Bookazine by Istec International

# VIBRATION

## The protection of rotating machinery using vibration measurements

# VIBRATION



Second edition, February 2019

# A brief history of vibration

## 1939

## Past

In 1939, T.C. Rathbone published a paper called 'Vibration Tolerance' in the magazine Power Plant Engineering. The ideas in this paper are considered the foundation of modern industrial vibration measurements.

Rathbone, working as a chief engineer at the turbine and machinery division of the Fidelity and Casualty Company of New York, provided a paper for condition assessment based on vibration velocity ranging from approximately 1 Hz to 120 Hz. The paper included several innovative thoughts on the link between vibration amplitudes and the condition of machines. Beside these insights, the paper included a series of amplitude versus frequency severity curves that approximated the constant velocity around the rotating frequencies of a typical steam turbine generator set.

Based on his observations, Rathbone defined severity criteria for linking the vibration amplitude to the machine condition, and to be more specific, the lifespan and risk of failure. These ideas and criteria as described by Rathbone form the basis of modern condition monitoring.

## Present

Nowadays, vibration measurements are generally accepted as a method for condition monitoring and part of predictive maintenance strategies. Data is acquired through acceleration, velocity and displacement sensors, and processed by fixed or portable vibration monitoring equipment. Methods include trend monitoring for the detection of abnormalities and in depth analysis like spectrum / FFT and orbit.

Present

## Future

In recent years, new technologies and innovations have been introduced, all claiming to be the new revolution in vibration measurements and condition monitoring.

Wireless sensors, machine learning, big data, cloud-based analysis and other buzz words have found their way into the world of machine vibration measurements. We are intrigued by these new developments, but will they really change the way we monitor and maintain our equipment?

*"By analysing the vibration data, developing failures and poor maintenance practices can be identified."*

→ p 39

# Preface

Over the years, we have published many articles on the subject of vibration measurements on rotating machinery. Some of these offer basic knowledge, some have valuable insights, and some are just fun to read. But they all have one thing in common: They are written out of our passion for measuring, protecting and analysing rotating machinery.

Although vibration is part of classical mechanics and introduced in your high school physics class, the application of vibration measurements on complex machinery is more of an art than a science. It requires a knowledge of physics, but above all it requires understanding of machines, their construction and behaviour, as well as the experience to relate the vibration signals to that knowledge. And do not forget the sensors and systems, because any analysis is meaningless if you cannot trust your inputs.

We would like to thank the Istec team for all their efforts in creating this bookazine. A special thanks to Michel and Daniël for their editing and design work, and to Koos, Sander and Lucas for sharing their knowledge and experience.

This bookazine is a compilation of our most popular articles. It is not meant to be your new vibration guide or maintenance bible and we do not claim it to be the complete story. We hope, however, that it offers you some new insights and thoughts on vibration monitoring and protection. Read it like a magazine, choose the articles you like and enjoy.

**Dé Verschuren & Wouter Verschuren**

# 1 Vibration on rotating machinery

# What are machine vibrations and why would you measure them?

In an ideal situation, rotating machinery would not produce vibrations at all. In practice, however, vibrations are considered part of rotating machinery, and they cannot be reduced to zero. Vibrations can only be monitored for unusual behaviour.

Machine vibrations contain a lot of information about the condition of the machine, required (future) maintenance and possible root causes of existing and potential damage.

It is important to measure and analyse vibrations, to detect possible failures at an early stage and to prevent damage from developing. The effects of damage and potential failures that are the source of the vibrations must not be underestimated – they can have catastrophic effects on human life, the environment and the machine. Early detection of vibrations and their causes ensures that accidents and unnecessary high costs can be avoided.

Vibration measurements are useful for every type of rotating machine or equipment. The lifespan can be increased by identifying machine vibrations at an early stage. It is crucial to measure vibrations on rotating machines that are vital to the process. ■

# 6 common causes of machine vibrations

**Excessive vibrations on rotating equipment like pumps, gearboxes, turbines and compressors are a clear sign that the equipment is not functioning properly. Equipment that is showing excessive vibrations will most likely not achieve the expected lifespan, and can be the source of unscheduled downtime or dangerous situations. Therefore, it is important to find the root cause of vibrations by measuring and analysing the vibration signals. Common causes of vibrations are discussed below.**

## Alignment problems

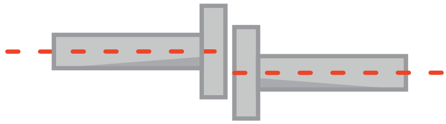
When two or more rotating machines are connected, the correct alignment is crucial.

Typical alignment errors are:

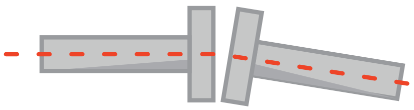
- **Parallel misalignment:**
  The shaft centre lines are parallel but are not in line. This can be both horizontal and vertical. Parallel misalignment is also known as offset misalignment.

- **Angular misalignment:**
  The shafts meet at a point, but are not parallel. This can be both on the horizontal and vertical axis. Angular misalignment is also known as gap misalignment.

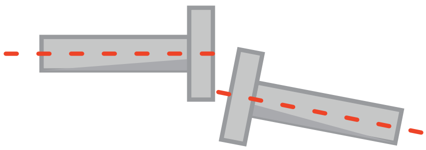
- **Combined parallel-angular misalignment:**
  A combination of both parallel and angular misalignment. Combined parallel-angular misalignment is the most common misalignment.



Parallel misalignment



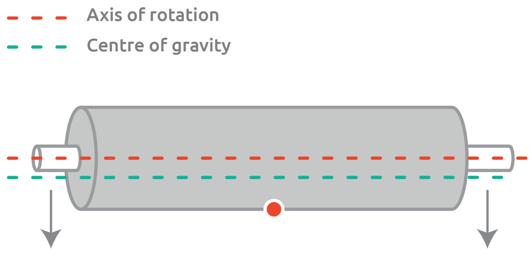
Angular misalignment



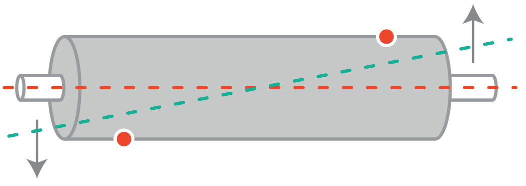
Combined parallel-angular misalignment

# Unbalance

When the centre of gravity of a rotating object is not exactly in the centre line, it causes machine unbalance resulting in vibration. When a machine is unbalanced, it can cause damage to the machine itself, the foundation, pipes, etc. There are three types of unbalance: static unbalance, coupled unbalance and dynamic unbalance.




Static unbalance



Coupled unbalance

### Static unbalance

Static unbalance is when the centre of gravity axis (inertia axis) is not in line with the centre of rotation (shaft centre line), and the heavy spot and the centre of gravity are in the same plane. Static unbalance can be the result of a parallel displacement of the principal mass axis relative to the shaft centre line, and can be caused by non-symmetric mass distribution or deformation. In theory, static unbalance can be detected by placing the object with a point of rotation on each end. When there is static unbalance and friction is zero, gravity will turn the heavy side downwards.

### Coupled unbalance

Coupled unbalance appears when a rotating object has two or more unbalanced masses in different planes, that equal each other out in rest position. The principal mass axis is no longer in parallel to the centre of gravity, but crosses the centre of gravity axis. When the system starts to rotate, these masses will be influenced by centrifugal forces, resulting in vibration.

### Dynamic unbalance

Dynamic unbalance is the most common type of unbalance and the result of static and coupled unbalance. The principal mass axis is displaced and not parallel to the shaft centre line.

# Resonance

Every machine has one or more resonance frequencies (natural frequency). When a rotation frequency coincides with the resonance frequency of the machine, resonance occurs. Resonance can have major impact.

# Loose parts

Loose bearings, loose bolts and corrosion can cause the machine to vibrate excessively. Due to the mechanical forces in the machine, loose parts can rapidly cause damage.

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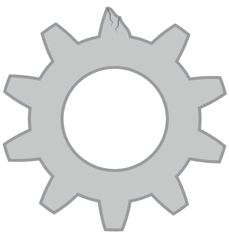


Worn out gear

Damaged gear

## Damaged or worn out gears

Gearbox vibrations are often caused by damaged or worn out gear teeth. When gear tooth engagement involves a damaged tooth, the force cannot be transferred as with the other gear tooth engagements. If a gear tooth is broken, less force can be transferred at this point of the cycle. Vibrations occur as a result.

## Bearing damage

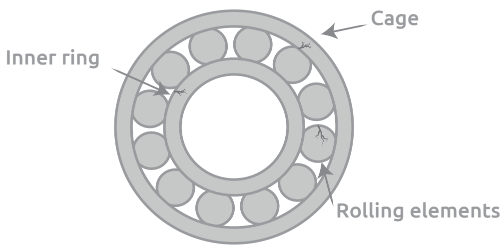
In rotating machinery, we come across two main types of bearings: roller bearings and sleeve bearings.

A roller bearing can be damaged in several ways, each with its own vibration fingerprint:

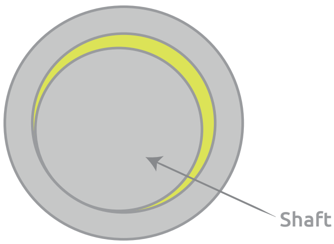
- Damage to the inner ring
- Damage to the outer ring
- Damage to the cage
- Damage to rolling elements (e.g. cylinders, cones and needles)

Each part of a roller bearing has its own frequency. By calculating these frequencies, it is possible to use vibration analysis to determine whether the vibrations are a result of bearing damage.

In contrast to roller bearings, sleeve bearings do not use a rolling element, but use a fluid (oil) film to reduce friction. Vibrations can be caused by inaccuracies in the fluid film; if a stable oil film cannot be formed, it can break, resulting in an oil whip or oil whirl. Additionally, this type of bearing is more sensitive to external influences on the position of the shaft, because its position in the bearing is not fixed. ■




Roller bearing




Sleeve bearing

# Vibration monitoring system prevents damage to centrifugal pumps

At a heat station in Rotterdam, the resonance frequency of seven vertical centrifugal pumps was 58 Hz. Reaching this frequency increased the vibration levels, which in turn caused damage to the suction and pressure pipes. A solution was needed to prevent reaching the resonance frequency.

The solution was to use an accelerometer with a vibration transmitter to measure the vibrations and generate a signal when the preset vibration amplitude and frequency range of 58 Hz was reached. With a direct connection to the control system, quick action could be taken and damage could be avoided.

# 8

# effects of machine vibrations

If **critical vibrations** are not identified at an early stage, damage to the machine can occur. **Early detection of the root cause** of vibrations saves money and **improves safety**.

→ p 12 - 15

**M**onitoring machine vibrations affords greater control over the safety and availability of the equipment. It reduces unscheduled downtime and potential damage or failure can be resolved at an early stage. The main effects of undetected, critical machine vibrations are described below.

## Safety issues

**1**

Safety within a plant must be guaranteed at all times. Although the sources of vibrations can usually be resolved easily at an early stage, they can develop into serious safety issues if action is not taken when required. Not only can unidentified machine vibrations cause serious damage, more importantly, they can cause human injuries and environmental harm.

## Machine damage

**2**

When critical vibrations are not identified at an early stage, (serious) damage to the machine can occur. In the most extreme cases, the machine must be replaced entirely as a result of excessive damage.

## Reduced availability

**3**

As a result of increasing vibration, it may be necessary to reduce the machine load, e.g. rotational speed or output. This leads to reduced availability.

## Unscheduled downtime

**4**

Vibrations often develop gradually and can be hard to detect without proper instrumentation. As soon as they become apparent, it is usually too late to take preventive measures and only mitigating measures are possible. Mitigating measures can only limit the effects of excessive vibrations, and damage may have occurred already. Mitigating measures are difficult to schedule and as a result unscheduled downtime is unavoidable. This leads to high costs because many plants in the process industry must be continuously operational. When machine vibrations are monitored properly, maintenance can be planned based on the vibration trend. This trend is built using long-term vibration data and allows the prediction of the future maintenance requirements.

## Supply issues

**5**

Many companies have to adhere to certain supply agreements. An unscheduled stop or reduced availability, as a result of defective machine parts or excessive damage, is likely to lead to the inability to comply to these supply agreements. This can lead to customer

*Although a machine seems to run properly, this is not always the case.*

dissatisfaction and fines (in business-to-business agreements).

## Unnecessary maintenance

6

Machine parts are often replaced preventively to ensure that the machine is available at all times. Although this prevents unscheduled downtime, there is a good chance that machines or machine parts are replaced unnecessarily, before the actual end-of-life. By monitoring the machine vibrations, repairs and replacements are only performed when needed.

## Semi-finished products

7

When a machine has to be stopped or fails unexpectedly, semi-finished products remain in the process. In many cases, these semi-finished products must be discarded, meaning that expensive raw materials are essentially thrown out or led to the flare.

## Quality issues

8

Although a machine seems to run properly, this is not always the case. Vibration measurements and analyses are helpful to determine potential malfunctions. If this does not take place, the quality of the manufactured products may drop or cannot be guaranteed. ■

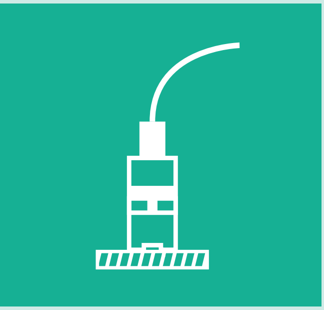
# Sensor solutions for vibration measurements

**Selecting the right sensor for the application is crucial for measuring machine vibration. The sensor signal is the input for the protection or monitoring system. A false sensor leads to a false input signal, which affects the quality and accuracy of the monitoring and protection functions.**

Considerations when selecting the correct sensor for the application:

- What is the vibration level and frequency range?
- Are the resonance frequencies of the application coinciding with those of the sensor?
- Are there size and weight considerations?
- What cable length is required?
- What is the temperature range?
- Is it an explosion hazard area?
- Are strong electromagnetic fields present?
- Is the environment corrosive?

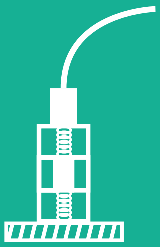
There are three types of sensors for vibration monitoring: acceleration sensors, velocity sensors and displacement sensors.



