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Predictive Maintenance

R Keith Mobley
The Plant Performance Group

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50.1 Introduction

Maintenance costs are a major part of the total operating costs of all manufacturing or production plants. Depending on the specific industry, maintenance costs can represent between 15 and 40 per cent of the costs of goods produced. For example in food related industries, the average maintenance cost represents about 15 per cent of the cost of goods produced; while in iron and steel, pulp and paper and other heavy industries maintenance represents up to 40 per cent of the total production costs.

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

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

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

Until recently, middle and corporate level management have ignored the impact of the maintenance operation on product quality, production costs and more importantly on bottom-line profit. The general opinion has been ‘Maintenance is a necessary evil’ or ‘Nothing can be done to improve maintenance costs’. Perhaps these were true statements ten or twenty years ago.

However, the developments of microprocessor or computer-based instrumentation that can be used to monitor the operating condition of plant equipment, machinery and systems have provided the means to manage the maintenance operation. They have provided the means to reduce or eliminate unnecessary repairs, prevent catastrophic machine failures, and reduce the negative impact of the maintenance operation on the profitability of manufacturing and production plants.

50.2 Benefits of predictive maintenance

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

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

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

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

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

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

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

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

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

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

The survey determined that advanced notice of machine-train and systems problems had reduced the potential for destructive failure, which could cause personal injury or death. The determination was based on catastrophic failures where personal injury would be most likely to occur. Several insurance companies offering reduction in premiums for plants that have a condition-based predictive maintenance program in effect have supported this benefit.

Several other benefits can be derived from a viable predictive maintenance management program: verification of new equipment condition, verification of repairs and rebuild work and product quality improvement.

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

Vibration analysis, a key predictive maintenance tool, can be used to determine whether or not the repairs corrected existing problems and/or created addition abnormal behavior before the system is re-started. This eliminates the need for the second outage that many times is required to correct improper or incomplete repairs.

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

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

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

50.3 Predictive maintenance techniques

A variety of technologies can and should be used as part of a comprehensive predictive maintenance program. Since mechanical systems or machines account for the majority of plant equipment, vibration monitoring is generally the key component of most predictive maintenance programs. However, vibration monitoring cannot provide all of the information that will be required for a successful predictive maintenance program. This technique is limited to monitoring the mechanical condition and not other critical parameters required for maintaining reliability and efficiency of machinery. Therefore, a comprehensive predictive maintenance program must include other monitoring and diagnostic techniques.

These techniques include (1) vibration monitoring (2) thermography, (3) tribology, (4) process parameters, (5) visual inspection and (5) other nondestructive testing techniques. This chapter will provide a description of each of the techniques that should be included in a full capabilities predictive maintenance program for typical plants.

50.3.1 Vibration monitoring

Vibration analysis is the dominant technique used for predictive maintenance management. Since the greatest population of typical plant equipment is mechanical, this technique has the widest application and benefits in a total plant program. This technique uses the noise or vibration created by mechanical equipment and in some cases by plant systems to determine their actual condition.

Using vibration analysis to detect machine problems is not new. During the 1960s and 70s, the US Navy, petrochemical and nuclear electric power generating industries invested heavily in the development of analysis techniques based on noise or vibration that could be used to detect and identify incipient mechanical problems in critical machinery. By the early 1980s, the instrumentation and analytical skills required for noise-based predictive maintenance were fully developed. These techniques and instrumentation had proven to be extremely reliable and accurate in detecting abnormal machine behavior. However, the capital cost of instrumentation and the expertise required to acquire and analyze noise data precluded general application of this type of predictive maintenance. As a result, only the most critical equipment in a few select industries could justify the expense required to implement a noise-based predictive maintenance program.

Recent advancements in microprocessor technology coupled with the expertise of companies that specialize in machinery diagnostics and analysis technology, have evolved the means to provide vibration-based predictive maintenance that can be cost-effectively used in most manufacturing and process applications. These microprocessor-based systems simplify data acquisition, automate data management, and minimize the need for vibration experts to interpret data. Commercially available systems are capable of routine monitoring, trending, evaluation and reporting the mechanical condition of all mechanical equipment in a typical plant. This type of program can be used to schedule maintenance on all rotating, reciprocating and most continuous process mechanical equipment.

Monitoring the vibration from plant machinery can provide direct correlation between the mechanical condition and recorded vibration data of each machine in the plant. Any degradation of the mechanical condition within plant machinery can be detected using vibration-monitoring techniques. Used properly, vibration analysis can identify specific degrading machine components or the failure mode of plant machinery before serious damage occurs. Most vibration-based predictive maintenance programs rely on one or more monitoring techniques. These techniques include broadband trending, narrowband trending, or signature analysis.

Broadband trending

This technique acquires overall or broadband vibration readings from select points on a machine-train. This data is compared to either a baseline reading taken from a new machine or to vibration severity charts to determine the relative condition of the machine. Normally an unfiltered broadband measurement that provides the total vibration energy between 10 and 10,000 Hertz is used for this type of analysis.

Broadband or overall RMS data is strictly a gross value or number that represents the total vibration of the machine at the specific measurement point where the data was acquired. It does not provide any information pertaining to the individual frequency components or machine dynamics that created the measured value.

Narrowband trending

Narrowband trending, like broadband, monitors the total energy for a specific bandwidth of vibration frequencies. Unlike broadband, narrowband analysis utilizes vibration frequencies that represent specific machine components or failure modes.

This method provides the means to quickly monitor the mechanical condition of critical machine components, not just the overall machine condition. This technique provides the ability to monitor the condition of gear sets, bearings and other machine components without manual analysis of vibration signatures.

Signature analysis

Unlike the two trending techniques, signature analysis provides visual representation of each frequency component generated by a machine-train. With training, plant staff can use vibration signatures to determine the specific maintenance required by plant machinery.

Most vibration-based predictive maintenance programs use some form of signature analysis in their program. However, the majority of these programs rely on comparative analysis rather than full root-cause techniques. This failure limits the benefits that can be derived from this type of program.

The capital cost for implementing a vibration-based predictive maintenance program will range from about $8,000 to more than $50,000. Your costs will depend on the specific techniques desired.

Training is critical for predictive maintenance programs based on vibration monitoring and analysis. Even programs that rely strictly on the simplified trending or comparison techniques require a practical knowledge of vibration theory so that meaningful interpretation of machine condition can be derived. More advanced techniques, i.e. signature and root-cause failure analysis, require a working knowledge of machine dynamics and failure modes.

The chapters on establishing and maintaining a total plant predictive maintenance program will provide the practical knowledge required implementing a cost-effective vibration-based program that will provide maximum benefits.

50.3.2 Thermography

Thermography is a predictive maintenance technique that can be used to monitor the condition of plant machinery, structures and systems. It uses instrumentation designed to monitor the emission of infrared energy, i.e. temperature, to determine their operating condition. By detecting thermal anomalies, i.e. areas that are hotter or colder than they should be, an experienced surveyor can locate and define incipient problems within the plant.

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

The surface of an object influences the amount of emitted or reflected energy. A perfect emitting surface is called a ‘blackbody’ and has an emissivity equal to 1.0. These surfaces do not reflect. Instead, they absorb all external energy and re-emit as infrared energy. Surfaces that reflect infrared energy are called ‘graybodies’ and have an emissivity less than 1.0. Most plant equipment falls into this classification. Careful consideration of the actual emissivity of an object improves the accuracy of temperature measurements used for predictive maintenance. To help users determine emissivity, tables have been developed to serve as guidelines for most common materials. However, these guidelines are not absolute emissivity values for all machines or plant equipment.

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

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

Collecting optics, radiation detectors and some form of indicator are the basic elements of an industrial infrared instrument. The optical system collects radiant energy and focuses it upon a detector, which converts it into an electrical signal. The instrument’s electronics amplifies the output signal and process it into a form which can be displayed. There are three general types of instruments that can be used for predictive maintenance: infrared thermometers or spot radiometers line scanners and imaging systems.

Infrared thermometers

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

Line scanners

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

Infrared imaging

Unlike other infrared techniques, thermal or infrared imaging provides the means to scan the infrared emissions of complete machines, process or equipment in a very short time. Most of the imaging systems function much like a video camera. The user can view the thermal emission profile of a wide area by simply looking through the instrument's optics. There are a variety of thermal imaging instruments on the market ranging from relatively inexpensive, black and white scanners to full color, microprocessor-based systems. Many of the less expensive units are designed strictly a scanners and do not provide the capability of store and recall thermal images. The inability to store and recall previous thermal data will limit a long-term predictive maintenance program.

