VIBES Corp®
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SERIOUS SERVICE®
Professional Machinery Health Care
(Fan Doctor®)
Vibration Industrial Balancing & Equipment Services, Corporation
720 - 999 W. Broadway, Vancouver, BC V5Z 1K5
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Phone: 604 - 619 - 9381 (24/7)

Learn About Vibration

Volume 2: Advanced Vibration Analysis

Revised as of 2022

VIBES Corp uses Symphony Industrial CX 8 Trio Watchman computer c/w ExpertAlert software version 4.0 in our everyday vibration analysis work. Vibes Corp is Canada Support for customer training and vibration monitoring program start for larger industrial sites.

This article contains sections of the Training Manual titled:

VIBRATION and the SPECTRUM and also a

VIBRATION Reference Guide

The following information is meant for sharing knowledge in the science and technology to help the reader understand advanced vibration analysis and reports submitted by any vibration specialists.

Please note: Mechanical inspections must always be done as well to confirm overall conditions.

Presented by: Garrett Sandwell, MET, CVA, ASNT 3

CEO

Revised as of 2022

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Introduction to **VIBES Corp®**

Why work with us? Serving Canadian Industry for over 50 Years.

VIBES Corp's reputation was built and established on thousands of promises fulfilled over 50 years in business across Canada. Superior quality service, sales and training courses provided on the intelligent specialist level has been the standard and always will be since our vibration and balancing business was formed in Calgary, AB, in 1982. (Formerly Industrial Balancing Ltd. Est. 1967) In the final real-time analysis VIBES Corp will deliver more value and peace of mind.

What do we do? Expert technical services and preventative maintenance programs using advanced instruments and tools to solve various vibration, balance and mechanical noise related problems.

Factory trained and repair specialists on HVAC, fans, blowers, cooling towers, pumps, motors, industrial rotors. FlaktWoods Varofoils and Aerofoils, Sheldons Axico, Aerovent, Novenco, New York Blower, Chicago Blower, Canadian/Buffalo Blower, CML Northern Blower, Joy Axivane, Twin City, Alphair, Allied Blower, Markhot Varivane, Loren Cook, BAC, Evapco, Marley, Hoffman, Spencer, Baldor, Reliance, Trane, Carrier, Eng.Air, Haakon, WEG, Leeson, GEC, GE, Emerson, Westinghouse, Toshiba, Siemens, US Electric, Delhi, PennBarry, Armstrong, Westcan, Bell & Gossett, and most types of rotating, diesel engines & reciprocating machinery.

What do we sell, supply, install & service?

- WEG Electric Motors
- Canada Support - Symphony Industrial AI - Engineered Vibration Solutions & Client Training
- COOLBLUE - Inductive Absorbers & Chokes = VFD any motor shaft current bearing damage protection
- DRIVE SYSTEM PARTS: Fans, Bearings, Sheaves, Couplings, Belts, Shafts, Misc.
- VIBRATION CONTROL, Isolation & thrust spring mounts, monitoring, trending, alarm/trip switch 24/7 machine protection

The machinery under our professional health care program = **VIBES-GUARD PdM Program®** are treated as if our own. We use proven technologies and methodologies along with our multi-technical and electro-mechanical (VIV, ASD, VPM, CPM, VFD, EIBD, EDM, Shaft Currents, etc.) training, skills, and experiences for total overall analysis and evaluations. When the total analyzed facts about a machine, motor or engine are known we formulate an accurate condition report and recommend the best possible solutions. We work with clients to organize necessary actions in order of urgency or budgets.

Where do we work? (Commercial Towers, Infrastructure Facilities, Industrial Plants, Lumber Processing & Marine Ports, etc.)

Our service area is mainly BC Lower Mainland and Vancouver Island. If requested we can service other areas.

Who have we worked with?

VIBES Corp service capabilities have been used and accepted by high-ranking officials in:

- other service companies
- manufacturing and processing
- engineering firms
- universities
- colleges
- hospitals
- cold storage
- power plants and dams
- sewage and water treatment plants
- government infrastructure facilities
- oil and gas
- biogas energy systems
- transportation and construction
- commercial towers
- agricultural
- mining
- ski hills
- marine-terminals and ships
- asphalt and cement
- saw mills
- pulp and paper
- research and development
- machining / fabrication
- chemical plants
- restaurants
- skytrain and railway tunnels

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We take due diligence to the highest level on all projects regardless of size or budget.

Learn About Articles

You can download educational articles from our home page at www.vibescorp.ca. Here are five:

1. Learn About Vibration Volume 1: Basic Understanding Of Machinery Vibration
2. Learn About Vibration Volume 2: Advanced Vibration Analysis
3. Learn About Electrically Induced Bearing Damage & Shaft Currents
4. Failure Prevention Of Variable Pitch in Motion Axial Fans and Controllable Pitch In Motion Axial Fans
5. Learn About Agricultural Machinery Vibration Solutions

The photos below show typical projects that we have completed.

Fig 1. The failure was due to defective bearing.
Fig 2. The stainless steel guard helps prevent moisture contamination in cooling tower fan bearings (a very common problem).
Fig 3. A new fan was installed due to a complete failure of the original.
Fig 4. Shows a 200HP motor and fan repair/replacement.

Fig. 1

Fig. 3

Solution to Fig. 1 Replaced both Fan Bearings & New Motor Required.

Solution to Fig. 2 The Guard has prolonged the Life Span of the Fan Bearings from 3 years to over 14 years.

Solution to Fig. 3 Installed Brand New Controllable Pitch Fan & Repaired Motor.

Solution to Fig. 4 Replaced the Old Motor based on 20 years of running time and Completed Variable Pitch in Motion Fan Maintenance.