## Acceleration sensors

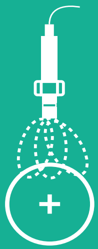
Acceleration sensors are most commonly used to measure casing vibration, in either acceleration or velocity (after integration) measurements. They measure low to high frequencies in single, dual and triaxial directions, and are available in a variety of general purpose and application-specific designs.

Two main sensor technologies are used: Piezoelectric and MEMS (microelectromechanical systems). The piezoelectric accelerometer is reliable, versatile and unmatched for frequency and amplitude range. A MEMS sensor is a semiconductor that offers lower accuracy on frequency and amplitude, but with improved power consumption. A MEMS sensor can measure static and dynamic acceleration.



## Velocity sensors

Velocity sensors are used to measure a frequency range of 1 – 1000 Hz. The measurement principle is based on a coil moving around a magnet, generating a voltage that is proportional to the movement. The sensors are suitable for vibration monitoring and balancing applications on rotating machinery. This type of sensor has a lower sensitivity for vibrations with high frequencies than accelerometers, and is therefore less susceptible to overload.
In some applications, piezoelectric acceleration sensors can also be used to generate a velocity signal, by integrating the acceleration signal.



## Displacement sensors

Displacement sensors, also known as non-contact proximity sensors, are used to measure shaft position or movement without physical contact in order to determine the internal movement and clearance on bearings. Proximity sensors measure the movement (vibration) of a shaft relative to a sleeve bearing or other supporting (fixed) parts. This type of sensor is used to measure a frequency range of 1 to 1500 Hz and low amplitudes, typical for sleeve bearing applications.

A non-contact proximity sensor consists of three parts: a probe, an extension cable and a driver. Together they create a tuned oscillation frequency which is disturbed by the metal surface of the target. All three parts are matched and can only be replaced by identical components, or the calibration of the system will become invalid.

## Expert observation on wireless sensors

*In recent years, wireless acceleration sensors with built-in digital signal processing have found their way onto the condition monitoring market. The major benefits of these wireless technologies are the greatly reduced infrastructural requirements and the automated (basic) analysis. But this comes at a price. To minimise battery usage, signal resolution and data throughput are reduced, resulting in low resolution data, while battery management and sensor logistics are becoming increasingly important, especially on large quantity installations. Power consumption of each sensor is influenced by its environment and application. Replacing batteries in the field is often complex, due to hazardous area restrictions, reachability and risk of pollution of the battery chamber.*

*Wireless sensors as they are today, are definitely of value for certain applications, but they do have their limitations. It is important to set the right expectations and understand the impact of a battery powered solution on data quality and sensor maintenance and logistics.* ■

# Machine protection

**"Although unscheduled downtime is highly undesirable, it is crucial to guarantee the plant safety and to protect the equipment."**

2

# What is machine protection?

Vibration protection systems are used to prevent dangerous situations and severe machine damage by measuring and acting on machine vibrations. To do so, preset limit values in accordence with the ISO guidelines or OEM guidelines are defined and programmed in the system logic. When these values are exceeded, the system logic will send an alarm and initiate a trip, which causes the machine to stop. Although unscheduled downtime is highly undesirable, it is crucial to guarantee the plant safety and to protect the equipment. A vibration protection system compares vibration data to the preset limit values. These limit values work as a range within which the vibration levels should or should not be. For example, reaching the resonance frequency of the machine(parts) causing the occurrence of resonance can be prevented by setting the right limits. ■

A condition monitoring system can be added to the machine protection system. With condition monitoring hardware, vibration data can be analysed using dedicated software. By doing so, the condition of the machine and parts can be monitored, a vibration trend can be established, and the causes of the vibrations identified. The goal is to effectively take measures against or be warned about potential future failures and damage to the machine. Condition monitoring will be discussed in detail in the third part of this book.

→ **p 38 - 71**


small things
can have
BIG
IMPACT

# Machine protection solutions and systems

**There are different system structures to facilitate machine vibration protection - one more advanced than the other. Which method is used depends on the application and the criticality of it.**

## 1. Distributed machine protection systems

Distributed protection systems are available in all shapes and sizes, and are used to protect a wide variety of balance of plant or other (critical) equipment. A distributed system is suitable for smaller or less critical equipment, remote locations and for plants with a distributed structure. The great advantages of distributed systems are the simplicity of the systems, the lower costs, and the reduction of infrastructural requirements.

### a. Vibration switches

Vibration switches can offer a basic but functional machine protection solution. A vibration switch senses vibration and will trigger a switch or an alarm when the preset values are reached. Vibration switches sense vibration as a result of, for example, imbalance, misalignment, resonance, looseness, worn-out bearings and damaged gears. Vibration switches are generally used for applications like cooling towers, fans, blowers and pumps, that require basic protection or that benefit from a simple, stand-alone system.

### b. Vibration transmitters

Vibration transmitters offer a more advanced machine protection solution. Basic vibration transmitters generally have more functionality on limits and settings than vibration switches, and different interfacing options. These transmitters can be used as an interface for a control system or display.

In addition to these basic vibration transmitters, more advanced transmitter systems are available that can offer additional functions similar to centralised systems, such as multiple channels, logic options and even advanced data analysis and communication. These systems can be used as stand-alone protection or monitoring systems and even replace rack based centralised systems.

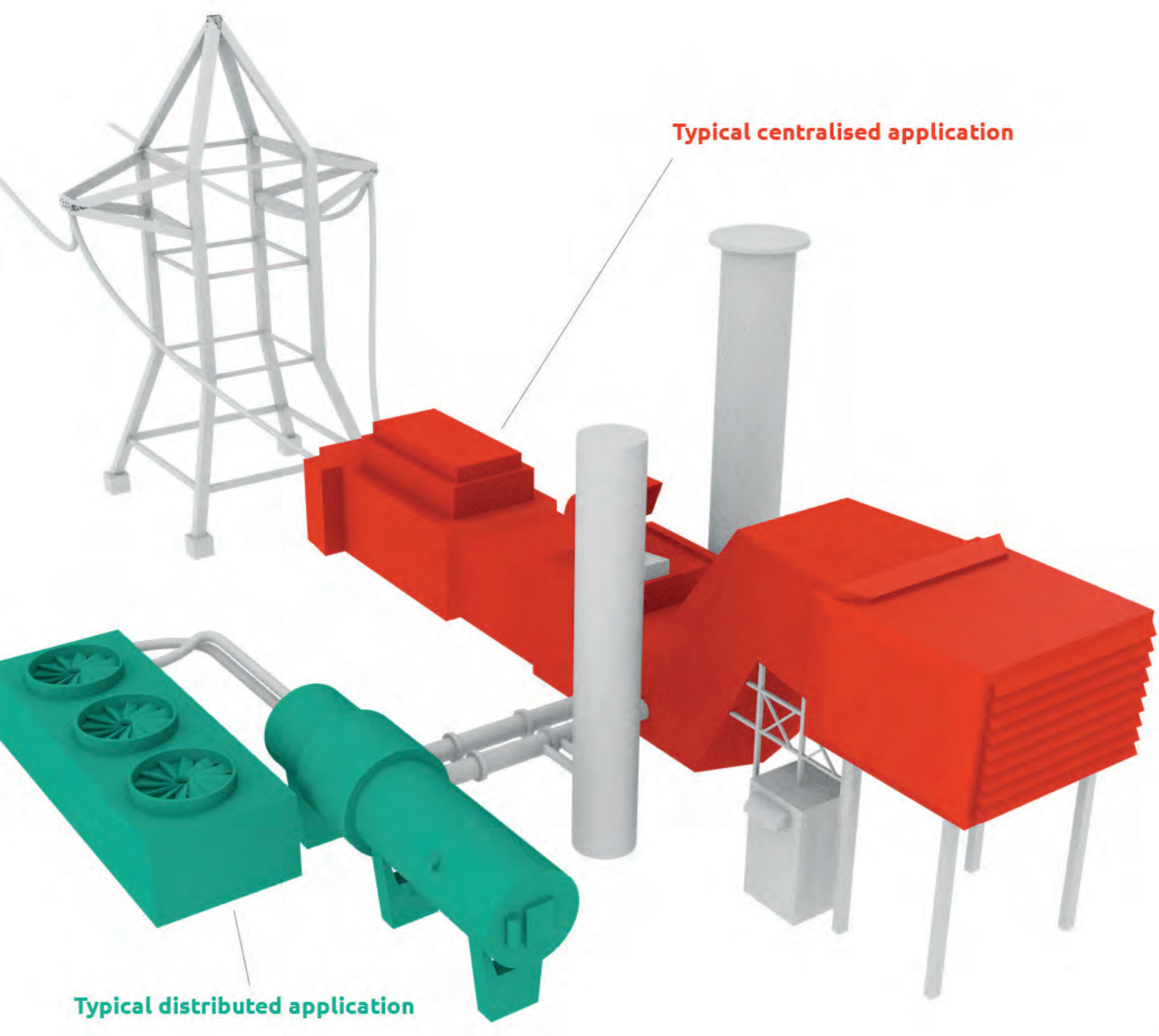
## 2. Centralised machine protection systems

A centralised machine protection system is used in plants with a more traditional setup, where data from all sensors is sent to a central, rack-based system.

Physical connection of the sensors to the system is required and increases the infrastructural demands. A centralised protection system receives inputs from various sensors and measurements from the machine, and uses advanced programmable logic to generate alarms and trigger trip systems. When condition monitoring hardware is implemented in the machine protection system, the input can be collected and analysed. Although condition monitoring is usually an optional feature in a centralised system structure, it is recommended in most cases.

## 3. Hybrid machine protection systems

In general, a combination of centralised and distributed systems offers the best solution for complex plant structures. Centralised systems offer the most advanced and reliable protection solutions and are used on the largest and most critical machines. Balance of plant equipment, remote located machinery and other machines with a lower demand or that inherently justify only lower investments can be better with a distributed protection system. ■



# Protection system functions

**The programming of a machine protection system can be divided in three general parts: input, processing and output.**

## Input

Programming the input starts with the type of measurement, such as displacement, acceleration or speed, followed by the sensor settings. This includes the sensor type, measurement signal (voltage or current), and the limits for sensor OK / sensor NOT OK indications. Additionally, the measurement range and the sensitivity of the sensor are programmed. The sensitivity is the relation of the sensor output value to the measuring unit of the sensor, such as mm, g or mm/s. In case of a speed measurement, the measurement location and target specifications are programmed as well.

## Processing

If the signal qualifies as a valid input, it enters the processing stage. Frequency bands confine the area in which the measurement is relevant, and the signal is processed and edited accordingly. These frequency bands can be configured machine-specifically or as indicated by ISO standards. The processed signal can be converted to a different measuring unit, e.g. from acceleration to velocity. For specific applications, a different measuring unit may be necessary to comply with an ISO standard, or is better to understand the behaviour of the machine. The processed signal is compared to the programmed alarm values. If the signal value crosses an alarm limit, the signal is tagged with a status change. This is visually reinforced with yellow and red LEDs, and can be programmed with an optional time delay. Resetting the alarms can be performed automatically or by manual reset. The alarm values can be linked and adjusted to certain factors to fit different machine stages (e.g. different speed) or external process conditions. Various input signals can be combined through logics in the programming to create more advanced alarm conditions.

## Output

The processed signal values and alarms are connected to external systems. For the protection part of the system, the relay outputs and analogue outputs are the most relevant. Relay outputs are used to transfer the alarm signals directly to a trip system, monitoring system or relay logic board. The analogue outputs are used to transfer the processed signal value to external systems like control systems and local indicators, for further processing. ■

*"If the signal value crosses* ***an alarm limit****, the signal is tagged with a* ***status change****."*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# Service and maintenance on machine protection systems

**A vibration protection system is used to trigger an alarm and initiate a trip when preset vibration limit values are reached. Malfunction of the protection system can lead to dangerous or catastrophic failures of the machine. Therefore, it is crucial that these protection systems are available and working properly at all times - there is no room for failure. These systems require frequent maintenance, verification and testing to guarantee the availability. These services are provided by specialised companies, and are mainly performed during turnaround projects.**

## Service scope

Servicing a vibration protection system includes the following steps and procedures.

**1**

### Installation assessment

Before the project starts, the system and the "as is" installed situation are identified and registered. The information is checked against the applicable standards and regulations, such as SIL and ATEX. Test procedures and requirements are collected, completed and implemented in the project plan. Any deviations from the applicable standards are registered, and the requirements for modification, replacement and spare parts are checked.

**2**

### Registration of system status

The status of the vibration protection system is checked at the start and end of a turnaround project. Any deviations are registered and checked to determine whether action is required.

**3**

### Dismounting of sensors

The sensors are dismounted before the mechanical work on the machine begins. During dismounting, the sensors are labelled, visually inspected and carefully stored.

CONTINUE READING ON P 32 ⟶

> ***"Service and maintenance on machine protection systems requires expertise, know-how and proven competence. Protection systems are critical for the safety and the availability of the machine. The machine specific settings and programming, interactions with other systems and the sensitivity of the components require proper training and experience. The applicable guidelines and regulations demand qualified expertise and the right tools. The impact of a mistake on safety, operational availability and financials justifies hiring an expert."***

4

### Inspection

The visual inspection of the sensors is the first step towards detecting any damage and provides a general impression of the installation. It also enables the detection of any structural issues. Every sensor is checked, from the machine to the protection system. With the help of simulation equipment, the wiring and the functionality of the machine protection system are verified. [IST-300]

5

### Calibration of sensors and measurement systems

In addition to the inspections, the complete measurement circuit in the field is checked. Every vibration measurement is verified for its operation and linearity. [IST-401] Other inputs, like speed, are functionally tested with specific simulation equipment as well. All the data is registered, including performance reports, type numbers and serial numbers. Particularly in ATEX or SIL environments, these registrations are an important part of the document requirements.

*"**Every** vibration measurement is verified for its operation and linearity...*

*...and **all the data** is registered."*

6

### Mounting of sensors

When the mechanical work is completed, the sensors are refitted to the machine and precisely positioned. The tested sensors are positioned in their standard positions. In some cases, axial measurements are verified with an axial rotor bump test.

