Troubleshooter's Guide to Test & Measurement Technologies

The careful selection and proper application of predictive maintenance and condition monitoring devices are an absolute necessity for industry to reduce maintenance costs.

BY LLOYD (TEX) LEUGNER


Photo: Flir Systems

The monitoring of equipment condition has been around ever since man created the wheel. When the wheel squeaked and the wheel hub began to burn, man learned to grease the wheel with tallow. As the application of the tallow became more precise, the mean time between potential failure of the wheel was extended.

Thus began the development of preventive maintenance, using the senses of sound, sight, touch and smell. However, sensory perceptions have the disadvantage of being subjective and imprecise, so over the years, condition monitoring techniques, predictive maintenance technologies and many other forms of testing and measurement have been developed and applied for industrial equipment.

In his book, *Reliability Centered Maintenance, Second Edition,* John Moubray describes 96 test and measurement techniques to monitor the operating condition of equipment. These range from a simple sensory technique, such as determining if a lubricant has an unusual odour and has darkened in colour, to the application of a highly sophisticated predictive maintenance technology such as the Fast Fourier Transform (FFT) analyzer to determine the causes of vibration frequencies in rotating equipment.

The use of test and measurement devices and techniques can only be justified if they can demonstrate a clear economic benefit. There is substantial evidence that the intelligent use of test and measurement techniques and predictive maintenance technologies will provide huge benefits to industry. These benefits include:

1. The elimination or reduction of catastrophic machine failures.
2. The elimination or reduction of secondary damage where a failure has occurred.
3. A reduction in maintenance costs by avoiding repairs.
4. A reduction in downtime by reducing the scope of repair.
5. An increase in production by scheduling repair at a time convenient to operations or when failure risk is at its lowest.
6. A reduction in downtime and costs by having advanced warning, which allows for thorough preparation and effective planning and scheduling of repairs.
7. A reduction in risk to equipment and personnel from a safety perspective.
8. A reduction in the cost of insurance.
9. The elimination of ineffective or unnecessary preventive maintenance tasks.
10. The extension of time-based intervals of necessary preventive maintenance tasks.
11. An improvement in the reliability, productivity and efficiency of industrial equipment.

By definition, the testing and measurement of equipment operating conditions requires that data be collected on an ongoing basis. In order to establish the necessary repeatable trend data, the following procedures must be used when applying condition monitoring techniques.

A. Test and measurement data must be obtained at regularly scheduled intervals, i.e. every 168 hours (weekly), or 672 hours (monthly), depending on the equipment type and/or operating conditions.
B. To ensure repeatability, the data must be gathered when equipment is at operating temperature.
C. Trending of conditions will not be accurate if the test and measurement data is not taken at the same point on the machine component each time the data is collected.

The following test and measurement techniques are common, easily applied and only require that operations and maintenance personnel have a sound knowledge and understanding of their equipment and its operation. They include: testing and measurement of lubricant condition; analytical ferrographic testing; testing and measurement of temperature conditions; testing and measurement using ultrasonic devices; electrical testing and measurement; and vibration analysis testing and measurement.

Testing and measurement of lubricant condition

Common oil analysis techniques such as spectroscopy and particle counts can measure wear rates and contaminant levels respectively, but common sense suggests that simple on-site tests can be very cost effective.

If an operator suspects contamination, a sample of oil can be obtained in a glass jar, which is then allowed to sit overnight. When the jar is turned over, any contaminant will remain visible on the bottom surface of the jar. A decision can then be made if laboratory testing is required.

Water contamination in the lubricant can also be determined very quickly by placing a few drops of oil on a hot plate. If the oil drops crackle or sizzle, there is excessive water present.

Every time an oil filter is replaced, the old filter should be cut open and the filter media spread on a bench. Using a good-quality magnifying glass or microscope, contaminants and wear metals will be obvious. Further testing can be applied if a magnet is passed under the filter media. All ferrous materials will move on the surface of the filter media as the magnet is moved (see figure 1).