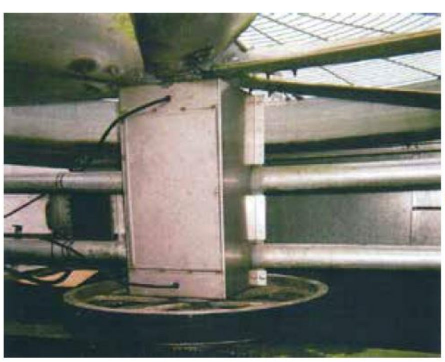

Fig. 2

Fig. 4

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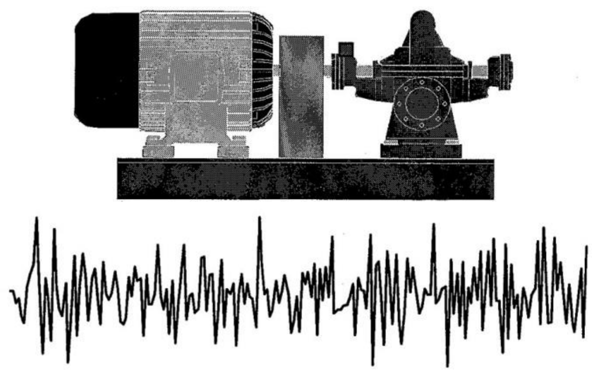


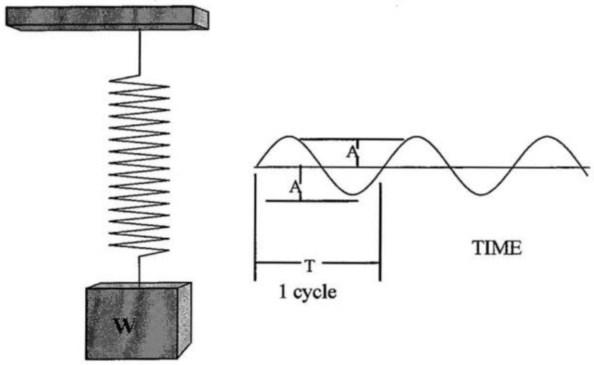
Vibration and the Spectrum

Objectives of this section

1. Understand simple harmonic motion and time domain representation of a sine wave.
2. Understand the relationship of vibration unit: amplitude (disp, veloc, accel, linear, log, VdB), Frequency (cpm, Hz, orders).

Simple Vibration

An example of simple vibration is a weight suspended on a spring as in Figure 1 below. If the weight is displaced downward from the point of rest of A and released, it will vibrate vertically through a distance of 2A. If we were to ignore losses due to friction the weight would continue vibrating definitely. This is called Simple Harmonic Motion, often abbreviated SHM. A plot of the movement of the weight versus time would be a sine wave. Because simple harmonic motion can be plotted with a sine wave, it is also know as sinusoidal motion.

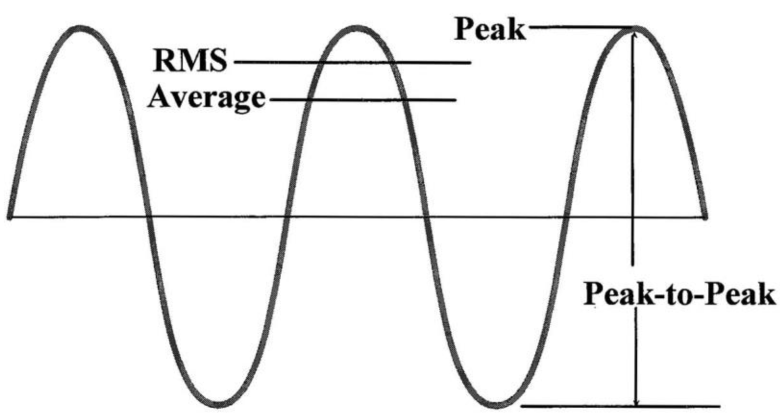


A = Amplitude or "How much does it move".

T = The time of one complete cycle or "How long does it take".

Sine Wave Relationships

Pk =	Peak Amplitude. The amplitude from zero reference to the positive or negative maximum, or top or bottom dead center.
Pk-Pk =	2xPk. Peak to Peak Amplitude. The amplitude from the positive or negative maximum. This value would be equal to the total indicated runout (TIR) of a dial indicator on an eccentric rotating shaft.
RMS =	0.707 Pk. The Root Mean Square Amplitude. Equal to the square root of the sum of squares for all the amplitude values of the sine wave in one cycle.



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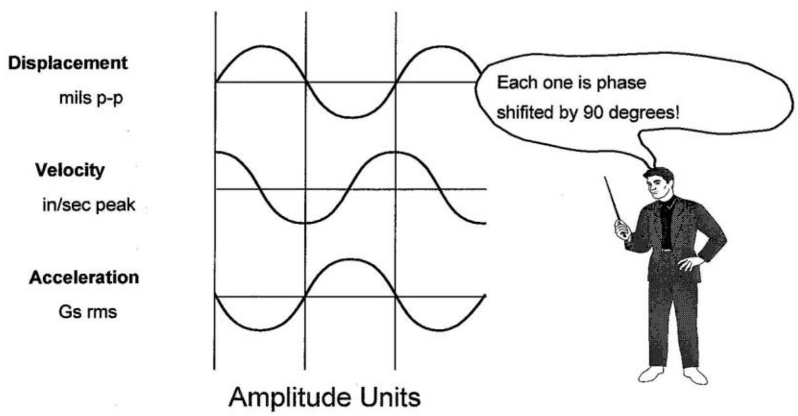
Vibration Units

So far, we have been looking at **displacement** of a vibrating object as a measure of its vibration amplitude. The displacement is simply the distance from a reference position, or equilibrium point. Displacement is defined as the actual distance the vibration causes a part to move, and is measured in thousands of an inch (mils) or millimeters (mm). By popular convention, displacement measurements are made in peak-to-peak units (p-p). In addition to varying displacement, a vibration object will experience a varying **velocity** and a varying **acceleration**. Velocity is defined as the rate of change of displacement and is usually measured in units of inches per second (ips). Acceleration is defined as the rate of change of velocity, and is usually measured in units of **G**, or the average acceleration due to gravity at the earth's surface.