7

### Functional SIL proof test

If the protection system is subject to SIL standards, a functional proof test is carried out. The proof test is performed according to the test procedures as specified by the system supplier and in compliance with the applicable standards and guidelines. Based on the test interval, a partial or full proof test can be required. ■


**IST-300**
**Vibration calibrator**


**IST-401**
**Automated probe calibrator**

**The required number** of independent protection layers depends on the complexity and **potential severity** of the consequences of a risk scenario.

# Risk evaluation: Layer of protection analysis

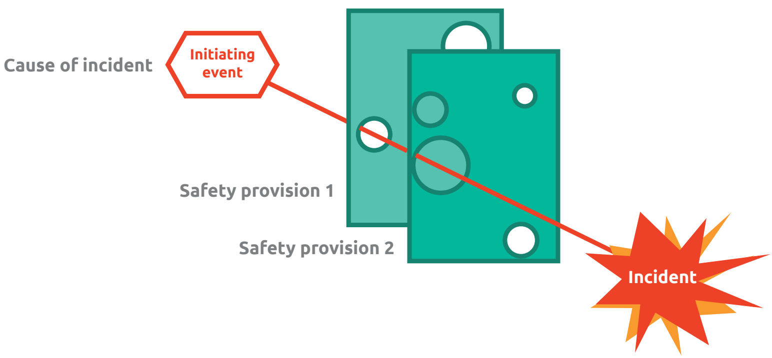
**A layer of protection analysis (LOPA) is a simplified form of risk evaluation that lies between qualitative and quantitative analysis. The purpose of a LOPA is to determine whether enough independent protection layers (IPL) are present to protect against potential risk scenarios.**

The required number of IPLs depends on the complexity and potential severity of the consequences of a certain risk scenario. The consequences of all potential risk scenarios are identified in advance using a qualitative hazard evaluation method, known as the hazard and operability study (HAZOP).

In theory, one IPL could be sufficient to prevent failures or dangerous situations and their consequences. However, no IPL can provide 100% coverage, meaning that several IPLs are required to minimise the occurrence of dangerous situations and malfunctions to a tolerable risk.

## Seven steps are followed for each scenario during a LOPA:

1. A potential situation / scenario is outlined.
2. An estimation of the consequences and severity of the situation / scenario is made, divided in consequence classes.
3. The initiating event and enabling condition are identified and the frequency of occurrence is determined.
4. The independent protection layers (IPL) are identified. For each IPL, the probability of failure on demand (PFD) is estimated.
5. The frequency of the scenario is calculated, using history logs of the plant.
6. The risk is evaluated to make a decision concerning the scenario.
7. Measures are taken to reduce the risk when the calculated risk is larger than the maximum tolerable risk. ■



# Functional Safety

"**The aim is to prevent accidents** with human, environmental and financial consequences."

→ p 32 - 37

# Functional Safety

**“is part of the overall safety that depends on a protection system or equipment operating correctly in response to its inputs”. (IEC 61508)**

**“is the detection of a potentially dangerous condition resulting in the activation of a protective or corrective device or mechanism to prevent hazardous events arising or providing mitigation to reduce the consequence of the hazardous event”. (IEC 61508)**

By complying with functional safety standards, it is possible to identify hazardous situations or events that might lead to accidents. The aim is to prevent accidents with human, environmental and financial consequences. Predictive, preventive and/or corrective measures can be taken to prevent dangerous situations or to mitigate the impact of these situations.

By implementing functional safety, the risk of certain (dangerous) events must be reduced to an acceptable level, and the impact of potential consequences must be limited as much as possible. It is important to be aware that "risk-free" does not exist and therefore, cannot be a target. The risk calculation is based on the probability of the occurrence of an event, and the severity of its consequences.

Functional safety is achieved by implementing an active machine protection system, and by maintaining the minimum required availability of each safety function of the system. The machine protection system is designed to maintain the required safety level during its safety life cycle. Functional safety provides structure to the company's safety measures, and is used to cover the responsibility for overall safety.

## IEC standards

Functional safety guidelines are defined in the standards IEC 61508 and IEC 61511. IEC 61508 provides machine manufactures with guidelines for the specification, design and operation of electrical, electronic and programmable safety systems based on a life cycle concept.

The standard IEC 61511 is also based on a life cycle concept. The main difference between IEC 61508 and IEC 61511 is that IEC 61511 is not written for machine manufacturers, but for the end-users of the equipment and focuses on Safety Instrumented Systems (SIS) in the process industry.

*You think safety is expensive?*

***Try having an accident!***

# Safety Integrity Level (SIL)

**The Safety Integrity Level (SIL) is part of functional safety. It is used to design Safety Instruments (SI) and Safety Instrumented Systems (SIS). The safety integrity level is rated based on different risk levels, taking into account the impact of system failures on humans, the environment and finances, and the likelihood of failure. A high safety integrity level requirement increases the demand for functional safety measures, and lowers and governs the chance of uncontrolled incidents.**

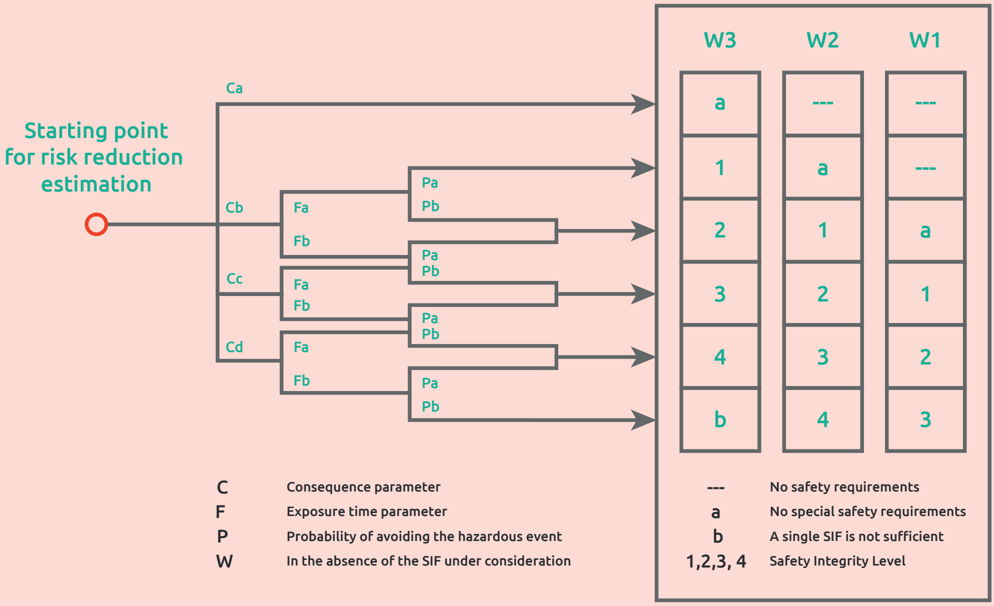



FIGURE 1 – RISK GRAPH TO DETERMINE THE RIGHT SIL

The required safety integrity level differs for each application. The risk and the impact of the consequences of a failure determine the recommended SIL rating. The risk level and the consequences of a failure are determined using hazard and operability (HAZOP) studies, risk graphs and layer of protection analysis (LOPA) information.

A SIL-certified safety system must be maintained and tested properly to guarantee its availability. The SIL rating of a safety system decreases over time. By testing and maintaining the system according to a preset frequency, the rating can be (partially) restored. This test frequency is described in the safety documentation provided by the supplier of the system. The interval is based on the Safe Failure Fraction (SFF), Probability of Failure on Demand (PFD) and Hardware Fault Tolerance (HFT).

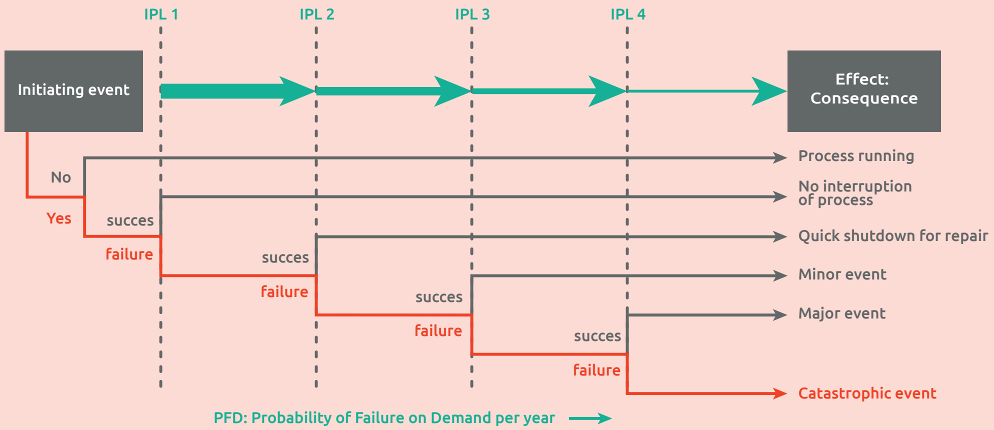



FIGURE 2 – INDEPENDENT PROTECTION LAYERS

# Safety Integrity Level proof tests

**Proof tests are used to ensure the safety integrity level of a safety system throughout the safety life cycle. A proof test verifies the system function and availability, and covers failures like dangerous failures, diagnostic failures and parametric failures. Proof tests are an important part of the safety life cycle and a key act in covering the companies safety responsibilities. The tests are performed by competent engineers and require proper procedures and documentation.**

## Full proof test

A full proof test is an end-to-end test of the safety system, with maximum coverage of the safety parts and functions. The proof test is usually performed at a pre-defined test interval, according to the safety requirement specification. Depending on the safety conditions, the test can be performed with active process conditions or simulated process conditions, and in practice the latter is usually considered the only option. The purpose of the test is to reveal undetected faults in the safety instrumented system so that, if necessary, the system can be restored to its designed functionality. By testing the complete system, including the loops and all the safety functions, the test can cover all the dangerous failure modes, including diagnostic failures and parametric failures.

Note: A full proof test should have 100% coverage, but this is usually not the case. The essence of a full proof test is that is covers all the parts and functions that can be tested, and that it offers the highest possible coverage for the application.

## Partial proof test

It is not always possible to do a full proof test, for instance if the test interval is not in parallel with other maintenance intervals. If a full proof test is impossible, or if it imposes unacceptable risks, partial proof tests are used as an alternative.

A partial proof test is a proof test that does not cover 100% of the parts and functions of the safety system. For various reasons, parts can be excluded from the test or the test can be divided into parts.

Example I: For practical reasons, the sensors of a safety system are not included in the test, but simulated on the input of the protection system. This partial test covers the functionality of the system, but does not cover all the parts.

Example II: During active process conditions, the 3 channels of a 2oo3 system are tested in sequence instead of in parallel, to avoid activating a trip. This partial test covers all the parts, but doesn't cover the combined functionality and the logic.

The proof test coverage is a measure to determine how many undetected failures are detected by the proof test. The IEC 61508 standard provides some equations as a guideline to determine the coverage ratio. A partial proof test restores the SIL rating of the safety system in proportion to its coverage ratio.

## Diagnostic proof test

Diagnostic tests usually refer to integrated, online tests that are performed continuously or with a high frequency. In general, the diagnostic test is a self-test that focuses on the function of the instrument. Diagnostic tests can be done by integrated diagnostic and/or simulation hardware and software features, but might require external components as well. Diagnostic tests are designed to detect dangerous failures and change them to safe situations, either by generating an alarm or bringing the process to a safe state. The tests might have a lower coverage ratio, but are important because their high frequency can identify critical failures quickly. ■

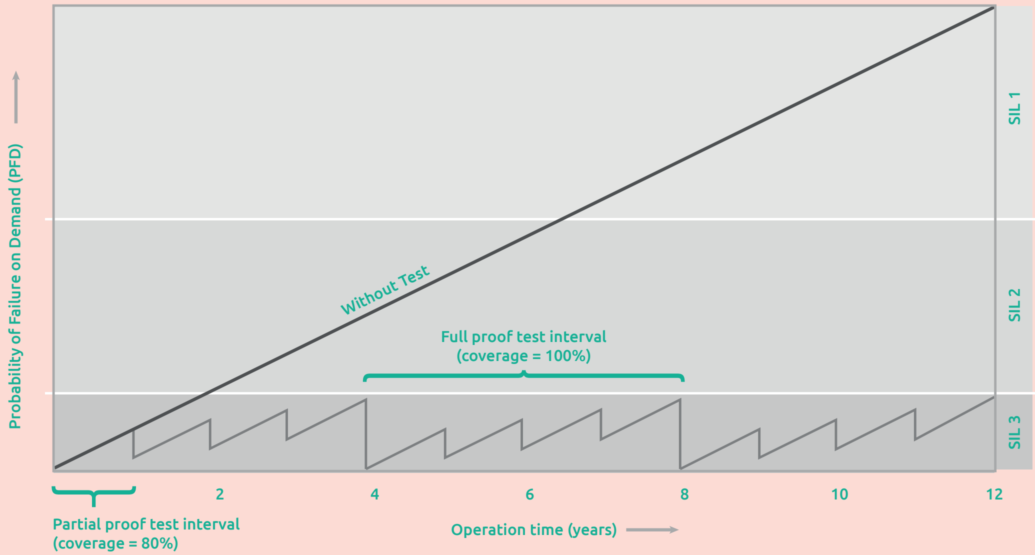



FIGURE 3 – SIL PROOF TEST INTERVAL

# Condition monitoring

**"By gathering and analysing data, insights into the performance, behaviour and wear of the machine and individual parts are gained."**

**Sander Bakker**

CONDITION MONITORING SPECIALIST (ISO 18436-2 LEVEL 4)

