Introduction guide to vibration monitoring

Measurements, analysis, and terminology

Summary
This guide introduces machinery maintenance workers to condition monitoring analysis methods used to detect and analyze machine component failures. This guide does not intend to make the reader an analysis expert. It merely informs the reader about common analysis methods and lays the foundation for understanding machinery analysis concepts. Moreover, it tells the reader what is needed to perform an actual analysis on specific machinery.

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1. Introduction

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Rule 1: Know what you do and do not know!

Often, a situation arises where the answer is not contained within analysis data. At this point, "I don't know" is the best answer. A wrong diagnosis can be costly and can rapidly diminish a machinery maintenance worker's credibility. Thus, a vibration specialist is required to analyze the problem.

1.1. Detection vs. Analysis

The differences between detecting a machinery problem and analyzing the cause of a machinery problem are vast. Replacing a new bearing with one that indicates a high level of vibration may or may not be the solution to bearing failure. Usually, a secondary issue developed in the machine and is attributing to premature bearing failure. To solve the problem, you must find the attributing factor or cause of the bearing failure (i.e. misalignment, looseness, imbalance). This process is referred to as finding the *root cause* of the failure. If this important step is not followed, you simply replace the bearing without developing a condition monitoring program. It is essential to detect machinery problems early enough to plan repair actions and minimize downtime.

Once detected, a cause and effect approach must be used to take further steps toward analyzing what caused the problem. Then develop a condition monitoring based program to prevent the problem from reoccurring. There are several key components that build the foundation for the development a successful condition monitoring program. First, know and understand industry terminology.

1.2. Vibration (Amplitude vs. Frequency)

Vibration is the behavior of a machine's mechanical components as they react to internal or external forces. Since most rotating component problems are exhibited as excessive vibration, we use vibration signals as an indication of a machine's mechanical condition. Also, each mechanical problem or defect generates vibration in its own unique way. Therefore, we analyze the "type" of vibration the machine is exhibiting to identify its cause and develop appropriate repair steps.

When analyzing vibration we look at two components of the vibration signal: *frequency* and *amplitude*.

- *Frequency* is the number of times an event occurs in a given time period (the event is one vibration cycle). The frequency at which the vibration occurs indicates the type of fault. That is, certain types of faults "typically" occur at certain frequencies. By establishing the frequency at which the vibration occurs, we can develop a clearer picture as to the cause of the vibration.
- *Amplitude* is the size of the vibration signal. The amplitude of the vibration signal determines the severity of the fault - the higher the amplitude, the higher the vibration, and the bigger the

problem. Amplitude depends on the type of machine and is always relative to the vibration level of fully functioning machine!

- When measuring vibration we use certain standard measurement methods:
- Overall Vibration or Trending
- Phase
- Enveloping or Demodulation
- High Frequency Detection (HFD)
- This guide is divided into several sections. Each section explains the key topic and develops that explanation with examples that help the reader gain a clear understand. A glossary is also provided. Reference the glossary for any unfamiliar terms.

2. Overall Vibration or Trending

In condition monitoring, the most common and logical area to begin with is a trend of the overall value at which the machine is vibrating. This is referred to as trending or looking at a machine's overall vibration level.

Overall vibration is the total vibration energy measured within a specified frequency range. For example, measure the overall vibration of a rotor and compare the measurement to its normal value (norm). Then, assess any inconsistencies. A higher than normal overall vibration reading indicates that something is causing the machine or component to increase its level of vibration. The key to success is determining what that something is.

Vibration is considered the best operating parameter to judge low frequency dynamic conditions such as imbalance, misalignment, mechanical looseness, structural resonance, soft foundation, shaft bow, excessive bearing wear, or lost rotor vanes. To determine precisely which operating parameter is the contributor, we need to explain the signature of a vibration signal. There are two major components of a vibration signature: *frequency range* and *scale factors*.

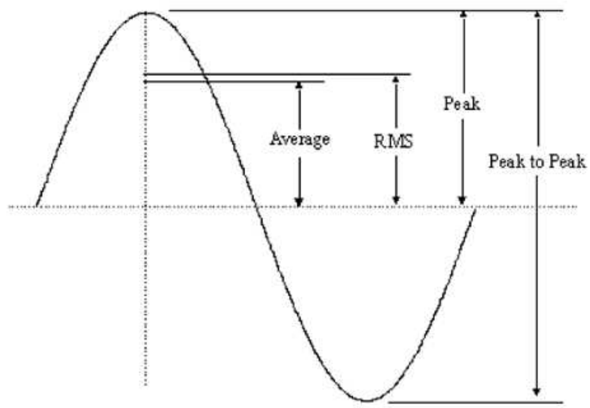
2.1. Frequency Range

Monitoring equipment determines the frequency range of the overall vibration reading. Some data collection devices have their own predefined frequency range for overall vibration measurements. Other data collectors allow the user to select the overall measurement's frequency range. Unfortunately, there is an ongoing debate regarding which frequency range best measures overall vibration (International Organization for Standardization (ISO) set a standard definition). For this reason, it is important to obtain both overall values from the same frequency range.

As an analogy, we can think of frequency range as a bucket or pail. If this bucket is sitting on the ground when it begins to rain, some rain falls into the bucket and some rain falls to the ground. The rain that falls into our bucket is within the defined frequency range. The rain that falls to the ground is outside the defined frequency range.

2.2. Scale Factors

Scale factors determine how a measurement is measured, and are: Peak, Peak-to-Peak, Average, and RMS. These scale factors are in direct relationship to each other when working with sinusoidal waveforms. When comparing overall values, scale factors must be consistent. Figure 1 shows the relationship of Average vs. RMS vs. Peak vs. Peak-to-Peak for a sinusoidal waveform.



Peak = 1.0
RMS = 0.707 x Peak
Average = 0.637 x Peak
Peak-to-Peak = 2 x Peak

Figure 1. Scale Factors on a Sinusoidal Vibration Waveform.

The *Peak* value represents the distance to the top of the waveform measured from a zero reference. For discussion purposes, we will assign a Peak value of 1.0.

The *Peak-to-Peak* value is the amplitude measured from the top of the waveform to the bottom of the waveform.

The *Average* value is the average amplitude of the waveform. The average of a pure sine waveform is zero (it is as much positive as it is negative). However, most waveforms are not pure sinusoidal waveforms. Also, waveforms that are not centered at approximately zero volts produce nonzero average values.

Visualizing how the *RMS* value is derived is a bit more difficult. Generally speaking, the RMS value is derived from a mathematical conversion that relates DC energy to AC energy. Technically, on a time waveform, it is the root mean squared (RMS). On an FFT spectrum, it is the square root of the sum of a set of squared instantaneous values. If you measured a pure sine wave, the RMS value is 0.707 times the peak value.

NOTE: Peak and Peak-to-Peak values can be either true or scaled. Scaled values are calculated from the RMS value.

Do not concern yourself with supporting mathematical calculations, as condition monitoring instrument calculate the values and display the results. However, it is important to remember to measure both signals on the same *frequency range* and *scale factors*.

NOTE: For comparison purposes, measurement types and locations must also be identical.

It is important to collect accurate, repeatable, and viable data. You can achieve this by following several key techniques for sensor position.

2.3. Measurement Sensor Position

Selecting the machine measurement point is very important when collecting machinery vibration data. Avoid painted surfaces, unloaded bearing zones, housing splits, and structural gaps. These areas give poor response and compromise data integrity. When measuring vibration with a hand-held sensor, it is imperative to perform consistent readings and pay close attention to sensor position, angle, and contact pressure.
When possible, vibration should be measured as an orthogonal matrix (three-positions of direction):

The axial direction (A)
The horizontal direction (H)
The vertical direction (V)

Horizontal measurements typically show the most vibration, as the machine is more flexible in the horizontal plane. Moreover, imbalance is one of the most common machinery problems, and imbalance produces a radial vibration that is part vertical and part horizontal. Thus, excessive horizontal vibration is a good indicator of imbalance.

Vertical measurements typically show less vibration than horizontal measurements, as stiffness is caused by mounting and gravity.

Under ideal conditions, *axial* measurements show very little vibration, as most forces are generated perpendicular to the shaft. However, issues with misalignment and bent shafts do create vibration in the axial plane.

