week cycle; Class III on a four- to six-week cycle; and Class IV on a six- to ten-week cycle. This frequency can, and should, be adjusted for the actual condition of specific machine-trains. If the rate of change of a specific machine indicates rapid degradation, you should either repair it or at least increase the monitoring frequency to prevent catastrophic failure.

The recommended data acquisition frequencies are the maximum that will ensure prevention of most catastrophic failures. Less frequent monitoring will limit the ability of the program to detect and prevent unscheduled machine outages.

To augment the vibration-based program, you should also schedule the nonvibration tasks. Bearing cap, point-of-use infrared measurements, visual inspections, and process parameters monitoring should be conducted in conjunction with the vibration data acquisition. Full infrared imaging or scanning on the equipment included in the vibration-monitoring program should be conducted on a quarterly basis. In addition, full thermal scanning of critical electrical equipment (e.g., switch gear, circuit breakers) and all heat transfer systems (e.g., heat exchangers, condensers, process piping) that are not in the vibration program should be conducted quarterly.

Lubricating oil samples from all equipment included in the program should be taken on a monthly basis. At a minimum, a full spectrographic analysis should be conducted on these samples. Wear particle or other analysis techniques should be used on an as-needed basis.

15.5.2 Setting Up Analysis Parameters

The next step in establishing the program's database is to set up the analysis parameters that will be used to routinely monitor plant equipment. Each of these parameters will be based on the specific machine-train requirements that we have just developed. For nonmechanical equipment, the analysis parameter set usually consists of the calculated values derived from measuring the thermal profile or process parameters. Each classification of equipment or system will have its own unique analysis parameter set.

15.5.3 Setting Boundaries for Signature Analysis

All vibration-monitoring systems have finite limits on the resolution or ability to graphically display the unique frequency components that make up a machine's vibration signature. The upper limit (F_{MAX}) for signature analysis should be set high enough to capture and display enough data so that the analyst can determine the operating condition of the machine-train, but no higher. Most vibration-based predictive maintenance systems are capable of resolutions up to 12,000 lines; the tendency is to acquire high-resolution signatures as part of the routine monitoring sequence. Although this approach is technically viable, the use of high-resolution signatures (i.e., 1,000 lines or higher) dramatically increases the memory required to store acquired data. Because most of the data collectors have limited memory, this will limit the number of signatures that can be stored without uploading them to the host computer. The time lost because of the combined use of high-resolution signatures and the limited data collector memory will severely hamper the program's effectiveness. Effective programs limit routine monitoring to a maximum of 800 lines of resolution. This resolution will provide enough definition to detect incipient problems without the negatives associated with higher resolutions.

To determine the impact of resolution, calculate the display capabilities of your system. For example, a vibration signature with a maximum frequency (F_{MAX}) of 1,000 Hz taken with an instrument capable of 400 lines of resolution would result in a display in which each line will be equal to 2.5 Hz or 150 rotations per minute (rpm). Any frequencies that fall between 2.5 and 5.0 (i.e., the next displayed line) would be lost.

15.5.4 Defining Alert and Alarm Limits

The methods of establishing and using alert and alarm limits vary depending on the particular vibration-monitoring system that you select. These systems usually use either static or dynamic limits to monitor, trend, and alarm measured vibration. We will not attempt to define the different dynamic methods of monitoring vibration severity in this book. We will, however, provide a guideline for the maximum limits that should be considered acceptable for most plant mechanical equipment.

The systems that use dynamic alert and alarm limits base their logic (correctly in my opinion) on the concept that the rate of change of vibration amplitude is more important than the actual level. Any change in the vibration amplitude is a direct indication that a corresponding change in the machine's mechanical condition has occurred; however, there should be a maximum acceptable limit (i.e., absolute fault).

The accepted severity limit for casing vibration is 0.628 inches per second, ips-Peak (velocity). This unfiltered broadband value normally represents a bandwidth between 10 and 10,000 Hz. This value can be used to establish the absolute fault or maximum vibration amplitude for broadband measurement on most plant machinery. The exception would be machines with running speeds below 1,200 rpm or above 3,600 rpm.

Narrowband limits (i.e., discrete bandwidth within the broadband) can be established using the following guideline: Normally, 60 to 70 percent of the total vibration energy will occur at the true running speed of the machine. Therefore, the absolute fault limit for a narrowband established to monitor the true running speed would be 0.42 ips-Peak. This value can also be used for any narrowbands established to monitor frequencies below the true running speed.

Absolute fault limits for narrowbands established to monitor frequencies above running speed could be ratioed using the 0.42 ips-Peak limit established for the true running speed. For example, the absolute fault limit for a narrowband created to monitor the blade-passing frequency of a fan with 10 blades would be set at 0.042 or 0.42 divided by 10. Narrowband designed to monitor high-speed components (i.e., above 1,000 Hz) should have an absolute fault of 3.0 inches per second, g's-Peak (acceleration).

Rolling-element bearings, based on factor recommendations, have an absolute fault limit of 0.01 ips-Peak. Sleeve or fluid-film bearings should be watched closely. If the fractional components that identify oil whip or whirl are present at any level, the bearing is subject to damage and the problem should be corrected. Nonmechanical equipment and systems will normally have an absolute fault limit that specifies the maximum recommended level for continued operation. Equipment or systems vendors can usually provide this information.

15.5.5 Selecting Transducers

The type of transducers and data acquisition techniques that you will use for the program is the final critical factor that can determine the success or failure of your program. Their accuracy, proper application, and mounting will determine whether valid data will be collected.

The optimum predictive maintenance program developed in earlier chapters is predicated on vibration analysis as the principle technique for the program. It is also the most sensitive to problems created by using the wrong transducer or mounting technique.

Three basic types of vibration transducers can be used to monitor the mechanical condition of plant machinery: displacement probe, velocity transducer, and accelerometers. Each has specific applications and limitations within the plant.

Displacement Probes

Displacement, or eddy-current, probes are designed to measure the actual movement (i.e., displacement) of a machine's shaft relative to the probe. Therefore, the displacement probe must be rigidly mounted to a stationary structure to gain accurate, repeatable data.

Permanently mounted displacement probes will provide the most accurate data on machines with a low—relative to the casing and support structure—rotor weight. Turbines, large process compressors, and other plant equipment should have displacement transducers permanently mounted at key measurement locations to acquire data for the program.

The useful frequency range for displacement probes is from 10 to 1,000 Hz or 600 to 60,000 rpm. Frequency components below or above this range will be distorted and therefore unreliable for determining machine condition.

The major limitation with displacement or proximity probes is cost. The typical cost for installing a single probe, including a power supply, signal conditioning, and so on, will average $1,000. If each machine in your program requires 10 measurements, the cost per machine will be about $10,000. Using displacement transducers for all plant machinery will dramatically increase the initial cost of the program.

Displacement data are normally recorded in terms of mils or .001 inch, peak-to-peak. This valve expresses the maximum deflection or displacement off the true centerline of a machine's shaft.

Velocity Transducers

Velocity transducers are electromechanical sensors designed to monitor casing or relative vibration. Unlike the displacement probe, velocity transducers measure the rate of displacement, not actual movement. Velocity data are normally expressed in terms of inches per second, peak (ips-peak) and are perhaps the best method of expressing the energy created by machine vibration. Velocity transducers, like displacement probes, have an effective frequency range of about 10 to 1,000 Hz. They should not be used to monitor frequencies below or above this range.

The major limitation of velocity transducers is their sensitivity to mechanical and thermal damage. Normal plant use can cause a loss of calibration, and therefore a strict recalibration program must be used to prevent distortion of data. Velocity transducers should be recalibrated at least every six months. Even with periodic recalibration, programs using velocity transducers are prone to bad or distorted data that results from loss of calibration.

Accelerometers

Accelerometers use a piezoelectric crystal to convert mechanical energy into electrical signals. Data acquired with this type of transducer are relative vibration, not actual displacement, and are expressed in terms of g's or inches per second. Acceleration is perhaps the best method of determining the force created by machine vibration.

Accelerometers are susceptible to thermal damage. If sufficient heat is allowed to radiate into the crystal, it can be damaged or destroyed; however, because the data acquisition time using temporary mounting techniques is relatively short (less than 30 seconds), thermal damage is rare. Accelerometers do not require a recalibration program to ensure accuracy.

The effective range of general-purpose accelerometers is from about 1 to 10,000 Hz. Ultrasonic accelerometers are available for frequencies up to 1 MHz. Machine data above 1,000 Hz or 60,000 rpm should be taken and analyzed in acceleration or g's.

Mounting Techniques

Predictive maintenance programs using vibration analysis must have accurate, repeatable data to determine the operating condition of plant machinery. In addition to the transducer, three factors will affect data quality: measurement point, orientation, and compressive load.

Key measurement point locations and orientation to the machine's shaft were selected as part of the database setup to provide the best possible detection of incipient machine-train problems. Deviation from the exact point or orientation will affect the accuracy of acquired data. Therefore, it is important that every measurement throughout the life of the program be acquired at exactly the same point and orientation. In addition, the compressive load or downward force applied to the transducer should be the same for each measurement. For accuracy of data, a direct mechanical link to the machine's casing or bearing cap is necessary. Slight deviations in this load will induce errors in the amplitude of vibration and may create false frequency components that have nothing to do with the machine.

The best method of ensuring that these three factors are the same each time is to hard-mount vibration transducers to the selected measurement points. This technique will guarantee accuracy and repeatability of acquired data, but it will also increase the initial cost of the program. The average cost of installing a general-purpose accelerometer will be about $300 per measurement point or $3,000 for a typical machine-train.

To eliminate the capital cost associated with permanently mounting transducers, a well-designed quick-disconnect mounting can be used. This mounting technique permanently mounts a quick-disconnect stud, with an average cost of less than $5, at each measurement point location. A mating sleeve, built into a general-purpose accelerometer, is then used to acquire accurate, repeatable data. A well-designed quick-disconnect mounting technique provides the same accuracy and repeatability as the permanent mounting technique but at a much lower cost.

The third mounting technique that can be used is a magnetic mount. For general-purpose use, below 1,000 Hz, a transducer can be used in conjunction with a magnetic base. Even though the transducer/magnet assembly will have a resonant frequency that may provide some distortion to acquired data, this technique can be used with marginal success. Because the magnet can be placed anywhere on the machine, it will not guarantee that the exact location and orientation is maintained on each measurement.

The final method used by some plants to acquire vibration data is handheld transducers. This approach is not recommended if any other method can be used. Handheld transducers will not provide the accuracy and repeatability required to gain maximum benefit from a predictive maintenance program. If this technique must be used, extreme care should be exercised to ensure that the exact point, orientation, and compressive load is used for every measurement point.

15.6 Getting Started

The steps we have defined provide guidelines for establishing a predictive maintenance database. The only steps remaining to get the program started are to establish measurement routes and take the initial or baseline measurements. Remember, the predictive maintenance system will need multiple data sets to develop trends on each machine. With this database, you will be able to monitor the critical machinery in your plant for degradation and begin to achieve the benefits that predictive maintenance can provide. The actual steps required to implement a database will depend on the specific predictive maintenance system selected for your program. The system vendor should provide the training and technical support required to properly develop the database with the information discussed in the preceding chapters.

15.6.1 Training

One of the key issues that has severely limited both equipment reliability and predictive maintenance programs is the lack of proper training of technicians, analysts, and engineers. Most programs have limited training to a few days or a few weeks of training that is typically provided by the system vendor. For the most part, these training programs are limited to use of the vendor's system and perhaps a cursory understanding of data acquisition and analysis techniques. Even the few plants that invest in vibration, thermography, or tribology training tend to limit the duration and depth of training provided to their predictive teams.

Contrary to popular opinion, the skills required to interpret the data provided by these predictive maintenance technologies cannot be acquired in a few three- to five-day courses. I have used these technologies for more than 30 years and still learn something new almost every day.

In addition to the limitations imposed by companies that will not authorize sufficient training for their predictive maintenance teams, there is also a severe lack of viable predictive training courses. If we exclude the overview courses offered by the system vendors, only one or two companies offer any training in predictive maintenance technologies. With few exceptions, these courses are less than adequate and do not provide the level of training required for a new analyst/engineer to master the use of these technologies.

Generally, these courses are either pure theory and have little practical use in the field or are basic introductions to one or more techniques, such as vibration or infrared interpretation. Few, if any, of these courses are designed to address the unique requirements of your plant. For example, vibration courses are limited to general machinery, such as compressors, pumps, and fans, and exclude the process systems that are unique to your industry or plant. Although these common machines are important, your predictive maintenance team must be taught to analyze the critical processes, such as paper machines, rolling mills, and presses, that you rely on to produce your products and revenue.

Over the past 30 years, we have trained several thousand predictive maintenance analysts and reliability engineers. We have found that a minimum of 13 to 26 weeks of formal training, along with a similar period of supervised practical application, is required before a new predictive maintenance engineer or analyst can become proficient in the use of the three basic technologies used in most predictive maintenance programs. A significant difference exists between the 5 to 15 days of training that most predictive analysts receive and the minimum level required to use basic predictive maintenance tools. How can you close the gap without an excessive investment?

Unfortunately, the answer is that you cannot. With the training courses that are available in today's market, you have only two options: (1) you either restrict training to the limited number of short courses that are available, or (2) you hire a consulting/training company to provide a long-term, plant-specific training program for your predictive maintenance staff. The former option costs less, but will severely limit your benefits. The latter option is expensive and will require a long-term investment, but will provide absolute assurance that your predictive maintenance program will generate maximum improvements in equipment reliability and profitability.

An ideal third option would be to use interactive training programs that would permit new analysts to learn predictive maintenance skills at their own pace and without the expense of formal instructor training. From our viewpoint, there is a real need for an interactive training program that can provide comprehensive, industry-specific predictive maintenance training. The computer technology exists to support this approach, but someone must develop the courses that are needed to provide this type of comprehensive training program.

Successful completion of this critical phase of creating a total-plant predictive maintenance program will require a firm grasp of the operating dynamics of plant machinery, systems, and equipment. Normally, some if not all of this knowledge exists within the plant staff; however, the knowledge may not be within the staff selected to implement and maintain the predictive maintenance program.

In addition, a good working knowledge of the predictive maintenance techniques and systems that will be included in the program is necessary. This knowledge probably does not exist within current plant staff. Therefore, training—before attempting to establish a program—is strongly recommended. The minimum recommended level of training includes user training for each predictive maintenance system that will be used, a course on machine dynamics, and a basic theory course on each of the techniques that will be used.

In some cases, the systems vendors can provide all of these courses. If not, several companies and professional organizations offer courses on most nondestructive testing techniques.

15.6.2 Technical Support

The labor and knowledge required to properly establish a predictive maintenance program is often too much for plant staff members to handle. To overcome this problem, the initial responsibility for creating a viable, total-plant program can be contracted to a company that specializes in this area. A few companies provide full consulting and engineering services directed specifically toward predictive maintenance. These companies have the knowledge required and years of experience. They can provide all of the labor required to implement a full-plant program and normally can reduce total time required to get the program up and running. Caution should be used in selecting a contractor to provide this startup service. Check references very carefully.

16

A TOTAL-PLANT PREDICTIVE MAINTENANCE PROGRAM

With all of the techniques that are available for predictive maintenance, how do we select the best methods required to monitor the critical machines, equipment, and systems in a plant? It would be convenient if a single system existed that would provide all of the monitoring and analysis techniques required to routinely monitor every critical piece of equipment. Unfortunately, this is not the case.

Each of the predictive techniques discussed in the preceding chapter are highly specialized. Each has a group of systems vendors that promote their technique as the single solution to a plant's predictive maintenance needs. The result of this specialization is that no attempt has been made by predictive maintenance systems vendors to combine all of the different techniques into a single, total-plant system. Therefore, each plant must decide which combination of techniques and systems is required to implement its predictive maintenance program.

If a plant decides to use all of the available techniques, a total capital cost for instrumentation and systems can easily exceed $150,000. In most cases, this fact alone would prohibit implementing a program; however, the true costs would be much higher. To implement a program that includes all of the predictive maintenance techniques would require extensive staffing, training, and technical support. A minimum staff of at least five trained technicians and three highly trained engineers would be required to maintain this type of program. The annual costs for this operation would be extremely high. The actual labor and overhead costs will depend on the salaries and overhead rates of each plant, but the annual cost could easily exceed $500,000.

Because of the high capital and operating costs, this type of program would have to save more than 1 million dollars each year to justify its costs. Even though this type of savings is possible in larger plants, most small to medium-sized plants cannot justify including all of the available techniques in their predictive maintenance programs.

How do you decide which techniques will provide a cost-effective method of controlling the maintenance activities in your plant? The answer lies in determining the type of plant equipment that needs to be monitored. Plants with a large population of electrical equipment (e.g., motors, transformers, switch gear) should use thermographic or infrared scanning as their primary tool, whereas plants with a large population of mechanical machines and systems should rely on vibration techniques. In most cases, your plant will require a combination of two or more techniques, but you may elect to establish one technique as an in-house tool and contract with an outside source for periodic monitoring using the secondary techniques. This approach would provide the benefits that the secondary techniques provide without the additional costs.

16.1 The Optimum Predictive Maintenance Program

The optimum predictive maintenance program will, in most cases, consist of a combination of several monitoring techniques. Because most plants have large populations of mechanical systems, vibration techniques will be the primary method required to implement a total-plant program.

16.1.1 Predictive Technologies

Vibration methods alone cannot provide all of the information required to maintain the operating condition of the plant. It cannot provide the data required to maintain electrical equipment or the operating efficiency of nonmechanical equipment. Therefore, secondary methods must be used to gain this additional information. At a minimum, a comprehensive predictive maintenance program should include:

- Visual inspection
- Process dynamics
- Thermography
- Tribology

Visual Inspection

All predictive maintenance programs should include visual inspection as one of the tools used to monitor plant systems. The cost—considered in conjunction with other techniques that require periodic monitoring of plant equipment—is relatively small. In most cases, visual inspection can take place as the predictive maintenance team conducts the regular data acquisition required by any of the other techniques and therefore adds little or no costs to the program. Visual inspection can provide a wealth of information about the operating condition of the plant. This simple but often neglected tool can detect leaks, loose mountings, structural cracks, and several other failure modes that can limit the plant's performance.

Most of the commercially available vibration-monitoring systems provide visual observation capabilities in their data acquisition instruments. Therefore, visual observations can automatically be recorded concurrent with data acquisition of vibration data.

Process Dynamics

A true understanding of plant condition cannot be accomplished without knowing the operating efficiency of every machine or system in the plant. For example, how do you know the operating condition of a shell-and-tube heat exchanger without knowing the efficiency and fouling factor? The calculations required to determine these two critical factors is extremely simple, but you must first know the actual process parameters (i.e., flow, pressure and temperature) on both the primary and secondary side of the heat exchanger. Six simple measurements will provide the data required to periodically calculate both the efficiency and fouling factor.

Monitoring process parameters usually require the addition of some plant instrumentation. Few plants have working instruments that monitor all of the variables required to determine the operating condition of critical systems; however, advancements in instrumentation technology have developed nonintrusive methods of acquiring most of the required process variables without the expense of installing permanent instrumentation. Several techniques have been developed to monitor process flow—the most difficult process parameter to measure—without installing a pitot or vortex-shedding flowmeter. These new instruments are commercially available and can often be read by the microprocessor-based, vibration-based predictive maintenance systems.

A few of the microprocessor-based, vibration-monitoring systems provide the ability to directly acquire process data from permanently installed instruments and allow for manual entry of analog gauges. This capability provides the means to automatically acquire process parameters in conjunction with routine acquisition of vibration data. In addition, some of these systems can automatically calculate unknown process parameters (e.g., efficiency, fouling factors). These systems record the process parameters that can be directly measured and then automatically calculate, store, and trend the unknown in the same manner as parameters that are acquired directly. This ability greatly enhances the predictive maintenance system's benefits and eliminates both the manual effort required to calculate unknowns and the potential errors that manual calculation may create.

Thermography

Implementing a full thermographic program is usually not cost effective; however, many of the vibration-based systems will permit direct acquisition of infrared data through a point-of-use scanner. This feature should be incorporated into every predictive maintenance program. The scanner can be used to acquire several process parameters that will augment the program. Typical applications for this technique include bearing cap temperatures, spot checks of process temperatures, motor winding temperatures, spot checks of electrical equipment, and many more.

Unless the plant has a large population of electrical equipment or heat transfer systems, the cost of implementing a full infrared scanning system is prohibitive. For plants that have less of this type of equipment or systems, the most cost-effective method of including the benefits of full infrared scanning is to purchase periodic surveys of plant equipment from companies that specialize in these services.

A full survey of plant equipment should be conducted at least twice each year. The frequency should be determined by the impact these systems have on plant production. In addition to process and electrical systems, a full thermal scan of roofs and other building envelope parameters should be conducted every five years.

Tribology

Unless the plant has a large population of machinery and systems that are highly susceptible to damage as the direct result of lubricating oil contamination or has an extremely high turnover on lubricating inventories, the cost associated with using tribology techniques as part of a continuous predictive maintenance program is prohibitive. In fact, even in the exception cases noted, the cost and training required to use these techniques may not be cost effective.

Numerous companies provide full lubricating oil analysis on either a regular schedule or an as-needed basis. Most plants can achieve the benefits of tribology without the capital or recurring costs required to perform the function in-house. As a routine predictive maintenance tool, tribology should be limited to the simpler forms of tribology analysis (i.e., lubricating oil analysis and spectroscopy). The data provided by these two techniques will provide all of the information required to maintain the operating condition of the plant.

Wear particle analysis should be limited to a failure-mode analysis tool. If there is a known, chronic problem in plant machinery, this technique can provide information that will assist the diagnostics process. Otherwise, it is an unnecessary expense.

16.1.2 The Optimum Predictive Maintenance System

Predicated on the predictive maintenance requirements of most manufacturing and process plants, the best predictive maintenance system would use vibration analysis as the primary monitoring technique. The system should provide the ability to automate data acquisition, data management, trending, report generation, and diagnostics of incipient problems, but the system should not be limited to this technique alone. The optimum system should include visual inspection, process parameter monitoring, limited thermographic monitoring, and the ability to calculate unknown values.

In addition, the optimum system will permit direct data acquisition from any commercially available transducer. This will permit direct monitoring of any variable that may affect plant performance. One example of this feature would be the ability to directly monitor, using a current loop tester, the electrical condition of motors. By acquiring data directly from the power cable or an electric motor and monitoring the motor's slip frequency, defects such as loose or broken rotor bars can be detected.

Few of the commercially available vibration-based predictive maintenance systems provide all of the required capabilities, but they do exist. Caution should be exercised in this selection process. A mistake can guarantee failure of any predictive maintenance program.

16.2 Predictive Is Not Enough

As a subset of preventive maintenance, predictive maintenance alone cannot improve plant performance. Because the only output of an effective predictive maintenance program is information, the capability to directly change performance levels is nil. Until the information is used to correct anomalies identified by using predictive technologies, nothing will change. Therefore, an effective preventive maintenance program must also exist. At a minimum, the overall maintenance management methods must include effective planning and scheduling, preventive maintenance tasks, motivations, and record keeping.

16.2.1 Effective Planning and Scheduling

The plant or facility must have an effective maintenance planning and scheduling function that incorporates the information provided by the predictive maintenance activity into a global plan that will provide effective maintenance for all critical plant equipment and systems. The purposes of the maintenance planning function are to:

- Create an area of improved management planning coupled with greater flexibility of the in-facility workforce in conjunction with other departments.
- Obtain the maintenance and equipment efficiency and profitability necessary to operate the enterprise, and simultaneously achieve the workers' desire for security.

Planning is not a natural function to most people because it is contemplative and non-action-oriented. The person determined to start a job, complete it on time, and establish a good record for him or herself will probably not plan unless he or she is particularly experienced or astute, or unless some discipline is imposed. Without a work plan, however, good maintenance is impossible. Because the natural inclination of most people is not to plan at all, or to spend as little time planning as possible, it is difficult to plan excessively.

