# *Integrated Condition Monitoring Technologies*

**Dennis H. Shreve**
**IRD® Balancing LLC**

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# Chapter 1 – Maintenance Methods

## Introduction

In this chapter, we will review the various maintenance methodologies that are typically applied to industrial equipment. Then, we will briefly review three strategic maintenance philosophies.

There are four universally recognized maintenance methodologies in use today. They include the following:

- Failure-Based or Breakdown Maintenance (FBM)
- Scheduled or Preventive Maintenance (PM)
- Predictive Maintenance (PdM)
- Proactive Maintenance (PaM).

The three strategic maintenance philosophies to be discussed include:

- Condition-Based Maintenance (CBM)
- Reliability-Centered Maintenance (RCM)
- Total Productive Maintenance (TPM).

At the end of the chapter, we will briefly discuss the Computerized Maintenance Management System (CMMS) and its key role in maintenance activities.

## Failure-Based or Breakdown Maintenance

Breakdown Maintenance is essentially no maintenance at all. Equipment is simply allowed to operate until complete failure, or where inefficiency or product quality problems force a shutdown.

Although many machines are maintained this way, breakdown maintenance has several distinct disadvantages. First, failures can be most untimely. There is little that can be done beforehand to anticipate the tools, personnel, and replacement parts that may be required to repair the equipment and return it to service. Secondly, machines allowed to run to failure generally require more extensive repair than would have been necessary if the problem had been detected and corrected earlier. Some failures can be catastrophic, requiring total replacement of the machine. It is estimated that on average, it costs about three times more to repair a machine that has been allowed to run to total failure compared to the cost to repair the machine before failure. Catastrophic machine failure can also pose a safety problem for plant personnel. And, the added cost of lost production while the machine is out of service can be staggering. (Reference 1)

In general, breakdown maintenance should be reserved for relatively small rotating equipment (less than 5 Hp motors for example) that is non-critical in nature. The decision may also be made to allow redundant machinery to run to total failure. Any machine that has a repair cost as high or higher than its replacement cost should be allowed to fail when it represents no risk to safety, production, or product quality.

## Scheduled or Preventive Maintenance

Compared to breakdown maintenance, a program of periodic disassembly, inspection, and replacement of worn parts has the distinct advantage of lessening the frequency of breakdown repairs and also permits scheduled shutdown. Under this program of preventive maintenance (PM), each critical machine is shut down after a specified period of time or operation and partially or completely dismantled for a thorough inspection and replacement of worn parts – if any.

This approach to maintenance also has disadvantages. First of all, to periodically disassemble every critical piece of equipment in the plant can be expensive and time consuming. Secondly, the interval between periodic inspections is difficult to predict. If the program is so successful that no machinery failures occur, it may be that the interval is too short and money and production is being wasted. If the interval is too long, costly failures may still occur. (Reference 1).

Some PM is absolutely essential. Filter changes, periodic tear down of very large rotating machinery (e.g. turbines and generators), and valve seat inspections are just a few examples of necessary PM's.

## Predictive Maintenance

Predictive Maintenance (PdM) involves the trending and analysis of machinery performance and operating parameters to detect and identify developing problems before failure and extensive damage can occur. On-line detection and diagnosis of problems is obviously the most desirable way to maintain machinery. If problems can be detected early, when defects are minor and do not affect performance, and if the nature of the problem can be identified while the machine runs, the following benefits are realized:

1) Shutdown for repairs can be scheduled for a convenient time.

2) A work schedule, together with the requirements for personnel, tools, and replacement parts can be prepared before the shutdown.

3) Extensive damage resulting from forced failure can be avoided.

4) Repair time can be kept to a minimum, resulting in reduced machinery downtime.

5) Costly trial and error approaches to solve a problem can be avoided since analysis identifies the nature of the problem.

6) Machines in good operating condition can continue to run as long as no problems develop. Time and money are not wasted dismantling machines that are already operating properly. (Reference 1).

## Proactive Maintenance

Proactive Maintenance (PaM) practices focus on circumventing the failure modes of machinery and minimizing the costs to maintain equipment. There are two general areas of proactive maintenance. The first is the area of proactive skills or proactive technologies. The second is proactivity from a programmatic perspective.

### Proactive Skills and Technologies

Several proactive technologies include precision alignment, balancing, proper foundations of machinery, acceptance testing, and proper lubrication practices. These technologies go hand-in-hand with the concept of fixing a problem right the first time. Establishing precision alignment and balancing criteria for equipment and making every effort to achieve exacting standards will minimize machinery deterioration and the need to perform maintenance. Proper foundations of machinery are paramount for extended life of the equipment. Poor foundations or footing on the equipment leads to continuous flexing of the machine and excessive dynamic forces that tend to wear machine components. Acceptance testing of new and rebuilt machinery ensures that the enterprise is procuring a quality machine with no defects upon delivery and installation at the plant site. Establishing and following such acceptance criteria are a major step in becoming a world class maintenance organization.

One of the leading causes of premature bearing failure is improper lubrication practices. These include introduction of contaminants, use of improper lubricant, excessive amounts of lubricants or not enough lubricant. The bearing division of TRW states, “contamination is the number one cause of bearing damage that leads to premature removal.” Lubrication provides the separation between moving component of critical production machinery. This lubrication film thickness is said to be about 10 micrometers, the diameter of a blood cell. Along with its base function of providing friction, wear and temperature control, the lubricant also becomes a diagnostic tool.

### Proactive Measures from a Programmatic Perspective

PdM techniques can go only so far to improve equipment availability and reliability. Engineering effort is needed to investigate problems that prevent the achievement of sustained reliability. The factors that impact reliability are; design imperfections, material deficiencies, operating abuse, and improper application.

There are two key proactive measures that should be addressed from a programmatic standpoint. The first is formation of a Reliability Team consisting of representatives from production, maintenance, and engineering personnel to address the following issues:

- Root Cause Failure Analysis,
- Equipment Brand consolidation,
- Equipment Upgrade and Redesign,
- Lubricant Consolidation,
- Materials Upgrade and Standardization,
- Spare Parts Consolidation and Inventory Reduction,
- Preventative Maintenance Modification, Improvements, and Elimination,
- Maintenance and Repair Work Methods Improvements,
- Audits of Outside Vendors That Perform Rebuild Work, and
- Publication of Periodic reports on programmatic accomplishments.

A second major programmatic issue that should be addressed is the development and implementation of a detailed plan for improvement that should be updated every year that includes:

- Defined Long Term Goals,
- The Skills Needed by Maintenance Personnel,
- A Training Plan to Instill the Required and Identified Skills,
- Projections of the Number and Distribution of Maintenance Personnel,
- Mechanisms to Keep Abreast of the State of the Art in Maintenance Technologies,
- Defined and Consistent Performance Measures and Reports,
- Updates and revisions to database, alarms, etc.,
- Mechanisms for Improvement of the Inspection and Maintenance Tasks Assigned to the Production Personnel, and
- A Distinct Plan Exists to Increase Equipment Reliability.

## Summary of Predictive and Proactive Practices

Predictive and Proactive techniques work together to maximize asset life. They have great potential as quality control devices in the acceptance of new equipment installations, and as follow-up on work done by the maintenance work force. Some conditions that prevent equipment from achieving its design life are; misalignment, unbalance, soft foot, lubricant contamination, design problems, and mechanical looseness.

The key to success is the establishment of a partnership to include these techniques in procurement and performance specifications. The Reliability Manager needs to work with engineering and procurement personnel to include recommendations in procurement specifications.

## Condition-Based Maintenance (CBM)

The philosophy of Condition-Based Maintenance is a practical maintenance strategy which seeks to optimize the mix of failure-based, preventive, predictive, and proactive maintenance practices. The strategy is typically implemented by first identifying a Reliability Team that performs a qualitative assessment of plant processes and machinery to determine criticality of the assets.

Second, the team studies the equipment to identify which types of maintenance practices will be applied to each asset. Fractional horsepower motors, for instance, might simply be allowed to run to failure. Conversely, a critical machining tool or large turbine/generator set will have a full complement of PM, PdM and PaM techniques applied.

Third, a review of PM tasks should be conducted to see which activities must be conducted, which may be deferred based on machine condition, and which activities may be eliminated altogether.

Fourth, an evaluation must be performed to decide which predictive and proactive techniques to implement in-house, which to out-source, and identify those that are not applicable. Evaluations must be carried out to identify the appropriate equipment (hardware and software) and vendors, and those tools must be procured.

Finally, the Reliability Team implements the program on a building block basis – introducing new technologies and new tools as the program matures. Importantly, the team must espouse Continuous Improvement and re-evaluate the program on a semi-annual or annual basis.

## Reliability-Centered Maintenance (RCM)

Very similar to CBM, Reliability-Centered Maintenance is a technical maintenance strategy that strives to identify the appropriate methodology based on the maintenance requirements for each asset. The major difference between RCM and CBM lies in the fact that RCM employs a rigorous quantitative evaluation of equipment criticality based on identified failure modes and effects.

Once these failure modes are identified, the maintenance requirements are specified for each piece of equipment. This approach goes on to develop procedures for the conduct of PM. The RCM approach was first developed in the 1970's for application in the aircraft and nuclear power industries. The approach is well proven to develop outstanding PM procedures and achieve high reliability. In the classical RCM approach, predictive and proactive maintenance requirements are not addressed.

## Total Productive Maintenance (TPM)

Total Productive Maintenance may be thought of as a management strategy for reliability. TPM deals with the resource side of maintenance including personnel, materials, financial, and scheduling. It is a manufacturing led approach to maintenance that is typically based on the use of cross-skilled teams.

TPM seeks to improve operational efficiencies and often is measured in terms of overall equipment effectiveness (OEE). OEE is the valuable operating time of an asset or process net of downtime, speed losses and quality losses as depicted in Figure 1-1. TPM uses a continuous improvement approach to preventive and predictive maintenance and also focuses on maintenance prevention.

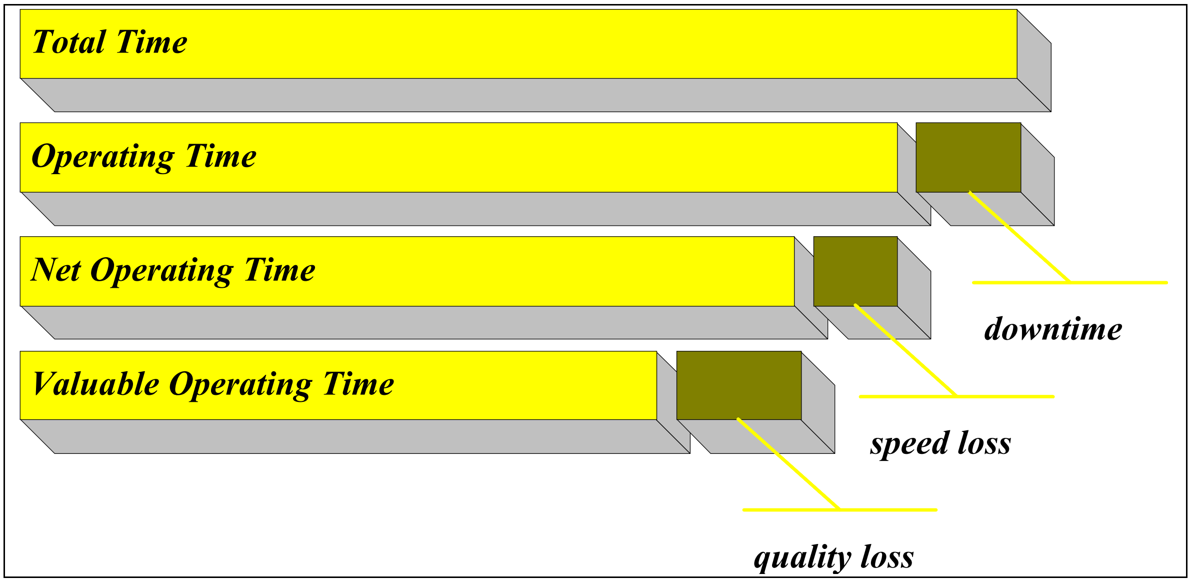


_Figure 1-1_. *Overall Equipment Effectiveness equals valuable operating time.*

## Computerized Maintenance Management Systems (CMMS)

The CMMS system is the main reliability management system. The CMMS is capable of tracking people (skills, schedules, and cost) and equipment (tools, spares, and stores). The system facilitates planning of maintenance through work request and work order management. Good CMMS practices may also lead to the equipment histories so necessary to achieve root cause failure analysis.

The CMMS system can be an invaluable source of information for financial data, equipment activity history, and metrics. A constraint to establishing a good CBM Program is often the lack of detailed equipment history. A machinery history guideline should be developed and implemented through the correct utilization of the CMMS. Storing basic information such as symptom, problem, corrective action and unusual conditions provides important historical data for future troubleshooting efforts. The machinery history must be part of the CMMS as shown in Figure 1-2 and should be integrated with the maintenance department database to ensure all pertinent information is available to the Reliability Team so they can make the best decision.

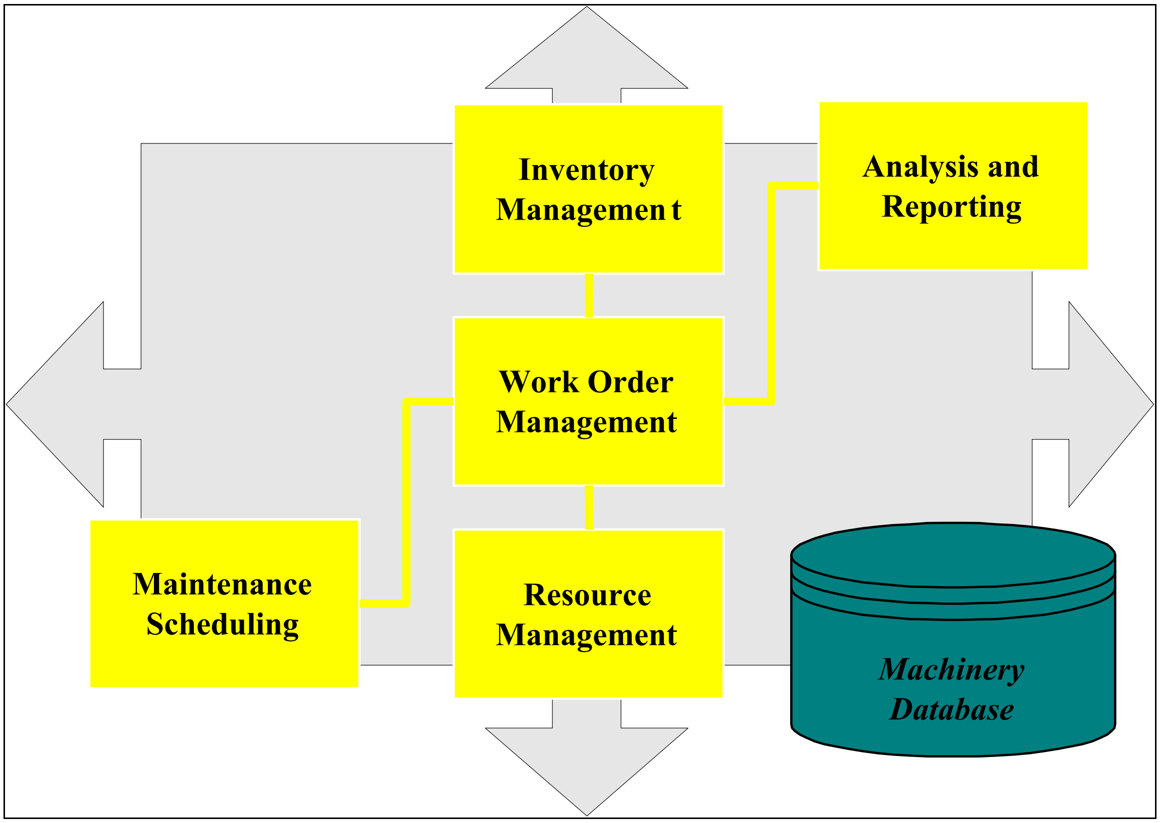


*Figure 1-2. The Computerized Maintenance Management - a lifeline to Maintenance personnel.*

## Summary - The Reliability Toolkit

CBM, RCM, TPM, and the CMMS system represent the reliability toolkit. Condition-Based Maintenance identifies the optimum mix of maintenance strategies for each asset in its operating context. Reliability-Centered Maintenance identifies the failure modes and effects and then develops the PM procedures for the equipment. Total Productive Maintenance establishes the resource requirements and seeks to continuously improve operational efficiencies. The CMMS system facilitates the maintenance planning and scheduling activities and hosts critical equipment histories, financial data, and metrics.

# Chapter 2 – Reliability Technologies

## Introduction

In this chapter, we will address many aspects of reliability and how reliability plays a key role in the various enterprises of today. The discussion will also investigate the interrelationships of the various reliability technologies and systems as enterprises seek to minimize the costs of maintenance.

## Value of Reliability

An enterprise may range from the six-year-old child's lemonade stand to a huge conglomerate consisting of dozens of manufacturing plants in various markets worldwide. There are many ways that reliability proves valuable to an industrial enterprise. Reliability can be effectively managed. Therefore, resource requirements, production rates and quality assessments may be routinely measured. By focusing on where the losses are coming from (downtime, speed, and/or quality), reliability can achieve greater throughput of product from existing assets.

Third, identifying the condition of operating machinery minimizes the risk associated with catastrophic failure and improves the asset protection capabilities of the enterprise. Reliability further allows increased product quality and consistency while reducing the production costs. Reliable systems guarantee improved product delivery to the end-user. Finally, using the effective tools, methods, and metrics available today, reliability can attain improved customer support.

As an example of improved reliability, let's take a look at a specific case history from Quantum Chemical (now EquiStar). Quantum Chemical implemented an aggressive reliability program in 1994 that targeted known performance problems with a Condition-Based Monitoring. During a two-year period, the Quantum Reliability Team earned the following achievements:

- Improved predicted equipment failures from 81% to 90.5%
- Overall equipment failures down 5%/year over 3 years
- Spare parts inventories reduced $3 million
- Overall maintenance costs reduced $10 million
- On-stream production up from 70% to 95%
- Increased prime product output by 5%.

