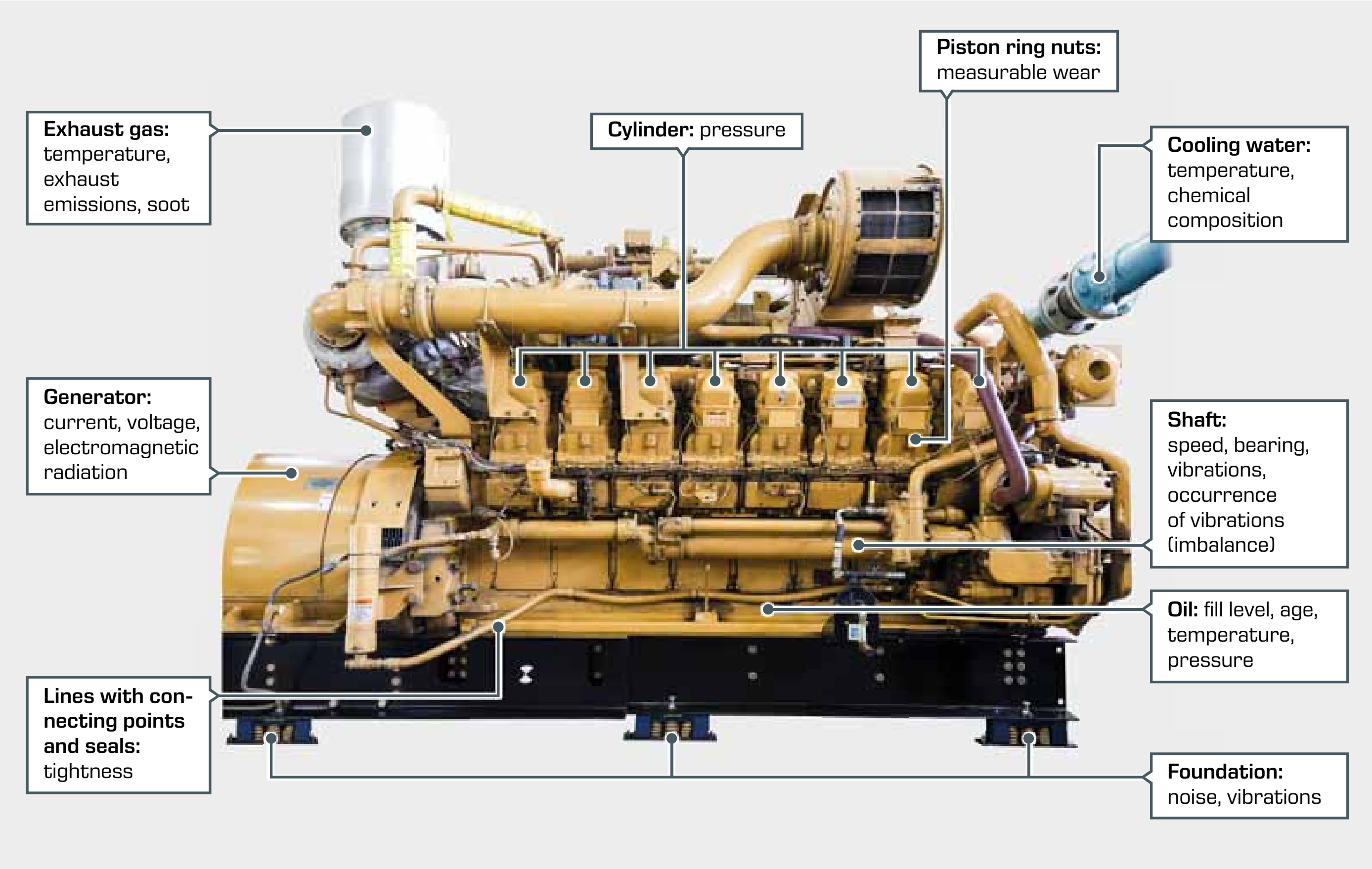
Machinery diagnosis

The aim of machinery diagnosis, also known as machinery status monitoring or condition monitoring system (CMS), is to conduct needs-based maintenance or repair and therefore to minimise the repair and downtimes of a machine. Damage should be detected when it occurs. This increases the overall equipment effectiveness (OEE), a measure of the added value of a plant, and optimises the cost structure.