The major planning failure is to plan at the beginning of a job and then neglect to update the plan as work progresses, so that a major portion of control is lost. Some facilities spend about 6 percent of their sales dollars on maintenance and repair. As figures repeatedly show, the days have passed when top management could regard maintenance as merely a bothersome expense to keep as low as possible. Not only is low-cost maintenance impossible, it may be undesirable.

What factors are causing this continuous increase in maintenance costs? It certainly isn't inflation because maintenance costs are related to the fixed percentage of fixed assets. Increased mechanization is one factor, although it increases the significance of equipment maintenance. This means that if you mechanize a facility (i.e., install better, faster, more complicated equipment to take care of production needs), then the maintenance staff must be increased proportionately with better-qualified, higher-salaried people. As mechanization continues, the equipment becomes more complex, necessitating highly skilled personnel, therefore creating the need for training of both operations and maintenance. This domino effect means increased maintenance parts and supplies, which again means sky-rocketing maintenance costs.

Another factor is that larger, more complex, single-line processes have increased the impact of any interruption in a single operation on the overall production scheme. This means maximized round-the-clock maintenance when a unit is down. These large single-line units again mean tighter delivery schedules that increase the effect of interruptions to operating equipment and demand more and better maintenance.

A third factor is competition and market saturation, which means increased quality requirements and calls for immediate correction of defective conditions. All of these factors—coupled with the continually rising costs of labor, supplies, and materials—have caused top management to focus more attention on the maintenance function.

16.2.2 Preventive Maintenance Tasks

Fundamental preventive maintenance tasks, such as lubrication, must be universally implemented before a predictive maintenance program can provide optimum results. If these fundamental tasks are not performed, the predictive maintenance program will be overwhelmed with chronic lubrication, calibration, alignment, balancing, and other problems that would be eliminated by basic preventive maintenance tasks.

Lubrication

Friction of two materials moving relative to each other causes heat and wear. Great Britain has calculated that friction-related problems cost their industries more than 1 billion dollars per year. They coined a new term, *tribology*—derived from the Greek work, "tribos," which means "rubbing"—to refer to new approaches to the old dilemma of friction, wear, and the need for lubrication. Technology intended to improve the wear resistance of metal, plastics, and other surfaces in motion has greatly improved over recent years, but planning, scheduling, and control of the lubricating program is often reminiscent of a plant handyman wandering around with his long-spouted oil can looking for trouble spots.

Anything that is introduced onto or between moving surfaces in order to reduce friction is called a *lubricant*. Oils and greases are the most commonly used substances, although many other materials may be suitable. Other liquids and even gases are being used as lubricants. Air bearings, for example, are used in gyroscopes and other sensitive devices in which friction must be minimal. The functions of a lubricant are to:

- Separate moving materials from each other in order to prevent wear, scoring, and seizure.
- Reduce heat.
- Keep out contaminants.
- Protect against corrosion.
- Wash away worn materials.

Good lubrication requires two conditions: (1) sound technical design for lubrication and (2) a management program to ensure that every item of equipment is properly lubricated.

Lubrication Program Development. Information for developing lubrication specifications can come from four main sources:

- Equipment manufacturers
- Lubricant vendors
- Other equipment users
- Individuals' own experience

Like most other preventive maintenance elements, initial guidance on lubrication should come from manufacturers. They should have extensive experience with their own equipment both in their test laboratories and in customer locations. They should know what parts wear and are frequently replaced. Therein lies a caution: A manufacturer could in fact make short-term profits by selling large numbers of spare parts to replace worn ones. Over the long term, however, that strategy will backfire and other vendors, whose equipment is less prone to wear and failure, will replace them.

Lubricant suppliers can be a valuable source of information. Most major oil companies will invest considerable time and effort in evaluating their customers' equipment to select the best lubricants and frequency or intervals for change. Figure 16–1 shows a typical report. Naturally, the vendor hopes that the consumer will purchase its lubricants, but the total result can be beneficial to everyone. Lubricant vendors perform a valuable service of communicating and applying knowledge gained from many users to their customers' specific problems and opportunities.

Experience gained under similar operating conditions by other users or in your own facility can be one of the best teachers. Personnel, including operators and mechanics, have a major impact on lubrication programs. Table 16–1 shows typical

LUBRICATION CHART
PREPARED BY
BEALE OIL COMPANY

NAME SERVICE INFOSYSTEMS, INC. DATE 2/10/99

EQUIPMENT			LUBRICANTS RECOMMENDED
ELECTRICAL DEPARTMENT			
Electric Motors			
Bearings	Ring Oiled	Ck W/Ch Y	MOBIL D.T.E. Oil Heavy Medium
Bearings	Hand Oiled	M	MOBIL D.T.E. Oil Heavy Medium
Bearings	Greased	2/Y	MOBILPLEX EP No. 1
Couplings	Greased	2/Y	MOBILPLEX EP No. 1
Motor—Generator Sets			
Bearings	Ring Oiled	Ck W/Ch Y	MOBIL D.T.E. Oil Heavy Medium
Bearings	Hand Oiled	M	MOBIL D.T.E. Oil Heavy Medium
Bearings	Greased	2/Y	MOBILPLEX EP No. 1
Couplings	Greased	2/Y	MOBILPLEX EP No. 1
York Refrigeration Compressor			
Brunner Refrigeration Compressor			
Crankcase & Cylinders	Splash		MOBIL D.T.E. Oil Heavy Medium
Transformers			
Circuit Breakers			
Compensators			
Insulating Oil			MOBILECT 25
Gear Motors			
Parallel Shafts	Splash	Ck M/Ch Y	MOBIL D.T.E. Oil Extra Heavy
Right Angle Worm Gears	Splash	Ck M/Ch Y	MOBIL 600 W Cylinder Oil

W — Weekly
M — Monthly
Y — Yearly
2/Y — Twice Yearly
Ck — Check
Ch — Change

Figure 16–1 Recommended lubricants report.

codes for methods of lubrication, intervals, actions, and responsibility. Figure 16–2 shows a typical lubrication schedule. Specific lubricants and intervals will not be discussed here because they can be more effectively handled by the sources listed previously.

The quality and quantity of the lubricant applied are the two most important conditions of any lube program. Lubrication properties must be carefully selected to meet the operating conditions. The viscosity of the oil (or the base oil, if grease is used) and additives to provide film strength under pressure are especially important for bearing lubrication. Too little lubricant is usually worse than too much, but excess can

Table 16–1 Lubrication Codes

Methods of Application		*Servicing Actions*	
ALS	Automatic lube system	CHG	Change
ALL	Air line lubricator	CL	Clean
BO	Bottle oilers	CK	Check
DF	Drip feed	DR	Drain
GC	Grease cups	INS	Inspect
GP	Grease packed	LUB	Lubricate
HA	Hand applied		
HO	Hand oiling	*Servicing Intervals*	
ML	Mechanical lubricator	H	Hourly
MO	Mist oiler	D	Daily
OB	Oil bath	W	Weekly
OC	Oil circulation	M	Monthly
OR	Oil reservoir	Y	Yearly
PG	Pressure gun	NOP	When not operating
RO	Ring oiled	OP	OK to service when operating
SLD	Sealed		
SFC	Sight feed cups	*Service Responsibility*	
SS	Splash system	MAE	Maintenance electricians
WFC	Wick feed oil cups	MAM	Maintenance mechanics
WP	Waste packed	MAT	Maintenance trades
		OPR	Operating personnel
		OIL	Oiler

cause problems such as overheating and churning. The amount needed can range from a few drops per minute to a complete submersion bath.

A major step in developing the lubrication program is to assign specific responsibility and authority for the lubrication program to a competent maintainability or maintenance engineer. The primary functions and steps involved in developing the program are to:

1. Identify every piece of equipment that requires lubrication.
2. Ensure that every piece of major equipment is uniquely identified, preferably with a prominently displayed number.
3. Ensure that equipment records are complete for manufacturer and physical location.
4. Determine the locations on each piece of equipment that need to be lubricated.
5. Identify the lubricant to be used.
6. Determine the best method of application.
7. Establish the frequency or interval of lubrication.
8. Determine if the equipment can be safely lubricated while operating or if it must be shut down.
9. Decide who should be responsible for any human involvement.

```
CARBON PLANT AREA    LUBRICATION  SCHEDULE  WEEK OF 12/15/99      AREA CODE  17
SCHEDULE LUBE DATE                                                PAGE       23
12/28/99   SHIFT 2

SEQUENCE   LUBE POINT                          TYPE OF                 OIL
 NUMBER    DESCRIPTION     METHOD  PLANTS   LUBRICATION   COMPLETED ADDED  CAPACITY

18-02      RACK & PINION    GUN       2      ANTI-SEIZE        Y N
18-03      SWIVEL           GUN       2      ANTI-SEIZE        Y N

*************************  NO.20  ELEPHANT B 665-10 ***************************
20-01      BALL JOINT       GUN       2      ANTI-SEIZE        Y N
20-02      RACK & PINION    GUN       2      ANTI-SEIZE        Y N
20=03      SWIVEL           GUN       2      ANTI-SEIZE        Y N

*************************  NO.21  ELEPHANT B-665-11 ***************************
22-01      BALL JOINT       GUN       2      ANTI-SEIZE        Y N
22-02      RACK & PINION    GUN       2      ANTI-SEIZE        Y N
22-03      SWIVEL           GUN       2      ANTI-SEIZE        Y N

                          - HOT PITCH STATION -

*************************  PITCH PUMPS-3-INSIDE      ***************************
30-03      BEARINGS         GUN       4      ANTI-SEIZE        Y N

                            - 502 BUILDING -

************************* CONE CRUSHER-D-635-7       ***************************
38-00      CONE CRUSHER     RES       1      #5                Y N           35
38-02      BALL LOCK STOP   GUN       1      #1                Y N
38-03      BAND ROLL BRNGS  GUN       4      #1                Y N

                      - 503 BLDG GRND FLOOR MERZ -

************************* 640 FARVAL AUTO LUBE SYS   ***************************
40-01      PUMP             DRUM             TEMP 78           Y N
40-02      AIRLINE OILER    RES              140               Y N

                      - 504 BUILDING GROUND FLOOR -

************************* KENNEDY VAN SAUN BALL MIL  ***************************
44-01      DRUM END BRNGS   GUN       4       1                Y N
44-02      GEAR DRIVE &N&S  RES       2       10               Y N
```

Figure 16–2 Typical lubrication schedule.

10. Standardize lubrication methods.
11. Package the previous elements into a lubrication program.
12. Establish storage and handling procedures.
13. Evaluate new lubricants to take advantage of state-of-the-art advances.
14. Analyze any failures involving lubrication and initiate necessary corrective actions.

Lubrication Program Implementation. An individual supervisor in the maintenance department should be assigned the responsibility for implementation and continued operation of the lubrication program. This person's primary functions are to:

- Establish lubrication service actions and schedules.
- Define the lubrication routes by building, area, and organization.
- Assign responsibilities to specific persons.
- Train lubricators.
- Ensure that supplies of proper lubricants are stocked through the storeroom.

- Establish feedback that ensures completion of assigned lubrication and follows up on any discrepancies.
- Develop a manual or computerized lubrication scheduling and control system as part of the larger maintenance management program.
- Motivate lubrication personnel to check equipment for other problems and to create work requests where feasible.
- Ensure continued operation of the lubrication system.

It is important that a responsible person who recognizes the value of thorough lubrication be placed in charge of this program. As with any activity, interest diminishes over time, equipment is modified without corresponding changes to the lubrication procedures, and state-of-the-art advances in lubricating technology may not be employed. A factory may have thousands of lubricating points that require attention. Lubrication is no less important to computer systems, even though they are often perceived as electronic. The computer field engineer must provide proper lubrication to printers, tape drives, and disks that spin at 3,600 rotations per minute (rpm). A lot of maintenance time is invested in lubrication. The effect on production uptime can be measured nationally in billions of dollars.

Calibration

Calibration is a special form of preventive maintenance whose objective is to keep measurement and control instruments within specified limits. A standard must be used to calibrate the equipment. Standards are derived from parameters established by the National Bureau of Standards (NBS). Secondary standards that have been manufactured to close tolerances and set against the primary standard are available through many test and calibration laboratories and often in industrial and university tool rooms and research laboratories. Ohmmeters are examples of equipment that should be calibrated at least once a year and before further use if subjected to sudden shock or stress.

Standards. The government sets forth calibration system requirements in MIL-C-45662 and provides a good outline in the military standardization handbook MIL-HDBK-52, *Evaluation of Contractor's Calibration System.* The principles are equally applicable to any industrial or commercial situation. The purpose of a calibration system is to prevent tool inaccuracy through prompt detection of deficiencies and timely application of corrective action. Every organization should prepare a written description of its calibration system. This description should cover measuring test equipment and standards, including:

- Establishing realistic calibration intervals.
- Listing all measurement standards.
- Establishing environmental conditions for calibration.
- Ensuring the use of calibration procedures for all equipment and standards.
- Coordinating the calibration system with all users.
- Ensuring that equipment is frequently checked by periodic system or cross-checks in order to detect damage, inoperative instruments, erratic readings,

and other performance-degrading factors that cannot be anticipated or provided for by calibration intervals.
- Providing timely and positive correction action.
- Establishing decals, reject tags, and records for calibration labeling.
- Maintaining formal records to ensure proper controls.

Inspection Intervals. The checking interval may be in terms of time (hourly, weekly, monthly), or based on amount of use (every 5,000 parts), or every lot. For electrical test equipment, the *power-on* time may be a critical factor and can be measured through an electrical elapsed-time indicator.

Adherence to the checking schedule makes or breaks the system. The interval should be based on stability, purpose, and degree of usage. If initial records indicate that the equipment remains within the required accuracy for successive calibrations, then the intervals may be lengthened; however, if equipment requires frequent adjustment or repair, the intervals should be shortened. Any equipment that does not have specific calibration intervals should be (1) examined at least every six months, and (2) calibrated at intervals of no longer than one year.

Adjustments or assignment of calibration intervals should be done so that a minimum of 95 percent of equipment or standards of the same type is within tolerance when submitted for regularly scheduled recalibration. In other words, if more than 5 percent of a particular type of equipment is out of tolerance at the end of its interval, then the interval should be reduced until less than 5 percent is defective when checked.

Control Records. A record system should be kept on every instrument, including:

- History of use
- Accuracy
- Present location
- Calibration interval and when due
- Calibration procedures and necessary controls
- Actual values of latest calibration
- History of maintenance and repairs

Test equipment and measurement standards should be labeled to indicate the date of last calibration, by whom it was calibrated, and when the next calibration is due (see Figure 16–3). When the size of the equipment limits the application of labels, an identifying code should be applied to reflect the serviceability and due date for next calibration. This provides a visual indication of the calibration serviceability status. Both the headquarters calibration organization and the instrument user should maintain a two-way check on calibration. A simple means of doing this is to create a small form for each instrument with a calendar of weeks or months (depending on the interval required) across the top, which can be punched and noticed to indicate the calibration due date. An example of this type of form is shown in Figure 16–4.

SN: 98013556
Last Date: 3/15/99
Calibrated by: RKM
Next Due: 3/15/00

Figure 16–3 A typical calibration label.

Month: 1 2 3 4 5 7 8 9 10 11

SN: 921355 Desc: Oscilloscope, Techtronix 213
User: Prototype Test Lab Acct: 121.355.722
Bldg 32, Rm 13 Int: 6 mo.
Attn: Mike Felluca Tel: 334-9126

Due — Date	— Act	By	Comments
12/ 1/97	12/ 4/97	JDP	OK
6/ 1/98	6/15/98	HCF	OK
12/ 1/98	8/ 3/98	JDP	Dropped. Repair/Recal.
12/ 1/98			

Figure 16–4 A typical calibration card.

If the forms are sorted every month, the cards for each instrument that should be recalled for check or calibration can easily be pulled out.

Alignment Practices

Shaft alignment is the proper positioning of the shaft centerlines of the driver and driven components (e.g., pumps, gearboxes) that make up the machine drive train. Alignment is accomplished either through shimming or moving a machine component. Its objective is to obtain a common axis of rotation at operating equilibrium for two coupled shafts or a train of coupled shafts.

Shafts must be aligned as perfectly as possible to maximize equipment reliability and life, particularly for high-speed equipment. Alignment is important for directly coupled shafts, as well as coupled shafts of machines that are separated by distance—even those using flexible couplings. It is important because misalignment can introduce a high level of vibration, cause bearings to run hot, and result in the need for frequent repairs. Proper alignment reduces power consumption and noise level, and helps achieve the design life of bearings, seals, and couplings.

Alignment procedures are based on the assumption that one machine-train component is stationary, level, and properly supported by its baseplate and foundation. Both angular and offset alignment must be performed in the vertical and horizontal planes, which is accomplished by raising or lowering the other machine components and/or moving them horizontally to align with the rotational centerline of the stationary shaft. The movable components are designated as "machines to be moved" (MTBM) or "machines to be shimmed" (MTBS). MTBM generally refers to corrections in the horizontal plane, whereas MTBS generally refers to corrections in the vertical plane.

Too often, alignment operations are performed randomly and adjustments are made by trial and error, resulting in a time-consuming procedure.

Alignment Fundamentals. This section discusses the fundamentals of machine alignment and presents an alternative to the commonly used trial-and-error method. This section addresses exactly what alignment is and the tools needed to perform it, why it is needed, how often it should be performed, what is considered to be "good enough," and what steps should be taken before performing the alignment procedure. It also discusses types of alignment (or misalignment), alignment planes, and why alignment is performed on shafts as opposed to couplings.

Shafts are considered to be in alignment when they are colinear at the coupling point. The term *colinear* refers to the condition when the rotational centerlines of two mating shafts are parallel and intersect (i.e., join to form one line). When this is the case, the coupled shafts operate just like a solid shaft. Any deviation from the aligned or colinear condition, however, results in abnormal wear of machine-train components such as bearings and shaft seals.

Variations in machine-component configuration and thermal growth can cause mounting-feet elevations and the horizontal orientations of individual drive-train components to be in different planes. Nevertheless, they are properly aligned as long as their shafts are colinear at the coupling point.

Note that it is important for final drive-train alignment to compensate for actual operating conditions because machines often move after startup. Such movement is generally the result of wear, thermal growth, dynamic loads, and support or structural shifts. These factors must be considered and compensated for during the alignment process.

The tools most commonly used for alignment procedures are dial indicators, adjustable parallels, taper gauges, feeler gauges, small-hole gauges, and outside micrometer calipers.

Why Perform Alignment and How Often? Periodic alignment checks on all coupled machinery are considered one of the best tools in a preventive maintenance program. Such checks are important because the vibration effects of misalignment can seriously damage a piece of equipment. Misalignment of more than a few thousandths of an inch can cause vibration that significantly reduces equipment life.

Although the machinery may have been properly aligned during installation or during a previous check, misalignment may develop over a very short period. Potential causes include foundation movement or settling, accidentally bumping the machine with another piece of equipment, thermal expansion, distortion caused by connected piping, loosened hold-down nuts, expanded grout, rusting of shims, and others. Indications of misalignment in rotating machinery are shaft wobbling, excessive vibration (in both radial and axial directions), excessive bearing temperature (even if adequate lubrication is present), noise, bearing wear pattern, and coupling wear.

Many alignments are done by the trial-and-error method. Although this method may eventually produce the correct answers, it is extremely time consuming and, as a result, it is usually considered "good enough" before it really is. Rather than relying on "feel" as with trial-and-error, some simple trigonometric principles allow alignment to be done properly with the exact amount of correction needed either measured or calculated, taking the guesswork out of the process. Such accurate measurements and calculations make it possible to align a piece of machinery on the first attempt.

What Is Good Enough? This question is difficult to answer because there are vast differences in machinery strength, speed of rotation, type of coupling, and so on. It also is important to understand that flexible couplings do not cure misalignment problems—a common myth in industry. Although they may somewhat dampen the effects, flexible couplings are not a total solution.

An easy (perhaps too easy) answer to the question of what is good enough is to align all machinery to comply exactly with the manufacturers' specifications; however, the question of which manufacturers' specifications to follow must be answered because few manufacturers build entire assemblies. Therefore, an alignment is not considered good enough until it is well within all manufacturers' tolerances and a vibration analysis of the machinery in operation shows the vibration effects caused by misalignment to be within the manufacturers' specifications or accepted industry standards. Note that manufacturers' alignment specifications may include intentional misalignment during "cold" alignment to compensate for thermal growth, gear lash, and the like during operation.

Coupling Alignment versus Shaft Alignment. If all couplings were perfectly bored through their exact center and perfectly machined about their rim and face, it might be possible to align a piece of machinery simply by aligning the two coupling halves; however, coupling eccentricity often results in coupling misalignment. This does not mean that dial indicators should not be placed on the coupling halves to obtain alignment measurements. It does mean that the two shafts should be rotated simultaneously when obtaining readings, which makes the couplings an extension of the shaft centerlines, whose irregularities will not affect the readings.

Although alignment operations are performed on coupling surfaces because they are convenient to use, it is extremely important that these surfaces and the shaft "run true." If there is any runout (i.e., axial or radial looseness) of the shaft and/or the coupling, a proportionate error in alignment will result. Therefore, before making alignment measurements, the shaft and coupling should be checked and corrected for runout.

Balancing Practices

Mechanical imbalance is one of the most common causes of machinery vibration and is present to some degree on nearly all machines that have rotating parts or rotors. Static, or standing, imbalance is the condition when more weight is exerted on one side of a centerline than the other; however, a rotor may be in perfect static balance and not be in a balanced state when rotating at high speed.

If the rotor is a thin disc, careful static balancing may be accurate enough for high speeds. If the rotating part is long in proportion to its diameter, however, and the unbalanced portions are at opposite ends or in different planes, the balancing must counteract the centrifugal force of these heavy parts when they are rotating rapidly.

This section provides information needed to understand and solve most balancing problems using a vibration/balance analyzer, a portable device that detects the level of imbalance, misalignment, and so on in a rotating part based on the measurement of vibration signals.

Sources of Vibration Caused by Mechanical Imbalance. Two major sources of vibration caused by mechanical imbalance in equipment with rotating parts or rotors are assembly errors and incorrect key length guesses during balancing.

Assembly errors. Even when parts are precision balanced to extremely close tolerances, vibration caused by mechanical imbalance can be much greater than necessary because of assembly errors. Potential errors include relative placement of each part's center of rotation, location of the shaft relative to the bore, and cocked rotors.

Center of rotation. Assembly errors are not simply the additive effects of tolerances, but also include the relative placement of each part's center of rotation. For example, a "perfectly" balanced blower rotor can be assembled to a "perfectly" balanced shaft and yet the resultant imbalance can be high. This can happen if the rotor is balanced on a balancing shaft that fits the rotor bore within 0.5 mil (0.5 thousandths of an inch) and then is mounted on a standard cold-rolled steel shaft allowing a clearance of more than 2 mils.

Shifting any rotor from the rotational center on which it was balanced to the piece of machinery on which it is intended to operate can cause an assembly imbalance four to five times greater than that resulting simply from tolerances. Therefore, all rotors should be balanced on a shaft with a diameter as nearly the same as the shaft on which it will be assembled.

For best results, balance the rotor *on its own shaft* rather than on a balancing shaft. This may require some rotors to be balanced in an overhung position, a procedure the balancing shop often wishes to avoid; however, it is better to use this technique rather than being forced to make too many balancing shafts. The extra precision balance attained by using this procedure is well worth the effort.

Method of locating position of shaft relative to bore. Imbalance often results with rotors that do not incorporate setscrews to locate the shaft relative to the bore (e.g., rotors that are end-clamped). In this case, the balancing shaft is usually horizontal. When the operator slides the rotor on the shaft, gravity causes the rotor's bore to make contact at the 12 o'clock position on the top surface of the shaft. In this position, the rotor is end-clamped in place and then balanced.

If the operator removes the rotor from the balancing shaft without marking the point of bore and shaft contact, it may not be in the same position when reassembled. This often shifts the rotor by several mils as compared to the axis on which it was balanced, thus introducing an imbalance. The vibrations that result are usually enough to spoil what should have been a precision balance and produce a barely acceptable vibration level. In addition, if the resultant vibration is resonant with some part of the machine or structure, a more serious vibration could result.