The displacement of a body undergoing simple harmonic motion is a sine wave as we have seen. It also turns out (and is easily proved mathematically), that the velocity of the motion is sinusoidal. When displacement is at a maximum, the velocity will be zero because that is the position at which its direction of motion reverses. When the displacement is zero (the equilibrium point), the velocity will be at a maximum. This means that the phase of velocity wave form will be displaced to the left by 90 degrees compared to the displacement wave form. In other words, the velocity is said to lead the displacement by a 90 degree phase angle.

Remembering that acceleration is the rate of change of velocity, it can be shown that the acceleration wave form of an object undergoing simple harmonic motion is also sinusoidal, and also that when the velocity is at a maximum, the acceleration is zero. In other words, the velocity is not changing at this instant. Then, when the velocity is zero, the acceleration is at a maximum – the velocity is changing the fastest at this instant. The sine curve of acceleration versus time is thus seen to be 90 degrees phase shifted to the left of the velocity curve, and therefore acceleration leads velocity by 90 degrees.

These relationships are shown here:

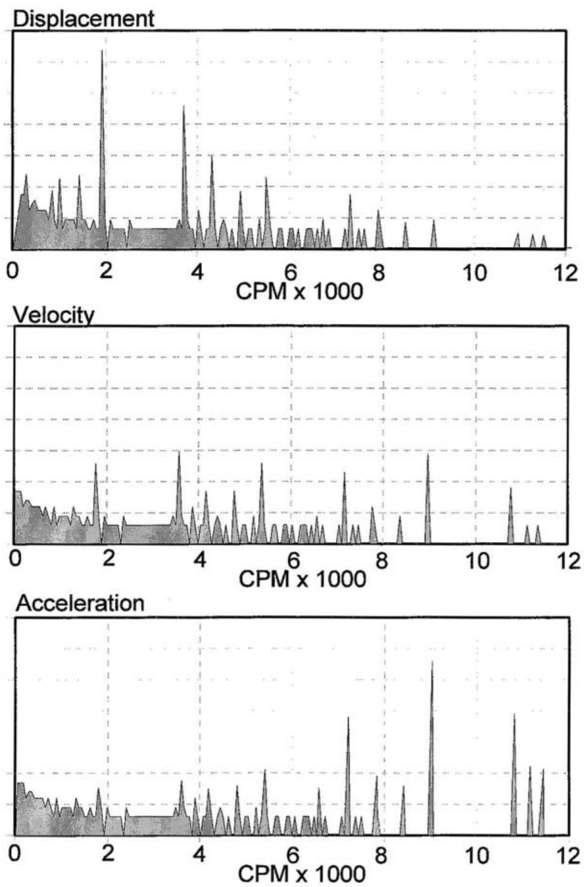


Note here that acceleration is 180 degrees out of phase with displacement. This means the acceleration of a vibration object is always in the opposite direction to displacement.

Displacement, Velocity, and Acceleration

A vibration signal plotted as displacement vs. frequency can be converted into a plot of velocity vs. frequency by a process called differentiation. Differentiation is a mathematical process, which converts a displacement signature to a velocity signature, or a velocity signature to an acceleration signature.

From these considerations, it can be seen that the same vibration data plotted in displacement, velocity, and acceleration will have very different appearances. The displacement curve will greatly emphasize the lowest frequencies, and the acceleration curve will greatly emphasize the highest frequencies at the expense of the lowest ones.

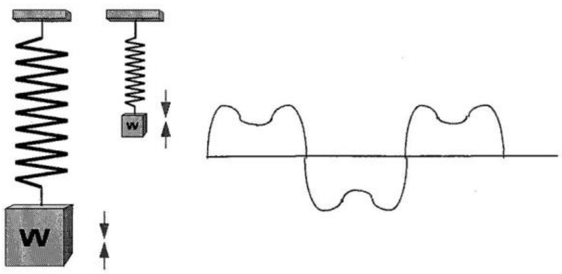


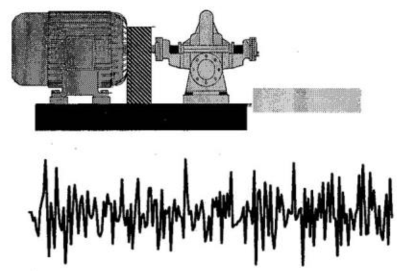
The three curves above display the same information, but the emphasis is changed. Note that the displacement curve is difficult to read at higher frequencies, and acceleration has enhanced higher frequency levels. The velocity curve is the most uniform in level over frequency. This is typical of most rotating machinery, but in some cases the displacement or acceleration curves will be most uniform. It is a good idea to select the units so the flattest curve is obtained – this provides the most visual information to the observer. Velocity is the most commonly used vibration parameter for machine diagnostic work.

Complex Vibration

In real machines, there is **usually more than one source of vibration**. For example, there may be one source of vibration from a gear mesh and another from a gear bearing. To illustrate this, let's take another look at the spring system described earlier.

If two different weights are suspended side by side from two different springs, there will be two separate sinusoidal vibratory inputs to the system. Two separate forces will act on the bar supporting the springs. The frequency and amplitude of the **two forces** will be different and will **add together** at the support. If an accelerometer is attached to the support, the resulting vibration signal that results from the input of the separate sinusoidal vibrations will be a complex cyclic wave. However, even though the wave from the accelerometer signal does not look like a sine wave, it can be broken down into two pure sine wave components.