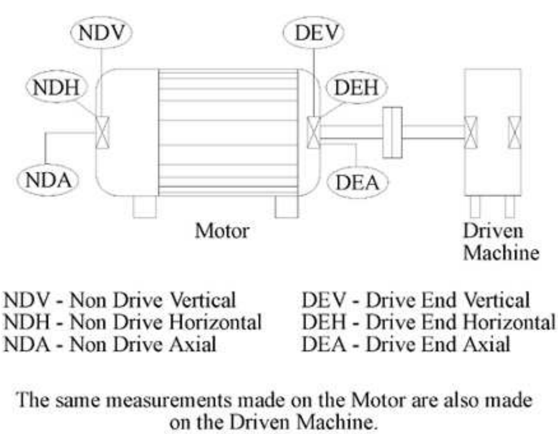


Figure 2. Standard Position Measurements.

NOTE: These descriptions are given as guidelines for "typical" machinery only. Equipment that is vertically mounted, or in some way not "typical" may show different responses.
Since we generally know how various machinery problems create vibration in each plane, vibration readings taken in these three positions can provide great insight. Measurements should be taken as close to the bearing as possible and avoid taking readings on the case (the case can vibrate due to resonance or looseness).

NOTE: Enveloping or demodulated measurements should be taken as close to the bearing load zone as possible.

If you choose not to permanently mount the accelerometer or other type of vibration sensing device to the machine, select a flat surface to press the accelerometer against. Measurements should be taken at the same *precise* location for comparison (moving the accelerometer only a few inches can produce drastically different vibration readings). To ensure measurements are taken at the exact location every time, mark the measurement point with a permanent ink marker. We highly recommended that the use of permanently mounted sensors whenever possible. This assures that data is repeatable and consistent. The following section contains mounting specifications for accelerometers. If permanently mounted sensors are not possible, use magnetic mounts.

Angle:

Always perpendicular to the surface (90° ± 10°)
Pressure:
Magnetic mount: The surface should be free of paint of grease.
Hand-held: Consistent hand pressure must be used (firm, but not hard). Please understand that we do not suggest use of this method.
Permanent mount: See specifications in Figure 3.

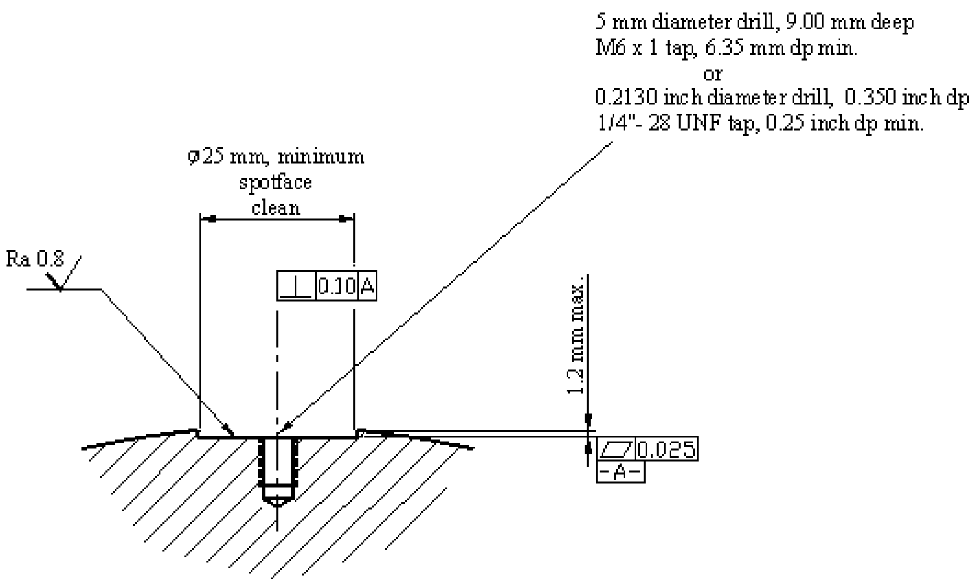


Figure 3. Example Spot Face Specifications for Permanently Mounted Sensors

2.4. Optimum Measurement Conditions

Ideally, measurements should be taken while the machine is operating under normal conditions. For example, the measurement should be taken when the rotor, housing, and main bearings reach their normal steady operating temperatures and the machine's running speed is within the manufacturer's specifications (rated voltage, flow, pressure, and load). If the machine is a variable speed machine, the measurements should be taken at the same point in the manufacturing or process cycle. This assures the machine's energy is not extremely variable. Additionally, we recommend obtaining measurements at all extreme rating conditions on occasion to guarantee there aren't outlying problems that only appear at extreme conditions.

2.5. Trending Overall Readings

Probably the most efficient and reliable method of evaluating vibration severity is to compare the most recent overall reading against previous readings for the same measurement. This allows you to see how the measurement vibration values are changing or trending over time. This trend comparison between present and past readings is easy to analyze when the values are plotted in a trend plot.

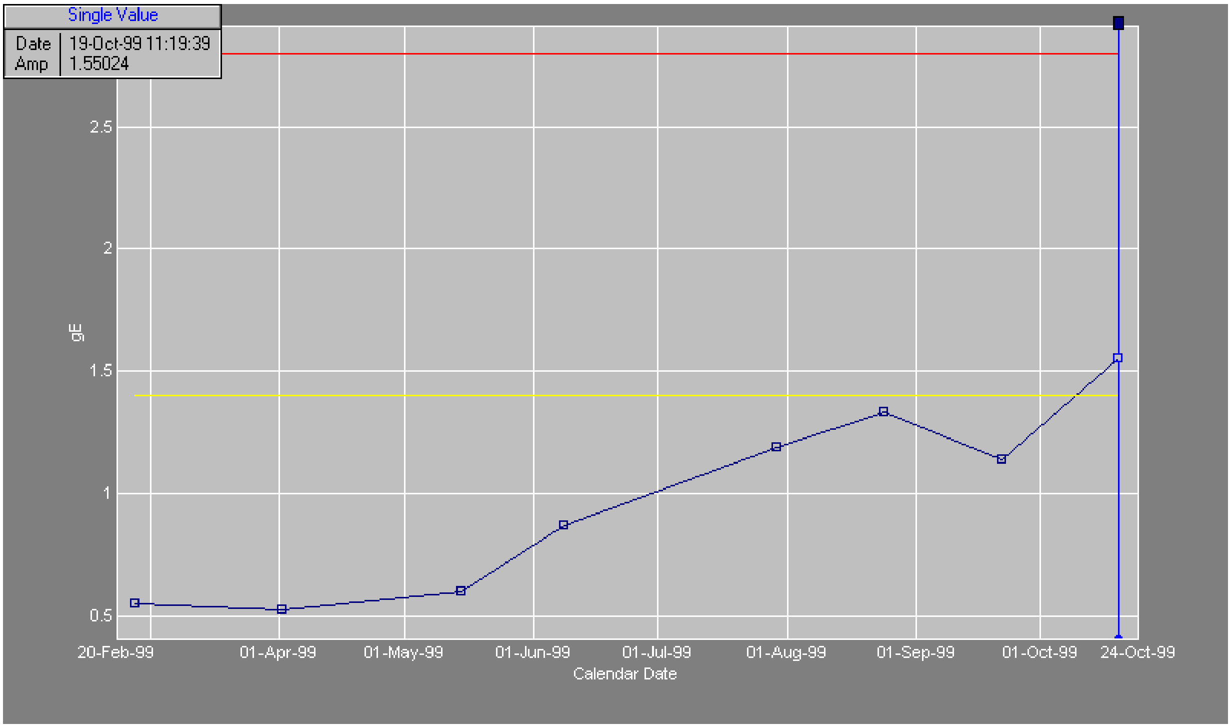


Figure 4. Example of a Trend Plot.

A trend plot is a line graph that displays current and past overall values plotted over time. Past values should include a base-line reading. The base-line value may be acquired after an overhaul or when other indicators show the machine running well. Subsequent measurements are compared to the base-line to determine machinery changes.

Comparing a machine to itself over time is the preferred method of machinery problem detection, as each machine is unique in its operation. For example, some components have a normal amount of vibration that would be considered problematic for most machines. Alone, the current reading might lead an analyst to believe a problem exists, whereas a trend plot and base-line reading would clearly show a certain amount of vibration is normal for that machine.

ISO Standards are a good place to start (until machine history is developed). However, ISO charts also define "good" or "not good" conditions for various wide-ranged machinery classifications. Remember that every machine is:

Manufactured differently
Installed differently (foundation)
Operated under different conditions (load, speed, materials, environment)
Maintained differently
It is unrealistic to judge a machine's condition by comparing the current measurement value against an ISO standard or other general rule or level. By comparing current values to historical values, you are able to easily see a machine's condition change over time.

3. Vibration Measurements Methods

Measuring vibration is the measurement of periodic motion. Vibration is illustrated with a spring-mass setup in Figure 5.

