The official journal of the Vibrations Association of New Zealand

Spectrum

Spring 2019 | Issue 94

Key Guidelines on Condition Monitoring & Reliability of Rotating Equipment

Part 1 of a 2 part series...

Skills & Practices

Motor Terminal Connections

Fan Bearing Failure

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VIBRATIONS ASSOCIATION *of* NEW ZEALAND

PRESIDENTS' REPORT

By Rodney Bell, VANZ President

Welcome all to the final Spectrum for 2019. Its been a busy and challenging year and now as we head towards warmer days, we get closer to summer holidays with Family/Friends...
Bring it on!

The conference committee has been busy planning the May 2020 conference. The location can now be confirmed as **Trinity Wharf Tauranga May 12th, 13th & 14th** this year's conference Theme is "Back to the Future"

We have some exciting new plans with re-introducing a technical papers day on Tuesday the 12th for those Analysts who love to absorb this information from field specialists. Tuesday will also include the other 2 streams Theory & Usage of tools for Predictive Asset Management (Hands On) plus Reliability Management. So, for those of you that usually come alone for the 2-day conference, do take advantage of the 3-day package which will be including 3 nights' accommodation, 3 days conference & food/beverage. Watch this space for more detail.

I can now also confirm the Principle sponsor for our Tauranga conference is CSE-W. Arthur Fisher and we thank them very much for their continued support. Without this and the other Exhibitors support, this event would not be possible to bring to us all.

Call for Papers
I ask that each one of you that have had the opportunity to read this version of Spectrum to have a think about putting a paper together about one of your Reliability successes, failures or even if still under investigation experiences. Typically, a paper length is 40 minutes, but this time can be reduced if necessary or you can even share your presentation with a work colleague, either way we just want to hear your work stories.

I would take this time now to wish you all a safe and happy Christmas/New Year period from the VANZ Team and I look forward to updating you all in the January Spectrum.

EDITORS' CORNER

Greetings dear readers, this being the last issue of the year we here at VANZ hope you've all had a productive 2019 and the next few months before the Christmas holidays eases you into the new year.

As another year passes we look back and reflect on the last 12 months within the industry, the changes that have been made, the new technologies discovered and the trials and tribulations that we've faced.

In this issue we have the first half of an article by Amin Almasi, a Lead Mechanical/Machinery Consultant in Australia, his paper is about Key Guidelines on Condition Monitoring & Reliability of Rotating Equipment. Also you can puzzle your grey matter with the latest quiz from Carl and be sure to read up on our Presidents latest musings.

As we start planning for the new year we have a busy team organising everything for the 2020 conference, the info we currently have available can also be found on our website **www.vanz.org.nz** so keep checking back for more details!

Many thanks go to the companies that advertise with us, we greatly appreciate your support for another year and hope to continue with you all next year, happy reading!

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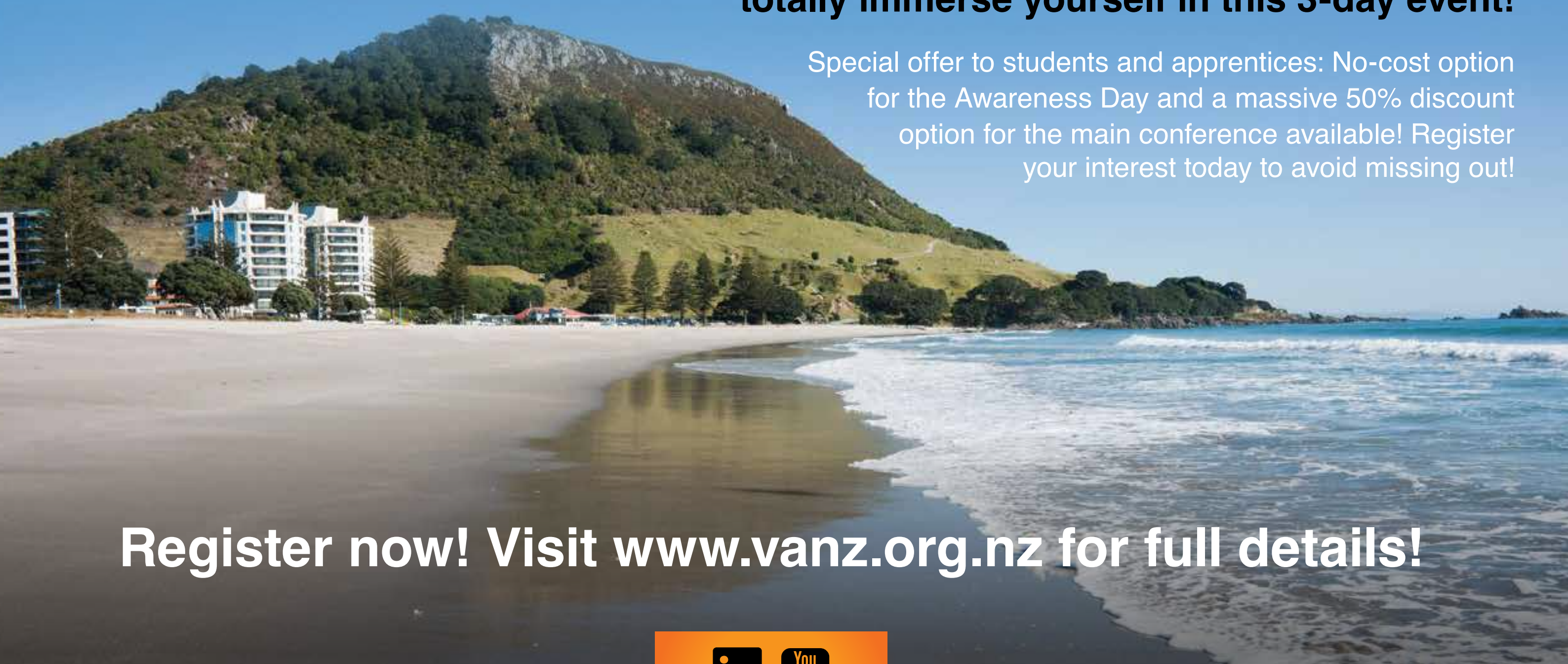

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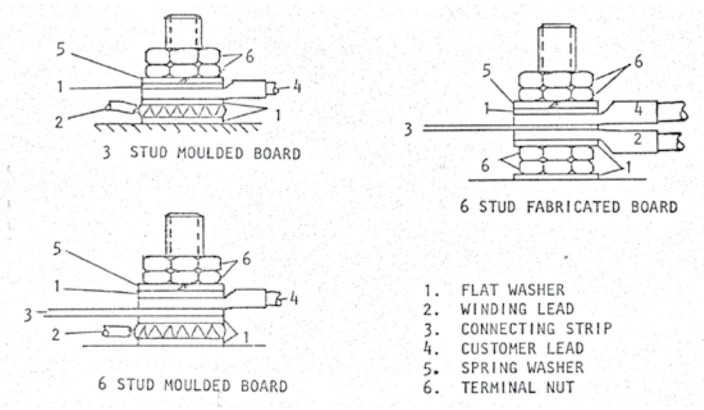
SKILLS AND PRACTICES

Motor Terminal Connections

There are a number of ways that we can introduce defects (faults) when connecting leads to motor terminals.

1. Order of assembly of parts.

The guiding principle here is that the parts must be assembled such that washers, nuts and stud are not in the current path. I.e. the lugs and links (all the conductors) must be in direct contact with each other. Refer to the illustrations opposite (courtesy of Pope electric motors).



Note the use of flat washers and spring washers. The flat washers protect the lugs from damage during tightening, while the spring washers keep the assembly tight in the event of significant temperature changes or vibration.
The same principles apply to earth connections. I.e. the earth terminal must be in direct contact with the earthing strip and flat and spring washers must be used. Use the largest diameter bolt that will fit through the hole in the lug. This will ensure good contact between the lug and the earth bar, and provide a robust connection.