If machine damage is suspected, or the level of contaminant or wear metals have increased since the last filter inspection, a ferrographic analysis of an oil sample should be carried out.

Analytical ferrographic testing

Ferrography is a specialized oil analysis technique that can determine the type of contaminant and/or wear particles and indicate their probable or possible source.

The analysis effectively detects contaminants in the range of fewer than 1 micrometres to about 250 micrometres. Analysis is done using a technique called bichromatic microscopic examination, which uses both reflected and transmitted light sources with green, red and polarized filters to distinguish the size, composition, shape and texture of ferrous, non-ferrous and non-metallic particles (see figures 2 & 3).

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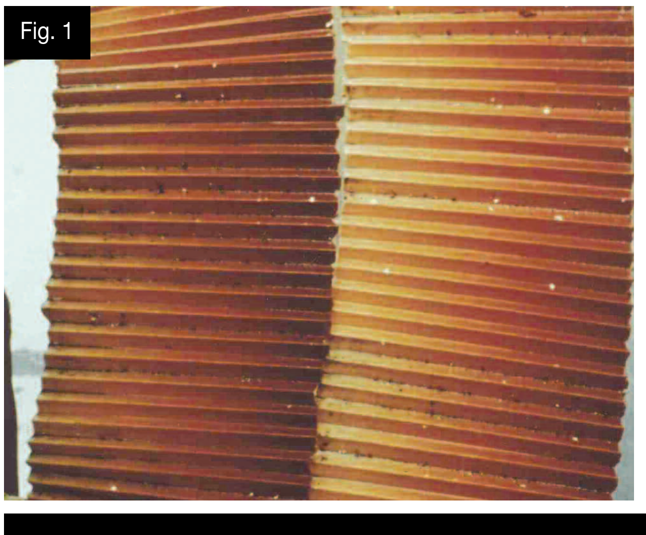
Fig. 1


Fig. 2


Fig. 3

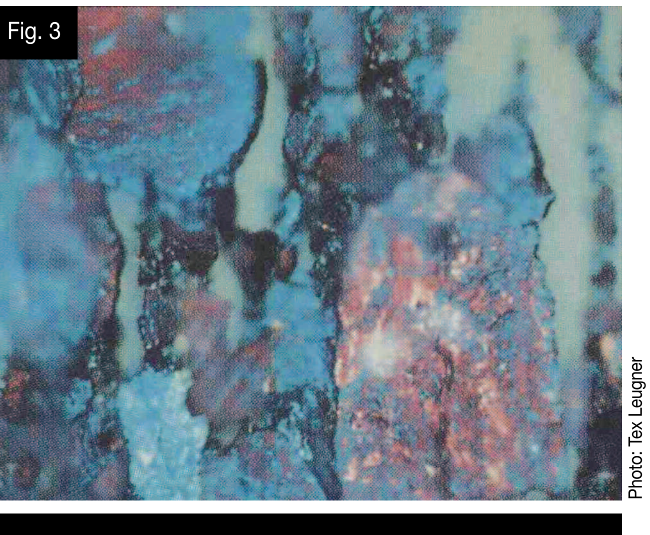



Photo: Tex Leugner

Fig. 1: All ferrous materials will move on the surface of the oil filter media as a magnet is moved under it, easily identifying them.

Fig. 2: This ferrogram shows several gold-coloured particles, indicating wear of brass or bronze components typical of hydraulic system wear conditions. If the pump is the only component in the system with this material, the source has been determined.

Fig. 3: This ferrogram shows both blue and purple temper colours, illustrating case-hardened and low-alloy steel respectively, indicating abnormal gear wear. An immediate inspection would be in order.

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Testing and measurement of temperature conditions

The operating temperatures of industrial equipment are often unknown or ignored and frequently never considered until after a failure has occurred.

The first step taken for any piece of equipment is to determine the operating temperature under normal conditions, record this standard in the maintenance files and investigate any change in that standard during the life of the equipment. Generally, the following component systems should not exceed the corresponding temperatures listed during operation.

Rolling element bearings — 71°C (160°F) is the temperature at which lubricating oil or grease begins to oxidize.

