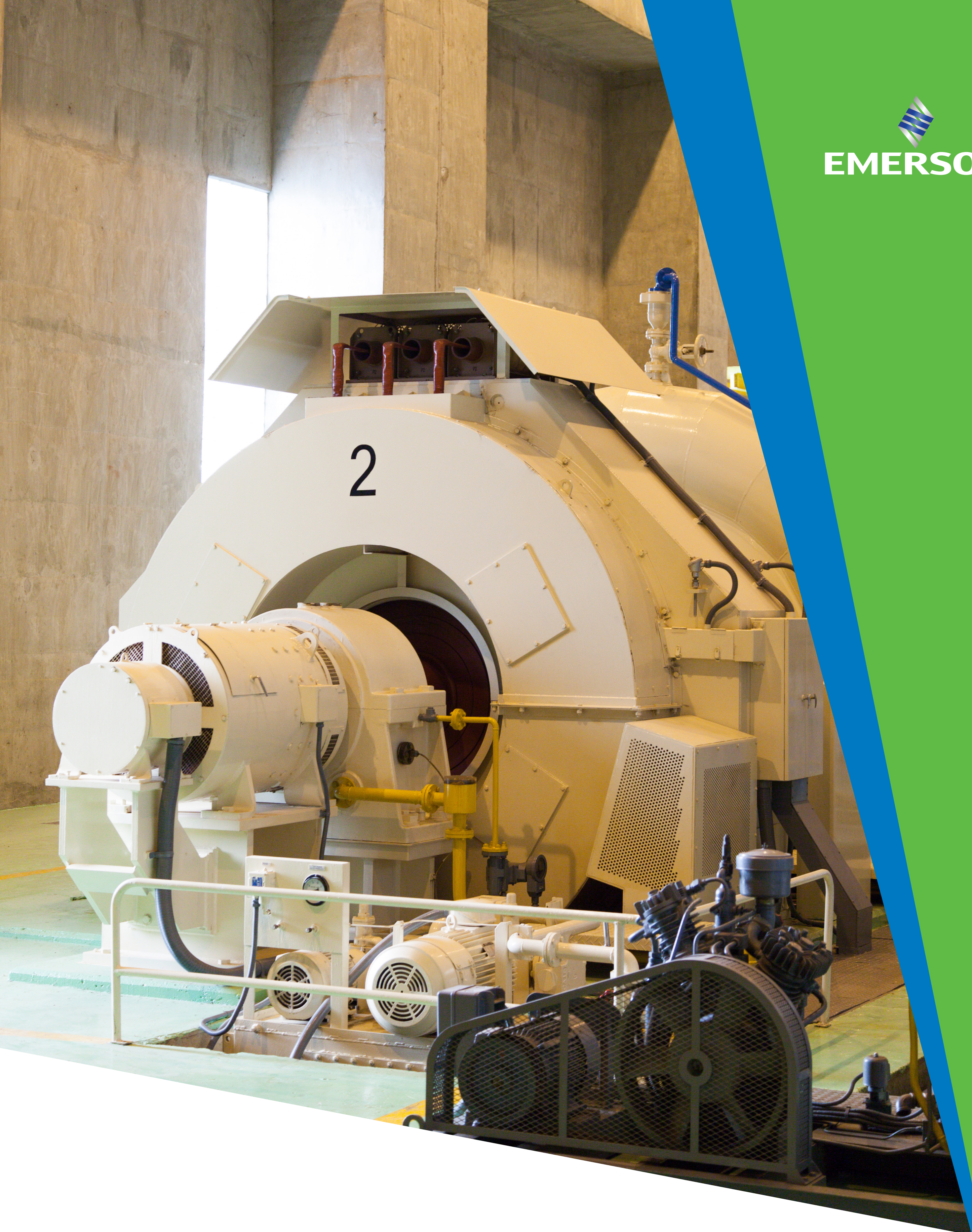



# MEASUREMENT TYPES

Online Machinery Monitoring

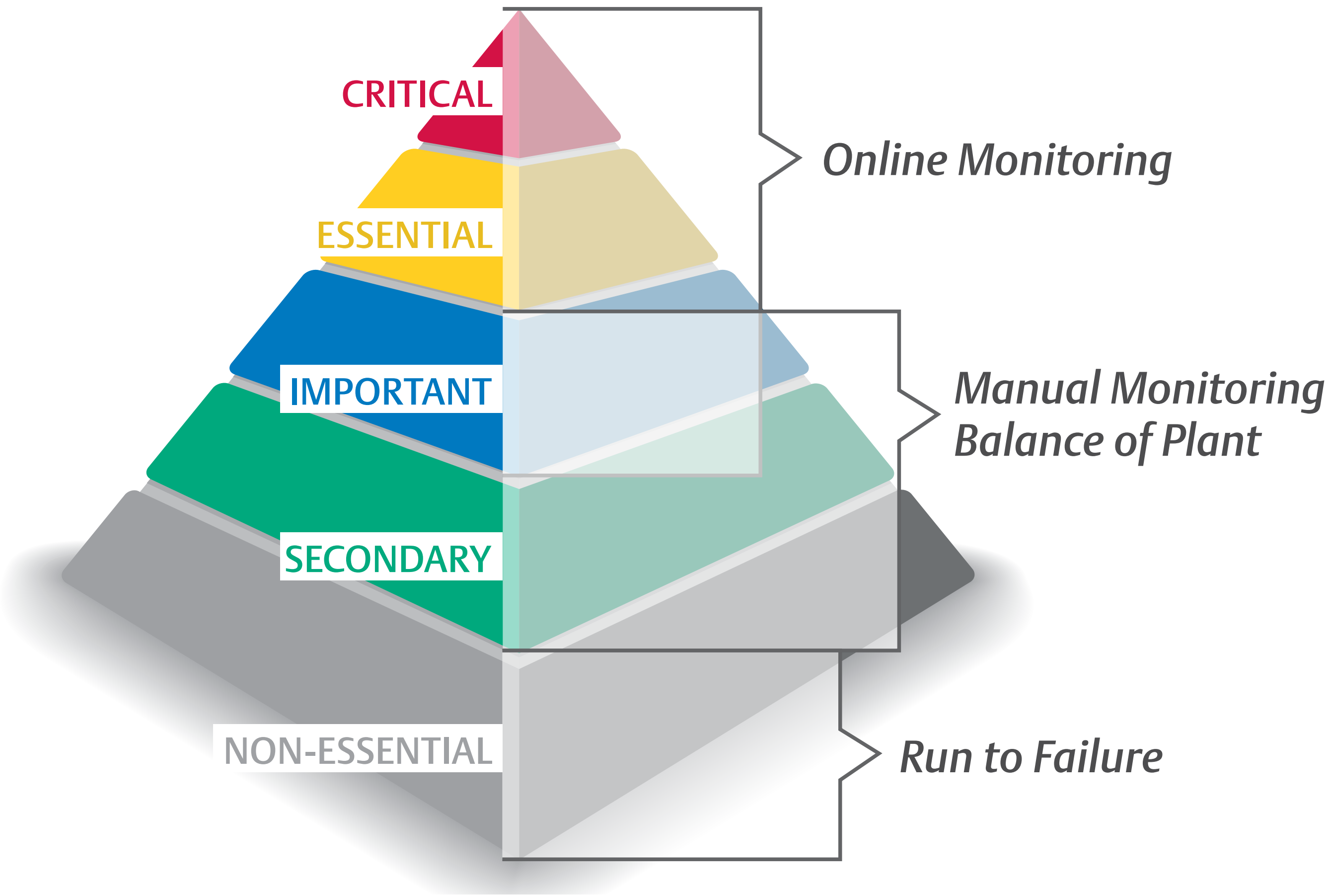
## Measurement Types

Online machinery monitoring for rotating equipment is typically divided into two categories: protection monitoring and prediction monitoring. The measurement types for protection monitoring somewhat overlap with those used for prediction, but there are many differences. The decision between whether protection monitoring or prediction monitoring is applied to a rotating asset depends on the criticality of the asset and the maintenance philosophy of the company that runs the asset. In general, rotating assets can be thought of in terms of their criticality to keep the process running and productive.

The asset pyramid shows the typical criticality distribution of rotating assets in any plant. Usually only the critical, essential, and more expensive important assets are considered for online monitoring. In addition to criticality, the type of component measured is another important factor in determining measurement type. For example, rotating assets have two general classes of bearings:

**Antifriction bearings** are roller or ball mechanical bearings. The components of these mechanical bearings rotate in contact with teach other and the shaft. They undergo stress and break down over time. There are well established methods to determine the health of antifriction bearings using the following measurements types: acceleration (absolute vibration), velocity (absolute vibration), or rotation (speed and phase).

**Fluid film sleeve bearings** support the rotating shaft on a wedge of oil. The bearing does not have any mechanical parts that rotate along with the shaft, so there are no parts to wear out. With respect to a sleeve bearing, it is important to know the position of the shaft relative to the bearing inner surface to ensure there is a good oil wedge for the shaft to run smoothly upon. Sleeve bearings use these measurement types to determine their condition: Displacement (position), Displacement (vibration), acceleration (absolute vibration) and rotation (speed and phase).



Most likely measurement types used on any bearings and nonbearing part of rotating assets (and their most commonly used sensor) are:

1. Acceleration (absolute vibration) – Piezoelectric-based accelerometer.
2. Velocity (absolute vibration) – Piezoelectric-based or electrodynamic-based accelerometers.
3. Displacement (position) – Eddy current or LVDT (Linear Variable Differential Transformer) sensors.
4. Displacement (vibration) – eddy current sensor.