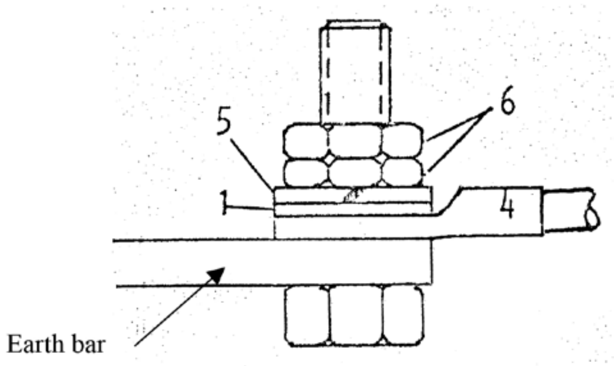
Continued on page 8 >

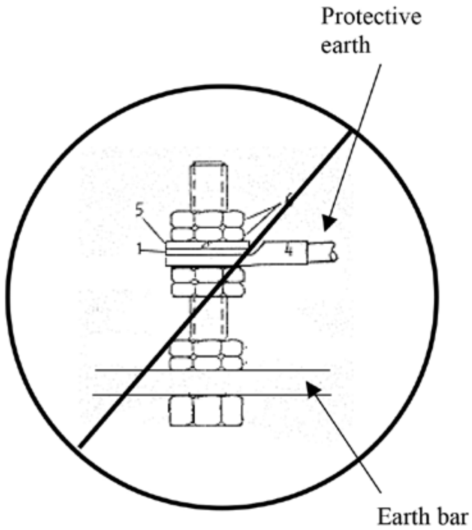
Prepared by Rod Bennett, Condition Monitoring Engineer.

2. Tightening of nuts.

In order to avoid nuts coming loose, or threads being stripped, nuts must be tightened to the correct torque as specified in the following table.

Stud Size	Tightening Torque in Newton Metres +- 10%	
	Brass	Steel
3.B.A	1.19	2.1
3/16" BSW	1.7	2.8
1/4" BSW	4.4	7.0
5/16" BSW	8.8	14.9
3/8" BSW	15	25.76
9/16" BSW	44.8	100
M16	83.4	137





This is an example of poor practice. It is NOT acceptable because the stud is required to carry the fault current.

Other tips.

- For motors where there are no terminal studs, and the lugs are simply bolted together, apply the same principles.
  Also make sure that the bolt used is no longer than necessary. This is to reduce the likelihood of the bolt touching other components and causing the insulation to wear off.
  Ensure that there is sufficient insulating tape over the connections. This insulation must be equivalent in performance to the insulation on the cables.
- These principles can be applied to bolted connections in MCC's, for example, not just motors.
- Terminal box covers must not be fitted without a gasket. Silicone sealant is not to be used to as an alternative, as it makes it difficult to remove the cover later on. Acid cure silicone will also cause corrosion of some components. So, use the correct gasket. This keeps the terminals clean and dry, and facilitates easy removal in the future.

When blowing out motors, ensure that the air line is fitted with a drier to remove any water in the air.

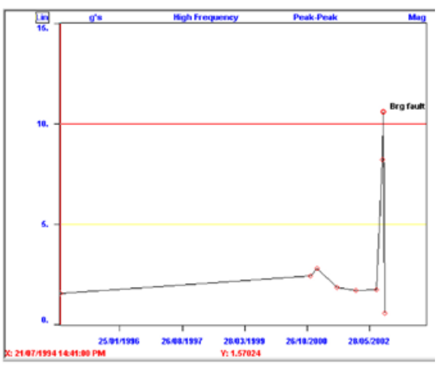
SKILLS AND PRACTICES

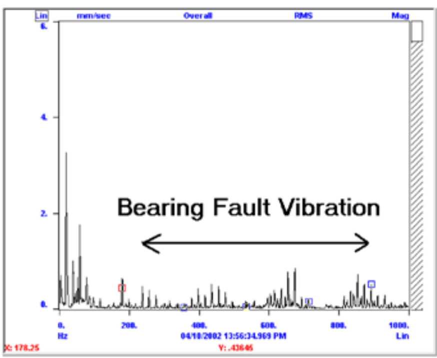
Fan Bearing Failure

The facts:
- **Type of bearing:** Spherical roller
- Failed after only 2 months in service
- **Root cause of failure:**
  – installation of bearing on damaged shaft
- **Corrective actions:**
  – shaft was repaired using Loctite Quickmetal
  – share learnings with rest of plant
- **Avoided cost:** $150,000 / 48 hrs delay (had it caused a line stop)
- **Actual cost to repair:** $2,000.

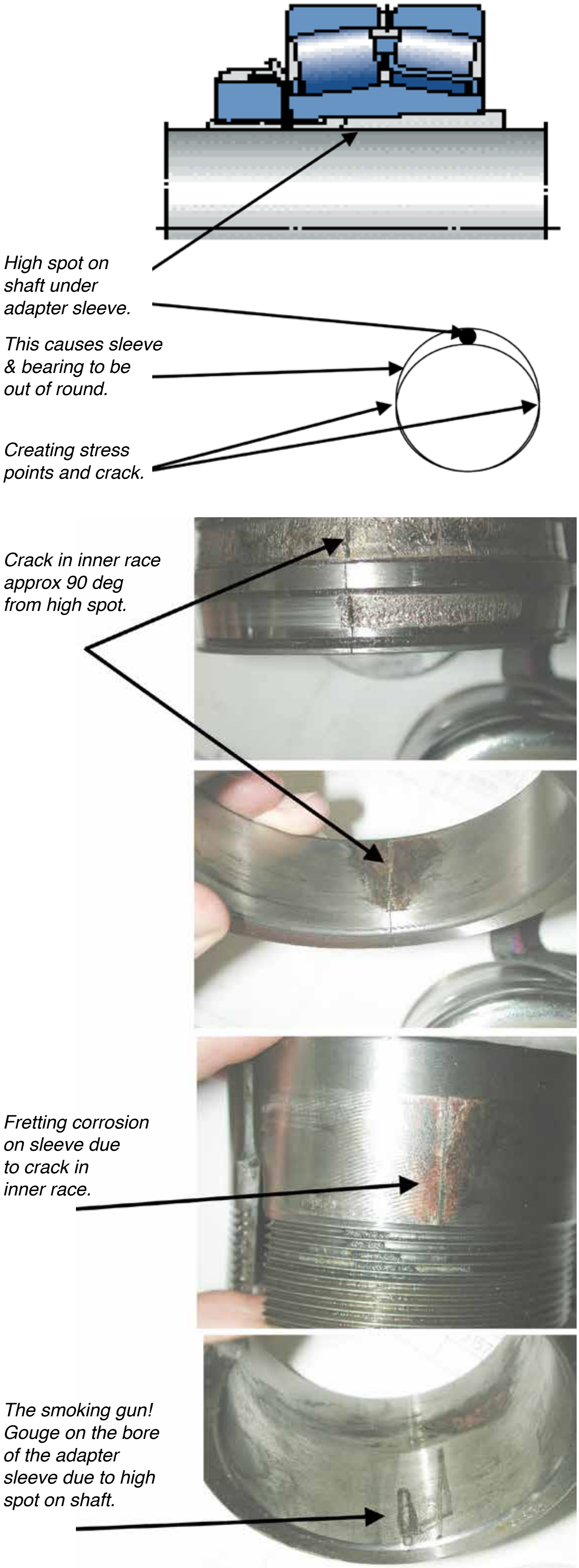
Detection
The fault was detected through routine vibration analysis.

Post mortem analysis of the bearing
Spalling on inner race due to high spot directly underneath, as shown in the photograph below.





Prepared by Rod Bennett, Condition Monitoring Engineer.



Learnings

- Shafts must be in good condition, otherwise early failure may result.
  - No high spots.
    This over stresses the bearing.
  - No significant wear.
    If a shaft is undersize, the sleeve will not grip the shaft. This will allow the adapter sleeve to spin on the shaft causing significant damage. (See photo above for an example of what can happen if an adapter sleeve comes loose).
- If a shaft is undersize, It may also prove difficult to correctly set the bearing internal clearance.
- For shafts, the fit is h9. For example, on a 50mm shaft this is +0.0, -0.062mm (or +0, –2.5 thou.). So, it doesn't take much before the shaft is undersize!
- For shafts that are undersize, the shaft must be replaced or repaired for reliable operation.
- There is a technique for repairing some shafts using products such as Loctite Quickmetal. This adds about 2 hours (drying time) to the job. This sort of repair should be seen as a temporary fix while a new shaft is made.
- DO NOT use emery cloth to clean up the shaft except to remove burrs / high spots. Removing stains and creating a nice bright surface is not necessary. All this does is make the shaft undersize!
- Follow the procedure to correctly set the bearing internal clearance.
- The procedures for self aligning bearings are in the plastic envelope attached to the bearing packet. The procedures for spherical roller bearings and self aligning ball bearings are different! This is a topic for the future.

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Key Guidelines on Condition Monitoring & Reliability of Rotating Equipment

Part 1 of a 2 part series...