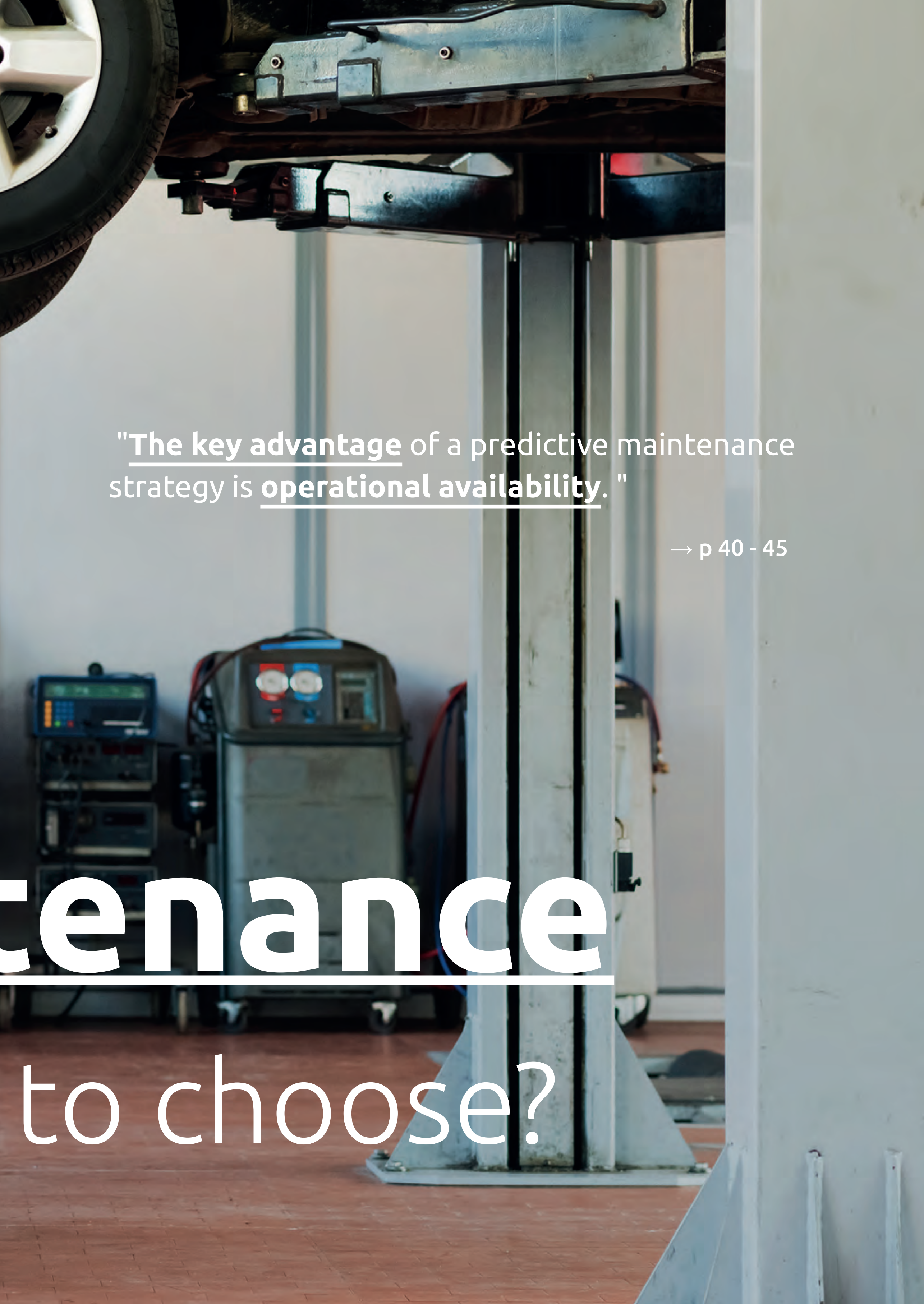
3

# Vibration monitoring and predictive maintenance

All rotating machinery produces vibrations as part of their machine dynamics. Vibrations can originate from numerous sources, including bearing issues, misalignment, unbalance, resonance or general wear. Measuring and analysing vibration data can provide valuable information about the mechanical condition and the environment of the equipment, and can identify mechanical failures or issues as they develop. This information can be used to predict maintenance requirements and to detect the root causes of vibration. By identifying these sources as they develop, maintenance can be scheduled in advance and consequential damage can be avoided.

Vibration measurements are non-intrusive, meaning that the measurements have no influence on the process. The measurements are mainly applied to rotating equipment like steam and gas turbines, pumps, motors, compressors and gear boxes. The signals can be acquired continuously with permanent monitoring equipment or at a regular interval using portable equipment, and are performed during normal operation. Additional information can be gathered during run-up and coast-down of the machine. By trending the data, developing failures and poor maintenance practices can be identified. ■

# which maint
# strategy



"**The key advantage** of a predictive maintenance strategy is **operational availability**. "

→ p 40 - 45

# tenance

# to choose?

# Which maintenance strategy to choose?

**A protection system is in place to trigger the trip system when needed. However, a machine trip leads to increased risk, high costs, unplanned downtime, emergency repairs and damaged production. Therefore, an appropriate maintenance strategy is required to avoid a run-to-failure situation on critical assets.**

## 1. Run to failure

Using this maintenance strategy, machines and machine parts are only replaced or fixed after failure, when it is clear that the machine can no longer function (safely) without doing so. The operation therefore, only comes to a standstill when it is really necessary. The reactive maintenance strategy makes it hard to schedule maintenance in advance and leads to unexpected operational interruptions. Therefore, the strategy is only suitable for assets of minimum importance to the process, which are easily replaced or repaired. It comes down to a trade-off: what is the value of preventing this asset to run to failure? And if that value is low, e.g. with non-critical assets, redundant equipment or in batch production situations, this maintenance strategy can work well. For critical assets in continuous active process conditions, a reactive maintenance strategy is a no go.

## 2. Scheduled maintenance: preventive strategies

This strategy is widely used to provide a basic structure for avoiding run-to-failure situations. Using this strategy, maintenance is performed according to a predefined schedule. The maintenance frequency can be based on fixed time intervals or active operational hours. Production stops and unexpected failures are reduced by replacing machinery and machine parts preventively. This largely eliminates the chance of failures occurring during active

*"**20 billion** per year is lost to **unscheduled downtime**"*

(AUTOMATION.COM, 2016)

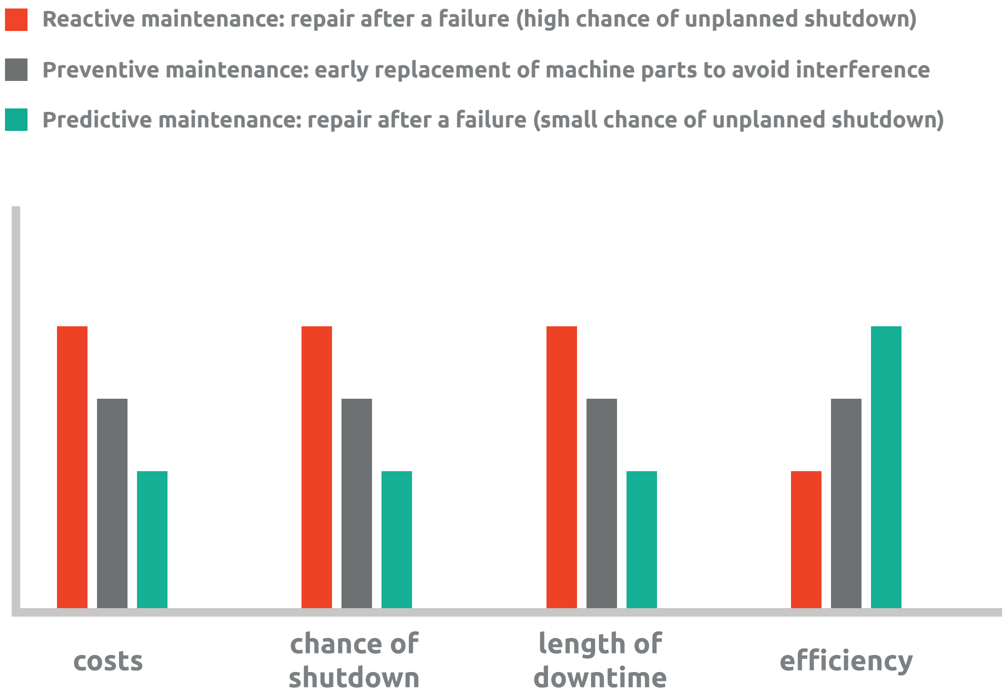



FIGURE 4 – COMPARISON OF MAINTENANCE STRATEGIES

process conditions. It might not be the most effective maintenance strategy due to the fact that machinery and machine parts are often replaced when not directly required, but this is again a trade-off between the value of prevention and risk. For example: The life expectancy of a fan is 50,000 operational hours, as stated by the OEM. Theoretically, this would mean that the fan will break down after 50,000 operational hours. A preventive maintenance strategy tells us to replace or overhaul this fan before the life expectancy is reached. However, chances are that the fan is in a perfectly healthy condition and can exceed its life expectancy by 4,000 operational hours. The preventive maintenance strategy adds the value of the 4,000 hours that are "thrown away" to the costs of replacing or overhauling the fan. However, it is imaginable that, when a plant is required to be continuously operational, a periodic turnaround is used to replace machinery and machine parts preventively. After all, it would be much more expensive to be forced into standstill unexpectedly.

Scheduled car maintenance is a great example of a preventive strategy that most of us follow; every year your car is serviced and the oil is replaced. You do not know whether it is technically required, but your manufacturer prescribes it, it is relatively cheap, and you do not want to risk a potential engine failure.

→

## 3. Predictive, condition-based maintenance

Predictive maintenance or condition-based maintenance is a maintenance strategy that focuses on the actual condition of the machinery. The strategy is often applied to critical assets and assets that are very complex or expensive to maintain, like turbines, generators and compressors. The key element of this maintenance strategy is to monitor the machine condition and to use this information to predict maintenance requirements. This can be done by monitoring various indicators, like temperature, pressure, oil condition and vibration, but for the purpose of this book, we are only focusing on vibration.

In order to monitor the machine condition using vibration, data needs to be acquired. This can be done through online condition monitoring hardware or by periodic measurements with portable measurement equipment. The data must then be analysed by a specialist to identify possible failures and damages. The monitoring hardware and specialist analysis require significant investments, which do require justification. Read more about the justification on page 68.

The key advantage of a predictive maintenance strategy is the operational availability. By gathering and analysing data, insight into the performance, behaviour and wear of the machine and individual parts is gained. This information is vital to adjust maintenance work to the condition of the equipment, avoid unnecessary scheduled maintenance stops, make scheduled maintenance stops more efficient, and reduce unexpected failures. Additionally, spare part management and other resource planning can benefit from this information. ■

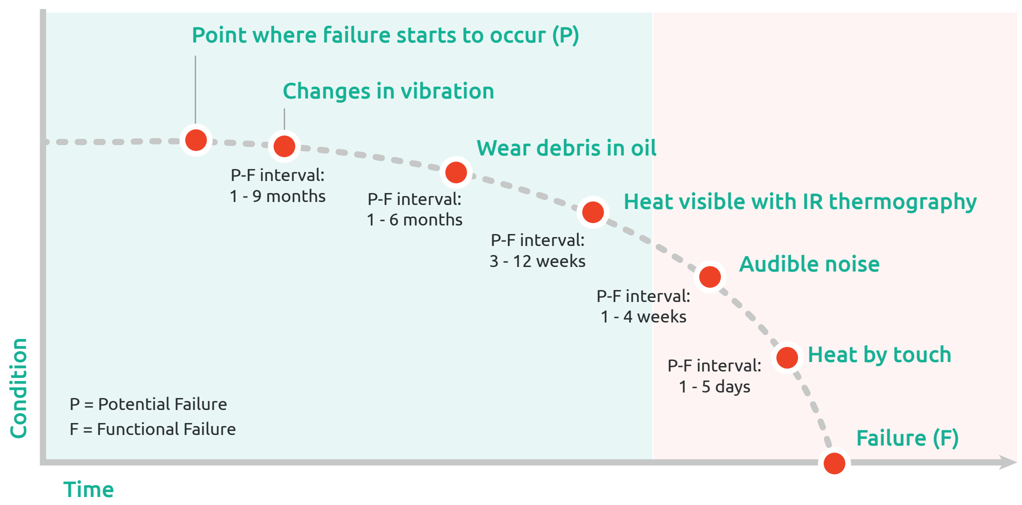



FIGURE 5 – PF INTERVAL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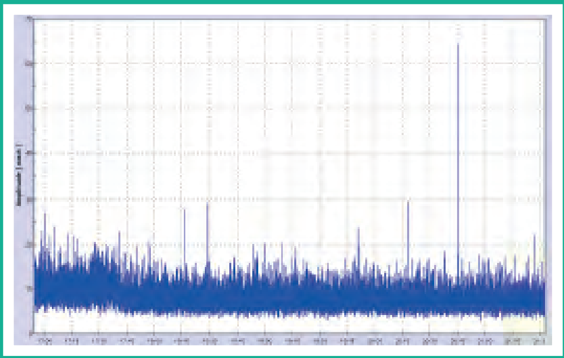
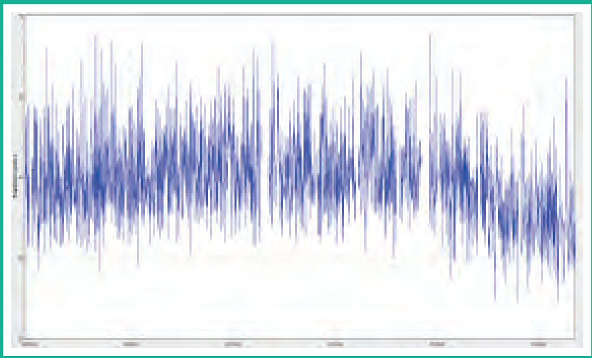
# Ignoring expert advice results in damage

**During a periodical vibration measurement on a recently reconditioned oil pump, a deviation was noticed in the vibration levels. The problems were characterised by increasing vibration values, which therefore exceeded the limits defined in ISO 10816. The installation was a steam turbine, that drove the oil pump. To identify the root cause of the increasing vibration levels, the data was analysed.**



*3 January - average overall level: 9 mm/s*



*28 January - average overall level: 50 mm/s*

## Analysis

The following frequencies are visible in the FFT-spectrum:

- 1xRPM oil pump (57 Hz), which amplitudes varying between 18 and 30 mm/s RMS.
- 2xRPM oil pump (114 Hz) of 1.5 mm/s RMS.
- 1xRPM turbine (104 Hz) of 2 mm/s RMS.
- A lot of harmonics of the turbine RPM, about 1 mm/s per peak.
- The gear mesh frequency of 14 mm/s RMS, with bandwidths of both RPMs (57 Hz and 104 Hz)

## Expert advice

The different frequencies and associated levels are an indication of wear and increasing clearances on the gears and bearings. Additionally, misalignment is expected. Because of the fast increase in the vibration levels, the situation is considered alarming.