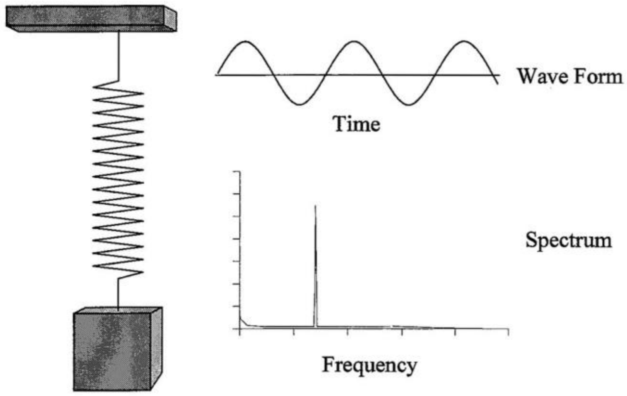


Vibration generated by a **typical machine** would appear as a **number of individual springs** or forces. A time domain plot of a typical machine is illustrated below.

Time Domain and Frequency Domain

Before we look at specific machine faults, it will be helpful to understand the relationship between vibration data displayed in the **time domain** and the same data displayed in the **frequency domain**. To help you understand why machine faults appear as they do on the frequency domain graphs, we will study an idealized example of mechanical motion.

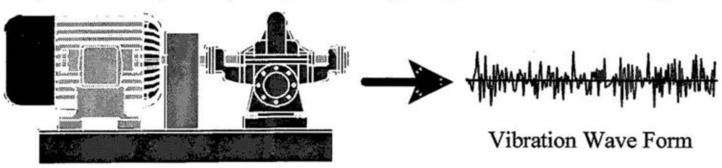
The following illustration compares the same information presented in the time domain and the frequency domain. The time domain representation is called the **wave form**, and the frequency domain graph is called the **spectrum**. A simple mass suspended from a spring will vibrate with a smooth up and down pattern that we call "simple harmonic motion". The shape of the graph of the instantaneous position of the mass vs. time is called a **sine wave**, and this is the same sine wave you may remember from your high school mathematics courses.
The complete characteristics of the motion of the mass can very easily be seen from either of the two presentations. The wave form shows repetitions of the same curve shape, and the time it takes for one repetition of the wave form is called the **period** of the wave. Any wave form which repeats the same shape over and over is called a **periodic** wave form. The number of these repetitions that occur in one second gives us the **frequency** of the motion. The excursion of the graph up and down from the zero position represents the **amplitude** of the motion. These two components, amplitude and frequency, can be more easily seen from the spectrum; The frequency is represented by the position along the horizontal axis, and the amplitude is simply equal to the maximum height of the peak.



The complex vibration from our **two oscillating weights** would be represented in the frequency domain by **two separate vertical lines** equal in height to the amplitude of each sine wave component that made up the complex wave. The amplitude lines of the sine waves would each be located on the X-axis, which would correspond to the frequency of each sine wave. Similarly, the height of each line would indicate the amplitudes of the sine waves.

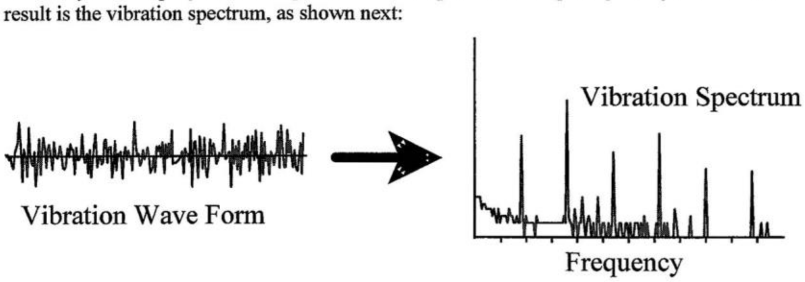
Time domain and Frequency domain display of the same data

Unfortunately the vibration data that you collect on your machinery will not produce such simple wave forms as in the previous example. They will produce complex signals that look something like the following illustration.



The wave form shown above contains all the information about the vibration of the machine at the point where it was measured, but the individual patterns of vibration caused by different effects in the machine are all overlapped and jumbled together. By examining this wave form, it would be very difficult, if not impossible, to separate all the individual motions of the machine that are represented.

To clarify and simplify the data representation, we perform a **frequency analysis** of this vibration signal, and the result is the vibration spectrum, as shown next:



Note that the spectrum generated from this wave form looks much simpler than the wave form, and there are discrete peaks present. These peaks are at specific frequencies that represent phenomena that are going on in the machine. Most of the discipline of machine diagnostics is involved with matching up the peaks in the spectrum with events that exist in the machine. That is the topic we will investigate in the next section.

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Although the spectrum is almost always a very simple and clear way to present vibration data, there are some instances where it is actually too simple, and the wave form is sometimes able to give us more information about the machine. Wave form analysis is a more advanced topic, and we will not go into it now, but you should be aware that it exists and can be of great benefit, especially with very slow-moving machines and in diagnosing cavitation in pumps, to name two applications.

Frequency Analysis

To get around the limitations in the analysis of the wave form itself, the common practice is to perform frequency analysis, also called *spectrum* analysis, on the vibration signal. The time domain graph is called a wave form, and the frequency domain graph is called the spectrum. Spectrum analysis is equivalent to transforming the information in the signal from the time domain into the frequency domain. The following relationships hold between time and frequency:

$$\text{Time} = \frac{1}{\text{Frequency}} \qquad \text{Frequency} = \frac{1}{\text{Time}}$$

Why perform Frequency Analysis?