Modern condition monitoring methods are used to operate rotating equipment reliably and efficiently. Latest practical notes and recent lessons learned on condition monitoring techniques, condition-based maintenance, trouble-shooting techniques and smart operation are discussed. The focus is on new technical knowledge, latest experiences and recent lessons learned on these topics. Mathematical formulations or complex charts, diagrams or graphics are avoided. Latest guidelines, novel technical notes, new technical knowledge and recent case studies are discussed. Predictive maintenance (condition-based maintenance) and its benefits are also discussed. Optimum configurations of condition monitoring for various rotating machineries are addressed. Latest recommendations regarding bearing monitoring, integrated condition monitoring, trip levels, alarms, gear unit reliability, failure root-cause analysis, inspection tips, and reliability-centred maintenance (RCM) are discussed. Key part of this article is eight (8) important case studies which are presented.

By Amin Almasi

Introduction

Modern plants and facilities depend heavily on rotating equipment such as pumps, compressors, turbines, electric machines, engines, fans, blowers, motors, material handling systems, and others [1-4]. To maximize plant's profit, rotating machineries should be operated with maximum reliability, maximum capacity, maximum efficiency and minimum operating and maintenance costs [5-9]. To achieve above-mentioned goals, great care should be taken from project basic design and specification writing to the installation, commissioning, operation and maintenance. An effective condition monitoring and maintenance strategy actually starts from basic-design phase, particularly with rotating machinery specification and machinery basic design [10-12]. Inadequate specification can significantly impact the reliability and availability of rotating machineries [6,10].

Key Challenges

Many operation companies maximize their profits by operating un-spared (critical) rotating equipment for long durations without any shutdown. They are investing heavily on identifying and eliminating potential reliability issues through effective condition monitoring and predictive maintenance to meet continuous and efficient operation. However, manufacturers of rotating equipment often maximize their profit by manufacturing machineries to meet project specifications and applicable codes at the lowest cost. Too often they only assure that equipment will be reliable for manufacturer's warrantee/guarantee period. Manufacturers may not initiate improvements to extend reliability and trouble-free operation beyond manufacturer's warrantee period. Many manufacturers believe they cannot stay competitive and in business if they design and manufacture expensive rotating equipment beyond the requirements of relevant codes and client specifications for a long-term (say 10 or 20 years) trouble-free operation. The above-mentioned is key to understand the reliability of rotating equipment and required actions to increase the reliability and availability.

For real improvements of reliability, failure root-cause analysis and trouble-shooting, all facts particularly operating condition changes, piping and foundation changes, and ambient condition changes need to be considered. A rotating machinery should be considered as a complete system including its driver, transmission system, coupling, all involving auxiliaries such as gear unit (if applicable), lubrication oil system, cooling system (if any), seal system, etc. A rotating machinery package regardless of its

Continued over page >

Amin Almasi is senior rotating equipment consultant in Australia. He is chartered professional engineer from Engineers Australia and IMechE and registered professional engineer in Australia (M.Sc. and B.Sc. in mechanical engineering). He specializes in rotating equipment, condition monitoring and reliability.

type usually becomes customized because of its environment such as its process, site conditions, its unique battery limits, unique piping arrangement, specific foundation, etc [1]. Each machinery has its own unique signature including unique vibrational signature, unique operational behaviour, and others.

Condition Monitoring: Baseline &Trending

The condition monitoring is based on trending. It requires that suitable sensors are used, dedicated parameters are monitored, baseline (normal condition) is defined and the trend of data is captured to identify condition changes. For an effective condition monitoring, all abnormal conditions should be identified compared to normal (or baseline) conditions. However, it is not possible for all and every component and parameters of a complex rotating machinery. Therefore, optimum number of parameters and components should be selected for an effective condition monitoring approach.

Major Machinery Components

Major machinery components considered in commonly-used condition monitoring systems are:

1. Bearings: Including radial and thrust bearings.
2. Seal and packing.
3. Rotors (shaft or crankshaft mechanisms).
4. Auxiliaries: such as lubrication oil system, seal system, cooling system, etc.

Regardless of type of machinery, monitoring of four above-mentioned categories usually determine condition of a machinery [1,2,5,6]. It is important to obtain baseline information as soon as possible after the start-up of rotating machinery. Too often, baseline conditions have ignored and it badly has affected condition monitoring. Without a baseline, there is no reference for the comparison and interpretation of data [1,10].

Failure Analysis & Trouble-Shooting

Rotating machineries do not fail randomly [1,7,8]. There are root-causes for each failure. Usually condition(s) of failed part has changed and it has led to failure. To stop failure, it is necessary to know why failure occurs [1,2,6]. Based on failure analysis knowledge, corrective actions should be taken. More importantly, based on previous failure studies, critical components and parameters should be selected for condition monitoring. On this basis, proper parameters, sensors, and set points should be defined for an effective condition monitoring. By being aware of major root-causes of failures and by observing conditions of key components, high level of reliability can be achieved. A important point is an entire rotating machinery system should be considered in such exercises. Defining a complete rotating machinery system including all components, systems and parts involved, in upstream of a machinery, downstream of it, driver or auxiliaries, is a very important step.

Major Failure Categories

Major failure categories are summarized as follows [1,2,9-11]:

1. 1Process/operational condition changes: including process and operating condition changes as well as changes in operating procedures. This is the most important reason for the failure of rotating machineries.
2. Installation or commissioning issues.
3. Design, fabrication and assembly problems.
4. Machinery wear-out.

All rotating machineries react to process/operational system requirements. They do what the process/operation requires. It shows why process/operational condition changes are so important. For positive displacement rotating machines (such as reciprocating compressors, screw compressors, screw pumps, etc), the flowrate may not be significantly affected by process/operational requirement, and it is adjusted by the machinery. The flowrate is a very good monitoring parameter to measure the health of a positive displacement machinery and determine if there is any problem or wear-out [2]. Turbo-machineries [13-15] (such as centrifugal compressors, axial compressors, centrifugal pumps, etc) are using high-speed rotating parts (such as blades, impellers, etc) to increase the velocity of fluid and then reduce the velocity of fluid mainly in volute to increase the fluid pressure. They usually offer variable flowrate. In other words, flowrate varies with operating conditions such as differential pressure or fluid density. The reliability of turbo-machineries (and reliability of its driver and auxiliaries) is considerably affected by the process and operating conditions [16-19]. Since the flowrate is determined by process/operational requirements, machinery loading, transmitted torques, driver power and auxiliary functioning are affected by the operation. As an example, requirement for a higher flowrate than the normal/baseline flowrate may result in driver overload. In case of an electric motor driver, trip may occur. The reliability of machinery components (bearing, seal, etc) is also directly related to the reliability of auxiliary systems. In many cases, root-cause of a component failure is found in a supporting auxiliary system. As an example, changes in an auxiliary system supply temperature, resulting from a change in cooling water temperature (for water cooled systems) or a change in ambient air temperature (for air-coolers) can be the root-cause of a component failure (such as a bearing failure in case of extra-hot lubrication oil). Operational changes can have similar effects. Usually a failure of a component or sub-system occurs because the equipment is subjected to conditions which exceed its design (rated) values.

Most machinery damage and wear occur during

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Spectrum

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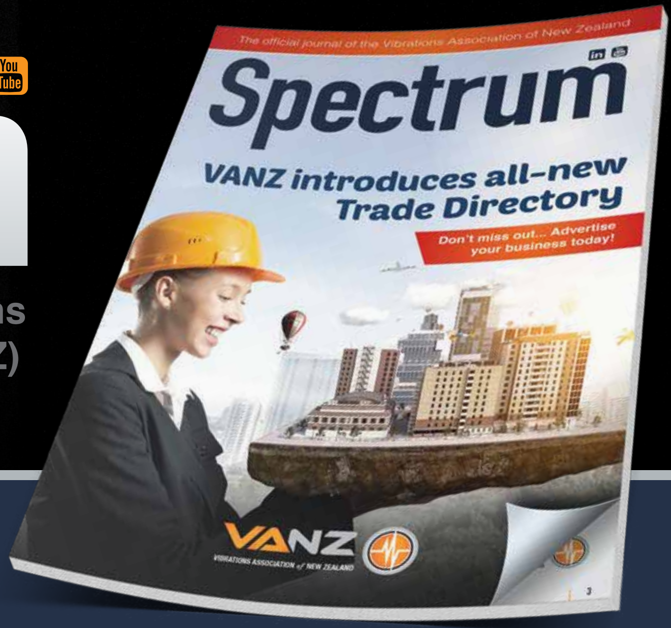

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transient conditions such as start-up or shutdown conditions [1,9,10]. During these transient times, equipment is subject to rapid changes in operational parameters such as temperature, pressure, speed and others. In many cases, the root-cause of mechanical damages of a rotating machinery (pump, compressor, etc) is higher head than design/rated one. In other words, required head (pressure) by the system exceeded the capability of machinery. For a given impeller vane slope, head which is produced by a dynamic-type compressor or pump is a function of impeller diameter and impeller speed. Once the impeller is designed and fabricated, it will produce only one value of head for a given shaft speed and flowrate. The only factor that causes a lower value of head is if the machinery is experienced mechanical damage or if it is fouled [1-3]. Produced discharge pressures (or differential pressures) are a good monitoring parameter to monitor the health of such machineries.
Based on experiences and observations, the main failure root-cause is a change in process or operating conditions. The second reason is installation and commissioning issues. Design or manufacturing problems (including engineering errors, material problems, manufacturing defects, etc) are at the third ranking. However, too often a design problem shows up shortly after start-up [1]. This is not a general rule, and sometimes, a design problem manifests itself after some operation time. The main cause of design problems and issues is that the component or part is not designed for specified operating conditions.
The component wear-out is often the effect and not the root-cause [1,4]. The wear-out of bearing, seal, wear-ring, etc could often happen because of operational condition changes. Too often various bearings suffer from the problems in the assembly or installation [2,6].