Figure 2-1 shows the anticipated increase in maintenance budget over the two year period. The expected increase in maintenance costs due to aging equipment and inflation never materialized between 1994 and 1996. In fact, overall maintenance expenditures dropped from $128 MM in 1994 to $118 MM in 1996. This represents a non-inflation adjusted 8% decrease in actual maintenance costs and a 12% decrease from the budgeted expense.

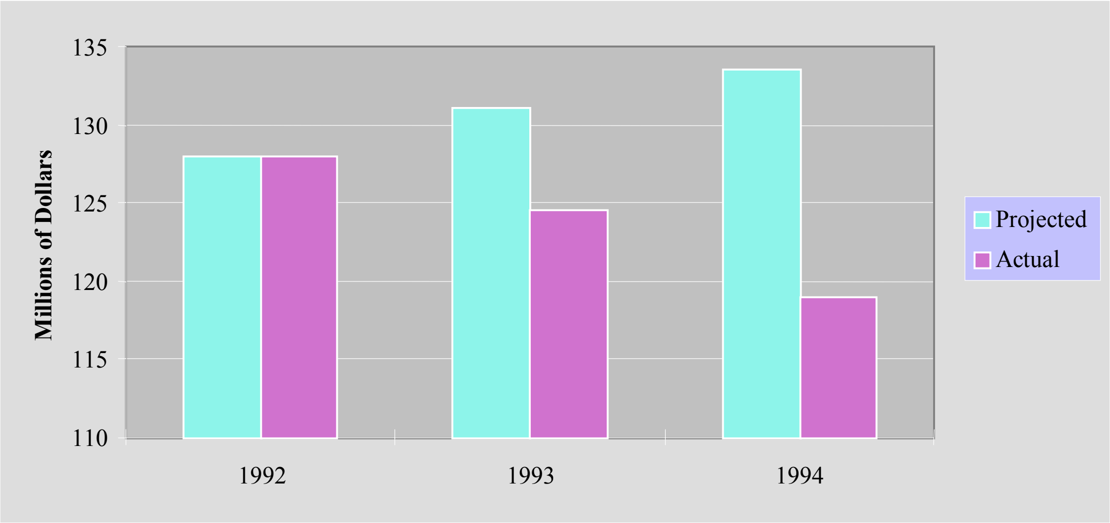


*Figure 2-1*. *Budgeted versus actual maintenance costs for Quantum Chemical after implementing CBM.*

Breakdown maintenance has been around since the Industrial Revolution brought us the age of machinery. Figure 2-2 shows how various reliability strategies have evolved through time. About 1940, the concept of inspecting and lubricating machinery became fairly commonplace. It was not until about 1950, however, that the concept of Preventive Maintenance came along. PM was a dramatic improvement over Breakdown Maintenance, and it remains a key ingredient to reliability systems today. Systematic planning and scheduling came about in the early 1960's as the early computers allowed automation of these processes. Today, CMMS systems allow very effective planning and scheduling of resources.

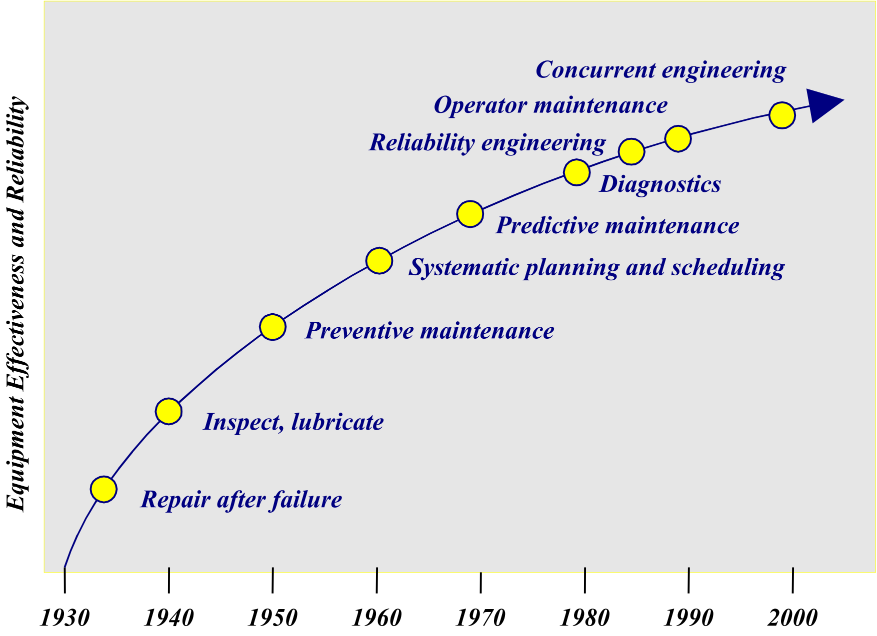


*Figure 2-2*. *The change in Reliability concepts through the century.*

During the early 70's, the concept of Predictive Maintenance became publicized. Using actual trend data to determine when machinery may have a problem had some distinct advantages of the time-based approach of PM. As the years have passed since 1970, the focus has been on better and better diagnostic evaluation tools to determine exactly what machine faults may exist at the component level. The role of the analysts in the Reliability Team is defining exactly what is wrong with a machine so that spares can be ordered, outages may be planned, and the proper tools and skilled workers can be assembled for the repair activity.

In the late 1980's, the first Reliability Engineering programs became available at some of the forward-thinking universities. Reliability engineers were sought after by enterprises looking to increase production and minimize costs. The next concept of Operator-based Maintenance came on the scene as companies looked to downsize across entire organizations. Using equipment operators to perform routine maintenance activities lessened the number of higher paid , skilled craftsmen. As we go forward into the new millenium, Concurrent Engineering activities are espoused by enterprises seeking to design out failures and lean on experience to improve designs and layouts for plants of the future.

Even with the technology and programs available today, the most typical Reliability strategy in place spends about 67% of the maintenance budget repairing breakdowns. The typical plant maintenance department is under extreme pressure to reduce direct maintenance costs, and management has a low level of awareness of the various reliability tools and systems available today. In general, fire-fighting tactics abound. The pressure is mounting and a "Do Anything" mentality reigns. The maintenance methodologies and reliability strategies can be used to improve the situation. By focusing on continuous improvement, maintenance teams will be able to reduce waste and minimize abuse on equipment.

## Enterprise Challenges and the Role of Reliability

The Information Age is well upon us now, and the ability to conduct business worldwide has never been easier. The resulting global competition demands lower cost of goods sold (COGS) and global pricing issues force the enterprise to look for more ways to cut costs. Economic prosperity and the resulting business boom have allowed industry to build newer plants with newer assets. Maintaining those assets is paramount, because of the high associated replacement costs.

Today's consumer is smarter than ever, and expectations run high from improved quality to reliable delivery. Enterprise challenges also include environmental and safety factors. Governments are forcing mandated spending on preventive environmental impact measures, clean-up practices, and safety training. With all of the challenges at hand, enterprises are forced to look for ways to increase productivity and reduce spending.

In order to cope with today's demands, enterprises are seeking to integrate and to more effectively plan resource expenditures. One goal is enhanced supply chain management in which the enterprise looks to streamline the process of procurement. One example is a plant that restricts procurement of spares and expendables to a few key vendors that can guarantee reliable, just-in-time delivery. Some vendors even become involved to the point of recommending what customers keep on-site and what is best ordered on demand. Enterprises are also looking continuously for new customer relationships that are more profitable.

Other integration goals include gaining greater throughput from existing assets, integrating data into strategic information, and optimized manufacturing execution.

Effective planning of resources involves:

- Accurate forecasting and planning
- Procurement of raw materials
- Customer order management
- Efficient manufacturing
- Maintaining an optimum inventory
- Effective distribution channels
- Accounts receivable (i.e. GETTING PAID!).

Enterprise resource planning (ERP) is all about having the right product at the right place and the right time for the right price. ERP is all about what it takes to GET PAID. Figure 2-3 shows the ERP process.

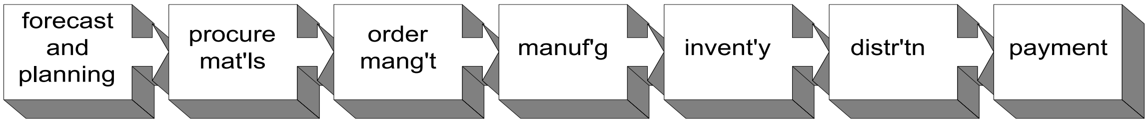


*Figure 2-3. Enterprise Resource Planning (ERP) cycle.*

How does reliability impact ERP? Reliability increases Overall Equipment Effectiveness (OEE). Remember that OEE is the valuable operating time of a piece of equipment. Reliability can improve the availability of the asset to operate, increase the running rate, and reduce scrap associated with quality problems. Further, effective reliability programs lessen the need for capital expenditures by reducing the %Replacement Asset Value (%RAV). The spares-on-hand may be greatly diminished by using a reliability approach to maintenance. Large inventories of spare parts and consumables cost a great deal of money to maintain. The result of optimizing stores is cash that is available for research and development, acquisitions, or other investment purposes. In short, the role of reliability in ERP is transitioning the mindset of management from the "cost of maintenance" to the "value of reliability".

**Reliability Economics**

Industry spends $200 Billion annually on maintenance in the United States alone. In most applications, maintenance represents fully 15%-40% of the operating cost of a plant. According to several independent studies, somewhere between 28% and 35% of all maintenance spending is unnecessary. This spending excess is hidden in activities that are reworked/redone, excessive stores, unnecessary PM, poor quality/scrap, inaccurate analysis, etc. Now, let's look at an example.

A widget manufacturer generates $100 MM in annual revenue at 20% gross margin. The operating costs, therefore, are $80 MM. If 40% of the operating costs is spent on maintenance, then that equates to $32 MM. If 35% of that maintenance is wasted or unnecessary or in the "hidden costs", then more than $11 MM has been wasted that could have gone to the bottom line. Had the enterprise been able simply to avoid 50% of the wasted maintenance budget, then operating costs would have been reduced to $74.4 MM. **In this example, an effective reliability program increased the gross margin from 20% to nearly 26%.** These results are achievable with the proper implementation of reliability methodologies and systems. Personnel responsible for this type of improvement can expect to be rewarded for their efforts.

The costs of maintenance may be divided into direct and indirect costs. Direct maintenance costs include staff, overtime pay, benefits, outside contractors, spare parts, and tools. Indirect costs (which often dominate) include high production costs, lost production, reduced quality, and poor customer service. Achieving success in reducing maintenance costs often involves a strategic assessment of the production process and support requirements to identify bottlenecks in the system. Figure 2-4 depicts the normal distribution between direct and indirect costs.

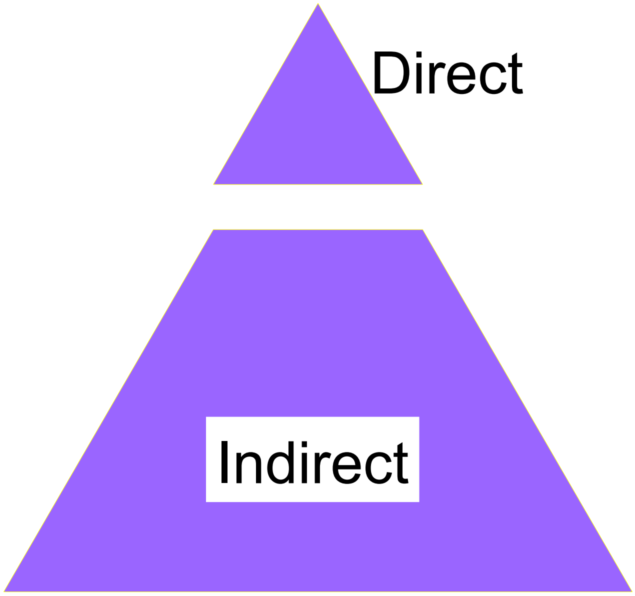


*Figure 2-4. Direct maintenance costs are often just the tip of the pyramid.*

Because of the high value-added capability of a successful reliability program indicated by the example discussed previously, it is very important for the enterprise to consider it's reliability strategy when performing strategic planning.  Remember that the reliability strategy includes both technical and management objectives as shown in Figure 2-5. The Condition-Based and Reliability-Centered approaches to maintenance focus on the technical challenges of improving reliability.  These methodologies assess the proper mix of breakdown maintenance, preventive maintenance, predictive maintenance, and proactive maintenance and develop the procedures required to conduct the program. The Total Productive Maintenance approach addresses the management side of reliability. TPM considerations include personnel, materials, financial, and scheduling.  The enterprise must focus on a blend of the various methodologies and systems in order to achieve a successful program.

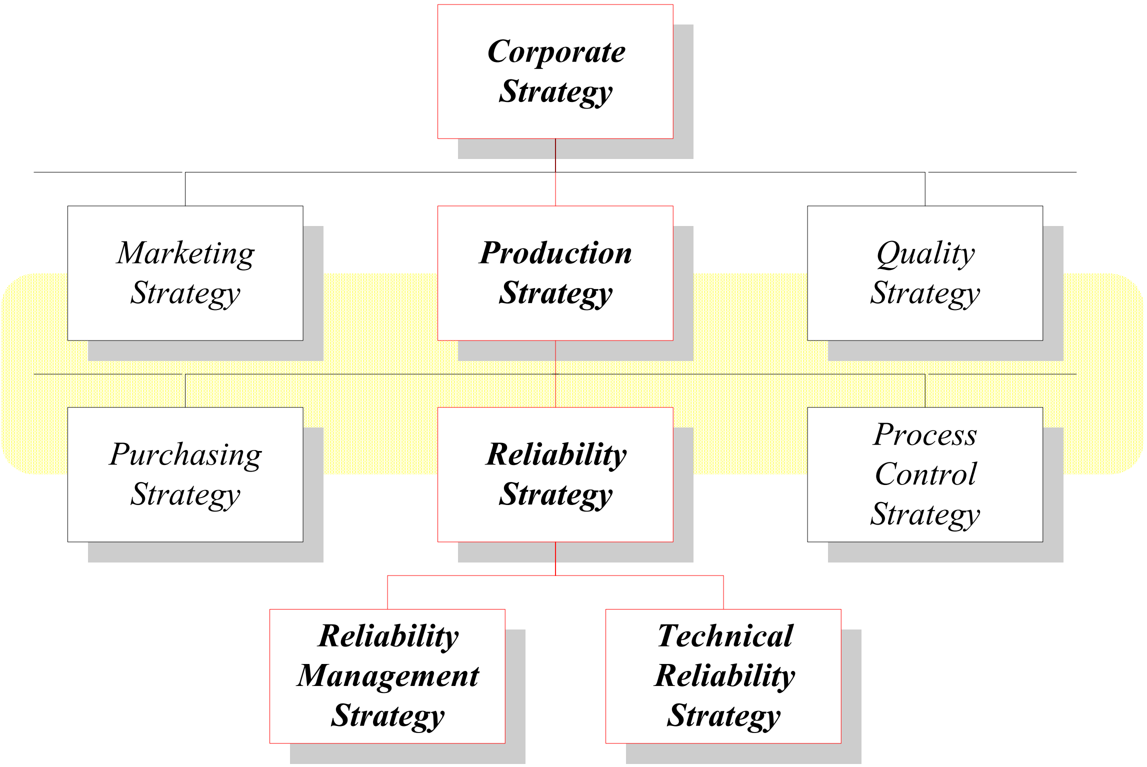


Figure 2-5.  Reliability must be an integral part of corporate strategic planning.

# Chapter 3 – Program Considerations

## Introduction

In the first two chapters, we looked at the various maintenance methodologies, reliability philosophies, and the importance of reliability in the enterprise. A key management support role in effective reliability programs is the constant tracking and posting of identified metrics. Chapter 3 will focus on a variety of metrics that may be employed, guidelines for management support, cost savings opportunities, personnel profiles, and training requirements for Reliability Team members.

## Management Support Requirements

There is a need to establish a dedicated team to coordinate Preventive Maintenance (PM), Predictive Maintenance (PdM), and Proactive Maintenance (PaM) capabilities. The scope of monitoring with predictive technologies should be methodically expanded until all non-disposable equipment in the facility is included in a monitoring program. Non-intrusive information on the condition of the HVAC systems, vacuum systems, chill water system, electrical systems and process equipment is critical for the optimum performance of the plants. Although a strong condition monitoring program does not translate into zero downtime or machinery failures, it will drastically reduce unforeseen problems and allow for improved reliability.

Developing excellent acceptance test specifications and limits for balancing, alignment, vibration, infrared thermography, oil and foundations of machinery are paramount to ensuring world-class reliability. Simple techniques for performing acceptance tests will be addressed later.

A condition monitoring program must be aggressively pursued to allow more focused maintenance effort and the elimination of unwarranted emergency repairs and costly downtime. Effective machinery condition information is required to efficiently plan maintenance during scheduled downtime. Maintenance downtime should be scheduled to assure the equipment performs as expected when needed instead of becoming the next "crisis of the day". A daily meeting of plant maintenance, engineering, planning and operations personnel is a good forum for coordinating maintenance and process activities. As the enterprise gains more control and confidence over the activities in the plants, this daily meeting can become a weekly meeting.

Commitment to dedicated personnel in a Condition-Based Maintenance (CBM) program is an essential element in developing and maintaining a world-class maintenance program. The lessons learned while establishing and maintaining this group should be incorporated into procedures, newsletters, and communications with other plants. Most world-class CBM Programs further provide a medium for sharing recommended "Best Practices" among corporate-wide personnel. Periodic group meetings provide an outstanding platform for this activity.

The presence of an equipment history for each major piece of equipment is essential to development of a long-term proactive maintenance environment. Evaluation of the Computerized Maintenance Management System (CMMS) capabilities needs to be performed to determine that provisions for statistical analysis of information, report generation, and equipment tracking are available. The ability to track "bad actors" provides the genesis for Root Cause Failure Analysis. Multiple failures of a single component and multiple components failing at a similar system locations/service life may quickly be identified. This system also provides indication of the quality of work performed. The ability to create detailed equipment histories through the CMMS should be emphasized in all plants.