To prevent this type of error, the balancer operators and those who do final assembly should follow the following procedure: (1) The balancer operator should permanently mark the location of the contact point between the bore and the shaft during balancing. (2) When the equipment is reassembled in the plant or the shop, the assembler should also use this mark. (3) For end-clamped rotors, the assembler should slide the bore on the horizontal shaft, rotating both until the mark is at the 12 o'clock position and then clamp it in place.

Cocked rotor. If a rotor is cocked on a shaft in a position different from the one in which it was originally balanced, an imbalanced assembly will result. If, for example, a pulley has a wide face that requires more than one setscrew, it could be mounted on-center but be cocked in a different position than during balancing. This can happen by reversing the order in which the setscrews are tightened against a straight key during final mounting as compared to the order in which the setscrews were tightened on the balancing arbor. This can introduce a pure couple imbalance, which adds to the small couple imbalance already existing in the rotor and causes unnecessary vibration.

For very narrow rotors (e.g., disc-shaped pump impellers or pulleys), the distance between the centrifugal forces of each half may be very small. Nevertheless, a very high centrifugal force, which is mostly counterbalanced statically (discussed in

Section 16.2.1) by its counterpart in the other half of the rotor, can result. If the rotor is slightly cocked, the small axial distance between the two very large centrifugal forces causes an appreciable couple imbalance, which is often several times the allowable tolerance because the centrifugal force is proportional to half the rotor weight (at any one time, half of the rotor is pulling against the other half) times the radial distance from the axis of rotation to the center of gravity of that half.

To prevent this, the assembler should tighten each setscrew gradually—first one, then the other, and back again—so that the rotor is aligned evenly. On flange-mounted rotors such as flywheels, it is important to clean the mating surfaces and the bolt holes. Clean bolt holes are important because high couple imbalance can result from the assembly bolt pushing a small amount of dirt between the surfaces, cocking the rotor. Burrs on bolt holes can also produce the same problem.

Other. Other assembly errors can cause vibration. Variances in bolt weights when one bolt is replaced by one of a different length or material can cause vibration. For setscrews that are 90 degrees apart, the tightening sequence may not be the same at final assembly as during balancing. To prevent this, the balancer operator should mark which setscrew was tightened first.

Key length. With a keyed-shaft rotor, the balancing process can introduce machine vibration if the assumed key length is different from the length of the one used during operation. Such an imbalance usually results in a mediocre or "good" running machine as opposed to a very smooth running machine.

For example, a "good" vibration level that can be obtained without following the precautions described in this section is amplitude of 0.12 in./sec. (3.0 mm/sec.). By following the precautions, the orbit can be reduced to about 0.04 in./sec. (1 mm/sec.). This smaller orbit results in longer bearing or seal life, which is worth the effort to ensure that the proper key length is used.

When balancing a keyed-shaft rotor, one half of the key's weight is assumed to be part of the shaft's male portion. The other half is considered part of the female portion that is coupled to it. When the two rotor parts are sent to a balancing shop for rebalancing, however, the actual key is rarely included. As a result, the balance operator usually guesses at the key's length, makes up a half key, and then balances the part. (Note: A "half key" is of full-key length but only half-key depth.)

In order to prevent an imbalance from occurring, *do not allow the balance operator to guess the key length*. It is strongly suggested that the actual key length be recorded on a tag that is attached to the rotor to be balanced. The tag should be attached so that another device (such as a coupling half, pulley, fan, etc.) cannot be attached until the balance operator removes the tag.

Theory of Imbalance. Imbalance is the condition when more weight is exerted on one side of a centerline than the other. This condition results in unnecessary vibration, which generally can be corrected by adding counterweights. There are four types of imbalance: (1) static, (2) dynamic, (3) couple, and (4) dynamic imbalance combinations of static and couple.

Static. Static imbalance is single-plane imbalance acting through the center of gravity of the rotor, perpendicular to the shaft axis. This imbalance can also be separated into two separate single-plane imbalances, each acting in-phase or at the same angular relationship to each other (i.e., 0 degrees apart); however, the net effect is as if one force is acting through the center of gravity. For a uniform straight cylinder, such as a simple paper machine roll or a multigrooved sheave, the forces of static imbalance measured at each end of the rotor are equal in magnitude (i.e., the ounce-inches or gram-centimeters in one plane are equal to the ounce-inches or gram-centimeters in the other).

In static imbalance**,** the only force involved is weight. For example, assume that a rotor is perfectly balanced and, therefore, will not vibrate regardless of the speed of rotation. Also, assume that this rotor is placed on frictionless rollers or "knife edges." If a weight is applied on the rim at the center of gravity line between two ends, the weighted portion immediately rolls to the 6 o'clock position because of the gravitational force.

When rotation occurs, static imbalance translates into a centrifugal force. As a result, this type of imbalance is sometimes referred to as *force imbalance,* and some balancing machine manufacturers use the word *force* instead of *static* on their machines; however, when the term *force imbalance* was just starting to be accepted as the proper term, an American standardization committee on balancing terminology standardized the term *static* instead of *force*. The rationale was that the role of the standardization committee was not to determine and/or correct right or wrong practices, but simply to standardize those currently in use by industry. As a result, the term *static imbalance* is now widely accepted as the international standard and, therefore, is the term used in this document.

Dynamic. Dynamic imbalance is any imbalance resolved to at least two correction planes (i.e., planes in which a balancing correction is made by adding or removing weight). The imbalance in each of these two planes may be the result of many imbalances in many planes, but the final effects can be characterized to only two planes in almost all situations.

An example of a case where more than two planes are required is flexible rotors (i.e., long rotors running at high speeds). High speeds are considered to be revolutions per minute (rpm) higher than about 80 percent of the rotor's first critical speed; however, in more than 95 percent of all common rotors (e.g., pump impellers, armatures, generators, fans, couplings, pulleys), two-plane dynamic balance is sufficient. Therefore, flexible rotors are not covered in this book because of the low number in operation and the fact that balancing operations are almost always performed by specially trained people at the manufacturer's plant.

In dynamic imbalance, the two imbalances do not have to be equal in magnitude to each other, nor do they have to have any particular angular reference to each other. For example, they could be 0 (in-phase), 10, 80, or 180 degrees from each other.

Although the definition of dynamic imbalance covers all two-plane situations, an understanding of the components of dynamic imbalance is needed so that its causes can be understood. An understanding of the components also makes it easier to understand why certain types of balancing do not always work with many older balancing machines for overhung rotors and very narrow rotors. The primary components of dynamic imbalance include number of points of imbalance, amount of imbalance, phase relationships, and rotor speed.

Points of Imbalance. The first consideration of dynamic balancing is the number of imbalance points on the rotor because there can be more than one point of imbalance within a rotor assembly. This is especially true in rotor assemblies with more than one rotating element, such as a three-rotor fan or multistage pump.

Amount of imbalance. The amplitude of each point of imbalance must be known to resolve dynamic balance problems. Most dynamic balancing machines or in situ balancing instruments are able to isolate and define the specific amount of imbalance at each point on the rotor.

Phase relationship. The phase relationship of each point of imbalance is the third factor that must be known. Balancing instruments isolate each point of imbalance and determine their phase relationship. Plotting each point of imbalance on a polar plot does this. In simple terms, a polar plot is a circular display of the shaft end. Each point of imbalance is located on the polar plot as a specific radial, ranging from 0 to 360 degrees.

Rotor speed. Rotor speed is the final factor that must be considered. Most rotating elements are balanced at their normal running speed or over their normal speed range. As a result, they may be out of balance at some speeds that are not included in the balancing solution. For example, the wheels and tires on your car are dynamically balanced for speeds ranging from 0 to the maximum expected speed (i.e., 80 miles per hour). At speeds above 80 miles per hour, they may be out of balance.

Coupled Imbalance. Couple imbalance is caused by two equal noncolinear imbalance forces that oppose each other angularly (i.e., 180 degrees apart). Assume that a rotor with pure couple imbalance is placed on frictionless rollers. Because the imbalance weights or forces are 180 degrees apart and equal, the rotor is statically balanced; however, a pure couple imbalance occurs if this same rotor is revolved at an appreciable speed.

Each weight causes a centrifugal force, which results in a rocking motion or rotor wobble. This condition can be simulated by placing a pencil on a table, then at one end pushing the side of the pencil with one finger. At the same time, push in the opposite direction at the other end. The pencil will tend to rotate end-over-end. This end-over-end action causes two imbalance "orbits," both 180 degrees out-of-phase, resulting in a "wobble" motion.

Balancing Standards. The International Standards Organization (ISO) has published standards for acceptable limits for residual imbalance in various classifications of rotor assemblies. Balancing standards are given in ounce-inches or pound-inches per pound of rotor weight or the equivalent in metric units (g-mm/kg). The ounce-inches are for each correction plane for which the imbalance is measured and corrected.

Caution must be exercised when using balancing standards. The recommended levels are for residual imbalance, which is defined as imbalance of any kind that remains *after* balancing. Table 16–2 is the norm established for most rotating equipment. Additional information can be obtained from ISO 5406 and 5343. Similar standards are available from the American National Standards Institute (ANSI) in their publication ANSI S2.43-1984.

Table 16–2 Balance Quality Grades for Various Groups of Rigid Rotors

Balance Quality Grade	Type of Rotor
G4,000	Crankshaft drives of rigidly mounted slow marine diesel engines with uneven number of cylinders.
G1,600	Crankshaft drives of rigidly mounted large two-cycle engines.
G630	Crankshaft drives of rigidly mounted large four-cycle engines; crankshaft drives of elastically mounted marine diesel engines.
G250	Crankshaft drives of rigidly mounted fast four-cylinder diesel engines.
G100	Crankshaft drives of fast diesel engines with six or more cylinders; complete engines (gasoline or diesel) for cars and trucks.
G40	Car wheels, wheel rims, wheel sets, drive shafts; crankshaft drives of elastically mounted fast four-cycle engines (gasoline and diesel) with six or more cylinders; crankshaft drives for engines of cars and trucks.
G16	Parts of agricultural machinery; individual components of engines (gasoline or diesel) for cars and trucks.
G6.3	Parts or process plant machines; marine main-turbine gears; centrifuge drums; fans; assembled aircraft gas-turbine rotors; fly wheels; pump impellers; machine-tool and general machinery parts; electrical armatures.
G2.5	Gas and steam turbines; rigid turbo-generator rotors; rotors; turbo-compressors; machine-tool drives; small electrical armatures; turbine-driven pumps.
G1	Tape recorder and phonograph drives; grinding-machine drives.
G0.4	Spindles, disks, and armatures of precision grinders; gyroscopes.

Source: "Balancing Quality of Rotating Rigid Bodies," *Shock and Vibration Handbook*, ISO 1940–1973; ANSI S2.19–1975.

So far, there has been no consideration of the angular positions of the usual two points of imbalance relative to each other or the distance between the two correction planes. For example, if the residual imbalances in each of the two planes were in-phase, they would add to each other to create more static imbalance.

Most balancing standards are based on a *residual* imbalance and do not include multiplane imbalance. If they are approximately 180 degrees to each other, they form a couple. If the distance between the planes is small, the resulting couple is small; if the distance is large, the couple is large. A couple creates considerably more vibration than when the two residual imbalances are in-phase. Unfortunately, nothing in the balancing standards considers this point.

Another problem could also result in excessive imbalance-related vibration even though the ISO standards were met. The ISO standards call for a balancing grade of G6.3 for components such as pump impellers, normal electric armatures, and parts of process plant machines. This results in an operating speed vibration velocity of 6.3 mm/sec. (0.25 in./sec.) vibration avelocity; however, practice has shown that an acceptable vibration velocity is 0.1 in./sec. and the ISO standard of G2.5 is required. Because of these discrepancies, changes in the recommended balancing grade are expected in the future.

16.2.3 Motivation

Staff motivation to perform preventive maintenance properly is a critical issue. A little extra effort in the beginning to establish an effective preventive maintenance program will pay large dividends, but finding those additional resources when so many "fires" need to be put out is a challenge. Like with most things we do, if we want to do it, we can. Herzberg's two levels of motivation, as outlined in Figure 16–5, help us understand the factors that cause people to want to do some things and not be so strongly stimulated to do others. Paying extra money, for example, is not nearly as motivating as are demonstrated results that show equipment running better because of the preventive maintenance and a good "pat on the back" from management for a job well done.

A results orientation is helpful because, as shown in Figure 16–6, an unfilled need is the best motivator. That need, in reference to effective maintenance management, is equipment availability and reliability, desire to avoid breakdowns, and opportunity to achieve improvement. The converse is failures and downtime, with resulting low production and angry customer users.

Production/Maintenance Cooperation

Some organizations, such as General Motors' Fisher Body Plant, have established the position of Production/Maintenance Coordinator. This person's function is to ensure that equipment is made available for inspections and preventive maintenance at the best possible time for both organizations. This person is a salesman for maintenance. This is an excellent developmental position for a foreman or supervisor. One year in

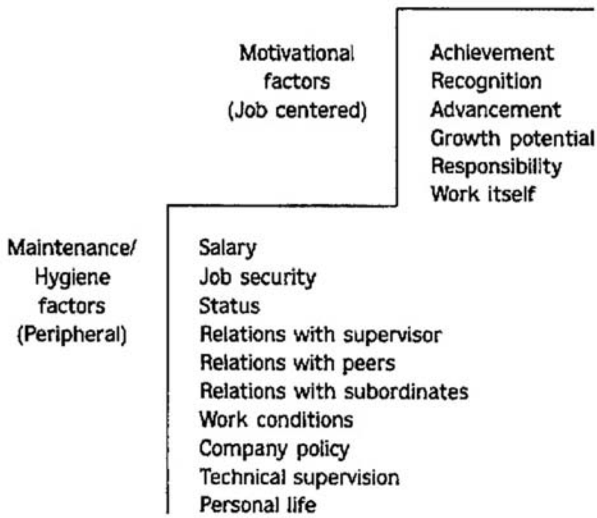


Figure 16–5 Two-factor theory of motivation.

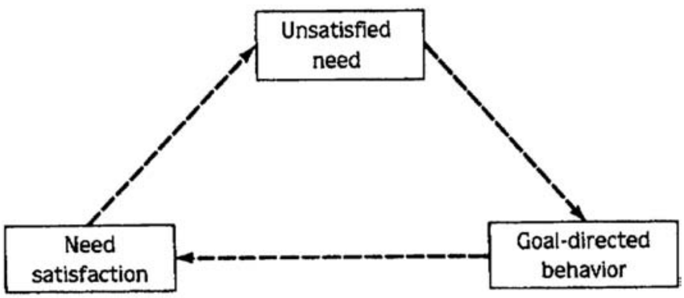


Figure 16–6 The process of motivation.

that position will probably be enough for most people to learn the job well and to become eager to move on to duties with less conflict.

Other organizations make production responsible for initiating a percentage of work orders. At Frito-Lay plants, for example, the production goal is 20 percent. This target stimulates both equipment operators and supervisors to be alert for any machine conditions that should be improved. This approach tends to catch problems before they become severe, rather than allowing them to break down. The results appear to be better uptime than in plants where a similar situation does not occur.

Effectiveness

Productivity is made up of both time and rate of work. Many people confuse motion with action. Utilization, which is usually measured as percentage of productive time over total time, indicates that a person is engaged in a productive activity. Drinking coffee, reading a newspaper, and attending meetings are generally classed as nonproductive. Hands-on maintenance time is classed as productive. What appears to be useful work, however, may be repetitious, ineffective, or even a redoing of earlier mistakes.

A technical representative of a major reprographic company was observed doing preventive cleaning on a large duplicator. He spread out a paper "drop cloth" and opened the machine doors. The flat area on the bottom of the machine was obviously dirty from black toner powder, so the technical representative vacuumed it clean. Then he retracted the developer housing. That movement dropped more toner, so he vacuumed it. He removed the drum and vacuumed again. He removed the developer housing and vacuumed for the fifth time. On investigation, it was found that training had been conducted on clean equipment. No one had shown this representative the "one best way" to do the common cleaning tasks. This lack of training and on-the-job follow-up counseling is too common! To be effective, we must make the best possible use of available time. There are few motivational secrets to effective preventive maintenance, but these guidelines can help:

1. Establish inspection and preventive maintenance tasks as recognized, important parts of the maintenance program.
2. Assign competent, responsible people.
3. Follow up to ensure quality and to show everyone that management does care.
4. Publicize reduced costs with improved uptime and revenues that are the result of effective preventive activities.

Total Employee Involvement

If the only measure of our performance were the effort we exerted in our day-to-day activities, life would be simpler. Unfortunately, we are measured on the performance of those who work for us, as well as on our own effectiveness. As supervisors and managers, our success depends more on our workforce than on our own individual performance. Therefore, it is essential that each of our employees consistently performs at his or her maximum capability. Typically, employee motivation skill is not the strong suit of plant supervisors and managers, but it is essential for both plant performance and success as a manager.

By definition, motivation is getting employees to exert a high degree of effort on their jobs. The key to motivation is getting employees to want to consistently do a good job. In this light, motivation must come from within an employee, but the supervisor must create an environment that encourages motivation on the part of employees. Motivation can best be understood using the following sequence of events: needs, drives or motives, and accomplishment of goals. In this sequence, *needs* produce *motives*, which lead to the *accomplishment of goals*. *Needs* are caused by deficiencies, which can be either physical or mental. For instance, a physical need exists when a person goes without sleep for a long period. A mental need exists when a person has no friends or meaningful relationships with other people. *Motives* produce action. Lack of sleep (*the need*) activates the physical changes of fatigue (*the motive*), which produces sleep (*the accomplishment*). The accomplishment of the goal satisfies the need and reduces the motive. When the goal is reached, balance is restored.

Employee Needs. All employees have common basic needs that must be addressed by the plant or corporate culture. These needs include the following:

> *Physical needs* are the needs of the human body that must be satisfied in order to sustain life. These needs include food, sleep, water, exercise, clothing, shelter, and the like.
>
> *Safety needs* are concerned with protection against danger, threat, or deprivation. Because all employees have a dependent relationship with the organization, safety needs can be critically important. Favoritism, discrimination, and arbitrary administration of organizational policies are actions that arouse uncertainty and affect the safety needs of employees.
>
> *Social needs* include love, affection, and belonging. Such needs are concerned with establishing one's position relative to that of others. They are satisfied by developing meaningful personal relations and by acceptance into meaningful groups of individuals. Belonging to organizations and identifying with work groups are ways of satisfying the social needs in organizations.
>
> *Esteem* or ego needs include both self-esteem and the esteem of others. All people have needs for the esteem of others and for a stable, firmly based, high evaluation of themselves. The esteem needs are concerned with developing various kinds of relationships based on adequacy, independence, and giving and receiving indications of self-esteem and acceptance.
>
> *Self-actualization* or self-fulfillment is the highest order of needs. It is the need of people to reach their full potential in terms of their abilities and interests. Such needs are concerned with the will to operate at the optimum and thus receive the rewards that are the result of doing so. The rewards may not be economic and social but also mental. The needs for self-actualization and self-fulfillment are never completely satisfied.

Recognizing Needs. Every supervisor knows that some people are easier to motivate than others. Why? Are some people simply born more motivated than others? No person is exactly like another. Each individual has a unique personality and makeup. Because people are different, different factors are required to motivate different people. Not all employees expect or want the same things from their jobs. People work for different reasons. Some work because they have to work; they need money to pay bills. Others work because they want something to occupy their time. Still others work so they can have a career and its related satisfactions. Because they work for different reasons, different factors are required to motivate employees.

When attempting to understand the behavior of an employee, the supervisor should always remember that people do things for a reason. The reason may be imaginary, inaccurate, distorted, or unjustified, but it is real to the individual. The reason, whatever it may be, must be identified before the supervisor can understand the employee's behavior. Too often, the supervisor disregards an employee's reason for a certain behavior as being unrealistic or based on inaccurate information. Such a supervisor responds to the employee's reason by saying, "I don't care what he thinks—that's not the way it is!" Supervisors of this kind will probably never understand why employees behave as they do.

Another consideration in understanding the behavior of employees is the concept of the self-fulfilling prophecy, known as the Pygmalion effect. This concept refers to the tendency of an employee to live up to the supervisor's expectations. In other words, if the supervisor expects an employee to succeed, the employee will usually succeed. If the supervisor expects employees to fail, failure usually follows. The Pygmalion effect is alive and well in most plants.

When asked the question, most supervisors and managers will acknowledge that they trust a small percentage of their workforce to effectively perform any task that is assigned to them. Further, they will state that a larger percentage is not trusted to perform even the simplest task without close, direct supervision. These beliefs are exhibited in their interactions with the workforce, and each employee clearly understands where he or she fits into the supervisor's confidence and expectations as individuals and employees. The "superstars" respond by working miracles and the "dummies" continue to plod along. Obviously, this is no way to run a business, but it has become the status quo. Little, if any, effort is made to help underachievers become productive workers.

Reinforcement. Reinforced behavior is more likely to be repeated than behavior that is not reinforced. For instance, if employees are given a pay increase when their performance is high, then the employees are likely to continue to strive for high performance in hopes of getting another pay raise. Four types of reinforcement—positive, negative, extinction, and punishment—can be used.

> *Positive reinforcement* involves providing a positive consequence because of desired behavior. Most plant and corporate managers follow the *traditional motivation theory* that assumes money is the only motivator of people. Under this assumption, financial rewards are directly related to performance in the belief that employees will work harder and produce more if these rewards are great enough; however, money is not the only motivator. Although few employees will refuse to accept financial rewards, money can be a negative motivator. For example, many of the incentive bonus plans for production workers are based on total units produced within a specific time (i.e., day, week, or month). Because nothing in the incentive addresses product quality, production, or maintenance costs, the typical result of these bonus plans is an increase in scrap and total production cost.

> *Negative reinforcement* involves giving a person the opportunity to avoid a negative consequence by exhibiting a desired behavior. Both positive and

negative reinforcement can be used to increase the frequency of favorable behavior.

Extinction involves the absence of positive consequences or removing previously provided positive consequences because of undesirable behavior. For example, employees may lose a privilege or benefit, such as flextime or paid holidays, that already exists.

Punishment involves providing a negative consequence because of undesirable behavior. Both extinction and punishment can be used to decrease the frequency of undesirable behavior.

Discipline

Discipline should be viewed as a condition within an organization where employees know what is expected of them in terms of rules, standards, policies, and behavior. They should also know the consequences if they fail to comply with these criteria. The basic purpose of discipline should be to teach about expected behaviors in a constructive manner.

A formal discipline procedure begins with an oral warning and progresses through a written warning, suspension, and ultimately discharge. Formal discipline procedures also outline the penalty for each successive offense and define time limits for maintaining records of each offense and penalty. For instance, tardiness records might be maintained for only a six-month period. Tardiness before the six months preceding the offense would not be considered in the disciplinary action. Preventing discipline from progressing beyond the oral warning stage is obviously advantageous to both the employee and management. Discipline should be aimed at correction rather than punishment.

One of the most important ways of maintaining good discipline is communication. Employees cannot operate in an orderly and effective manner unless they know the rules. The supervisor has the responsibility of informing employees of these rules, regulations, and standards. The supervisor must also ensure that employees understand the purpose of these criteria. If an employee becomes lax, it is the supervisor's responsibility to remind him or her and if necessary enforce these criteria. Employees also have a responsibility to become familiar with and adhere to all published requirements of the company.

Whenever possible, counseling should precede the use of disciplinary reprimands or stricter penalties. Through counseling, the supervisor can uncover problems affecting human relations and productivity. Counseling also develops an environment of openness, understanding, and trust. This encourages employees to maintain self-discipline.

To maintain effective discipline, supervisors must always follow the rules that employees are expected to follow. There is no reason for supervisors to bend the rules for themselves or for a favored employee. Employees must realize that the rules are for everyone. It is the supervisor's responsibility to be fair toward all employees.