Focus on Troubleshooting

Troubleshooting is to discover and eliminate root-cause(s) of trouble. Incomplete facts and insufficient information are well-known reasons for unsuccessful trouble-shooting exercises [1]. Usually in rush to define what the problem is, many troubleshooting engineers do not take sufficient time to obtain all of involved facts. All changes should be properly identified for all components in the entire rotating machinery system (all parts such as auxiliaries, etc). It is also necessary to include all involved groups such as operators, maintenance personnel, manufacturers, sub-vendors, related contractors, etc in condition monitoring or trouble-shooting exercises. It is important to find all baselines related to major parameters involved. Following guides for trouble-shooting investigations should be considered:

1. Failed component(s), its conditions and mode of failure should carefully be observed and investigated. Thorough inspection of failed component is critical.
2. The operational history of the failed rotating equipment should be investigated. Particularly the operation time before the failure and the history of previous failures (especially similar failures) should properly be investigated.
3. Operating parameters, particularly parameters related to failed components (prior to failure) should be identified and examined. Baseline conditions should be obtained or established. Operator's logs and reliability data are very useful sources of information. Special attention is required for parameters exceeding normal values. Trends are always important.
4. Data of failed component supply source (and manufacturing sources), design, materials, manufacturing details as well as assembly data and tolerances should be found and investigated.
5. All changes particularly changes in operating conditions, operational procedures, and any new thing happen in process, operation or unit should be identify. Unit's piping, foundation and all surrounding facilities should also be investigated.

New modelling methods, advanced simulation techniques and numerical calculations play important roles in modern condition monitoring, troubleshooting and failure root-cause analysis [1,2]. For example, steam turbine rotor rub to casing are sometimes reported. Realistic dynamic and thermal expansion simulations of rotor and inner casing are required for a successful failure root-cause analysis of such cases. For many reliability issues, an accurate finite element analysis (FEA) of the machinery is necessary to find the real root-cause of failure and correct troubleshooting of machinery. Short cuts or simplified models may result in a wrong conclusion.

Bearing Monitoring

Bearings fall usually into three major categories:

- Rolling-element bearings (anti-friction bearings).
- Hydro-dynamic bearings.
- Magnetic bearings.

Rolling-element bearings rely on rolling elements to carry loads of rotating equipment and reduce power losses (friction, etc). Hydro-dynamic bearings rely on a liquid film, usually lubricating oil, to carry loads of rotating equipment and minimize the friction. In general rolling-element bearings (also known as anti-friction bearings) are used for equipment of low horse-power (say below 300 kW) or for special rotating machineries such as aero-derivative gas turbines where a light-weight design is absolutely necessary [1-3,9-10]. Magnetic bearings are the latest technology using modern digital control techniques to offer contact-less, oil-free, compact, light, reliable and very robust bearing. The shaft location is identified with advanced sensors. A digital control is employed to

New modelling methods, advanced simulation techniques and numerical calculations play important roles in modern condition monitoring, troubleshooting and failure root-cause analysis.

analyse deviation from anticipated shaft centre and calculated magnetic forces are applied to correctly position high-speed rotating shaft. Involved position and forced signals can be used for condition monitoring of magnetic bearings. In other words, magnetic bearing technology offers one of most reliable bearing types, lowest power loses as well as built-in condition monitoring capabilities [3,4,6]. High cost, lack of references and the conservative nature of rotating machinery industry limited the wide use of magnetic bearings. The technology is new and a few manufacturers can offer it. Nowadays magnetic bearings are used in special rotating machineries which require compact and light-weight designs combined with very high reliability such as subsea machinery units, offshore services, machineries for remote locations as well as rotating machineries for services which need absolutely oil-free operation. The future use of magnetic bearings is predicted by many experts particularly for direct drive seal-less high-speed rotating machineries (next generation of rotating machineries). However, in near future, rolling-element bearings and hydro-dynamic bearings will maintain large portion of the conventional rotating machinery market while magnetic bearing applications slowly and steadily grow in special purpose rotating equipment market.

A radial bearing is responsible for supporting main static and dynamic loads (including rotating assembly weight, fluid forces, etc) of rotating equipment. As a very rough indication, dynamic forces for centrifugal and axial machineries are often in the order of 10-45% of static loads [9,12-16]. Static loads on bearings are often well-known. Sources of dynamic and unpredicted forces on bearings are categorized as follows:

1. Misalignment or unbalance.
2. Increased piping loading on machinery which eventually can cause high loads on bearings. High piping loads could be because of different reasons such as poor piping layout, unequal flow distribution, improper piping stress study, etc.
3. The fouling of machinery.
4. Foundation forces (such as soft-foot, different settlement, etc).
5. Thermal expansions; for example, changes in cooling loop, operating temperature exceeding limits, etc.
6. Improper assembly (or installation) clearances.

The life of a bearing is closely related to loads and forces on it. The relationship between forces and

Continued over page >

bearing's life is usually nonlinear. As an indication, the life of a rolling-element bearing is directly dependent on forces acting on the bearing to the third (3rd) power [1-3]. As an example, if forces are twice the design/rated values, the life of bearing would be reduced eight folds. In other words, exceeding the specified limit on loads, forces, foundation loads, piping loads on machineries, etc, can lead to a significant reduction in the life of bearing.

A bearing should be installed in accordance with its manufacturer's instructions. Differences in bearing design, model, type and manufacturing should be seriously considered for the installation, operation and maintenance since each type has its own requirements and weak points. Regarding bearing's condition monitoring, the vibration, bearing temperature, and bearing lubrication oil conditions should continuously be monitored [1,2,4,5].

Thrust bearings are usually vulnerable components considering their critical roles, their relatively fragile structures, and their relatively low load capacity considering large axial forces in high pressure machineries. There have been many reports about failures and malfunctions of thrust bearings. Main reasons are:

1. More load than anticipated or insufficient bearing area.
2. Incorrect installation.
3. Unclean, insufficient or hot lubrication oil supply. Sometimes incorrect oil type or viscosity.

Cases of more load than anticipated/rated have been reported as the main reason for failures of thrust bearings [1,2]. This can be a result of higher discharge pressure, insufficient clearances or operation errors (such as sudden closing of a discharge valve, etc).

Monitoring & Reliability of Gear Units

Dynamic gear meshing forces and vibration present challenge to the reliability of gear unit and connected machinery [20]. Gear units require very careful sizing and design of its bearings. For gear units, dynamic load components are made up principally of meshing forces of gear teeth. Loads will vary from zero to maximum. The monitoring, evaluation and failure analysis of gear units are discussed here. Many of presented monitoring methods and details (in previous sections) are applicable for gear units such as gear unit bearing monitoring, etc. Specific methods and details for gear units are discussed here.

With a gear unit running, it is useful to conduct a general inspection of the area around the gear unit, including support structure, bolting, its foundation block, base-plate and grout. These elements should be in a good condition. Therefore, they can help resist dynamic and cyclic forces. Dynamic forces have been high and they can distort housing of gear unit and cause excessive gear and bearing wear. A detailed vibration analysis is a necessary monitoring step and a useful reliability tool for any gear unit. It should be determined if there are significant differences in vibration levels in a gear unit housing, base-plate and the foundation block. Normally there should only be a small percentage of change in the vibration as it goes from the housing of the gear unit to the base-plate and then on to the foundation block. A large difference might indicate an issue such as a looseness problem. Any such problem will increase operating stresses and lead to damages. Particular attention is required for any unusual or irregular signals of vibration or irregular noises. It can indicate cyclical loading, looseness, or other problems. Visual inspection and online measurements of critical clearances and distances are important. As an indication, root clearance on a spur gear ideally should be around "0.07 × tooth height", but there is always some run-out. As another indication, on large, special-purpose and critical gears, the minimum allowable root clearance is generally taken as about "0.05 × tooth height" [22,23].