5. Rotation (speed and phase) – eddy current or hall effect sensors with phase targets, or an optical sensor with optical target.
6. Rotation (acceleration) – eddy current sensor with gear target.
7. Rotation (direction) – dual-eddy current sensor with gear target.
8. Temperature (simple surface or infrared) – surface temp sensors in tandem with an accelerometer. Infrared sensors are not typically used with online systems.
9. Pressure (static and/or dynamic) – static/dynamic pressure or dynamic pressure sensors.
10. Sound (ultrasonic and acoustic emissions) – Ultrasound detectors are not typically used with online systems.

The most frequently used for online monitoring are measurement types one through seven and sometimes eight (surface temperature only). In some processes that have fluid flow, dynamic pressure pulsations analysis helps in understanding the process assets.

## Protection Type Measurements

Not all assets require or have all these measurement types. In the case of critical assets such as large steam turbines, guidelines such as the API 670 specification are considered the standard for fulfilling the correct protection for those assets.

- Shaft Vibration *(relative)*
- Shaft Vibration *(absolute)*
- Bearing Vibration *(relates to prediction monitoring)*
- Position Measurement
- Eccentricity
- Phase *(reference pulse, relates to prediction monitoring)*
- Differential Expansion
- Valve Position
- Speed Measurement *(acceleration, direction, and more)*
- Axial Position Protection
- Process Variables

## Shaft Vibration (relative)

This measurement type is always done on a fluid film sleeve bearing and is supplied using eddy current sensor technology. For each monitored bearing there will be either one or two eddy current sensors mounted radially. If there is just one eddy current sensor per bearing, it will usually be located exact top center on the bearing (Figure 3 and Figure 4). If two eddy current sensors are used, they are usually mounted 90° apart at the 10:30 and 1:30 clock positions on the bearing (Figures 5 - 7). When using the two-sensor dual-channel mode, the orbit of the shaft can be recorded (Figure 2).

Eddy current sensors require converters to power them and to convert their output to the correct scaled voltage data per displacement unit, typically mV/micron or mv/mil. An eddy current sensor with its cable and converter all together form a chain and should be calibrated together to ensure the highest accuracy displacement measurement. The eddy current sensor chain output is always measured in terms of displacement as shown in Figure 4 through Figure 7.