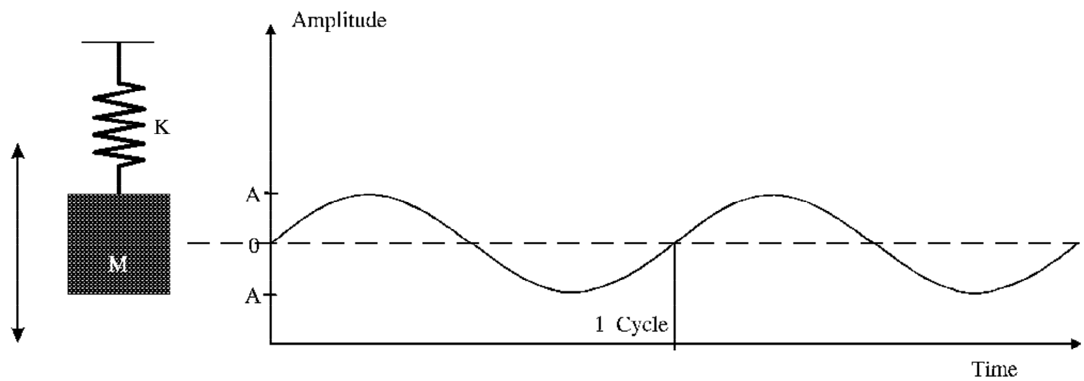


Figure 5. Spring-Mass System.

When in motion, mass oscillates on the spring. Viewing the oscillation as position over time produces a sine wave. The starting point (when mass is at rest) is the zero point. One complete cycle displays a positive and a negative displacement of the mass in relation to its reference (zero). Displacement is the change in distance or position of an object relative to a reference. The magnitude of the displacement is measured as amplitude.

There are two measurable derivatives of displacement: velocity and acceleration.

Velocity is the change in displacement as a function of time. It is the speed at which the distance is traveled (i.e.0.2 in/sec).

Acceleration is the rate of change of velocity. For example, if it takes 1 second for the velocity to increase from 0 to 1 in/sec, then acceleration is 1 in/sec2.
Thus, vibration has three measurable characteristics: *displacement, velocity, and acceleration*. Although these three characteristics are related mathematically, they are three different characteristics, not three names for the same quantity.

It is necessary to select a vibration measurement and sensor type that measures the vibration likely to reveal expected failure characteristics.

3.1. Displacement

Measured in mils or micrometers, displacement is the change in distance or position of an object relative to a reference. Displacement is typically measured with a sensor commonly known as a displacement probe or eddy probe. A displacement probe is a non-contact device that measures the relative distance between two surfaces. Displacement probes most often monitor shaft vibration and are commonly used on machines with fluid film bearings.

Displacement probes only measure the motion of the shaft or rotor relative to the machine casing. If the machine and rotor are moving together, displacement is measured as zero even though the machine can be heavily vibrating.

Displacement probes are also used to measure a shaft's phase. The shaft phase is the angular distance between a known mark on the shaft and the vibration signal. This relationship is used for balancing and shaft orbital analysis.

Figure 6. A Dial Gage (Left) Measures Displacement. A Common Displacement Probe (Right).

3.2. Velocity

Velocity measurements are taken in in/sec or mm/sec. Velocity is the measure of a signal's rate of change in displacement. It is the most common machine vibration measurement. Historically, the velocity sensor was one of the first electrical sensors used for machine condition monitoring. This is due in part to the resultant of an equal amount of generated dynamic motion; velocity remains constant regardless of frequency. However, at low frequencies (under 10 Hz) or high frequencies (above 2 kHz), velocity sensors lose their effectiveness.

The original velocity transducer employed a coil vibrating in a magnetic field to produce a voltage proportional to the machine's surface velocity. Today, with the arrival of low cost and versatile accelerometers, most velocity values are obtained by integrating an acceleration reading into the velocity domain.

3.3. Acceleration

Acceleration is the rate of change in velocity. Vibration, in terms of acceleration, is measured with accelerometers. An accelerometer usually contains one or more piezoelectric crystal element and a mass.

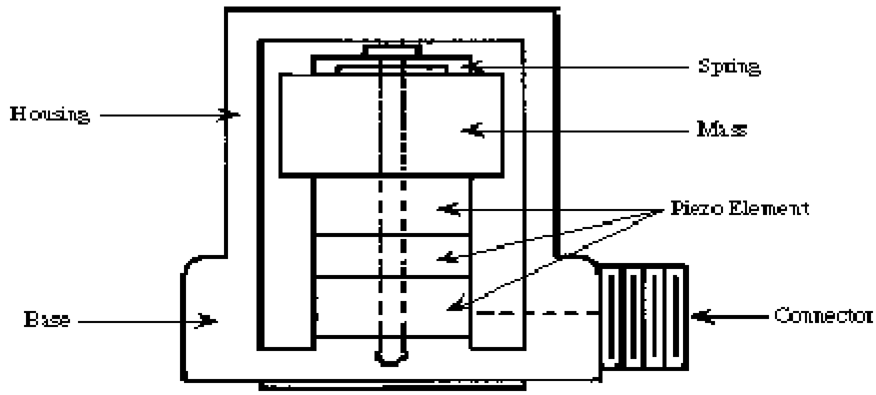


Figure 7. Accelerometer.

When the piezoelectric crystal is stressed it produces an electrical output proportional to acceleration. The crystal is stressed by the mass when the mass is vibrated by the component to which they are attached.

Accelerometers are rugged devices that operate in a wide frequency range (zero to well above 400 kHz). This ability to examine a wide frequency range is the accelerometer's major strength. However, since velocity is the most common measurement for monitoring vibration, acceleration measurements are usually integrated to get velocity (either in the accelerometer itself or by the data collector). Acceleration units are G's, in/sec2, or m/sec2.

We can measure acceleration and derive velocity by mounting accelerometers at strategic points on bearings. These measurements are recorded, analyzed, and displayed as tables and plots by the condition monitoring equipment. A plot of amplitude vs. time is called a time waveform. Vibration Analysis Methods

3.4. Time Waveform Analysis

The time waveform plot in Figure 8 illustrates how the signal from an accelerometer or velocity probe appears when graphed as amplitude (y-axis) over time (x-axis). A time waveform in its simplest terms is a record of what happened to a particular system, machine, or parameter over a certain period of time. For example, a seismograph measures how much the Earth shakes in a given amount of time when there is an earthquake. This is similar to what is recorded in a time waveform.

Time waveforms display a short time sample of raw vibration. Though typically not as useful as other analysis formats, time waveform analysis can provide clues to machine condition that are not always evident in a frequency spectrum. Thus, when available, time waveform should be used as part of your analysis program

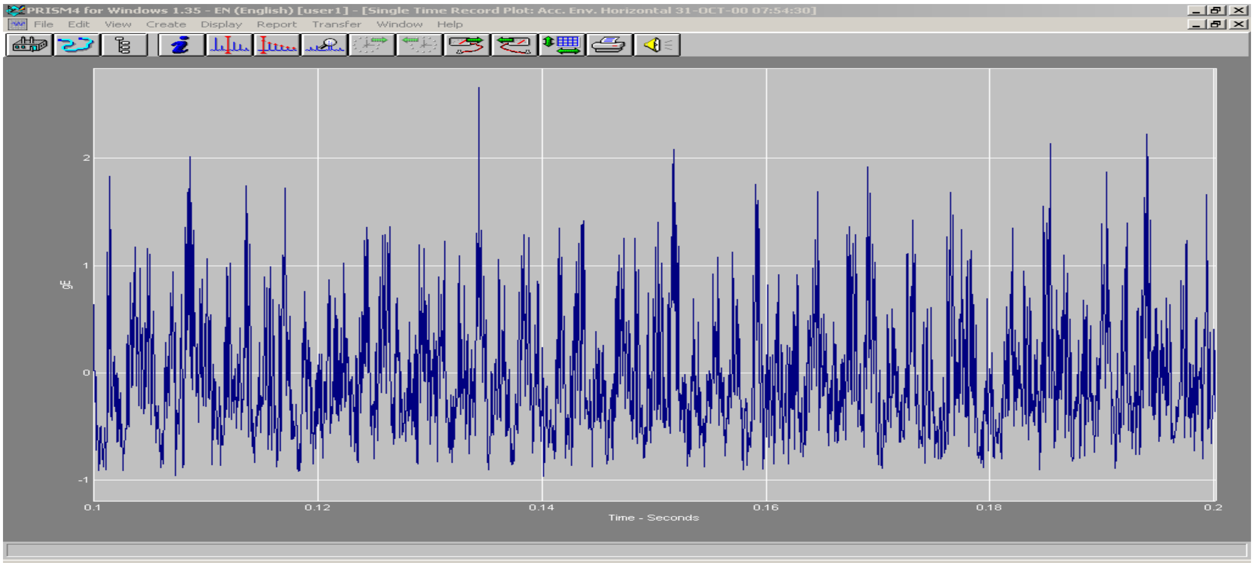


Figure 8. Example of a Time Waveform

3.5. FFT Spectrum Analysis

A Fast Fourier Transformation (FFT) is another useful method of viewing vibration signals. In non-mathematical terms, the signal is broken down into specific amplitudes at various component frequencies. As an example, Figure 9 shows a motor (left) coupled to a gearbox (right). Each piece of the machine has individual components associated with it. In a simplified form, the motor has a shaft and bearings. The gearbox has several shafts and sets of gears.