If the contact portions of tooth profiles of meshing gears are not involute or as theoretically should be, then the gears do not execute conjugate action. That is the output gear will not have constant angular velocity. This is called interference. Generally, the interference is an invitation to disaster [20-23]. Slightly more clearances are better than interference, but it changes geometry of tooth meshing, increasing cantilever tooth loads, and wear rates. A very useful step in the visual inspection of gear unit could be the observation of contact pattern; from a head-on view, it should be observed that how contact pattern changes as the bull gear rotates.

It is necessary to understand the pattern of gear contact for any condition monitoring of a gear unit. An ideal situation is to have a contact pattern completely across each tooth which should be uniform all around each gear. A gear design is usually based on full contact. However, sometimes there are machining or assembly errors and other times there is distortion of the housing supports (of the gear unit), etc. Consequently, tooth stresses can increase. Less than full contact should be carefully recorded for the condition monitoring and reliability. Any evidence of contact on the back of gear teeth is a cause for great concern as it indicates very high peak tooth loads, and an experienced manufacturer or a skilled consultant should evaluate the situation. Using an infrared thermography inspection is a good monitoring method for any gear set. It is recommended to measure variations of temperature both across gear teeth and around gears to get an idea of the loading and

Continued on page 22 >

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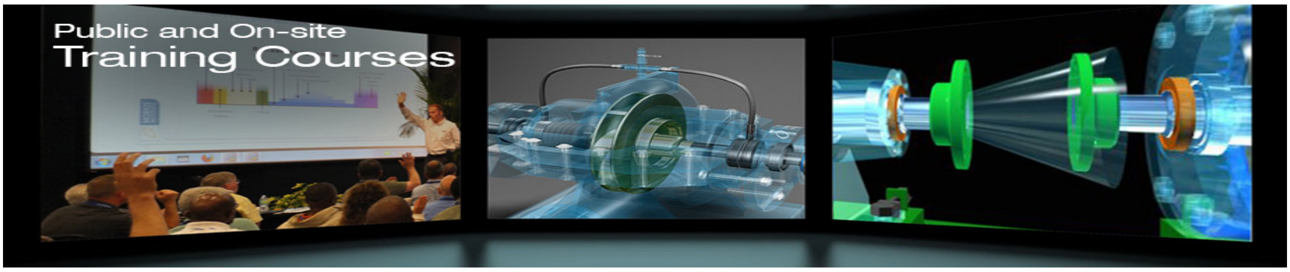

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misalignment. As a very rough indication, maximum temperature variation should not exceed 6oC. Other useful gear unit monitoring steps [19-22]:

1. Power verification and both the peak and average power required by a gear unit should be calculated and verified. These data should be compared to the machinery's design and rating power.
2. During a heavily loaded period, housing and lubricant temperatures should be measured and analysed.

Most gears used in different machineries are case hardened (also called surface hardened) to somewhere between HRC 52 and HRC 64. Ideally, they should never show measurable wear or pitting. However, large gears, open gears set, and many older gear units had through hardened teeth with lower hardness. As an indication, the hardness could be in the range of BHN 130 - BHN 410. For the comparison, BHN 410 could be around HRC 44. In fact, most open gears are relatively soft. Some old-fashioned gears made from medium grade carbon steels and then teeth hardened to about HRC 36 - HRC 40. If the tooth's hardness is above HRC 42, it may be considered as case hardened. If hardness tester is not available, a fine file can be used to just very roughly estimate the hardness. Simply try to cut the top of teeth using the fine file; if the file just skids, it may be concluded that teeth are hardened.
There have been many articles written about various forms of through hardened gear wear and pitting [22,24]. In those articles, terms like polishing, corrective pitting, destructive pitting and normal dedendum wear have been used. Unfortunately, they all mean that gear set is wearing out one way or another. From an operational and maintenance viewpoint, what is most important is determining the rate of wear.

One benefit of through-hardened gear is that the wear can be monitored. For instance, using a gear tooth micro-meter as a predictive tool and periodically taking measurements at several points across the teeth and around the circumference, some estimates might be obtained. Even a charted wear rate can be used in planning for gear replacement. This also might be used to evaluating overall operation or effectiveness of lubrication in the gear unit.
Unlike through-hardened gears, surface (case) hardened ones cannot tolerate any surface damage. On a surface hardened gear, even small pits (which would be ignored on a through hardened one) can be an indication of a looming disaster. Therefore, the evaluation of surface-hardened gears should be very different from that of through-hardened components. The case on a surface hardened gear is much harder and much stronger than its softer core. These gears are almost always machined to much closer tolerances than through-hardened gears. Hardened surfaces tend not to wear. Consequently, damages to that hard-external-shell of the gear are frequently difficult to see, making surface-hardened gears far more difficult to inspect than through-hardened ones. A hardened case is not ductile at all. The alignment of such a gear unit is much more critical than on the one with through-hardened gears. Once damage penetrates the hard-outer case of gear, it grows rapidly through weaker core of the gear.

The internal inspection of surface hardened gears should begin with a very careful inspection of teeth and their contact patterns. Ideally teeth should look like new and show no surface damage other than mild polishing. Using a bright light for the close visual inspection of teeth is strongly recommended. Because of their usual fine surface finish, determining the contact pattern on surface-hardened gear teeth may be difficult.

While broken teeth clearly are the most serious problem, because of relative weakness of softer core material, any tooth that has substantial surface deterioration may be at the risk of breakage. The following paragraphs describe some common forms of tooth damage and dangers they present. The most common surface damage mechanisms in gears are pitting and micro-pitting. The gear pitting occurs as the result of a combination of "Hertzian" fatigue forces and surface tension. Any pits on a surface-(case-) hardened gear are cause for great concern because they may show teeth loads are far in excess of design/

Continued on page 24 >

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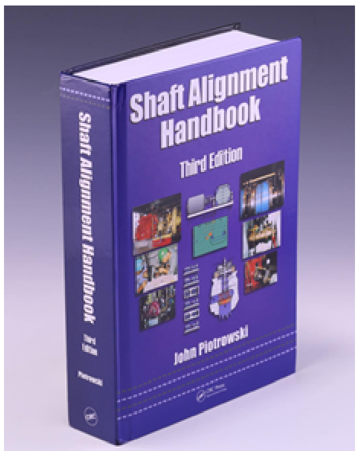

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rated loads. The pitting also is an indication of either serious overloading or metallurgical problems [22-24]. In addition, once the strong and hard outer layer is penetrated, remaining core is much weaker and there is a great risk of tooth breakage in a short time.
The micro-pitting, a less severe form of surface fatigue damage, sometimes occurs when there is an inadequate lubrication oil film. This shows up where high spots of mating gear surfaces create pressures great enough to cause a series of tiny fatigue spalls which look as though the area had been sandblasted. If the micro-pitting occurs in bands (particularly when it is uniform and well distributed), it indicates that gears are heavily loaded or there were some machining/ manufacturing errors. This type of micro-pitting, however, poses no real problem.
For example, in a case study for a pair of around 20-years old case-hardened gears from a 700-kW gear unit, there was no perceptible wear except for bands of micro-pitting across teeth. Although this showed that these gears have been heavily loaded, after having run for several billion cycles, the degree of micro-pitting they revealed was not a cause of concern. However, when micro-pitting is off to one side of a gear, it can indicate there is an excessive misalignment within the gear unit and a serious chance of catastrophic failure.

The normal progression of damage in a surface-hardened tooth with excessive loads and misalignment is that the micro-pitting eventually yields to pitting, followed rapidly by a tooth fracture. If an entire active face of teeth is covered by micro-pitting, it would indicate that teeth are extremely heavily loaded, the lubrication oil film is not adequate and there is a substantial likelihood of pitting and eventual catastrophic failure. Poor tooth contact, eccentric loading (which causes pitting) and resultant tooth fracture are the most frequently seen and reported problems for surface-hardened gears.
There have been several other tooth damage modes. The rippling occurs when contact loads are so heavy that there are plastic deformations of the hardened-case. Inspection of a rippled tooth surface will show surface variations which look like ripples in water. It should be watched carefully. Case crushing is seen when loads on the case are so heavy that the ductile supporting core plastically deforms. It cannot support the gear case and the case can fracture. A typical symptom is a crack horizontally across a tooth, indicating loads are excessive and the tooth is in danger of breaking.