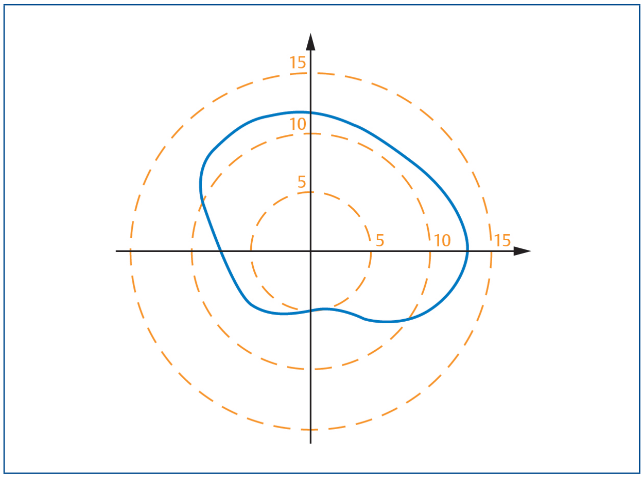



***Figure 2:*** *Shaft Orbit: the path of a shaft rotation.*

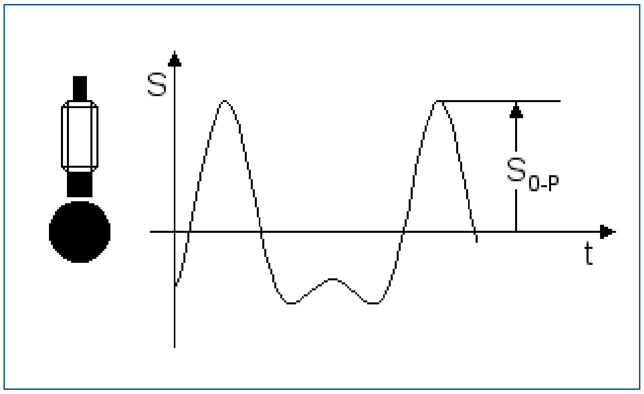



***Figure 3:*** *Shaft vibration So-p: 0 to Peak Displacement.*

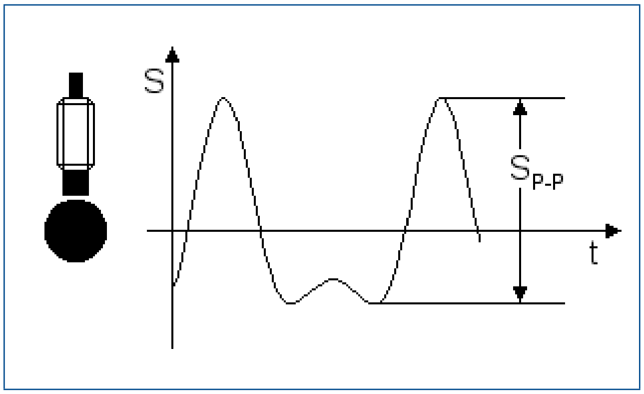



***Figure 4:*** *Shaft vibration Sp-p: Peak to Peak Displacement.*

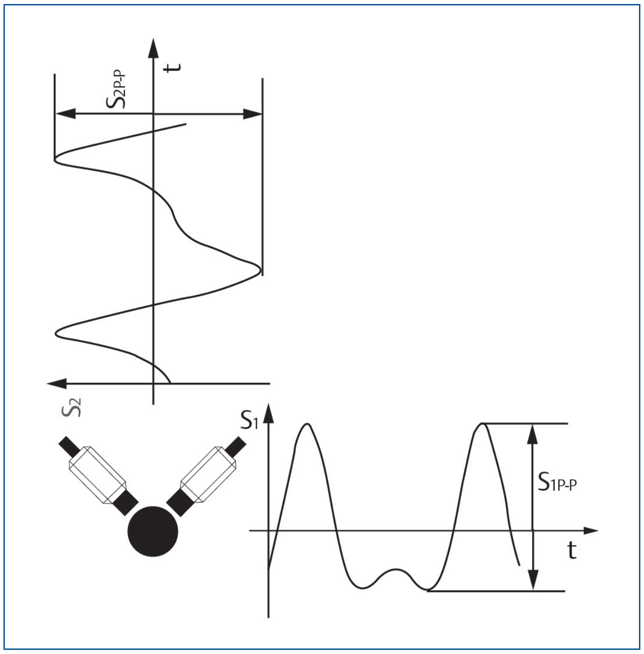



***Figure 5:*** *Shaft vibration Sp-p: Peak to Peak Displacement according to API 670: Dual-channel peak-peak displacement measurement. The maximum of the two channels is reported as Sp-p max.*

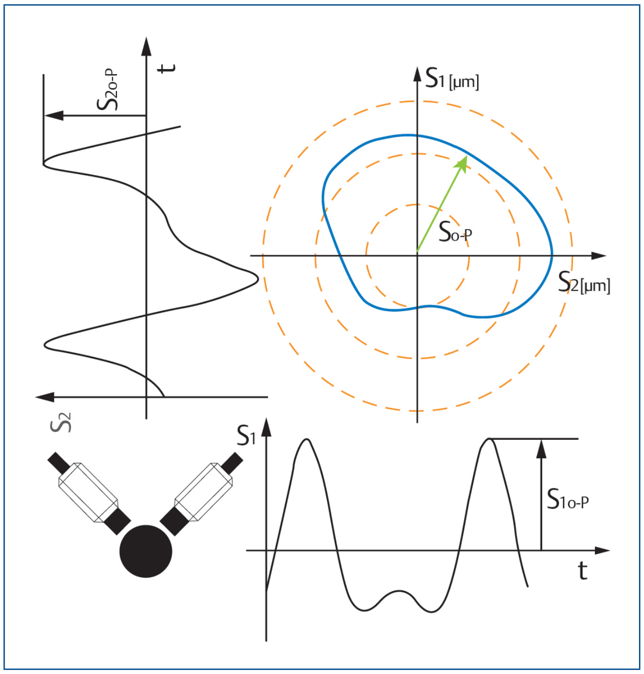



***Figure 6:*** *Shaft vibration So-p max: 0 to Peak Maximum Displacement according to VDI 2059. Two channel measurement of the 0 to Peak Displacement. The S1 and S2 outputs are vector summed to produce a new time series called an "orbit," which is equal to one shaft rotation. The maximum value of the new time is Smax.*

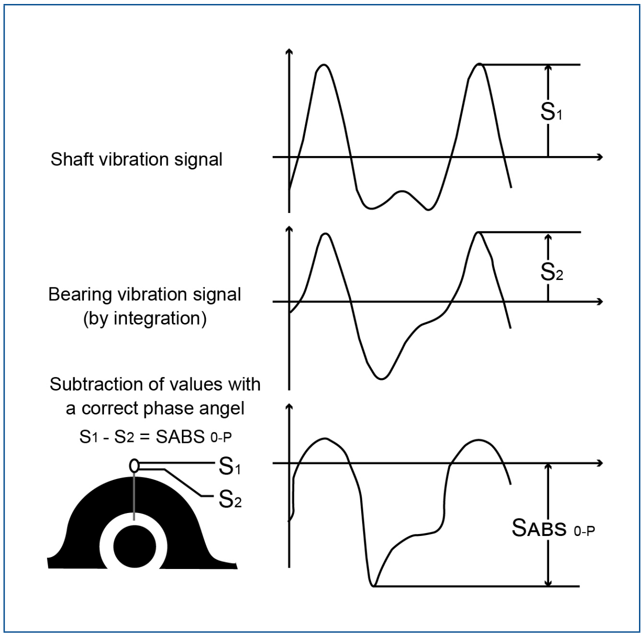



***Figure 7:*** *Shaft vibration in Sp-p max: Peak to Peak Displacement according to DIN 45670. Two channel measurement of the peak-peak displacement. A maximum value selection of the two measurements is the result.*