A maintenance history combined with data obtained from the condition monitoring program is an integral part of the equipment history and should be used in identifying and scheduling all types of work (preventive, predictive, project, shutdown, etc.). An equipment history is a great advantage when forecasting realistic maintenance budgets instead of using last year numbers. A reliable and easily accessible equipment history is indispensable when investigating recurring problems and evaluating success of corrective actions.

The following elements have consistently proven successful in developing management support and plant culture that subscribes to Condition-Based Maintenance:

- A clearly identified and visible site champion who has the means to implement the necessary philosophical and technical techniques.

- An objective methodology through some level of RCM Analysis for each asset and gathering data for CMMS and CBM set-up.

- Benchmarking assessment to determine baseline conditions within the plant. Agreed upon standard measurement metrics and comparison with others in the same industry and across industries. Pre-specified performance targets are a must.

- System implementation that selects the best CMMS package and best CBM equipment. System integration and implementation with clear goals, training, and motivation. Some level of TPM to optimize activities.

- Performance indicators for measuring program results. Indicators agreed upon by production, maintenance, and management personnel. They should be tracked on a monthly basis and posted in common areas where cross-functional personnel tend to congregate.

- Work assignments that are preplanned and scheduled on a regular basis. Priorities for work should be developed based on production and maintenance inputs to a formalized work priority procedure.

- Identify and schedule most types of work (routine, capital and project, shutdown, etc.) through the use of equipment history and data obtained from the condition monitoring program.

- A ***dedicated*** predictive maintenance group under the direction of one individual. Lateral communication among PM, PdM, and PaM personnel is essential in developing and maintaining a world class maintenance program.

- Routine communication of success through reporting of financial gains, cost comparisons, and internal/external marketing programs.

- Dedication to Continuous Improvement through reliability optimization.

- The development of integrated PM and PdM where equipment condition dictates the scheduling of maintenance as well as equipment repair will lead to more cost-effective maintenance. Coupled with the use of PaM to establish acceptance levels for new/rebuilt equipment or supplies (lubricating oils, filters, etc.), this entire CBM program will result in the ability to increase equipment availability and significantly lower maintenance costs.

## Program Implementation Guidelines and Performance Indicators

The following recommendations are directly applicable to developing CBM programs and are based on the observed best practices from over fifty different organizations including Malcolm Baldridge Award winners. The Malcolm Baldridge Awards were established in 1987 by Congress in order to promote quality awareness, recognize U.S. business achievements, and publicize successful strategies. Baldridge award winners are good sources of innovative practices, and these companies are also open to benchmarking exchanges and information sharing.

1. The goals of the CBM program should be incorporated into personnel objectives.

2. As the predictive technologies are added, they should be incorporated into the incident review process where the cause of the incident is attributable to maintenance.

3. The benefits of predictive maintenance analysis as well as other monitoring efforts should be formally communicated to all levels of management on a routine basis.

4. As monitoring technologies and points are added they should be reviewed for safety considerations. Especially during the initial surveys, the Reliability Program Manager should observe data acquisition and recommend appropriate safety measures including installing permanent sensors where conditions warrant.

5. Develop a list of equipment to be monitored that includes the initial periodicity and technology to be utilized.

6. Develop a timetable for implementing each technology.

## Performance Indicators

Selection of six to eight high-level performance indicators is needed to share plant wide the effects the CBM program is having on the plant. The performance indicators discussed in this section can be used within the production and maintenance for examination of the program’s progress.

Parameters for tracking the performance of the CBM team must be established early in the implementation of the program. Initially, this may seem like measurement for measurement sake. However, without true measurable indications of the success or short-falls, the program cannot be directed toward the areas of most opportunity or to relax in areas of diminishing returns. Without constant reminders of performance, strong beginning programs can tend to rest on initial accomplishments and not reach maturity.

Implementing truly proactive measures should be the goal of every Condition-Based Monitoring program. This maturity level builds desire to find problems before they become plant wide headaches or affect production rates and product quality.

The CMMS should offer the capability to correlate strategic information. This capability should be used to routinely analyze work orders for recurring items or tasks that require substantial rework. This information could prove vital in directing improvement efforts to specific high-cost areas. Cost and percentage of corrective work orders vs. total work orders are parameters that can easily be adapted to track and display trends in equipment maintenance and frequency of problems occurring on equipment covered by the Condition Monitoring program. An analysis of average "delay time" on work orders by priority category can aid in improving any backlog that may develop.

The amount of emergency work, equipment availability and the economic benefits of the Condition Monitoring program should be reported and charted on a monthly basis. Similarly, the number of outstanding work orders and the cost of preventive maintenance items should be utilized to monitor the economic benefits associated with problem avoidance as well as the effectiveness of the preventive maintenance performed. While cost avoidance estimates sometimes raise emotions among operations and maintenance personnel, they are an important indicator of the success of maintenance activities. To avoid confrontations on these numbers, agree in advance on guidelines for estimating savings. If consistent guidelines are followed, these numbers will offer a solid indicator of success for the Condition Monitoring program.

Track the number of unnecessary, intrusive Preventive Maintenance tasks and the number of these that are revised or eliminated by non-intrusive techniques. Do not forget to account for the cost avoidance associated with extending PM intervals or eliminating certain PM procedures altogether. Unnecessary PM not only erodes maintenance manpower resources, but can contribute to accelerated equipment degradation and may also result in equipment malfunction upon re-assembly. There are additional Preventive Maintenance and other plant wide indicators that can contribute to an effective CBM Program.

The following examples of related performance indicators are offered:

- Number of vibration (or other PdM) related problems found and corrected per month.
- Number of vibration (or other PdM) related problems/workorders open at the end of the month.
- Number of vibration (or other PM) related jobs over 30,60, and 90 days old.
- A monthly record of the accumulated economic benefits or cost savings/avoidance for various CBM; e.g., Vibration Analysis, Thermography, Oil Analysis, etc.
- Number of spare parts eliminated from inventory as a result of the Condition-Based Maintenance Program.
- Number of overdue Preventive Maintenance jobs at the end of the month. The total number of deferred PM actions should increase as CBM matures.
- Number of PM tasks over 30, 60, and 90 days old.
- Number of work orders by priority that are over 30, 60, and 90 days old.
- Aggregate vibration and alarm levels (downward trend until maturity).
- Mean Time Between Failures (MTBF).
- Mean Time To Repair (MTTR).

## Condition-Based Maintenance Performance Indicator Calculations

In this section, some basic metrics oriented toward plant and CBM performance are presented. As mentioned previously, six to eight high level indicators should be chosen and tracked monthly.

- Plant or equipment Availability

$$\text{Availability} = \text{MTBF} / (\text{MTBF} + \text{MTTR})$$

- PERCENT OF PLANT AVAILABILITY (TARGET = 96%)

$$\% = \frac{\text{Hours the Facility is Available to Run at Capacity}}{\text{Total Hours During the Reporting Time Period}}$$

- PERCENT OF PLANT UTILIZATION (TARGET = 96%)

$$\% = \frac{\text{Hours the Facility Ran at Capacity}}{\text{Hours the Facility is Available to Run at Capacity}}$$

- MAINTENANCE OVERTIME PERCENTAGE (TARGET = 5% OR LESS)

$$\% = \frac{\text{Total Maintenance Overtime Hours During Period}}{\text{Total Regular Maintenance Hours During Period}}$$

- EMERGENCY WORK PERCENTAGE (TARGET = 10% OR LESS)

$$\text{Manhours } \% = \frac{\text{Total Hours Worked on Emergency Jobs}}{\text{Total Hours Worked}}$$

$$\text{Jobs } \% = \frac{\text{Total Emergency Jobs Worked}}{\text{Total Jobs Worked}}$$

- % EQUIPMENT COVERED BY PREDICTIVE MAINTENANCE (TARGET = 100%)

$$\% = \frac{\text{Number of Equipment Items in Predictive Maintenance Program}}{\text{Total Equipment Candidates for Predictive Maintenance}}$$

- % of EMERGENCY WORK TO PDM AND PM WORK (TARGET = 20% OR LESS)

$$\% = \frac{\text{Total Emergency Hours}}{\text{Total Predictive and Preventive Maintenance Hours}}$$

- % of FAULTS FOUND IN THERMOGRAPHIC SURVEY

$$\% = \frac{\text{Number of Faults Found}}{\text{Number of Devices Surveyed}}$$

- Process Reliability (Target = TBD)

PR = NET PRODUCTION / (TARGET RATE * SCHEDULED TIME).

The reliability performance indicators should be trended, published, and displayed monthly. In particular, the Process Reliability should be charted as a per month trend. The number of faults found and corrected per month and the accumulated economic and production up time benefits derived from correcting those faults should also be charted. These charts should be posted in the maintenance areas and around critical areas in the production area to keep the value of the program prominent among line operations as well as maintenance personnel. Encourage feedback on how to improve in these areas.

Display a “trophy case" of CBM’s success in a prominent place. Include failed parts along with the root cause of the failure and the means of preventing such failures or prolonging component life. The return on this type of display, will be an increased exchange of ideas between operators, maintenance, engineering, and the Condition Monitoring group personnel.

## Program Organization and Training Requirements

There is a need to focus on an organizational development of a Condition-Based Maintenance Program. A clearly defined plan and organizational structure for implementing the CBM philosophy needs to be put in place with the defined roles and responsibility for each member of the team along with a timetable for achieving full integration of the CBM philosophy into the plant's business philosophy. Figure 3-1 is a representative organizational structure for a reliability team based upon a three shift operation. The organization grows or shrinks depending upon the number of shifts and the amount of equipment in the plant.

*Figure 3-1. A Possible Organization Chart for a Reliability Program.*

Dedicating personnel and organizing a team as the focal point for all CBM activities is an essential step to improving the effectiveness of maintenance efforts. Many corporations have reliability personnel in place on a corporate-wide level. These organizations are outstanding in the development of technical and strategic guidelines for dissemination to those at the plant level. There is a fundamental need, however, for an organization to be established to support sustained improvements in maintenance and operations practices at each facility. Full time and cross-trained personnel will provide for implementation of the program and the addition of applicable capabilities.

A very significant amount of training is required in order to establish and maintain a world-class Condition-Based Maintenance organization. The training must consist of both formal, in-class exposure to the technologies and products which represent the “tools of the trade” and also on-the-job experience in working with each technology.

## The Costs of Condition-Based Maintenance Programs

Condition Monitoring systems are the main technical reliability system. These systems allow management of individual assets based on condition. There is a wide array of available measurement technologies from portable systems to continuous on-line systems with permanently mounted transducers. Through effective monitoring, the technologies allow fault identification, diagnosis, and sometimes prognosis.

The potential payback is monumental, but it should be obvious from the requirements stated thus far in Chapter 4 that a significant investment is required in order to establish and run an effective reliability program. Approximate hardware and software costs are identified in Table 3-1. In addition to these costs are the labor associated with the Program manager, Shift Leaders, and Technicians. Other costs include equipment upgrades, computers, contracted repairs, and training. Managers have a tendency to ask the question, “What have you done for me lately?” And the language of management is money. Cost justification is an absolute requirement in order to achieve world-class reliability.

*Table 3-1. Approximate Costs to Start CBM in Various Technologies.*

| Technology | Hardware Costs | Software Costs | Training Costs |
|---|---|---|---|
| Vibration | $10K-$15K | $8K-$30K | $10K-$20K |
| Balancing | $15K-$100K+ | included | $2K-$10K |
| Alignment | $2K-$30K | included | $2K-$6K |
| Infrared Thermography | $35K-$100K | $2K-$10K | $2K-$10K |
| Oil Analysis | $10K-$40K | $4K-$10K | $5K-$10K |
| Ultrasonic Emission | $5K+ | $1K+ | $1K-$5K |
| Motor Circuit Testing | $4K-$10K | $1K-$2K | $1K-$5K |
| Motor Current Signature Analysis | $5K-$25K | $10K | $3K-$6K |

In general, enterprise management should do a cost analysis before buying hardware and software to implement any CBM technology. Vibration is at the basic foundation of CBM activities, and an effective program may be implemented using vibration alone. In essence, if the plant cannot afford to assign at least one full-time individual to as the program manager, then it likely makes more sense to contract the work to an outside vendor. Similarly, effective thermography programs can be run by using an outside vendor for one to three service days every six months. It seldom makes sense for a single plant to purchase an infrared camera unless it may also be used in support of production efforts.

## Why Do Many Programs Fail?

About half of all plants that begin a CBM program fail to achieve the documented savings to justify the investment in technology and labor resources. There are a number of reasons that this happens. Let's look at most of them.

First, there is a tendency among new program leaders to try and "reinvent the wheel". New program managers with little training seek to set up their own programs, and the resulting inefficiencies cost the company time and money. It is strongly recommended that the initial vibration database be properly set up by an experienced field service engineer who works for a vendor of the technology. The service cost of a five to ten day visit will be far offset by the speed and accuracy of the set-up process. Far too often, novice program managers struggle to implement the database for six months or more -- sometimes never achieving the proper measurement settings. In the worst case scenario, a customer acquired vibration data for nearly 18 months that was all but useless because of improper set-up.

Second, programs fail because reliability personnel become too involved in a "bells and whistles" mentality. They beg for the latest and greatest technology while forgetting to focus on the fundamentals. At the same time they request dollars from the capital budget, these personnel forget to provide the strategic information to management that will make them successful.

Third, loss of key personnel causes program to fail. There is strong competition among corporations for skilled Reliability personnel. It takes a significant investment for companies to train individuals to be effective in the CBM technologies. If there is not due consideration for successor planning, the loss of one key individual to another company or position can devastate a thriving, mature reliability effort.

Fourth, lack of management support is another key reason while programs fail. Some managers are willing to make the initial investment in hardware and software. They forget, however, the necessity for ongoing investment in training for the personnel. Although it may not be "rocket science", CBM technology requires ongoing technical training. Personnel who do not receive this training are handicapped in their ability to perform.

Fifth, a lack of cost justification results in failure of some programs. Most program managers are very technically oriented, and they forget to show management what their effective programs are doing for the "bottom line". In order to run a world-class reliability team, program managers must learn to speak in terms of critical metrics and dollar savings.

Finally, some programs are destined to fail simply because they were sold a system … not a solution. Unfortunately, some salespeople are driven to sell without determining the true requirements for the customer. Consequently, predictive maintenance equipment and CMMS systems are sold that can never be fully utilized in the customer's plant. One sure-fire way to sour a manager on the concept of reliability is to sell him a system that can never be implemented properly in the plant.

## Summary

In this chapter, we have reviewed a number of different aspects of implementing a successful, cost-effective reliability program. Management support requirements identified the best practices of many successful reliability programs and the need to use the reliability tool-kit effectively. A possible organizational structure was presented, and the duties of each individual were spelled out in detail. Education requirements are a critical need in any successful reliability organization, and these requirements were also discussed. A discussion followed on the approximate costs of implementing various technologies into an effective CBM program and the possibility of out-sourcing key components to third-party vendors. Finally, we looked at why about 50% of all programs fail to achieve outstanding results.

# Chapter 4 – Predictive Technologies

Predictive maintenance (PdM) is at the basic foundation (or fulcrum) of Condition-Based Maintenance (CBM). Accurate PdM data makes the proper balance of preventive (PM) and proactive (PAM) maintenance possible and cost effective. PdM is an essential tool to assure maximum safety and improved reliability in a production or operations support facility. Predictive technologies allow the detection of possible system or equipment failures in the early stages and reduce the possibility of catastrophic failures during critical operations. Predictive technologies available are vibration, oil analysis, infrared thermography, motor current signature analysis (MCSA), ultrasonic detection and many others. This chapter will focus on the three, most widely used technologies: vibration, oil and thermography. Other, ancillary technologies will be discussed in a subsequent chapter.

## Vibration

Vibration analysis has been proven to be the most successful predictive tool when used on rotating equipment, both in increasing equipment availability and reliability. In order to maximize the finite life associated with rolling element bearings and optimize equipment production life, excessive wear caused by misalignment, unbalance, and resonance must be minimized. The presence of trained vibration specialists with equipment to conduct analysis will form the basis of a strong vibration program. Routine and consistently gathered narrow band vibration data is vital to analysis and trending of machinery health. Acceptance standards of rebuilt or newly installed equipment will be established and verified using vibration monitoring.

Studies by the U.S. Navy and Tracor Applied Sciences on equipment ranging in size from 15 to 4,000 Hp have shown that monitored equipment has one-sixth the catastrophic failure rate of unmonitored equipment. In addition, the probability of detecting an impending failure ranged between 92 and 95% with a false alarm probability of between 5 and 8% when the proper monitoring interval and alarm values were selected.

Routine vibration monitoring is normally conducted at intervals of one to three months. When potential problems are identified during production runs, the interval between collection activities should be reduced to weekly (or even daily) in order to preempt catastrophic failure. For components that are very critical to plant operation, or cause serious safety and/or environmental problems, continuous monitoring or permanently installed transducers, shall be utilized along with detailed root cause analysis.

Key elements of a routine Vibration Monitoring Program include the following:

- ♦ Acceptance criteria for procurement of new equipment.
- ♦ Acceptance criteria for rebuilt equipment.
- ♦ Defined database for critical equipment.

- ♦ The incorporation of remaining rotating equipment into program. Studies have shown that two-thirds of cost improvement opportunities in maintenance come from the non-critical equipment after the first year.
- ♦ A formal process for setting and review of alarm levels, periodicity of monitoring and maximum frequency of interest (refine database).
- ♦ Readily available information on replacement bearings and other rotating components. This information will greatly speed analysis and trending of vibration data.
- ♦ When preventive maintenance schedules call for verification of vibration to be acceptable, use vibration monitoring equipment.

The use of detailed reports helps direct corporate attention to critical machinery problems. The first section of this chapter will summarize the interpretation of a typical Machine Condition Report.

## **Report Interpretation**

This section explains the typical report used in reporting machinery problems. Before examining a sample report, discussion of common plots used in vibration analysis are covered.