Although most employees do follow the organization's rules and regulations, there are times when supervisors must use discipline. Supervisors must not be afraid to use the disciplinary procedure when it becomes necessary. Employees may interpret failure to act as meaning that a rule is not to be enforced. Failure to act can also frustrate employees who are abiding by the rules. Applying discipline properly can encourage borderline employees to improve their performance.

Before supervisors use the disciplinary procedure, they must be aware of how far they can go without involving higher levels of management. They must also determine how much union participation is required. If the employee to be disciplined is a union member, the contract may specify the penalty that must be used.

Because a supervisor's decisions may be placed under critical review in the grievance process, supervisors must be careful when applying discipline. Even if there is no union agreement, most supervisors are subject to some review of their disciplinary actions. To avoid having a discipline decision rescinded by a higher level of management, it is important that supervisors follow the guidelines.

Every supervisor should become familiar with the law, union contracts, and past practices of the company as they affect disciplinary decisions. Supervisors should resolve with higher management and human resources department any questions they may have about their authority to discipline.

The importance of maintaining adequate records cannot be overemphasized. Not only is this important for good supervision, but it can also prevent a disciplinary decision from being rescinded. Written records often have a significant influence on decisions to overturn or uphold a disciplinary action. Past rule infractions and the overall performance of employees should be recorded. A supervisor bears the burden of proof when his or her decision to discipline an employee is questioned. In cases where the charge is of a moral or criminal nature, the proof required is usually the same as that required by a court of law (i.e., beyond a reasonable doubt).

Another key predisciplinary responsibility of the supervisor is the investigation. This should take place before discipline is administered. The supervisor should not discipline and then look for evidence to support the decision. What appears obvious on the surface is sometimes completely discredited by investigation. Accusations against any employee must be supported by facts. Supervisors must guard against taking hasty action when angry or when a thorough investigation has not yet been conducted. Before disciplinary action is taken, the employee's motives and reasons for rule infraction should be investigated and considered.

Conclusions

With few exceptions, employees are not self-motivated. The management philosophy and methods that are adopted by plants and individual supervisors determine whether the workforce will constantly and consistently strive for effective day-to-day performance or continue to plod along as they always have. As a supervisor or manager, it is in your best interest, as well as your duty, to provide the leadership and motivation that your workforce needs to achieve and sustain best practices and world-class performance.

16.2.4 Record Keeping

The foundation records for preventive maintenance are the equipment files. The equipment records provide information for purposes other than preventive maintenance. The essential items include:

- Equipment identification number
- Equipment name
- Equipment product/group/class
- Location
- Use meter reading
- Preventive maintenance interval(s)
- Use per day
- Last preventive maintenance due
- Next preventive maintenance due
- Cycle time for preventive maintenance
- Crafts required, number of persons, and time for each
- Parts required

Figure 16–7 shows a typical accounts cost matrix developed for a SAP R-4 computerized maintenance management system (CMMS). The figure illustrates the major cost

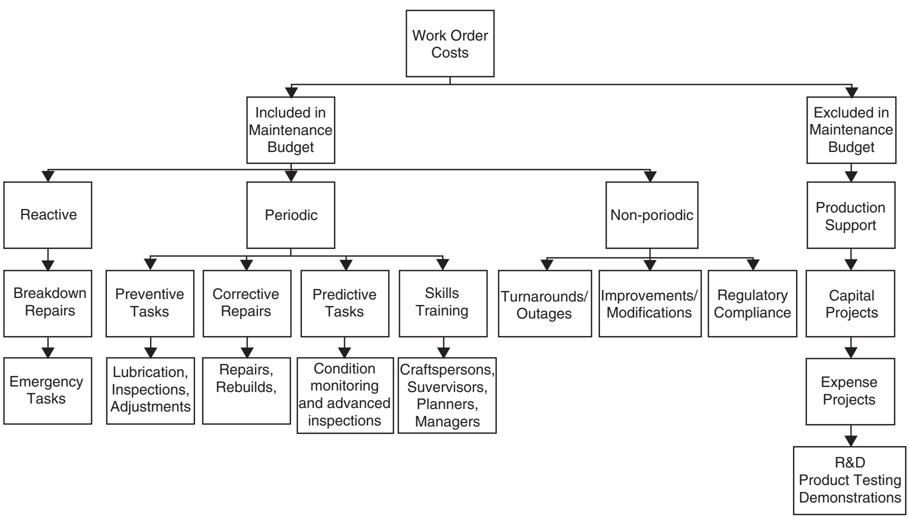


Figure 16–7 G/L accounts cost matrix.

classifications and how they will be used to support the maintenance improvement process. Date collected in the eight "cost buckets" will be used to develop performance indicators, maintenance strategy, realistic maintenance budgets, and benchmark data.

Work Orders

All work done on equipment should be recorded on the equipment record or on related work order records that can be searched by equipment. The equipment failure and repair history provide vital information for analysis to determine if preventive maintenance is effective. How much detail should be retained on each record must be individually determined for each situation. Certainly, replacement of main bearings, crankshafts, rotors, and similar long-life items that are infrequently replaced should be recorded. That knowledge is helpful for planning major overhauls both to determine what has recently been done, and therefore should not need to be done at this event, and for obtaining parts that probably should be replaced. There is certainly no need to itemize every nut, bolt, and lightbulb.

Cost Distribution

Maintenance improvement depends on the ability to accurately determine where costs are expended. Therefore, the SAP R-3 CMMS must be configured to accurately capture and compile maintenance cost by type, production area, process, and specific equipment or machinery. This task is normally accomplished by establishing a work breakdown structure that will provide a clear, concise means of reporting expenditures of maintenance dollars. Within the SAP system, cost will be allocated into the following eight classifications:

- Emergency
- Maintenance
- Repair
- Condition monitoring and inspections
- Training
- Turnarounds/shutdown
- Improvements, modifications, and technical innovations
- Regulatory compliance

Emergency. All work performed in response to actual or anticipated emergency breakdowns, OSHA-reportable incidents, and safety-related repairs will be charged to the *emergency* classification. The intent of the maintenance improvement process is to eliminate or drastically reduce the percentage of time and cost associated with this type of work. In the SAP system, these tasks and activities will be assigned priority code 1.

Maintenance. As defined as, *all activities performed in an attempt to retain an item in specified condition by providing systematic, time-based inspection and visual* *checks; any actions that are preventive of incipient failures. All work and actions are planned.* Preventive maintenance tasks, such as inspections, lubrication, calibration, and adjustments, will be allocated to this cost classification. The intent of the maintenance improvement program is to increase the efforts in this classification to between 25 and 35 percent of total maintenance costs. In the SAP system, these tasks and activities will be assigned a priority code 6.

Repair. Includes *all activities performed to restore an item to a specified condition, or any activities performed to improve equipment and its components so that preventive maintenance can be carried out reliably*. All costs associated with repair, corrective maintenance, noncapital improvements, and rebuilds will be allocated to this classification. Examples of tasks include diagnostics, remediation of damage, and follow-up work and documentation. SAP priority codes 2, 3, or 4 will be assigned to these tasks.

Condition Monitoring and Inspections. The activities are defined as *all activities involved in the use of modern signal-processing techniques to accurately diagnose the condition of equipment (level of deterioration) during operation. The periodic measurement and trending of process or machine parameters with the aim of predicting failures before they occur.* Included in these activities are visual inspection, functional testing, material testing (all NDE/NDT), inspection, and technical condition monitoring. These tasks will be assigned SAP priority code 6.

Training. This cost center is defined as *training provided to the maintenance workforce to enhance effectiveness.* Examples of costs that should be allocated to this cost center include proactive maintenance, life-cycle cost, and total cost of ownership.

Turnarounds/Shutdowns. All activities required during a planned and scheduled temporary operating unit shutdown to *maintain or restore operating efficiency, inspect equipment for purposes of mechanical or instrument/electrical integrity, and perform tests and inspections*. Examples of activities that should be allocated to this cost center include major shutdowns and modifications of industrial systems and upgrading of buildings, steel structures, and pipeline systems. These tasks will be assigned an SAP priority code 5.

Improvements, Modifications, and Technical Innovations. All activities and measures taken to improve/optimize plant performance that are not carried out as a part of a project. This would include improvements relative to efficiency, availability, or safety improvements. Also included are improvement of plant technology, adaptation to current engineering requirements and regulations, and optimization of spare and replacement parts inventory.

Regulatory Compliance. Cost for the initial actions taken to achieve compliance with regulatory, safety, environmental, or quality requirements. For example, OSHA 1910.119, ISO 9000, FDA, Kosher, and others.

Cost Accounts Not Included in Maintenance and Repair. Some maintenance-related cost classifications may be omitted from the *key performance indicators* (KPIs) used to measure maintenance effectiveness. These omissions include the following:

- Production support. *All activities required to support operations*. These tasks and activities include connections, recommendations, retrofits, and cleaning work necessitated by operations, as well as opening and closing of equipment for filling, emptying, cleaning, and filter changes required for production.
- New investment. *All activities required by in-house personnel to support capital equipment projects.* These costs should be allocated to the appropriate project cost center.
- Improve existing assets. *All activities required by in-house personnel to support expense projects.* As in the case of capital projects, these costs should be allocated to the appropriate project cost center.
- Demonstrations. *Follow the Corporate Capitalization Policy.*

16.2.5 Special Concerns

Several factors can limit the effectiveness of maintenance. The primary factors that must be considered include (1) parts availability, (2) repairable parts, (3) detailed procedures, (4) quality assurance, (5) avoiding callbacks, (6) repairs at preventive maintenance, and (7) data gathering.

Parts Availability

Parts to be used for preventive maintenance can generally be identified and procured in advance. This ability to plan for investment of dollars for parts can save on inventory costs because it is not necessary to have parts continually sitting on the shelf waiting for a failure. Instead, they can be obtained just-in-time to do the job.

The procedures should list the parts and consumable materials required. The scheduler should ensure availability of those materials before the job is scheduled. Manually checking inventory when the preventive maintenance work order is created achieves this goal. The order should be held in a “waiting for resources” status until the parts, tools, procedures, and personnel are available. Parts will usually be the missing link in those logistics requirements. The parts required should be written on a pick list or a copy of the work order given to the stock keeper. He or she should pull those parts and consolidate them into a specified pickup area. It is helpful if the stock keeper writes that bin number on the work order copy or pick list and returns it to the scheduler so that the scheduler knows a person can be assigned to the job and production can be contacted to make the equipment available, knowing that all other resources are ready. It may help to send two copies of the work order or pick list to the stock keeper so that one of them can be returned with the part confirmation and location. Then, when the craftsperson is given the work order assignment, he or she sees on the work order exactly where to go to find the parts ready for immediate use.

It can be helpful, when specific parts are often needed for preventive maintenance, to package them together in a kit. This standard selection of parts is much easier to pick, ship, and use, compared to gathering the individual items. Plugs, points, and a condenser are an example of an automobile tune-up kit, while air filters, drive belts, and disposable oilers are common with computer service representatives. Kits also make it easier to record the parts used for maintenance with less effort than the individual recording of piece parts. Any parts that are not used, either from kits or from individual draws, should be returned to the stockroom.

With a computer support system, parts availability can be automatically checked when the work order is dispatched. If the parts are not in the stockroom, the computer will indicate in a few seconds by a message on the screen that "All parts are not available; check the pick list." The pick list will show what parts are not on hand and what their status is, including availability with other personnel and quantities on order, at the receiving dock, or at the quality-control receiving inspection. The scheduler can then decide whether the parts could be obtained quickly from another source to schedule the job now, or perhaps to place the parts on order and hold the work request until the parts arrive. The parts should be identified with a work order so that receiving personnel know to expedite their inspection and shipment to the stockroom, or perhaps can be shipped directly to the requiring location.

A similar capability should be established for parts that are required to do major overhauls and unique planned jobs. Working with the equipment drawing and replaceable parts catalog, one should prepare a list of all parts that may possibly be required. Failure-rate data and predictive information from condition monitoring should be reviewed to indicate any parts with a high probability of need. Parts replaced on previous, similar work should also be reviewed—both for those that obviously must be replaced at every teardown and for those that will definitely not be replaced because they were installed the last time.

Once the list of parts needs is established, internal inventory should be checked and available parts should be staged to an area in preparation for the planned work. Special orders should be placed for the additional required parts, just as they are placed to fill any other need.

Repairable Parts

Repairable parts should receive the same kind of advance planning. If it can be afforded as a trade-off against reduced downtime, a good part should be available to install and the removed repairable parts should be rebuilt later and then restocked to inventory. If a replacement part cannot be made available, then at least all tools, fixtures, materials, and skilled personnel should be standing by when the repairable part is removed.

The condition of repairable parts, as well as those that are throwaways, should be evaluated as soon as convenient. The purpose is to measure the parameters that could lead to failure and to determine how much longer the part could be expected to operate without failure. If examination shows that considerable life is left on the part, then the preventive maintenance task or rebuild interval should be extended in the future. Removed repairable parts should be tagged to indicate why they were removed. Nothing is more frustrating to a repairperson then trying to find a defect that does not exist.

Detailed Procedures

This topic has been covered earlier but should be reemphasized to ensure that the best balance is developed between details and general functions. The following are some general guidelines:

- Common words in short sentences should be used, with a reading comprehension level no higher than seventh grade.
- Illustrations should be used where possible, especially to point out critical measurements.
- Commonly done tasks should be referred to by function, whereas those tasks that are done once a year or less frequently may be described in detail.
- Daily and weekly checklists should be protected with a transparent cover and kept on equipment.
- Inspections and maintenance done once a month or less often should be issued as specific work orders.
- The craftsperson's signature should be required on every completed job.
- Management should complete a follow-up inspection on at least a large sample of the jobs in order to ensure quality.
- Failure rates on equipment should be tracked to increase inspection and preventive maintenance on items that are failing and to decrease efforts where there is little payoff.
- What was done and how much time it took should be recorded as guidance for future work.

Quality Assurance

Quality of maintenance is a subject that requires more emphasis than it has received in the past. Like quality of any product, maintenance quality must be designed and built in. It cannot be inspected into the job.

The quality of inspection and preventive maintenance tasks starts with well-designed procedures, equipment, and a surrounding environment that is conducive to good maintenance and management emphasis. The procedures must then be followed properly, adequate time provided to the craftsperson to do the job well, and standards available with training to illustrate what is expected. There is one best way to do most inspections and preventive maintenance. That way should be detailed in a set of procedures and controlled to ensure successful completion.

First-line supervision is critical. Forepersons should spend most of their time managing their people at the work site and ensuring that customers are satisfied. It is not possible to manage preventive maintenance from behind a desk. A foreperson must get out and participate in the jobs as they are being done and inspect them on completion. This motivates people to do both high-quantity and high-quality work. The foreperson will be on the site to apply corrective action as needed and to provide final job inspection and close out the work order.

Avoiding Callbacks

"Callbacks" are generally defined as any repeat requirements for maintenance that may result from problems that should have been alleviated earlier or that were caused by earlier maintenance. Some organizations define a callback as any emergency maintenance on the same equipment within 24 hours for any reason. Other organizations narrow their definition to the same problem but within periods as long as 30 days. A measure should be chosen that suits the specific type of equipment. If your organization services for pay, you certainly should not charge additional for callback service because the problem should have been fixed the first time.

The fact remains that low-reliability people often service highly reliable equipment. Preventive maintenance often incurs exposure to potential damage. The same steps that improve quality assurance also reduce the incidence of callbacks:

1. Establish and follow detailed procedures.
2. Train and motivate persons on the importance of thorough preventive maintenance.
3. If it works, don't fix it.
4. Conduct a complete operational test after maintenance is complete.

Repairs at Preventive Maintenance

Two philosophies exist on the best way to handle repairs that are detected during preventive maintenance. One approach is to fix everything as it is discovered. The other extreme is to repair nothing but rather mark it on the work order and ensure that follow-up work orders are created. A policy that falls between the two is recommended: fix the minor things that can be most quickly done while the equipment is available, and identify other problems for separate work orders. A guideline limit of 10 minutes has proved useful to separate tasks that should be done at the time from those that should be scheduled separately. Naturally, any safety problem that is found should result in shutdown of the equipment and be repaired before the equipment is operated again. Restricting the amount of repair done on preventive maintenance work orders helps control these activities so they can stay on schedule. Table 16–3 outlines the criteria to be considered for repair with preventive versus separate repair.

It can thus be seen that a small workforce with multiskilled persons servicing equipment that requires long travel, has delay time to get on the equipment, and requires

Table 16–3 Criteria for Preventive Maintenance Repair Method

Repair Separate from PM	*Repair with PM*
Enables more accurate scheduling of PM, at consistent times.	Best if:
Allows use of inspection specialists with separate repair experts.	Equipment is difficult to get from production.
Allows parts, tools and documents to be obtained as required, instead of carrying extensive inventory.	Extensive tear down is involved that would have to be repeated for separate repairs.
	Extensive travel time is required to return to the location.
	It is difficult for the person discovering the problem to describe it to another repair person.

extensive preparation and access time should make repairs at the same time as preventive tasks. If, however, the workforce is large enough to be specialized and supports large numbers of similar equipment that are located close together, then the inspection/preventive maintenance function should be separated from repairs. In general, most manufacturing plants should do repairs separately from preventive tasks. Most field service personnel will do both at the same time.

Data Gathering

Maintenance management needs data, but maintenance personnel do not like to report data. Given this disparity between supply and demand, everything possible should be done to minimize data requirements, make data easy to obtain, and enforce accurate reporting. The main information needed from inspection and preventive activity is as follows:

- That the job was done
- Equipment used in meter reading
- Part numbers of any parts replaced
- Repair work requests to fix discovered problems
- Time involved

As preventive maintenance sophistication increases toward predictive maintenance, the test measurements should be recorded so that signature and trend analysis with control limits can be used to guide future maintenance actions.

16.3 Conclusion

The following points summarize some of the main concepts in the preceding discussions:

- Preventive maintenance is necessary for most durable hardware.
- Preventive maintenance enables *preaction*, which is better than reaction.
- It is necessary to plan.

- A good data collection and information analysis system must be established to guide efforts.
- All possible maintenance should be done at a single access.
- Safety must be regarded as paramount.
- Vital components must be inspected.
- Anything that is defective must be repaired.
- If it works, don't fix it.

17

MAINTAINING THE PROGRAM

The labor-intensive part of predictive maintenance management is complete. A viable program has been established, the database is complete, and you have begun to monitor the operating condition of your critical plant equipment. Now what?

Most programs stop right here. The predictive maintenance team does not continue its efforts to get the maximum benefits that predictive maintenance can provide. Instead it relies on trending, comparative analysis, or—in the case of vibration-based programs—simplified signature analysis to maintain the operating condition of the plant. This is not enough to gain the maximum benefits from a predictive maintenance program. In this chapter, we discuss the methods that can be used to ensure that you gain the maximum benefits from your program and improve the probability that the program will continue.

17.1 Trending Techniques

The database that was established in Chapter 5 included broadband, narrowband, and full-signature vibration data. It also included process parameters, bearing cap temperatures, lubricating oil analysis, thermal imaging, and other critical monitoring parameters. What do we do with this data?

The first method required to monitor the operating condition of plant equipment is to trend the relative condition over time. Most of the microprocessor-based systems provide the means of automatically storing and recalling vibration and process parameters trend data for analysis or hard copies for reports. They will also automatically prepare and print numerous reports that quantify the operating condition at a specific point. A few will automatically print trend reports that quantify the change over a selected time frame. All of this is great, but what does it mean?

Monitoring the trends of a machine-train or process system will provide the ability to prevent most catastrophic failures. The trend is similar to the bathtub curve used to schedule preventive maintenance. The difference between the preventive and predictive bathtub curve is that the latter is based on the actual condition of the equipment, not a statistical average.

The disadvantage of relying on trending as the only means of maintaining a predictive maintenance program is that it will not tell you the reason a machine is degrading. One good example of this weakness is an aluminum foundry that relied strictly on trending to maintain its predictive maintenance program. In the foundry are 36 cantilevered fans that are critical to plant operation. The rolling-element bearings in each of these fans are changed on an average of every six months. By monitoring the trends provided by the predictive maintenance program, the plant can adjust the bearing changeout schedule based on the actual condition of the bearings in a specific fan. Over a two-year period, no catastrophic failures or loss of production resulted from the fans being out of service. Did the predictive maintenance program work? In their terms, the program was a total success; however, the normal bearing life should have been much greater than six months. Something in the fan or process created the reduction in average bearing life. Limiting the program to trending only, the plant was unable to identify the root-cause of the premature bearing failure. Properly used, your predictive maintenance program can identify the specific or root-cause of chronic maintenance problems. In the example, a full analysis provided the answer. Plate-out or material buildup on the fan blades constantly increased the rotor mass and therefore forced the fans to operate at critical speed. The imbalance created by operation at critical speed was the forcing function that destroyed the bearings. After taking corrective actions, the plant now gets an average of three years from the fan bearings.

17.2 Analysis Techniques

All machines have a finite number of failure modes. If you have a thorough understanding of these failure modes and the dynamics of the specific machine, you can learn the vibration analysis techniques that will isolate the specific failure mode or root-cause of each machine-train problem. The following example will provide a comparison of various trending and analysis techniques.

17.2.1 Broadband Analysis

The data acquired using broadband data are limited to a value that represents the total energy that is being generated by the machine-train at the measurement point location and in the direction opposite the transducer. Most programs trend and compare the recorded value at a single point and disregard the other measurement points on the common-shaft.

Rather than evaluate each measurement point separately, plot the energy of each measurement point on a common-shaft. Figure 17–1 illustrates this technique for a

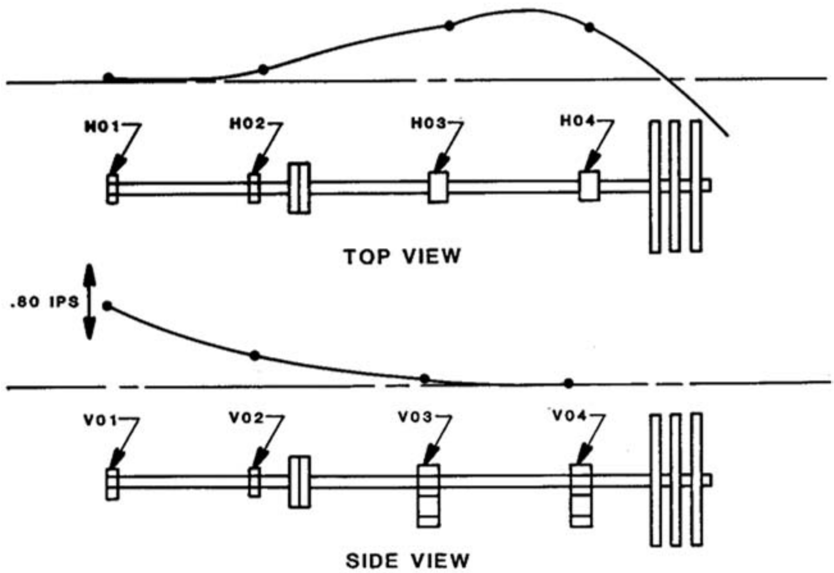


Figure 17–1 Horizontal and vertical mode shape shaft.

Hoffman blower. First, the vertical measurements were plotted to determine the mode shape of the machine's shaft. This plot indicates that the outboard end of the motor shaft is displaced much more than the remaining shaft. This limits the machine problem to the rear of the motor. Based strictly on the overall value, the probable cause is loose motor mounts on the rear motor feet. The second step was plotting the horizontal mode shape. This plot indicates that the shaft is deflected between the pillow block bearings. Without additional information, the mode shaft suggests a bent shaft between the bearings. Even though we cannot identify the absolute failure mode, we can isolate the trouble to the section of the machine-train between the pillow block bearings.

17.2.2 Narrowband Analysis

The addition of unique narrowbands that monitor specific machine components or failure modes provides more diagnostic information. If we add the narrowband information acquired from the Hoffman blower, we find that the vertical data are primarily at the true running speed of the common-shaft. This confirms that a deflection of the shaft exists. No other machine component or failure mode is contributing to the problem. The horizontal measurements indicate that the blade-pass, bearing defect, and misalignment narrowbands are the major contributors.