## Shaft Vibration (absolute)

This measurement type is always done on a fluid film sleeve bearing. With absolute shaft vibration, the relative shaft vibration is measured using an eddy current sensor as detailed in the prior section, and the absolute bearing housing vibration is measured using an accelerometer or velocity sensor along the same axis as the eddy current sensor. Subtracting the relative vibration from the correct phase of the absolute vibration results in the absolute shaft vibration of the shaft in space. The evaluation of the measurement is done as So-p (displacement 0 to peak) or Sp-p (displacement peak to peak), as shown in Figure 8 and Figure 9.

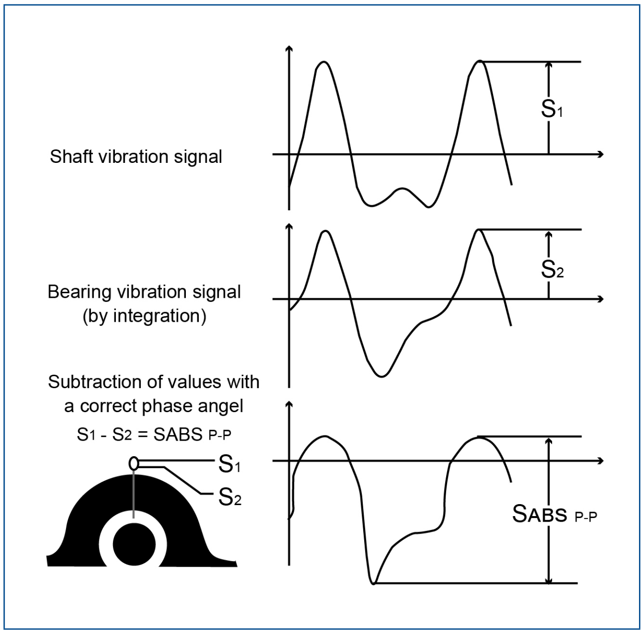



***Figure 8:*** *Shaft Orbit: the path of a shaft rotation.*

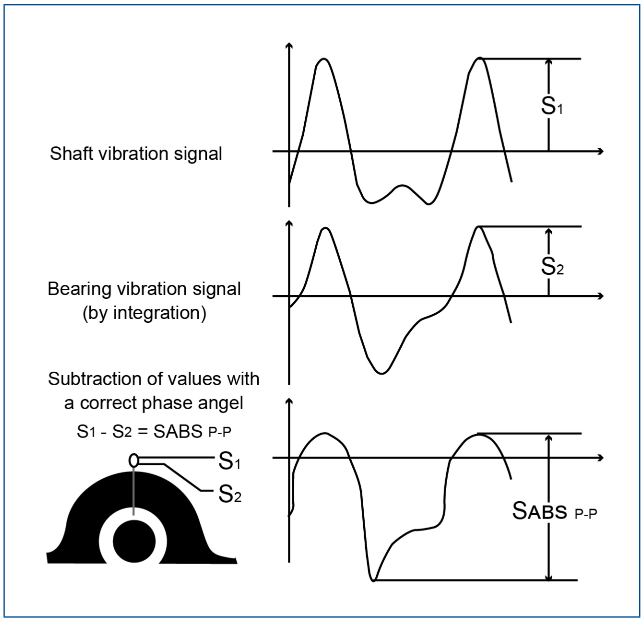



***Figure 9:*** *Absolute shaft vibration Sp-p: Peak to Peak Displacement.*

## Bearing Vibration

Bearing vibration readings are taken on both antifriction bearings and fluid film sleeve bearings. To measure the bearing or machine case overall absolute vibration, the following measurement technologies are usually employed:

1. Accelerometer *(piezoelectric-based)*
2. Velocity sensor *(piezoelectric-based)*
3. Velocity sensor *(seismic, electrodynamic-based)*

These sensors are all surface mounted on the bearing or machine case and will report all the vibration (absolute) that they detect in their perpendicular axis to the mounting surface.

4. Displacement *(position)*
5. Displacement *(vibration)*

### Accelerometer (piezoelectric-based)

Almost all modern accelerometers used for vibration measruements are piezoelectric. They have quartz or most often ceramic crystal measurement elements and special circuitry inside that change vibration motion into a voltage ouput. Interestingly, the power that is supplied to the acceolerometer is the carrier of the voltage signal ouput of the accelerometer.

The voltage output of an accelerometer can be measured as "G's 0 to peak" or "G's peak to peak". G's can be replaced with metric (m/s2) or imperial units (in/s2). For prediction measurements expecially on antifriction bearings the accelerometer output in G's is used to determine the bearing health. One method of doing this consists of mining the time series for high frequency stress content. Emerson uses a technique called PeakVue™ technology to analyze the high frequency accelerometer time series content for mechanical dailures for its prediction analysis. For protection systems the absolute vibration signal from an accelerometer is used to analyze whether there is too much overall vibration and to supply the bearing vibration component of the absolute shaft vibration measurement (requires a phase reference from a tachometer) detailed in the prior section. To combine the accelerometer measurement with the eddy current measurement requires that the acceleration signal be double integrated to displacement.