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

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

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

50.3.3 Tribology

Tribology is the general term that refers to design and operating dynamics of the bearing-lubrication-rotor support structure of machinery. Several tribology techniques can be used for predictive maintenance: lubricating oils analysis, spectrographic analysis, and ferrography and wear particle analysis.

Lubricating oil analysis, as the name implies, is an analysis technique that determines the condition of lubricating oils used in mechanical and electrical equipment. It is not a tool for determining the operating condition of machinery. Some forms of lubricating oil analysis will provide an accurate quantitative breakdown of individual chemical elements, both oil additive and contaminates, contained in the oil. A comparison of the amount of trace metals in successive oil samples can indicate wear patterns of oil wetted parts in plant equipment and will provide an indication of impending machine failure.

Until recently, tribology analysis has been a relatively slow and expensive process. Analyses were conducted using traditional laboratory techniques and required extensive, skilled labor. Microprocessor-based systems are now available which can automate most of the lubricating oil and spectrographic analysis, thus reducing the manual effort and cost of analysis.

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

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

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

The full benefit of oil analysis can only be achieved by taking frequent samples trending the data for each machine in the plant. It can provide a wealth of information on which to base maintenance decisions. However, major payback is rarely possible without a consistent program of sampling.

Lubricating oil analysis

Oil analysis has become an important aid to preventive maintenance. Laboratories recommend that samples of machine lubricant be taken at scheduled intervals to determine the condition of the lubricating film that is critical to machine-train operation. Typically eleven tests are conducted on lube oil samples:

1. *Viscosity* is one of the most important properties of lubricating oil. The actual viscosity of oil samples is compared to an unused sample to determine the thinning of thickening of the sample during use. Excessively low viscosity will reduce the oil film strength, weakening its ability to prevent metal-to-metal contact.

   Excessively high viscosity may impede the flow of oil to vital locations in the bearing support structure, reducing its ability to lubricate.
2. *Contamination* of oil by water or coolant can cause major problems in a lubricating system. Many of the additives now used in formulating lubricants contain the same elements that are used in coolant additives. Therefore, the laboratory must have an accurate analysis of new oil for comparison.
3. *Fuel dilution* of oil in an engine weakens the oil film strength, sealing ability, and detergency. Improper operation, fuel system leaks, ignition problems, improper timing, or other deficiencies may cause it. Fuel dilution is considered excessive when it reaches a level of 2.5 to 5 per cent.

4. *Solids content* is a general test. All solid materials in the oil are measured as a percentage of the sample volume or weight. The presence of solids in a lubricating system can significantly increase the wear on lubricated parts. Any unexpected rise in reported solids is cause for concern.
5. *Fuel soot* is an important indicator for oil used in diesel engines and is always present to some extent. A test to measure fuel soot in diesel engine oil is important since it indicates the fuel burning efficiency of the engine. Most tests for fuel soot are conducted by infrared analysis.
6. *Oxidation* of lubricating oil can result in lacquer deposits, metal corrosion, or thickening of the oil. Most lubricants contain oxidation inhibitors. However when additives are used up, oxidation of the oil itself begins. The quantity of oxidation in an oil sample is measured by differential infrared analysis.
7. *Nitration* results from fuel combustion in engines. The products formed are highly acidic and they may leave deposits in combustion areas. Nitration will accelerate oil oxidation. Infrared analysis is used to detect and measure nitration products.
8. *Total acid number* (TAN) is a measure of the amount of acid or acid-like material in the oil sample. Because new oils contain additives that affect the TAN number, it is important to compare used oil samples with new, unused, oil of the same type. Regular analysis at specific intervals is important to this evaluation.
9. *Total base number* (TBN) indicates the ability of an oil to neutralize acidity. The higher the TBN, the greater is its ability to neutralize acidity. Typical causes of low TBN include using the improper oil for an application, waiting too long between oil changes, overheating and using high sulfur fuel.
10. *Particle count* tests are important to anticipating potential system or machine problems. This is especially true in hydraulic systems. The particle count analysis made a part of a normal lube oil analysis is quite different from wear particle analysis. In this test, high particle counts indicate that machinery may be wearing abnormally or that failures may occur because of temporarily or permanently blocked orifices. No attempt is made to determine the wear patterns, size and other factors that would identify the failure mode within the machine.
11. *Spectrographic analysis* allows accurate, rapid measurements of many of the elements present in lubricating oil. These elements are generally classified as wear metals, contaminates, or additives. Some elements can be listed in more than one of these classifications. Standard lubricating oil analysis does not attempt to determine the specific failure modes of developing machine-train problems. Therefore, additional techniques must be used as part of a comprehensive predictive maintenance program.
12. *Wear particle analysis* is related to oil analysis only in that the particles to be studied are collected through drawing a sample of lubricating oil. Where lubricating oil analysis determines the actual condition of the oil sample, wear particle analysis provides direct information about the wearing condition of the machine-train. Particles in the lubricate of a machine can provide significant information about the condition of the machine. This information is derived from the study of particle shape, composition, size and quantity. Wear particle analysis is normally conducted in two stages.

The first method used for wear particle analysis is routine monitoring and trending of the solids content of machine lubricant. In simple terms the quantity, composition and size of particulate matter in the lubricating oil is indicative of the mechanical condition of the machine. A normal machine will contain low levels of solids with a size less than 10 microns. As the machine's condition degrades, the number and size of particulate matter will increase.

The second wear particle method involves analysis of the particulate matter in each lubricating oil sample. Five basic types of wear can be identified according to the classification of particles: rubbing wear, cutting wear, rolling fatigue wear, combined rolling and sliding wear and severe sliding wear. Only rubbing wear and early rolling fatigue mechanisms generate particles predominantly less than 15 microns in size.

(a) *Rubbing wear* is the result of normal sliding wear in a machine. During a normal break-in of a wear surface, a unique layer is formed at the surface. As long as this layer is stable, the surface wears normally. If the layer is removed faster than it is generated, the wear rate increases and the maximum particle size increases. Excessive quantities of contaminate in a lubrication system can increase rubbing wear by more than an order of magnitude without completely removing the shear mixed layer. Although catastrophic failure is unlikely, these machines can wear out rapidly. Impending trouble is indicated by a dramatic increase in wear particles.

(b) *Cutting wear particles* are generated when one surface penetrates another. These particles are produced when a misaligned or fractured hard surface produces an edge that cuts into a softer surface, or when abrasive contaminate become embedded in a soft surface and cut an opposing surface. Cutting wear particles are abnormal and are always worthy of attention. If they are only a few micron long and a fraction of a micron wide, the cause is probably a contaminate. Increasing quantities of longer particles signal a potentially imminent component failure.

(c) *Rolling fatigue* is associated primarily with rolling contact bearings and may produce three distinct particle types: fatigue spall particles, spherical particles, and laminar particles. Fatigue spall particles are the actual material removed when a pit or spall opens up on a bearing surface. An increase in the quantity or size of these particles is the first indication of an abnormality. Rolling fatigue does not always generate spherical particles and they may be generated by other sources. Their presence is important in that they are detectable before any actual spalling occurs. Laminar particles are very thin and are formed by the passage of a wear particle through a rolling contact. They frequently have holes in them. Laminar particles may be generated throughout the life of a bearing, but at the onset of fatigue spalling the quantity increases.

(d) *Combined rolling and sliding wear* results from the moving contact of surfaces in gear systems. These larger particles result from tensile stresses on the gear surface, causing the fatigue cracks to spread deeper into the gear tooth before pitting. Gear fatigue cracks do not generate spheres. Scuffing of gears is caused by too high a load or speed. The excessive heat generated by this condition breaks down the lubricating film and causes adhesion of the mating gear teeth. As the wear surfaces become rougher, the wear rate increases. Once started, scuffing usually affects each gear tooth.

(e) *Severe sliding wear* is caused by excessive loads or heat in a gear system. Under these conditions, large particles break away from the wear surfaces, causing an increase in the wear rate. If the stresses applied to the surface are increased further, a second transition point is reached. The surface breaks down and catastrophic wear ensures.

Normal spectrographic analysis is limited to particulate contamination with a size of 10 microns or less. Larger contaminants are ignored. This fact can limit the benefits that can be derived from the technique.

Ferrography

This technique is similar to spectrography but there are two major exceptions. First, ferrography separates particulate contamination by using a magnetic field rather than burning a sample as in spectrographic analysis. Because a magnetic field is used to separate contaminants, this technique is primarily limited to ferrous or magnetic particles.

The second difference is that particulate contamination larger than 10 microns can be separated and analyzed. Normal ferrographic analysis will capture particles up to 100 microns and provides a better representation of the total oil contamination than spectrographic techniques.