As we discussed, fans and blowers are prone to aerodynamic instability. The indication of abnormal vane-pass suggests that this may be contributing to the problem. The additional data provided by the narrowband readings help eliminate many of the possible failure modes that could be affecting the blower; however, we still cannot confirm the specific problem.

17.2.3 Root-Cause Failure Analysis

A visual inspection of the blower indicated that the discharge is horizontal and opposite the measurement point location. By checking the process parameters recorded concurrent with the vibration measurements, we found that the motor was in a no-load or run-out condition and that the discharge pressure was abnormally low. In addition, the visual inspection showed that the blower sits on a cork pad and is not bolted to the floor. The discharge piping, 24-inch-diameter schedule 40 pipe, was not isolated from the blower and did not have any pipe supports for the first 30 feet of horizontal run. With all of these clues in hand, we concluded that the blower was operating in a run-out condition (i.e., it was not generating any pressure) and was therefore unstable. This part of the machine problem was corrected by reducing (i.e., partially closing) the damper setting and forcing the blower to operate within acceptable aerodynamic limits.

After correcting the damper setting, all of the abnormal horizontal readings were within acceptable limits. The vertical problem with the motor was isolated to improper installation. The weight of approximately 30 feet of discharge piping compressed the cork pad under the blower and forced the outboard end of the motor to elevate above the normal centerline. In this position, the motor became an unsupported beam and resonated in the same manner as a tuning fork. After isolating the discharge piping from the blower and providing support, the vertical problem was eliminated.

If you followed the suggested steps in Chapter 5, your predictive maintenance teams receive training on how to use the predictive maintenance system or systems that were selected for your program. In addition, they have been exposed to the theory behind each of the techniques that will be used to employ the data acquired by the systems. Was it enough to gain maximum benefit from your program?

17.4 Additional Training

The initial user's training and basic theory will not be enough to gain maximum benefits from a total-plant predictive maintenance program. You will need to continue the training process throughout the life of the program.

A variety of organizations, including predictive maintenance systems vendors, provide training programs in all of the predictive maintenance techniques. Caution in selecting both the type of course and instructor is strongly recommended. Most of the public courses are in reality sales presentations. They have little practical value and will not provide the knowledge base required to gain the maximum benefit from your program.

Practical or application-oriented courses are available that will provide the additional training required to gain maximum diagnostic benefits from your program. The best way to separate the good from the bad is to ask previous attendees. Request a list of recent attendees and then talk to them. If reputable firms present the courses, they will gladly provide this information.

17.5 Technical Support

None of the predictive maintenance technologies is capable of resolving every possible problem that may develop in a manufacturing or process plant. For example, the microprocessor-based vibration systems use single-channel data collectors. These systems cannot monitor transient problems, torsional problems, and many other mechanical failures that could occur. At best, they can resolve 85 to 90 percent of the most common problems that will occur.

To resolve the other 10 to 15 percent of mechanical problems and the other nondestructive testing that may occasionally be required to maintain the plant, you will need technical support. Few of the predictive maintenance systems vendors can provide the level of support required. Therefore, you will need to establish contacts with consulting and engineering services companies that have a proven record of success in each of the areas required to support your program. Many consulting and engineering services companies offer full support to predictive maintenance. These companies specialize in the nondestructive testing and analysis techniques required to solve plant problems. Caution in selecting a technical support contractor is recommended. As in training suppliers, there are 10 bad ones for every good one.

17.6 Contract Predictive Maintenance Programs

The benefits that are derived from a total-plant predictive maintenance provide the means of controlling maintenance costs, improving plant performance, and increasing the profits of most manufacturing and production plants. Unfortunately, many plants do not have the staff to implement and maintain the regular monitoring and analysis that is required to achieve these goals. There is a solution to this problem.

The proven benefits derived from predictive maintenance and staff limitations at numerous plants have created a new type of service company. Numerous reputable companies now specialize in providing full-capability predictive maintenance services on an annual contract basis. These companies will provide all of the instrumentation, database development, data acquisition, and analysis responsibility and provide periodic reports that quantify plant condition. Using contract predictive maintenance will provide plants with all of the benefits of predictive maintenance without the major expense required to set up and maintain an in-house program.

As stated, numerous reputable companies can provide this service; however, some of these firms claim to provide full predictive maintenance services but do not actually do so. Extreme caution must be exercised in the selection process. As in the case of selecting a system and vendor for an in-house program, references should be thoroughly checked.

18

WORLD-CLASS MAINTENANCE

Good maintenance is good business. The prime motivator in manufacturing, especially as it pertains to equipment maintenance, is to keep production running in high gear. Competition mandates it. Maintenance directly affects the productivity, quality, and direct costs of production. Yet, today the most commonly practiced approach to maintenance continues to be purely reactive (i.e., an almost universal focus on equipment breakdowns). This *breakdown maintenance* mentality stands in direct opposition to the target of high productivity. The postmortem being that production stops and the maintenance department draws exceptional and unwanted visibility created by the extraordinary costs that such practices incur in terms of competitiveness and real dollars.

18.1 What Is World-Class Maintenance?

To keep production in high gear—and to survive—manufacturers are increasingly obliged to move from a breakdown maintenance mindset toward a concept of *proactive maintenance* organized around a well-trained staff, within a carefully defined plan, and with meaningful participation of employees outside of what is normally thought of as traditional maintenance. It's a move toward a total team approach of effective preventive maintenance and total quality management (TQM).

At the core of world-class maintenance is a new partnership among the manufacturing or production people, maintenance, engineering, and technical services to improve what is called *overall equipment effectiveness* (OEE). It is a program of zero breakdowns and zero defects aimed at improving or eliminating the six crippling shop-floor losses:

- Equipment breakdowns
- Setup and adjustment slowdowns
- Idling and short-term stoppages

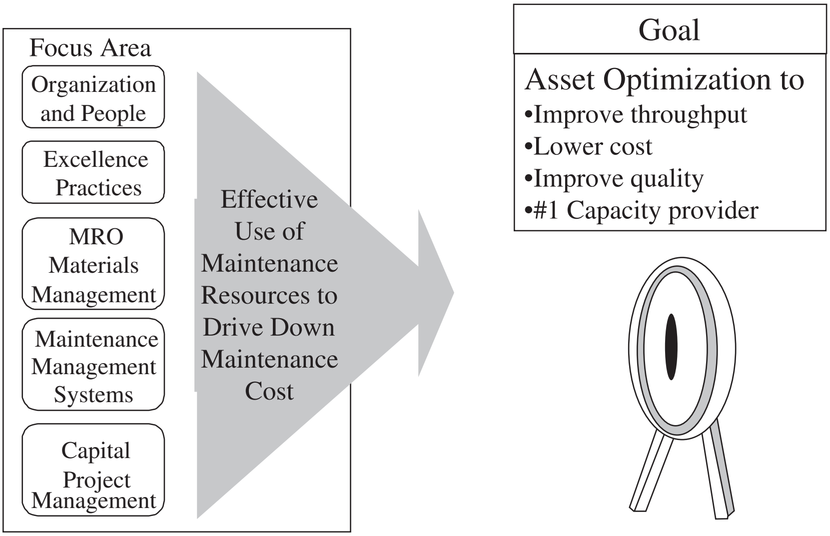


Figure 18–1 Components of world-class maintenance.

- Reduced capacity
- Quality-related losses
- Startup/restart losses

A concise definition of world-class maintenance is elusive, but improving equipment effectiveness comes close. The partnership idea is what makes it work.

18.2 Five Fundamentals of World-Class Performance

World-class maintenance stresses the basics of good business practices as they relate to the maintenance function. The five fundamentals of this approach include improving equipment effectiveness, involving operators in daily maintenance, improving maintenance efficiency and effectiveness, educating and training, and designing and managing equipment for maintenance prevention.

18.2.1 Improving Equipment Effectiveness

In other words, looking for the six big losses, finding out what causes your equipment to be ineffective, and making improvements.

18.2.2 Involving Operators in Daily Maintenance

This does not necessarily mean actually performing maintenance. In many successful programs, operators do not have to actively perform maintenance. They are involved in the maintenance activity—in the plan, in the program, in the partnership, but not necessarily in the physical act of maintaining equipment.

18.2.3 Improving Maintenance Efficiency and Effectiveness

In most world-class organizations, the operator is directly involved in some level of maintenance. This effort involves better planning and scheduling, better preventive maintenance, predictive maintenance, reliability-centered maintenance, spare parts equipment stores, tool locations—the collective domain of the maintenance department and the maintenance technologies.

18.2.4 Educating and Training

This is perhaps the most important task in the world-class approach. It involves everyone in the company: Operators are taught how to operate their machines properly and maintenance personnel to maintain them properly. Because operators will be performing some of the inspections, routine machine adjustments, and other preventive tasks, training involves teaching operators how to do those inspections and how to collaborate with maintenance. Also involved is training supervisors on how to supervise in a proactive-type team environment.

18.2.5 Designing and Managing Equipment for Maintenance Prevention

Equipment is costly and should be viewed as a productive asset for its entire life. Designing equipment that is easier to operate and maintain than previous designs is a fundamental part of proactive performance. Suggestions from operators and maintenance technicians help engineers design, specify, and procure equipment that is more effective. By evaluating the costs of operating and maintaining the new equipment throughout its life cycle, long-term costs will be minimized. Low purchase prices do not necessarily mean low life-cycle costs.

18.3 Competitive Advantage

In most companies today, management is looking for every possible competitive advantage. Companies focus on total quality (TQC, TQM), just-in-time (JIT), and total employee involvement (TEI) programs. All require complete management commitment and support to be successful. Consider the following questions regarding competition and maintenance:

- Is it possible to produce quality products on poorly maintained equipment?
- Can quality products come from equipment that is consistently out of specification or worn to the point that it cannot consistently hold tolerance?
- Can a JIT program work with equipment that is unreliable or has low availability?

- Can employee involvement programs work for long if management ignores the pleas to fix the equipment or get better equipment so a world-class product can be delivered to the customer on a timely basis, thus satisfying the employee concerns and suggestions?

Proactive maintenance management can help improve reliability, maintainability, operability, and profitability, but achieving these goals requires the talents and involvement of every employee. Through *autonomous* activities, in which the operator is involved in the daily inspection and cleaning of his or her equipment, companies will discover that the most important asset in achieving continuous improvement is people.

Companies are beginning to realize that the management techniques and methods previously used to maintain equipment are no longer sufficient to compete in world markets. Attention is beginning to focus on the benefits of proactive maintenance, yet the number of companies that have successfully implemented new maintenance management methods is relatively small. The reason is that many companies try to use tools, such as predictive maintenance, to compensate for an immature or dysfunctional maintenance operation. They fail to realize that achieving world-class performance is an evolutionary step, not a revolutionary one. To fully understand the character of world-class maintenance, it is necessary to consider the evolution of a typical quality program.

18.4 Focus on Quality

In Figure 18–2, the various stages of a quality improvement program are highlighted along the bottom of the arrow. In the early days, a company would ship almost anything to the customer. If the product did not meet customer standards, nothing was done about it until the customer complained and shipped it back; however, this approach eventually became costly when competitors would ship products that the customer would accept because there was no quality problem. Complacency

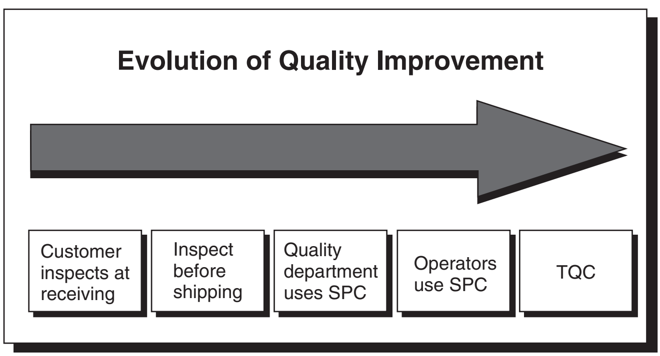


Figure 18–2 The various stages of the quality maturity continuum.

sabotaged competitiveness. To stay in the game, the company was forced to make changes in the way it did business.

The second step was to begin inspecting the product in the final production stage or in shipping just before it was loaded for delivery to the customer. Because this approach reduced the number of customer complaints, it was better than before and the company realized that it was expensive to produce a product only to reject it just before it was shipped. In effect, they were shooting themselves in the foot. It was far more economical to find the defect earlier in the process and eliminate running defective material through the rest of the production process.

This led to the third step in quality system maturity—the development of the quality department. This department's responsibility was to monitor, test, and report on the quality of the product as it passed through the plant. At first, this approach seemed to be much more effective than before, with the defects being found earlier, even to the point of statistical techniques being used to anticipate or predict when quality would be out of limits; however, there were still problems. The more samples the quality department was required to test, the longer it would take to get the results back to the operations department. It was still possible to produce minutes', hours', or even shifts' worth of product that was defective or out of tolerance before anyone called attention to the affected piece of equipment.

Solving this problem led to the fourth step—training the operators in the statistical techniques necessary to monitor and trend their own quality. In this way, the phrase "quality at the source" was coined. This step enabled the operator to know down to the individual part when it was out of tolerance, and no further defective components were produced. This approach eliminated the production of any more defects and prevented rework and expensive downstream scrap; however, circumstances beyond the control of the operator still contributed to quality problems, which led to the next step—the involvement of all departments of the company in the quality program.

From the product design phase, through the purchasing of raw materials, to final production and shipping of the product, all involved recognized that producing a quality product for the lowest price, the highest quality, and the quickest delivery was the company's goal. This meant that products were designed for productivity; the materials used to make the product had to be of the highest quality; and the production process had to be closely monitored to ensure that the final product was perfect. The company had evolved to the world-class stage of maturity.

18.5 Focus on Maintenance

How does this path to maturity relate to the path to maturity for asset or equipment maintenance? Figure 18–3 compares the two. In stage 1 of the path to world-class performance, the equipment is not maintained or repaired unless the customer (i.e., operations, production, or facilities) complains that it is broken. Only then will the

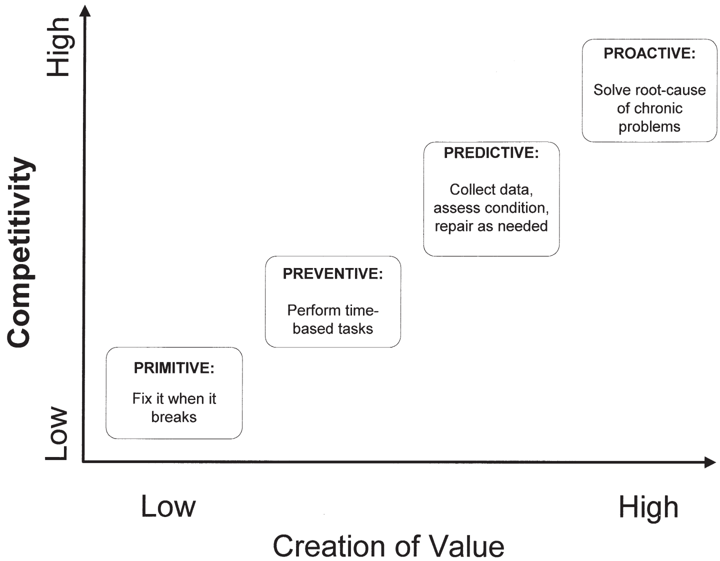


Figure 18–3 Evalution of maintenance.

maintenance organization work (or in some cases be allowed to work) on the equipment. In other words, "if it ain't broke, don't fix it."

Over time, companies began to realize that when equipment breaks down it always costs more and takes longer to fix than if it was maintained on a regularly scheduled basis. This cost is compounded when the actual cost of downtime is calculated. Companies began to question the policy, understanding that it is cost effective to allow the equipment to be shut down for shorter periods for minor service to reduce the frequency and duration of breakdowns. This leads to the second step on the road to proactive maintenance—establishing a good preventive maintenance program or building on one already in place.

This step allows for the inspection and routine servicing of the equipment before it fails and results in fewer breakdowns and equipment failures. In effect, the product is inspected before the "customer" gets it. Some of the techniques of preventive maintenance include routine lubrication and inspections for major defects.

This second step, while producing some results, is not sufficient to prevent certain types of failures. The third step, then, is to implement predictive and statistical techniques for monitoring the equipment. The most common of these techniques are the following:

- Vibration analysis
- Tribology

- Thermographic or infrared temperature monitoring
- Nondestructive testing
- Ultrasonics

The information produced from proper utilization of these techniques reduces the number of breakdowns to a low level, with overall availability being more than 90 percent. At this point, the "hidden" problems are discovered before they develop into major problems; however, the quest for continuous improvement emphasizes the need to do better. This leads to the fourth step—involvement of the operators in maintenance activities.

This step does not mean that all maintenance activities are turned over to the operators. Only the basic tasks are included, such as some inspection, basic lubrication, adjusting, and routine cleaning of equipment. The rationale for having operators involved in these activities is that they know best when something is not right with the equipment. In actual practice, the tasks they take over are the ones that the maintenance technicians have trouble finding the time to do. Freed of the burden of doing some of the more routine tasks, the maintenance technicians can concentrate on refining the predictive monitoring and trending of the equipment. They also will have more time to concentrate on equipment failure analysis, which will prevent future or repetitive problems on the equipment. This step increases not only the availability of the equipment but also reliability over its useful life.

The last step of the evolution process is involving all employees in solving equipment problems, thereby increasing equipment effectiveness. The most common method is the use of cross-functional teams formed of members from various organizational disciplines to produce total solutions for these problems. Through team-building training, the team members learn the function, need, and importance of each team member, and in a spirit of understanding and cooperation allow for production and service to reach world-class standards.

To reach these goals, certain resources must be in place or accounted for. They can be divided into three main categories: (1) management support and understanding, (2) sufficient training, and (3) allowance for sufficient time for evolution. If not in place, the lack of these resources becomes an obstacle to achieving the goals of world-class performance.

> *Management support*. Management must completely understand the true goal of the program and back it. If management begins the program by emphasizing its desire to eliminate maintenance technicians, they have failed to understand the program's true purpose. The real goal is to increase overall equipment effectiveness, not reduce the labor head-count. Without management understanding of the true goal of asset utilization, the program is doomed to failure.
>
> *Sufficient skills training*. It must be given on at least two different levels. The first addresses the increased skills required for the maintenance technicians.

The technicians will be trained in advanced maintenance techniques, such as predictive maintenance and equipment improvement. They also must have extensive training and guidance in data analysis to prepare them to find and solve equipment failure and effectiveness problems. Refresher training in the fundamentals of sound equipment maintenance methods is also considered a vital part of the program. Second, operators must be trained to do basic maintenance on their equipment in areas such as inspections, adjustments, bolt tightening, lubrication, and proper cleaning techniques. Also, before doing any repairs, operators must receive training to be certified to do the assigned tasks. Without proper training in selected skills, the equipment's effectiveness will decrease. The degree of operator involvement must also fit with the company culture. Additional training for work groups, leadership, engineers, planners, and others is a vital part of the proactive work culture.

Allowing enough time for evolution to occur. The change from a reactive program to a proactive program will take time. By some estimates, it may be a three- to five-year program to achieve a competitive position. By failing to understand this point, many managers condemn their programs to failure before they ever get started.

Successful world-class programs focus on specific goals and objectives. When the entire organization understands the goals and how they affect the company's competitiveness, the company will be successful. The five central objectives are to:

- Ensure equipment capacities.
- Develop a program of maintenance for the entire life of the equipment.
- Require support from all departments involved in the use of the equipment or facility.
- Solicit input from employees at all levels of the company.
- Use consolidated teams for continuous improvement.

Ensuring equipment capacity emphasizes that the equipment performs to specifications. It operates at its design speed, produces at the design rate, and yields a quality product at these speeds and rates. The problem is that many companies do not even know the design speed or rate of production of their equipment. This allows management to set arbitrary production quotas. A second problem is that over time, small problems cause operators to change the rate at which they run equipment. As these problems continue to build, the equipment output may be only 50 percent of what it was designed to be. This will lead to the investment of additional capital in equipment, trying to meet the required production output.

Implementing a program of maintenance for the life of the equipment is analogous to the popular preventive and predictive maintenance programs that companies presently use to maintain their equipment, but with a significant difference—it changes just as the equipment changes. All equipment requires different amounts of maintenance as it ages. A good preventive/predictive maintenance program considers these changing requirements. Monitoring failure records, trouble calls, and basic equipment conditions can help modify the program to meet the changing needs of the equipment.

A second difference is that world-class maintenance involves all employees, from shop floor to top floor. The operator may be required to perform basic inspecting, cleaning, and lubricating of the equipment, which is really the front-line defense against problems. Upper managers may be required to ensure that maintenance gets enough time and budget to properly provide any service or repairs required to keep the equipment in good condition so that it can run at design ratings. Requiring the support of all departments involved in the use of the equipment or facility will ensure full cooperation and understanding of affected departments. For example, including maintenance in equipment design/purchase decisions ensures that equipment standardization will be considered. The issues surrounding this topic alone can contribute significant cost savings to the company. Standardization reduces inventory levels, training requirements, and startup times. Proper support from stores and purchasing can help reduce downtime, but more important, it will aid in optimizing spare parts inventory levels, thus reducing on-hand inventory.

Soliciting input from employees at all levels of the company allows employees to contribute to the process. In most companies, this step takes the form of a suggestion program, but it needs to go beyond that; it should include an open-door management policy. This indicates that managers, from the front line to the top, must be open and available to listen to and consider employee suggestions. A step further is the response that should be given to each discussion. It is no longer sufficient to say “That won’t work” or “We are not considering that now.” To keep communication flowing freely, reasons must be given. It is just a matter of developing and using good communication and management skills. Without these skills, employee input will be destroyed at the outset, and the ability to capitalize on the greatest savings generator in the company will be lost.

The more open management is to the ideas of the workforce, the easier it is for teams to function. Areas, departments, lines, process, or equipment can form these teams. They will involve the operators, maintenance, and management personnel. Depending on the needs, they will involve other personnel on an as-needed basis, such as engineering, purchasing, or stores. These teams will provide answers to problems that some companies have tried to solve independently for years.

18.6 Overall Equipment Effectiveness

Overall equipment effectiveness (OEE) is the benchmark used for world-class maintenance programs. The OEE benchmark is established by measuring equipment performance. Measuring equipment effectiveness must go beyond just the availability or machine uptime. It must factor in all issues related to equipment performance. The formula for equipment effectiveness must look at the availability, the rate of performance, and the quality rate. This allows all departments to be involved in determining equipment effectiveness. The formula could be expressed as:

$$\text{Availability} \times \text{Performance Rate} \times \text{Quality Rate} = \text{OEE}$$

The availability is the required availability minus the downtime, divided by the required availability. Expressed as a formula, this would be:

$$\frac{\text{Required Availibility} - \text{Downtime}}{\text{Required Availability}} \times 100 = \text{Availability}$$

The required availability is the time production is to operate the equipment, minus the miscellaneous planned downtime, such as breaks, scheduled lapses, meetings, and so on. The downtime is the actual time the equipment is down for repairs or changeover. This is also sometimes called *breakdown downtime*. The calculation gives the true availability of the equipment. This number should be used in the effectiveness formula. The goal for most companies is greater than 90 percent.