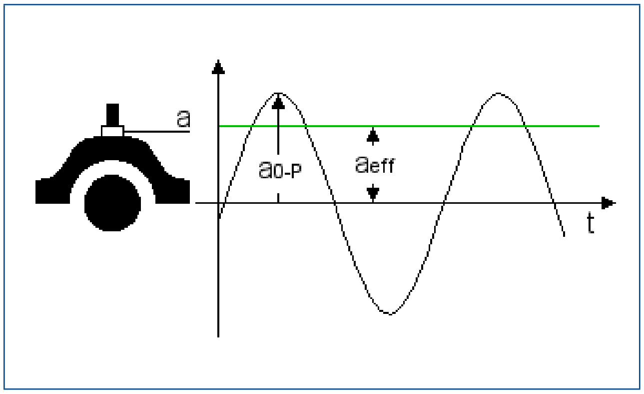



***Figure 10:*** *Bearing acceleration RMS (arms): RMS.*

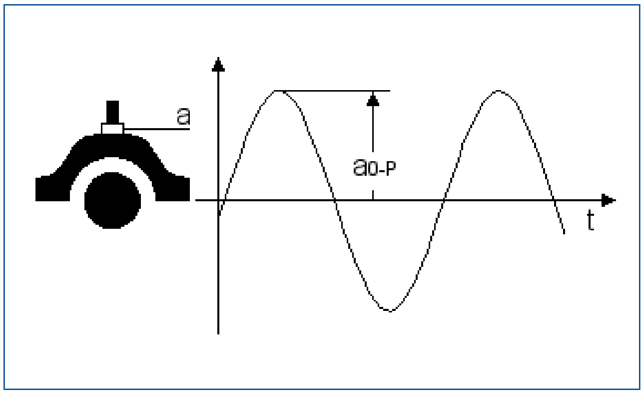



***Figure 11:*** *Bearing acceleration Peak (a0-o): 0 to Peak.*

## Velocity sensor (piezoelectric-based)

Almost all modern velocity sensors used for prediction measurements are actually piezoelectric accelerometers which have an integrating circuit built into them to convert acceleration to velocity. These velocity sensors – by the nature of the integration – will always have less freuqncy range than their accelerometer counterparts. Another factor that has to be considered when using these sensors is the integration tends to create high amplitudes at the very low frequencies such as from just above 0 to as high as approximately 3 Hz. To overcome this low-frequency integration error, these piezoelectric velocity sensors usually contain a high pass filter to eliminate the first few 2 or 3 Hertz of data.

## Velocity sensor (seismic, electrodynamic-based)

Another volicty sensor type that is mostly used with machinery protection systems is the electrodynamic velocity sensor, sometimes called a seismic sensor. This is a mechnical sensor consisting of a spring and mass. This sensor type is ideal for high-amplitude velocity measurements on bearings and the machine case; it should be used when the vibration is between 4 Hz to about 1000 Hz. Below 4 Hz the spring and mass move with the sensor body and the measurement is not usable. Mechnically, going beyond 1000 Hz is not practical. These sensors are self-powered.

## Displacement (position)

This measurement is taken by an eddy current sensor or an LVDT. Generally LVDT's are used for very large movement such as 4mm and much larger. Simpler eddy current sensors are used for small displacement measurements up to 4mm. When an eddy current sensor is used to measure position, the range of the sensor is biased in the direction of the expected displacement to maximize the range of the sensor. While the displacement can be measured in all modes (o-p, p-p, or rms), it will typically be in terms of displacement 0 to Peak (So-p).

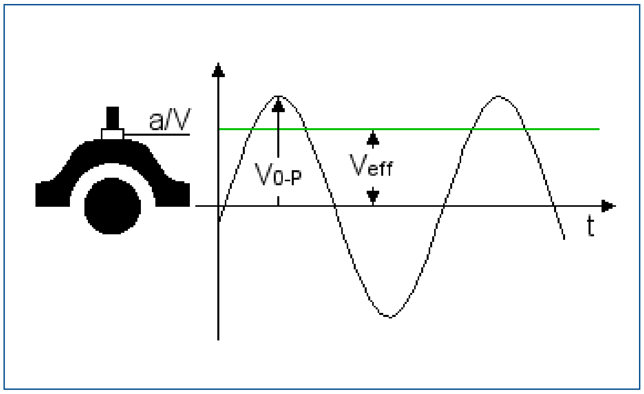



***Figure 12:*** *Bearing velocity (Vrms): RMS.*

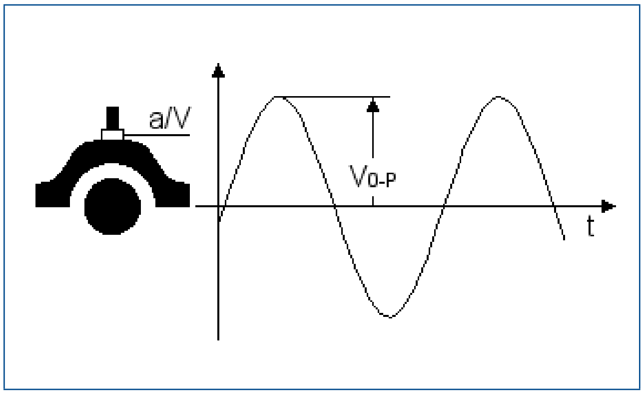



***Figure 13:*** *Bearing velocity Peak (Vo-p): 0 to Peak.*

### Displacement (vibration)

Displacement vibration on fluid flim sleeve oil bearings is measured using eddy current sensors. The vibration measurement is biased toward the mid-point of the sensors range so the vibration is usually measured in displacement Peak to Peak (Sp-p). Absolute displacement can also be measured with an accelerometer or velocity sensor by employing integration of the senors signal as detailed in the prior section. Figures 14-16 illustrate the differences between vibration 0 to Peak, Peak to Peak, and RMS levels for the same vibration signal.