### Overall Trend

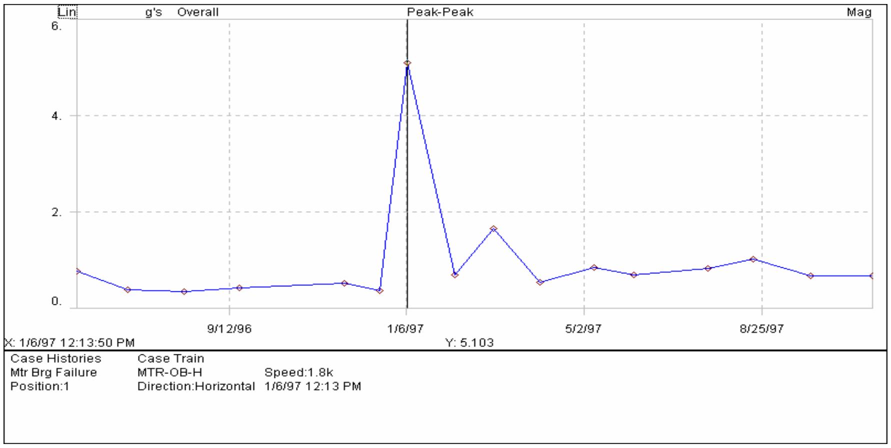
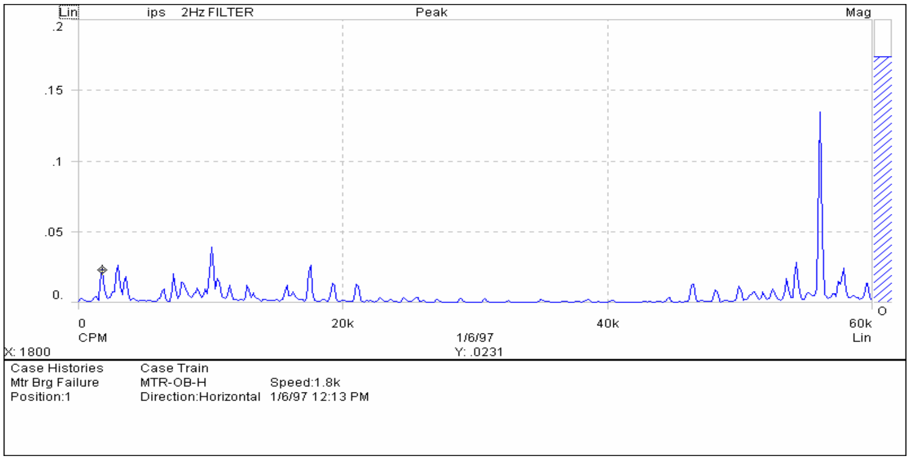


*Figure 4-1. Example Overall Trend Plot.*

The Overall Trend plot (Figure 4-1) is a plot of the overall vibration magnitude versus time. Overall vibration is the vibration you would feel if you put your hand on the machine. It is the sum of all the vibration being generated by the machine as well as any background vibration from other machines in the system. This plot shows vibration increased at one point in time due to a bearing defect on the motor. The legend on the plot shows at which position the reading was taken, the type of reading, and the date of the reading.

## Spectrum Plot



Case Histories
Mtr Brg Failure
Position:1

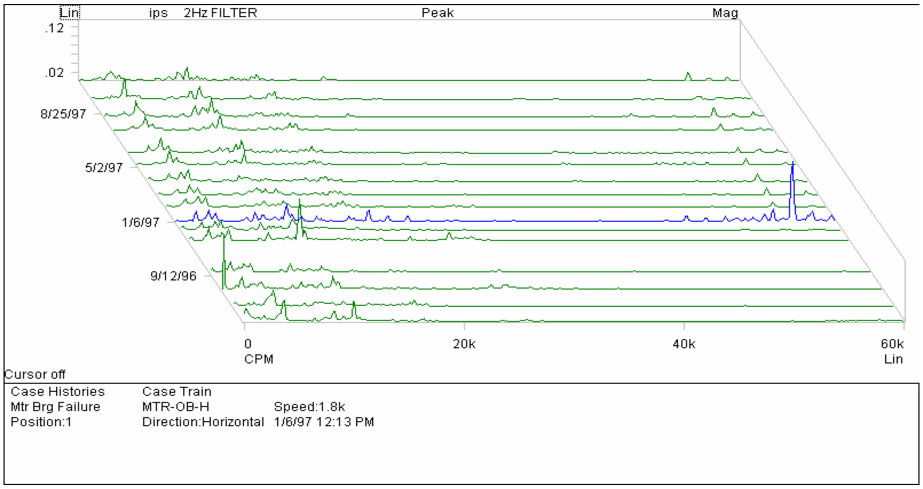
Case Train
MTR-OB-H
Direction:Horizontal

Speed:1.8k
1/6/97 12:13 PM

*Figure 4-2. Example Spectrum Plot.*

The spectrum plot, Figure 4-2, is a plot of amplitude vs. frequency. This shows how much vibration is occurring at a specific frequency. The specific frequency relates to the components of the machine and their relationship to the rotating speed of the machine. This indicates the type of defect the machine may possibly have (such as unbalance, misalignment, defective bearings, etc.).

## Waterfall or Cascade Plot



Case Histories
Mtr Brg Failure
Position:1

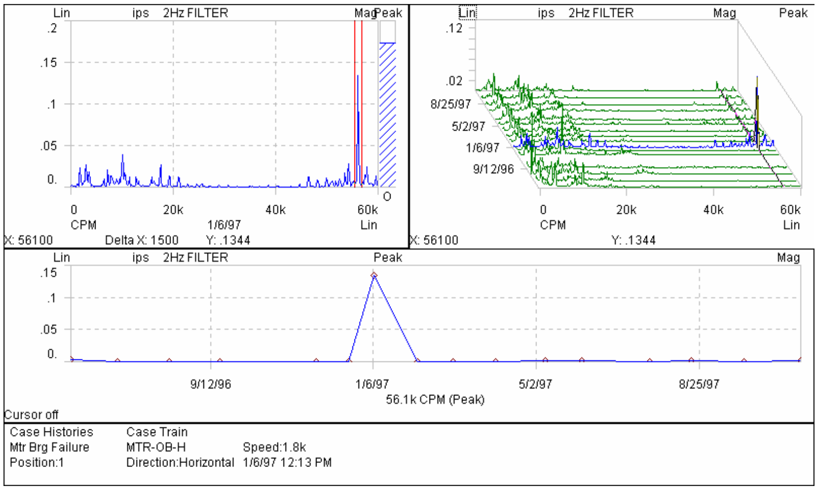
Case Train
MTR-OB-H
Direction:Horizontal

Speed:1.8k
1/6/97 12:13 PM

*Figure 4-3. Example Waterfall Plot.*

Figure 4-3 is a plot showing the history of a single position over time. The top line is the most recent data. The data on this particular plot shows the bearing defect occurring at this position on 01/06/97. This waterfall plot is from the same position as the previous trend plot. The defect spectrum shown on 01/06/97 is also the same as the spectrum shown in Figure 4-2.

## Frequency Trend



Case Histories
Mtr Brg Failure
Position:1

Case Train
MTR-OB-H
Direction:Horizontal

Speed:1.8k
1/6/97 12:13 PM

*Figure 4-4. Example Frequency Trend Plot.*

Figure 4-4 shows the plot of a trend of the single frequency peak (between the 2 vertical lines on the spectrum plot and marked by a diagonal line on the waterfall plot) that is associated with the bearing defect. Trending a specific frequency over time allows one to track a specific type of defect, such as a bearing defect in this case.

The above plots help to identify problems on a machine, as well as identify a possible root cause of the defect. The setup on the database for a plant site will have similar plots with certain variables being defined for different types of machines. For example, the frequency ranges may vary from the 60,000-cycle/minute range on the above plots to higher or lower frequency ranges based on the speed of the machine.

## Sample Report

An entire sample of a report follows at the end of this section. The report on the motor with the defective bearing, from which all the above data was taken, appeared as follows.

| Machine Name | Comments | Recommendation | Severity |
|---|---|---|---|
| COMPRESSOR 1 | Overall vibration increased on the motor outboard bearing. There was an increase in the upper frequency range peaks of the associated spectral data. The frequency increase was at a peak calculated to be a bearing defect frequency. | Due to the significance of the increase replace the outboard motor bearing ASAP. | 3 |

| Severity Level – | | |
|---|---|---|
| | 1 | Monitor Trend Closely. |
| | 2 | Warning. There was an increase that warrants closer observation. Further analysis may be required. |
| | 3 | Critical. Corrective action required. |
| | 0 | No action required; machine operating under normal operating conditions. |

The different columns contain the following information:

- The 'Machine Name' column shows the name and/or other designator for a machine.
- 'Comments' details the findings of the survey, but only is filled-in for machines with severity levels greater than zero (0). If there is a flat trend or only minor increases in the trend no comments will be made.
- 'Recommendation' explains what should be done to the machine if there is a severity level of 1-3.

In order to reduce vibration levels on a machine it is sometimes necessary to step through a process of elimination. The steps of this process will accompany a report of this nature. Communications between the analyst and the site managers is of a vital concern in implementing a good Predictive Maintenance Program (PdM). Recommendations in the report are based on known vibration standards (a Vibration Severity Chart is included along with the report), the trend of the data and the rate of increase in the trends of various plots. Personal experience with a wide range of machine types also plays a part in analyzing data.

Machines with level 3 Severity will usually be listed on separate pages so the plots can be included in along with the data. Machines in the 0-2 level will all be put on the same pages. In some cases a digital camera may be used to photograph a specific machine to include the photo in the report. This is useful when recommending structural changes or changes to a base. When using a digital camera it is imperative to comply with whatever security measures are in effect at the plant site.

**Sample Report**

The following pages show the setup for a typical report. Customers may ask for as much information to be included in the report, but the primary format as shown above is a currently accepted standard.

# *Machine Condition Report*

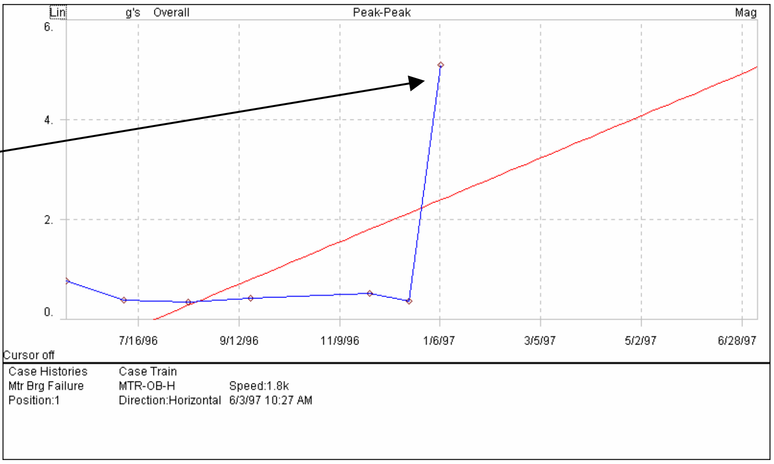
## Company Name

*A-Building*
1st & 3rd Floor Mechanical Rooms

January 23, 2001

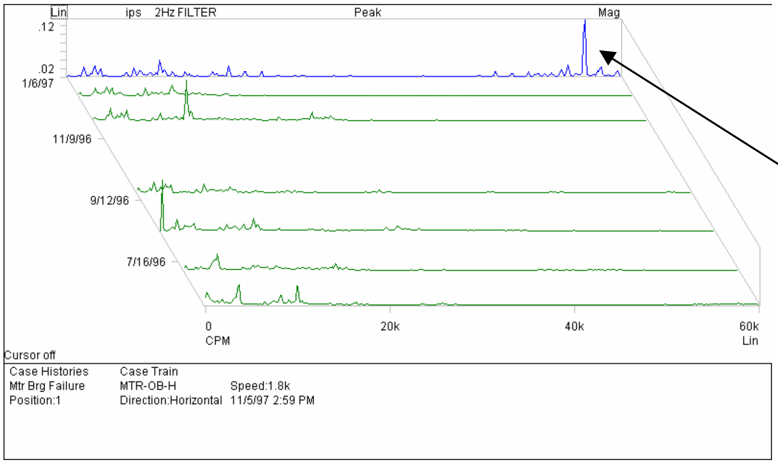
Survey Results – Severity 3
The following machines were found to be in alarm or have significant increases in vibration and are considered to be Severity Level 3.

| Machine Name | Comments | Recommendation | Severity |
|---|---|---|---|
| COMPRESSOR 1 | Overall vibration increased on the motor outboard bearing. There was an increase in the upper frequency range peaks of the associated spectral data. The frequency increase was at a peak calculated to be a bearing defect frequency.<br>See the plots inserted below. | Due to the significance of the increase replace the outboard motor bearing ASAP. | 3 |



```
Case Histories   Case Train
Mtr Brg Failure  MTR-OB-H              Speed:1.8k
Position:1       Direction:Horizontal  6/3/97 10:27 AM
```

Overall Acceleration amplitude increased significantly.



```
Case Histories   Case Train
Mtr Brg Failure  MTR-OB-H              Speed:1.8k
Position:1       Direction:Horizontal  11/5/97 2:59 PM
```

Increased amplitudes in frequencies relating to bearing defect frequencies.

# *Machine Condition Report*

| Machine Name | Analysis | Recommendations | Severity |
|---|---|---|---|
| HEF – 1A | No Alarms, Machine Normal | | 0 |
| AC – 2A | No Alarms, Machine Normal | | 0 |
| RAF – 2A | Vibration levels raised in upper frequency range on motor.<br>Acceleration showing gradual upward trend | Lubricate motor bearings | 1 |
| PUMP P – 3A | No Alarms, Machine Normal | | 0 |
| PUMP P - 4 A | No Alarms, Machine Normal | | 0 |
| PUMP P - 5 A | No data collected | | 0 |
| PUMP P – 6A | No data collected | | 0 |
| AC – 3A | No Alarms, Machine Normal | | 0 |
| RAF – 3A | High vertical vibration on motor. Spectrum data showing 1x and harmonic peaks | Check motor base for looseness, such as loose mounting bolts, cracked or broken grout, etc. | 2 |
| RAF – 1A | No data collected | | 0 |

## Basic Theory

## Vibration Acceptance and Testing Criteria

It is highly recommended that equipment acceptance testing be performed on all new and newly rebuilt hardware. The testing efforts should include the following:

1) Vibration measurements on each bearing in two radial directions and the axial direction (i.e. 12 measurements per four-bearing machine).
2) Vibration measurements at each hold-down bolt location.
3) Measurements of velocity and high frequency energy (spike energy or ESP) in rolling element bearing machines and velocity and displacement in sleeve bearing machines.
4) Measurements should be taken with the unit under a loaded condition (at least 70% load when possible). Uncoupled motor data is not acceptable for acceptance testing.

In general, the industry subscribes to a vibration severity level chart as shown in Tables II & III of the RA/ICM Vibration Analysis Level I (VAI) Training Manual, pages 7-22 through 26. These data indicate Warning and Fault conditions for in-service equipment. Acceptance criteria for new or newly rebuilt equipment should be specified at 50% of the overall velocity “Warning” condition for a particular machine type. For instance, acceptance criteria for a centrifugal compressor should be specified at 50% of the identified warning level of 0.3 in/sec pk, or .15 in/sec pk. In addition, acceptance criteria should stipulate that no properly specified band alarms are violated according to the methodology identified in Chapter 7 of the RA/ICM Vibration Signature Analysis I manual.

Acceptance testing on motors must be conducted with the motor under at least 70% load. Experience has shown time and again that when the motor is unloaded, symptoms of serious electrical problems may not show up in the vibration (or MCSA) signatures. Without significant loading on the motor, internal temperatures may not become pronounced enough to exhibit typical characteristics of short and open circuits internal to the motor.

Generally, acceptable foundation/mounting conditions may be established using overall velocity measurements acquired at the mounting interface. Provided no measurement at a securing bolt location exceeds 0.05 in/sec pk, then it is likely that no sprung foot, soft foot, or looseness condition exists. It is recommended that this requirement be implemented in procurement/installation specifications.

It is further recommended that the following stipulation be added to the Specification Requirements document for new equipment or newly redesigned equipment:

“The installed system shall not induce a resonance condition in any system component nor in any existing facility component.” This requirement mandates that the equipment vendor “owns” any problem related to a resonance condition until that problem has been resolved. This simple requirement has been shown to save many thousands of dollars in problem rectification over a wide range of industrial applications.

Acceptance criteria for proper balance of new or newly rebuilt equipment is addressed in ISO 1940 Quality Grade G-2.5. Although ISO G-2.5 is typical for general purpose machinery in industrial applications, most vibration specialists recommend a more stringent G-1.0 classification for new or newly rebuilt equipment. Though balancing to a G-1.0 tolerance is more time consuming (and initially higher cost), the reduced dynamic loading results in diminished power consumption and mechanical wear that will extend the life of the asset.

## Oil Analysis

One of the leading causes of premature bearing failure is improper lubrication practices. These include introduction of contaminants, use of improper lubricant, excessive amounts of lubricants or not enough lubricant. The bearing division of TRW states, "contamination is the number one cause of bearing damage that leads to premature removal." Lubrication provides the separation between moving component of critical production machinery. This lubrication film thickness is said to be about 10 micrometers, the diameter of a blood cell. Along with its base function of providing friction, wear and temperature control, the lubricant also becomes a diagnostic tool.

Oil condition monitoring requires an examination of the physical, chemical and additive properties to maintain oil stability as needed by the operating equipment. Routine oil monitoring can provide information about additive breakdown, viscosity changes, water content, coolant leakage and wear particle contamination. The dimensions of equipment condition monitoring with oil analysis include: fluid contaminant analysis and control, fluid property analysis, and fluid wear debris analysis. These fluid parameters are typically monitored using on-site screening and laboratory analysis. Typical tests performed are:

- Particle Count
- Viscosity
- Water
- Elemental Spectroscopy
- FTIR Spectroscopy
- Total Acid Number
- Wear Density (by exception from particle count)
- Analytical Ferrography ( by exception from wear density).