Hydraulic systems — bulk oil temperature at the exterior of the reservoir should not exceed 60°C (140°F).

Gear drives — operate best in a temperature range of 49°C - 60°C (120°F - 140°F). Remember that an operating temperature rise of 50°C (90°F), combined with an ambient temperature of 15.6°C (60°F), will result in a 'total oil operating' temperature of about 66°C (150°F).

Worm gears — operate best at oil temperatures of about 60°C-65°C (140°F-150°F). Higher temperatures may promote pitting of the phosphor bronze gear; the use of polyglycol synthetic oil can reduce temperatures by up to 10°C, as well as reduce gear pitting.

V-belts — should not operate at temperatures higher than 60°C (140°F) and should never be covered completely by a safety shroud. Wire mesh shrouds should be used.

Gas turbines — oil temperatures should normally be in the range of 54°C-71°C (130°F-160°F).

Electric motors — there are four classes of motor winding insulation, each with a corresponding maximum temperature rating. Insulation Class A has a Maximum Winding Temperature of 105°C (221°F), B is 130°C (266°F); F is 155°C (311°F) and H is 180°C (356°F).

The temperatures listed include combined ambient temperature and temperature rise. For every 10°C increase in temperature above the rating, the service life of that particular motor is reduced by 50%. Various studies suggest that 40% of all electric motor problems are directly caused by excessive heat (see figure 4).

Common and inexpensive methods of testing temperature conditions include the use of infrared thermometers using laser beams for instant and accurate temperature display. Another common temperature monitor is the digital temperature indicator shown in figure 5.

Remember that when measuring the temperature of any component, it is the housing temperature which is being recorded. It is safe to assume that the actual operating temperature of the internal components, such as electric motor windings, rolling element bearings, or the lubricant in a reservoir or gear housing, will be about 20°C higher than the recorded temperature.