Each component in the diagram vibrates at a certain, individual rate. By processing the vibration signal using a mathematical formula, an FFT, we can distinguish between several different rates and determine the which rate vibration coincides with which component.

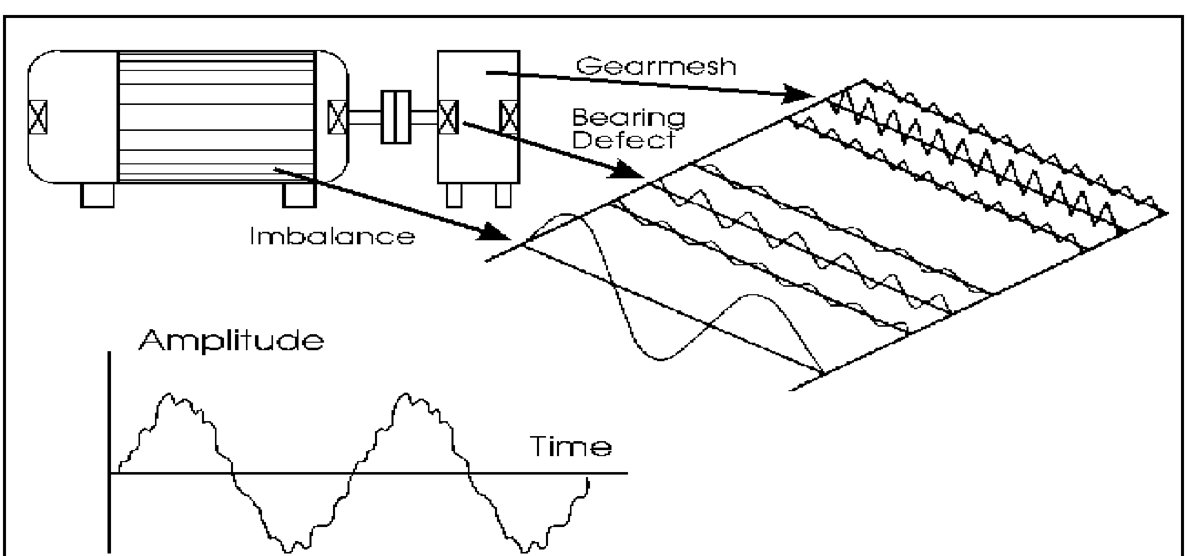


Figure 9. Frequency Scales Show Component Vibration Signals.

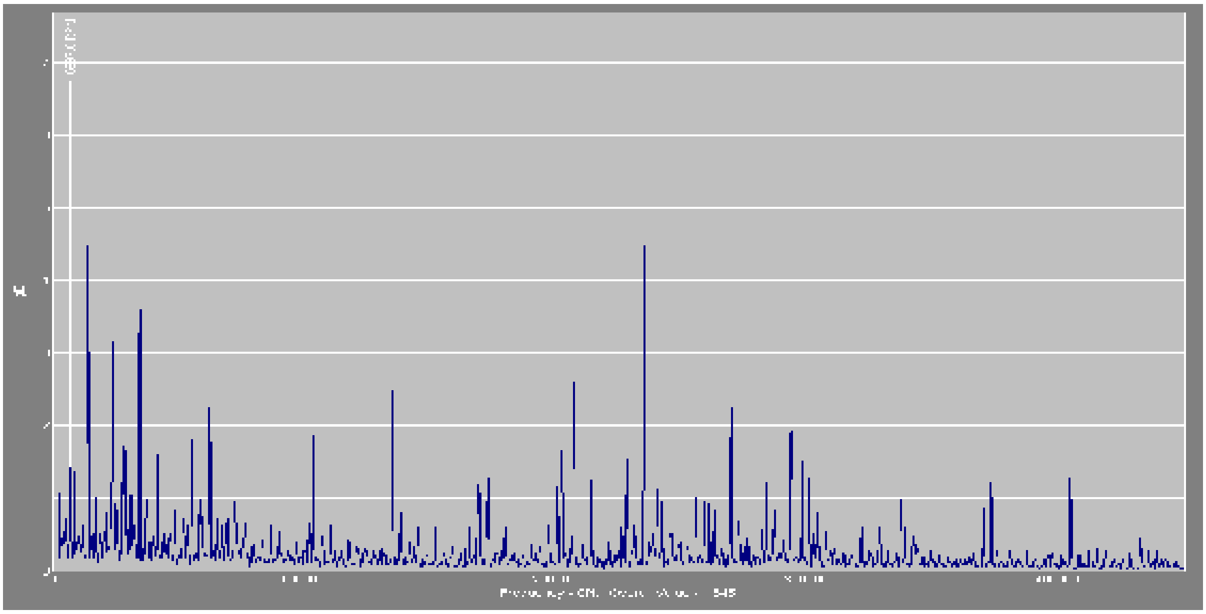


Figure 10. Example of an FFT Spectrum

For example, we measure the signal's amplitude at 10 Hz, then again at 20 Hz, etc., until we have a list of values for each frequency contained in the signal. The values or amplitudes are then plotted on the frequency scale. The number of lines of resolution is the waveform divided by number of components. The resulting plot is called an FFT spectrum.

An FFT spectrum is an incredibly useful tool. If a machinery problem exists, FFT spectra provide information to help determine the location of the problem. In addition, spectra can aid in determining the cause and stage of the problem. With experience we learn that certain machinery problems occur at certain frequencies. Thus, we can determine the cause of the problem by looking for amplitude changes in certain frequency ranges.

In addition to time waveforms and FFT spectra, vibration signals can be analyzed through other types of signal processing methods to determine specific equipment problems and conditions. Processing vibration signals via multiple processing methods also provides a greater number of ways in which to analyze the signal and measure deviations from the "norm." The following section contains examples of alternate processing methods.

3.6. Envelope or Demodulated Process Detection

Repetitive bearing and gear-mesh activity create vibration signals of much lower amplitude and much higher frequencies than that of rotational and structural vibration signals.

The objective of enveloping or demodulated signal processing, as it relates to bearings, is to filter out low frequency rotational vibration signals and enhance the repetitive components of bearing defect signals that occur in the bearing defect frequency range. Envelope detection is most commonly used for rolling element bearing and gear mesh analysis where a low amplitude, repetitive vibration signal may be saturated or hidden by the machine's rotational and structural vibration noise.

For instance, when a rolling element bearing generates a defect on its outer race, each rolling element of the bearing over-rolls the defect as they come into contact. This impact causes a small, repetitive vibration signal at the bearing's defects frequencies. However, the vibration signal is so low in energy that it is lost within the machine's other rotational and structural vibration noises.

Similarly, you can strike a bell and create a ringing sound. This ringing is similar to the ringing that occurs when a rolling element in a bearing strikes a defect in the bearing. However, unlike the bell you cannot hear the ringing in the bearing, as it may be masked by the machine's other sounds or it occurs at a frequency that cannot be detected by the human ear.