One of the first key elements in oil analysis is the International Standards Organization Code (ISO 4406). This solid contaminant code is a standard for expressing the cleanliness levels of liquids and is internationally recognized. The code is based upon the number of particles per unit of volume greater than 5 microns and 15 microns in size. These two sizes are significant because the concentration at the lower range gives an accurate assessment of the "silting" condition of fluid and the 15 micron range reflects the "wear" type particle concentration. The ISO code is represented by the 5 micron range number, over (slash), a 15 micron range number. A chart and example are provided in Table 4-1 below.

*Table 4-1. ISO Solid Contaminant Code Range Numbers.*

Number of particles per ml, R

| More than | Up to and including | Range number |
|---|---|---|
| 80,000 | 160,000 | 24 |
| 40,000 | 80,000 | 23 |
| 20,000 | 40,000 | 22 |
| 10,000 | 20,000 | 21 |
| 5,000 | 10,000 | 20 |
| 2,500 | 5,000 | 19 |
| 1,300 | 2,500 | 18 |
| 640 | 1,300 | 17 |
| 320 | 640 | 16 |
| 160 | 320 | 15 |
| 80 | 160 | 14 |
| 40 | 80 | 13 |
| 20 | 40 | 12 |
| 10 | 20 | 11 |
| 5 | 10 | 10 |
| 2.5 | 5 | 9 |
| 1.3 | 2.5 | 8 |
| 0.64 | 1.3 | 7 |
| 0.32 | 0.64 | 6 |
| 0.16 | 0.32 | 5 |
| 0.08 | 0.16 | 4 |
| 0.04 | 0.08 | 3 |
| 0.02 | 0.04 | 2 |
| 0.01 | 0.02 | 1 |

The ISO code is expressed as $R_{5\ \text{microns}}$ / $R_{15\ \text{microns}}$. The following is an example of how an ISO code is derived from a particle count.

Example 1: 400 particles > 5 microns/ml
65 particles > 15 microns/ml

Thus, ISO 16/13.

Take the 400 particle count and find it on the ISO chart. It is between 320 and 640 making the range number a 16. Then find the 65 particle count on the chart, which is between 40 and 80 making the ISO range number a 13. This provides the user with valuable information about the hard particle contamination in a fluid. We can now tell if new oil is more contaminated then the recommended cleanliness level and if so we can filter it down to the necessary cleanliness code. Through trending analysis, this cleanliness level will provide information on in-service lubricants as they degrade or ingress contaminants.

Water contamination is another critical component of oil analysis. Water contamination is expressed in PPM (parts per million) of water content. One percent (1%) of water equals 10,000 PPM. The lower the percentage (or PPM) of water the less contamination is present and better protection of the asset will result.

Viscosity is the single most critical physical property of oil. An increase in viscosity is more tolerable than a decrease in viscosity. Viscosity limits are usually enveloped with an upper and lower limit. The specification sheets from lubricant vendors along with the baseline laboratory results of new oil will provide the viscosity limits.

The Neutralization Number or Total Acid Number (TAN) corresponds to the acidity of the oil. This acid can be produced from oil degradation. Acid numbers vary depending upon the additives in a lubricant.

Most experts in tribology recommend that oil analysis be performed on all new oils. This testing should include the following:

- On-site particle count using pore blockage (10 micron screen)
- On-site Viscosity
- On-site Water screen.

The laboratory tests listed below should be performed on the “critical” fluids. These are the lubricants that are used in the equipment that is tested on a more routine basis than 60 or 90 days. The following tests will provide baseline information used for trending and analysis:

- Off-site Karl Fischer
- Off-site Elemental Spectroscopy
- Off-site FTIR spectroscopy
- Off-site Total Acid Number (TAN).

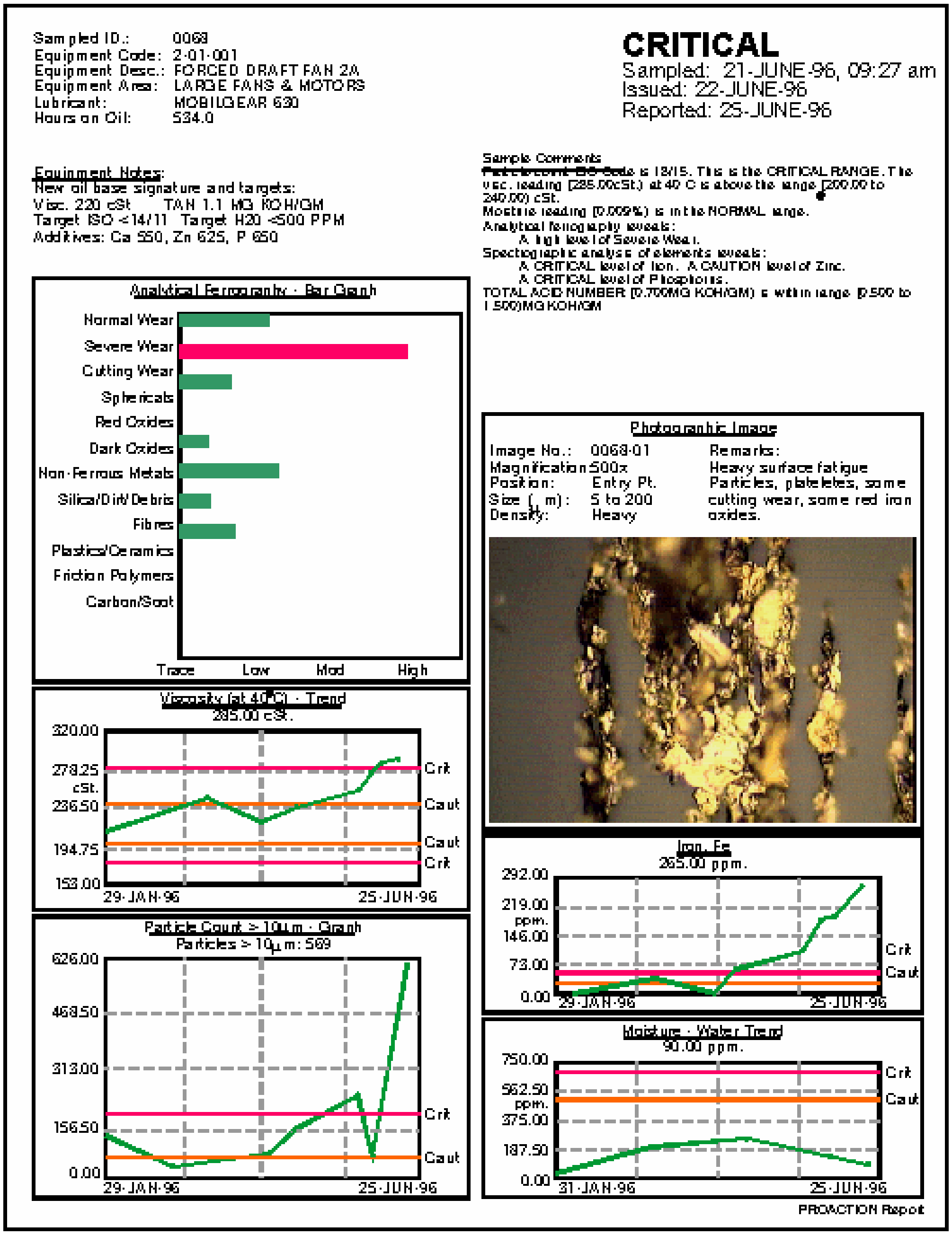
The new oil ISO code and water count should be at the World Class level or better. If the new oil does not meet the necessary criteria, then it will need to be filtered down to that cleanliness level or the contract with the vendor will need to be reviewed.

The tribology program for used and in-service oil will focus on controlling both the root causes of machine and lubricant degradation (proactive maintenance) as well as detect and describe abnormal lubricant and machine condition (predictive maintenance). These can be satisfied through on-site screening of all used and in-service oils with interacting laboratory test for benchmarking and exception analysis. These test and oil samples can be route based with the information and test results input into a database for report generation.

The cost savings are approximately 10 times greater if contamination is removed before being introduced to operating equipment than after it is in service. With return on investment and reliability the major drivers in a reliability program, the following are key elements in an oil analysis program:

- Acceptance criteria for new oil
- Acceptance criteria for in service oil
- Defined storage facility
- Procedure for lubricant storage
- Procedure for handling and transporting lubricants (topping up)
- Procedure for oil changes
- Proper oil filtration (beta carts)
- Proper machine filtration
- Proper oil breather requirements.

Oil analysis results are typically reported back from an off-site lab. There are on-site capabilities available from some systems. The on-site reports will report the amount of contamination present (particle count). The off-site reports will examine the oil to determine the exact material present and the level of contamination from each source. Figure 4-5 shows a sample oil analysis report.



Sampled ID.: 0068
Equipment Code: 2-01-001
Equipment Desc.: FORCED DRAFT FAN 2A
Equipment Area: LARGE FANS & MOTORS
Lubricant: MOBILGEAR 630
Hours on Oil: 534.0

**CRITICAL**
Sampled: 21-JUNE-96, 09:27 am
Issued: 22-JUNE-96
Reported: 25-JUNE-96

Equipment Notes:
New oil base signature and targets:
Visc. 220 cSt TAN 1.1 MG KOH/GM
Target ISO <14/11 Target H20 <500 PPM
Additives: Ca 550, Zn 625, P 650

Sample Comments
~~Particle count ISO Code~~ is 18/15. This is the CRITICAL RANGE. The visc. reading (285.00cSt.) at 40 C is above the range (200.00 to 240.00) cSt.
Moisture reading (0.009%) is in the NORMAL range.
Analytical ferrography reveals:
A high level of Severe Wear.
Spectrographic analysis of elements reveals:
A CRITICAL level of Iron. A CAUTION level of Zinc.
A CRITICAL level of Phosphorus.
TOTAL ACID NUMBER (0.700MG KOH/GM) is within range (0.500 to 1.500)MG KOH/GM

Photographic Image
Image No.: 0068-01
Magnification: 500x
Position: Entry Pt.
Size (μm): 5 to 200
Density: Heavy
Remarks:
Heavy surface fatigue Particles, platelets, some cutting wear, some red iron oxides.

*Figure 4-5. Example Oil Contaminant Report.*

## Infrared Analysis

The real power of thermography is that it allows one to quickly locate and monitor, in real time, both maintenance and production problems. This technology works alone in many applications, i.e., detecting problems that can not be detected with any other means. This information can be particularly important where electrical circuits and connections may show no visible signs of deterioration until moments before failure. Modern thermographic equipment can allow effective scanning and problem detection of very difficult problems. Infrared monitoring and testing is non-intrusive and is performed with equipment in service at normal operating conditions.

Thermography works by revealing the thermal patterns present with all equipment and processes. The invisible thermal or infrared energy radiates from hot and cold areas. Thermal imaging systems “see” the radiation by focusing the infrared radiation on a detector or detector element. This radiation is then converted into electrical energy, amplified and processed into a visible image and then presented on a viewfinder or monitor as a thermogram. Figures 4-6 through 4-8. are examples of thermograms taken on a motor and jaw coupling. The temperature scale shown in Figure 4-6 applies to all three figures.

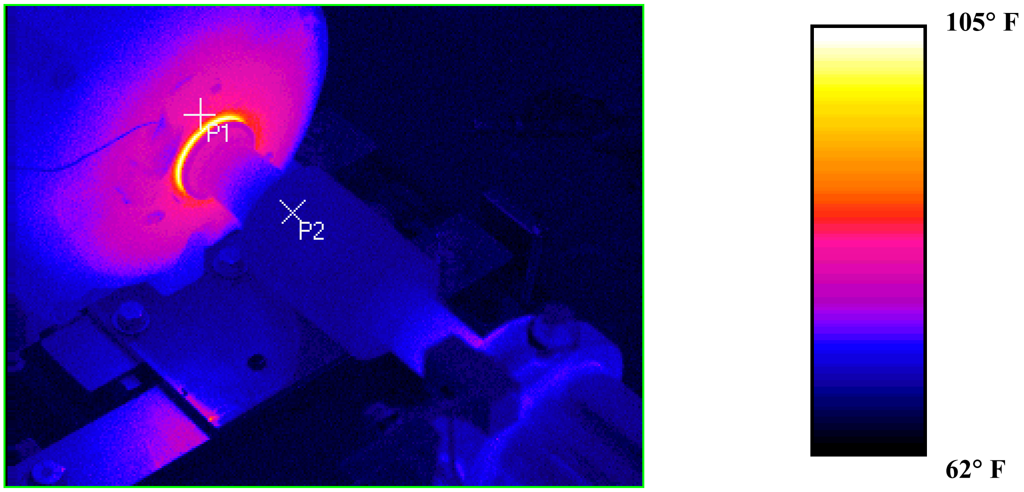


*Figure 4-6. Example Thermogram Showing Misalignment (a).*

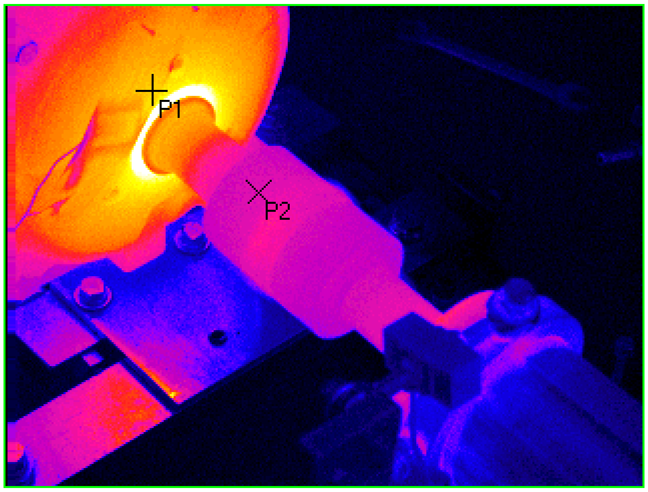


*Figure 4-7. Example (b).*

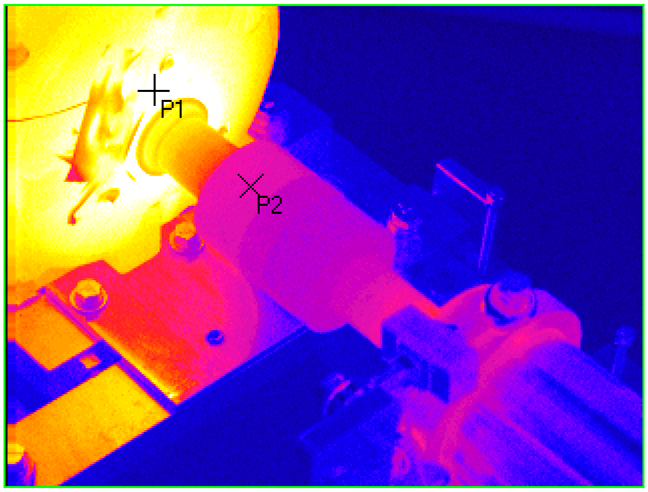


*Figure 4-8. Example (c).*

The use of thermography is split into two categories, electrical and mechanical. Some applications for both categories are introduced below.

**Electrical**

Electrical applications monitor temperature increases caused by loose, oxidized, or corroded connections or component malfunction. Some example components are:

- Main Transformers
- Motor Control Centers
- Circuit Breakers
- Distribution Panels
- Connections
- Cable trays
- Control Systems.

**Mechanical**

Mechanical applications monitor the heat generated by friction of defective parts, misalignment, wear, poor lubrication and misuse. Some example problems are:

- Rotating Equipment Bearings
- Electric Motor and Pump Casings
- Couplings
- Steam Traps
- Condensers, Heat Exchangers, Piping
- Steam and Compressor Leaks
- Valves
- Brick Furnaces
- Process Applications

- Insulation deterioration
- Vacuum Leaks.

Conditions that are routinely monitored with the use of thermography include:

- Surfaces
- Bearings
- Internal Structure Temperature
- Electrical Connections
- Processes.

## Thermography Acceptance and Severity Criteria

Table 4-2 identifies criteria for evaluating equipment acceptance and fault severity for electrical systems only. These classifications are based on observed temperature rise above nominal (or baseline) only. The importance of the item involved to the operation must be considered when determining timing of corrective action. In addition, the temperature rise is dependent on the load on the equipment; a minor finding on lightly loaded equipment could be more serious when the equipment is fully loaded.

*Table 4-2. Electrical Equipment Severity Criteria.*

| Classification | Temp. Rise | Comments |
|---|---|---|
| **Minor Problem** | **1 – 18 deg F** | Repair as a part of regular maintenance. Little probability of physical damage. |
| **Intermediate Problem** | **18 – 63 deg F** | Repair in the near future (2-4 weeks). Watch load and change accordingly. Inspect for physical damage. There is probability of damage in the component, but not in surrounding components |
| **Serious Problem** | **63 – 135 deg F** | Repair in the immediate future (1-2 days). Inspect the surrounding components for probable damage. |
| **Critical Problem** | **135 deg F or Greater** | Repair immediately. Inspect surrounding components. Repair while IR camera is still available to inspect after correction. |

Other findings on mechanical equipment such as bearing temperatures, heat transfer or cooling equipment, etc., are classified according to a qualitative assessment of normal versus abnormal temperatures by the thermographer(s) or according to the severity of the problems found. One example might be based on 30% of the cooling fins on a transformer or heat exchanger being plugged. Some qualitative assessment of severity will most often be required when evaluating mechanical components.

# Chapter 5 – Proactive and Corrective Actions

## Introduction

In this chapter, we will look at various proactive and corrective actions that may be taken to eliminate problems identified by the primary CBM technologies. Balancing, alignment, soft foot, and foundations of machinery will be discussed as they relate to problems most easily diagnosed using vibration analysis. Some examples of cause and effect relationships between the corrective action and the resulting vibration levels will be discussed.

## Balancing

Unbalance of rotating machine components remains as one of the leading causes of vibration, simply because there are so many different ways unbalance can occur. Correcting unbalance, however, is a fairly simple task once one understands a few of the basic principles. We will not attempt to explain balancing procedures in this short overview, because the process is a technical class in itself.