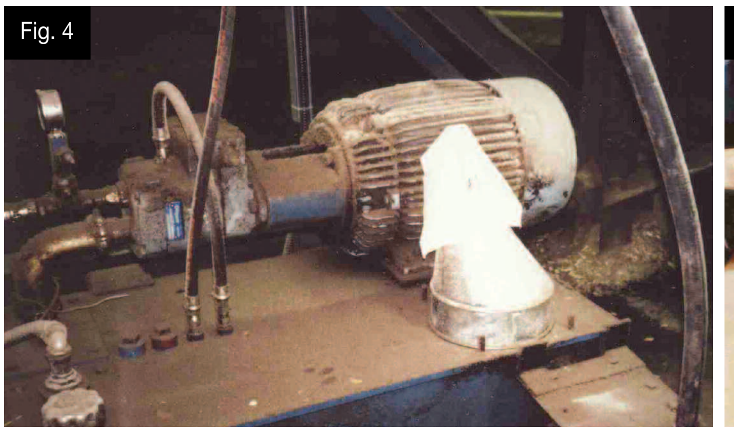
Fig. 4

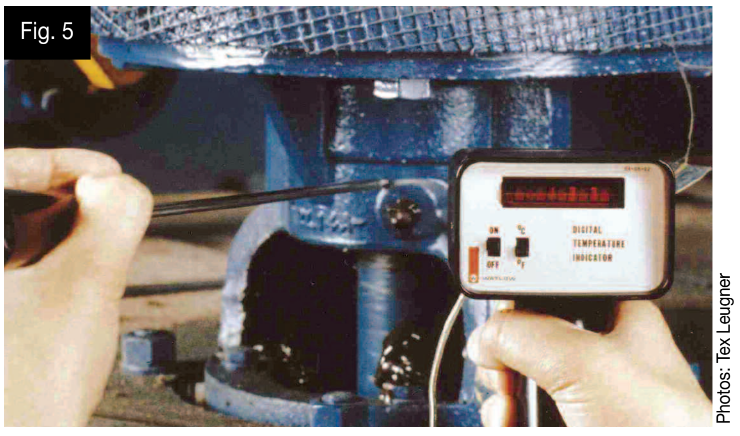

Fig. 5

Photos: Tex Leugner


Fig. 6

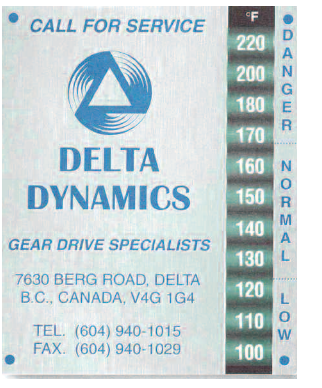

Fig. 7

Fig. 4: This motor is driving a hydraulic pump. The sawdust and dirt covering the motor, pump and the reservoir surface has been allowed to accumulate. Both the motor and pump are running at operating temperatures that will cause both components to fail prematurely. The oil temperature in the reservoir is also higher than it should be, because the exterior is coated with oil-soaked sawdust. Equipment operating in such conditions must be kept clean if reliability is to be assured. Note the reservoir filler cap. It should be replaced with a filler cap containing a 2-micron filter, otherwise this reservoir will be subjected to excessive contaminant drawn into the tank. Also, the oil filler spout left on the reservoir is a totally unacceptable practice. Using this spout is tantamount to pouring contaminants into the reservoir.

Fig. 5: Handheld digital temperature indicator.

Fig. 6: Handheld infrared thermography unit.

Fig. 7: 'Thermo label' indicators turn from green to black when a component reaches a temperature shown on the card.

At least once each year, an infrared thermographic analysis should be carried out to locate hot spots in electric motors and switchgear, mechanical devices such as drive couplings, bearings and gear drives, as well as roof insulation, kilns and refractories.

There is almost no limit to which infrared thermography may be used in testing and measuring temperature-related problems. Handheld devices such as Flir's Thermocam are available for this purpose (see figure 6).

One of the biggest problems experienced in industrial facilities are poor electrical connections in switchgear, fuse boxes and other wired devices. Electrical system reliability can be improved up to 40% with a substantial overall reduction in temperature, if infrared scanning is carried out on a regular basis and connections are maintained properly. The following standards should be considered as benchmarks when scanning electrical system components or connections.

- Temperature differences (above the normal reference temperature) of 1°C-3°C indicates a possible deficiency which should be investigated when time permits.
- Temperature differences of 4°C-15°C indicate a deficiency and should be investigated as soon as possible.
- Temperature differences of 16°C and higher indicate a major deficiency that should be investigated immediately.

Finally, a simple, cost-effective device to measure temperature that can be installed on any piece of equipment is a constant temperature monitor. These adhesive 'thermo labels' (see figure 7) are made with a heat-sensitive liquid crystal indicator sealed under a transparent heat-resistant window. They are applied adhesively to the surface of a component and the indicator turns from green to black at the temperature rating shown on the card.

After an excessive temperature problem is corrected, the temperature rating returns to the normal operating level.

Testing and measurement using ultrasonic devices

A. Ultrasonic leak detection: During a leak, a liquid or gas moves away from high pressure. As it passes through the leak site, a turbulent flow is generated that has strong ultrasonic sound wave components, which can be monitored. The intensity of the ultrasound produced by the leak will be loudest at or near the leak site. Since the ultrasound is considered directional, locating the source of most leaks is quite simple.

Ultrasonic leak detection can be used to locate the following problems:

- Internal hydraulic system leaks, such as oil passing through a closed control valve that should not be leaking.
- Manifold vacuum leaks in engines.
- Steam trap leakage.
- Air leaks on air brake systems on transportation equipment.
- Leaks in heat exchangers, boilers, condensers, chillers and vacuum systems.
- Compressor valve operation.
- Seal and gasket integrity.

B. Ultrasonic bearing and mechanical inspection: Mechanical movement produces a wide variety of sounds. Based on experience and trending techniques, early warning of bearing failures can be detected using ultrasound techniques.