This detection method proves to be a successful indicator of a major class of machine problems. Faults in roller element bearings, defective teeth in gearboxes, paper mill felt discontinuities, and electric motor / stator problems are all applications for enveloping technology

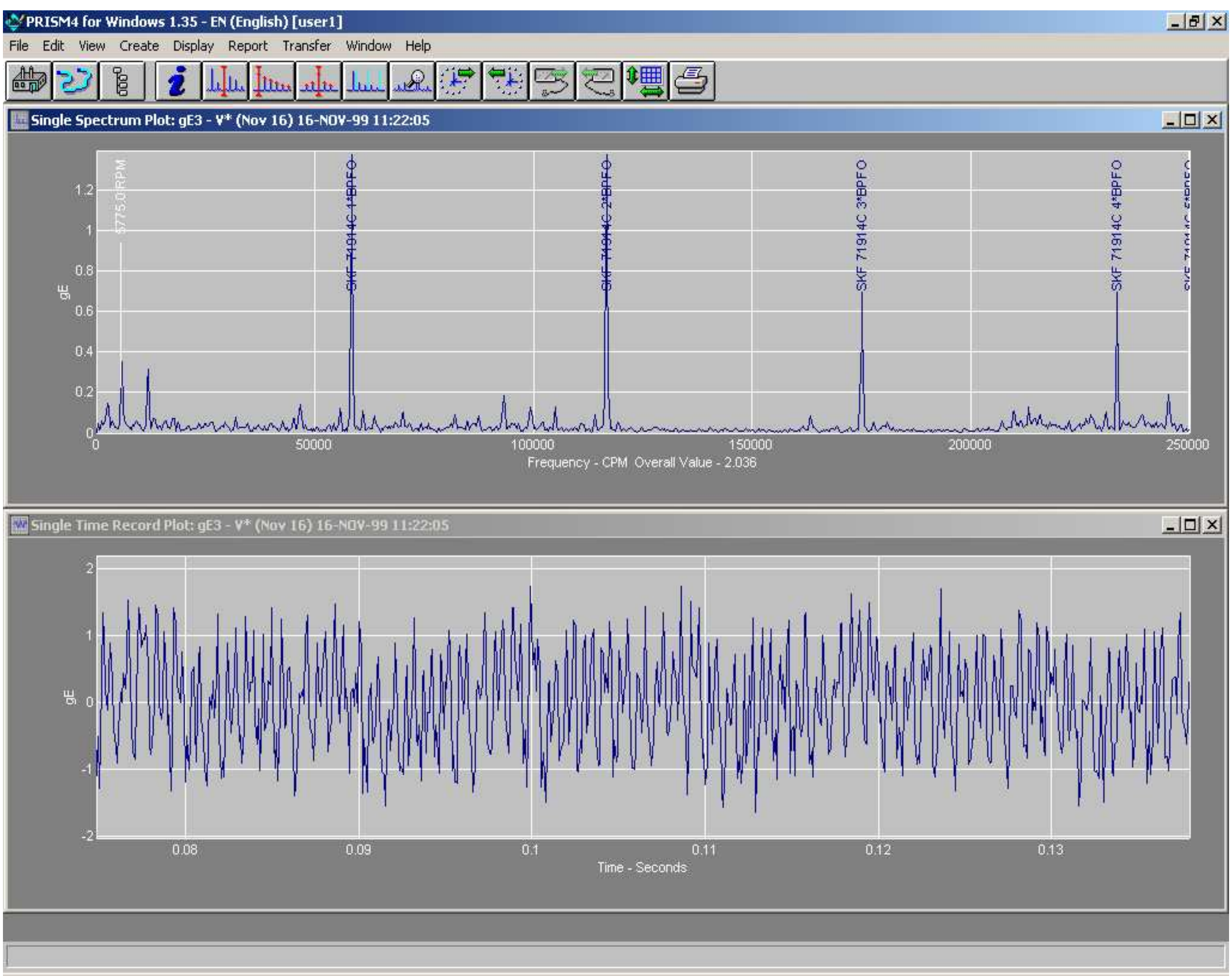


Figure 11. Enveloped and Time Waveform Spectrum With Outer Race Defect. Envelope Detection Filters Out Low Frequency Rotational Signals and Enhances the Bearing's Repetitive Impact Type Signals to Focus on Repetitive Events in the Bearing Defect Frequency Range. (For Example, Repetitive Bearing and Gear-Tooth Vibration Signals.)

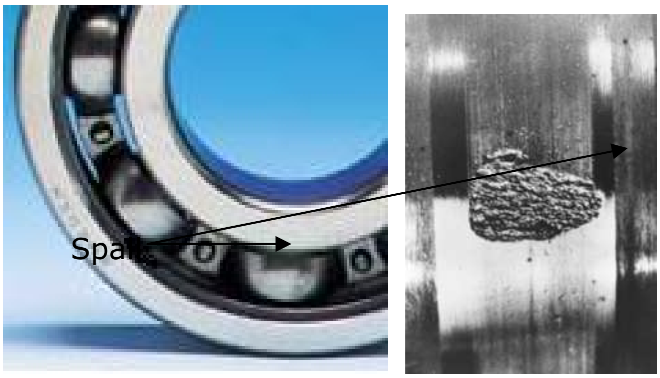


Figure 12. Indication of a Spall (Defect in the Outer Race)

3.7. Phase Measurements

Phase is a measurement, not a processing method. Phase measures the angular difference between a known mark on a rotating shaft and the shaft's vibration signal. This relationship provides valuable information on vibration amplitude levels, shaft orbit, and shaft position, and is very useful for balancing and analysis purposes.

3.8. High Frequency Detection (HFD)

High Frequency Detection (HFD) provides early warning of bearing problems. The HFD processing method displays a numerical, overall value for high frequency vibration generated by small flaws that occur within a high frequency bandpass (5 kHz to 60 kHz). The detecting sensor's resonant frequency is used to amplify the low level signal generated by the impact of small flaws. Due to its high frequency range, the HFD measurement is made with an accelerometer and displays its value in G's. The HFD measurement may be performed as either a peak or RMS overall value.

3.9. Other Sensor Resonant Technologies

There are varying types of technologies that use sensor resonant to obtain a measurement similar to HFD. Sensor resonant technologies use the sensor's resonant frequency to amplify events in the bearing defect range. These technologies enhance the repetitive components of a bearing's defect signals and report its condition. The resultant reading is provided by an overall number that represents the number of impacts (enhanced logarithmically) the system senses.

As vibration analysis evolves, sensor resonant technology is used less frequently. Instead, enveloping or demodulation processing is used, as they allow greater flexibility within the monitoring system. For example, resonant technology requires that the exact same type of accelerometer is used.

4. On-line Measurements vs. Off-line Measurements

In general, there are two types of measurement processes: *on-line* and *off-line.* Acquiring data in an *on-line* situation requires permanently mounted sensors, cabling, a multiplexing device, and a computer for data storage. On-line measurements are acquired continuously from the machinery based upon a user defined collection period. The benefits of on-line data collection are numerous. On-line data collection allows condition monitoring and maintenance departments to concentrate their efforts on corrective actions and system modification to more readily diagnose problems. Additionally, permanently mounted sensors do not interrupt the manufacturing process and data is repeatable and accurate. The disadvantage of an on-line system is the initial cost. It is important to keep in mind that the return on investment of an on-line system is usually realized in a relatively short time period.

An *off-line* measurement program is similar to a route-based collection program. In a route-based collection program, the user defines the types of measurements and machinery to analyze and develops a roadmap or route of the machinery in the plant. He/she then follows the developed route to obtain the data needed. Additionally, off-line collection requires a handheld analyzer, cabling, and a sensor or sensors. Unfortunately, it requires a substantial amount of time to collect route-based data. It also requires manpower from

the maintenance or condition monitoring department and machine operators. On the other hand, off-line measurements methods are associated with relatively low costs.

Once you make the decision to develop a condition based monitoring program, it is imperative to follow a standard process to diagnose, document, and solve plant problems. The development of standards is defined to help you develop a condition monitoring program.

5. International Standards Vibration Diagnostic Tables

The following sections contain agreed upon International Standards as they relate to vibration monitoring. These standards are a basis for developing a condition monitoring program. However, they are to be used in conjunction with manufacturer suggested acceptability levels for specific machines and industries. Many of the industry or machine type standards can also be obtained through condition monitoring or vibration monitoring companies

ISO 2372 Vibration Diagnostic Table (Overhung – Horizontal Shaft)

	Excessive **Horizontal** Vibration Indicates:	Excessive **Vertical** Vibration Indicates:	Excessive **Axial** Vibration Indicates:	Excessive **Structural** Vibration Indicates:	**Notes**
Imbalance	**YES**	**NO**	**YES**	**NO**	Horizontal and Axial > Vertical
Misalignment	**YES**	**NO**	**YES**	**NO**	Horizontal and Axial > Vertical
Looseness	**YES**	**YES**	**NO**	**YES**	Vertical □ Horizontal
Electrical Faults Measured as Vibration					To detect an electrical problem: Turn off machine power and monitor vibration. If the vibration immediately drops, the problem is electrical.

Note: On an overhung machine, imbalance and misalignment may display similar characteristics. Use phase measurements to differentiate between the two.

Note: YES = ISO 2372 Unsatisfactory – Unacceptable Levels.

NO = ISO 2372 Good – Satisfactory Levels.

ISO 2372 Vibration Diagnostic Table (Vertical Shaft)

	Excessive Horizontal Vibration Indicates:	Excessive Vertical Vibration Indicates:	Excessive Axial Vibration Indicates:	Excessive Structural Vibration Indicates:	Notes
Imbalance	YES	NO	NO	NO	Radial > Axial
Misalignment	YES	NO	YES	NO	Axial > Radial
Looseness	YES	NO	NO	YES	
Electrical Faults Measured as Vibration					To detect an electrical problem: Turn off machine power and monitor vibration. If the vibration immediately drops, the problem is electrical.