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

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

Simple lubricating oil analysis by a testing laboratory will range from about $20 to $50 per sample. Standard analysis will normally include: viscosity, flash point, total insolubles, total acid number (TAN), total base number (TBN), fuel content, and water content.

More detailed analysis, using spectrographic or ferrographic techniques, that include metal scans, particle distribution (size), and other data can range to well over $150 per sample.

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

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

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

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

50.3.4 Process parameters

Many plants do not consider machine or systems efficiency as part of the maintenance responsibility. However, machinery that is not operating within acceptable efficiency parameters severely limits the productivity of many plants. Therefore a comprehensive predictive maintenance program should include routine monitoring of process parameters.

As an example of the importance of process parameters monitoring, consider a process pump that may be critical to plant operation. Vibration-based predictive maintenance will provide the mechanical condition of the pump and infrared imaging will provide the condition of the electric motor and bearings. Neither provides any indication of the operating efficiency of the pump. Therefore, the pump can be operating at less than 50 per cent efficiency and the predictive maintenance program would not detect the problem.

Process inefficiencies, like the example, are often the most serious limiting factor in a plant. Their negative impact on plant productivity and profitability is often greater than the total cost of the maintenance operation. However, without regular monitoring of process parameters, many plants do not recognize this unfortunate fact.

If your program included monitoring of the suction and discharge pressures and amp load of the pump, then you could determine the operating efficiency. The brake-horsepower formula

$$\text{Brake horsepower} = \frac{\text{Flow (GPM)} \times \text{Specific gravity} \times \text{Total dynamic head (TDH)}}{3960 \times \text{Efficiency}}$$

could be used to calculate operating efficiency of any pump in the program. By measuring the suction and discharge pressure, the total dynamic head (TDH) can be determined. Using this data, the pump curve will provide the flow and the amp load the horsepower. With this measured data, the efficiency can be calculated.

Process parameters monitoring should include all machinery and systems in the plant process that can affect its production capacity. Typical systems include heat exchangers, pumps, filtration, boilers, fans, blowers, and other critical systems.

Inclusion of process parameters in a predictive maintenance can be accomplished in two ways: manual or microprocessor-based systems. However, both methods will normally require installing instrumentation to measure the parameters that indicate the actual operating condition of plant systems. Even though most plants have installed pressure gages, thermometers and other instruments that should provide the information required for this type of program, many of them are no longer functioning. Therefore including process parameters in your program will require an initial capital cost to install calibrated instrumentation.

Data from the installed instrumentation can be periodically recorded using either manual logging or with a microprocessor-based data logger. If the latter is selected, many of the vibration-based, microprocessor systems can also provide the means of acquiring process data. This should be considered when selecting the vibration monitoring system that will be used in your program. In addition, some of the microprocessor-based predictive maintenance systems provide the ability to calculate unknown process variables. For example, they can calculate the pump efficiency used in the example. This ability to calculate unknowns based on measured variables will enhance a total plant predictive maintenance program without increasing the manual effort required. In addition, some of these systems include non-intrusive transducers that can measure temperatures, flows and other process data without the necessity of installing permanent instrumentation. This further reduces the initial cost of including process parameters in your program.

50.3.5 Visual inspection

Regular visual inspection of the machinery and systems in a plant is a necessary part of any predictive maintenance program. In many cases, visual inspection will detect potential problems that will be missed using the other predictive maintenance techniques.

Even with the predictive techniques discussed, many potentially serious problems can remain undetected. Routine visual inspection of all critical plant systems will augment the other techniques and insure that potential problems are detected before serious damage can occur.

Most of the vibration-based predictive maintenance systems include the capability of recording visual observations as part of the routine data acquisition process. Since the incremental costs of these visual observations are small, this technique should be incorporated in all predictive maintenance programs.

All equipment and systems in the plant should be visually inspected on a regular basis. The additional information provided by visual inspection will augment the predictive maintenance program regardless of the primary techniques used.

50.3.6 Ultrasonic monitoring

This predictive maintenance technique uses principles similar to vibration analysis. Both monitor the noise generated by plant machinery or systems to determine their actual operating condition.

Unlike vibration monitoring, ultrasonics monitors the higher frequencies, i.e. ultrasound, produced by unique dynamics in process systems or machines. The normal monitoring range for vibration analysis is from less than 1 Hertz to 20,000 Hertz. Ultrasonics techniques monitor the frequency range between 20,000 and 100 kHz.

The principal application for ultrasonic monitoring is in leak detection. The turbulent flow of liquids and gases through a restricted orifice, i.e. leak, will produce a high frequency signature that can easily be identified using ultrasonic techniques. Therefore, this technique is ideal for detecting leaks in valves, steam traps, piping and other process systems.

Two types of ultrasonic systems are available that can be used for predictive maintenance: structural and airborne. Both provide fast, accurate diagnosis of abnormal operation and leaks. Airborne ultrasonic detectors can be used in either a scanning or contact mode. As scanners, they are most often used to detect gas pressure leaks. Because these instruments are sensitive only to ultrasound, they are not limited to specific gases as are most other gas leak detectors. In addition, they are often used to locate various forms of vacuum leaks.

In the contact mode, a metal rod acts as a waveguide. When it touches a surface, it is stimulated by the high frequencies, ultrasound, on the opposite side of the surface. This technique is used to locate turbulent flow and or flow restriction in process piping.

Some of the ultrasonic systems include ultrasonic transmitters that can be placed inside plant piping or vessels. In this mode, ultrasonic monitors can be used to detect areas of sonic penetration along the container's surface. This ultrasonic transmission method is useful in quick checks of tank seams, hatches, seals, caulking, gaskets or building wall joints.

Most of the ultrasonic monitoring systems are strictly a scanner that does not provide any long-term trending or storage of data. They are in effect a point-of-use instrument that provides an indication of the overall amplitude of noise within the bandwidth of the instrument. Therefore, the cost of this type of instrument is relatively low. Normal cost of ultrasonic instruments will vary from less than $1,000 to about $8,000. Used strictly for leak detection, little training is required to utilize ultrasonic techniques. The combination of low capital cost, minimum training required to use the technique and potential impact that leaks may have on plant availability provide a positive cost-benefit for including ultrasonic techniques in a total plant predictive maintenance program.

However, care should be exercised in applying this technique in your program. Many ultrasonic systems are sold as a bearing condition monitor. Even though the natural frequencies of rolling element bearings will fall within the bandwidth of ultrasonic instruments, this is not a valid technique for determining the condition of rolling element bearings. In a typical machine, many other machine dynamics will also generate frequencies within the bandwidth covered by an ultrasonic instrument. Gear meshing frequencies, blade pass and other machine components will also create energy or noise that cannot be separate from the bearing frequencies monitored by this type of instrument. The only reliable method of determining the condition of specific machine components, including bearings, is vibration analysis. The use of ultrasonics to monitor bearing condition is not recommended.

50.3.7 Other techniques

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

Other techniques that can support predictive maintenance include acoustic emissions, eddy-current, magnetic particle, residual stress and most of the traditional nondestructive methods.

If you need specific information on the techniques that are available, the American Society of Nondestructive Testing (ANST) has published a complete set of handbooks that provide a comprehensive database for most nondestructive testing techniques.

50.4 Selecting a predictive maintenance system

After developing the requirements for a comprehensive predictive maintenance program, the next step is to select the hardware and software system that will most cost-effectively support your program. Since most plants will require a combination of techniques, i.e. vibration, thermography, tribology, etc., the system should be able to provide support for all of the required techniques. Since a single system that will support all of the predictive maintenance is not available, you must decide on the specific techniques that must be used to support your program. Some of the techniques may have to be eliminated to enable the use of a single predictive maintenance system. However, in most cases, two independent systems will be required to support the monitoring requirements in your plant.

Most plants can be cost-effectively monitored using a microprocessor-based system designed to use vibration, process parameters, visual inspection and limited infrared temperature monitoring.

Plants with large populations of heat transfer systems and electrical equipment will need to add a full thermal imaging system in order to meet the total plant requirements for a full predictive maintenance program. Plant with fewer systems that require full infrared imaging may elect to contract this portion of the predictive maintenance program. This will eliminate the need for an additional system. A typical microprocessor-based system will consist of four main components: a meter or data logger, host computer, transducers, and a software program. Each component is important, but the total capability must be evaluated to get a system that will support a successful program. The first step in selecting the predictive maintenance system that will be used in your plant is to develop a list of the specific features or capabilities the system must have to support your program. As a minimum, the total system must have the following capabilities:

User-friendly software and hardware The premise of predictive maintenance is that existing plant staff must be able to understand the operation of both the data logger and software program. Since plant staff normally have little, if any, computer or microprocessor background, the system must use simple, straightforward operation of both the data acquisition instrument and software. Complex systems, even if they provide advanced diagnostic capabilities, may not be accepted by plant staff and therefore will not provide the basis for a long-term predictive maintenance program.