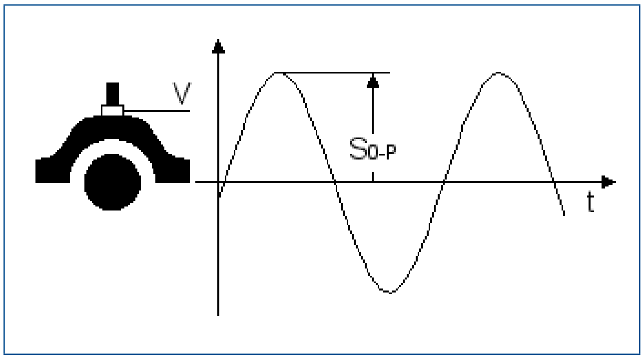



***Figure 14:*** *Bearing velocity So-p: 0 to Peak.*

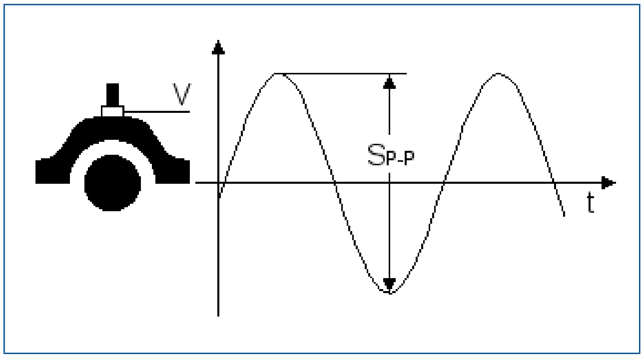



***Figure 15:*** *Bearing velocity Sp-p: Peak to Peak.*

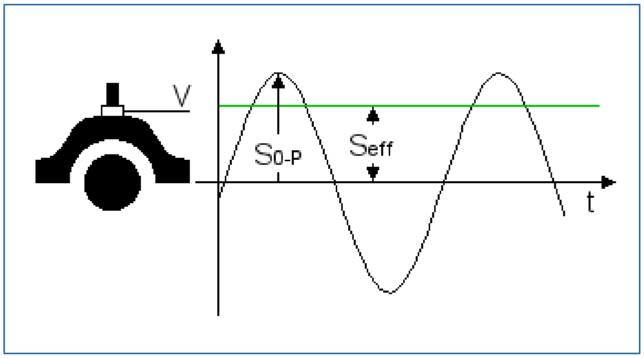



***Figure 16:*** *Bearing vibration Srms: RMS.*

## Position Measurement

Eddy current sensors are used to measure position and expansion on shafts, bearing housings, and machine cases on rotating machines.

Because of the large range in shaft and case sizes and the large possible range of movement, a range of different eddy current sensor sizes must be available to optimize the measurement. Some position measurements are single channel, and some are dual channel. Axial position measurements on shafts are typically taken to ensure the rotating assembly inside the machine case is not close to rubbing a casing seal. A seal rub can result in a catastrophic failure of the machine rotor.

**Single Channel** – the most common position measurement type is a single channel using an eddy current sensor. Eddy current sensors come in many sizes. Generally, the bigger they are, the longer their measurement range. Typical eddy current sensor position measurement ranges are from a few microns up to 4mm.

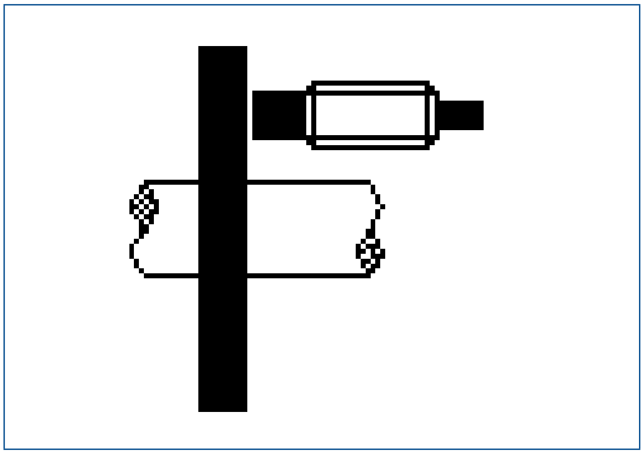


***Figure 17:*** *Single channel position measurement.*

**Dual Channel** – Using two eddy current sensors allows the measurement to be calculated as a n expansion difference (e.g., slanted movement of a bearing block) or the min or max analysis of the two measuring channels or sometimes a second sensor is a back up for the first sensor to ensure reliable measurements are being taken.

There are many custom setup configurations that employ two sensors and the geometry of the position measurement to extend the listed eddy current sensor measurement range to a much higher value than the simple addition of the two sensor ranges. Also, special eddy current sensor converter electronics can be used to extend the typical measurement ranges of the sensors by as much as three times the normal range.

The simplest tandem eddy current sensor arrangement is shown in Figure 19. This arrangement results in a near doubling of the eddy current sensor measuring range. The two eddy current sensors are placed opposite each other in either side of the reference disk. Each sensor provides half of the overall range. The actual overall measuring range should be approximately 10% smaller than the sum of the individual sensor ranges to ensure there is not dead point in the range.

Measurement ranges greatly exceeding the eddy current specified range can be realized with cone or double-cone measurements. Cones are slightly sloped transitions in shaft diameter. Depending on the eddy current sensor displacement measurement range and the cone angle, significant shaft axial movement ranges can be monitored by using a simple displacement conversion calculation.