What characterises the condition of a machine? The following are some measurable state variables using the example of a diesel generator:



Machinery diagnosis is used for

- weak-point analysis to optimise a process or to detect expected errors in good time
- condition-based maintenance, e.g. the use of car tyres when these fail to meet the prescribed minimum tread depth
- avoid or minimise failures thanks to pre-determined maintenance, e.g. oil change in motor vehicle at a fixed interval or after a certain mileage

Machinery diagnosis leads to

- increased and optimum use of the lifecycle of plant and machinery
- improved operational safety
- increased plant reliability
- optimised operating processes
- reduced disturbances
- reduced costs

Machinery diagnosis is conducted on

machines at standstill by:

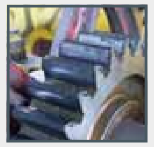
- disassembly and visual inspection
- wear measurement
- crack testing (X-rays, ultrasound, magnetic penetration, natural frequency measurement)

running machines by:

- measuring the state variables, e.g. vibration measurement
- acoustic measurement
- extension of the shaft
- lubricant analysis

The significance of vibrations in machinery diagnosis

The mechanical condition of a machine or its parts can be assessed by the nature and extent of the vibrations produced. To do this, vibrations are recorded and analysed by sensors and measuring instruments. The correct interpretation of the measuring signals requires a good understanding of the operating mechanisms and a certain amount of experience.

Causes of vibration	Examples from practice for remedy
1. Circumferential or periodic forces from ■ pressing or punching ■ jamming, alignment errors	 Elastic vibration-damping mount of the machine to prevent/minimise propagation of the vibration.
2. Inertial forces due to rotating and oscillating masses ■ reciprocating pistons ■ rotating imbalances	 Tyres are balanced to correct imbalances.
3. Plungers ■ play in the contact points and thereby changing contact surfaces in positive force transmission ■ contact loss in the case of non-positive force transmission ■ rolling over faults in the surface	 Preloaded bearings make it possible to align the shaft precisely, increase the rigidity and reduce the bearing clearance.  Good lubrication must be provided to minimise damage to the gears and to prevent the occurrence of fault points in the surface.
4. Gas forces ■ expansion due to the build up of dynamic gas forces and excitation of longitudinal and bending vibrations ■ non-uniform rotation and excitation of torsional vibrations	 Forces occur in the crankcase from the transmission of gas forces from the cylinder head to the crankshaft bearing. Stiffened crankcase and expanding screws avoid vibrations and fatigue in the material.
5. Flow forces ■ surfaces are excited by turbulence, with associated pressure fluctuations in the form of positive surge waves (howling, noise, whistling); this is the opposite of sound radiation ■ periodic flow forces on blades	 When designing rotors, such as those for fans and compressors, the number and shape of the rotors must be taken into account relation to of the possible occurrence of vibrations.
6. Electromagnetic forces ■ dynamic magnetic fields or cyclical changes in the geometry (pole faces) ■ similarity to excitation via pressure fluctuations (transformer hum, stator vibrations in engines)	 Asynchronous motor: In an asymmetrical air gap, the circulating magnetic forces cause torsional and bending vibrations. By varying the air gap between stator and rotor, it is possible to change the mechanical vibrations that are produced.