The performance rate is the ideal or design cycle time to produce the product multiplied by the output and divided by the operating time. This will give a performance rate percentage. The formula is:

$$\frac{\text{Design Cycle Time} \times \text{Output}}{\text{Operating Time}} \times 100 = \text{Performance Rate}$$

The design cycle time or production output will be in a unit of production, such as parts per hour. The output will be the total output for the given period. The operating time will be the availability value from the previous formula. The result will be a percentage of performance. This formula is useful for spotting capacity reduction breakdowns. The goal for world-class companies is greater than 95 percent. The quality rate is the production input into the process or equipment minus the volume or number of quality defects divided by the production input. The formula is:

$$\frac{\text{Production Input} - \text{Quality Defects}}{\text{Production Input}} \times 100 = \text{Quality Rate}$$

The product input is the unit of product being fed into the process or production cycle. The quality defects are the amount of product that is below quality standards (not rejected; there is a difference) after the process or production cycle is finished. The formula is useful in spotting production-quality problems, even when the customer accepts the poor-quality product. The goal for world-class companies is higher than 99 percent. Combining the total for these goals, it is seen that:

$$90\% \times 95\% \times 99\% = 85\%$$

To be able to compete for the national total productive maintenance (TPM) prize in Japan, the equipment effectiveness must be greater than 85 percent. Unfortunately, the

Table 18–1 Twelve-Point Data Collection Process Facilitates Analysis of OEE Information

Overall Equipment Effectiveness	
1. *Planned* Time Available 8 hours × 60 minutes = 480 minutes × 15 turns or shifts	7,200 minutes
2. Planned Downtime For preventive maintenance, lunch, breaks, etc.	250 minutes
3. Net Available Run Time Item 1 – Item 2	6,950 minutes
4. Downtime Losses Breakdowns, setups, adjustments	4,640 minutes
5. Actual Operating Time Item 3 – Item 4	2,310 minutes
6. Equipment Availability $\frac{\text{Item 5}}{\text{Item 3}} \times 100$	33%
7. Total Output for Operating Time Total produced in units, pieces, tons, etc.	15,906 units
8. Design Cycle Time	0.109 minutes/unit
9. Operational Efficiency $\frac{\text{Item 8} \times \text{Item 7}}{\text{Item 5}} \times 100$	75%
10. Rejects During Turn (Shift)	558 units
11. Rate of Product Quality $\frac{\text{Item 7} - \text{Item 10}}{\text{Item 7}} \times 100$	96.8%
12. OEE Item 6 × Item 9 × Item 11	23.96%

equipment effectiveness in most U.S. companies barely breaks 50 percent. It is little wonder that there is so much room for improvement in typical equipment maintenance management programs.

A plastic injection molding plant had a press with the following statistics:

- The press was scheduled to operate 15 eight-hour shifts per week.
- This gave a total possibility of 7,200 minutes of run time per week.
- Planned downtime for breaks, lunches, and meetings totaled 250 minutes.
- The press was down for 500 minutes for maintenance for the week.
- The changeover time was 4,140 minutes for the week.
- The total output was 15,906 pieces.
- The design cycle time was 9.2 pieces per minute.
- There were 558 rejected pieces for the week.
- What is the OEE for the press for the week in question?

A form to collect and analyze OEE information is pictured in Table 18–2. The equipment availability is calculated in the first section of the form. The gross time

Table 18–2 Overlaying World-Class Standard on the Baseline Data

Overall Equipment Effectiveness	
1. Planned Time Available 8 hours × 60 minutes = 480 minutes × 15 turns or shifts	7,200 minutes
2. Planned Downtime For preventive maintenance, lunch, breaks, etc.	250 minutes
3. Net Available Run Time Item 1 − Item 2	6,950 minutes
4. Downtime Losses Breakdowns, setups, adjustments	695 minutes
5. Actual Operating Time Item 3 − Item 4	6,255 minutes
6. Equipment Availability $\frac{\text{Item 5}}{\text{Item 3}} \times 100$	90%
7. Total Output for Operating Time Total produced in units, pieces, tons, etc.	54,516 units
8. Design Cycle Time	0.109 minutes/unit
9. Operational Efficiency $\frac{\text{Item 8} \times \text{Item 7}}{\text{Item 5}} \times 100$	95%
10. Rejects During Turn (Shift)	545 units
11. Rate of Product Quality $\frac{\text{Item 7} - \text{Item 10}}{\text{Item 7}} \times 100$	99%
12. OEE Item 6 × Item 9 × Item 11	85%

available for the press is entered in line 1. The planned downtime, which involves activities that management sets a priority on and cannot be eliminated, is entered in line 2 (the 250 minutes for the week). The net available time for operation is entered in line 3 (this is actually line 1 minus line 2). The downtime losses, which are all unplanned delays, are entered in line 4. This would include maintenance delays, changeovers (which can be minimized), setups, adjustments, and so on. The actual time the press operated is entered on line 5 (this is the difference between lines 3 and 4). The equipment availability (line 6) is line 5 divided by line 3 times 100 percent.

The OEE is calculated in the next section. The total output for the operating time is entered in line 7. The actual design cycle time (this number must be accurate) is entered on line 8. The operational efficiency is calculated and entered on line 9. The operational efficiency is line 7 (the total output) times line 8 (design cycle time) divided by line 5 (the actual operating time) times 100 percent. This number should be evaluated carefully to ensure that the correct design capacity was used. If the percentage is high or exceeds 100 percent, then the wrong design capacity was probably used.

The quality rate is determined by the total output for the operating time (line 7) minus the number of rejects for the measured period (line 10) divided by the total output (line 7) times 100 percent. In the sample, the availability is 33 percent; the operational efficiency is 75 percent; and the quality rate is 96.8 percent. The OEE for the press for the week is 23.96 percent.

What do these conditions mean? What do the indicators show the typical manufacturer? The answers are evident when a second model using the same press is examined. In Table 18–2, the parameters are set at world-class standards to give an OEE of 85 percent. As can be quickly observed, the major improvement is in the total output for the operating time (line 7).

The press now will make 54,516 parts, compared to 15,348 with the 23.96 percent OEE. Because the resources to make the parts (labor and press time) are the same, it makes the company more products and ultimately more profits. With the press operating at an OEE of 85 percent, the same productivity results as if 3.5 presses were running at the 23.96 percent OEE. The potential for increased profitability and ultimate competitiveness is staggering.

Proactive maintenance can have a positive impact on any company's productivity and profitability, as long as the entire organization is willing to change its culture and the way in which day-to-day business is conducted.

18.7 Elements of Effective Maintenance

The first hurdle to overcome before pitching maintenance improvement to upper management is taking a close look at where you are now in terms of corporate culture and willingness to change. Once this has been assessed and the program's starting point set, the next hurdle is selling upper management on the long-term positive effect on the overall bottom line. It will take not only an environment in which you have the technical expertise but also a climate in which people are excited enough to become involved and want to make a contribution. Most of the ongoing improvement activities depend primarily on employee involvement and employees taking ownership of equipment and processes.

Employee empowerment and involvement are essential to effective maintenance, and it will take top management commitment, an adequate budget, and changes in corporate culture to make it happen. Unless workers are given the power to act on problems; unless they are given the opportunity to become involved; and unless they are given the authority to make things happen, total productive maintenance will be a futile effort at best.

18.7.1 Commitment

The importance of management commitment in a maintenance improvement program is that proactive maintenance is an empowering process. As such, one of the most dif-

Table 18–3 Adjusted to Physical Time Available, World-Class Is Not So Good

Overall Equipment Effectiveness	
1. Gross Time Available 8 hours × 60 minutes = 480 minutes × 21 turns or shifts	10,080 minutes
2. Planned Downtime For preventive maintenance, lunch, breaks, etc.	3,130 minutes
3. Net Available Run Time Item 1 − Item 2	6,950 minutes
4. Downtime Losses Breakdowns, setups, adjustments	695 minutes
5. Actual Operating Time Item 3 − Item 4	6,255 minutes
6. Equipment Availability $\frac{\text{Item 5}}{\text{Item 1}} \times 100$	62.1%
7. Total Output for Operating Time Total produced in units, pieces, tons, etc.	54,516 units
8. Design Cycle Time	0.109 minutes/unit
9. Operational Efficiency $\frac{\text{Item 8} \times \text{Item 7}}{\text{Item 5}} \times 100$	95%
10. Rejects During Turn (Shift)	558 units
11. Rate of Product Quality $\frac{\text{Item 7} - \text{Item 10}}{\text{Item 7}} \times 100$	96.8%
12. OEE Item 6 × Item 9 × Item 11	57.1%

ficult things to struggle with on a day-to-day basis is convincing workers that (1) they are empowered to do things that before they weren't and, (2) management is serious about change.

The problem of empowerment is one of getting the workers to test the water in order to convince them that their ideas are important, that they are now decision makers in the company, and that management is there to back them up. Management commitment can be exhibited in the following ways:

- By being accessible, on the factory floor and in the office.
- By sending improvement teams to national conferences. This sends the message that management is willing to invest in its people; production workers seldom get the opportunity to attend conferences of any kind.
- By staying involved, taking an active interest in what the improvement teams are doing on the plant floor.

- By keeping visibility high: publishing articles in company newsletters, recognizing significant achievements, keeping communication channels fluid and open, and providing the means to have workers' voices heard.
- By demonstrating that management has a team mindset, as opposed to an autocratic one.
- By providing an environment in which management is open to change and willing to permit workers to plan for and implement change.

18.7.2 Cost

Like all other programs, maintenance improvement comes with a price tag. From the very beginning, it must be impressed on senior management that launching a program will cause an initial increase in costs as a result of accelerated maintenance activities, team-building training, and technical training. Startup costs will be incurred in assessing current equipment effectiveness and *baseline* pilot equipment in the plant. Introducing the plan to the entire workforce and communicating it on a regular basis will require additional outlays for newsletters, communication centers, and the like.

But the long-term payoffs from proactive maintenance will overwhelm costs. To the extent that downtime of your equipment can be reduced, you are going to save money by keeping production running. To the extent that the performance of your equipment can be enhanced, you are going to maintain throughput, and you are going to improve product quality. To the extent that your equipment is adequately maintained, you are going to keep it in service longer and reduce your capital expenditures.

18.7.3 Culture

Company culture is one of the most critical aspects in determining if the program will be successful. The company that truly believes in using the talents of its people is more likely to have a successful maintenance improvement program than one still hanging onto the autocratic principles of *Taylorism*. Experience has shown that workers thrive on involvement in an environment where they are treated as productive individuals who have a voice in their workplace.

Productivity is fostered when management is willing to provide the latitude for people to try new things, even if they fail occasionally. Maintenance improvement requires a culture where there is a commitment to change, a commitment to ongoing improvement, and a commitment to treating each individual as a valued employee. Implementation will have a profound, positive effect on the culture of a company. It will change the culture. It will change relationships across organizations of the company. It will distribute decision making and disperse the authority base.

A definite correlation exists between management style and the culture of an organization. How people are led and managed affects how they feel about the company and how much discretionary effort they contribute. It also affects the health of the company.

Conventional practice in recent years has seen many companies restructure and downsize their operations. Those that could not compete successfully are gone. Among those that survived, there is a common denominator: all recognized that they must change, and the change involved the fundamentals of the way they conducted their businesses. In some companies, culture changed dramatically. For most, the new culture evolved. In all, a more participative climate emerged.

Buy-in by everyone in the company is central to creating a climate for proactive maintenance. Each person must recognize the need for change and be dedicated to making it happen. The need for change does not necessarily mean that the company is on the verge of going out of business. It does mean, however, that everyone in the organization must realize that changes are necessary to maintain a competitive advantage, to make the company—and themselves—prosper. Status quo must be seen as a sure way to weaken the company.

There is no magic formula for making changes, but starting at the top of the organization works best. Senior management must have a contagious vision. Each company must develop its own vision, which must be translated into strategy and tactics. Measurable goals and objectives have to be developed. Buy-in and commitment must be gained from everyone in the organization to achieve the vision and, as time goes on, the vision will need to be adjusted to meet new challenges and opportunities. This will cause further changes. This change continuum will become a way of life, because it has no end.

Indicators of successful change in organizations form around certain common characteristics. Change in this context means the company will likely succeed in implementing a strong total productive maintenance program. Some of the characteristics may not be possible in terms of what is practical, but collectively they form a good starting point for understanding where the organization of a company stands.

18.7.4 Customer Focus

The priority of everyone in the maintenance improvement program must be the internal customer. The maintenance department's customer is the machine operator. Operators expect their equipment to be serviced and repaired regularly. The operator's customer is management, who is responsible for throughput rate. This group expects equipment to have zero downtime; the manager's customer is the company's customer, who expects zero-defect products quickly and at competitive cost; the final customer is the owner/shareholder, who expects the company to be profitable and have production-ready assets.

18.7.5 Management Commitment

The bottom line is that management must “walk the talk.” Actions must be directed toward improving OEE. Management cannot vacillate in this regard; workers pick up on this and quickly assume that management is not serious.

18.7.6 Change

Change should be taking place on a wide scale. Not all change works, but people should be, and generally are, willing to try new things.

18.7.7 Management Philosophy

Old management styles should disappear and be replaced by more involvement of the workers. Empowered workers believe that they are a vital part of the company.

18.7.8 Risk Taking

Risk should be recognized as a part of the business climate. People should be able to take risks and know that they will not damage their careers. Because of this approach, problems will be solved quickly.

18.7.9 Information

There should be a good flow of information within the company. People should feel informed and trusted. They should have the information needed to do their jobs and to help in planning the future.

18.7.10 Roles

The role of each person in the company should be clearly defined. Everyone ought to be aware of where he or she must go for help or information.

18.7.11 Teamwork

The organization should foster team spirit. People working cooperatively should relax controls to permit self-direction of tasks and projects.

18.7.12 Strategy

The strategy of the company should be clearly represented in the way resources are intermeshed. Carefully planned integration of technology, organization, and people makes a strong message for the importance of each individual in the organization.

18.7.13 Tasks

The form of the organization should be flexible enough to perform various routine tasks in an effective manner.

18.7.14 Decision Making

The organization should be designed to drive decision making to the lowest level possible. Those who will be personally affected usually make the best decisions. Attention should be placed on an organization that can make decisions quickly.

18.7.15 Stability

To encourage a feeling of belonging and dedication, the organization should not be changed often without good reason. Where a change is required, extensive efforts must be made to accommodate the change and to communicate to all the rationale for the change.

18.7.16 Innovation

The organization should provide for the constant development of innovative approaches to improve, enhance, and strengthen the maintenance improvement process. Much of the grist for this development will come from the shop floor. Let it be heard and recognized.

18.7.17 Trust

The organization should promote a high degree of trust among its employees. One part of the organization must not be pitted against another in an adversarial relationship. Teamwork and cooperation must prevail throughout the organization.

18.7.18 Problem Solving

The company should have a problem-solving process that is widely understood and used. The common thread binding these characteristics of successful change is the individual worker as the focal point in a team-driven organization. By using people's talents and ideas, not just their physical abilities, a great deal of positive change can be effected.

Those involved with the equipment on a daily basis are the primary equipment stewards, or caretakers, in a proactive culture. The most receptive culture for implementation is one where people at all levels understand the business environment in which they function, why they are there, the company's mission, and what kind and level of competition they are facing or expecting to face. If the workers are prepared to make the changes necessary in terms of their work habits to ensure the long-term survival of the organization, a proactive culture is defined.

Operators have the most knowledge about how a machine or process works. They know what to do to increase the company's profitability at the shop-floor level, to make the company competitive worldwide. That's why it is absolutely essential that shop-floor workers be involved in the decision-making process, that they have the facts and information at hand to make informed choices. Armed with proper and sufficient information, workers don't have to wait to get something done. They don't have to wait for the process of going up the ladder and then back down. They go across functions, saving a lot of time. Efficiency is the result.

18.8 Responsibilities

Too many maintenance functions continue to pride themselves on how fast they can react to a catastrophic failure or production interruption rather than on their ability to prevent these interruptions. Although few will admit their continued adherence to this breakdown mentality, most plants continue to operate in this mode. Contrary to popular belief, the role of the maintenance organization is to maintain plant equipment, not to repair it after a failure. The mission of the maintenance department in a world-class organization is to achieve and sustain optimum availability, optimum operating condition, maximum utilization of maintenance resources, optimum equipment life, minimum spares inventory, and the ability to react quickly.

18.8.1 Optimum Availability

The production capacity of a plant is partly determined by the availability of production systems and their auxiliary equipment. The primary function of the maintenance organization is to ensure that all machinery, equipment, and systems within the plant are always online and in good operating condition.

18.8.2 Optimum Operating Condition

Availability of critical process machinery is not enough to ensure acceptable plant performance levels. The maintenance organization must maintain all direct and indirect manufacturing machinery, equipment, and systems so that they will continue to be in optimum operating condition. Minor problems, no matter how slight, can result in poor product quality, reduced production speeds, or other factors that limit overall plant performance.

18.8.3 Maximum Utilization of Maintenance Resources

The maintenance organization controls a substantial part of the total operating budget in most plants. In addition to an appreciable percentage of the total-plant labor budget, the maintenance manager often controls the spare parts inventory, authorizes the use of outside contract labor, and requisitions millions of dollars in repair parts or replacement equipment. Therefore, one goal of the maintenance organization should be effective use of these resources.

18.8.4 Optimum Equipment Life

One way to reduce maintenance cost is to extend the useful life of plant equipment. The maintenance organization should implement programs that will increase the useful life of all plant assets.

18.8.5 Minimum Spares Inventory

Reductions in spares inventory should be a major objective of the maintenance organization; however, the reduction cannot impair the ability to meet goals 1 through 4. With the predictive maintenance technologies that are available today, maintenance can anticipate the need for specific equipment or parts far enough in advance to purchase them on an as-needed basis.

18.8.6 Ability to React Quickly

All catastrophic failures cannot be avoided. Therefore, the maintenance organization must maintain the ability to react quickly to unexpected failures.

18.9 Three Types of Maintenance

There are three main types of maintenance and three major divisions of preventive maintenance, as illustrated in Figure 18–4.

18.9.1 Corrective Maintenance

The little finger in the analogy to a human hand used previously in the book represents corrective (i.e., emergency, repair, remedial, unscheduled) maintenance. At present, most maintenance is corrective. Repairs will always be needed. Better improvement maintenance and preventive maintenance, however, can reduce the need for emergency corrections. A shaft that is obviously broken into pieces is relatively easy to maintain because little human decision is involved. Troubleshooting and diagnostic fault detection and isolation are major time consumers in maintenance. When the problem is obvious, it can usually be corrected easily. Intermittent failures and hidden defects are more time-consuming, but with diagnostics, the causes can be isolated and corrected. From a preventive maintenance perspective, the problems and causes that result in failures provide the targets for elimination by viable preventive maintenance. The challenge is to detect incipient problems before they lead to total failures and to correct the defects at the lowest possible cost. That leads us to the middle three fingers—the branches of preventive maintenance.

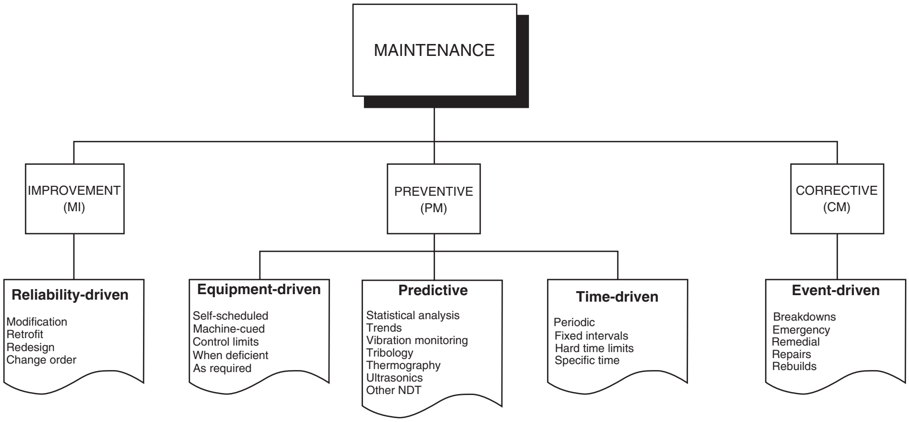


Figure 18–4 Structure of maintenance.

18.9.2 Preventive Maintenance

As the name implies, preventive maintenance tasks are intended to prevent unscheduled downtime and premature equipment damage that would result in corrective or repair activities. This maintenance management approach predominantly consists of a time-driven schedule or recurring tasks, such as lubrication and adjustments, which are designed to maintain acceptable levels of reliability and availability.

Reactive

Reactive maintenance is done when equipment needs it. Inspection using human senses or instrumentation is necessary, with thresholds established to indicate when potential problems start. Human decisions are required to establish those standards in advance so that inspection or automatic detection can determine when the threshold limit has been exceeded. Obviously, a relatively slow deterioration before failure is detectable by condition monitoring, whereas rapid, catastrophic modes of failure may not be detected. Great advances in electronics and sensor technology are being made.

Also needed is a change in the human thought process. Inspection and monitoring should disassemble equipment only when a problem is detected. The following are general rules for on-condition maintenance:

- Inspect critical components.
- Regard safety as paramount.

- Repair defects.
- If it works, don't fix it.

Condition Monitoring

Statistics and probability theory are the basis for condition-monitoring maintenance. Trend detection through data analysis often rewards the analyst with insight into the causes of failure and preventive actions that will help avoid future failures. For example, stadium lights burn out within a narrow time range. If 10 percent of the lights have burned out, it may be accurately assumed that the rest will fail soon and should, most effectively, be replaced as a group rather than individually.

Scheduled

Scheduled, fixed-interval preventive maintenance tasks should generally be used only if there is opportunity for reducing failures that cannot be detected in advance, or if dictated by production requirements. The distinction should be drawn between fixed-interval maintenance and fixed-interval inspection that may detect a threshold condition and initiate condition-monitoring tasks. Examples of fixed-interval tasks include 3,000-mile oil changes and 48,000-mile spark plug changes on a car, whether it needs the changes or not. This approach may be wasteful because all equipment and their operating environments are not alike. What is right for one situation may not be right for another.

The five-finger approach to maintenance emphasizes eliminating and reducing maintenance need wherever possible, inspecting and detecting pending failures before they happen, repairing defects, monitoring performance conditions and failure causes, and accessing equipment on a fixed-interval basis only if no better means exist.

18.9.3 Maintenance Improvement

Picture these divisions as the five fingers on your hand. Maintenance improvement efforts to reduce or eliminate the need for maintenance are like the thumb, the first and most valuable digit. We are often so involved in maintaining that we forget to plan and eliminate the need at its source. Reliability engineering efforts should emphasize elimination of failures that require maintenance. This is an opportunity to *pre-act* instead of react.

For example, many equipment failures occur at inboard bearings that are located in dark, dirty, inaccessible locations. The oiler does not lubricate inaccessible bearings as often as he or she lubricates those that are easy to reach. This is a natural tendency. One can consider reducing the need for lubrication by using permanently lubricated, long-life bearings. If that is not practical, at least an automatic oiler could be installed.

A major selling point of new automobiles is the elimination of ignition points that require replacement and adjustment, the introduction of self-adjusting brake shoes and clutches, and the extension of oil-change intervals.

18.9.4 Advantages and Disadvantages

Overall, preventive maintenance has many advantages. It is beneficial, however, to overview the advantages and disadvantages so that the positive may be improved and the negative reduced. Note that in most cases the advantages and disadvantages vary with the type of preventive maintenance tasks and techniques used. Use of on-condition or condition-monitoring techniques is usually better than fixed intervals.

Advantages

There are distinct advantages to preventive maintenance management. The primary advantages include management control, reduced overtime, smaller parts inventories, less standby equipment, better safety controls, improved quality, enhanced support to users, and better cost–benefit ratio.

Management Control. Unlike repair maintenance, which must react to failures, preventive maintenance can be planned. This means pre-active instead of reactive management. Workloads may be scheduled so that equipment is available for preventive activities at reasonable times.

Overtime. Overtime can be reduced or eliminated. Surprises are reduced. Work can be performed when convenient. Proper distribution of time-driven preventive maintenance tasks is required, however, to ensure that all work is completed quickly without excessive overtime.

Parts Inventories. Because the preventive maintenance approach permits planning, of which parts are going to be required and when, those material requirements may be anticipated to be sure they are on hand for the event. A smaller stock of parts is required in organizations that emphasize preventive tasks compared to the stocks necessary to cover breakdowns that would occur when preventive maintenance is not emphasized.

Standby Equipment. With high demand for production and low equipment availability, standby equipment is often required in case of breakdowns. Some backup may still be required with preventive maintenance, but the need and investment will certainly be reduced.