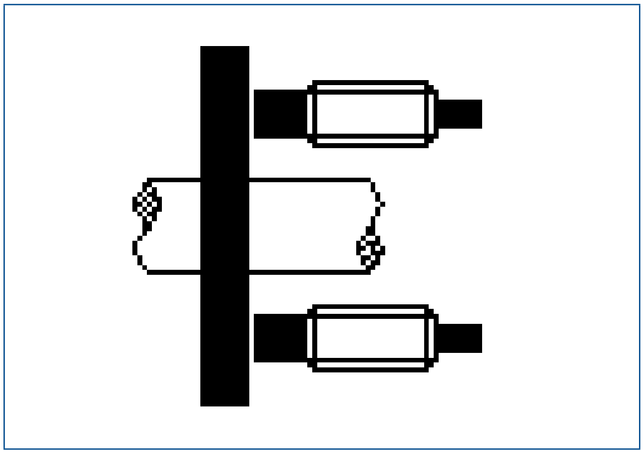


***Figure 18:*** *Two channel measurement.*

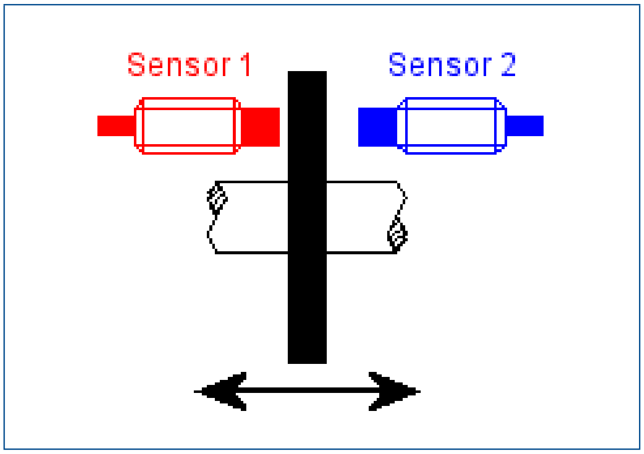



***Figure 19:*** *Tandem measurement set-up.*

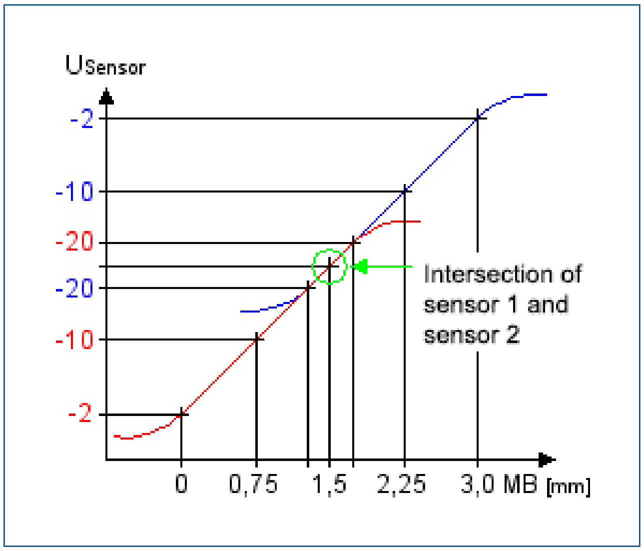



***Figure 20:*** *Tandem measurement graph.*

**Single-Cone Measurement** – Two eddy current sensors are used to measure shaft axial position using a cone. Both sensor signals are captured simultaneously.

- The signal from sensor 2 is subtracted from the sensor 1 signal to compensate for the shaft runout.
- Sensor 1 measures the shaft axial position by its change in gap measurement divided by the sin(α), (S=d/sin(α)). The small angle of the cone allows large axial measurement ranges to be reached using sensors that only have small measuring ranges.

**Double-Cone Measurement** – Two eddy current sensors are also used with a double cone measurement. The difference between this measurement type and the single cone measurement type is that both eddy current sensors are used to record the displacement. Each can be used to compensate the other to perform the same result as the single cone measurement but in this case the signals can be compared.

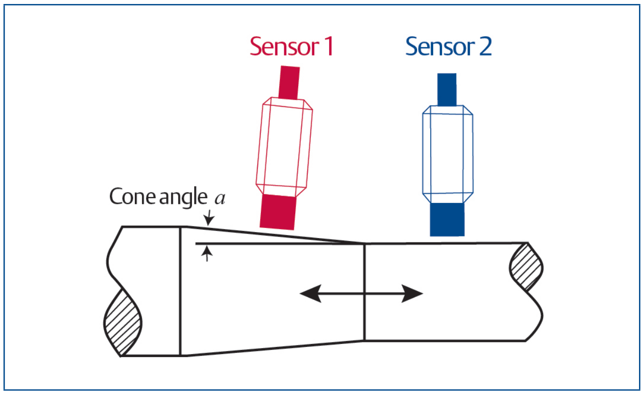



***Figure 21:*** *Single-cone measurement set up.*

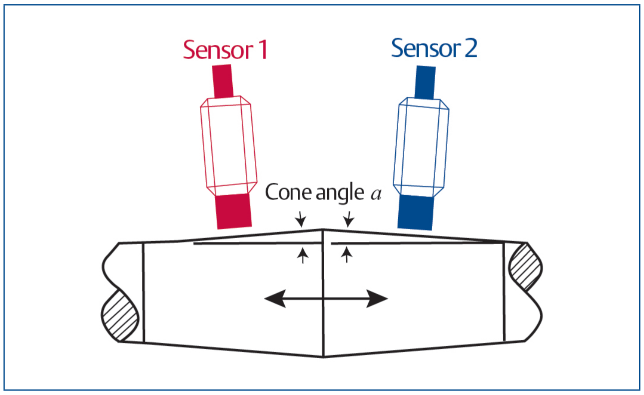



***Figure 22:*** *Double-cone measurement set up.*

**Measuring Range Calculation** – The maximum measuring range with cone measurement can be calculated according to the following formula:

S = d/sin(α) or S = d* cotan(α)

d = measuring range of the sensor

(α) = cone angle

The chart in figure 23 shows the relationship between and eddy current sensor with a +1.0mm measurement range and the cone angle.

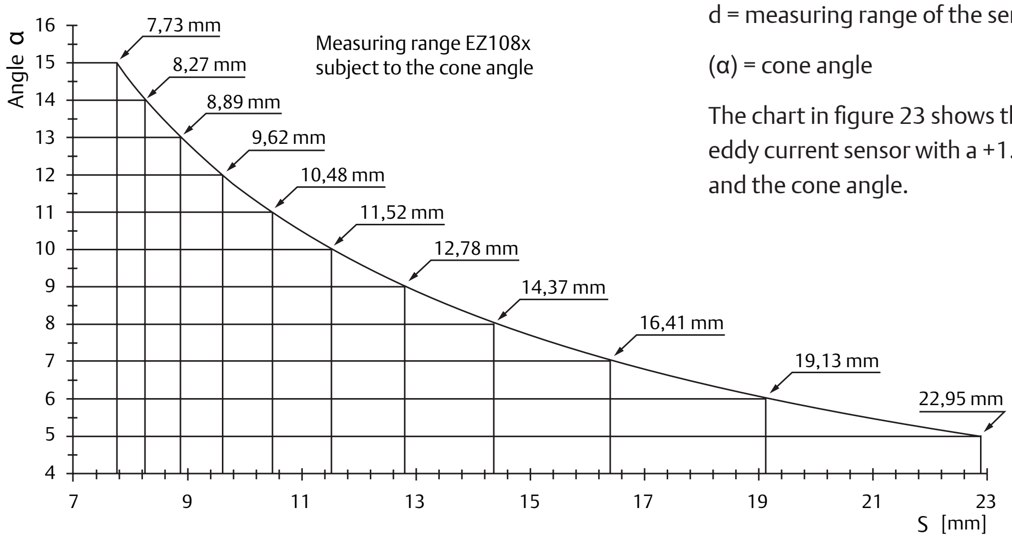



***Figure 23:*** *Axial measuring range versus cone angle.*

## Eccentricity

Shaft eccentricity is the dynamic movement of the outer shaft surface to the geometrical center of the shaft (also called residual gap). This measurement requires a tachometer phase reference to initiate the time series collection and the measurement consists of one complete shaft revolution measured with an eddy current sensor.

The signal is measured in a frequency range of 0.017 Hz (1.02 rpm) to 70 Hz (4200 rpm) using eddy current sensor data. Sp-p (Shaft Displacement Peak to Peak, Figure 24) and Smin/max (Shaft minimum/maximum, Figure 25) are typical expected analysis parameters.