For the measurement, three different sensors and two different measurement systems were used to measure and verify the expectations and conclusions. According to ISO-10816-3, the vibration levels are categorised as zone D; Vibration values within this zone are normally considered to be of sufficient severity to cause damage to the machine.

Based on the findings, it is crucial that the pump is shut down for inspection and revision as soon as possible. During this revision it is important to check the following parts:

- Check all pump bearings on clearances
- Check the pump alignment and tooth profiles

## Result

The customer acknowledged the findings, but decided to take the risk and keep the machine running. After a few weeks, the oil pump suddenly failed and the auxiliary pump took over.

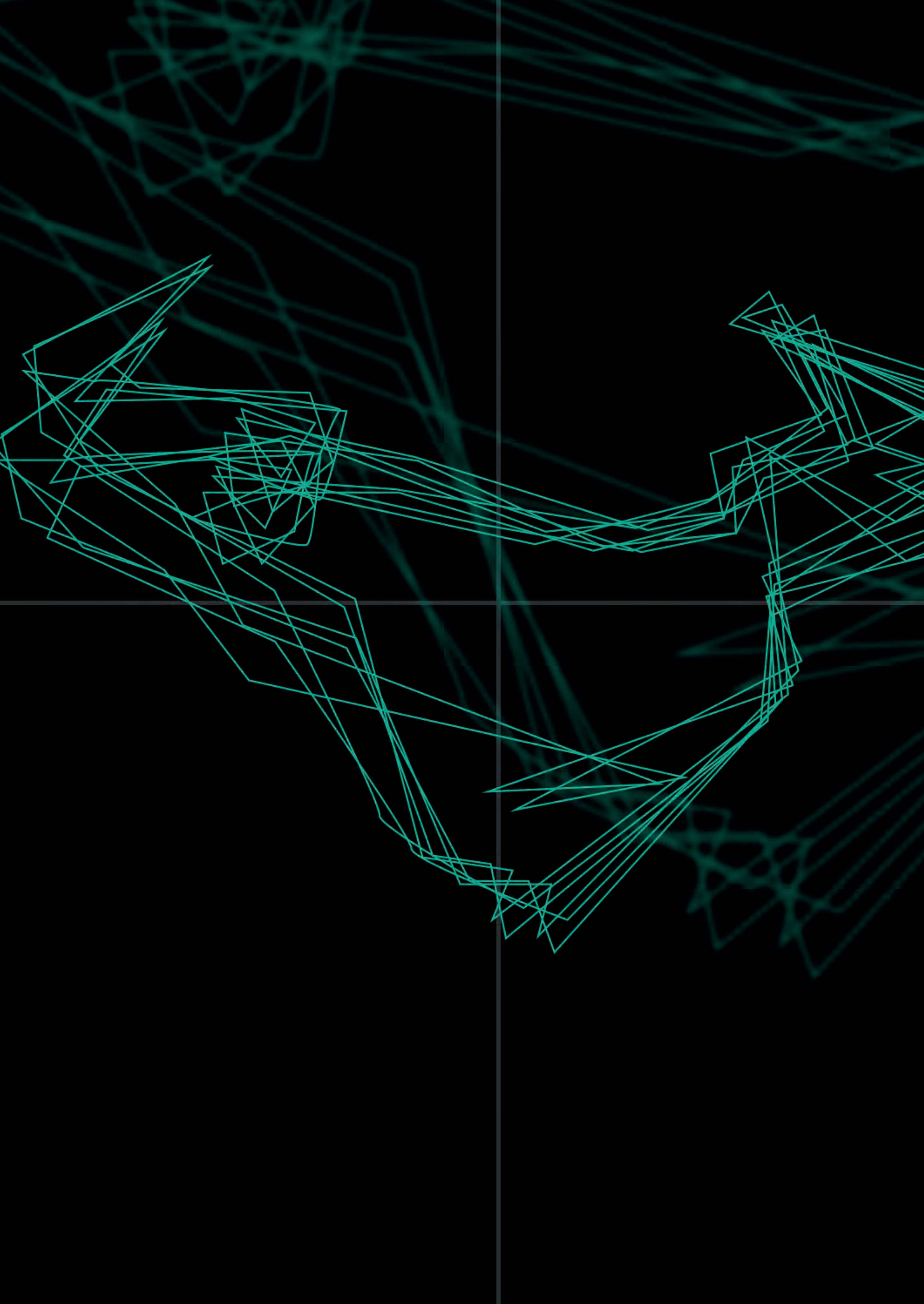
*Fatigue crack - turbine side*

*Fatigue crack - pump side*

## Root cause

Both pictures show the typical surfaces caused by a torsional fatigue failure. The growth lines, also known as beachmarks, and the fracture plane right of the centre can be seen clearly. It is also clearly apparent that the source can be found in the transition at the bottom and side of the keyway. The fatigue failure has caused some damage on the beachmarks, seen as secondary damage.

A common cause of a fatigue failure is misalignment. This misalignment causes a dynamic force to the shaft, which accelerates the fatigue process. ■



# Analysing vibration data

**Once the required vibration data is made accessible for analysis by the condition monitoring hardware, the dedicated software can be used to perform specific analyses like spectrums (FFT), orbits and trends.**

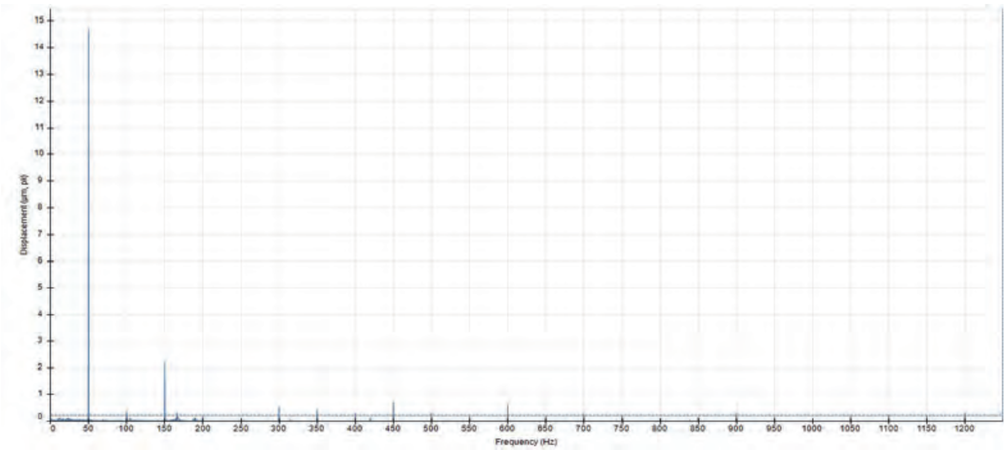


FIGURE 6 – SPECTRUM ANALYSIS

## Spectrum

A spectrum analysis (FFT) plays an important role in monitoring machine vibrations. There are several known deviations in machine vibration behaviour that do not exceed a single norm, but still pose a risk to the operational reliability of the equipment. With a spectrum analysis, the root-cause of the changes in the machine vibration behaviour can be identified. If necessary, corrective measures can be taken which can include lubrication, alignment check or replacing machine parts.

Every machine has its own specific characteristics and mechanical composition. Based on the type of machine and its components, there are numerous forcing frequencies. A forcing frequency is the frequency of an oscillating force applied to a system. Forcing frequencies can be caused by the normal behaviour of the machine or by mechanical malfunctions or wear. Each deviation from the normal behaviour of the machine introduces its own forcing frequencies. By analysing the spectra, the cause of the deviation can be determined, and information can be provided to decide whether the introduced forcing frequency needs attention, such as replacing parts or correcting alignments.

→

Several "standard" forcing frequencies are decribed in the literature, each with its own specific pattern spectrum. In reality however, the spectra are never that clean. It requires the experience and the specific machine knowledge of a vibration analyst to determine the source and impact of the forcing frequencies, and to provide decent information for corrective actions if necessary.

The most common (unwanted) forcing frequencies in rotating machinery are caused by unbalance, misalignments, bearing damage and tooth/teeth damage on gearboxes.

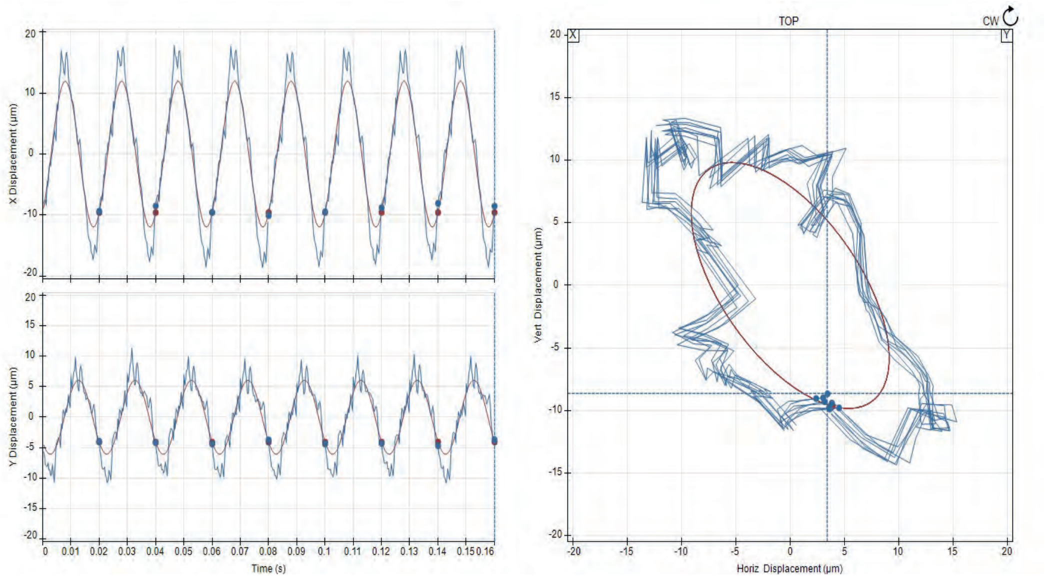



FIGURE 7 – ORBIT ANALYSIS

## Orbit analysis

Just like the spectrum, the orbit is a tool for the vibration analyst to analyse the behaviour of a machine. The orbit measurements are used particularly for sleeve bearing applications, and to provide data on the motion pattern of the shaft inside a bearing. In contrast to the spectrum, the orbit measurement is not based on forcing frequencies but on the dynamics of the shaft. When there is a preload on the shaft, the natural motion of the shaft is influenced, and in most cases this results in a non-orbital movement of the shaft. The most common machine faults detected with orbit analysis are misalignment, rub of a shaft on a static part and fluid instability in the bearing (oil whirl or oil whip).

The data for creating an orbit is generated using proximity probes (displacement probes). With these probes, the vibration analyst can collect more critical machine information, like the shaft centre line. A shaft centre line measurement provides information on the radial position of a shaft inside the bearing, and together with the orbit analysis this provides great insight into the wear of a sleeve bearing and possibly non-natural position of the shaft caused by misalignment.

The orbit measurement is a sensitive measurement that can easily be influenced by distortions like scratches on the measurement surface of the shaft. Because it is a relative measurement, casing vibrations can also influence the shape of the orbit. Experience and knowledge of this measuring concept are essential for a good analysis.