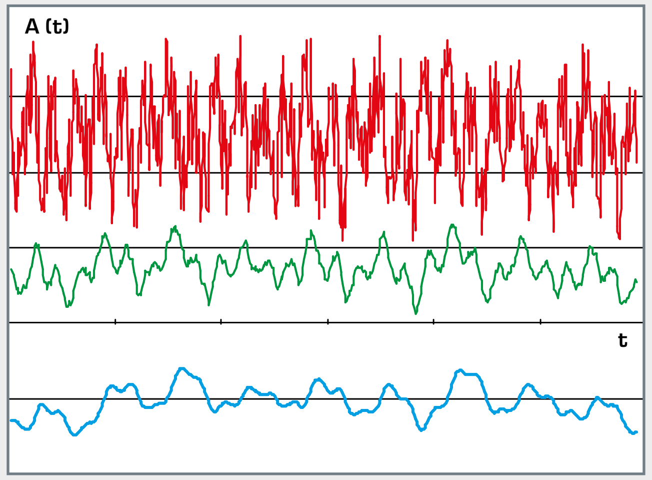
Machinery diagnosis

Methods of machinery diagnosis

Internal forces and **energies** of the machine are of real interest for machine diagnostics. These variables cannot be measured directly, but their effects – **vibration** – can. Vibration measurement and analysis allows a picture of these forces to be obtained. We can see the structure of the forces, their causes and their behaviour over time from the vibration measurements. The measuring signals are mostly frequency spectra, which arise from superposition of various vibrations with different frequencies. Some of these vibrations are part of the proper normal operation of the machine, others are amplified or produced by defects. By interpreting the measuring signals, we can assess the condition of the machine and identify defects.

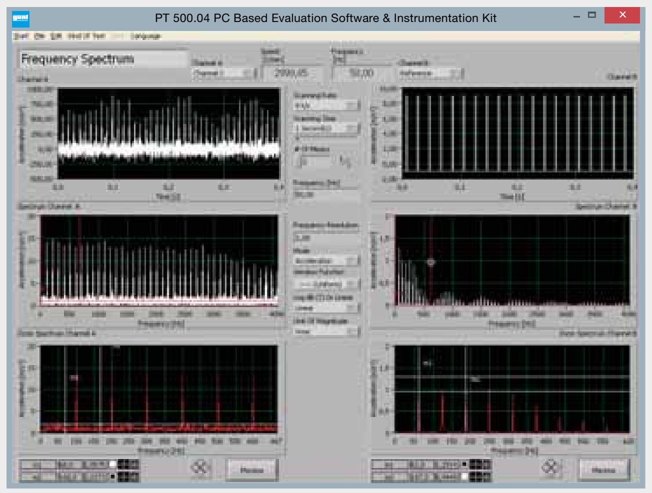
In machinery diagnosis we differentiate between **characteristic-value monitoring** and **frequency analysis.**

In **characteristic-value monitoring,** the amplitude of the measured vibration signal is compared to a limit value. Characteristic-value monitoring can be performed continuously and automatically. It is easy to implement and its use requires relatively little expertise. One widely applied characteristic value is the effective value of the velocity of the vibration in the frequency range of 10 – 1000 Hz. This is used in the DIN ISO 10816-3 standard, that relates to drive systems. In simple standard units, characteristic-value monitoring is sufficient for diagnostics. In more complex systems, the reliability of this method is sometimes not sufficient.



Typical vibration signals in the time domain

- Acceleration
- Velocity
- Path



The use of the **analysis in the frequency domain** is considerably more complex but also more powerful. The analysis makes it possible to identify the nature of damage. Consequently, repair measures can be implemented effectively. Frequency analysis requires a good understanding of the mechanisms of action and sufficient experience in interpreting the results. Usually, frequency analysis is used as a complementary method in conjunction with characteristic-value monitoring.

Learning objectives

Mechanical vibrations	Causes, mechanisms of occurrence, imbalance, Laval rotor, resonance, damping, shock
Vibration measuring methods	Measuring sensor, measuring amplifier, representation, oscilloscope, speed measurement
Vibration analysis	Acceleration, vibration velocity, vibration path, characteristics, representation in time and frequency domain, spectrum, FFT (Fast Fourier Transformation), orders, tracking analysis, envelope analysis, orbit, trajectory
Machinery diagnosis	Bearing and shaft vibrations, permissible vibration levels, roller bearing damage, electromagnetic vibrations, imbalance vibrations and balancing, gear damage, vibrations on belt drives, cavitation in pumps, blade oscillations, vibrations and shocks in crank mechanisms, speed-dependent vibrations

Furthermore, practical skills and experience are taught for dealing with and assembling machine elements such as bearings, shafts and couplings. The structure of mechanical machines can also be studied.