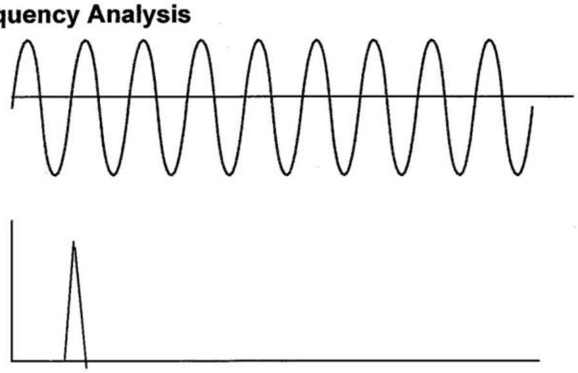
In the time domain wave form, individual frequency components are difficult to extract, and are not easily identifiable. The vibration wave form contains a great deal of information which is not apparent to the eye. Some of the information is in very low-level components whose magnitude may be less than the width of the line of the wave form plot. Nevertheless, such very low-level components may be important if they indicate a developing problem such as a bearing fault. The essence of predictive maintenance is the early detection of incipient faults, so we must be sensitive to very small values of vibration signals, as we will see shortly.

On the other hand, there are circumstances where wave form provides more information to the analyst than does the spectrum.

Basic rules in performing Frequency Analysis

Following are some wave forms and spectra which illustrate some important characteristics of frequency analysis. While these are idealized, they do show certain attributes which are commonly seen in machine vibration spectra.

Rule #1 for Frequency Analysis



A sine wave consists of a single frequency only, and its spectrum is a single point. Theoretically, a sine wave exists over an infinite time and never changes. The mathematical transform which converts the time domain wave form into the frequency domain is called the *Fourier transform*, and it compresses all the information in the sine wave over infinite time into one point.

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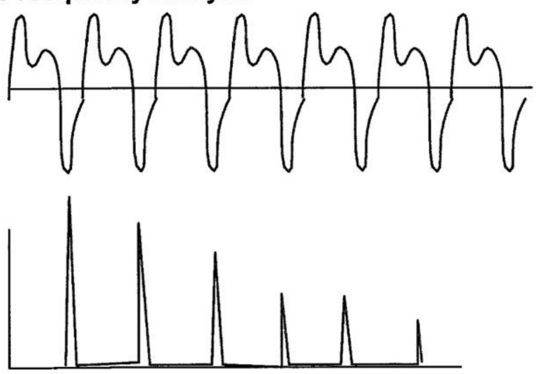
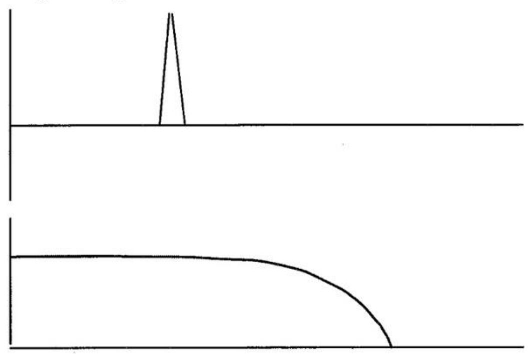
Rule #2 for Frequency Analysis



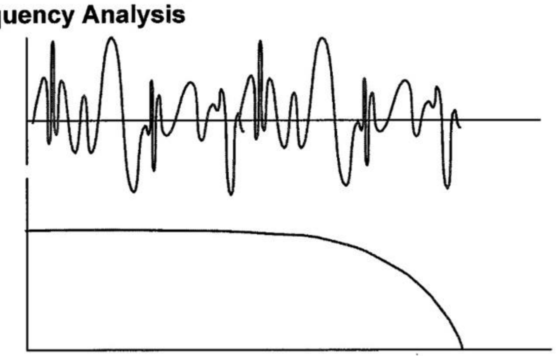
A periodic signal produces harmonics.

Rule #3 for Frequency Analysis

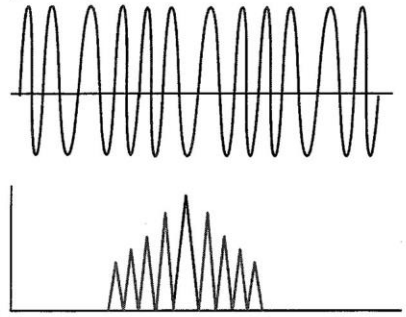


An impulse produces a continuous spectrum. Note that the spectrum above is continuous rather than discrete. In other words, the energy in the spectrum is spread out continuously over a range of frequencies rather than being concentrated only at specific frequencies. This is a characteristic of non-deterministic signals such as random noise and transients.

Rule #3.5 for Frequency Analysis

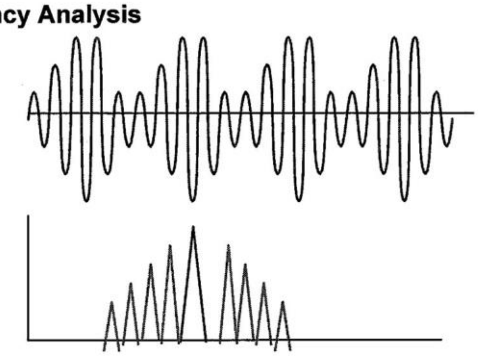


Rule #4 for Frequency Analysis



Amplitude Modulation produces Sidebands. Notice that the frequency of the wave form seems to be constant and that it is fluctuating up and down in level at a constant rate. The spectrum has a peak at the frequency of the carrier, and two more components on each side. These extra components are sidebands. You will see that there are only two sidebands here compared to the great number produced by frequency modulation. This type of signal is often produced by defective bearings and gears, and can be easily identified by the sidebands in the spectrum.