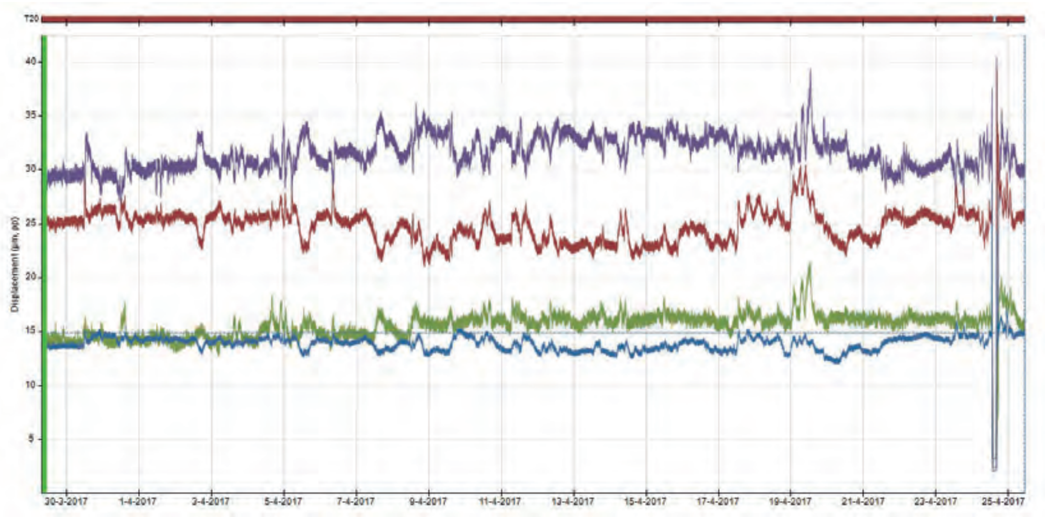


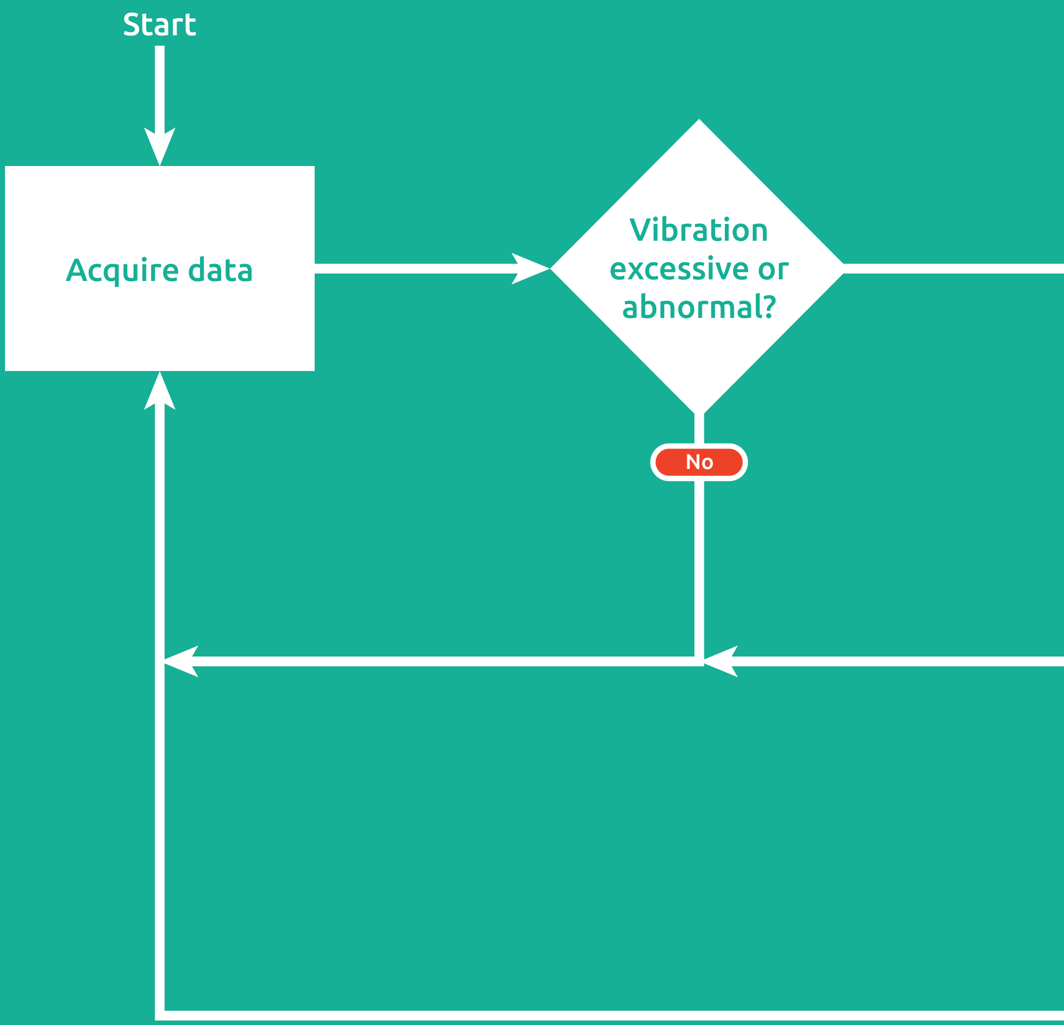

FIGURE 8 – TREND ANALYSIS

## Trend analysis

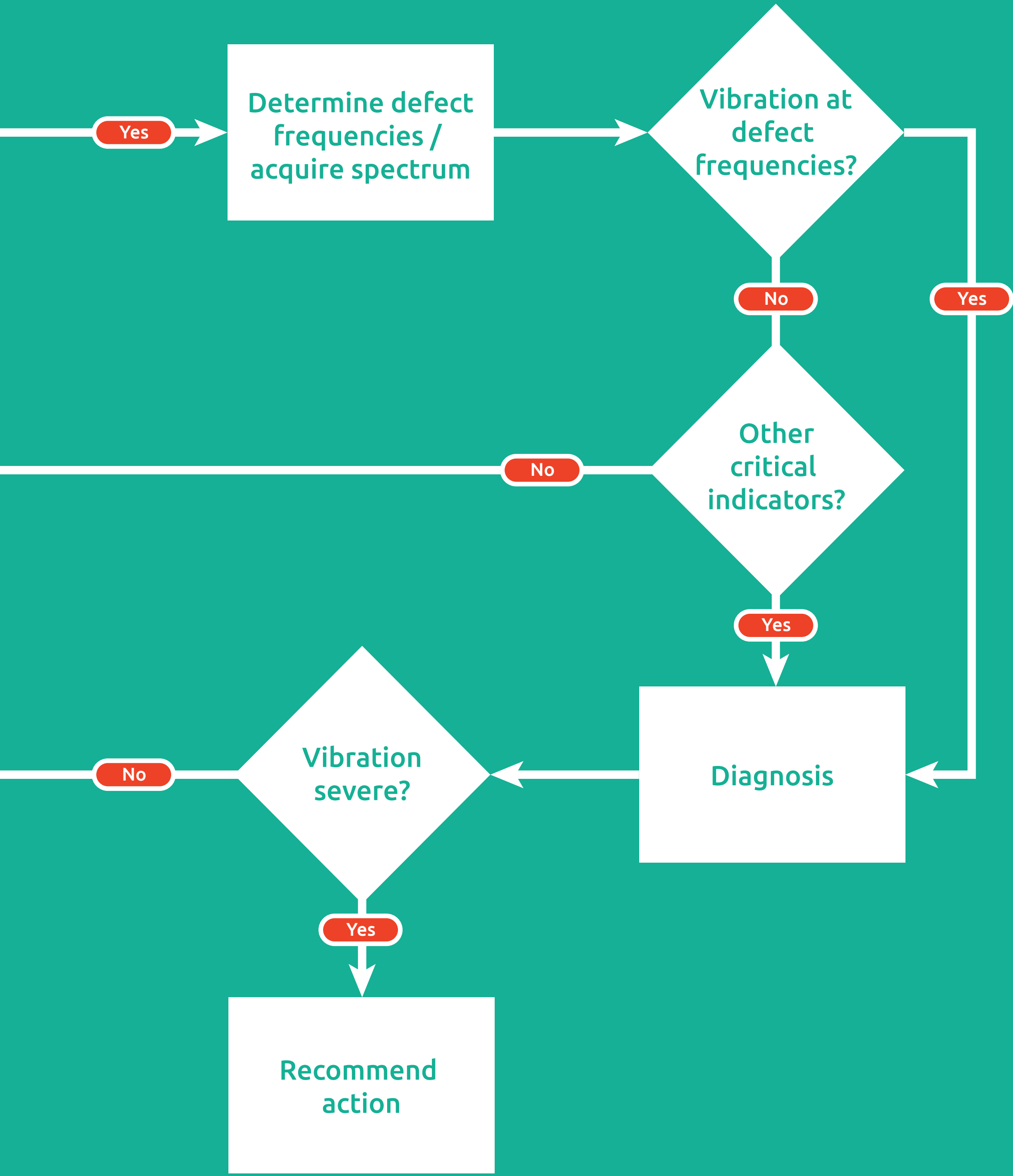
Trend data is commonly used to determine the machine state on a very basic level or as a first indicator. Trend analysis generally refers to measuring the vibration level in a certain frequency range. These frequency ranges can be determined using the ISO guidelines for the specific type of measurement (shaft or casing vibrations) and machine.

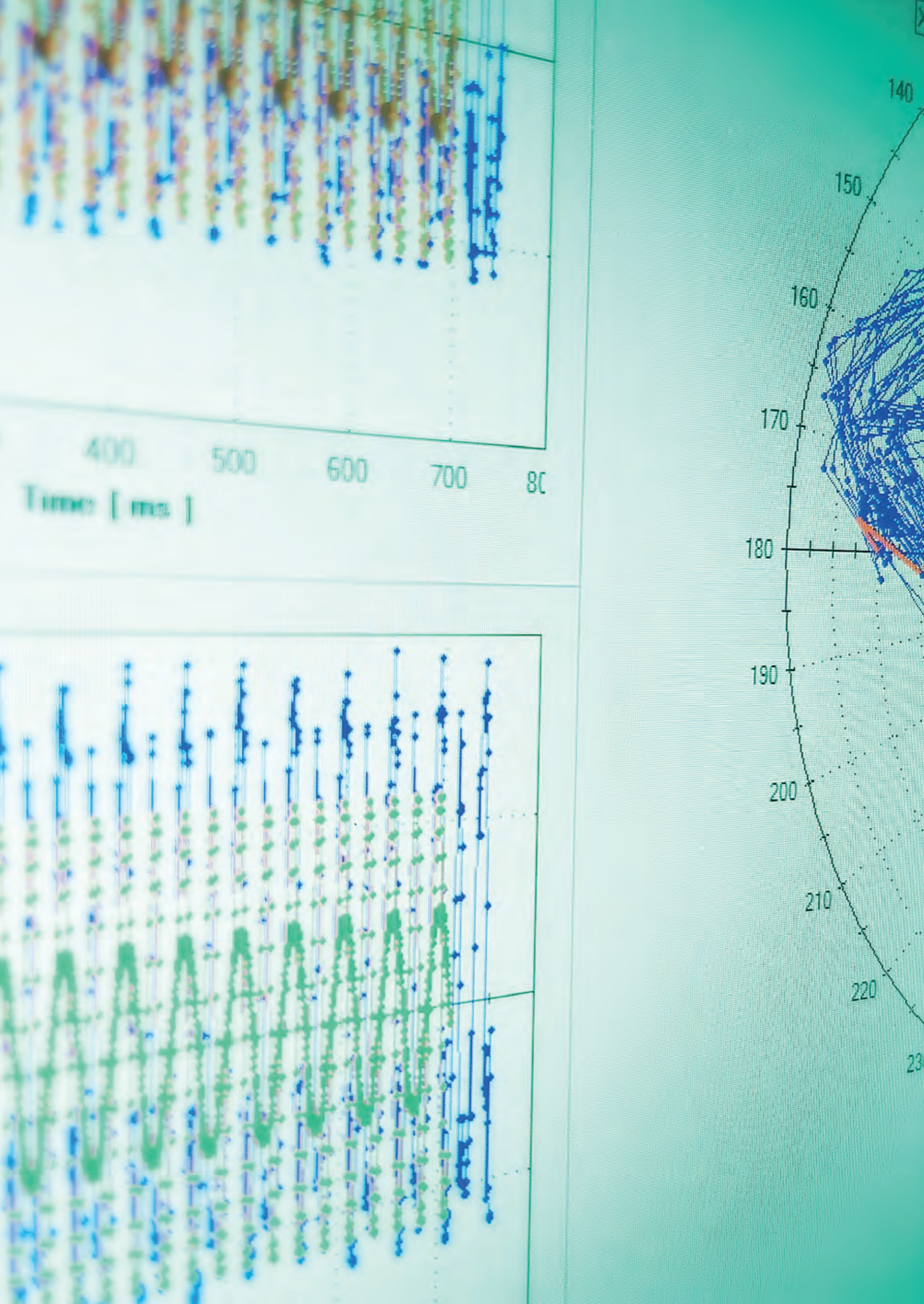
A typical measurement for trend data is a 10-1000Hz overall value. This measurement provides a numerical value for all the vibrations in the chosen frequency range. Because it is a calculated value of all frequencies in the range, it does not provide any information about the cause of the vibration levels.

In addition to the overall value, there are numerous other types of trend data and analysis. For instance, an extracted value on the running speed combined with data of a phase trigger (if available) can be used in a phase/amplitude measurement and can provide information about the natural frequencies during a run-up of a machine (bode plot). Or, as another example, an analysis based on specific frequency ranges, such as a gear mesh frequency, that can provide information about the load on a gearbox and the wear of the tooth. ■




# Standard methodology for vibration analysis


Yes
Determine defect frequencies / acquire spectrum
Vibration at defect frequencies?
No
Yes
Other critical indicators?
No
Yes
Diagnosis
Vibration severe?
No
Yes
Recommend action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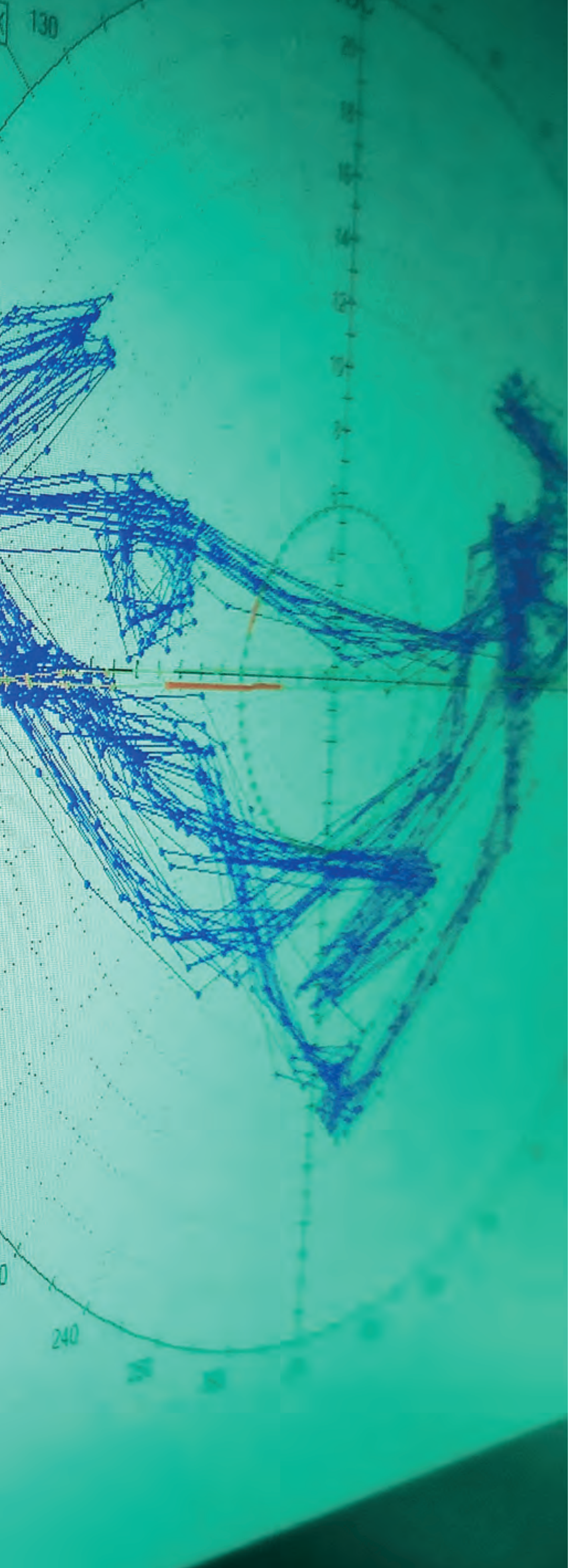


# Personal certifications for vibration analysis

The standard ISO 18436-2 describes the requirements for specialists performing condition monitoring and machine diagnostics using vibration measurements and analysis. The standard covers the requirements for training, experience and examination.