There are many metallurgical/manufacturing defects which can cause gear problems, most of them require very extensive studies [22,24]. One such defect is the appearance of a single large spall or a few large spalls on teeth. This might be due to manufacturing problems. If these large surface flaws are well separated, they may not require immediate action. Nevertheless, they should be carefully monitored, with plans for eventual replacement. There are always multiple contributors to the deterioration of a gear unit and its failure. During any reliability or condition-based analysis, it is recommended to go back, review the installation and particularly with the help of various teams (operators, vendor, maintenance team, etc) try to understand changes and their effects on the life gear unit and its reliability. Through-hardened gears are rarely broken, because of high local contact stresses, they usually wear and pit.
Through-hardened gears are usually designed in a way that corrective pitting makes up for minor surface irregularities and misalignment. This initial wear removes areas of hardest contact and slowly redistributes loads over a greater surface area. Then, as contact becomes better, local stresses decrease and the wear rate drops rapidly.

Modern Infrared Thermography

Infrared thermography (IRT), thermal imaging, and thermal video are examples of infrared imaging. Thermographic cameras detect radiation in the infrared range of the electromagnetic spectrum (very roughly 8–15 μm) and produce thermographic images.
The amount of radiation emitted by an object increases with temperature. Therefore, thermography indicates variations in temperature and it can be used for condition monitoring purposes. For instance, thermography can be used to locate overheating joints in electrical power lines, which can be a sign of impending failure. In another example, it can be used to see thermal signatures which indicate heat leaks in faulty thermal insulation. These can be used to improve the efficiency of rotating equipment, machineries or mechanical equipment.
Infrared thermography monitoring and analysis has one of the widest ranges of applications from high-speed to low-speed equipment, etc. It can be effective for spotting both mechanical and electrical problems. It is currently one of the most cost-effective monitoring technologies.

Modern Acoustical Monitoring

Acoustical analysis can be done on a sonic or ultrasonic level. New ultrasonic techniques for the condition monitoring make it possible to “hear” friction and stress in rotating machinery, which can predict deterioration earlier than conventional monitoring techniques. Ultrasonic technology is sensitive to high-frequency sounds that are inaudible to the human ear and distinguishes them from lower-frequency sounds and mechanical vibration. The friction and

Continued on page 26 >

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TEST YOUR KNOWLEDGE - PART 58 OF A SERIES

1 Where might you be most-likely to encounter the words "buffered output"?

a When analysing high-frequency acceleration signals
b When conducting modal analysis of structures
c When analysing the signals from proximity probes that are part of an on-line monitoring system
d When calibrating accelerometers

2 What inputs are necessary in order to produce an orbit plot from proximity probes mounted on a turbine journal bearing?

a Signal from proximity probe A
b Signal from proximity probe B
c Signal from a key-phasor (tacho signal)
d All of the above are necessary

3 Which of the following is true about vibration analysis on gearboxes?

a Oil analysis results can be a useful co-indicator of condition
b Vibration signals are un-influenced by load changes
c Vibration signals are un-influenced by speed changes
d All of the above

4 The input shaft of a gearbox rotates at 25 Hz. The gearbox has 44 teeth on the input shaft, and 46 teeth on the output shaft. The hunting tooth frequency is likely to be …

a 1.08 Hz
b 10.8 Hz
c 108 Hz
d 1080 Hz

5 A special torque wrench is sometimes used so that the proper internal clearance can be set on spherical roller bearings mounted on adapter sleeves. What specifically does this help set?

a The starting point from which the angular take-up can be measured
b The final clearance take-up point
c The mid-way point of the angular take-up
d None of the above

6 Interchangeable tips of differing hardness might be found where?

a On probes or "stingers" used for routine vibration analysis
b On proximity probes used for shaft vibration measurement on turbines
c On impact hammers used in modal analysis work.
d All of the above

7 What percentage of pre-trigger might be best when conducting impact tests for determining resonance?

a 10%
b 50%
c 60%
d 80%

8 What might be the best means of establishing whether torsional vibrations are present?

a Analysis of dynamic strain gauge signals via telemetry
b Looking for smearing of peaks in the velocity spectra collected from casing measurements
c Looking for phase changes in velocity spectra collected from casing measurements
d Looking for variations in shaft rpm

9 "Reference" and "roving" are terms you might see used together where?

a High-frequency analysis of bearing signals
b Demodulated signal analysis
c 2-channel phase comparison studies on machines or structures
d Single channel route-mode data collection

10 A machine runs smoothly, but its vibration increases sharply as the speed is increased and it enters resonance. How much might the phase change from the stable speed range to the resonant speed range?

a 10 degrees
b 90 degrees
c 180 degrees
d 360 degrees

Answers on page 31

Further enquiries can be directed to: Carl Townsend at Carlton Technology Ltd.
Phone: 64-6-759 1134 | Email: ctownsend@xtra.co.nz | Address: P.O. Box 18046 Merrilands, New Plymouth 4360, NZ

Sonic monitoring equipment is less expensive than ultrasonic ones, but it also has fewer uses than ultrasonic technologies.

stress waves produce distinctive sounds in the upper ultrasonic range. Changes in these friction and stress waves can suggest deteriorating conditions much earlier than technologies such as vibration analysis or lubrication oil analysis. With proper ultrasonic measurement and analysis, it is possible to differentiate normal wear from abnormal wear, physical damage, lubrication problems and others.
Sonic monitoring equipment is less expensive than ultrasonic ones, but it also has fewer uses than ultrasonic technologies. Sonic technology is useful only on mechanical equipment, while ultrasonic equipment can detect electrical problems and is more flexible and reliable in detecting mechanical problems.

Modern Oil Analysis

Oil analysis (lubrication oil analysis) is usually a long-term program that, where relevant, can eventually be more effective than many of other monitoring technologies. This could be the case for many oil wetted parts of machineries such as oil lubricated bearings. Sometimes it can take one year (or even more) for an oil analysis program in a plant to reach high level of sophistication and effectiveness. In most general forms, analytical techniques performed on oil samples can be classified in two categories: oil analysis on used oil(s) and wear particle analysis. Used oil analysis determines the condition of the lubrication oil (lubricant) itself, determines its quality, checks its suitability for continued use, etc. Wear particle analysis (also known as wear debris analysis) determines the mechanical condition of machinery components that are lubricated through particles in the oil (wear particles). For instance, the composition of solid materials present in the lubrication oil can be identified. Type, size, concentration, distribution, and morphology of those particles can be evaluated which could reveal developing problems. Advanced online oil analysis sensors are also introduced and used in many applications.