Rule #4.5 for Frequency Analysis



Frequency Modulation produces sidebands. Frequency modulation is the varying in frequency of one signal by the influence of another signal, usually of lower frequency. In the spectrum shown above, the largest component is the carrier, and the other components, which look like harmonics, are the sidebands. The sidebands are symmetrically located on either side of the carrier, and their spacing is equal to the modulating frequency. Frequency modulation occurs in machine vibration spectra, especially in gearboxes where gear mesh frequency is modulated by the rpm of the gear.

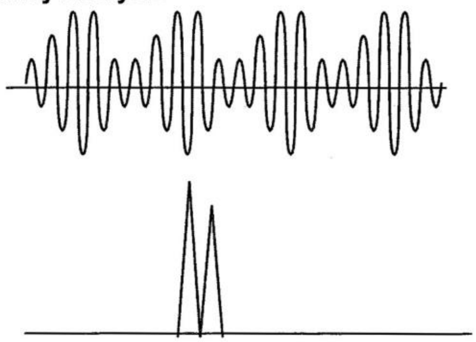
Modulation Summary

Modulation is a non-linear effect in which several signals interact with one another to produce new signals with frequencies not present in the original signals. The modulated signal is called the carrier and the carrier is usually higher in frequency than the modulated signal. In rotating machinery there are many fault mechanisms which can cause amplitude and frequency modulation, and vibration analysis can expose the sidebands, or can perform demodulation to detect the faults.

Sidebands

Sidebands are spectral components which are the result of Amplitude or Frequency modulation. The frequency spacing of the sidebands is equal to the modulating frequency, and this fact is used in diagnosing machine problems by examining sideband 'families' in the vibration spectrum.

Rule #5 for Frequency Analysis



Beats do not produce sidebands. If two vibration components are quite close together in frequency, they will combine in such a way that their sum will vary in level up and down at a rate equal to the difference in frequency between the two components. This phenomenon is known as beating, and its frequency is the beat frequency.

There is confusion in some areas between beating and amplitude modulation, which also can produce undulating vibration level. Amplitude modulation is a different effect, and is caused by a low-frequency component being multiplied by a higher-frequency component and is thus a non-linear effect, whereas, beating is simply a linear addition of two components

The following example provides another view of the relationship between Time Domain and Frequency Domain Analysis:

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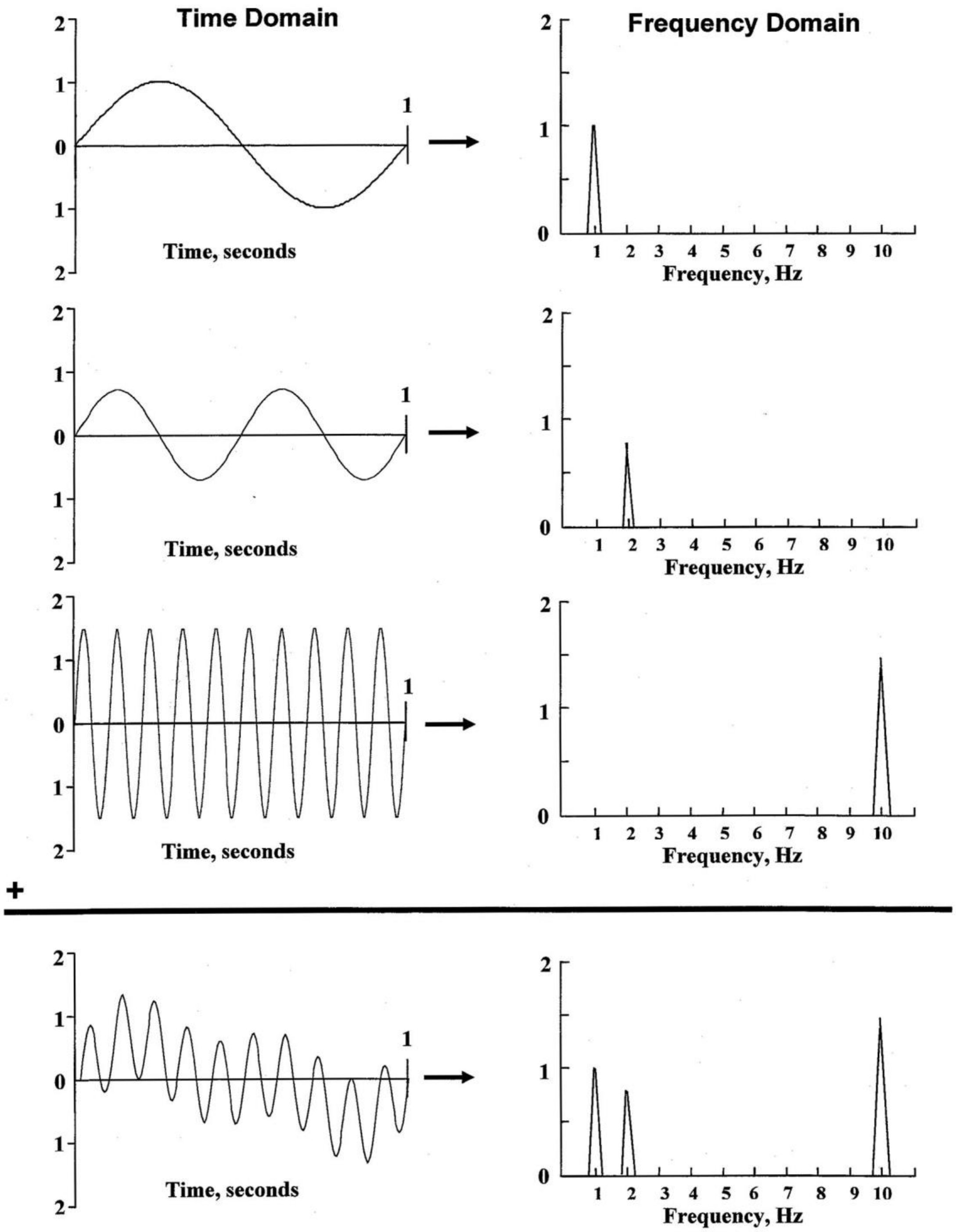
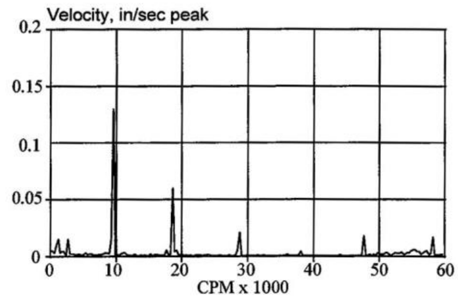