Certification according to ISO 18436-2 indicates that an individual is competent to perform vibration measurements and analysis using portable and permanently installed equipment. The ISO standard is based on a four-category system to differentiate the certified levels of competence. ■

# Ways to perform condition monitoring

## Periodic condition monitoring

Through periodic condition monitoring, insights into changes in the vibration behaviour of machinery can be identified. Periodic refers to a certain preset measurement interval that can be determined based on the type of application and the criticality of the equipment. With this strategy, a specialist goes on site and collects data using portable equipment. By performing vibration measurements at a fixed interval, trend data can be generated and stored in a database. This database contains information about the condition and technical specifications of the equipment. It is crucial that the system is set up properly to collect appropriate data. To do this, specialist knowledge and experience is required. Any deviations found during periodic measurements are analysed to find the root cause using various analysing techniques.

Periodic condition monitoring is performed using portable condition monitoring hardware, and therefore does not require major upfront investments. It can be the most economical solution or a first step into condition monitoring. For critical equipment, online condition monitoring can be applied to obtain more data and continuous information.

## Online condition monitoring

Online condition monitoring is the systematic monitoring of a machine or process, using permanent monitoring hardware. An online condition monitoring system continuously collects vibration data. During critical moments like run up, coast down and critical speeds, the data collection frequency can be increased to enhance machine insights and maximise process control and reliability.

*"During critical moments like run up, coast down and critical speeds, the data collection frequency can be increased to enhance machine insights and maximise process control and reliability."*

SANDER BAKKER
CONDITION MONITORING SPECIALIST (ISO 18436-2 LEVEL 4)

Certain vibration limit values can be set in the condition monitoring system to trigger an alarm. These limit values are set at lower / different values to the machine protection limits. Reaching the limit values that are set for condition monitoring does not necessarily indicate a risk, but can be used as an alarm for excessive wear or required maintenance, or to initiate a specialist analysis.

## Remote condition monitoring

Online condition monitoring hardware with network access enables remote expert data analysis as an addition to online condition monitoring. A strong advantage is that the measurement data can be analysed remotely without disturbing the organisation and expertise can be used as a service on demand. Remote condition monitoring is often implemented when vibration measurements and analysis are (partly) outsourced.

# Which vibration monitoring strategy fits your machine?

When the decision has been made to start a machine condition monitoring programme, there are various ways to implement it. The following infographic explains the various options and what considerations are involved.

Which

# vibration monitoring strategy

fits my machine?

## Troubleshooting

If failures are predictable and easy to solve, predictive maintenance might be not necessary. When a failure is perceptible, the best way to discover the root cause of the problem is to use vibration measurements and analyses. Experts use portable data collectors to collect vibration data.

## Periodic measurements using portable data collectors by yourself

With portable data collectors, you can perform vibration measurements on the machine by yourself. Istec International provides courses to train personnel to be able to perform vibration measurements and vibration data analysis.

No

Are you planning to outsource vibration measurement and analysis?

Yes

No

Are the causes and timing of failures predictable?

No

Is the machine critical to the process?

Yes

## Periodic measurements with portable data collectors by external experts

If the machine is not critical, but periodic insights into the machine condition are desirable, a periodic visit by our experts with portable data collectors is the best approach.

After their visit, the experts will analyse the data using condition monitoring software. After vibration analysis, a detailed report will be provided containing our findings and recommendations.

## Troubleshooting

If a machine is critical to the process, we strongly recommend using a condition-based maintenance strategy with periodic vibration measurements. However, if it has already been decided that a CBM strategy is not an option, vibration experts will use portable data collectors to collect vibration data when a problem seems to occur.

Yes

No

Are you considering to move to a CBM strategy?

Yes

Yes

Is there a redundant machine available?

No

## Portable multichannel analyser

Experts will visit the machine with a portable multichannel analyser at a fixed interval. This analyser is developed by Istec International and enables the expert to collect data over a period of time.

After collecting sufficient data, the experts will analyse the data using condition monitoring software. After our analysis, a detailed report will be provided containing our findings and recommendations.

## Online condition monitoring

When condition monitoring hardware is installed, vibration data is continuously collected. Hence this approach is called an *online* strategy.

Because the analysis cards constantly receive and store data, our specialists can be warned immediately when a limit value is reached. This allows our specialists to respond ad hoc and perform an analysis to determine the root cause. When a limit value is reached, the system will start collecting data on a higher frequency so that the vibration specialist can literally zoom in on the exact moment the limit value was triggered.

This approach is often combined with remote condition monitoring.

**Is condition monitoring hardware installed?**

No

Yes

**Has a machine vibration protection system currently been installed?**

## Online condition monitoring with recurring visit

When condition monitoring hardware is installed, vibration data is continuously collected. Our experts visit the machine periodically within a fixed time interval. Reasons to use this approach can be related to the unavailability of a computer or server to transfer data to our experts remotely. Our experts will retrieve the data on-site using a portable data collector.

No

Is it desirable that our expert can analyse data without on-site visitation?

Yes

## Online condition monitoring with remote strategy

When condition monitoring hardware is installed, vibration data is continuously collected. A remote condition monitoring strategy enables our experts to analyse the vibration data remotely, without having to be physically present at the plant. They can simpy login to the condition monitoring system remotely, enabling them to retrieve and analyse the data directly.

Yes

No

Read article on p 62
“The financial justification of condition monitoring”

Yes

No

Will there be condition monitoring hardware installed?

# The financial justification of condition monitoring

It is easy to justify why you would want or need to implement a condition monitoring system. However, it is not easy to financially justify the actual purchase. A relatively large investment is required to purchase, implement and maintain a condition monitoring system.

In general, an investment can be financially justified by means of a simple calculation comparing the initial and running costs with the benefits of the investment (e.g. cost savings, increased profit). It is then determined whether the investment can be paid back within a reasonable timeframe. However, the benefits of condition monitoring are hard to quantify, which makes the financial justification more complex.

→ p 62 - 71

# Different factors support the decision to purchase a condition monitoring system:

- Frequency of failures
- Randomness of failures
- Hazards related to poor machine performance
- Recurring repairs
- Number of incorrectly manufactured products
- Reduced output during operation
- Excessive fuel consumption during operation
- Build quality

The financial advantage of a condition monitoring system is hard to quantify, because the variables that affect the results are difficult to measure. It is impossible to precisely determine the damage, maintenance and replacements that are prevented by condition monitoring. From a technical perspective, it can make sense to implement a condition monitoring system. Machine vibration insights can increase the efficiency and effectiveness of the maintenance. Moreover, critical failures can be detected in advance, avoiding unscheduled downtime and emergency repairs. The question remains, how do you financially justify the investment that is required for a condition monitoring system?

## Maintenance policy <u>without</u> a condition monitoring system

To financially justify the investment in a condition monitoring system, it is important to understand the baseline.

Firstly, insights into past performance data on the reliability of the plant are needed. Additionally, information related to other equipment, the operation of which could be improved and malfunctions prevented, is crucial.

Secondly, financial data of the current performance of condition monitoring measures, without the presence of an actual condition monitoring system, must be taken into account. To do this, the involved departments must provide insight into the current costs that are made within their responsibilities, and covers:

### 1. Costs of production loss and additional work

Both production loss and additional work, as a result of unscheduled downtime, can be financially quantified relatively easily. For example: ten hours of downtime result in a number of products that are not produced. Another number might be damaged due to the interruption of the process and restarting the machine. The costs of the additional hours of work and components that are required for maintenance to the machine must be added. (Figure 9)

### 2. Costs as a result of delivery obligations, production correction and quality loss

Some factors are harder to quantify financially. Unscheduled downtime can result in delayed product delivery to customers, or wear to the machine can lead to efficiency and quality loss. Both will result in customer dissatisfaction, which is hard to quantify financially. Additionally, supply obligation agreements can result in high costs resulting from fines or the necessity to purchase products from the competition in order to meet delivery obligations. Moreover, changes in the normal production schedule

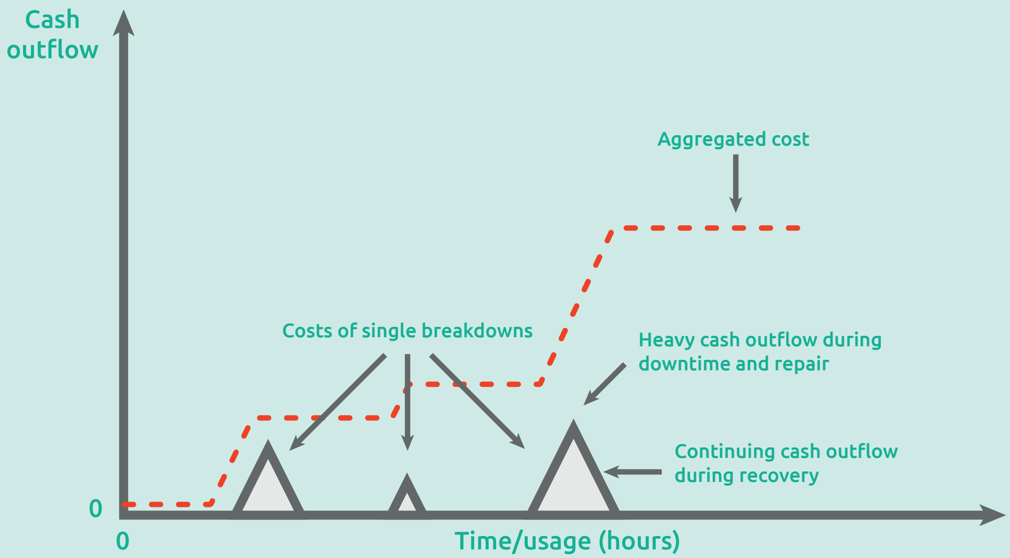


FIGURE 9 – AGGREGATED COST

might be necessary to correct the production loss. When taken separately, these costs might be considered acceptable, but together they show the real impact.

### 3. Frequency and duration of failures

The hardest part of the justification to determine is the frequency in which failures will occur and the duration of these failures. Past performance reports of a plant help to make an accurate estimation of both the frequency and duration of failures, and the resulting costs. However, this is not a guarantee for the future. At best, a trend can recognised in the previously occurred failures. If this is not the case, and the failures occur randomly, the performance reports can offer insights into the costs (per hour) as a result of the average unscheduled downtime.

### 4. Costs as a result of aging

Machinery and installations within a plant will deteriorate over time. This deterioration process can only be slowed down by taking maintenance measures on time. Vibrating bearings and gearboxes can lead to wear on different machine parts. When no condition monitoring system is available to monitor these vibrations, the damaged parts will be replaced without relating the damage directly to causative vibrations. Predictive maintenance will not be possible without a condition monitoring system. As a result, the costs for the replacements of machine parts will rise. (Figure 10)

Predictive maintenance offers a way to gain insights faster, and to make predictions about the possible wear that will occur in the future, as well as the root cause of this wear. Based on condition monitoring analysis, accurate statements about the condition of the machine can be made, and the maintenance measures that are required can be determined. These analyses show where, why and when maintenance is required.

→

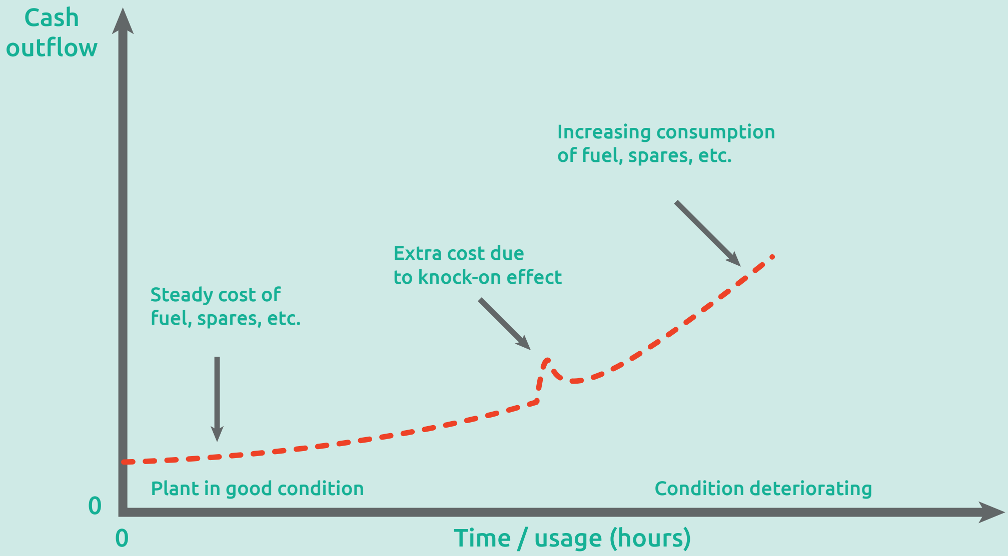


FIGURE 10 – RISING COSTS AS A RESULT OF DETERIORATING CONDITION

### 5. Costs of current (preventive) maintenance strategy

The costs of the current maintenance strategy must be considered as well, as this is partly replaced by the condition monitoring system using a predictive maintenance strategy instead of preventive maintenance strategy. These costs will generally be relatively easy to determine and include: wages, spare parts, overhead expenses, etc. These costs grow exponentially as the plant ages due to a lack of available spare parts, competent engineers and system complexity. (Figure 11)

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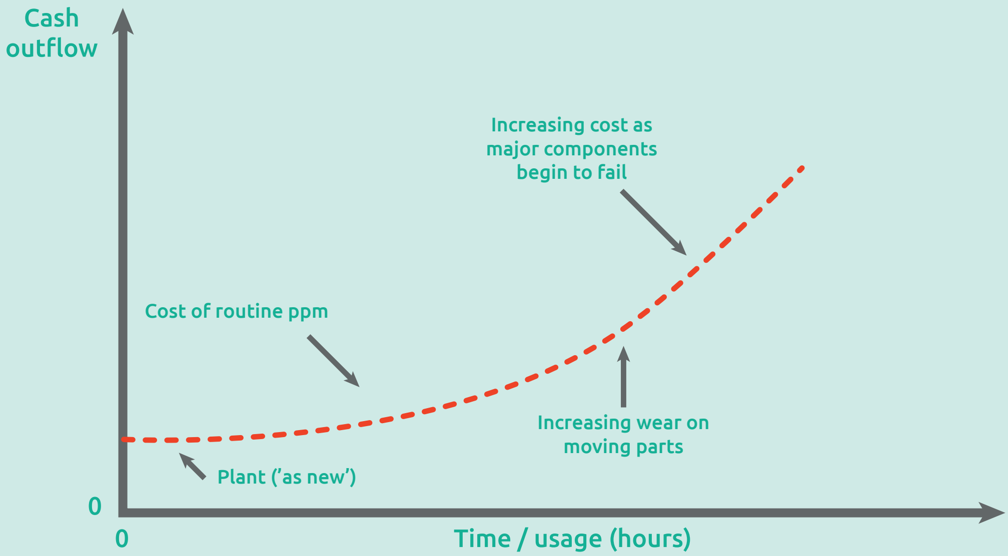


FIGURE 11 – EXPONENTIAL GROWTH OF COSTS AS THE PLANT AGES

*"With a fixed condition monitoring system, maintenance requirements can be predicted more accurately."*

## Maintenance policy with a condition monitoring system

Besides financial arguments and the effects of a maintenance policy without a condition monitoring system, it is important to evaluate the costs of purchasing, implementing, operating and maintaining a condition monitoring system. Comparing both maintenance policies will create a better impression if a condition monitoring system can be financially justified.