Modern Integrated Condition Monitoring

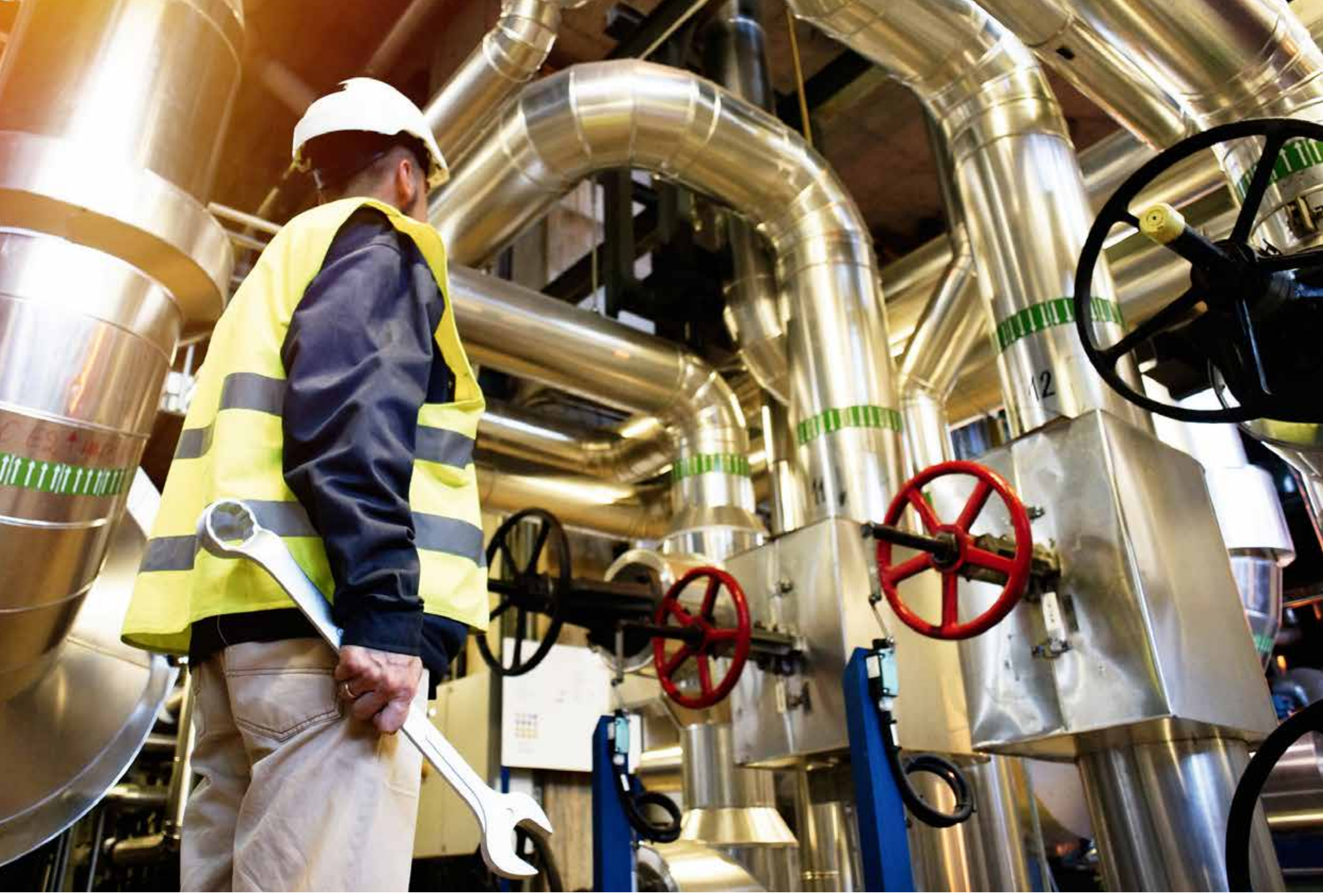
A very important development in modern condition monitoring of the machineries and rotating equipment is the concept of integrated condition monitoring. This means combining and interpretation of all monitoring data available, for example, from online vibration monitoring, thermal imaging and so on, all together to see if they all pointed the same direction.
For most problems in machineries and equipment, a single monitoring method might not be effective for an early prediction of a problem. There have been many shortfalls and ineffectiveness when using just one (single) monitoring method.

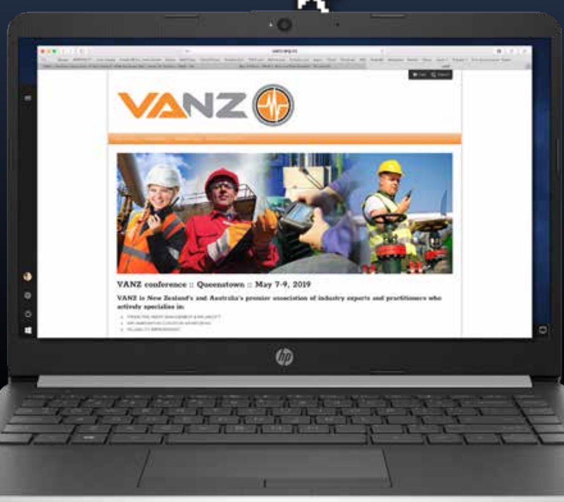
However, there are great benefits from having different condition monitoring methods combined to detect any developing problem at early stage. It is a greater degree of confidence when two (or more) condition monitoring technologies reveal the same problem. There are some obstacles which should be properly overcome in order to have an integrated condition monitoring system. Unfortunately, in some plants, each condition monitoring system such as vibration analysis, oil analysis, etc. are typically carried out by different groups within the organization. Making matters worse, some condition monitoring systems such as some oil analysis programs usually consist of submitting occasional samples to a laboratory in exchange for results that frequently look more like chemistry than machinery condition monitoring. Integrating all these condition monitoring methods/data is the key for success in modern condition monitoring.

The latest generation of vibration analysers comprises more capabilities and automated functions than its predecessors. Many units display the full vibration spectrum of three axes simultaneously, providing a snapshot of what is going on with a particular machinery. However, despite such capabilities, not even the most sophisticated vibration monitoring equipment can successfully predict developing problems in all cases. For instance, if vibration measurements are high then it could indicate that machinery is not in good condition. On the other hand, there were cases that high vibration was just misleading and there was not a serious problem. There have been cases where the vibration has been increased, but the machinery was healthy and it continued to work for a relatively long time. Another issue is for some problems and malfunctions, it should actually be developed to a certain degree to increase the vibration above noticing points. In other words, the early waring could be missed using only vibration monitoring.

This can be generalized when using only single monitoring method. When only one method or one sensor is utilized, the prediction is not usually reliable. The solution is to use different (independent) techniques to achieve reliable and early warning signals. For example, when three different monitoring methods, such as online vibration monitoring, thermal imaging and on-site wear debris analysis, are used simultaneously, the monitoring quality is significantly improved and an accurate prediction can be obtained. If all these methods indicate a developing malfunction

Continued on page 28 >





in a component (for instance, a bearing) such a prediction can be reliable.

Why Condition-Based Maintenance?

Preventive maintenance strategy is a time-based maintenance strategy. In such a strategy, the maintenance works should be performed at predetermined intervals. This, however, is inefficient and even sometimes problematic. Too often, there is no solid basis for maintenance or replacing components/ parts on time basis. An unnecessary component replacement exposes any machinery to a wide range of potential failure causes such as improper assembly, wrong installation, component improper handling, etc [1,2]. In addition, such an approach is very expensive and ineffective. The practice of unnecessary maintenance works and component replacement at every turnaround regardless of conditions is costly, risky and inefficient one.

Another problem is such as time-based maintenance is blind and could even be misleading. In a case study for a critical rotating equipment, bearings and seals were inspected in a planned shutdown. Deteriorations were found and all seals and bearings were replaced. It was decided to disassemble rotating equipment to inspect its interior and its overall condition for possible cause of problems and premature deteriorations of seals and bearings. No significant abnormality was found within the rotating equipment and it was reassembled. The time-based maintenance even if by chance leads to proper, on-time and correct replacement of components, it cannot identify the cause of problem (component wear-out or deterioration). In the above-mentioned example, if seal and bearing parameters were properly monitored for change, the conclusion would have been made to change only bearing and seal, without unnecessary disassembly of the rotating equipment. For the disassembly of a large and critical rotating equipment, significant additional tools, resources, materials and man-powers have been required. Typical time can be one week and there have been many risks associated.

Focus on Predictive/Condition-Based Maintenance
Predictive maintenance techniques are designed to help determine the condition of rotating equipment in order to predict when maintenance works should be performed. This approach promises cost savings over routine or time-based preventive maintenance, because maintenance tasks are performed only when needed. The main promise of predicted maintenance is to allow convenient scheduling of corrective maintenance, and to prevent unexpected equipment failures. The key is right monitoring information in the right time. By knowing which part(s) or section(s) needs maintenance, maintenance works can be better planned (spare parts, technicians, etc.) and what would have been unplanned shutdowns are transformed to shorter and fewer planned stops. This significantly increases overall reliability, availability and safety of the plant. Other potential advantages include increased rotating equipment lifetime, fewer accidents, and optimized spare parts handling. Predictive maintenance usually evaluates the condition of machinery by performing an integrated condition monitoring approach. The ultimate goal of predictive maintenance is to perform maintenance at a scheduled point in time when the maintenance activity is most cost-effective and before the rotating equipment loses performance within a threshold. This is in contrast to time-based maintenance, where a piece of equipment gets maintained whether it needs it or not. Time-based maintenance is labour intensive, ineffective in identifying problems that develop between scheduled inspections, and is very expensive.

Most predictive maintenance monitoring/inspections are performed while rotating equipment is in operation. To evaluate machinery and rotating equipment condition, predictive maintenance usually utilizes inspection and monitoring technologies such as infrared thermography, acoustic monitoring, vibration analysis, sound level measurements, oil analysis, and other specific online monitoring methods. New methods in this area is to utilize measurements on the targeted rotating equipment in combination with measurements of the performance, measured by other devices and instruments. Vibration analysis is most productive on high-speed rotating equipment and it can be an important component of any predictive maintenance program.