Ultrasound is monitored in dB or decibel levels and various stages of bearing failure have been established through previous research. For example, an 8-dB increase over the baseline indicates a lack of lubrication, or an initial bearing problem, such as a tiny crack, spall or rough bearing surface. A 12-dB increase indicates the start of the

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failure condition. A 16-dB increase over baseline indicates an advanced failure condition, while a 35-dB to 50-dB gain over baseline provides warning of a catastrophic failure.

It is very important to remember that a baseline ultrasound level must be established for each bearing if comparative ultrasonic readings are to be effective.

C. Ultrasonic electrical inspection: Electrical component arcing, tracking and corona discharge often do not generate heat and therefore ultrasonic testing can be more effective than thermographic imaging.

When arcing, tracking or corona occur, some form of ionization is generated that disturbs the air around the discharge. The ultrasonic testing detects these high-frequency noises and translates them down to audible ranges.

The specific sound of each type of discharge can be heard in headphones, while the discharge intensity can be observed on the meter.

Normal electrical equipment may be silent, or in the case of transformers, produce a steady 60-cycle hum. The arcing, tracking or corona will be associated with an erratic sizzling or uneven popping sound of electrical discharges (see figure 8).

D. Determining grease quantity: Ultrasonic devices are available that can be connected to a grease gun. The use of the device is intended to provide the technician or the operator with a sound level that indicates when a sufficient amount of grease has been applied to the bearing.

Electrical testing and measurement

1. Batteries: Measuring AC voltage across the battery when it is connected to a battery charger has proven to be an excellent indicator of incipient failure. Simply measure and record the AC millivolts across each battery when the string of batteries is first installed, such as in a UPS system.

Record this voltage for each battery. As the internal resistance of the battery increases, the AC voltage will increase and trends can be established.

Fig. 10

Fig. 8: Ultrasonic probe is used to monitor arcing, tracking of insulation or corona discharge.

The actual value will vary, depending upon the amount of AC ripple in the charger output, however once trends are established, any change in the trend for a particular battery can be considered a warning of imminent failure and the battery should be replaced.

2. Transformers: Common tests for transformers include the following:

- Power factor testing measures power loss through the insulation caused by leakage to ground or moisture in cables. A newly filled oil transformer should have a power factor of under 0.5% and an in-service oil-filled transformer under 2%.
- Standard and recommended oil tests for transformers include, but are not limited to: 'Dielectric Breakdown' in kilovolts, with a normal reading of 35; 'Neutralization Number', which should not exceed 0.04 with a maximum limit of 0.40, at which point the oil must be scrapped; and 'Water Content' in parts per million, which must not exceed 30. In addition, dissolved gas analysis is a recently developed test for oil-filled transformers.

Whenever there is an incipient fault, specific gases are generated and dissolved in the oil. These gases include carbon monoxide and carbon dioxide. When large quantities of these gases are present in the oil, it indicates severe levels of overheated windings in the transformer.

3. Electric motors: There are dozens of potential faults that may occur in electric motors. These include electrical problems associated with internal motor circuits, such as faulty insulation, open circuits, short circuits in windings, broken rotor bars, uneven rotor-stator air gap, or high resistance between rotor bars and rings.

Some very useful tests to locate these problems include motor circuit and motor current analysis.

Mechanical problems that may affect electric motor efficiency include bearing problems, misalignment, unbalance, mechanical looseness or eccentric V-belt pulleys. Vibration analysis should be carried out if mechanical problems are suspected. Infrared thermography will pinpoint any hot spots that may be associated with any potential motor faults.

4. V-belt drives: V-belt drives are usually ignored until a problem develops. Besides the requirements for proper adjustment and alignment, an often-ignored problem with belts is their tendency to discharge static electricity through support bearings on the sheaves, or in the components that the belts are driving.

V-belts used in potentially explosive applications (such as in plants that generate fine dust that could ignite due to static discharge) should be grounded. Grounding brushes can be installed and connected to ground to discharge static electricity. Belts used in these applications should have an electrical resistance of 6 megohms or less and be of the 'static conducting' type.