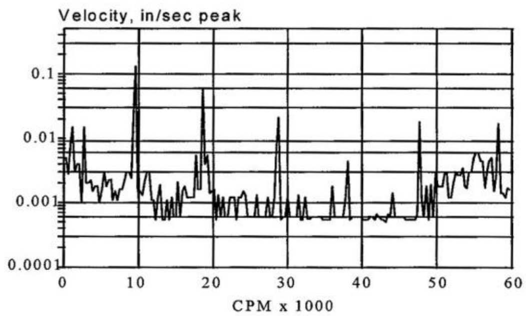
Vibration Amplitude Scales

Linear Amplitude Scaling

It might seem at first glance that the logical way to graph a vibration velocity spectrum would be to simply express the amplitudes directly in inches per second along the vertical axis of the graph. This is known as a linear amplitude representation. An example of such a velocity spectrum is shown in the figure below:



Linear Amplitude Scaling



Logarithmic Amplitude Scaling

Here, the amplitude scale runs from zero at the bottom to 0.2 ips at the top of the graph. In order to express the levels of the various peaks in the spectrum, we use decimal points, i.e., at 9990 CPM, the level is 0.129 ips, and at 55,000 CPM, the level is 0.0034 ips.

Note that this linear spectrum shows the **larger peaks very well**, but **low-level** information is **difficult to see**. In the case of machine vibration analysis, we are often interested in the smaller components of the spectrum, e.g., in the case of rolling element bearing diagnosis. Remember that in the case of machine vibration monitoring, we are interested in the **increases in level** of certain spectral components that **indicate incipient faults in the machine**. A ball bearing in a motor may develop a very small defect in one of the races or in a ball, but the vibration component at its particular signature frequency will be very small. This does not mean it is not important, for it is the ability to detect faults in their very early stages that gives the advantage to predictive maintenance practice. We must **monitor the level of this small fault over a period of time in order to predict when it will become a significant problem that requires action**.

It is obvious that if the level of any vibration component caused by a **fault doubles in magnitude, then a significant change has occurred** in the fault. The power, or energy, in a vibration signal is proportional to the vibration level squared, so a doubling in level means four times as much energy is being dissipated. If we are trying to trend the level of a spectral peak of 0.0034 ips, we will have a difficult time to do it visually because it appears so small on the graph compared to the much higher level components of the spectrum.

Why Use Logarithmic Amplitude Scale?

Remember that the purpose of vibration analysis is to detect early signs of machine faults. A fault such as a **failing bearing** in a machine will often first show up in the signature as **an increase in amplitude from a small vibration peak to a peak that is still small, but perhaps two or three times as large as it had been.** On a linear display of amplitude, this very important increase of the low amplitude signal will probably go unnoticed at the bottom of the vibration signature plot. On the other hand, small increases in amplitudes that are already large, such as rotor imbalance, will stand out more on the linear plot, and thus draw attention away from the more important change in the low amplitude peak. However, **on the logarithmic amplitude plot, a doubling, or any significant increase in the vibration amplitude, will always show up as a significant increase on the plot**.

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Logarithmic Amplitude Scaling

It is possible to scale the vertical vibration axis in term of the logarithm of the actual level in ips rather than the level itself. This has the effect of **reducing the differences between the highest peaks and increasing the visual amplitude and differences between the lower level peaks**.

Since this spectrum is on a log amplitude scale, multiplication by any constant value simply translates the spectrum up on the graph without changing its shape or the relationship between its components. According to the laws of logarithms, multiplication of the signal level translates into addition on a log scale. This means that if the amount of amplification of a vibration signal is changed, the shape of the spectrum is not affected. For instance, **if all the spectral components were multiplied by two, the entire curve would rise by about a half inch on the graph, but the shape of the spectral pattern would not change**. This fact greatly simplifies visual interpretation of log spectra taken at different gain settings, because with a linear scaling, the shape of the spectrum changes drastically with different degrees of amplification.

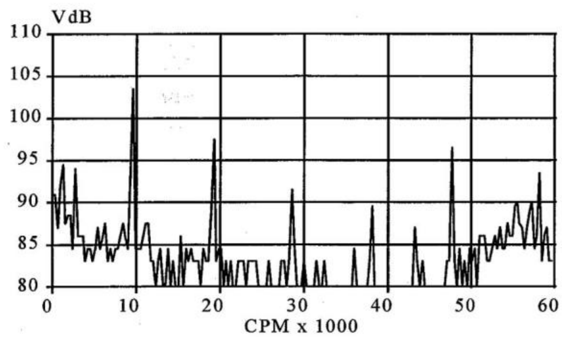
Note that the levels indicated on the left side of the graph still list the level in units of ips, but progressively more zeros are used as the level decreases. In order to quantify the absolute level of any peak in the spectrum still requires us to use the same notation as we did with a linear representation, e.g. with plenty of zeros and decimal points.