Automated data acquisition The object of using microprocessor-based systems is to remove any potential for human error, reduce manpower and to automate as much as possible the acquisition of vibration, process and other data that will provide a viable predictive maintenance database. Therefore the system must be able to automatically select and set monitoring parameters without user input. The ideal system would limit user input to a single operation. However this is not totally possible with today's technology.

Automated data management and trending The amount of data required to support a total plant predictive maintenance program is massive and will continue to increase over the life of the program. The system must be able to store, trend and recall the data in multiple formats that will enable the user to monitor, trend and analyse the condition of all plant equipment included in the program. The system should be able to provide long-term trend data for the life of the program. Some of the microprocessor-based systems limit trends to a maximum of 26 data sets and will severely limit the decision-making capabilities of the predictive maintenance staff.

Limiting trend data to a finite number of data sets eliminates the ability to determine the most cost-effective point to replace a machine rather than let it continue in operation.

Flexibility Not all machines or plant equipment are the same, nor are the best methods of monitoring their condition. Therefore, the selected system must be able to support as many of the different techniques as possible. As a minimum, the system should be capable of obtaining, storing, and presenting data acquired from all vibration and process transducers and provide accurate interpretation of the measured values in user-friendly terms. The minimum requirement for vibration monitoring systems must include the ability to acquire: filter broadband, select narrowband, time traces and high-resolution signature data using any commercially available transducer. Systems that are limited to broadband monitoring or to a single type of transducer cannot support the minimum requirements of a predictive maintenance program.

The added capability of calculating unknown values based on measured inputs will greatly enhance the system capabilities. For example, the neither fouling factor nor efficiency of a heat exchanger can be directly measured. A predictive maintenance system that can automatically calculate these values based on the measured flow, pressure and temperature data would enable the program to automatically trend, log and alarm deviations in these unknown, critical parameters.

Reliability The selected hardware and software must be proven in actual field use to ensure it's reliability. The introduction of microprocessor-based predictive maintenance systems is still relatively new and it is important that you evaluate the field history of a system before purchase.

Ask for a users list and talk to the people who are already using the systems. This is a sure way to evaluate the strengths and weakness of a particular system before you make a capital investment.

Accuracy Decisions on machine-train or plant system condition will be made based on the data acquired and reported by the predictive maintenance system. It must be accurate and repeatable. Errors can be input by the microprocessor and software as well as the operators. The accuracy of commercially available predictive maintenance system varies. While most will provide at least minimum acceptable accuracy, some are well below the acceptable level.

It will be extremely difficult for the typical plant user to determine the level of accuracy of the various instruments that are available for predictive maintenance. Vendor literature and salesmen will assure the potential user that their system is the best, most accurate, etc. The best way to separate fact from fiction is a comparison of the various systems in your plant. Most vendors will provide a system on consignment for periods up to thirty days. This will provide sufficient time for your staff to evaluate each of the potential systems before purchase.

Training and technical support Training and technical support is critical to the success of your predictive maintenance program. Regardless of the techniques or systems selected, your staff will have to be trained. This training will take two forms: system users training and application knowledge for the specific techniques included in your program. Few, if any, of the existing staff will have the knowledge base required implementing the various predictive maintenance techniques discussed in preceding chapters. None will understand the operation of the systems that are purchased to support your program.

Many of the predictive systems manufacturers are strictly hardware and software oriented. Therefore, they offer minimal training and no application training or technical support. Few plants can achieve minimum benefits from predictive maintenance without training and some degree of technical support. It is therefore imperative that the selected system or system vendors provide a comprehensive support package that includes both training and technical support.

System cost Cost should not be the primary deciding factor in system selection. The capabilities of the various systems vary greatly and so does the cost. Care should be taken to ensure a fair comparison of the total system capability and price is made before selection of your system.

For example, vibration-based systems are relatively competitive in price. The general spread is less than $1,000 for a complete system. However, the capabilities of these systems are not comparable. A system that provides minimum capability for vibration monitoring will be about the same price as one that provides full vibration monitoring capability and provides process parameter, visual inspection and point-of-use thermography.

Operating cost The real cost of implementing and maintaining a predictive maintenance program is not the initial system cost. Rather it is the annual labor and overhead costs associated with acquiring, storing, trending and analyzing the data required to determine the operating condition of plant equipment. This is also the area where a predictive maintenance system has the greatest variance in capability. Systems that fully automate data acquisition, storing, etc. will provide the lowest operating costs. Manual systems and many of the low-end microprocessor-based systems require substantially more manpower to accomplish the minimum objectives required by predictive maintenance. The users list will again help you determine the long-term cost of the various systems. Most users will share their experience, including a general indication of labor cost.

The microprocessor

The data logger or microprocessor selected by your predictive maintenance program is critical to the success of the program. There is a wide variety of systems on the market that range from handheld overall value meters to advanced analyzers that can provide an almost unlimited amount of data. The key selection parameters for a data acquisition instrument should include the expertise required to operate, accuracy of data, type of data, and manpower required to meet the program demands.

Expertise required to operate One of the objectives for using microprocessor-based predictive maintenance systems is to reduce the expertise required to acquire error-free, useful vibration and process data from a large population of machinery and systems within a plant. The system should not require user input to establish: maximum amplitude, measurement bandwidths, filter settings, or allow free-form data input. All of these functions force the user to be a trained analyst and will increase both the cost and time required to routinely acquire data from plant equipment. Many of the microprocessors on the market provide easy, menu-driven measurement routes that lead the user through the process of acquiring accurate data. The ideal system should require a single key input to automatically acquire, analyze, alarm and store all pertinent data from plant equipment. This type of system would enable an unskilled user to quickly and accurately acquire all of the data required for predictive maintenance.

Accuracy of data The microprocessor should be capable of automatically acquiring accurate, repeatable data from equipment included in the program. The elimination of user input on filter settings, bandwidths and other measurement parameters would greatly improve the accuracy of acquired data. The specific requirements that determine data accuracy will vary depending on the type of data. For example, a vibration instrument should be able to: average data, reject spurious signals, auto-scale based on measured energy, and prevent aliasing.

The basis of frequency-domain vibration analysis assumes that we monitor the rotational frequency components of a machine-train. If a single block of data is acquired, non-repetitive or spurious data can be introduced into the database. The microprocessor should be able to acquire multiple blocks of data, average the total and store the averaged value. This approach will enable the data acquisition unit to automatically reject any spurious data and provide reliable data for trending and analysis. Systems that rely on a single block of data will severely limit the accuracy and repeatability of acquired data. They will also limit the benefits that can be derived from the program. The microprocessor should also have electronic circuitry that automatically checks each data set and block of data for accuracy and reject any spurious data that may occur. Auto-rejection circuitry is available in several of the commercially available systems. Coupled with multiple block averaging, this auto-rejection circuitry assures maximum accuracy and repeatability of acquired data. A few of the microprocessor-based systems require the user to input the maximum scale that is used to acquire data. This will severely limit the accuracy of data. Setting the scale too high will prevent acquisition of factual machine data. A setting that is too low will not capture any high-energy frequency components that may be generated by the machine-train. Therefore, the microprocessor should have auto-scaling capability to ensure accurate data. Vibration data can be distorted by high frequency components that fold-over into the lower frequencies of a machine's signature. Even though these aliased frequency components appear real, they do not exist in the machine. Low frequency components can also distort the mid-range signature of a machine in the same manner as high frequency. The microprocessor selected for vibration should include a full range of anti-aliasing filter to prevent the distortion of machine signatures. The features illustrated in the example also apply to non-vibration measurements. For example, pressure readings require the averaging capability to prevent spurious readings. Slight fluctuations in line or vessel pressure are normal in most plant systems. Without the averaging capability, the microprocessor cannot acquire an accurate reading of the true system pressure.

Alert and alarm limits The microprocessor should include the ability to automatically alert the user to changes in machine, equipment or system condition. Most of the predictive maintenance techniques rely on a change in the operating condition of plant equipment to identify an incipient problem. Therefore, the system should be able to analyze data and report any change in the monitoring parameters that were established as part of the database development.

Predictive maintenance systems use two methods of detecting a change in the operating condition of plant equipment: static and dynamic. Static alert and alarm limits are pre-selected thresholds that are downloaded into the microprocessor. If the measurement parameters exceed the pre-set limit, an alarm is displayed. This type of monitoring does not consider the rate of change or historical trends of a machine and therefore cannot anticipate when the alarm will be reached.