Note: Radial 1 and Radial 2 positions differ by 90 degrees.

Note: YES = ISO 2372 Unsatisfactory – Unacceptable Levels.

NO = ISO 2372 Good – Satisfactory Levels.

6. Spectrum Analysis Table

The following section contains a list of common issue within the vibration gamut. Moreover, it contains a general guide to the type of measurements used to diagnose problems, suggested vibration signatures, and phase relationships of those signatures.

Use this as a generalized reference chart to develop your condition monitoring program. Manufacturer reference resources are also available. Please contact them for further suggestions and standards of the industry.

	Primary Plane	Detection Units	Dominant Frequencies	Phase Relationship (Note: phase ref. within ±30 degrees)	Comments
IMBALANCE					
Mass	Radial	Acceleration / Velocity / Displacement	1x	90-degree phase shift as sensor is moved from horizontal to vertical position with no phase shift in the radial direction across the machine or coupling.	
Overhung Mass	Axial and Radial	Acceleration / Velocity / Displacement	1x	Axial reading will be in phase	Account for change in sensor orientation when making axial measurements.
Bent Shaft	Axial and Radial	Acceleration / Velocity / Displacement	1x	180-degree phase shift in the axial direction across the machine with no phase shift in the radial direction.	
MISALIGNMENT					
Angular	Axial	Acceleration / Velocity / Displacement	1x and 2x	180-degree phase shift in the axial direction will exist across the coupling.	With severe misalignment, the spectrum may contain multiple harmonics from 3x to 10x running speed. If vibration amplitude in the horizontal plane is increased 2 or 3 times, then misalignment is again indicated. (Account for change in sensor orientation when making axial measurements)
Parallel	Radial	Acceleration / Velocity / Displacement	1x and 2x	180-degree phase shift in the radial direction will exist across the coupling. Sensor will show 0-degrees or 180-degrees phase shift as it is moved from horizontal to vertical position on the same bearing.	
Combination of Angular and Parallel	Axial and Radial	Acceleration / Velocity / Displacement	1x and 2x	180-degree phase shift in the radial and axial direction will exist across the coupling.	
MECHANICAL LOOSENESS					
Wear / Fitting	Axial and Radial	Acceleration / Velocity / Displacement	1x, 2x, 3x…10x	Phase reading will be unstable from one reading to the next.	Vibration amplitudes may vary significantly as the sensor is placed in differing locations around the bearing. (Account for change in sensor orientation when making axial measurements)

	Primary Plane	Detection Units	Dominant Frequencies	Phase Relationship (Note: phase ref. within ±30 degrees)	Comments
LOCAL BEARING DEFECTS					
Race Defect	Radial	Acceleration / Enveloping	4x…15x	No correlation.	With acceleration measurements, bearing defect frequencies appear as a wide "bump" in the spectrum. Bearing defect frequencies are non-integer multiples of running speed (i.e., 4.32 x running speed)
GEAR DEFECTS					
Gear Mesh	Radial	Acceleration / Enveloping	20x…200x	No correlation.	The exact frequency relates to the number of teeth each gear contains times the rotational speed (running speed) to which the gear is attached.
ELECTRICALLY INDUCED VIBRATION					
AC Motors	Radial	Acceleration / Velocity / Displacement	Line Frequency (100 or 120 Hz)	No correlation.	Defect Frequencies can be seen at exactly twice the line frequency.
DC Motors	Radial	Acceleration / Velocity / Displacement	SCR Frequency	No correlation.	DC Motor problems due to broken fields windings, bad SCR's or loose connections are reflected as higher amplitudes at the SCR frequencies

7. Conclusion

This guide simply provides an introduction to the field of vibration monitoring and diagnosis. A few references are suggested for more information and related @ptitudeXchange documents.

8. Further Reading

Barkov A., Barkova, N. "Condition Assessment and Life Prediction of Rolling Element Bearings - Parts I and II". *Sound & Vibration*, June pp. 10-17 and September pp. 27-31, 1995.

Berry, James E. "How to track rolling element bearing health with vibration signature analysis". *Sound and Vibration*, November 1991, pp. 24-35.

Hewlett Packard, *The Fundamentals of Signal Analysis.* Application Note 243: 1994.

Hewlett Packard, *Effective Machinery Measurements using Dynamic Signal Analyzers*. Application Note 243-1: 1997.

Mitchell, John. *Machinery Analysis and Monitoring*. Penn Well Books, Tulsa OK: 1993.

SKF Evolution journal, a number of case studies: http://evolution.skf.com

Paper Mills Gaining from Condition Monitoring, 1999/4

Paper Mill Gains from Condition Monitoring, 2000/3

High Tech keeps Mine competitive, 2001/2
Fault Detection for Mining and Mineral Processing Equipment, 2001/3

Technical Associates of Charlotte (diagnostic charts, background articles and books): http://www.technicalassociates.net

Vibration Institute: http://www.vibinst.org

Vibration Resources: http://vibrate.net

9. Appendix A: Website links

9.1. Instruments

Advanced Monitoring Technologies: http://www.amt.nb.ca

ACIDA GmbH: http://www.acida.de

Alta Solutions, Inc: http://www.altasol.com

Bently Nevada: http://www.bently.com

Brüel & Kjær North America: http://www.bkhome.com

Brüel & Kjær Vibro: http://www.bkscms.com

CSI : http://www.compsys.com/index.html

Commtest Instruments : http://www.commtest.com

Dactron : http://www.dactron.com

Development Engineering International : http://www.dei-ltd.co.uk/index.htm

Diagnostic Instruments : http://www.diaginst.co.uk

Entek : http://www.entek.com

G-Tech Instruments Incorporated : http://www.g-tech-inst.com

Icon Research : http://www.iconresearch.co.uk

Indikon Company, Inc : http://www.iconresearch.co.uk

IOtech : http://www.iotech.com

L M S International : http://www.lmsintl.com

Machinery Condition Monitoring Inc : http://www.mcmpm.com

Müller-BBM VibroAkustik Systeme : http://www.muellerbbm-vas.com/eng

OROS : http://www.oros-signal.com

PdMA Corporation : http://www.pdma.com

Predict-DLI : http://www.predict-dli.com

Prüftechnik AG : http://www.pruftechnik.com/main/index.htm

SKF Condition Monitoring : http://www.skfcm.com

SKF Dymac : http://www.dymac.net

Solartron : http://www.solartron.com

SoundTechnology : http://www.soundtechnology.com/home.htm

SPM Instrument AB : http://www.spminstrument.se

Stanford Research Systems : http://www.srsys.com

VMI Vibrations Mät Instrument AB: http://www.vmi-instrument.se/index.htm

Vibrationsteknik AB : http://www.vtab.se

Vibro-Meter : http://www.vibro-meter.com

Windrock, Inc : http://www.windrock.com/Main.htm

9.2. Sensors

Entran Accelerometers - Complete on-line catalog. Manufacturing quality accelerometers for 30 years.
http://www.entran.com

National Instruments - Accelerometers - NI allows you to use industry-standard technologies to create custom measurement and automation solutions that deliver greater productivity, shorter development time, and lower total costs.
http://www.ni.com

Omega Engineering, Inc. Flow & Level - Omega Engineering, Inc. - world leader in process measurement & control products. The one stop source for all your pressure, load, and force needs.
http://www.omega.com

Accelerometer Measurement Products - Accelerometer-based sound and vibration measurement products from IOtech. Free catalog and signal conditioning handbook.
http://www.iotech.com

Accelerometer at Globalspec.com - Find information on accelerometer through SpecSearch, the powerful parametric search engine that enables you to search for the exact performance characteristics you need.
http://www.globalspec.com

Data Loggers - Small, Simple, Affordable - 32k data pts/ch, 16 bit - Smallest data loggers available for temperature, humidity, count, acceleration, voltage, 4-20mA, pressure. Wireless data loggers. Also rugged, waterproof units.
http://www.microdaq.com

Accelerometers - Manufacturers - On Direct Industry you can browse the list of accelerometers manufacturers and ask for documentation or a quotation.
http://www.directindustry.com

Signal Conditioning - Strain gage, bridge completion, accelerometer, anti alias filter, excitation, thermocouple, RTD, software controlled.
http://www.alligatortech.com