The Carlisle company has developed a belt adjustment tool called the Tension Finder that is recommended for belt adjustments.

5. Electrical circuit insulation testing: Insulation will deteriorate over time due to extremes in temperature, moisture, dirt, dust and other contaminants.

Using a megohmeter (or other comparable device), a voltage is applied across the insulation from conductor to ground. This test voltage should be one voltage range higher than the voltage normally applied during circuit operation. For wire insulation, the minimum resistance that is considered acceptable for the insulation is 1 megohm per 1,000 volts of applied voltage.

For motors and transformers, the minimum acceptable resistance is 1 megohm per 1,000 volts of applied voltage plus 1 megohm, with a minimum of 2 megohms. It is not uncommon for a new motor to measure 50 megohms or more.

6. Harmonics detection testing: In the past, electrical machines and equipment most often were resistive or linear loads. In other words, the current increased as the voltage increased, with the result that both current and voltage waveforms were similar in shape and no distortions were created.

However, the development of solid state control devices and switched-mode power supplies has dramatically changed the load characteristics. These devices do not draw current in a linear fashion. Instead, they draw current in bursts, creating harmonic currents that in turn cause distortions in the voltage wave form.

A harmonic is a multiple of the fundamental waveform at 60 cycles per second, thus the second harmonic occurs at 120 cycles per second and the third at 180 cycles per second. Although all harmonic distortions can create problems, the third harmonic is particularly troublesome.

The third harmonic can cause many

problems in electrical systems, among them: overheating of motors and transformers, excessive neutral current causing the potential for fires in neutral conductors, problems in PLC control systems, computer lockups or loss of data, shaft currents in electric motors causing bearing failures if the bearings are not insulated, and audible and/or excessive noise in telephone circuits and transformers.

To determine if harmonics are present in any system, measure the load current with an average reading ammeter, then again with a true RMS reading ammeter, and compare the readings. If harmonics are present, the average reading instrument will read lower than the RMS instrument.

Measuring neutral-to-ground voltages in excess of 2 volts will also indicate the presence of the third harmonic. If the instrument measures frequency, do not be surprised to read 180 Hz, confirming the presence of the third harmonic in the neutral conductor.

An excellent reference that outlines methods to control or eliminate harmonics in electrical systems is *Recommended Practice for Electrical Equipment Maintenance, 2002 Edition,* published by the National Fire Protection Association (www.nfpa.org).

Fig. 12

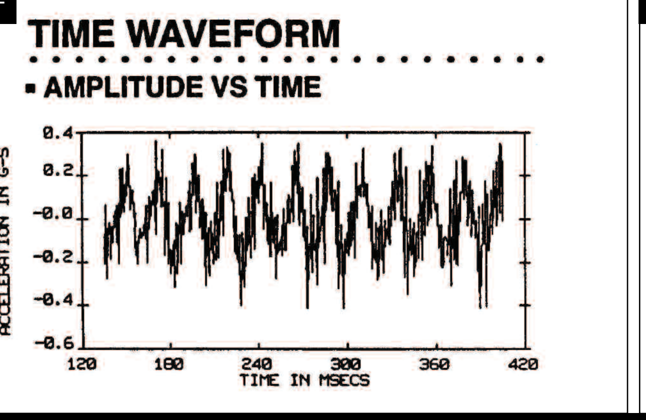

Fig. 13

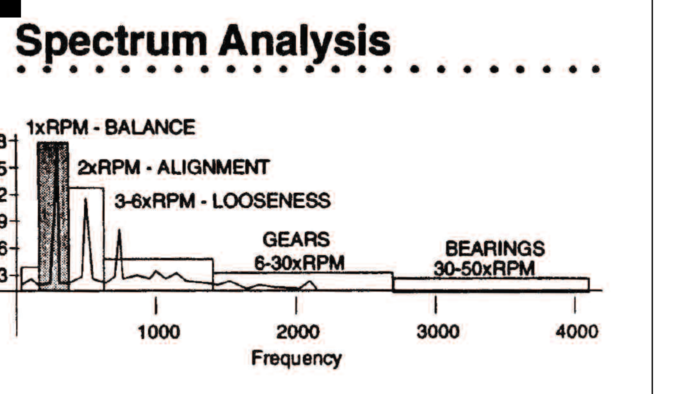

Fig. 9: Using an FFT analyzer, vibrations can be measured and displayed in a time waveform, which indicates vibration severity.
Fiig. 10: An FFT analyzer can display a spectrum analysis, which illustrates the frequencies of the various sources of vibration.