General Guidelines on Set Points

Alarm and trip set points are very important for efficient and reliable operation of rotating equipment. These set-points should be properly selected to avoid unnecessary alarm or shutdown (trip) in transient but safe situations. On the other hand, malfunctions and problems should be identified in early stages to avoid catastrophic failures. Set-points should be selected case by case considering all involved factors such as process/operating conditions, machinery details, shop test results, performance test data, baseline, etc, but some rule of thumb and practical recommendations are noted as follows. As a very rough indication, for rolling-element (anti-friction) bearings, housing vibration (peak) and bearing housing temperature limits are recommended around 8 mm/s and 85oC, respectively. For hydro-dynamic (or tilting-pad) bearings, housing vibration (peak to peak) and bearing housing temperature limits are recommended around 60 microns and 110oC, respectively. Most often limits are higher for hydro-dynamic bearings compared to rolling-element (anti-friction) ones. Recommendations regarding the maximum temperature at hydro-dynamic (or tilting-pad) bearings are varying. Some experts have advised 110°C as the limit (as noted above). Some other have allowed maximum of 115°C for bearing temperatures under certain conditions if there is no issue for long-term operation and reliability of bearings. Few engineers recommended 120°C (or sometimes more). In addition, any temperature spikes and fluctuations (or vibration peak spikes and fluctuations) could an indication of an abnormal behaviour which should be investigated.

For rolling-element (anti-friction) and hydro-dynamic thrust bearings, axial velocity and displacement limits are around 1 mm/s and 0.5 mm, respectively. Lubrication oil supply and return temperatures are expected to be around 60oC and 90oC, respectively. Radial bearings of modern turbomachineries are mainly sized based on rotordynamics. They should not normally be affected by minor machinery load changes or slightly modified operating conditions unless there is a link to lubrication oil conditions or machinery rotordynamics. On the other hand, thrust bearings have been designed based on machinery loads (with respect to balance piston(s) and impeller arrangements) and they can be affected by machinery load changes and new operating conditions.
A lubrication oil analysis is very effective tool to evaluate health of bearings. The reduction of lubrication oil viscosity to less than a 50% (compared to lubrication oil producer specification), particle size larger than 20 micron or water content above 150 ppm need careful attention. These can be considered as alarm limits.

As an indication, for turbomachineries, if for a given flowrate and shaft speed, produced head falls below predicted value (based on certified and tested curve) by greater than 10%, the turbomachinery should be investigated, even if possible and appropriate, inspected at the first opportunity. Significant changes in operating conditions can cause damages to machinery components. More complex the relationship between machinery and overall process/operation of plant, more difficult to predict and monitor the situation. Turbo-compressors usually offer a complex behaviour. The head required by the process/plant is usually inversely-proportional to the gas density. Usually if gas density decreases, the head required by process increases. Gas density decreases if gas temperature increases, inlet pressure decreases or molecular weight decreases. If required head by the process increases, flowrate of any turbo-compressor usually decreases. If gas density increases, required head by process most often decreases and the flowrate increases.

Continues next issue with eight case studies...

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How many words of three or more letters can you make, using each letter only once? Plurals are allowed, but no foreign words or words beginning with a capital. There is at least one 5 letter word.
10 - Good | **14** - Very Good | **18+** - Excellent

R	A	M	H	C

WORD MARCH

Draw a path from one square to another to find the secret nine letter word. You may move in any direction. Each square can only be used once.
There is **70** words (three letters or more) that can be made from the combination of letters below. How many can you make?
Solution on page 31.

H	E	R
P	P	Y
E	R	I

Nine letter word is... ______

SODUKU

To solve, each number from 1 to 9 must appear once in:
- Each of the nine vertical columns
- Each of the nine horizontal rows
- Each of the nine 3 x 3 boxes.

9	7			3		8	1	
		8	7					5
			1					4
	8					6		1
				7				
3		2					7	
8					5			
7					4	5		
	6	4		8			2	3

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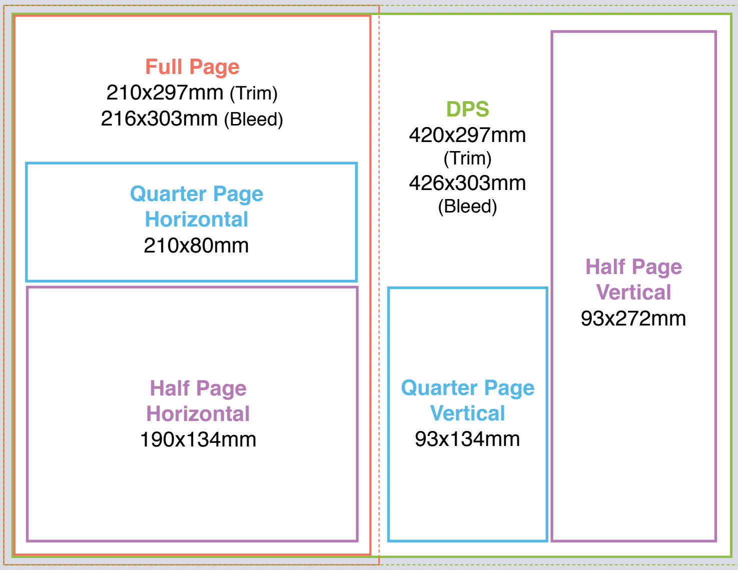

Answers to Carlton Technology Quiz 58:
1C, 2D, 3A, 4A, 5A, 6C, 7A, 8A, 9C, 10B

Answer to Word March #94: Periphery

BANNER

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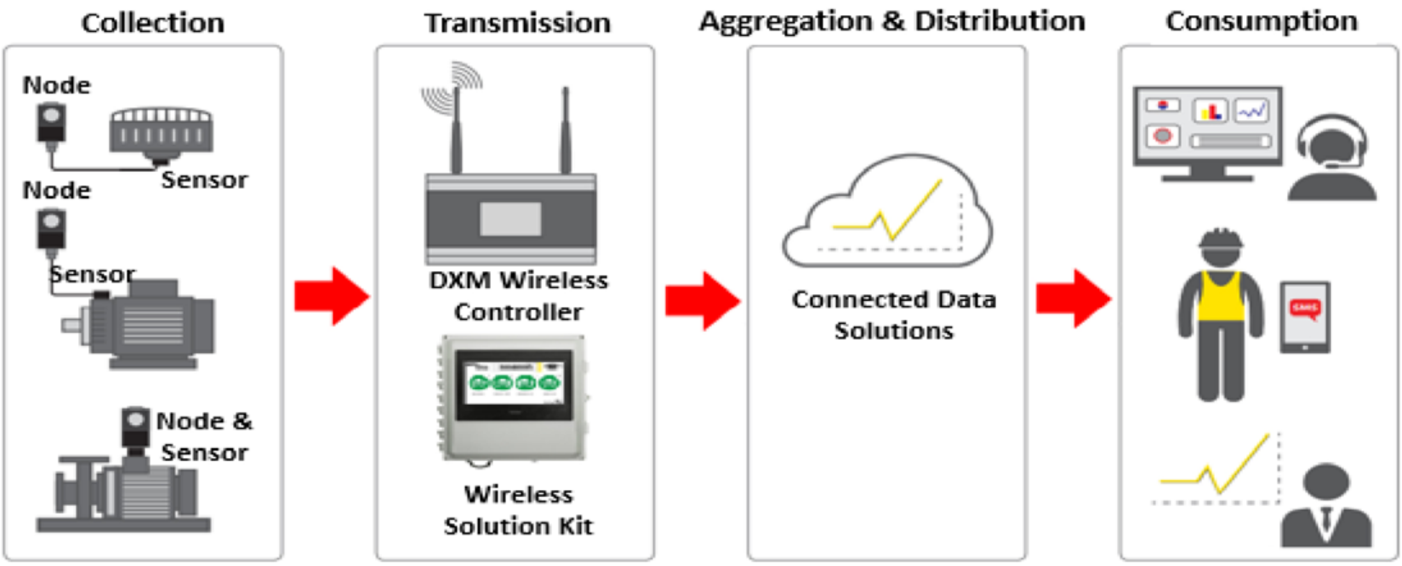
Banner Wireless End-to-End Vibration Monitoring Solution



Banner Wireless Value

- **Visualize Data and Alarms** - HMI displays alarms and graphs of raw vibration data along with baseline, warning and alarm values.
- **Simplicity** - Plug in box, no programming required.
- **Capability** - Monitor vibration and temperature on up to 40 assets.
- **Automatic Data Metrics** - No need to manually set data baselines or thresholds.
- **Vibration Analytics** - Fault indicators prior to major failures or disruptions by analyzing RMS Velocity and High Frequency Acceleration on the X and Z axis.
- **Peel and Stick** - Battery-powered nodes
- **IIoT** - Connect to cloud.
- **Productivity** - Avoid unexpected downtime and be able to schedule repairs.

Solution Kit

Wireless Temp & Vibration Sensor Node