Complete line of Low Cost Accelerometers and Inclinometers. - Rieker manufactures a complete line of Inclinometers, Accelerometers, Tilt Switches, Ball Bank Indicators, Slip Indicators & Safe Curve Speed Indicators servicing the Construction Industry, Aircraft, and DOT since 1917.
http://www.riekerinc.com

Accelerometers and Acceleration products in Stock at Sensotec - Accelerometers and Acceleration products from Sensotec. We have general-purpose, piezoelectric, and submersible accelerometers.
http://www.sensotec.com/accelstk.htm

DC-Operated Inclinometers and Accelerometers - DC-Operated Inclinometers and Accelerometers
http://www.schaevitz.com/products/inertial/index.html

ENDEVCO - is the world's leading supplier of dynamic instrumentation systems. - ENDEVCO is the world's leading supplier of dynamic instrumentation http://www.endevco.com

New Age Consulting Service, Inc. Nacs.Net web developement, e-commerce solutions, Bandwidth - New Age Consulting Service, Inc. provides Internet and network consulting services for both business and personal computing. We specialize in integrating Internet technology with existing networks to suit your present and future Internet communication...
http://www.summitinstruments.com

ThinkQuest Library of Entries - ThinkQuest is an online program that challenges students, educators at all levels to develop educational Web sites for curriculum and staff development
http://library.advanced.org/2745/data/meter.htm

HCI Accelerometer - Want to brush up on your aerobatics but think you can't afford the expense or panel space for an accelerometer? Accelerometer (G-Meter) Order by phone of mail using check, money order, or credit card. HCI 3461 Dissen Road New Haven, MO. 63068 (573)...
http://www.halcyon.com/wpowers/gmeter.html

Patriot Sensor and Controls Corporation - Patriot Sensors and Controls Corporation (PSCC) is a leading supplier of Accelerometers, Pressure Transducers, and Linear Motion Transducers. We utilize state of the art technologies to provide innovative, reliable and versatile sensor solutions for...
http://www.xducer.com

Precision Aligned Tri-Axial Accelerometer with Signal Conditioning - Specification Accelerometer34103:
http://www.wuntronic.de/accelerometer/34103_sp.htm

A triaxial rate gyroscope and accelerometer - A triaxial rate gyroscope and accelerometer. The acquisition of extensive kinematics information with a sensor system with minimal external complexity is important in the field of biomedical and automotive applications,
http://www.stw.nl/projecten/T/tel4167.html

SKF

10. Appendix B: Some Vibration Terminology

1X – The Running Speed of the machine (Fundamental Frequency).

2X, 3X, etc … – The frequency at 2, 3, etc … times the running speed of the machine.

Acceleration – The time rate of change of velocity. Acceleration measurements are usually made with accelerometers.

Accelerometer – A sensor whose output is directly proportional to acceleration.

Acoustic Emissions – Sound emissions that are emitted when an object or material vibrates. These emissions may or may not be heard but can be detected with proper equipment.

Aerodynamic and Flow induced Vibration – Air flow from fans and fluid flow pumps induced vibration each time the fan or pump impeller discharges air of fluid. These pulsing discharges can be detected at a frequency equal to the shaft speed times the number of fan blades or pump impellers.

Alarm Setpoint – Any value beyond which is considered unacceptable or dangerous to machinery operation.

Alignment – A condition whereby the axes of machine components are either coincident, parallel, or perpendicular, according to design requirements.

Amplitude – The magnitude of dynamic motion or vibration. Expressed in terms of peak-to-peak, zero-to-peak, or RMS.

Analog-To-Digital Converter – A device, or subsystem, that changes real-world analog data (as from sensors, for example) to a form compatible with digital (binary) processing.

Anti-aliasing Filter – A low pass filter designed to filter out frequencies higher than ½ the sample rate in order to prevent aliasing.

Attenuation – The reduction in signal strength over the distance traveled. The amount of attenuation will vary with the type of material.

Asynchronous – Vibration components that are not related to rotating speed (non-synchronous).

Averaging – In a dynamic signal analyzer, digitally averaging several measurements to improve statistical accuracy or to reduce the level of random asynchronous components.

Axial – In the same direction as the shaft centerline.

Axial Vibration – Vibration that is in line with a shaft centerline.

Axis – The reference plane used in plotting routines. The X-axis is the frequency plane. The Y-axis is the amplitude plane.

Balancing – A procedure for adjusting the radial mass distribution of a rotor so that the centerline of the mass approaches the geometric centerline of the rotor.

Ball Pass Frequency – The frequency generated when a rolling element passes over a flaw in the inner race, BPFI, or over the outer race, BPFO.

Band-Pass Filter – A filter with a single transmission band extending from lower to upper cutoff frequencies. The width of the band is determined by the separation of frequencies at which amplitude is attenuated by 3 dB (0.707).

Bandwidth – The spacing between frequencies at which a bandpass filter attenuates the signal by 3 dB.

Base-line Spectrum – A vibration spectrum taken when a machine is in good operating condition; used as a reference for monitoring and analysis.

Blade or Vane pass frequency – The number of fan blades or pump vanes times the rotational speed equals the specific frequency.

Center Frequency – For a bandpass filter, the center of the transmission band.

Centerline Position – The average location, relative to the radial bearing centerline, of the shaft dynamic motion.

Clipping – A condition reached when the signal amplitude exceeds the limits of the amplifier or supply voltage. Signal peaks will be rounded or flattened resulting in inaccurate data.

Condition Monitoring – Determining the condition of a machine by interpretation of measurements taken either periodically or continuously while the machine is running.

CPM – Cycles per minute.

CPS – Cycles per second. Also referred to as Hertz (Hz).

Critical Speeds – In general, any rotating speed that is associated with high vibration amplitude. Often the rotor speeds, which correspond to natural frequencies of the system.

Cycle – One complete sequence of values of a periodic quantity.

Damping – The absorption of energy that will bring a system to rest when the driving force is removed.

Decay Rate – The rate at which an object stops vibrating after being struck.

Decibel (dB) – A logarithmic representation of amplitude ratio, defined as 20 times the base ten logarithm of the ratio of the measured amplitude to a reference.

Displacement – The change in distance or position of an object relative to a reference.

Download – Transferring information to the measurement device from the host computer.

Dynamic Range – The difference between the highest voltage level that will overload the instrument and the lowest level that is detectable. Dynamic range is usually expressed in decibels.

Engineering Units – Physical units in which a measurement is expressed, such as in/sec, micrometers, or mils. Selected by the user.

EU – See ENGINEERING UNITS.

Enveloping Process – The signal processing technique where the higher frequency harmonic signals are electronically processed to provide a mathematical sum of these harmonics over a selected range.

Fast Fourier Transform – A calculation method of converting a time waveform to a frequency display that shows the relationship of discrete frequencies and their amplitudes.

Field – One data item. Examples of fields are POINT Type, Description, etc.

Filter – An electronic device designed to pass or reject a specific frequency band.

FFT – See Fast Fourier Transform.

Frequency – The repetition rate of a periodic event, usually expressed in cycles per second (Hz), cycles per minute (CPM), revolutions per minute (RPM), or multiples of running speed (orders). Orders are commonly referred to as 1X for running speed, 2X for twice running speed, and so on.

Frequency Domain – An FFT graph (amplitude vs. frequency).

Free Running – A term used to describe the operation of an analyzer or processor, which operates continuously at a fixed rate, not in synchronism with some external reference event.

Frequency Range – The frequency range (bandwidth) over which a measurement is considered valid. Usually refers to upper frequency limit of analysis, considering zero as the lower analysis limit.

G (g) – A standard unit of acceleration equal to one of earth's gravities, at mean sea level. One g equals 32.17 ft/sec squared or 9.807 meters per second squared.

Gap – (See Probe Gap.)

Gear Mesh Frequency – The frequency generated by two or more gears meshing teeth together.

Global Bearing Defect – Relatively large damage on a bearing element.

Hanning Window – DSA window function that provides better frequency resolution than the flat top window, but with reduced amplitude accuracy.

Harmonic – A frequency that is an integer multiple of a fundamental frequency. For example 5400 RPM is the third harmonic of 1800 RPM. Harmonics are produced either by an event that occurs multiple times per revolution, or by a distortion of the running speed component's pure sine wave.

Hertz (Hz) – Cycles per second. CPM/60.

Hertzian Contact Zone – In a bearing, the area at which the ball transfers the load on the raceway.

High Pass Filter – A filter with a transmission band starting at a lower cutoff frequency and extending to (theoretically) infinite frequency.

Imbalance – A condition such that the mass of a shaft and its geometric centerlines do not coincide.

Keyphasor Phase Reference Sensor – A signal used in rotating machine measurements, generated by a sensor observing a once-per-revolution event. (Keyphasor is a Bently-Nevada trade name.)