Most present-day vibration analyzers and even data collectors have the means of providing the necessary data—vibration amplitude and phase—needed to solve most balancing problems. Some instruments actually incorporate balancing programs that automatically calculate the needed balance corrections. All the operator needs to do is follow a simple menu of instructions.

Once an unbalance condition has been diagnosed through analysis, it may be possible to actually balance the machine in-place, eliminating costly and time consuming disassembly. All that is required is that the unbalanced component be accessible for the addition or removal of balance correction weights.

Unbalance is often defined as simply the unequal distribution of the weight of a rotor about its rotating centerline. Or, according to the International Standards Organization (ISO),"…that condition which exists in a rotor when vibratory force or motion is imparted to its bearings as a result of centrifugal forces." (Reference 1).

Sources of unbalance include:

- CASTING IMPERFECTIONS
- ECCENTRICITY
- ADDITION OF KEYS AND KEYWAYS
- DISTORTION
- CLEARANCE TOLERANCES
- CORROSION AND WEAR
- DEPOSIT BUILDUP.

From the above discussion, it should be apparent that there are many reasons a rotor could be out-of- balance. And, in many cases, a rotor may have more than one source of unbalance. As a result, it is impossible to simply look as a rotor and determine the actual amount and location of unbalance. Fortunately, regardless of the number of unbalance sources a rotor may have, all sources of unbalance in a given reference or balance plane will "vectorially" combine to produce a single "heavy spot" at a certain angular location on the rotor where weight can be removed to successfully balance the rotor. Of course, if weight can not be removed from the heavy spot, weight can be added directly opposite the heavy spot on the "light spot". (Reference 1).

Balancing of rotating machinery is one of the single easiest ways to avoid failures. By limiting the dynamic forces associated with rotating unbalance, every component in the asset and the surrounding structure has reduced mechanical stresses and the opportunity for increased reliability and extended life.

An oil refinery in Louisiana currently has no vibration-based PdM program in place, and yet they have 98% equipment availability and almost zero equipment failures. The reason for this success is an outstanding PM program coupled with an exacting balancing program. No piece of equipment is placed in service at the refinery until its rotor has been balanced in a balancing machine to an ISO 1940 grade G-1.0. This represents an extremely tight balance tolerance usually reserved for critical finishing machine tools and other tight tolerance rotors. The refinery has determined, however, that the extra time spent on the balancing stand to affect a premium balance more than pays for itself in terms of production uptime.

The single-plane balancing process simply involves:

1) Analyzing amplitude and phase vibration data to identify the cause of vibration is UNBALANCE.
2) Collecting stable data at running condition and operating temperature in the original "O" state .
3) Next, a safe trial weight calculation is made using the procedure identified below.
4) A trial weight is added, and the machine is run again to collect the unbalance effects of the original unbalance plus the trial weight, "O+T".
5) Calculation of a Correction Weight that, when applied, will affect the balance desired.
6) Trim balancing as required to meet the specified balancing tolerances for the piece of equipment.

It is important when applying a trial weight that the weight is not so great that it may cause excessive vibration and damage or even destroy the machine. Therefore, it is a good idea to use a simple rule of thumb when determining a trial weight amount. The rule of thumb states that the dynamic force associated with the trial weight unbalance should be no greater than 10% of the static weight of the rotating element. Using this method will prevent damaging levels of vibration even if the trial weight is placed inadvertently right on the "Heavy Spot". The following example shows the simple procedure using English units of measure.

*TRIAL WEIGHT CALCULATION*

*Example:*

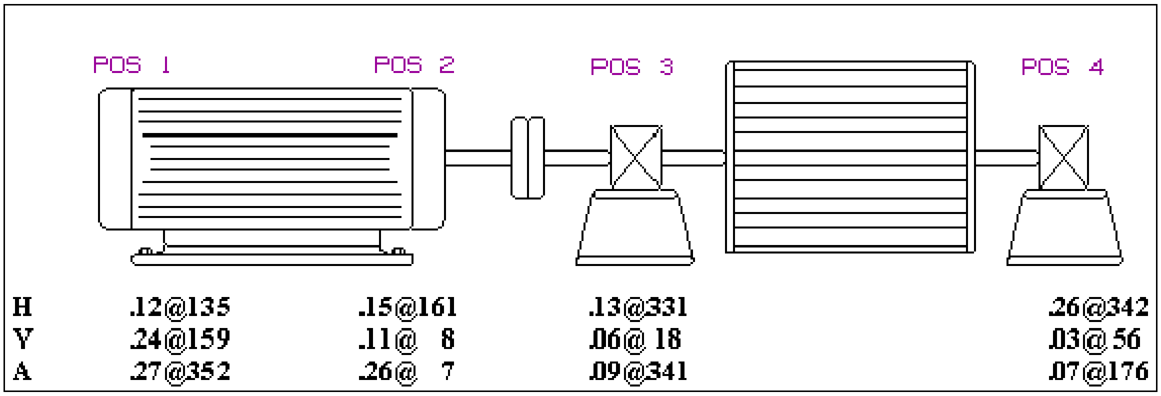
Rotor weight = 1000 lbs. Each bearing supports 500 lbs.

$F_{lbs}$ = 10% of 500 lbs. = 50 lbs.
$F_{lbs} = 1.77 \times W \times R \times (RPM/1000)^2$
$F_{lbs}$ = Force generated in pounds
W = Trial Weight in ounces
R = Trial Weight radius in inches

RPM = 3600 ; (1.77 is a conversion factor.)
$F_{lbs}$ = 50 lbs.
W = ? oz.
R = 10 in.

$10\%(\text{Rotor weight}) = 1.77 \times W \times R \times ({}^{RPM}/_{1000})^2$
$50 \text{ lbs.} = 1.77 \times W \times 10 \text{ in.} \times ({}^{3600}/_{1000})^2$
W = 0.218 ounces. (See Reference 1.)

Next, we will look at a practical example of performing a balance operation on a basic center-hung induced draft fan on an air handling unit. The plant was down for a regularly scheduled annual outage. The reliability team had identified worsening vibration on the motor and, to a lesser extent, on the fan. In this example, we will focus on the fan at right in Figure 5-1. Later, we will discuss the motor on the left.

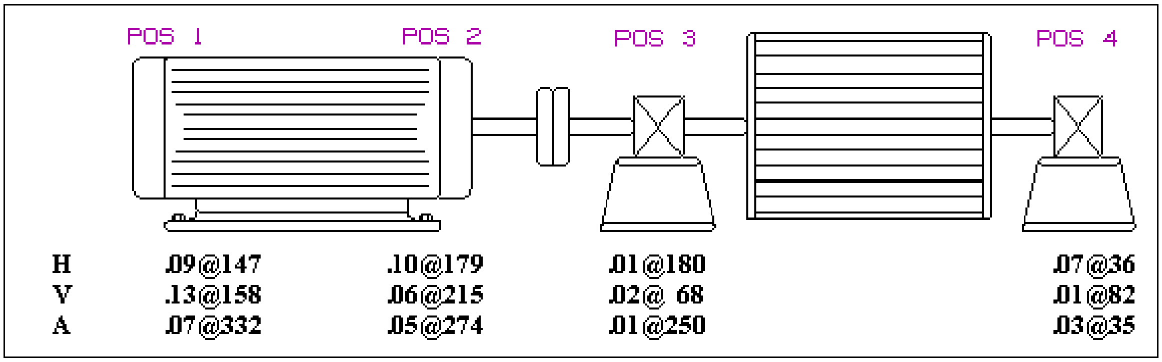


| | POS 1 | POS 2 | POS 3 | POS 4 |
|---|---|---|---|---|
| H | .12@135 | .15@161 | .13@331 | .26@342 |
| V | .24@159 | .11@ 8 | .06@ 18 | .03@ 56 |
| A | .27@352 | .26@ 7 | .09@341 | .07@176 |

<u>Figure 5-1</u>. *Dynamic unbalance is indicated on the fan at right **before** balancing.*

Note that the fan data shows .13 in/sec pk @ 331 deg on the inboard horizontal (pos. 3-H) and .26 in/sec pk on the outboard (OB) horizontal (pos. 4-H). There is approximately a 47 degree and 74 degree phase shift between horizontal and vertical on the IB and OB ends, respectively. **These data indicate a probable two plane balance problem.** The axial data indicate a 165 degree phase shift from one end of the machine to the other indicating a bent shaft or bowed rotor condition. Because the problem with the fan was secondary in this case (and the pressure was on to return the unit to service), the decision was made to remove the static unbalance in the fan and reduce the unbalance as much as possible in the least amount of time.

A trial weight of 0.5 ounces was selected and applied by tack-welding to the outside diameter of the fan wheel at the center of the rotating element. The resulting unbalance vector indicated that a correction weight of 2.75 ounces need to be applied 40 degrees against rotation from where the trial weight had been applied. The trial weight was removed, and the correction weight was applied at the appropriate location with the resulting data shown on the fan in Figure 5-2.



| | POS 1 | POS 2 | POS 3 | POS 4 |
|---|---|---|---|---|
| H | .09@147 | .10@179 | .01@180 | .07@36 |
| V | .13@158 | .06@215 | .02@ 68 | .01@82 |
| A | .07@332 | .05@274 | .01@250 | .03@35 |

*Figure 5-2. Single plane balancing was used to remove the static unbalance in the fan. Data are shown* ***after*** *application of a correction weight.*

Due to time constraints, the residual dynamic unbalance was left alone and the results were deemed "satisfactory" by the customer. Comparing the 1X rpm amplitudes at positions 3 & 4 Horizontal, Vertical, & Axial, one can see the dramatic improvement due to the balancing correction. Field balancing can be a very effective corrective action.

## Alignment

All shaft misalignment conditions can be characterized as angular or offset. Angularity is simply the angle between the shaft centerline of the Stationary Machine, (STAT) and the Machine To Be Moved, (MTBM), in both the horizontal and vertical planes independently. The STAT machine is always considered zero degrees.

Since shaft centerlines can be extended theoretically to any length, the shaft centerlines in either plane will cross at some point, (unless the angle is zero). Of course, the angle between the coupling faces is always the same as the angle between the shaft centerlines. Offset, unlike angularity will be different at any place along the shaft centerlines, (again unless the angularity is zero). Angularity for alignment purposes is normally specified in MILS per inch (or pitch). This type of specification is identical to the "rise and run" pitch used by carpenters for roof and stair angles. At the point where the shaft centerlines meet, the offset is zero. As you move away from the point of the intersection, the offset increases, (negative or positive), at the rate of the pitch. (Reference 2).

The preferred running condition for a piece of equipment is for all phase angles to be the same in the horizontal, vertical, and axial directions, respectively. Any variations are due to machine distortion, unbalance, misalignment, etc. Figure 5-3 is a representation of angular offset misalignment. In the case of purely angular misalignment, one may expect 1X rpm vibration that is nearly 180 degrees out of phase in the axial direction across the coupling as shown by the "tick marks" in the figure. Vibration spectra may show any combination of 1X, 2X, 3X, or higher harmonic vibration. On the other hand, as shown in Figure 5-4, parallel offset misalignment tends to act as a crank mechanism generating high 1X amplitude of vibration that is nearly 180 degrees out of phase in the radial direction. Again, spectral data might indicate any combination of 1X and harmonics (with 2X rpm vibration being very common).

Most misalignment occurs as a combination of angular and offset misalignment. Therefore, the 180 degree rule of phase change across the coupling does not always apply. An indication of 120 degree to 240 degree phase shift across the coupling is likely the contribution of misalignment.

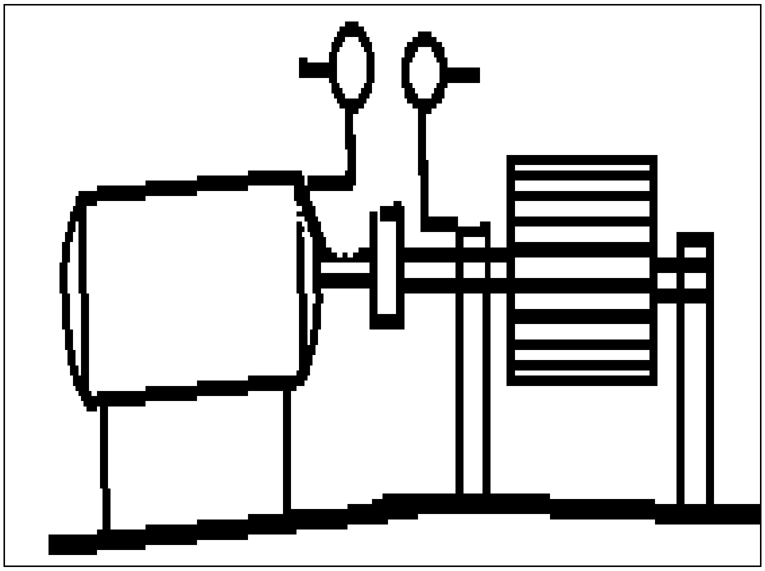


*Figure 5-3. Representation of angular misalignment. Note the out-of-phase characteristics across the coupling in the axial direction.*

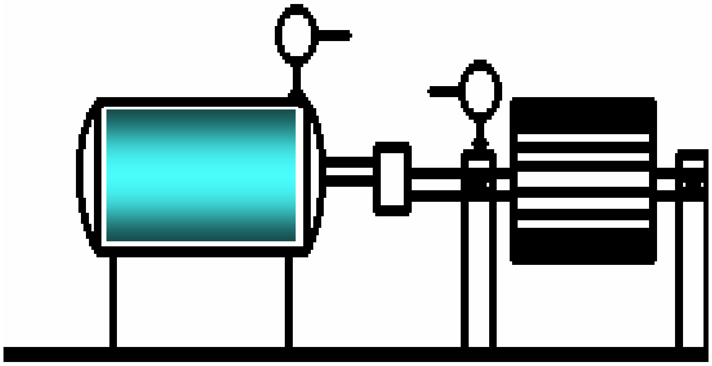


*Figure 5-4. Representation of parallel offset misalignment. Note phase differential in the radial direction across the coupling.*

Some general guidelines for good alignment practice are listed below:

- Precision alignment to tight tolerances should be accomplished in the hot operating condition.
- Thermal growth should be factored into the alignment and measured if necessary.
- Machinery should be set in place and aligned before piping is attached.
- Piping alignment should be corrected if changes to coupling alignment exceed 2 MILS angular or offset and 1 Mils for machines greater than 3500 rpm.
- Soft Foot conditions (discussed later) should be removed prior to performing alignment.
- Bent shafts, eccentric couplings, and skewed coupling bore centerlines can give false alignment readings. Runout should be measured using dial indicators to verify roundness to within .001"/inch of diameter on OD, and .0005"/inch diameter on shaft and bore.
- Monitor bearing temperatures on the first run after an alignment to ensure proper results (including thermal growth and pipe strain conditions) have been obtained.
- Also check vibration amplitude and phase to confirm that any misalignment condition has been removed.
- Shim first to achieve vertical alignment, then move the unit into horizontal alignment.
- Whenever possible, use precut and machined shims that closely approximate the size and shape of the machine foot.
- It is a good idea to have .125" to .250" of shim under each foot before beginning the alignment process.
- Never stack more than three shims under a foot since the resulting spring-effect can degrade structural stiffness and promote foot-related resonance.
- After shimming or moving, tighten hold-down bolts gradually and one at a time while monitoring dial indicators or laser alignment tool.

Tolerances are an important consideration in any alignment procedure. Many large machine trains have tolerances specified by the manufacturer. Plants may also have their own tolerances established from experience. When other sources are not available, a table of generally acceptable tolerance is provided as Table 5-1. The EXCELLENT tolerance levels are the preferred ones; the ACCEPTABLE tolerance levels are only provided as a last resort level when machine are bolt bound or bottomed out. The EXCELLENT tolerances may lower than those used in many plants. It is sometimes a good idea to take the extra effort to achieve the lower tolerances. (Reference 2).

*Table 5-1. General Purpose Machinery Alignment Tolerances.*

| Direct Coupled Machines | RPM | Excellent Mils | Acceptable Mils |
|---|---|---|---|
| Parallel | 600 | 5.0 | 9.0 |
| | 900 | 3.0 | 6.0 |
| | 1200 | 2.5 | 4.0 |
| | 1800 | 2.0 | 3.0 |
| | 3600 | 1.0 | 1.5 |
| | 7200 | 0.5 | 1.0 |
| Angular (mils/inch) | 600 | 1.0 | 1.5 |
| | 900 | 0.7 | 1.0 |
| | 1200 | 0.5 | 0.8 |
| | 1800 | 0.3 | 0.5 |
| | 3600 | 0.2 | 0.3 |
| | 7200 | 0.1 | 0.2 |
| Machines with Spool Pieces (mils/in) | 600 | 1.8 | 3.0 |
| | 900 | 1.2 | 2.0 |
| | 1200 | 0.9 | 1.5 |
| | 1800 | 0.6 | 1.0 |
| | 3600 | 0.3 | 0.5 |
| | 7200 | 0.15 | 0.25 |

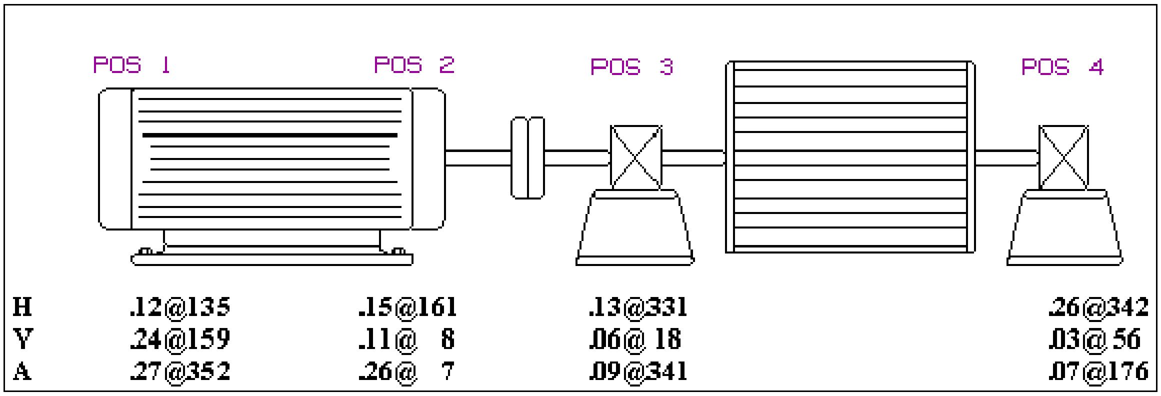
Permissible Gap Difference = Coupling Diameter X Permissible Slope

## Soft-Foot

When machine feet are not coplanar with the base, or when shims are not installed properly, a soft foot condition exists. When soft foot is present, undue stress is applied to the machine frame. The results are unpredictable results from machine moves, frustrating the alignment effort. To test for soft foot conditions, each foot bolt is loosened independently and the amount of movement is measured. As a general rule, if foot tested causes more than 2 MILS deflection, a soft foot condition exists and should be corrected before final alignment moves are attempted.