The second method uses dynamic limits that monitor the rate of change in the measurement parameters. This type of monitoring can detect minor deviations in the rate that a machine or system is degrading and anticipate when an alarm will be reached. The use of dynamic limits will greatly enhance the automatic diagnostic capabilities of a predictive maintenance system and reduce the manual effort required to gain maximum benefits.

Data storage The microprocessor must be able to acquire and store large amounts of data. The memory capacity of the various predictive maintenance systems varies. As a minimum, the system must be able to store a full eight hours of data before transferring it to the host computer. The actual memory requirements will depend on the type of data acquired. For example, a system used to acquire vibration data would need enough memory to store about 1000 overall reading or 400 full signatures. Process monitoring would require a minimum of 1000 readings to meet the minimum requirements.

Data transfer The data acquisition unit will not be used for long-term data storage. Therefore, it must be able to reliability transfer data into the host computer. The actual time required to transfer the microprocessor's data into the host computer is the only non-productive time of the data acquisition unit. It cannot be used for acquiring additional data during the data transfer operation. Therefore, the transfer time should be kept to a minimum. Most of the available systems use an RS 232 communications protocol that will allow data transfer at rates of up to 19,200 baud. The time required to dump the full memory of a typical microprocessor can be 30 minutes or more.

Some of the systems have incorporated an independent method of transferring data that eliminates the dead time altogether. These systems transfer stored data from the data logger into a battery-backed memory bypassing the RS 232 link. Using this technique, data can be transferred at more than 350,000 baud and will reduce the non-productive time to a few minutes.

The microprocessor should also be able to support modem communication with remote computers. This feature will enable multiple plant operation and direct access to third party diagnostic and analysis support. Data can be transferred anywhere in the world using this technique. Not all predictive maintenance systems use a true RS 232 communications protocol or support modem communications. These systems can severely limit the capabilities of your program. The various predictive maintenance techniques will add other specifications for an acceptable data acquisition unit.

The host computer

The host computer provides all of the data management, storage, report generation, and analysis capabilities of the predictive maintenance program. Therefore, care should be exercised during the selection process. This is especially true if multiple technologies will be used within the predictive maintenance program. Each predictive maintenance system will have a unique host computer specification that will include: hardware configuration, computer operating system, hard disk memory requirements and many others. This can become a serious if not catastrophic problem. You may find that one system requires a special printer that is not compatible with other programs to provide hard copies of reports or graphic data. One program may be compatible with PC-DOS, while another requires a totally different operating program.

Therefore, you should develop a complete computer specification sheet for each of the predictive maintenance systems that will be used. A comparison of the list will provide a compatible computer configuration that will support each of the techniques. If this is not possible, you may have to reconsider your choice of techniques.

Computers, like plant equipment, fail. Therefore, the use of a commercially available computer is recommended. The critical considerations include: availability of repair parts and local vendor support.

Most of the individual predictive maintenance techniques will not require a dedicated computer. Therefore there is usually sufficient storage and computing capacity to handle several, if not all, of the required techniques and still leave room for other support programs, i.e. word processing, database management, etc. Use of commercially available PCs provides the user with the option of including these auxiliary programs in the host computer. The actual configuration of the host computer will be dependent on the specific requirement of the predictive maintenance techniques that will be used.

The software

The software program provided with each predictive maintenance system is the heart of a successful program. It is also the hardest to evaluate before purchase. The methodology used by vendors of predictive maintenance systems varies greatly. Many appear to have all of the capabilities required to meet the demands of a total plant predictive maintenance program. However on close inspection, usually after purchase, they are found to be lacking.

Software is also the biggest potential limiting factor of a program. Even though all vendors use some form of formal computer language, i.e. FORTRAN, Cobol, basic, etc., they are normally not interchangeable with other programs. The apparently simple task of having one computer program communicate with another can often be impossible. This lack of compatibility between various computer programs prohibits transferring a predictive maintenance database from one vendor's system into a system manufactured by another vendor. The result is that once a predictive maintenance program is started, a plant cannot change to another system without losing the data already developed in the initial program.

As a minimum the software program should provide: automatic database management, automatic trending, automatic report generation and simplified diagnostics. As in the case of the microprocessor used to acquire data, the software must be user-friendly.

User-friendly operation The software program should be menu-driven with clear on-line user instructions. The program should protect the user form distorting or deleting stored data. Some of the predictive maintenance systems are written in DBASE software shells. Even though these programs provide a knowledgeable user with the ability to modify or customize the structure of the program, i.e. report formats, etc., they also provide the means to distort or destroy stored data. A single key entry can destroy years of stored data. Protection should be built into the program to limit the user's ability to modify or delete data and to prevent accidental data base damage.

The program should have a clear, plain language user's manual that provides the logic and specific instructions required to set up and use the program.

Automatic trending The software program should be capable of automatically storing all acquired data and updating the trends of all variables. This capability should include multiple parameters not just a broadband or single variable. This will enable the user to display trends of all variables that affect plant operations.

Automatic report generation Report generation will be an important part of the predictive maintenance program. Maximum flexibility in format and detail is important to program success. The system should be able to automatically generate reports a multiple levels of detail. As a minimum, the system should be able to report:

- A listing of machine-trains or other plant equipment that have exceeded or are projected to exceed one or more alarm limits. The report should also provide a projection to probable failure based on the historical data and last measurement.
- A listing of missed measurement points, machines overdue for monitoring and other program management information. These reports act as reminders to ensure that the program is maintained properly.
- A listing of visual observations. Most of the microprocessor-based systems support visual observations as part of their approach to predictive maintenance. This report provides hard copies of the visual observations as well as maintaining the information in the computer's database.
- Equipment history reports should also be available. These reports provide long-term data on the condition of plant equipment and are valuable for analysis.

Simplified diagnostics Identification of specific failure modes of plant equipment requires manual analysis of data stored in the computer's memory. The software program should be able to display, modify and compare stored data in a manner that simplifies the analysis of the actual operating condition of the equipment.

As a minimum, the program should be able to directly compare data from similar machines, normalize data into compatible units and display changes in machine parameters, i.e. vibration, process, etc.

Transducers

The final portion of a predictive maintenance system is the transducer that will be used to acquire data from plant equipment. Since we have assumed that a microprocessor-based system will be used, we will limit this discussion to those sensors that can be used with this type of system.

Acquiring accurate vibration and process data will require several types of transducers. Therefore, the system must be able to accept input from as many different types of transducers as possible. Any limitation of compatible transducers can become a serious limiting factor. This should eliminate systems that will accept inputs from a single type of transducer. Other systems are limited to a relatively small range of transducers that will also prohibit maximum utilization of the system. Selection of the specific transducers required to monitor the mechanical condition, i.e. vibration, and process parameters, i.e. flow, pressure, etc., will also deserve special consideration and will be discussed latter.

50.5 Establishing a predictive maintenance program

The decision to establish a predictive maintenance management program is the first step toward controlling maintenance costs and improving process efficiency in your plant. Now what do you do? Numerous predictive maintenance programs can serve as models for implementing a successful predictive maintenance program. Unfortunately, more were aborted within the first three years because a clear set of goals and objectives were not established before the program was implemented. Implementing a total plant predictive maintenance program is expensive. In addition to the initial capital cost, there is a substantial recurring labor cost required to maintain the program.

To be successful, a predictive maintenance program must be able to quantify the cost-benefit generated by the program. This can be achieved if the program is properly established, uses the proper predictive maintenance techniques and has measurable benefits. The amount of effort expended to initially establish the program plant is directly proportional to its success or failure. Proper implementation of a predictive maintenance program must include the items listed in Sections 50.5.1–50.5.5.

50.5.1 Goals, objectives and benefits

Constructive actions issue from well-established purpose. It is important that the goals and objectives of a predictive maintenance program be fully developed and adopted by the personnel who perform the program and upper management of the plant. A predictive maintenance program is not an excuse to buy sophisticated, expensive equipment. Neither is the purpose of the program to keep a number of people busy measuring and reviewing data from the various machines, equipment and systems within the plant.

The purpose of predictive maintenance is to minimize unscheduled equipment failures, maintenance costs and lost production. It is also intended to improve the production efficiency and product quality in the plant. This is accomplished by regular monitoring of the mechanical condition, machine and process efficiencies and other parameters that define the operating condition of the plant. Using the data acquired from critical plant equipment, incipient problems are identified and corrective actions taken to improve the reliability, availability and productivity of the plant.

Specific goals and objectives will vary from plant to plant. However, we will provide an example that will illustrate the process. Before goals and objectives can be developed for your plant, you must determine the existing maintenance costs and other parameters that will establish a reference or baseline dataset. Since most plants do not track the true cost of maintenance, this may be the most difficult part of establishing a predictive maintenance program.