### Costs of the system and its installation

It goes without saying that a condition monitoring system involves considerable costs. The purchase costs, installation costs, operational costs and maintenance costs have to be included in the total costs. In addition, costs related to the accessibility, protection, power supply and service access need to be taken into account. Moreover, possible consultancy costs are incurred during the installation process. Ideally, the condition monitoring system is implemented during a planned stop, so that extra production loss can be prevented. In addition, employees could require training to operate the system. (Figure 12)

### Costs of use

After purchasing and implementing the condition monitoring system, the costs are mainly caused by the required personnel. Although, costs can be saved assuming that the staff is provided with (the right) training. Without a fixed condition monitoring system, engineers are required to take spot measurements at various locations on the machine. The condition monitoring system can collect this data at one central point, after which the data only has to be interpreted using dedicated analysis software. Because of this, conclusions can be drawn faster and maintenance requirements can be

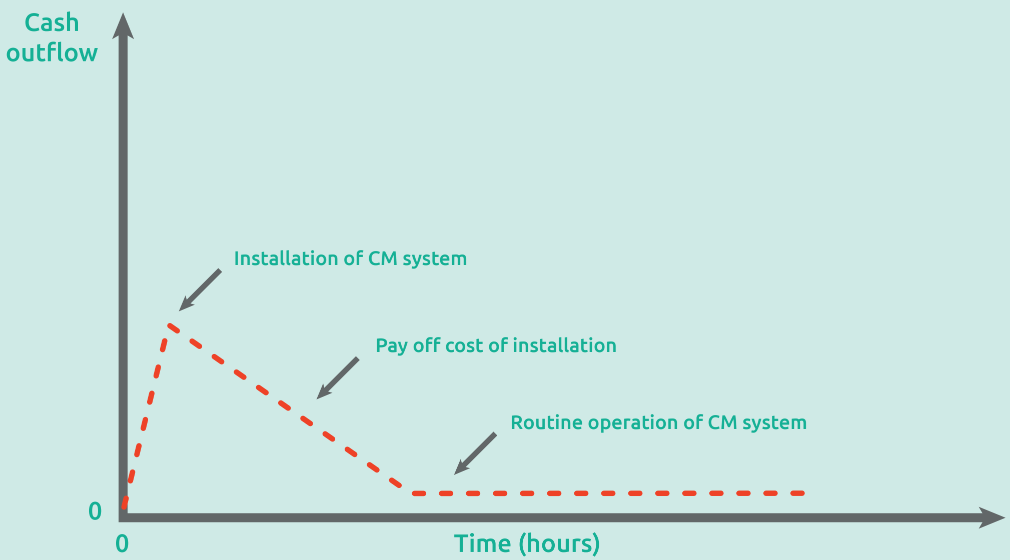


FIGURE 12 – CASH OUTFLOW WHEN INSTALLING A CONDITION MONITORING SYSTEM

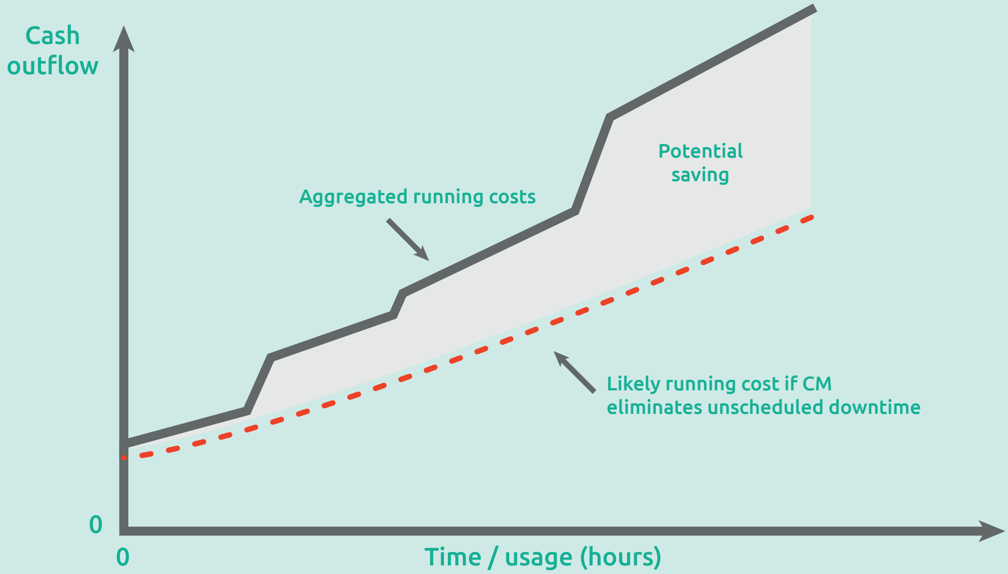


FIGURE 13 – POTENTIAL SAVING

predicted more accurately. Using a condition monitoring system, large maintenance measures are replaced by small maintenance measures.

Costs of personnel can vary significantly for each plant. However, it is relatively easy to estimate what can be gained. Costs of personnel to install, train, operate and perform required maintenance compared to the personnel costs for the current maintenance strategy, clear figures for which should be available for every plant. In addition to costs for personnel to operate and maintain the system, running costs also includes other costs, like power. Although these costs are relatively low, they should still be included in the total costs. (Figure 13)

→

*"Using a condition monitoring system,* ***large maintenance*** *measures are replaced by* ***small maintenance*** *measures."*

## Condition monitoring; the return on investment (ROI)

Both the costs and effects of a maintenance policy with and without a condition monitoring system have been evaluated. However, the goal of any financial investment is that it must ultimately save or generate money. It is, therefore, important to calculate what can be saved by investing in a condition monitoring system, which can financially justify the purchasing and implementing such a system. Several calculation methods can be used to determine this. Combining these methods will provide better information on the effects of an investment in a condition monitoring system. Several important decision-making methods are discussed.

### Payback period (PP)

A very important factor: within what time frame will the investment be recouped? A company can set an ultimatum within which the investment must be recouped. The payback period is relatively easy to determine. A disadvantage of this method is that it does not take inflation into account and assumes even reimbursement.

The payback period (PP) can be calculated as follows (table 1):

- costs (c) / annual savings (s) = Payback Period in years (PP)

### Rate of Return (RR)

Strongly related to payback time (PP). Here too, inflation is not included in the calculation. It can be calculated as follow (Table 1):

- annual savings (s) / costs (c) = Rate of Return (RR)

### Return on Investment (ROI)

This method is more accurate than the methods above because it takes into account depreciation and the salvage costs (after end of life) of the equipment. Moreover, the total benefit during a certain period is included. A ROI calculation

| Method | Formula | Calculations | Outcome |
|---|---|---|---|
| Payback period (PP) in years | c / s = PP | €160,000 / €40,000 = 4 | It takes four years to recoup the costs |
| Rate of Return (RR) | s / c = RR (%) | €40,000 / €160,000 = 0.25 = 25% | Annual Rate of Return is 25% |
| Annual Costs (Cy) | (c – rv) / y = Cy | (€160,000 - €10,000) / 10 years = €15,000 | Annual: €15,000 (total costs: €150,000 in ten years) |
| Annual Cost Advantage (CAy) | (tb – tc*) / y = CAy<br>* after correcting for the scrap value (€10,000 in example) | (€270,000 - €150,000) / 10 years = €12,000 | Annual Cost Advantage of €12,000 |
| Annual Return on Investment (ROI) | Cy / CAy = ROIy | €12,000 / €15,000 = 0.8 = 80% | The average annual Return on Investment is 80% |
| Present Value (PV) | tb / (1 + I)² = PV | €270,000 / (1 + 0.04)² = €249,630 | Present Value of €249,630 |
| Net Present Value (NPV) | PV – tc* = NPV<br>* after correcting for the scrap value (€10,000 in example) | €249,630 – €150,000 = €99,630 | Net Present Value of €99,630 |
| Cost-benefit ratio (CBR) | (tc* + NPV) / tc* = CBR<br>* after correcting for the scrap value (€10,000 in example) | €150,000 + €99,630 / €150,000 = 1.66 | A CBR of 1.66 |

TABLE 1

consists of three parts (table 1):

- (costs (c) – residual value (rv)) / years (y) = Annual Costs (Cy)
- (total benefits (tb) – total costs* (tc)) / years (y) = Annual Cost Advantage (CAy)
- Annual Costs (Cy) / Annual Cost Advantage (CAy) = Annual Return on Investment (ROIy)

*after correcting for the scrap value (€10.000 in example)

## Net Present Value

This method is even more accurate because different flows of costs and benefits during all periods of the equipment lifespan are taken into account. It also includes inflation. This method is more complex than previously mentioned methods. Firstly, the Present Value (PV) must be calculated (Table 1). Subsequently, the Net Present Value (NPV) can be calculated (Table 1).

- total benefits (tb) / (1 + Interest (I)2 = Present Value (PV)
- Present Value (PV) – total costs* (tc) = Net Present Value (NPV)

*after correcting for the scrap value (€10,000 in example)

## Cost-Benefit Ratio

The Cost-Benefit Ratio (CBR) takes the size of the financial investment into account. After all, it is possible that Net Present Value (NPV) is equal for two concurring projects, while there can be a huge difference in project costs. The Cost-Benefit Ratio is calculated as follows:

- (total costs* (tc) + Netto Present Value (NPV)) / total costs* (tc) = Cost-Benefit Ratio (CBR)

*after correcting for the scrap value (€10,000 in this example)

Table 1 provides an overview of the relevant calculations to financially justify the purchase of a condition monitoring system. Note that all numbers are fictitious and are used purely for illustration. An overview of the abbreviations in the formulas are explained in the table below (Table 2). ■

| Abbreviation | Meaning |
|---|---|
| C | Costs |
| tc | total costs |
| s | saving |
| rv | residual value |
| y | years |
| tb | total benefit |
| I | Interest |
| P | Payback period |
| RR | Rate of Return |
| Cy | Annual costs |
| CAy | Annual cost advantage |
| ROI | Return on investment |
| PV | Present value |
| NPV | Net present value |
| CBR | Cost-benefit ratio |

TABLE 2

# Expert considerations on automated analysis

**In recent years, the application of condition monitoring and predictive maintenance has been growing significantly, due to increasing demands for machine availability and overall efficiency. Technological developments like big data, smart algorithms, cloud and wireless find their way to the market, boost the possibilities for automated analysis and create opportunities to reshape the process of monitoring and analysing.**

## Expertise on demand

In our view, the main opportunity of these developments is to improve efficiency and effectiveness of condition monitoring. Using automated data processing to provide a first-line analysis, without the need for local expertise, can be a game changer. Wireless sensors and connected monitoring systems can reduce the infrastructural impact and initial investments for monitoring systems. Shared data can improve the algorithms for automated analysis and offers opportunities for remote support. These technologies increase the overall effectiveness and value of condition monitoring systems and structures, and change service models to *expertise on demand*.

## Considerations

Despite the opportunities with these new technologies, the right considerations have to be made.

> *"As analysis and decision making are transferred to automated systems and remote experts, local engineers will become less involved with the machinery."*

### 1. Validation of data

The input is key for any automated or remote analysis, as they solely rely on the information provided by these inputs. Therefore the data input must be validated, including:

- Selecting the right sensor for the application
- Sensor calibration
- Signal to noise ratio

In addition, the accuracy of the data must be verified. The presented data needs to be relevant and accurate to get to a working predictive maintenance structure. Low accuracy data cannot be used for monitoring. In light of data accuracy, it is very hard to handle (exceptional) environmental influences, like changes in the environment, exceptional process conditions or human error. E.g. vibration caused by another machine (cross vibration), could trigger the automated system to generate a false alarm.

### 2. Logistics and maintenance

To collect relevant data, the measurement and data stream must be guaranteed. Proper maintenance and logistics must be in place and include:

- Preventing cross-wiring of sensors
- Preventing false placement/location of sensors
- Relevant data collection interval
- Availability of spare sensors
- Sensor battery management and replacement strategy
- Stable, secure and reliable network connections

### 3. Local expertise

As analysis and decision making are transferred to automated systems and remote experts, local engineers will become less involved with the machinery. As a result, a growing dependency on external experts for analysis and support arises.

### 4. Security and privacy

By connecting sensors and monitoring hardware to the internet, cyber security becomes a risk and new guidelines regarding storage and handling of data, like ISO 27001, become applicable. The vulnerabilities and regulations increase the complexity of the implementation of a connected system. ■

*"The application of vibration measurements on complex machinery is more of an art than a science."*

**Istec International B.V.**

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