Soft foot can cause a number of significant problems within a machine. First, excessive vibration almost always results from a soft foot condition. Second, foot related resonance may manifest due to soft foot and result in extremely high vibration. Third, soft foot causes machine distortion and dynamic stresses that affect proper alignment and may also deteriorate the machine. Motors are especially susceptible to soft foot conditions, because the continual flexing of the stator causes air gap variation that leads to fluctuations in the rotating electromagnetic field. Over time, the combination of mechanical and electromagnetic induced stresses break down the stator and cause an electrical fault. Figure 5-5 is an example of such a case.

Recall that we addressed the fan balance problem on this unit in the previous Balancing section. Note from Figure 6-5, however, that the 1X rpm vibration amplitudes are far higher on the motor. Note also that the axial amplitudes are higher than the radial direction. This is very uncommon, since a healthy machine would have very limited axial forces. These data indicated a potential soft foot, and an investigation was conducted to evaluate the situation.



| | POS 1 | POS 2 | POS 3 | POS 4 |
|---|---|---|---|---|
| H | .12@135 | .15@161 | .13@331 | .26@342 |
| V | .24@159 | .11@ 8 | .06@ 18 | .03@ 56 |
| A | .27@352 | .26@ 7 | .09@341 | .07@176 |

*Figure 5-5. 1X rpm amplitude (in/sec pk) and phase data showing high amplitudes and strange phase behavior.*

Figure 5-6 shows 1X rpm amplitude and phase readings at each of the hold-down bolt locations. The arrows indicate near 180-degree phase shifts that show that the motor is rocking back and forth from North to South and especially from NE to SW. These data conclusively show that a soft foot condition exists, so the unit was shut down. Dial indicators were placed around the machine at the feet, and one hold-down bolt at a time was loosened. Once each foot was completely loose, dial indicator measurements were recorded and the bolts were re-tightened before progressing to the next foot. This evaluation clearly indicated that the NE foot was soft.

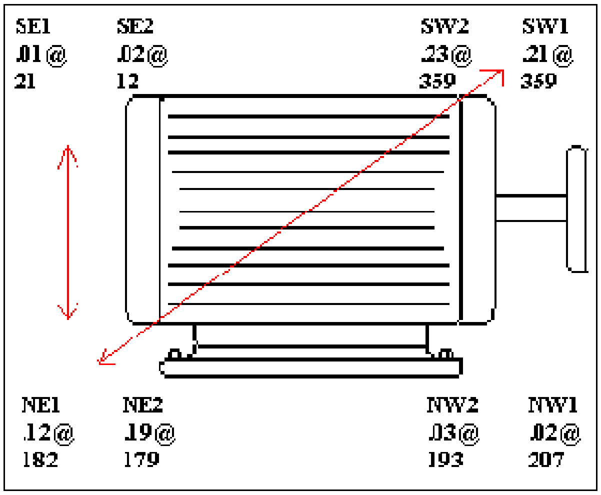


*Figure 5-6. Assessment of phase data indicates soft foot.*

Step shimming was necessary to achieve the results shown in Figure 5-7. More than .065" of shim was necessary to correct this problem. Note that all amplitudes dropped significantly when compared to Figure 5-5 and that the axial amplitudes improved most dramatically. This soft foot condition resulted from an improper cure of new grout or non-parallel sole plates. The motor had been placed on brand new sole plates the previous day. As the outage neared an end, the pressure to get back on-line forced the maintenance crew to start the machine before the recommended 24-hour cure of the grout. The grout pulled loose at the NE corner of the motor and the vibration problem resulted. To completely alleviate the problem, the foot needs to be re-grouted with a proper cure time.

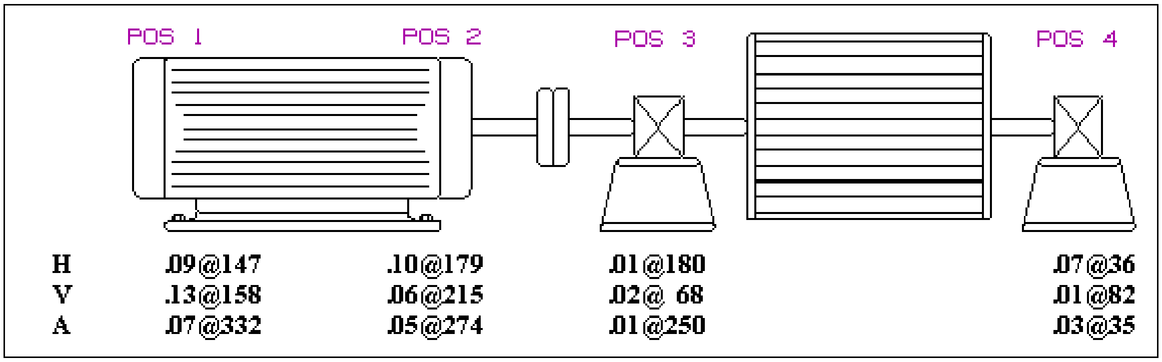


*Figure 5-7. Note the dramatic reduction in amplitude and more logical phase data after partial correction of the soft-foot condition.*

This is just one example of a soft foot identification and correction. This is a fairly common problem in all industrial and office building applications. Soft foot causes the accelerated deterioration of machines, structures, and components. Further, it forces greater electrical power consumption of motors due to the unnecessary work that is going toward machine degradation.

## Foundations of Machinery

Good design practice recognizes the need for foundation consideration where machinery is concerned. An excellent foundation is absolutely necessary to help minimize vibration and the associated alternating stresses that limit machine life. Improper foundation design can lead to low support stiffness and resonance. Both phenomena lead to high vibration.

Whenever possible, rotating machinery should be mounted on a concrete pedestal rather than a fabricated steel foundation. Concrete pedestals are inherently more stiff than steel fabrications. Natural frequencies of the pedestal should be within +/- 20% of any running speed of equipment to be mounted on the pedestal.
Whenever possible, equipment should be located at ground label. Installations on mezzanines and higher floors are notorious for having high vibration characteristics due to structural weaknesses and the potential for resonance.

Integral bases are extremely important in the proper setting of machinery. Separate pedestals lead to unhealthy relative motion between inboard and outboard bearings or from the driver to the driven piece of equipment. Resulting stresses impact machine life. The distance from the foundation floor to the machine centerline should also be minimized to minimize the effects of rocking motion. When setting a new machine, maintenance or construction personnel should leave ample room near the machine to install auxiliary equipment, anchor bolts, piping, and maintenance clearance.

Figure 5-8 is a sketch showing key dimensions and physical properties. The following recommendations apply:

- Minimize the distance between the slab and the shaft centerline, h.
- $M_b$ should be 3X-5X $M_{m.}$
- W/h should be greater than 1.5 to minimize rocking.
- Place machine symmetrically on the foundation (i.e. machine evenly supported by foundation).

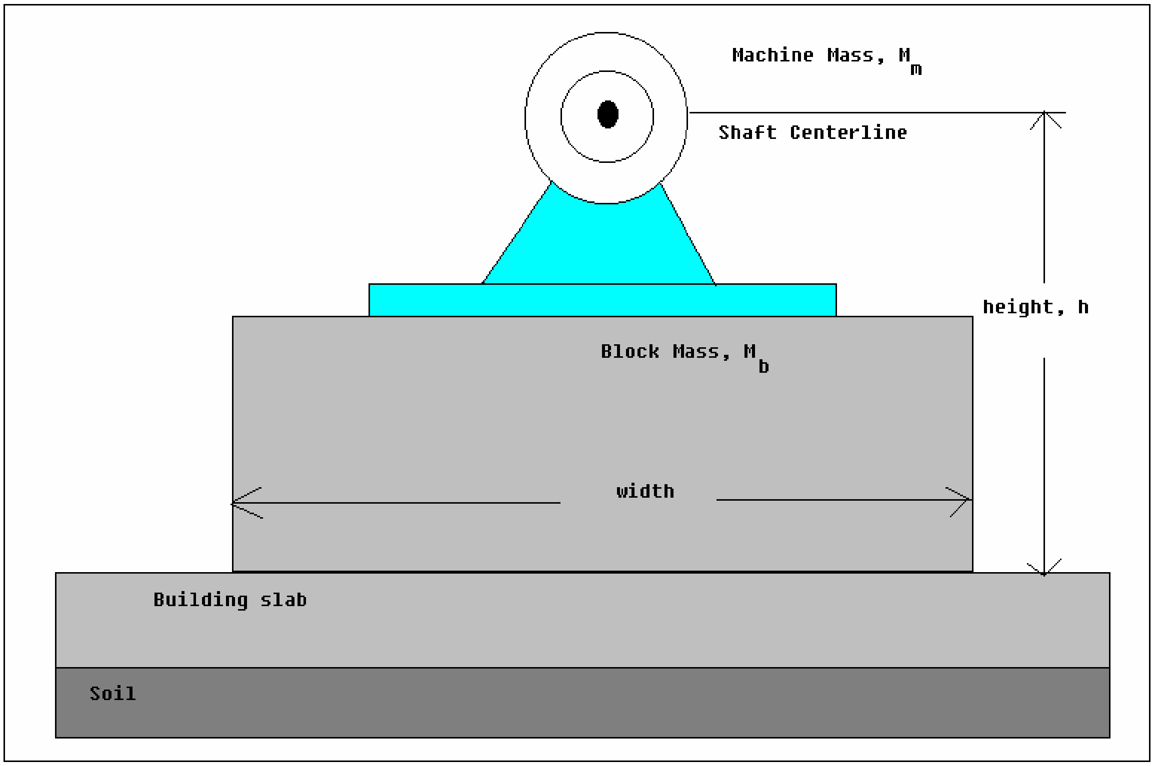


*Figure 5-8. General purpose machinery foundation and layout.*

## Summary

In this chapter, we have introduced several corrective actions that may be employed to resolve machinery problems. Each of these methods: balancing, alignment, soft foot correction, and proper foundations of machinery may also be employed proactively to maximize machine life and reliability from the outset of service. Each of these topics may be treated as a course in itself, but the general guidelines and examples specified herein represent an overview of corrective methods and the potential impact on systems.

# Chapter 6 – Other Condition Monitoring Techniques

## Introduction

In this chapter, we will take a look at Motor Current Signature Analysis (MCSA), Motor Circuit Testing, and Ultrasonic Emissions. A brief description of each technology will be given. The various applications for each technology as well as the advantages and disadvantages will also be introduced.

## Motor Current Signature Analysis (MCSA)

As a reliability program matures, MCSA should be implemented on all critical drive motors. MCSA complements vibration analysis in terms of quantifying the severity of electrical faults, static eccentricity, and dynamic eccentricity in the motor under operating circumstances. These data are acquired using a clamp-on current probe, special filters, a digital signal analyzer, and (normally) an expert system to evaluate the results. Data are acquired with the unit under normal operating conditions (at least 70% load), and the resulting analysis is capable of identifying:

Phase unbalance
Bad rotor bars
Faulty collector rings
Dynamic eccentricity
Static eccentricity.

The rotor bar/end ring faults are easily quantified through this technique, whereas vibration analysis is a more qualitative assessment of these types of problems. When clarification is required, MCSA is an excellent means of gaining an understanding of the severity of the electrical fault as depicted in Figure 6-1.

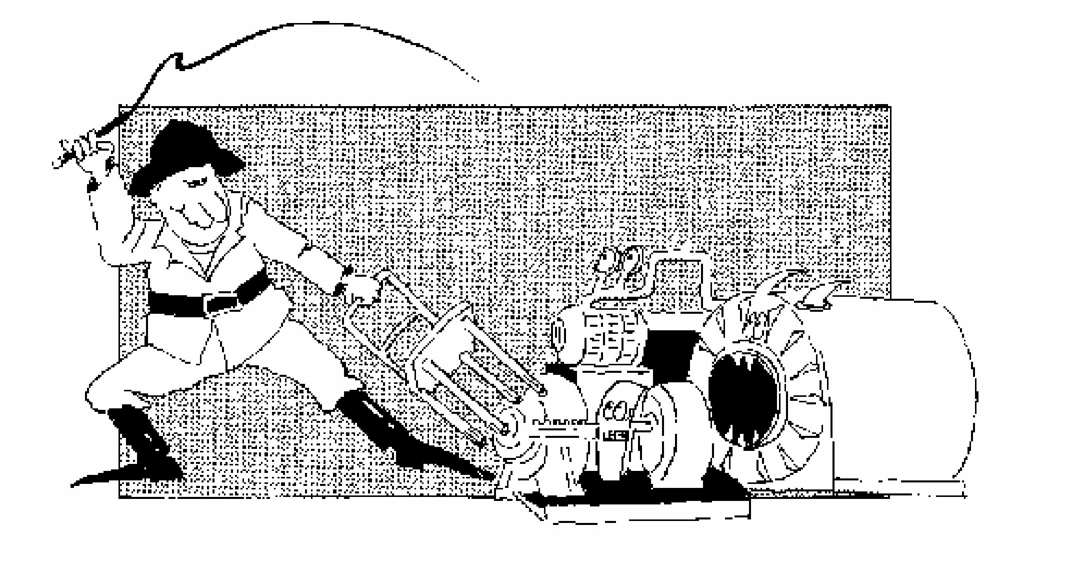


*Figure 6-1. MCSA can be used to quantify the severity of electric motor faults that vibration detects.*

MCSA identifies eccentricity problems associated with non-concentric rotor and stator, soft/sprung foot conditions, and bowed rotor conditions. Identifying these problems in large motors (above 150 Hp) is especially critical, since eccentricity causes electromagnetic unbalance and associated alternating stresses on the stator elements. These alternating stresses degrade the stator over time and can result in loose iron, insulation breakdown, and shorts.

Figure 6-2 shows a breakdown of typical motor failures. One can see that approximately 55% of the faults occur in the rotor and stator. These problems typically manifest as an electrical breakdown and localized arcing that causes alternating variations in the electromagnetic pull. However, it is often a mechanical problem such as soft foot that is the root cause of the electrical failure. Also note that approximately 40% of failures are bearing related.

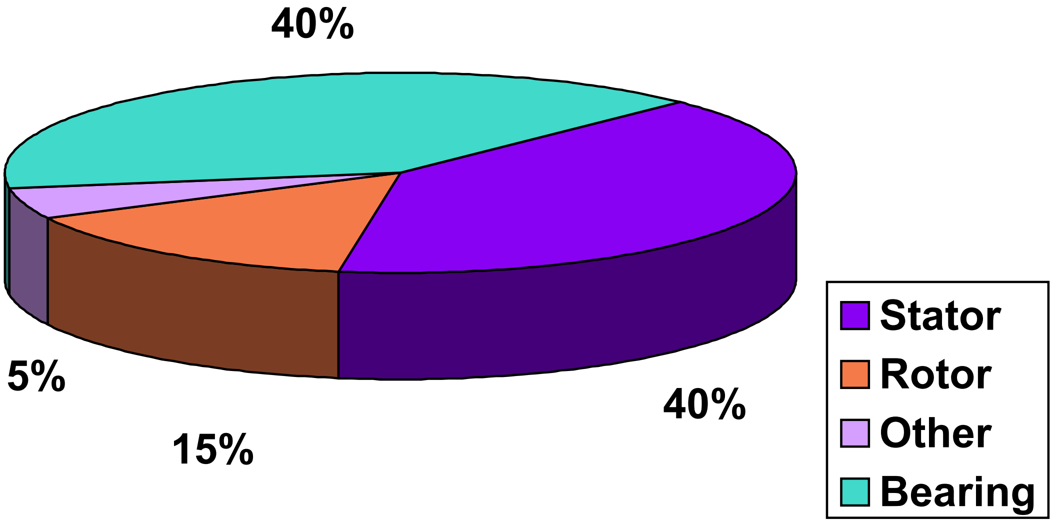
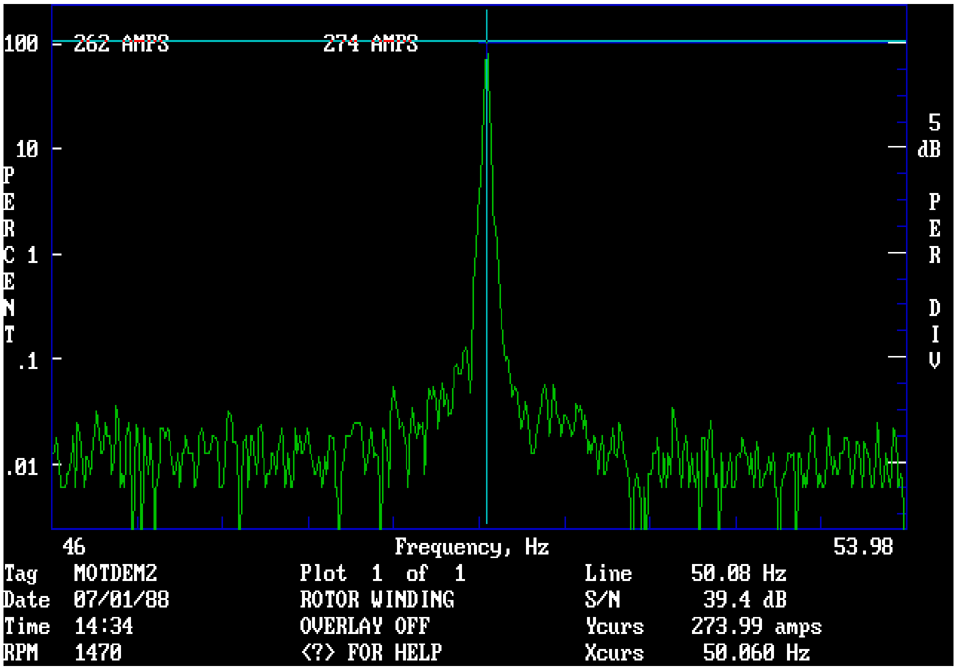