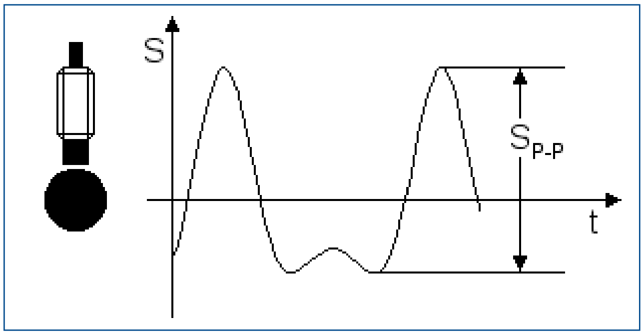



***Figure 24:*** *Analysis of the shaft eccentricity in peak-peak.*

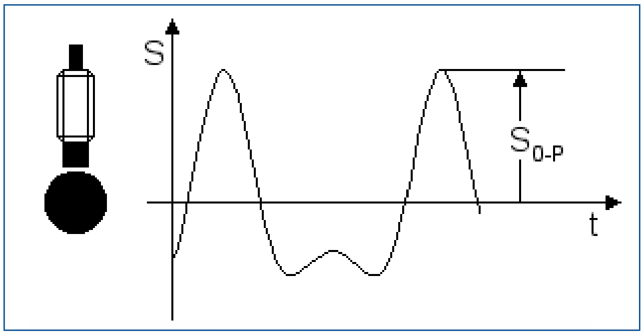



***Figure 25:*** *Analysis of the shaft eccentricity in peak-peak.*

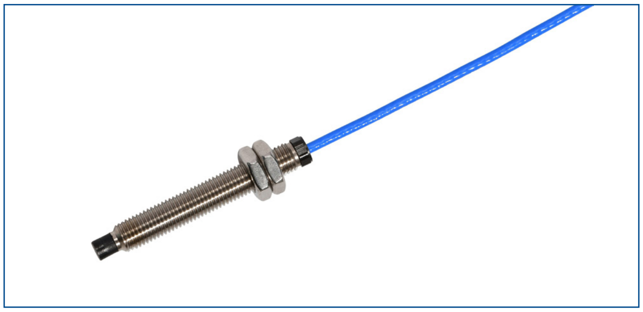
## Reference Pulse

A tachometer typically an eddy current sensor, is used to produce a pulse when a shaft keyway or some other target passes it once per shaft revolution. This tachometer timing pulse can be used to provide a phase reference point for all the vibration measurements on a machine.

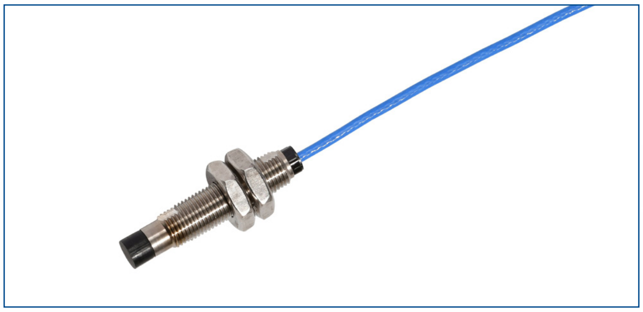
This allows phase comparisons of the multiple vibration measurements on a machine using two dimensional visuals such as each bearings XY orbit data. Since the shaft has a reference mark that the phase is based upon, the angular position of the absolute vibration data can be calculated.

A trigger wheel cannot be used with a tachometer to generate a phase reference pulse because there is no unique tooth on the trigger wheel to reference.

### Examples of reference pulse sensors and converters



*EZ105X*



*EZ1080*

## Differential Expansion

Differential expansion (relative expansion) is a measure of the change in the clearances between machine parts caused by thermal expansion or contraction. (e.g., rotor disks to turbine housing). A variety of methods to measure this effect are used but the most common method is by using eddy current sensors.

Smaller thermal expansion displacements can be treated as single or tandem eddy current sensor measurements. Larger expansions have to be handled through Tandem or Double Cone dual eddy current sensor setups.

A pre-calculation of the expected maximum expansion must be done to determine the best differential expansion measurement type setup required.

## Speed Measurement

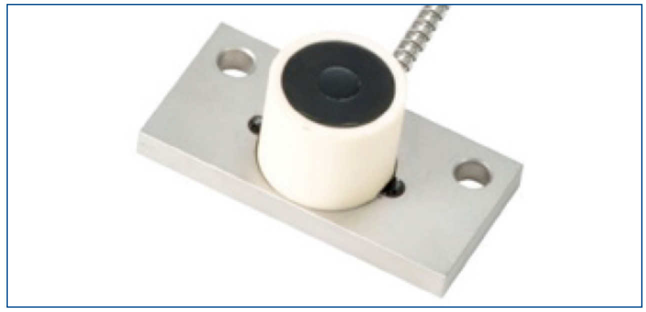
Speed measurements are usually collected by an eddy current sensor reading a pulse wheel or a gearwheel. The current speed in hertz is calculated by dividing the amount of pulses per second by the number of gear teeth on the wheel. By having many pulses per revolution it’s possible to quickly determine if the asset speed is consistent, accelerating or decelerating.

The use of two speed sensors on the same trigger wheel allows the direction of rotation to be detected and monitored.

### Example of speed measurement tachometer

*A0430L3*

### Examples of differential expansion and axial position protection sensors



*PR 6426*

*PR 6424*

*PR 6425*

## Axial Position Protection

A fluid film sleeve oil "thrust" bearing is designed to be the fixed bearing of a fixed/floating bearing pair. This bearing is expected to keep the shaft from wandering in the axial direction which will result in a catastrophic event when the clearances in a rotating machine such as a steam turbine disappear and high-speed metal to metal contact of the rotor with the housing and seals occur.

It is important to know that the thrust restraint fixing mechanism is intact. This measurement is sometimes setup as a 2 out of 3 (2oo3) measurement to ensure there is no doubt that the thrust restraint is intact and not moving axially.

## Process Variables

Because of the growing application of sophisticated and networked modern analysis and diagnostic online prediction and protection systems, it becomes increasingly easy and essential to capture process parameters and trend them along with the online prediction and protection analysis parameters to allow the visualization of potential relationships between them.

For a steam turbine the important parameters to capture and trend are the effective power and the reactive power of the turbine. In addition, temperature and steam pressures should be tracked and trended.

## Valve Position

Valves have long travel displacements and the travel amount is used to determine whether a valve is open, partially open or closed. LVDT's have the long displacement measurement capability to measure valve position.

### Example of eddy current converter


*EZ 1000*

### Example of valve position sensors


*PR 9350*



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