Questions provide valuable experience for future industrial practice:

- Which sensor should I use?
- Where can I expect a usable measuring signal?
- How do I remove interference effectively?

Damage on drive elements using the example of bearings

Indicators of damage to drive elements include:

- deposits on the running surfaces, e.g. fretting corrosion in the bore of an inner ring
- corrosion due to moisture and bearing standstill
- surface distress in the form of pitting
- bearing damage caused by slip
- cracks or fractures

If the first signs of damage to the machine are ignored, the damage increases and can lead to fracture.

Machinery diagnosis

Typical experimental results in machine diagnosis

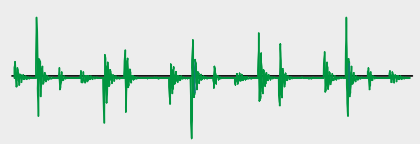
1. Identification of bearing damage

Envelope analysis

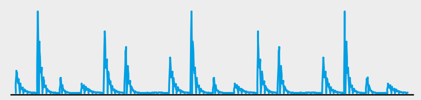
Envelope analysis is used to identify, for example, damage to roller bearings and gears. The damage produces shocks with very-high-frequency vibration components. The low shock frequency that is relevant for diagnosing damage can be identified in a normal spectrum only with difficulty, or may even be impossible to identify. Envelope analysis demodulates the high-frequency shock signal and allows the shock frequency to be measured.

Process of envelope analysis

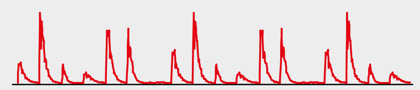
Measurement of high-frequency shock signal and high-pass filtering to suppress low-frequency interference (imbalance, alignment errors)



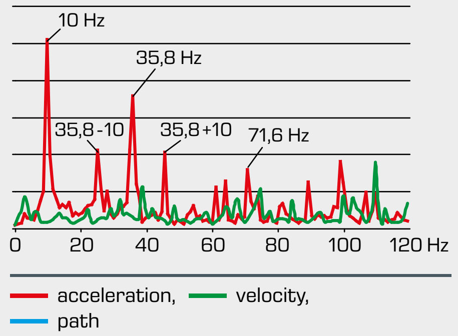
Rectification of the high-frequency signal

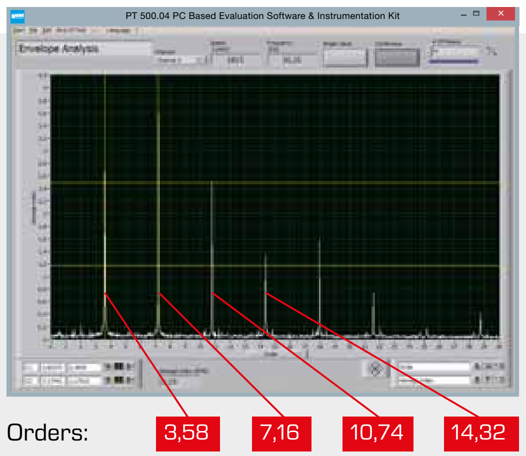


Envelope of the rectified signal by low-pass filtering



Conduct FFT to obtain spectrum of the envelope. The speed (10 Hz) and the shock frequency (35,8 Hz) can be seen clearly.
The sidebands spaced at the speed (35,8 -10, 35,8 +10) indicate an amplitude modulation. This is evidence of damage to the outer ring with rotating load.