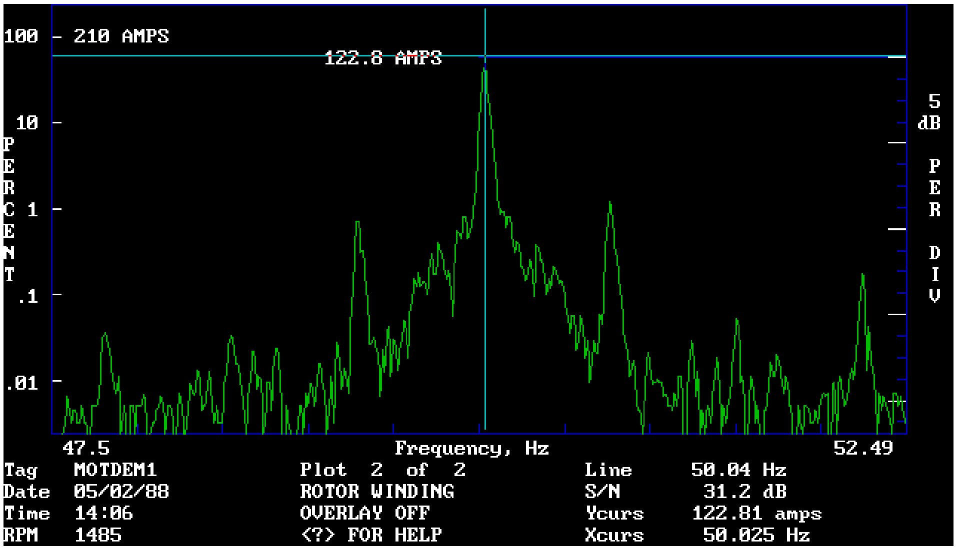
*Figure 6-2. Breakdown of electrical motor failures by component.*

As noted above, MCSA uses a clamp-on current probe around a primary or secondary circuit to evaluate the motors condition. By looking at the amperage at line frequency (60 Hz in the US; 50 Hz in Europe, Australia, and others) relative to the amplitude at the so-called slip frequency side band frequencies, MCSA can be used to determine if a problem exists in the rotor of the motor. Figure 6-3 is a spectrum from a healthy motor. Note that the amperage at 50 Hz is greater than 60 dB higher than that at either the upper or lower slip frequency sideband. On the other hand, Figure 6-4 indicates a severe problem in the rotor. The amplitude at 50 Hz is only 38 dB greater than the peak at the upper slip frequency sideband. Amplitude ratios between 50 Hz and slip sidebands of less than 50 dB indicate broken rotor bars and less than 45 dB indicate multiple broken rotor bars and probable end ring problems.



```
Tag   MOTDEM2      Plot  1  of  1      Line     50.08 Hz
Date  07/01/88     ROTOR WINDING       S/N       39.4 dB
Time  14:34        OVERLAY OFF         Ycurs    273.99 amps
RPM   1470         <?> FOR HELP        Xcurs     50.060 Hz
```

*Figure 6-3. Current spectrum from a healthy rotor.*



```
Tag   MOTDEM1      Plot  2  of  2      Line     50.04 Hz
Date  05/02/88     ROTOR WINDING       S/N       31.2 dB
Time  14:06        OVERLAY OFF         Ycurs    122.81 amps
RPM   1485         <?> FOR HELP        Xcurs     50.025 Hz
```

*Figure 6-4. Current spectrum from a severely damaged rotor.*

Figure 6-5 is a photograph of the motor identified as faulty in Figure 6-4. Note that many of the rotor bars are actually broken completely through and isolated from the end ring. Had this problem not been identified through predictive techniques (vibration and MCSA), an almost certain catastrophic failure would have resulted.

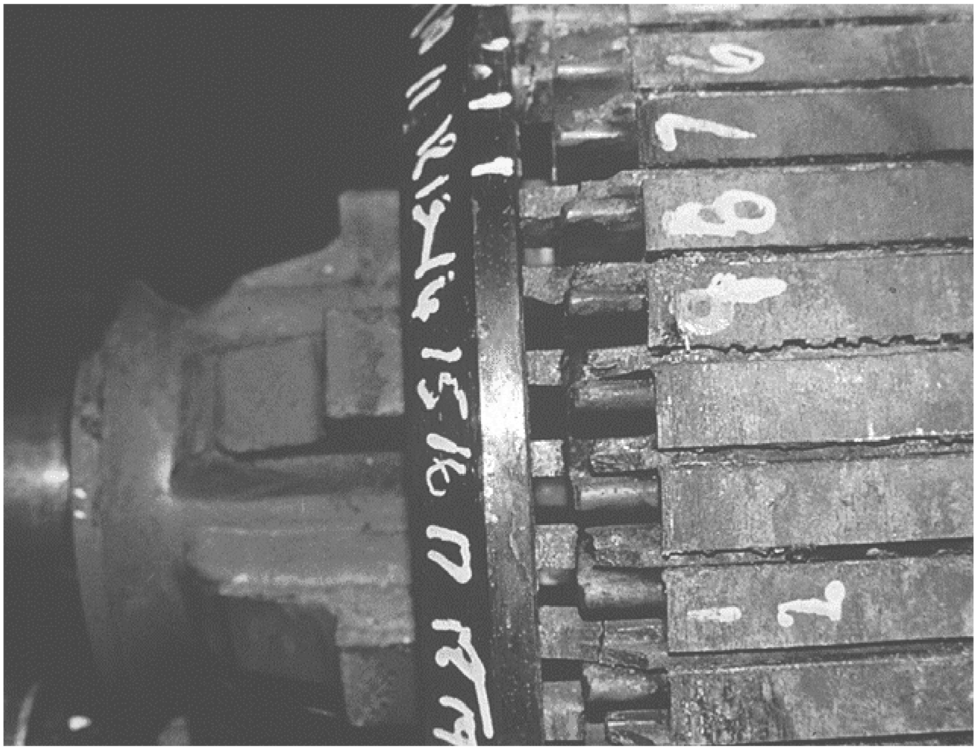


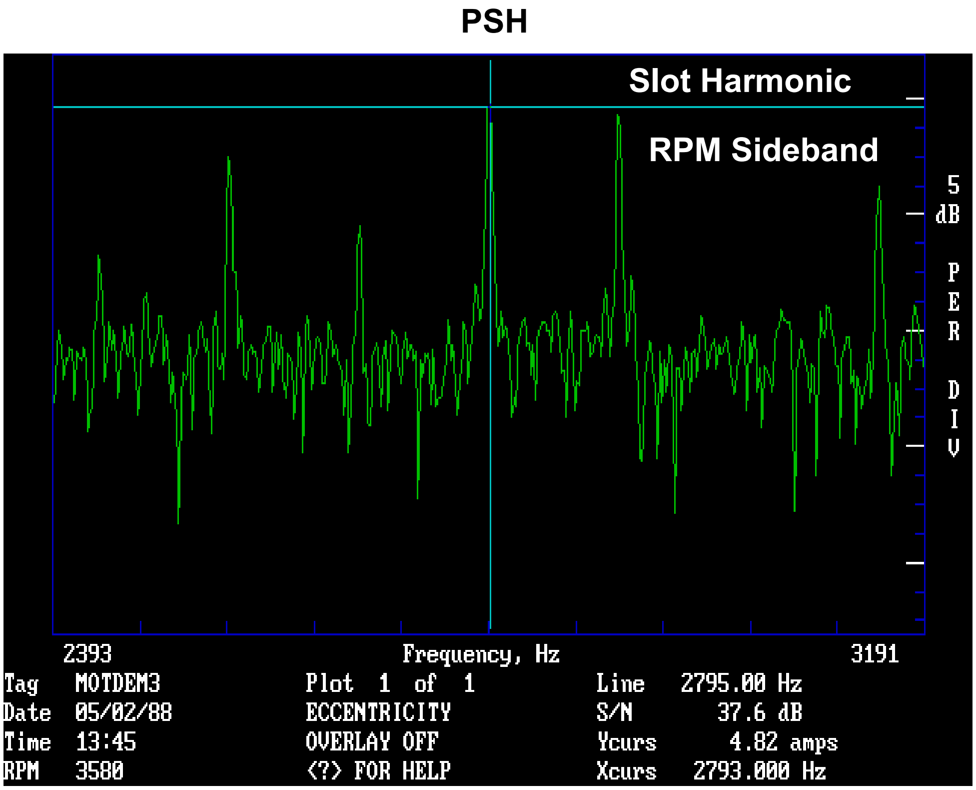
*Figure 6-5. View of the motor rotor shows severe damage where rotor bars are broken away from the end ring.*

Similar to the rotor evaluation, dynamic and static eccentricity problems may also be identified through MCSA. Static eccentricity causes an uneven air gap between the rotor and stator. Since the problem is typically a distortion of the stator housing , the air gap proble is stationary. Dynamic eccentricity is an uneven air gap between the rotor and stator that follows the rotation of rotor. It is typically caused by a bent shaft or bearing centerlines offset from the stator centerline.

Eccentricity problems are typically found through interpretation of amperage at the principal slot harmonic frequency (PSH) or other slot harmonics spaced at twice line frequency from the principal slot harmonic with sidebands occurring at multiples of running speed (in Hz). The equation for PSH is:

$$\boxed{\text{PSH} = ((\text{No.Bars x Running RPM}) / 60)) + \text{Line Frequency.}}$$

Dynamic eccentricity shows up in the spectrum as running speed sidebands around slot harmonic frequencies as shown in Figure 6-6.  Static eccentricity shows up as an increase in amplitude at slot harmonic frequencies from survey to survey.



```
Tag   MOTDEM3        Plot  1  of  1      Line    2795.00 Hz
Date  05/02/88       ECCENTRICITY        S/N        37.6 dB
Time  13:45          OVERLAY OFF         Ycurs      4.82 amps
RPM   3580           <?> FOR HELP        Xcurs   2793.000 Hz
```

*Figure 6-6. Current spectrum indicative of a dynamic eccentricity problem.*

The advantages of MCSA include: quantifiable evidence of rotor damage in the motor, the ability to identify eccentricity problems that may or may not be evident in the vibration spectra, and confidence in the diagnosis.  Disadvantages include: MCSA hardware and software is fairly expensive, these types of failures are somewhat uncommon, and noisy electrical signals sometimes make valid data hard to obtain.

## Motor Circuit Testing

"The stator windings in an induction motor are designed to create magnetic poles that induce the opposite magnetic pole in the rotor.  The motor windings are insulated from ground.  The parameters for electrical circuits are inductance, resistance, and capacitance.  The stator winding circuits possess the attributes of each.  The circuit from any lead to ground have capacitance and resistance.  The resistance lead-to-lead is very low, usually measured in micro-ohms.  The resistance to ground is very high, measured in meg-ohms."

“On a three-phase motor there are three leads (phases A, B, and C) connected so that the three individual circuits are balanced. Each circuit, A to B, B to C, and C to A, should have equal inductance and resistance. Damaged windings that have shorted turns or faulty connections will be unbalanced, resulting in inefficient motor operation and unbalanced load on the power circuit.” (Reference 2). Phase to phase variation greater than 5% signifies a fault condition.

“ The entire winding, all three phases, should be insulated from ground. When insulation fails, a circuit to ground is created. The flow of current to ground will further damage the insulation and cause the motor to fail.”

“There are a variety of motor circuit tests available. The simplest tests are testing the winding resistance to ground (meg testing) and testing circuit continuity. Resistance to ground is measured in meg-ohms. Meg testers use a high-test voltage, usually a thousand volts above the operating voltage. Testing circuit resistance is not possible with ordinary ohmmeters, because the resistance is too low to indicate. However, it will indicate if there is continuity and any measurable resistance is an indication of a faulty connection.”

“More sophisticated tests involve applying a voltage to the winding and recording the current flow over time. If the voltage is applied across the winding, from phase to phase, a high speed waveform of the current flow can be compared for each of the three-phase pairs. This test is referred to as a surge test.” (Reference 2)

Unlike MCSA, motor circuit testing is conducted with the motor de-energized. It is especially beneficial on new and rebuilt motors when a baseline “signature” can be determined and archived. The motor may then be checked versus this baseline through time to evaluate deterioration of components. A true benefit of this technology is its ability to identify problems that are located outside of the motor, but within its circuitry. These include loose connections, problems in wiring harnesses, and even transformer problems. Motor circuit testing is often used in acceptance testing on new and newly rebuilt motors or when significant problems are suspected. Most problems that can be identified through motor circuit testing may be seen with thermography as well.

The advantages of motor circuit testing include the facts that basic testing may be done easily, quickly, and with inexpensive equipment. More advanced equipment is available from several vendors that is able to conduct sophisticated testing and identify problems such as voids in castings, core problems, and shorted laminations. The only significant disadvantage is associated with surge testing. Because this test is done at such a high voltage (1000 V above normal operating voltage), it can cause accelerated deterioration in the motor or cause actual failure during the test if minor problems already exist.

## Ultrasonic Emissions Evaluation

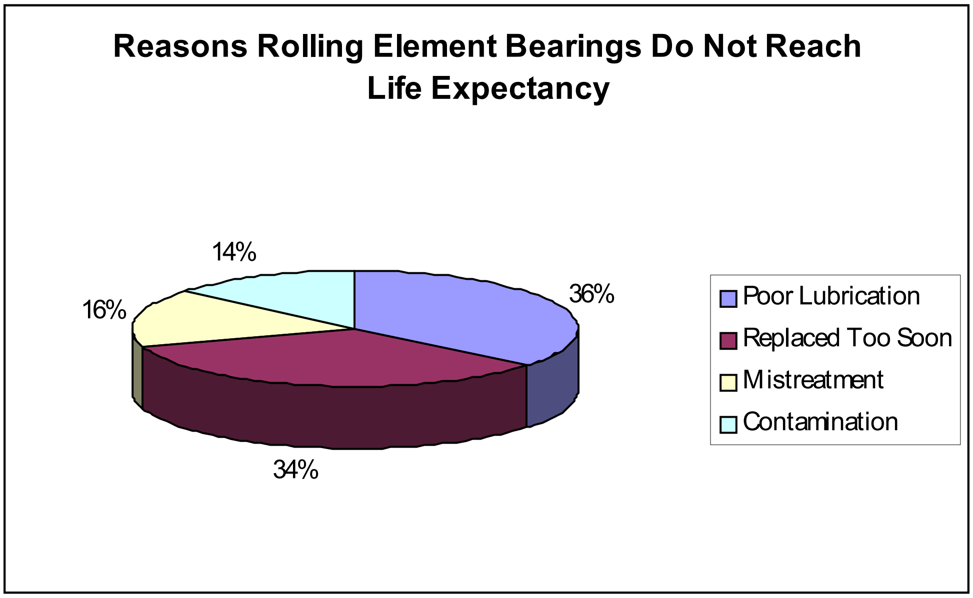
Ultrasound is similar to the dynamic pressure the human ear can hear as audible sound, but ultrasound occurs at frequencies far above the audible range of humans. While most humans hear in the range from 20 Hz to 20 kHz, the ultrasonic range is typically accepted to be from 20 kHz to 100 kHz. Much like vibration, low frequency sound energy travels long distances while high frequency ultrasound energy dissipates very quickly. Unlike vibration which can be highly directional in nature, however, ultrasound propagates radially in all directions. Due to the quick dissipation of high frequency energy, therefore, the ultrasonic intensity will be greatest at the source. This characteristic makes ultrasonic emissions evaluation ideal for locating the precise source of problems.

An airborne ultrasonic device can be an effective, integral part of the equipment utilized by the predictive maintenance program. Ultrasound detectors complement the infrared instruments for routine surveys of electrical equipment. While thermography allows technicians to detect light that the eye cannot see, ultrasound allows them to detect sounds that the ear cannot hear. Corona, arcing, and tracking, which may not show up using thermography, are revealed by ultrasound. Other applications for airborne ultrasonics include:

- Pressurized gas, air leaks
- Vacuum leaks
- Boiler tube, Heat Exchanger leaks
- Steam traps
- Valve seat leaks
- Bearing lubrication timing
- Bearing faults
- Compressor Valve Leakage.

Fault conditions associated with each application generate dynamic pressure in a particular frequency range. Using ultrasonic instruments, the maintenance personnel may identify the presence of a problem in the equipment and then pinpoint its source. Most equipment involves the use of head-phones and filters which make the ultrasonic frequency range audible to the human ear.

Advantages associated with ultrasonic emission technology include a strong ability to pinpoint problems and an excellent problem confirmation and diagnostic capability. It is an easy to use technology that can be implemented with just one to two days of training, and it is relatively inexpensive. Disadvantages associated with this technology include the facts that it is sometimes difficult to filter out background, “non-problem” noise and the equipment often gives extremely early warning. For instance, bearings are often changed out too early when relying on Ultrasonic Emission Evaluation alone. An evaluation conducted by SKF (Figure 6-7) suggests that 34% of bearings are replaced too soon.



*<u>Figure 6-7</u>. Reasons rolling element bearings do not reach the calculated life. (Reference 3).*

**Summary**

In this chapter, a brief discussion of the ancillary predictive maintenance technologies of motor current signature analysis, motor circuit testing, and ultrasonic emissions evaluation has been presented. Focus was placed on some of the practical applications of the technologies and the advantages/disadvantages associated with each.

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