Lines – Common term used to describe the filters of a Digital Spectrum Analyzer (e.g. 400 line analyzer).

Linear, non-linear – When the vibration levels are trended over time and the trend is a straight line, either rising or falling, the trend is referred to as linear because the amount of increase is the same for each equal increase in time. A non-linear increase would be the case where, as time progresses, the amplitude increases or decreases, at a larger and larger amount, each time frame. Projections can be made from linear trends, they cannot be made from none-linear trends.

Measurement units – Mils. Displacement is measured in mils, a mil is one thousandths of an inch. Displacement is stated in Peak to Peak. See sine Wave.

IPS. Inches per second. A measurement of velocity, the speed the item being measured is moving. Velocity is stated in Peak.

G's. Acceleration . The rate of change of the velocity. A measure of the force being applied to the item being measured. Acceleration is stated in Peak.

These measurement units are mathematically related. IPS can be derived from the integration of Gs and displacement derived by integration of velocity.

GE. Enveloped acceleration. A special signal processing method that uses selectable filters and mathematical processing to enhance very low level signals. Used primarily for bearing and gear analysis.

Misalignment – A physical condition where the shafts of two coupled units are not parallel (angular misalignment) or are not in the same vertical and horizontal planes, (offset) Misalignment will generate a spike on the frequency spectrum at twice the operating speed of the units.

Low Pass Filter – A filter whose transmission band extends from an upper cutoff frequency down to DC.

Measurement units – Mils. Displacement is measured in mils, a mil is one thousandths of an inch. Displacement is stated in Peak to Peak. See sine Wave.

IPS. Inches per second. A measurement of velocity, the speed the item being measured is moving. Velocity is stated in Peak.

G's. Acceleration . The rate of change of the velocity. A measure of the force being applied to the item being measured. Acceleration is stated in Peak.

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Misalignment – A physical condition where the shafts of two coupled units are not parallel (angular misalignment) or are not in the same vertical and horizontal planes, (offset) Misalignment will generate a spike on the frequency spectrum at twice the operating speed of the units.

Modulating – When the vibration signal amplitude rises and falls over time. For example, a flaw on the inner race of a bearing will rotate in and out of the load zone. When in the zone, the amplitude will be high and when it rotates out of the zone the amplitude will fall. In the frequency spectrum modulating signals will generate sideband harmonics, the spacing of the harmonics will equal the speed (CPM) of the shaft.

Mounting stud – a threaded screw used to attach a sensor to the structure.

Multi-Parameter Monitoring – A condition monitoring method that uses various monitoring technologies to best monitor machine condition.

Natural Frequency – The frequency of free vibration of a system. The frequency at which an non-damped system with a single degree of freedom will oscillate upon momentary displacement from its rest position.

Noise – Any undesired signal

Non-intrusive examination – The technique of determining the mechanical condition of equipment without stopping, opening, or modifying the equipment

Non-synchronous – The amplitude sum of all frequencies that are not below 1X or multiples of 1X. See synchronous and sub-synchronous.

Oil analysis – A laboratory technique to analyze the composition of lubricating oil to determine if any foreign materials are present. Presence of bearing material would indicate wearing of the bearing and the quantity would indicate the amount of wear. Used primarily on plain bearings.

Orbit – The path of shaft centerline motion during rotation.

Outage – There are two types of outages, planned or forced. A planned outage is when the unit is shutdown and work is performed as planned. A forced outage is when the unit fails and work is performed usually on an emergency basis.

Overall – A number representing the amount of energy found between two frequencies. The frequency range that the overall is derived from and the type (Average, RMS, Peak, Peak-to-Peak) are usually user selectable.

Overall Amplitude – Total amount of vibration occurring in the frequency range selected.

Overlap Processing – The concept of performing a new analysis on a segment of data in which only a portion of the signal has been updated (some old data, some new data).

Peak – The maximum positive amplitude shown on a sine curve. See sine wave.

Peak Hold – A menu choice on data collectors. The data collector will continuously collect data and as the amplitude varies, will capture and hold the latest peak amplitude. This will continue until the data collection is halted.

Peak Spectra – A frequency domain measurement where, in a series of spectral measurements, the one spectrum with the highest magnitude at a specified frequency is retained.

Peak to Peak – The sum of the maximum and minimum amplitudes shown on a sine curve. See sine wave.

Period – The time required for a complete oscillation or for a single cycle of events. The reciprocal of frequency, F=1/T

Periodic maintenance – Maintenance that is performed on a calendar or some measure of time basis, i.e., every 12 or 18 months, every so many RPMs, or every so many hours.

Phase – A measurement of the timing relationship between two signals, or between a specific vibration event and a Keyphasor pulse.

Phase Reference – A signal used in rotating machinery measurements, generated by a sensor observing a once-per-revolution event.

Phase Response – The phase difference (in degrees) between the filter input and output signals as frequency varies; usually expressed as lead and lag referenced to the input.

Phase Spectrum – Phase frequency diagram obtained as part of the results of a Fourier transform.

Piezoelectricity – The property exhibited by some materials where a mechanical stress causes the material to produce an electric charge. Both man made and natural piezoelectric materials are used in accelerometers.

POINT – Defines a machinery location at which measurement data is collected and the measurement type.

Position – The average location, relative to the radial bearing centerline, of the shaft dynamic motion.

Predictive Maintenance – Usually maintenance that is performed again based on a calendar. The term is usually interchanged with periodic maintenance.

Probe – An eddy-current sensor, although sometimes used to describe any vibration sensor.

Probe Gap – The physical distance between the face of an eddy probe tip and the observed surface. The distance can be expressed in terms of displacement (mils, micrometers) or in terms of voltage (millivolts), which is the value of the (negative) dc output signal and is an electronic representation of the physical gap distance. Standard polarity convention dictates that a decreasing gap results in an increasing (less negative) output signal; increasing gap produces a decreasing (more negative) output signal.

Radial – Direction perpendicular to the shaft centerline.

Radical measurement – Measurements taken perpendicular to the axis of rotation to measure shaft dynamic motion or casing vibration

Radial Vibration – Vibration that is perpendicular to a shaft's centerline.

Resonance – Resonance – The condition of vibration amplitude and phase change response caused by a corresponding system sensitivity to a particular forcing frequency. A resonance is typically identified by a substantial amplitude increase, and related phase shift. See natural frequency

RMS – Root Mean Square – The measure of energy displayed in a frequency spectrum. It is derived by squaring each spectrum line, summing the results, and taking the square root of the sum. It also equals (Peak) X 0.707. See sine wave.

Rolling element Bearing – Bearings whose low friction qualities derive from lubricated rolling elements (balls or rollers).

Rotor – The rotating portion of a pump, fan or motor.

ROUTE – A measurement POINT collection sequence.

Runout – The amount of wobble at the end of a rotating shaft.

Run Up/Run Down – The monitoring of machinery conditions during a start up or shut down process.

SEE Technology (Spectral Emitted Energy) – The analysis process where the high frequency acoustic signals generated when the rolling element in a bearing passes over a flaw in the bearing surface. The signals are emitted by the microscopic movement of the metal crystals as they rub against each other. These signals are then enveloped and presented in the low frequency spectrum. The display signal will be at the characteristic bearing frequencies, BPFO, BPFI, etc.

Sensitivity – The ratio of magnitude of an output to the magnitude of a quantity measured. Also the smallest input signal to which an instrument can respond.

Sensor – A transducer that senses and converts a physical phenomenon to an analog electrical signal.

Setpoint – (See alarm setpoint.)

Sidebands – Evenly spaced peaks centered on a major peak.

Signal Analysis – Process of extracting information about a signal's behavior in the time domain and/or frequency domain. Describes the entire process of filtering, sampling, digitizing, computation, and display of results in a meaningful format.

Spectrum – A display of discrete frequencies and their amplitudes.

Spectrum Analyzer – An instrument that displays the frequency spectrum of an input signal.

Thermocouple – A temperature sensing device comprised of two dissimilar metal wires which, when thermally affected (heated or cooled), produce a change in electrical potential.

Time Domain – A dynamic amplitude vs. time graph.

Time Waveform – (See Waveform.)

Transducer – A device that translates a physical quantity into an electrical output.

Trend – The measurement of a variable (such as vibration) vs. time.

Trigger – Any event that can be used as a timing reference.

Upload – Transferring data from the measuring device to the host computer.

Vibration – The behavior of a machine's mechanical components as they react to internal or external forces. Magnitude of cyclic motion; may be expressed as acceleration, velocity, or displacement. Defined by frequency and time-based components.

Waveform – A presentation or display of the instantaneous amplitude of a signal as a function of time.