As a minimum, your baseline data set should include the labor, overhead, overtime premiums and other payroll costs of the maintenance department. It should also include all maintenance related contract services, excluding janitorial, and the total costs of spare parts inventories. The baseline should also include the percentage of unscheduled maintenance repairs versus scheduled; actual repair costs on critical plant equipment; and the annual availability of the plant.

This baseline should include the incremental cost for production created by catastrophic machine failures and other parameters. If they are available or can be obtained, they will help greatly in establishing a valid baseline.

The long-term objectives of a predictive maintenance program are to:

- Eliminate un-necessary maintenance
- Reduce lost production caused by failures
- Reduce repair parts inventory
- Increase process efficiency
- Improve product quality
- Extend operating life of plant systems
- Increase production capacity
- Reduce overall maintenance costs
- Increase overall profits.

However just stating these objectives will not make it happen nor will it provide the means of measuring the success of the program. Establish specific objectives, i.e. reduce un-scheduled maintenance by 20 per cent, or increase production capacity by 15 per cent. In addition to quantifying the expected goals, define the methods that will be used to accomplish each objective and the means that can be used to measure the actual results.

Management support

Implementing a predictive maintenance program will require an investment in both capital equipment and manpower. If a program is to get started and survive to accomplish its intended goals, management must be willing to commit the necessary resources. They must also insist on the adoption of vital record-keeping and information exchange procedures that are critical to program success and are outside the control of the maintenance department. In most aborted programs, management committed to the initial investment for capital equipment but did not invest the resources required for training, consulting support and in-house manpower that are essential to success. A number of programs have been aborted during the time between 18 and 24 months following implementation. They were not aborted because the program failed to achieve the desired results. They failed because upper management did not clearly understand how the program works. During the first 12 months, most predictive maintenance programs identify numerous problems in plant machinery and systems. Therefore, the reports and recommendations for corrective actions generated by the predictive maintenance group are highly visible. After the initial 12 to 18 months, most of the serious plant problems have been resolved and the reports begin to show little need for corrective actions. Without a clear understanding of this normal cycle and the means of quantifying the achievements of the predictive maintenance program, upper management often concludes that the program is not providing sufficient benefits to justify the continued investment in manpower.

Dedicated and accountable personnel

All successful programs are built around a full time predictive maintenance team. Some of these teams may cover multiple plants and some monitor only one. However, every successful program has this dedicated team that can concentrate their full attention to achieving the objectives established for the program. Even though a few successful programs have been structured around part-time personnel, this approach cannot be recommended. All too often, the part-time personnel will not or cannot maintain the monitoring and analysis frequency that is critical to a successful program.

The accountability expected of the predictive maintenance group is another factor that is critical to program effectiveness. If measures of program effectiveness are not established, neither management nor program personnel can determine if the program's potential is being achieved.

Efficient data collection and analysis procedures

Efficient procedures can be established if adequate instrumentation is available and the monitoring tasks are structured to emphasize program goals. A well-planned program should not be structured so that all machines and equipment in the plant receive the same scrutiny. Typical predictive maintenance programs will monitor from 50 to 500 machine-trains in a given plant. Obviously some of the machine-trains are more critical to the continued, efficient operation of the plant than others. The predictive maintenance program should be set up with this in mind and concentrate the program's efforts in the areas that will provide maximum results. The use of microprocessor and personal computer-based predictive maintenance systems will greatly improve the data collection and data management functions required for a successful program. They can also provide efficient data analysis. However procedures that define the methods, schedule and other parameter of data acquisition, analysis and report generation must be included in the program definition.

Viable database

The methods and systems that you choose for your program and the initial program development will largely determine the success or failure of predictive maintenance in your plant.

Proper implementation of a predictive maintenance program is not easy. It will require a great deal of thought and perhaps for the first time a complete understanding of the operation of the various systems and machinery in your plant.

The initial database development required to successfully implement a predictive maintenance program will require man-months of effort. The extensive labor required to properly establish a predictive database often results in either a poor or incomplete database. In some cases, the program is discontinued because of staff limitations. If the extensive labor required establishing a database is not available in-house, there are consultants available that will provide the knowledge and labor required to accomplish this task.

The ideal situation would be to have the predictive systems vendor establish a viable database as part of the initial capital equipment purchase. This service is offered by a few of the systems vendors. Unfortunately, many predictive maintenance programs have failed because these important first critical steps were omitted or ignored. There are a variety of technologies and predictive maintenance systems that can be beneficial. How do you decide which method and system to use?

A vibration-based predictive maintenance program is the most difficult to properly establish and will require much more effort than any of the other techniques. It will also provide the most return on investment. Too many of the vibration-based programs fail to use the full capability of the predictive maintenance tool. They ignore the automatic diagnostic power that is built into most of the microprocessor-based systems and rely instead on manual interpretation of all acquired data.

The first step is to determine the types of plant equipment and systems that are to be included in your program. A plant survey of your process equipment should be developed that lists every critical component within the plant and its impact on both production capacity and maintenance costs. A plant process layout is invaluable during this phase of program development. It is very easy to omit critical machines or components during the audit. Therefore, care should be taken to ensure that all components that can limit production capacity are included in your list.

The listing of plant equipment should be ordered into the following classes depending on their impact on production capacity or maintenance cost: essential, critical, serious, others.

Class I or essential machinery or equipment must be on-line for continued plant operation. Loss of any one of these components will result in a plant outage and total loss of production. Plant equipment that has excessive repair costs or repair parts lead-time should also be included in the essential classification.

Class II or critical machinery would severely limit production capacity. As a rule-of-thumb, loss of critical machinery would reduce production capacity by 30 per cent or more. Also included in the critical classification are machines or systems with chronic maintenance histories or that have high repair or replacement costs.

Class III or serious machinery include major plant equipment that do not have a dramatic impact on production but that contribute to maintenance costs. An example of the serious classification would be a redundant system. Since the inline spare could maintain production, loss of one component would not affect production. However, the failure would have a direct impact on maintenance cost.

Class IV machinery would include other plant equipment that has a proven history of impacting either production or maintenance costs. All equipment in this classification must be evaluated to determine whether routine monitoring is cost-effective. In some cases, replacement costs are lower than the annual costs required to monitor machinery in this classification.

The completed list should include every machine, system or other plant equipment that has or could have a serious impact on the availability and process efficiency of your plant.

The next step is to determine the best method or technique for cost-effectively monitoring the operating condition of each item on the list. To select the best methods for regular monitoring, you should consider the dynamics of operation and normal failure modes of each machine or system to be included in the program.

A clear understanding of the operating characteristics and failure modes will provide the answer to which predictive maintenance method should be used.

Most predictive maintenance programs will use vibration monitoring as the principal technique. The inclusion of visual inspection, process parameters, ultrasonics and limited thermographic techniques should also be added to the in-house program. The initial cost of systems and advanced training required by full thermographic and tribology techniques prohibit their inclusion into in-house programs. Plants that require these techniques normally rely on outside contractors to provide the instrumentation and expertise required to provide these monitoring and diagnostic techniques.

50.5.2 Database development

The next step required to establish a predictive maintenance program is the creation of a comprehensive database.

Establishing data acquisition frequency

During the implementation stage of a predictive maintenance program, all classes of machinery should be monitored to establish a valid baseline data set. Full vibration signatures should be acquired to verify the accuracy of the database setup and determine the initial operating condition of the machinery.

Since a comprehensive program will include trending and projected time-to-failure, multiple readings are required on all machinery to provide sufficient data for the microprocessor to develop trend statistics. Normally during this phase, measurements are acquired every two weeks.

After the initial or baseline of the machinery, the frequency of data collection will vary depending on the classification of the machine-trains. Class I machines should be monitored on a two to three week cycle; Class II on a three to four week cycle; Class III on a four to six week cycle and Class IV on a six to ten week cycle. This frequency can, and should, be adjusted for the actual condition of specific machine-trains. If the rate of change of a specific machine indicates rapid degradation, you should either repair it or at least increase the monitoring frequency to prevent catastrophic failure.

The recommended data acquisition frequencies are the maximum that will ensure prevention of most catastrophic failures. Less frequency monitoring will limit the ability of the program to detect and prevent un-scheduled machine outages.

To augment the vibration-based program, you should also schedule the non-vibration tasks. Bearing cap, point-of-use infrared measurements, visual inspections and process parameters monitoring should be conducted in conjunction with the vibration data acquisition.

Full infrared imaging or scanning on the equipment included in the vibration-monitoring program should be conducted on a quarterly basis. In addition, full thermal scanning of critical electrical equipment, i.e. switch gear, circuit breakers, etc., and all heat transfer systems, i.e. heat exchangers, condensers, process piping, etc., that are not in the vibration program should be conducted quarterly.