Vibration analysis testing and measurement

Every piece of equipment contains moving parts, each of which vibrate at certain frequencies. These frequencies are governed or generated by the vibration sources and will vary across a wide range, referred to as a spectrum. Common sources of vibration are unbalance, misalignment, bent shafts, defective bearings or gears, mechanical looseness and electrically induced problems.

Technically defined, vibration is the oscillation of an object about its position of rest and the number of these oscillations (or cycles) in a given length of time is referred to as the frequency of vibration. It is measured in cycles per minute (cpm), or cycles per second (Hz). The amplitude of vibration is measured in either displacement (distance or movement), velocity (speed) and/or acceleration (force) of the source of the frequency.

Using an FFT analyzer, vibrations can be measured and displayed in either a time waveform, which indicates vibration severity, or in a spectrum analysis, which illustrates the frequencies of the various sources of vibration (see figures 9 & 10).

In addition to sophisticated vibration analyzers, there are many devices available today which can be used to determine if a vibration exists within a piece of rotating equipment. They include the following test and measurement tools:

Stroboscope: This device can be used to determine the phase of vibration. Phase refers to the position of a vibrating part at a given instant with reference to a fixed point or another vibrating part on the machine. For example, the strobe light will flash in synchronization with a fixed point on any rotating component that has been previously marked. If the fixed point moves erratically and does not appear to be stopped when the strobe flashes, this behaviour confirms that some vibration is present and further analysis will be required. The stroboscope is also an extremely useful tool when measuring unbalance and in correcting this cause of vibration.

Shock pulse measurement: All rotating rolling bearings emit shock pulses, which are pressure waves generated in the contact zone between the ball or roller and raceway. These shock pulses are measured on a decibel scale and compared with severity against the ISO Standard 2372, which provides vibration tolerance limits.

SKF vibration pen: This handheld device can be used to assess rotating machine condition in the 600 rpm to 12,000 rpm range. The device measures vibration severity in either mm/s, RMS or in./s peak. The vibration severity can then be compared to ISO Standard 3945.

SKF "SEE" pen: This handheld device incorporates SKF's patented Spectral Emitted Energy or SEE to monitor bearing condition. The SEE device measures very high frequencies relating to poor lubrication, damaged bearings or overloading. The device is recommended to be used in conjunction with the low-frequency vibration pen described above.

SKF Marlin condition detector: This is a handheld device which can be used to gather velocity and acceleration vibration data, as well as for temperature monitoring for all types of rotating equipment. Simple to use, it can incorporate bar coding and oil analysis data, and can be used with many of the common computerized maintenance management software (CMMS) programs available today.

Summary

To summarize, this article has only scratched the surface in describing the many testing and measurement devices and methods that should be applied if equipment productivity and reliability improvements are the goal of industry.

The careful selection and proper application of these predictive maintenance and condition monitoring devices are an absolute necessity if industry wishes to reduce maintenance costs.

One example of such success is the Palo Verde Nuclear Power Plant in the U.S., where the annual net benefit of a carefully applied testing and measurement predictive technology program is an average of $5 million in reduced maintenance costs, which goes directly to the profit line.

If North American industry intends to compete globally today, it must stop burning up its maintenance dollars and instead, learn to apply these proactive techniques. MRO

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References: *Reliability Centered Maintenance, 2nd Edition,* John Moubray; *The Practical Handbook of Machinery Lubrication, 3rd Edition,* L. Leugner; *Recommended Practice For Electrical Equipment Maintenance 2002 Edition,* National Fire Protection Association.