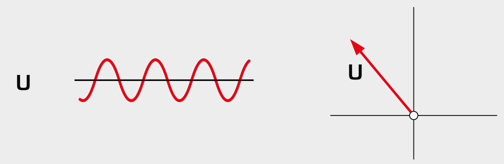


The illustration shows the envelope spectrum of typical bearing damage. To obtain a display that is independent of rotation frequency, the order was chosen as the abscissa. A rotational frequency signal is of the first order. Frequency lines are read in multiple of the order 3,58. This indicates damage to the outer ring of the bearing. The absence of first-order sidebands indicates a constant force direction, i.e. belt tension in this case, and no rotating imbalanced load.

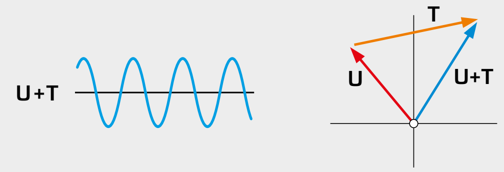
2. Field balancing

In balancing we try to bring the centre of gravity of the rotor back in line with the axis of rotation. To do this, weights are added to or removed from the rotor. In order to determine the position and size of the required balancing masses, it is first necessary to determine the unknown imbalance. Since the imbalance cannot be measured directly, it must be determined indirectly from the measurable bearing vibrations.

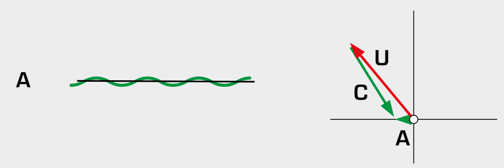
Measurement of the bearing vibrations of the out-of-balance machine (original imbalance **U**).



Measurement of bearing vibrations according to which known imbalance was added to the machine (test imbalance **T**).
It is possible to calculate the original imbalance by comparing of the two measurements.



Calculation of the size and position of the balancing masses **(C)** to be added or removed. Control measurement **(A)** after performing mass correction. Depending on the success of balancing, this procedure is repeated until the desired limit value of the bearing vibration is met.



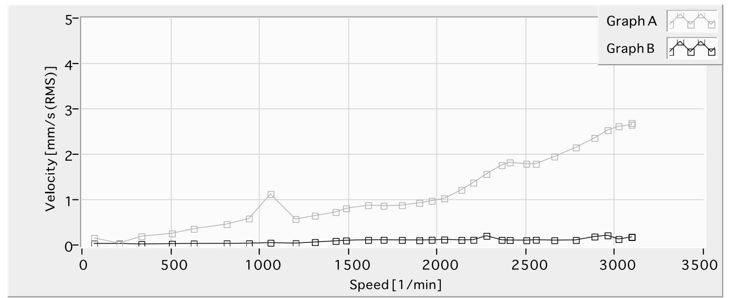
3. Identification of cracks in shafts

Shafts with cracks produce a characteristic vibration signal that can be used to identify the crack. One analysis method is **tracking analysis,** in which the vibration signal is recorded over a large speed range and studied in a special filter for different orders of rotation-frequency.

Graph A shows the component of the first-order bearing vibration (1Ω), graph B shows the component of the second order (2Ω).

Condition without crack:

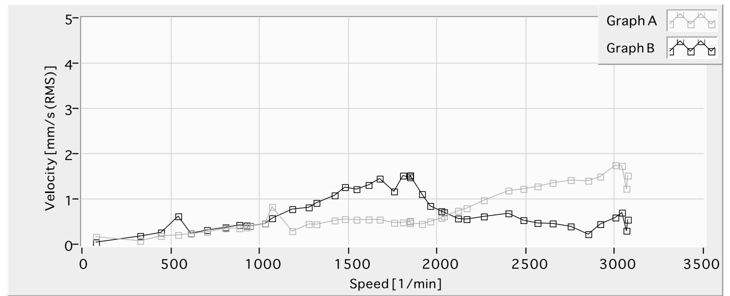
The first-order bearing vibrations increase normally with speed because of the imbalance. The second-order bearing vibrations are very small.



Tracking analysis shaft without crack

Condition with deep crack:

Whereas the first-order bearing vibrations show behaviour similar to a shaft without a crack, there is a very sharp rise in the second-order vibrations in the medium speed range, which is a strong indication of a crack.



Tracking analysis shaft with crack