Safety and Pollution. If there are no preventive inspections or built-in detection devices, equipment can deteriorate to a point where it is unsafe or may spew forth pollutants. Performance will generally follow a sawtooth pattern, as shown in Figure 18–5, which does well after maintenance and then degrades until the failure is noticed

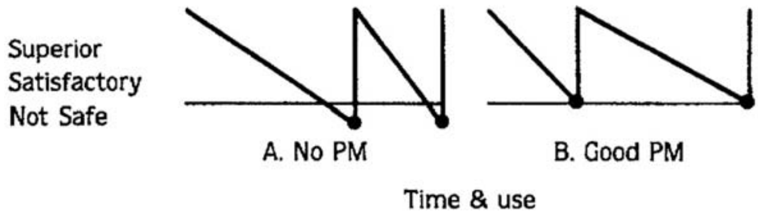


Figure 18–5 Preventive maintenance to keep acceptable performance.

and brought back up to a high level. A good detection system catches degrading performance before it ever reaches this level.

Quality. For the same general reasons discussed previously, good preventive maintenance helps ensure quality output. Tolerances are maintained within control limits. Productivity is improved, and the investment in preventive maintenance pays off with increased revenues.

Support to Users. If properly publicized, preventive maintenance tasks help show equipment operators, production managers, and other equipment users that the maintenance function is striving to provide a high level of support. Note that an effective program must be published so that everyone involved understands the value of performed tasks, the investment required, and individual roles in the system.

Cost–Benefit Ratio. Too often, organizations consider only costs without recognizing the benefit and profits that are the real goal. Preventive maintenance allows a three-way balance between corrective maintenance, preventive maintenance, and production revenues.

Disadvantages

Despite all the good reasons for doing preventive maintenance, several potential problems must be recognized and minimized.

Potential Damage. Every time a person touches a piece of equipment, damage can occur through neglect, ignorance, abuse, or incorrect procedures. Unfortunately, low-reliability people service much high-reliability equipment. The *Challenger* space shuttle failure, the Three Mile Island nuclear power plant disaster, and many less publicized accidents have been affected by inept preventive maintenance. Most of us have experienced car or home appliance problems that were caused by something that was done or not done at a previous service call. This situation results in the slogan: “If it works, don’t fix it.”

Infant Mortality. New parts and consumables have a higher probability of being defective, or failing, than the materials that are already in use. Replacement parts are too often not subjected to the same quality assurance and reliability tests as parts that are put into new equipment.

Parts Use. Replacing parts at preplanned preventive maintenance intervals, rather than waiting until a failure occurs, will obviously terminate that part's useful life before failure and therefore require more parts. This is part of the trade-off between parts, labor, and downtime, of which the cost of parts will usually be the smallest component. It must, however, be controlled.

Initial Costs. Given the time-value of money and inflation that causes a dollar spent today to be worth more than a dollar spent or received tomorrow, it should be recognized that the investment in preventive maintenance is made earlier than when those costs would be incurred if equipment were run until failure. Even though the cost will be incurred earlier, and may even be larger than corrective maintenance costs would be, the benefits in terms of equipment availability should be substantially greater from doing preventive tasks.

Access to Equipment. One of the major challenges when production is at a high rate is for maintenance to gain access to equipment in order to perform preventive maintenance tasks. This access will be required more frequently than it is with breakdown-driven maintenance. A good program requires the support of production, with immediate notification of any potential problems and a willingness to coordinate equipment availability for inspections and necessary tasks.

The reasons for and against doing preventive maintenance are summarized in the following list. The disadvantages are most pronounced with fixed-interval maintenance tasks. Reactive and condition-monitoring tasks both emphasize the positive and reduce the negatives.

Advantages

- Can be performed when convenient
- Increases equipment uptime
- Generates maximum production revenue
- Standardizes procedures, times, and costs
- Minimizes parts inventory
- Cuts overtime
- Balances workload
- Reduces need for standby equipment
- Improves safety and pollution control
- Facilitates packaging tasks and contracts
- Schedules resources on hand
- Stimulates pre-action instead of reaction
- Indicates support to user
- Ensures consistent quality
- Promotes cost–benefit optimization

Disadvantages

- Exposes equipment to possible damage
- Makes failures in new parts more likely
- Uses more parts
- Increases initial costs
- Requires more frequent access to equipment

18.10 Supervision

Supervision is the first, essential level of management in any organization. The supervisor's role is to encourage members of a work unit to contribute positively toward accomplishing the organization's goals and objectives. If you have ever attempted to introduce change or continuous improvement in your plant without the universal support of your first-line supervisors, you should understand the critical nature of this function. As the most visible level of management in any plant, front-line supervisors play a pivotal role in both existing plant performance and any attempt at change.

Although the definition is simple, the job of supervision is complex. The supervisor must learn to make good decisions, communicate well with people, make proper work assignments, delegate, plan, train people, motivate people, appraise performance, and deal with various specialists in other departments. The varied work of the supervisor is extremely difficult to master. Yet, mastery of supervision skills is vital to plant success.

Most new supervisors are promoted from the ranks. They are the best mechanicals, operators, or engineers within the organization. Employees with good technical skills and good work records are normally selected by management for supervisory positions; however, good technical skills and a good work record do not necessarily make a person a good supervisor. In fact, sometimes these attributes can act adversely to productive supervisory practices. Other skills are also required to be an effective supervisor. The complex work of supervision is often categorized into four areas, called the functions of management or the functions of supervision. These functions are planning, staffing, leading, and controlling.

18.10.1 Functions of Supervision

Planning involves determining the most effective means of achieving the work of the unit. Generally, planning includes three steps:

1. *Determining the present situation*. Assess such things as the present conditions of the equipment, the attitude of employees, and the availability of materials.
2. *Determining the objectives*. Higher levels of management usually establish the objectives for a work unit. Thus, this step is normally done for the supervisor.

3. *Determining the most effective way of attaining the objectives*. Given the present situation, what actions are necessary to reach the objectives?

Everyone follows these three steps in making personal plans; however, the supervisor makes plans not for a single person, but for a group of people. This complicates the process.

Organizing involves distributing the work among the employees in the work group and arranging the work so that it flows smoothly. The supervisor carries out the work of organizing through the general structure established by higher levels of management. Thus, the supervisor functions within the general structure and is usually given specific work assignments from higher levels of management. The supervisor then sees that the specific work assignments are completed.

Staffing is concerned with obtaining and developing good people. Because supervisors accomplish their work through others, staffing is an extremely important function. Unfortunately, first-line supervisors are usually not directly involved in hiring or selecting work group members. Normally, higher levels of management make these decisions; however, this does not remove the supervisor's responsibility to develop an effective workforce. Supervisor's are, and should be, the primary source of skills training in any organization. Because they are in proximity with their work group members, they are the logical source of on-the-job training and enforcement of universal adherence to best practices.

Leading involves directing and channeling employee behavior toward accomplishing work objectives. Because most supervisors are the best maintenance technicians or operators, the normal tendency is to lead by doing rather than by leading. As a result, the supervisor spends more time performing actual work assigned to the work group than he or she does in management activities. This approach is counterproductive in that it prevents the supervisor from accomplishing his or her primary duties. In addition, it prevents workforce development. As long as the supervisor performs the critical tasks assigned to the work group, none of its members will develop the skills required to perform these recurring tasks.

Controlling determines how well the work is being done compared with what was planned. This involves measuring actual performance against planned performance and taking any necessary corrective actions.

An effective supervisor will spend most of each workday in the last two categories. The supervisor must perform all of the functions to be effective, but most of his or her time must be spent on the plant floor directly leading and controlling the workforce. Unfortunately, this is not the case in many plants. Instead, the supervisor spends most of a typical workday generating reports, sitting in endless meetings, and performing a variety of other management tasks that prevent direct supervision of the workforce.

The supervisor's work can also be examined in terms of the types of skills required to be effective:

Technical skills refer to knowledge about such things as machines, processes, and methods of production or maintenance. Until recently, all supervisors were required to have a practical knowledge of each task that his or her work group was expected to perform as part of its normal day-to-day responsibility. Today, many supervisors lack this fundamental requirement.

Human relations skills refer to knowledge about human behavior and to the ability to work well with people. Few of today's supervisors have these basic skills. Although most will make a concerted attempt to learn the basic people skills that are essential to effective supervision, few are given the time to change. The company simply assigns them to supervisory roles and provides them with no training or direction in this technical area.

Administrative skills refer to knowledge about the organization and how it works—the planning, organizing, and controlling functions of supervision. Again, few companies recognize the importance of these skills and do not provide formal training for newly appointed supervisors.

Decision-making and *problem-solving skills* refer to the ability to analyze information and objectively reach logical decisions.

In most organizations, supervisors need a higher level of technical, human relations, and decision-making skills than of administrative skills. As first-line supervisors, these skills are essential for effective management.

18.10.2 Characteristics of Effective Supervision

Supervisors are successful for many reasons; however, five characteristics are critical to supervisory success:

- *Ability and willingness to delegate.* Most supervisors are promoted from operative jobs and have been accustomed to doing the work themselves. An often difficult, and yet essential, skill that such supervisors must develop is the ability or willingness to delegate work to others.
- *Proper use of authority*. Some supervisors let their newly acquired authority go to their heads. It is sometimes difficult to remember that the use of authority alone does not garner the support and cooperation of employees. Learning when *not* to use authority is often as important as learning when to use it.
- *Setting a good example*. Supervisors must always remember that the work group looks to them to set the example. Employees expect fair and equitable treatment from their supervisors. Too many supervisors play favorites and treat employees inconsistently. Government legislation has attempted to reduce this practice in some areas, but the problem is still common.

- *Recognizing the change in role*. People who have been promoted into supervision must recognize that their role has changed and that they are no longer one of the gang. They must remember that being a supervisor may require unpopular decisions. Supervisors are the connecting link between the other levels of management and the operative employees and must learn to represent both groups.
- *Desire for the job*. Many people who have no desire to be supervisors are promoted into supervision merely because of their technical skills. Regardless of one's technical skills, the desire to be a supervisor is necessary for success. That desire encourages a person to develop the other types of skills necessary in supervision—human relations, administrative, and decision-making skills.

18.10.3 Working without Supervision

There is a growing trend in U.S. industry to eliminate the supervisor function. Instead, more plants are replacing this function with self-directed teams, using a production supervisor to oversee maintenance, or using hourly workers to direct the work function. Each of these methods can provide some level of work direction, but all eliminate many of the critical functions that should be provided by the first-line supervisor.

Self-Directed Teams

This approach is an adaptation of the Japanese approach to management. The functional responsibilities of day-to-day plant operation are delegated to individual groups of employees. Each team is then required to develop the methods, performance criteria, and execution of their assigned tasks. The team decides how the work is to be accomplished, who will perform required tasks, and the sequence of execution. All decisions require a consensus of the team members.

In some environments, this approach can be successful; however, the absence of a clearly defined leader, mentor, and enforcer can severely limit the team's effectiveness. By nature, any process that requires majority approval of actions taken is slow and inefficient. This is especially true of the self-directed work team. Composition of the work team is also critical to success. Typically, one of three scenarios takes place. Some teams have a single, strong individual who in effect makes all team decisions. This individual controls the decision process and the team always adopts his or her ideas. The second scenario is a team with two or more natural leaders. In this team composition, the strong members must agree on direction before any consensus can be reached. In many cases, the team is forced into inaction simply because disagreement exists among the strongest team members. The third team composition is one without any strong-willed members. Generally, this type of group founders and little, if any, productive work is provided. Regardless of the team composition, this attempt to replace first-line supervisors severely limits plant performance.

Cross-Functional Supervision

A common approach to the reduction in first-line supervisors is to use production supervisors to oversee maintenance personnel. This is especially true on back-turns (i.e., second and third shifts). In most plants, maintenance personnel are assigned to these shifts simply as insurance in case something breaks down. Because of this understood mission, these work periods tend to yield low productivity from the assigned maintenance personnel. Therefore, first-line supervision that can ensure maximum productivity from these resources is essential. The companies who recognize this fact are attempting to resolve the need for direct supervision and still reduce what is viewed as nonrevenue overhead (supervisors) by assigning a production supervisor to oversee back-turn maintenance personnel.

One of the fundamental requirements of an effective supervisor is his or her knowledge of the work to be performed. In most cases, production supervisors have little, if any, knowledge or understanding of maintenance. Moreover, they have little interest or desire to ensure that critical plant systems are properly maintained. The normal result of this type of supervision is that nothing, with the possible exception of emergencies, is accomplished during these extended work periods. The maintenance personnel assigned to the back-turns simply sit in the break room waiting for something to malfunction.

Hourly Workers as Team Leaders

With few exceptions, this is the most untenable approach to supervisor-less operation. In this scenario, hourly workers are assigned the responsibility of first-line supervision. This responsibility is typically in addition to their normal work assignments as an operator or maintenance craftsperson. I cannot think of any position in corporate America that is more unfair or has the least chance of success.

If you were in the military, this position is similar to a Warrant Officer in the Army. Real officers look down on them, but expect them to produce results; noncommissioned officers view them with total disdain; and soldiers treat them with less respect than officers from higher ranks. They simply cannot win.

It is the same with the team leader concept. Senior management expects the team leader to provide effective leadership, enforce discipline, and perform all of the other duties normally assigned to a first-line supervisor; hourly workers tend to either treat the team leader as "one of them" or totally ignore their direction. The team leader is truly a pariah; he or she does not belong to the management team or the hourly workforce. They are caught in purgatory, disliked by both management and their peers.

The common problem with these attempts to replace first-line supervision is the lack of training and infrastructure support that is essential to effective performance. As is the case in most functions within a plant or corporation, employees are simply not provided with the skills essential to the successful completion of assigned tasks.

Combine this with corporate policies and procedures that do not provide clear, universal direction for the day-to-day operation of the plant, and the potential for success is nil.

18.11 Standard Procedures

First, we should define the term *standard procedure*. The concept of using standards is predicated on the assumption that there is only one method for performing a specific task or work function that will yield the best results. It also assumes that a valid procedure will permit anyone with the necessary skills to correctly perform the duty or task covered by the procedure.

In the case of operations or production, there is only one correct way to operate a machine or production system. This standard operating method will yield the maximum, first-time-through prime capacity at the lowest costs. It will also ensure optimum life-cycle costs for the production system. In maintenance, there is only one correct way to lubricate, inspect, or repair a particular machine. Standard maintenance procedures are designed to provide step-by-step instructions that will ensure proper performance of the task as well as maximum reliability and life-cycle cost from the machine or system that is being repaired.

This same logic holds true for every task or duty that must be performed as part of the normal activities that constitute a business. Whether the task is to develop a business plan; hire new employees; purchase Maintenance, Repair, and Operations (MRO) spares; or any of the myriad of other tasks that make up a typical day in the life of a plant, standard procedures ensure the effectiveness of these duties.

18.11.1 Reasons for Not Using Standard Procedures

There are many reasons that standard procedures are not universally followed. Based on our experience, the predominant reason is that few plants have valid procedures. This is a two-part failure. In some plants, procedures simply do not exist. For whatever the reason, the plant has never developed procedures that are designed to govern the performance of duties by any of the functional groups within the plant. Each group or individual is free to use the methods that he or she feels most comfortable with. As a result, everyone chooses a different method for executing assigned tasks.

The second factor that contributes to this problem is the failure to update procedures to reflect changes in the operation of the business. For example, production procedures must be updated to correct for changes in products, production rates, and a multitude of other factors that directly affect the mode of operation. The same is true in maintenance. Procedures must be upgraded to correct for machine or system modifications, new operating methods, and other factors that directly affect maintenance requirements and methods.

The second major reason for not using standard procedures is the perception that "all employees know how to do their job." Over the years, hundreds of maintenance managers have reported that standard maintenance procedures are unnecessary because the maintenance craftspeople have been here for 30 years and know how to repair, lubricate, and so on. Even if this were true, maintenance craftspeople who have been in the plant for 30 years will retire soon. Will the new 18-year-old replacement know how to do the job properly?

18.11.2 Creating Standard Procedures

Creating valid standard procedures is not complicated, but it can be time and labor intensive. When you consider every recurring task that must be performed by all functional groups within a typical plant, the magnitude of the effort required to create standards may seem overwhelming; however, the long-term benefits more than justify the effort. Where do you start?

The first step in the process must be a complete duty-task analysis. This evaluation identifies and clarifies each of the recurring tasks or duties that must be performed within a specific function area, such as production or maintenance, of the plant. When complete, the results of the duty-task analysis will define task definition, frequency, and skill requirements for each of these recurring tasks.

With the data provided by the duty-task analysis, the next step is to develop best practices or standard procedures for each task. For operating and maintenance procedures, the primary reference source for this step are the operating and maintenance manuals that come with the machine or production system. These documents define the vendors' recommendations for optimum operating and maintenance methods. The second source of information is the actual design of the involved systems. Using best engineering practices as the evaluation tool, the design will define the operating envelope of each system and system component. This knowledge, combined with the vendors' manuals, provides all of the information required to develop valid standard operating and maintenance procedures.

The content of each procedure must be complete. Assume that the person (or persons) who will perform the procedure is doing it for the first time. Therefore, the procedure must include enough definition to ensure complete compliance with best practices. Because each procedure requires specific skills for proper performance, the procedure must also define the minimum skills required.

The level of detail required for a viable standard procedure will vary with the task's complexity. For example, an inspection procedure will require much less detail than one for the complete rebuild of a complex production system; however, both must have specific, clearly defined methods. In the case of an inspection, the procedure must include specific, quantifiable methods for completion. A procedure that says "inspect V-belt for proper tension" is not acceptable. Instead, the procedure should state exactly how to make the inspection as well as the acceptable range of tension. For a major repair, the procedures should include drawings, tools, safety concerns, and a step-by-step disassembly and reassembly procedure.

18.11.3 Standard Procedures Are Not Enough

Without universal adherence, standard procedures are of no value. If adherence is left to the individual operators and maintenance craftspeople, the probability of measurable benefit is low. To achieve benefit, every employee must constantly and consistently follow these procedures. The final failure of most corporations is a failure to enforce adherence to established policies and procedures. It seems to be easier to simply let everyone do his or her own thing and hope that most will choose to follow established guidelines. Unfortunately, this simply will not happen. The resultant impact on plant performance is dramatic, but few corporate or plant managers are willing to risk the disfavor of their employees by enforcing compliance.

From my viewpoint, this approach is unacceptable. The negative impact on performance created by a failure to universally follow valid procedures is so great that there can be no justification for permitting it to continue. The simple act of implementing and following standard procedures can eliminate as much as 90 percent of the reliability, capacity, and quality problems that exist in most plants. Why then, do we continue to ignore this basic premise of good business practices?

18.12 Workforce Development

When one thinks logically about the problems that limit plant and corporate performance, few could argue that improving the skills of the workforce must rank very high. Yet, few corporations address this critical issue. In most corporations, training is limited to mandated courses, such as safety and drug usage. Little, if any, of the annual budget is allocated for workforce skills training. This failure is hard to understand. It should be obvious that there is a critical need for skills improvement throughout most organizations. This fact is supported by three major factors: (1) lack of basic skills, (2) workforce maturity, and (3) unskilled workforce pool.

18.12.1 Lack of Basic Skills

Evaluations of plant organization universally identify a lack of basic skills as a major contributor to poor performance. This problem is not limited to the direct workforce but includes all levels of management as well. Few employees have the minimum skills required to effectively perform their assigned job functions.

18.12.2 Workforce Maturity

Most companies will face a serious problem within the next 5 to 10 years. Evaluations of the workforce maturity indicate that most employees will reach mandatory retirement age within this period. Therefore, these companies will be forced to replace experienced employees with new workers who lack basic skills and experience in the job functions needed.

18.12.3 Unskilled Workforce Pool

The decline in the fundamental education afforded by our education system further compounds the problem that most companies face in the workforce replacement process. Too many potential new employees lack the basic skills sets, such as reading, writing, mathematics, and so on that are fundamental requirements for all employees. This problem is not limited to primary education. Many college graduates lack a minimum level of the basic skills or practical knowledge in their field of specialty (e.g., business, engineering). If you accept these problems as facts, why not train? One of the more common reasons is a lack of funds. Many corporations face serious cash-flow problems and low profitability. As a result, they believe that training is a luxury they simply cannot afford.

Although this might sound like a logical argument, it simply is not true. Training does not require a financial investment. External funds are available from other sources that can be used to improve workforce skills. Leading the list of providers of training funds are the federal, state, and local governments. Although these funds are primarily limited to the direct workforce, grants are also available for all levels of management. In fact, government-sponsored agencies are available that will help small and medium-sized companies develop and grow.

18.12.4 Manufacturing Extension Partnership

The Manufacturing Extension Partnership (MEP) is a nationwide network of not-for-profit centers in more than 400 locations nationwide, whose sole purpose is to provide small and medium-sized manufacturers with the help they need to succeed. The centers, serving all 50 states, the District of Columbia, and Puerto Rico, are linked through the Department of Commerce's National Institute of Standards and Technology. That makes it possible for even the smallest firm to tap into the expertise of knowledgeable manufacturing and business specialists all over the United States. To date, MEP has assisted more than 62,000 firms.

Each center has the ability to assess where your company stands today, to provide technical and business solutions, to help you create successful partnerships, and to help you keep learning through seminars and training programs. The special combination of each center's local expertise and their access to national resources really makes a difference in the work that can be done for your company (www.mep.nist.gov). The primary focus of training grants is through the U.S. Department of Labor. The Job Training Partnership Act and several other federal initiatives, such as the Employment and Training Administration (ETA), have been established with the sole mission of resolving the workforce skills problem that is a universal problem in U.S. industry.

18.12.5 U.S. Department of Labor Employment and Training Administration

The ETA's mission is to contribute to the more efficient and effective functioning of the U.S. labor market by providing high-quality job training, employment, labor market information, and income maintenance services primarily through state and local workforce development systems. The ETA seeks to ensure that American workers, employers, students, and those seeking work can obtain information, employment services, and training by using federal dollars and authority to actively support the development of strong local labor markets that provide such resources (www.doleta.gov).

18.12.6 Apprenticeship Programs

Within the framework of the ETA, the U.S. Department of Labor provides apprenticeship training. The purpose of these programs, authorized by The National Apprenticeship Act of 1937, is to stimulate and assist industry in developing and improving apprenticeships and other training programs designed to provide the skills workers need to compete in a global economy. On-the-job training and related classroom instruction in which workers learn the practical and theoretical aspects of a highly skilled occupation are provided. Joint employer and labor groups, individual employers, and/or employer associations sponsor apprenticeship programs.

The Bureau of Apprenticeship and Training (BAT) registers apprenticeship programs and apprentices in 23 states and assists or oversees Apprenticeship Councils (SACs), which perform these functions in 27 states, the District of Columbia, Puerto Rico, and the Virgin Islands. The government's role is to safeguard the welfare of the apprentices, ensure the quality and equality of access, and provide integrated employment and training information to sponsors and the local employment and training community.

Job Training Partnership Act

The Job Training Partnership Act (JTPA) provides job-training services for economically disadvantaged adults and youth, dislocated workers, and others who face significant employment barriers. The act, which became effective on October 1, 1983, seeks to move jobless individuals into permanent self-sustaining employment. State and local governments, together with the private sector, have primary responsibility for development, management, and administration of training programs under JTPA (www.doleta.gov/programs/factsht/jtpa.htm).

Economic Dislocation and Worker Adjustment Assistance Act (EDWAA)

This act, as part of the JTPA, provides funds to states and local grantees so they can help dislocated workers find and qualify for new jobs. It is part of a comprehensive approach to aid workers who have lost their jobs that also includes provisions for retraining displaced workers. Workers can receive classroom, occupational skills, and/or on-the-job training to qualify for jobs that are in demand. Basic and remedial education, entrepreneurial training, and instruction in literacy or English-as-a-second-language (ESL) training may be provided.

18.12.7 Training Grants

Training grants are distributed though state and local agencies. The following list provides the initial contact point for information and applications for these funds. Note that all states do not currently participate in these federally funded programs, but most provide funds and/or other assistance for employee skills training.