Lubricating oil samples from all equipment included in the program should be taken on a monthly basis. As a minimum, a full spectrographic analysis should be conducted on these samples. Wear particle or other analysis techniques should be made on an ‘as-needed’ basis.

Setting up analysis parameters

The next step in establishing the program’s database is to set up the analysis parameters that will be used to routinely monitor plant equipment. Each of these parameters will be based on the specific machine-train requirements that we have just developed.

Normally for non-mechanical equipment the analysis parameter set will consist of the calculated values derived from measuring the thermal profile or process parameters. Each classification of equipment or system will have its own unique analysis parameter set.

Boundaries for signature analysis

All vibration monitoring systems have finite limits on the resolution, or ability to graphically display the unique frequency components that make up a machine’s vibration signature. The upper limit (F_{MAX}) for signature analysis should be set high enough to capture and display enough data so that the analyst can determine the operating condition of the machine-train but no higher.

To determine the impact of resolution, calculate the display capabilities of your system. For example, a vibration signature with a maximum frequency (F_{MAX}) of 1000 Hertz taken with an instrument capable of 400 lines of resolution would result in a display in which each displayed line will be equal to 2.5 Hertz or 150 rpm. Any frequencies that fall between 2.5 and 5.0, i.e. the next displayed line, would be lost.

Define alert and alarm limits

The method of establishing and using alert/alarm limits varies depending on the particular vibration monitoring system that you select. Normally these systems will use either static or dynamic limits to monitor, trend and alarm measured vibration. We will not attempt to define the different dynamic methods of monitoring vibration severity in this book. We will however provide a guideline for the maximum limits that should be considered acceptable for most plant mechanical equipment.

The systems that use dynamic alert/alarm limits base their logic on the rate of change of vibration amplitude. Any change in the vibration amplitude is a direct indication that there is a corresponding change in the machine’s mechanical condition. However, there should be a maximum acceptable limit, i.e. absolute fault.

The accepted severity limit for casing vibration is 0.628 ips-peak (velocity). This is an un-filtered broadband value and normally represents a bandwidth between 10 and 10,000 Hertz. This value can be used to establish the absolute fault or maximum vibration amplitude for broadband measurement on most plant machinery. The exception would be machines with running speeds below 1200 rpm or above 3600 rpm.

Narrowband limits, i.e. discrete bandwidth within the broadband, can be established using the following guideline. Normally 60 to 70 per cent of the total vibration energy will occur at the true running speed of the machine. Therefore, the absolute fault limit for a narrowband established to monitor the true running speed would be 0.42 ips-peak. This value can also be used for any narrowbands established to monitor frequencies below the true running speed.

Absolute fault limits for narrowbands established to monitor frequencies above running speed can be ratioed using the 0.42 ips-peak limit established for the true running speed. For example, the absolute fault limit for a narrowband created to monitor the bladepassing frequency of fan with 10 blades would be set at 0.042 or 0.42/10.

Narrowband designed to monitor high-speed components, i.e. above 1000 Hertz, should have an absolute fault of 3.0 g’s-peak (acceleration).

Rolling element bearings, based on factor recommendations, have an absolute fault limit of 0.01 ips-peak. Sleeve or fluid-film bearings should be watched closely. If the fractional components that identify oil whip or whirl are present at any level, the bearing is subject to damage and the problem should be corrected.

Non-mechanical equipment and systems will normally have an absolute fault limit that specifies the maximum recommended level for continued operation. Equipment or systems vendors will, in most cases, be able to provide this information.

Transducers

The type of transducers and data acquisition techniques that you will use for the program is the final critical factor that can determine the success or failure of your program. Their accuracy, proper application and mounting will determine whether valid data will be collected.

The optimum predictive maintenance program developed in earlier chapters is predicated on vibration analysis as the principle technique for the program. It is also the most sensitive to problems created by the use of the wrong transducer or mounting technique.

Three basic types of vibration transducers can be used for monitoring the mechanical condition of plant machinery: displacement probe, velocity transducer and accelerometers. Each has specific applications within the plant. Each also has limitations.

Displacement probes

Displacement or eddy-current probes are designed to measure the actual movement, i.e. displacement, of a machine's shaft relative to the probe. Therefore, the displacement probe must be rigidly mounted to a stationary structure to gain accurate, repeatable data.

Permanently mounted displacement probes will provide the most accurate data on machines with a low rotor weight, relative to the casing and support structure. Turbines, large process compressors, and other plant equipment should have displacement transducers permanently mounted at key measurement locations to acquire data for the program.

The useful frequency range for displacement probes is from 10 to 1000 Hertz or 600 to 60,000 rpm. Frequency components below or above this range will be distorted and therefore unreliable for determining machine condition.

The major limitation with displacement or proximity probes is cost. The typical cost for installing a single probe, including a power supply, signal conditioning, etc., will average $1,000. If each machine in your program requires ten measurements, the cost per machine will be about $10,000. Using displacement transducers for all plant machinery will dramatically increase the initial cost of the program.

Displacement data is normally recorded in terms of mils or 0.001 inch, peak-to-peak. This valve expresses the maximum deflection or displacement off the true centerline of a machine's shaft.

Velocity transducers

Velocity transducers are an electro-mechanical sensor designed to monitor casing or relative vibration. Unlike the displacement probe, velocity transducers measure the rate of displacement not actual movement. Velocity data is normally expressed in terms of ips or inches-per-second peak and is perhaps the best method of expressing the energy created by machine vibration.

Velocity transducers, like displacement probes, have an effective frequency range of about 10 to 1000 Hertz. They should not be used to monitor frequencies below or above this range.

The major limitation of velocity transducers is their sensitivity to mechanical and thermal damage. Normal plant use can cause a loss of calibration and therefore a strict re-calibration program must be used to prevent distortion of data. As a minimum, velocity transducers should be re-calibrated at least every six months. Even with periodic re-calibration, programs using velocity transducers are prone to bad or distorted data that results from loss of calibration.

Accelerometers

Accelerometers use a piezoelectric crystal to convert mechanical energy into electrical signals.

Data acquired with this type of transducers are relative vibration, not actual displacement, and are expressed in terms of g's or inches/second/second. Acceleration is perhaps the best method of determining the force created by machine vibration.

Accelerometers are susceptible to thermal damage. If sufficient heat is allowed to radiate into the crystal it can be damaged or destroyed. However since the data acquisition time, using temporary mounting techniques, is relatively short, i.e. less than thirty seconds, thermal damage is rare. Accelerometers do not require a re-calibration program to insure accuracy.

The effective range of general-purpose accelerometers is from about 1 Hertz to 10,000 Hertz. Ultrasonic accelerometers are available for frequencies up to 1 MHertz.

Machine data above 1,000 Hertz or 60,000 rpm should be taken and analyzed in acceleration or g's.

Mounting techniques

Predictive maintenance programs using vibration analysis must have accurate, repeatable data to determine the operating condition of plant machinery. In addition to the transducer, three factors will affect data quality: measurement point, orientation and compressive load.

Key measurement point locations and orientation to the machine's shaft were selected as part of the database setup to provide the best possible detection of incipient machine-train problems. Deviation from the exact point or orientation will affect the accuracy of acquired data. Therefore, it is important that every measurement throughout the life of the program be acquired at exactly the same point and orientation. In addition, the compressive load or downward force applied to the transducer should also be the same for each measurement.

For accuracy of data, a direct mechanical link to the machine's casing or bearing cap is necessary. Slight deviations in this load will induce errors in the amplitude of vibration and may create false frequency components that have nothing to do with the machine.

The best method of ensuring these three factors are the same each time is to hard mount vibration transducers to the selected measurement points. This will guarantee accuracy and repeatability of acquired data. It will also increase the initial cost of the program. The average cost of installing a general-purpose accelerometer will be about $300 per measurement point or $3000 for a typical machine-train.

To eliminate the capital cost associated with permanently mounting transducers a well-designed quick-disconnect mounting can be used. This mounting technique permanently mounts a quick-disconnect stud, with an average cost of less than $5, at each measurement point location. A mating sleeve, built into a general-purpose accelerometer, is then used to acquire accurate, repeatable data. A well-designed quick-disconnect mounting technique will provide the same accuracy and repeatability as the permanent mounting technique but at a much lower cost.

The third mounting technique that can be used is a magnetic mount. For general purpose use, below 1000 Hertz, a transducer can be used in conjunction with a magnetic base. Even though the transducer/magnet assembly will have a resonant frequency that may provide some distortion to acquired data, this technique can be used with marginal success. Since the magnet can be placed any where on the machine, it will not guarantee that the exact location and orientation is maintained on each measurement.