ARIZONA Ms. Joni Saad Arizona State Clearinghouse 3800 N. Central Avenue Fourteenth Floor Phoenix, Arizona 85012 Telephone: (602) 280-1315 FAX: (602) 280-8144 jonis@ep.state.az.us	**ARKANSAS** Mr. Tracy L. Copeland Manager, State Clearinghouse Office of Intergovernmental Services Department of Finance and Administration 1515 W. 7th St., Room 412 Little Rock, Arkansas 72203 Telephone: (501) 682-1074 FAX: (501) 682-5206 tlcopeland@dfa.state.ar.us
CALIFORNIA Grants Coordination State Clearinghouse Office of Planning and Research 1400 10th Street, Room 121 Sacramento, California 95814 Telephone: (916) 445-0613 FAX: (916) 323-3018 No e-mail address	**DELAWARE** Executive Department Office of the Budget 540 S. Dupont Highway Suite 5 Dover, Delaware 19901 Telephone: (302) 739-3326 FAX: (302) 739-5661 No e-mail address
DISTRICT OF COLUMBIA Mr. Charles Nichols State Single Point of Contact Office of Grants Management and Development 717 14th Street, N.W. - Suite 1200 Washington, D.C. 20005 Telephone: (202) 727-1700 (direct) (202) 727-6537 (secretary) FAX: (202) 727-1617 No e-mail address	**FLORIDA** Florida State Clearinghouse Department of Community Affairs 2555 Shumard Oak Blvd. Tallahassee, Florida 32399-2100 Telephone: (850) 922-5438 FAX: (850) 414-0479 Contact: Ms. Cherie Trainor (850) 414-5495 cherie.trainor@dca.state.fl.us

Note: This list is based on the most current information provided by the states.

GEORGIA Ms. Deborah Stephens Coordinator Georgia State Clearinghouse 270 Washington Street, S.W. - 8th Floor Atlanta, Georgia 30334 Telephone: (404) 656-3855 FAX: (404) 656-7901 ssda@mail.opb.state.ga.us	**ILLINOIS** Ms. Virginia Bova, Single Point of Contact Illinois Department of Commerce and Community Affairs James R. Thompson Center 100 West Randolph, Suite 3-400 Chicago, Illinois 60601 Telephone: (312) 814-6028 FAX: (312) 814-1800
INDIANA Ms. Allison Becker State Budget Agency 212 State House Indianapolis, Indiana 46204-2796 Telephone: (317) 7221 (direct line) FAX: (317) 233-3323 No e-mail address	**IOWA** Mr. Steven R. McCann Division for Community Assistance Iowa Department of Economic Development 200 East Grand Avenue Des Moines, Iowa 50309 Telephone: (515) 242-4719 FAX: (515) 242-4809 steve.mccann.@ided.state.ia.us
KENTUCKY Mr. Kevin J. Goldsmith, Director Sandra Brewer, Executive Secretary Intergovernmental Affairs Office of the Governor 700 Capitol Avenue Frankfort, Kentucky 40601 Telephone: (502) 564-2611 FAX: (502) 564-0437 kgoldmkgosmith@mail.state.ky.us sbrewer@mail.state.ky.us	**MAINE** Ms. Joyce Benson State Planning Office 184 State Street 38 State House Station Augusta, Maine 04333 Telephone: (207) 287-3261 FAX: (207) 287-6489 joyce.benson@state.me.us
MARYLAND Ms. Linda Janey Manager, Plan & Project Review Maryland Office of Planning 301 W. Preston Street - Room 1104 Baltimore, Maryland 21201-2365 Telephone: (410) 767-4490 FAX: (410) 767-4480 linda@mail.op.state.md.us	**MICHIGAN** Mr. Richard Pfaff Southeast Michigan Council of Governments 660 Plaza Drive - Suite 1900 Detroit, Michigan 48226 Telephone: (313) 961-4266 FAX: (313) 961-4869 pfaff@semcog.org
MISSISSIPPI Ms. Cathy Mallette Clearinghouse Officer Department of Finance and Administration 550 High Street 303 Walters Sillers Building Jackson, Mississippi 39201-3087 Telephone: (601) 359-6762 FAX: (601) 359-6758 No e-mail address	**MISSOURI** Ms. Lois Pohl Federal Assistance Clearinghouse Office of Administration P.O. Box 809 Jefferson Building, Room 915 Jefferson City, Missouri 65102 Telephone: (573) 751-4834 FAX: (573) 522-4395 pohll@mail.oa.state.mo.us

Note: This list is based on the most current information provided by the states.

NEW MEXICO Mr. Nick Mandell Local Government Division Room 201 Bataan Memorial Building Santa Fe, New Mexico 87503 Telephone: (505) 827-4991 FAX: (505) 827-4984 No e-mail address	**NORTH CAROLINA** Ms. Jeanette Furney North Carolina Department of Administration 116 West Jones Street - Suite 5106 Raleigh, North Carolina 27603-8003 Telephone: (919) 733-7232 FAX: (919) 733-9571 jeanette furney@mail.doa.state.nc.us
NEVADA Department of Administration State Clearinghouse 209 E. Musser Street, Room 200 Carson City, Nevada 89710 Telephone: (702) 684-0222 FAX: (702) 684-0260 Contact: Ms. Heather Elliot (702) 684-0209 helliot@govmail.state.nv.us	**NEW HAMPSHIRE** Mr. Jeffrey H. Taylor Director, New Hampshire Office of State Planning Attn: Intergovernmental Review Process Mr. Mike Blake 2½ Beacon Street Concord, New Hampshire 03301 Telephone: (603) 271-4991 FAX: (603) 271-1728 No e-mail address
NORTH DAKOTA North Dakota Single Point of Contact Office of Intergovernmental Assistance 600 East Boulevard Avenue Department 105 Bismarck, North Dakota 58505-0170 Telephone: (701) 328-2094 FAX: (701) 328-2308 No e-mail address	**RHODE ISLAND** Mr. Kevin Nelson Review Coordinator Department of Administration Division of Planning One Capitol Hill, 4th Floor Providence, Rhode Island 02908-5870 Telephone: (401) 222-1220 (secretary) FAX: (401) 222-2093 (direct) knelson@planning.state.ri.us
SOUTH CAROLINA Ms. Omeagia Burgess State Single Point of Contact Budget and Control Board Office of State Budget 1122 Ladies Street - 12th floor Columbia, South Carolina 29201 Telephone: (803) 734-0494 FAX: (803) 734-0645 No e-mail address	**TEXAS** Mr. Tom Adams Governors Office Director, Intergovernmental Coordination P.O. Box 12428 Austin, Texas 78711 Telephone: (512) 463-1771 FAX: (512) 936-2681 tadams@governor.state.tx.us
UTAH Ms. Carolyn Wright Utah State Clearinghouse Office of Planning and Budget Room 116 State Capitol Salt Lake City, Utah 84114 Telephone: (801) 538-1535 (direct) FAX: (801) 538-1547 cwright@state.ut.us	**WEST VIRGINIA** Mr. Fred Cutlip, Director Community Development Division W. Virginia Development Office Building #6, Room 553 Charleston, West Virginia 25305 Telephone: (304) 558-4010 FAX: (304) 558-3248 fcutlip@wvdo.org

Note: This list is based on the most current information provided by the states.

WISCONSIN Mr. Jeff Smith Section Chief, Federal/State Relations Wisconsin Department of Administration 101 East Wilson Street - 6th Floor P.O. Box 7868 Madison, Wisconsin 53707 Telephone: (608) 266-0267 FAX: (608) 267-6931 sjt@doa.state.wi.us	**WYOMING** Ms. Sandy Ross State Single Point of Contact Department of Administration and Information 2001 Capitol Avenue, Room 214 Cheyenne, WY 82002 Telephone: (307) 777-5492 FAX: (307) 777-3696 srossl@missc.state.wy.us
TERRITORIES GUAM* Mr. Joseph Rivera Acting Director Bureau of Budget and Management Research Office of the Governor P.O. Box 2950 Agana, Guam 96932 Telephone: (671) 475-9411 or 9412 FAX: (671) 472-2825	**PUERTO RICO** Mr. Jose Caballero-Mercado Chairman, Puerto Rico Planning Board Federal Proposals Review Office Minillas Government Center P.O. Box 41119 San Juan, Puerto Rico 00940-119 Telephone: (787) 727-4444 (787) 723-6190 FAX: (787) 724-3270
NORTH MARIANA ISLANDS Mrs. Viginia Villagomez Acting Special Assistant Office of Management and Budget Office of the Governor Caller Box 10007 Saipan, MP 96950 Telephone: (670) 664-2265 or 2266 or 2267 FAX: (670) 664-2272	**VIRGIN ISLANDS*** Nellon Bowry Director, Office of Management and Budget #41 Norregade Emancipation Garden Station Second Floor Saint Thomas, Virgin Islands 00802 Please direct all questions and correspondence about intergovernmental review to: Linda Clarke Telephone: (809) 774-0750 FAX: (809) 776-0069

Note: This list is based on the most current information provided by the states.

Most labor agreements include a stipulation that a percentage of union dues will be set aside for employee (membership) training. In some cases, the available funds are substantial and often go unused. Although these funds are exclusively limited to the hourly workforce, they represent a real source of funding that can be effectively used to improve plant performance.

A lack of money is not the reason that corporations fail to provide the training that is sorely needed to improve workforce performance. Millions of dollars are available to fund these training programs. The sad part is that much of this available funding is not used. Corporations, for whatever reasons, fail to recognize the seriousness of this problem or to do anything about it.

18.12.8 America's Job Bank

Employees who become displaced because of layoffs, plant closures, or who simply want to seek a more rewarding position have a free resource that is also provided by the government. America's Job Bank is a partnership between the U.S. Department of Labor and the public Employment Service. The latter is a state-operated program that provides labor exchange service to employers and job seekers through a network of 1,800 offices throughout the United States.

Since 1979, the states have cooperated to exchange information that offers employers national exposure of their job openings. In the spring of 1998, the additional service of posting résumés from job seekers was initiated. Publicizing job listings on a national basis has helped employers recruit the employees needed to help their business succeed, while providing the American labor force with an increased number of opportunities to find work and realize their career goals.

The America's Job Bank computerized network links state Employment Service offices to provide job seekers with the largest pool of active job opportunities available anywhere. It also offers nationwide exposure for job seekers' résumés. Most of the jobs listed on the America's Job Bank are full-time listings and most are in the private sector. The job openings come from all over the country and represent all types of work, from professional and technical to blue collar, from management to clerical and sales. Perhaps the best feature of the America's Job Bank is that it's free. There is no charge to either the employer who lists jobs or to job seekers who use the Job Bank to obtain employment. These services are funded through the Unemployment Insurance taxes paid by employers.

دانشنامه نت

INDEX

A
Abrasion, 247
Acceleration, 131
Accelerometers, 154, 347
Acceptance testing, 115
Alert/alarm limits, 339, 345
Alignment, 314
Amplitude, 130
Analysis parameters, 344
Asset protection, 62

B
BHP, 277
BPFI, 303
BPFO, 303
BSF, 303
Backlash, 303
Ball spin frequency, 303
Ballpass frequency, inner race, 303
Ballpass frequency, outer race, 303
Bearings
  rolling element, 302
  sleeve or Babbitt, 303
Belt drives
Benefits, 60, 61
Bent shaft
Blackbody, 172
Brake horsepower, 277
Broadband, 131, 390
Broadband trending, 161, 165, 390

C
Cage defect frequency, 302
Calibration, 362
Chemical attack, 247
Compressors, 235
Computers, 340
Contamination, 203
Corrective maintenance, 46, 413
Corrosion, 247
Critical speeds, 286
Cutting wear, 206

D
Data acquisition, 327, 343
Data collection, 327
Data management, 341
Data storage, 340
Data transfer, 340
Database, 326
Degrees of freedom, 142
Displacement, 130
Displacement probes, 153, 346

E
Eddy current, 153, 346
Electric motors
Electrical testing, 112
Electro-magnetic spectrum, 176
Electro-mechanical systems, 13

Equipment reliability, 52
Emmissitivy, 172, 178

F
FTF, 302
Failure data, 51
Failure modes analysis, 285
  critical speeds, 286
  imbalance, mechanical, 288
  mechanical looseness, 290
  misalignment, 293
  modulations, 294
  process instability, 296
  resonance, 297
Failure modes, 5, 218
  baghouses, 240
  conveyors, pneumatic, 229
  conveyors, mechanical, 229
  control valves, 249
  cyclonic separators, 240
  dust collectors, 240
  fans, centrifugal, 225
  fans, positive displacement, 228
  compressors, centrifugal, 229
  compressors, positive displacement, 231
  compressors, reciprocating, 235
  gearboxes, 242
  inverters, 249
  mixers and agitators, 240
  process rolls, 241, 312
  pumps, centrifugal, 218
  pumps, positive displacement, 222
  seals and packing, 251
  steam traps, 249
Ferrography, 207
Frequency, 129
Frequency domain, 74, 101, 119, 148
Fuel dilution, 203
Fuel soot, 204
Fundamental train frequency, 302

G
Gear damage
  abrasion, 247
  chemical attack, 247
  overloading, 248
  defective gear profiles, 307
  excessive wear, 307
  cracked or broken teeth, 307
Goal and objectives, 325
Graybody, 172

H
Heat transfer concepts, 177
Host computer

I
ISO certification, 62
Imbalance, 239, 288, 320
Infrared equipment, 178
Infrared imaging, 175
Infrared technology, 15, 105, 174, 176
Infrared thermometers, 174
Impact of maintenance, 9

L
Leak detection, 116
Line scanning, 175
Lubrication, 358
Lubricating oil analysis, 202, 203

M
MTBF, 4, 72, 264
MTTF, 3
Machine dynamics, 132, 271
Machine-train, 74
Maintenance cost of, 1, 23, 408
  Impact of, 9
  management of, 2, 398, 406
  role of maintenance, 43
  types of, 45
  world-class, 394
Management support, 327, 400, 410
Mean-time-between-failure, 4, 72, 264
Mean-time-to-failure, 3
Mechanical looseness, 290
Microprocessor, 338
Misalignment, 293, 303, 321
Mode shapes, 93
Monitoring parameters, 74
  bearings, 303
  belt drives, 322
  chain drives, 78, 304
  compressors, centrifugal, 86
  compressors, reciprocating, 87
  couplings, 79
  electric motors, 75
  fans, 92
  gearboxes, 81, 306

generators, 93
process equipment, 94, 312
pumps, centrifugal, 95
pumps, positive displacement, 97
steam turbines, 77
v-belt drives, 83

N

Narrowband trending, 162, 165, 391
Narrowbands, 74, 131, 345, 391
Nitration, 204
Non-destructive testing, 6, 400

O

OEE, 8, 402
Objectives and goals, 325
Operating dynamics analysis, 14, 267
interpreting data, 281
Overall equipment effectiveness, 8, 402
Oxidation, 204

P

Particle count
Periodic motion, 125
Plant optimization, 16
Predictive maintenance, 4, 16, 115, 414
assessing the need for, 24
benefits of, 60, 64, 325
database development, 343
designing a program, 50, 208, 325
economics of, 32
functional requirements, 326, 335
getting started, 348
justifying, 29
keys to success, 330
primary uses of, 16, 61
reasons for implementation, 61
cost of, 25, 62
optimizing, 10
proper use of, 12
selecting a systems, 334
Preloads
Preventive maintenance, 3, 357, 414
calibration, 362
lubrication, 353
Process instability, 296
Process dynamics, 217, 353
Process parameters monitoring, 217, 353

Pumps
centrifugal, 218
reciprocating

R

RCM, 6, 9
RMS
Record keeping, 380
Reliability-center maintenance, 6, 9
Reliability improvement, 16
Resonance, 297, 324
Rolling fatigue, 206
Root-cause failure analysis, 392
Rotating machinery, 122
Rubbing wear, 206
Run-to-failure, 2

S

Signature analysis, 164, 344
Sliding wear, 206
Software, 341
Solids content, 204
Spectrographic analysis, 206
Standard procedures, 424

T

TAN, 204
TBN, 204
TPM, 6
Technical support, 350, 393
Tilting pad bearings
Thermography, 16, 105, 172, 354, 400
blackbody, 172
emissivity, 172, 178
instruments, 178
graybody, 172
infrared imaging, 174
infrared thermometers, 106, 175
line scanners, 106, 175
safety issues, 107, 179
uses of, 179, 182
Thermal imaging, 174
Time domain, 118, 146
Total productive maintenance, 6
Training, 7, 337, 349, 382, 392, 400
Transducers, 121, 346
Tribology, 108, 202, 355, 399
ferrography, 207
lubricating oil analysis, 108, 202, 203
uses of, 108

limitations of, 109
wear particle analysis, 205
Total acid number, 204
Total base number, 204
Total plant predictive maintenance, 70, 352

U
Ultrasonic monitoring, 111, 256, 400
types of systems, 257
limitations, 258
uses of, 256

V
Velocity, 130
Velocity transducer, 347
Vibration analysis, 72, 114, 117, 283, 399
broadband trending, 161, 165
interpretation of, 120
narrowband trending, 162, 165, 391
signature analysis, 164
technology limitations, 100
uses of, 114
Vibration-measuring equipment, 121
Vibration monitoring, 13, 99, 121, 399
Vibration sources, 122
rotating machinery, 122
reciprocating and linear, 124
Vibration theory, 125
periodic motion, 125
harmonic motion, 125, 127
non-harmonic motion, 128
Viscosity, 203
Visual inspection, 111, 259, 353
inspection methods, 260
thresholds, 263

W
Wear particle analysis, 109, 205
Wear, rolling and sliding combined
Workforce development, 426
World-class maintenance, 394

Errors & Warnings

	Severity	Description
❖	Caution	Text point size 2.5 is less than 3.0
❖	Caution	Document uses an unknown colorspace (6x)
❖	Caution	Effective resolution of color or grayscale image is larger than 400
❖	Caution	Effective resolution of single-bit black & white image is less than 800

General File Information

Item	Value
Profile	BestSetB&W
Created by	BestSet
	BestSet
PDF Version	1.3
Creation Date	July 26, 2002 - 18:55:13
Modification Date	July 26, 2002 - 20:31:8
Producer	Acrobat Distiller 4.05 for Macintosh
Creator	QuarkXPress[a]: LaserWriter 8 Z1-8.7.1
Author	g4
Title	IPM1
Filters	ASCII85Decode
	FlateDecode
Data Format	binary
Compressed	yes
Pages	438
Page Range	1 - 438

Font Information

	PostScript font name	Type	Encoding	Embed	Subset
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	MacRoman	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-Condensed	Type 1	WinAnsi	yes	yes
❖	Helvetica-Condensed-Light	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	MacRoman	yes	yes
❖	Helvetica-Condensed	Type 1	WinAnsi	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	TimesTen-Roman	Type 1	WinAnsi	yes	yes
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	MacRoman	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes

	PostScript font name	Type	Encoding	Embed	Subset
❖	Times-Roman	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Palatino-Roman	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Helvetica-Oblique	Type 1	WinAnsi	yes	yes
❖	Symbol	Type 1	Custom	yes	yes
❖	Times-Roman	Type 1	WinAnsi	yes	yes
❖	TimesTen-Italic	Type 1	WinAnsi	yes	yes
❖	TimesTen-Roman	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes

	PostScript font name	Type	Encoding	Embed	Subset
❖	Helvetica-Oblique	Type 1	WinAnsi	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	Times-Italic	Type 1	WinAnsi	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-Oblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Oblique	Type 1	WinAnsi	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	TimesTen-Italic	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	WinAnsi	yes	yes
❖	Helvetica-Condensed	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	WinAnsi	yes	yes

	PostScript font name	Type	Encoding	Embed	Subset
❖	Symbol	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	MacRoman	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	MacRoman	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	MathematicalPi-Six	Type 1	Custom	yes	yes
❖	Helvetica	Type 1	MacRoman	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	WinAnsi	yes	yes
❖	Helvetica-Oblique	Type 1	WinAnsi	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes

	PostScript font name	Type	Encoding	Embed	Subset
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Times-Italic	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	SymbolBS-I	Type 1	Custom	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Times-RomanSC	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes

	PostScript font name	Type	Encoding	Embed	Subset
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	MacRoman	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Italic	Type 1	MacRoman	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Helvetica-BoldOblique	Type 1	WinAnsi	yes	yes
❖	Helvetica-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	WinAnsi	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Times-Roman	Type 1	WinAnsi	yes	yes
❖	Helvetica-BoldOblique	Type 1	MacRoman	yes	yes
❖	Times-BoldItalic	Type 1	MacRoman	yes	yes
❖	Helvetica	Type 1	WinAnsi	yes	yes
❖	SymbolBS	Type 1	Custom	yes	yes
❖	TimesTen-Bold	Type 1	WinAnsi	yes	yes
❖	Times-Roman	Type 1	MacRoman	yes	yes
❖	Times-Bold	Type 1	WinAnsi	yes	yes

Color Information

	Item	Value
❖	ColorSpace	CMYK
❖	ColorSpace	Gray
❖	ColorSpace	Pattern
	Pattern Type	Colored Tile
❖	ColorSpace	Pattern
	Pattern Type	Colored Tile

Image Information

	Type	Color Space	Physical Res.	Effect.Res.(dpi)	Page	Angle (degrees)	Skew	Flipped	Custom Transfer	Custom Halftone	Custom BG	Custom UCR
❖	GrayScale	Gray	1090x744	300.0x300.0	4	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2224x2087	600.0x600.0	40	0.0	-	-	+	+	+	+
❖	Mask	CMYK	1907x2525	600.0x600.0	41	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2312x661	600.0x600.0	49	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2860x1570	600.0x600.0	53	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1850x740	600.0x600.0	81	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	918x843	300.1x300.1	86	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	999x780	300.0x300.0	87	0.0	-	-	+	+	+	+
❖	Mask	CMYK	5716x3838	1199.9x1199.8	89	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1059x602	300.1x300.1	91	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	2858x2406	600.0x600.0	96	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2362x1544	600.0x600.0	119	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2360x1799	600.0x600.0	120	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1129x662	400.0x400.9	126	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2244x1698	600.0x600.0	132	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1811x1858	600.0x600.0	137	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2150x1405	642.5x642.5	147	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2290x1742	600.0x600.0	149	0.0	-	-	+	+	+	+
❖	Mask	CMYK	1993x1335	600.0x600.0	150	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2325x1715	600.0x600.0	153	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2128x1265	847.3x847.2	154	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2800x2570	1199.6x1199.6	155	0.0	-	-	+	+	+	+
❖	Mask	CMYK	3591x3516	1200.0x1200.0	156	0.0	-	-	+	+	+	+
❖	Mask	CMYK	1456x1087	600.0x600.0	157	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	2600x1192	600.0x600.0	176	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1361x640	300.0x299.9	177	0.0	-	-	+	+	+	+
❖	Mask	CMYK	2685x3528	600.0x600.0	241	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	501x806	300.0x300.0	247	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	478x763	300.1x300.1	247	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	471x757	300.0x300.0	248	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	482x768	300.1x300.1	248	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	875x342	300.0x300.0	262	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	744x632	300.0x300.0	262	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1150x518	300.0x300.0	264	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1300x414	300.0x300.0	265	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1200x1578	600.0x600.0	265	0.0	-	-	+	+	+	+
❖	Mask	CMYK	3750x5582	1000.1x1000.1	359	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1464x1304	300.0x300.0	361	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	531x276	300.0x300.0	364	0.0	-	-	+	+	+	+

	Type	Color Space	Physical Res.	Effect.Res.(dpi)	Page	Angle (degrees)	Skew	Flipped	Custom Transfer	Custom Halftone	Custom BG	Custom UCR
❖	GrayScale	Gray	1204x934	300.0x300.0	364	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	945x817	300.0x300.0	374	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1063x462	300.0x300.0	374	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1300x894	300.0x300.0	391	0.0	-	-	+	+	+	+
❖	Mask	CMYK	149x300	210.7x211.2	395	0.0	-	-	+	+	+	+
❖	Mask	CMYK	4781x3808	1275.0x1275.0	399	0.0	-	-	+	+	+	+
❖	GrayScale	Gray	1181x347	300.0x300.0	417	0.0	-	-	+	+	+	+

OPI Information

Item	Value
	No OPI