The final method used by some plants to acquire vibration data is hand held transducers. This approach is not recommended if any other method can be used. Hand held transducers will not provide the accuracy and repeatability required to gain maximum benefit from a predictive maintenance program. If this technique must be used, extreme care should be exercised to ensure that the exact point, orientation and compressive load is used for every measurement point.

50.5.3 Getting started

The steps we have defined will provide the guideline for establishing a predictive maintenance database. The only steps remaining to get the program started are to establish measurement routes and take the initial or baseline measurements. Remember, the predictive maintenance system will need multiple data sets to develop trends on each machine. With this database, you will be able to monitor the critical machinery in your plant for degradation and begin to achieve the benefits that predictive maintenance can provide. The actual steps required to implement a database will depend on the specific predictive maintenance system selected for your program. The system vendor should provide the training and technical support required to properly develop the database with the information developed in the preceding sections.

Training

Successful completion of this critical phase of creating a total plant predictive maintenance program will require a firm knowledge of the operating dynamics of plant machinery, systems and equipment. Normally some if not all of this knowledge exists within the plant staff. However, the knowledge may not be within the staff selected to implement and maintain the predictive maintenance program.

In addition, a good working knowledge of the predictive maintenance techniques and systems that will be included in the program is necessary. This knowledge in all probability will not exist within existing plant staff. Therefore training, before attempting to establish a program, is strongly recommended. The minimum recommended level of training includes: user's training for each predictive maintenance system that will be used, a course on machine dynamics, and a basic theory course on each of the techniques, i.e. vibration, infrared, etc., that will be used.

In some cases, the systems vendors can provide all of these courses. If not, there a number of companies and professional organizations that offer courses on most non-destructive testing techniques.

Technical support

The labor and knowledge required to properly establish a predictive maintenance program is often too much for plant staff to handle. To overcome this problem, the initial responsibility for creating a viable, total plant program can be contracted to a company that specializes in area.

There are companies that provide full consulting and engineering services directed specifically toward predictive maintenance. These companies have the knowledge required and years of experience. They can provide all of the labor required to fully implement a full plant program and normally can reduce total time required to get the program up and running.

Caution should be used in selecting a contractor to provide this startup service. Check references very carefully.

50.5.4 Maintaining the program

The labor-intensive part of predictive maintenance management is complete. A viable program has been established, the database is complete and you have begun to monitor the operating condition of your critical plant equipment. Now what?

Most programs stop right here. The predictive maintenance team does not continue their efforts to get the maximum benefits that predictive maintenance can provide. Instead, they rely on trending, comparative analysis or in the case of vibration-based programs simplified signature analysis to maintain the operating condition of their plant. This is not enough to gain the maximum benefits from a predictive maintenance program.

In this section, we will discuss the methods that can be used to ensure that you gain the maximum benefits from your program and at the same time improve the probability that the program will continue.

Trending techniques

The database that was established for your program included broadband, narrowband and full signature vibration data. It also included process parameters, bearing cap temperatures, lubricating oil analysis, thermal imaging and other critical monitoring parameters. What do we do with this data?

The first method required to monitor the operating condition of plant equipment is to trend the relative condition over time. Most of the microprocessor-based systems will provide the means of automatically storing and recalling vibration and process parameters trend data for analysis or hard copies for reports. They will also automatically prepare and print numerous reports that quantify the operating condition at a specific point in time. A few will automatically print trend reports that quantify the change over a selected time frame. All of this is great, but what does it mean?

Monitoring the trends of a machine-train or process system will provide the ability to prevent most catastrophic failures. The trend is similar to the bathtub curve used to schedule preventive maintenance. The difference between the preventive and predictive bathtub curve is that the latter is based on the actual condition of the equipment, not a statistical average.

The disadvantage of relying on trending as the only means of maintaining a predictive maintenance program is that it will not tell you the reason a machine is degrading. One good example of this weakness is an aluminum foundry that relied strictly on trending to maintain their predictive maintenance program. In the foundry are 36 cantilevered fans that are critical to plant operation. The rolling element bearings in each of these fans are changed on average every six months. By monitoring the trends provided by their predictive maintenance program, they can adjust the bearing change out schedule based on the actual condition of the bearings in a specific fan. Over a two-year period, there were no catastrophic failures or loss of production that resulted from the fans being out of service.

Did the predictive maintenance program work? In their terms, the program was a total success. However, the normal bearing life should have been much greater than six months. Something in the fan or process created the reduction in average bearing life. Limiting their program to trending only, they were unable to identify the root-cause of the premature bearing failure. Properly used, your predictive maintenance program can identify the specific or root-cause of chronic maintenance problems. In the example, a full analysis provided the answer. Plate-out or material buildup on the fan blades constantly increased the rotor mass and therefore forced the fans to operate at critical speed. The imbalance created by operation at critical speed was the forcing function that destroyed the bearings. After taking corrective actions, the plant now gets an average of three years from the fan bearings.

Analysis techniques

All machines have a finite number of failure modes. If you have a thorough understanding of these failure modes and the dynamics of the specific machine, you can learn the vibration analysis techniques that will isolate the specific failure mode or root-cause of each machine-train problem.

The following example will provide a comparison of various trending and analysis techniques.

Broadband analysis

The data acquired using broadband data is limited to a value that represents the total energy that is being generated by the machine-train at the measurement point location and in the direction opposite the transducer. Most programs trend and compare the recorded value at a single point and disregard the other measurement points on the common-shaft.

Rather than evaluate each measurement point separately, plot the energy of each measurement point on a common shaft. First, the vertical measurements were plotted to determine the mode shape of the machine's shaft. This plot indicates that the outboard end of the motor shaft is displaced much more than the remaining shaft. This limits the machine problem to the rear of the motor. Based strictly on the overall value, the probable cause is loose motor mounts on the rear motor feet. The second step was plotting the horizontal mode shape. This plot indicates that the shaft is deflected between the pillow block bearings. Without additional information, the mode shaft suggests a bent shaft between the bearings.

Even though we cannot identify the absolute failure mode, we can isolate the trouble to the section of the machine-train between the pillow block bearings.

Narrowband analysis

The addition of unique narrowbands that monitor specific machine components or failure modes add more diagnostic information.

If we add the narrowband information acquired from the Hoffman blower, we find that the vertical data is primarily at the true running speed of the common shaft. This confirms that a deflection of the shaft exists. No other machine component or failure mode is contributing to the problem. The horizontal measurements indicate that the bladepass, bearing defect and misalignment narrowbands are the major contributors.

As we discussed, fans and blowers are prone to aerodynamic instability. The indication of abnormal vanepass suggests that this may be contributing to the problem. The additional data provided by the narrowband readings help to eliminate many of the possible failure modes that could be affect the blower. However, we still cannot confirm the specific problem.

Root cause failure analysis

A visual inspection of the blower indicated that the discharge is horizontal and opposite the measurement point location. By checking the process parameters recorded concurrent with the vibration measurements, we found that the motor was in a no-load or run-out condition and that the discharge pressure was abnormally low. In addition, the visual inspection showed that the blower sits on a cork pad and is not bolted to the floor. The discharge piping, 24 inch diameter schedule 40 pipe, was not isolated from the blower nor did it have any pipe supports for the first 30 feet of horizontal run. With all of these clues in hand, we concluded that the blower was operating in a 'run-out' condition, i.e. it was not generating any pressure, and was therefore unstable. This part of the machine problem was corrected by reducing, i.e. partially closing, the damper setting and forcing the blower to operate within acceptable aerodynamic limits. After correcting the damper setting, all of the abnormal horizontal readings were within acceptable limits. The vertical problem with the motor was isolated to improper installation. The weight of approximately 30 feet of discharge piping compressed the cork pad under the blower and forced the outboard end of the motor to elevate above the normal centerline. In this position, the motor became an unsupported beam and resonated in the same manner as a tuning fork. After isolating the discharge piping from the blower and providing support, the vertical problem was eliminated.

50.5.5 Additional training

The initial user's training and basic theory will not be enough to gain maximum benefits from a total plant predictive maintenance program. You will need to continue the training process throughout the life of the program. A variety of organizations, including predictive maintenance systems vendors, provide training programs in all of the predictive maintenance techniques. Caution in selecting both the type of course and instructor is strongly recommended. Most of the public courses are in reality sales presentations. They have little practical value and will not provide the knowledge base required to gain maximum benefit from your program.

Practical or application oriented courses are available that will provide the additional training required to gain maximum diagnostic benefits from your program. The best way to separate the good from the bad is to ask previous attendees. Request a list of recent attendees and then talk to them. If reputable firms present the courses, they will gladly provide this information.