We now have a **tremendous advantage in visually interpreting the spectrum, for the overall pattern of the peaks is fixed when they are in a constant relationship with each other**. In other words, if we compare a log spectrum of a vibration signal from a machine whose bearings are wearing, the bearing tones will rise in level while everything else remains at the same level. The pattern of the spectrum will be visually different, and can be noticed at a glance.

While the log amplitude spectrum is a definite advantage in comparing spectra, there is another step we can take to simplify the situation even more. That is known as the Decibel, discussed next.

Decibel Amplitude Scaling

The spectrum shown below is presented in decibels, which is a convenient and widely used type of log scaling.



Decibel Amplitude Scaling

The **decibel scale is a log scale that represents amplitude ratios rather than amplitude values directly**, as explained in the glossary. In the case of vibration velocity decibels, abbreviated VdB, the values are defined by the following equation:

$$L_{dB} = 20\log_{10}\frac{L_1}{L_{ref}}$$ where, LdB = The signal level in dB

L_1 = Vibration level in Acceleration, Velocity, or Displacement

L_{ref} = Reference level, equivalent to 0 dB, = 10^{-8} meter/sec

The VdB value is the number of decibels above the reference value, or above the zero dB level.

The **decibel scale has the distinct advantage that all the amplitudes are represented by fairly small numbers with few decimal points, and the same number of dB represents the same level ratio regardless of absolute level**

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of the signal. For instance, a change of 6 dB is always a change by a factor of two in amplitude. This is also a change in power by a factor of four, as explained in the appendix.

There are several rules of thumb that are convenient to memorize when working with dB scales.

dB Change	Level ratio
3	1.4
6	2
10	3
20	10

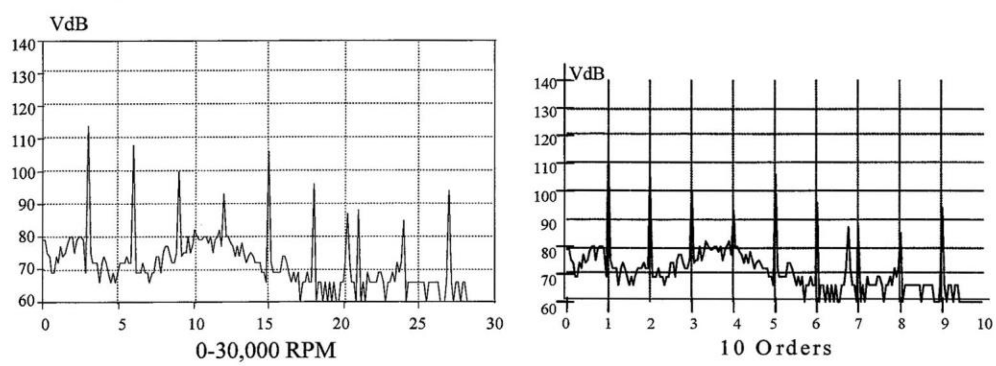
Order Normalization

One must be careful with order normalization, however. For instance if a machine has two or more shafts turning at different speeds, the spectrum can be normalized for only one shaft speed at a time.

Instead of expressing vibration spectra in frequency units of hertz (Hz) or CPM (RPM), it is often desirable to use orders, or multiples of the RPM of the machine. The first order is called 1X, the second 2X, etc. In an order normalized spectrum, each of the harmonics of turning speed is in the same location on the graph, regardless of the speed. This is especially valuable if you want to compare several measurements on the same machine that were taken at different times, and the speed has varied a little between measurements.

Order normalization is performed by the software, and under certain conditions it is possible for the software to select the wrong peak as the 1X component. For this reason it is important for the analyst to verify that the normalization was correctly done if a spectrum looks vastly different than other spectra taken from the same machine. In such a case, the analyst must re-normalize the spectrum.

The following is a **non-order normalized** spectrum, scaled from zero to 30,000 RPM.



Conventional Vibration Spectrum Order Normalized Spectrum

Note that the peaks on the left appear to be equally spaced, but it may be difficult to tell which one near 20,000 CPM is a shaft harmonic. The next figure is a normalized spectrum scaled from 0 to 10 orders. Note that the harmonics of rotation speed are integers on the frequency scale, and that the peak below 7X is immediately seen as a **non-synchronous** component. Non synchronous tones are described in the section on rolling element bearings.

Why use Order Normalization?

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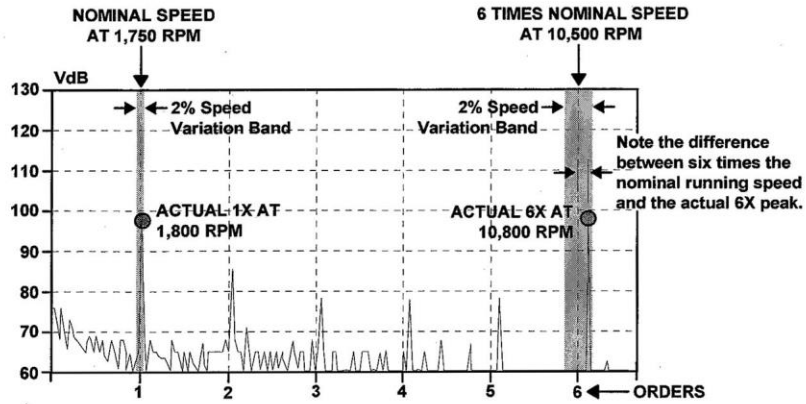
As an example, we have a machine with the nominal running speed entered as 1750 RPM, and a speed variation of 2%. We have also entered a 6X vane rate frequency for this machine in the relevant Machinery Identification Designator (MID). As illustrated below, when a spectrum from this machine is sent to the normalization procedure, it will first look for the highest peak in an band of 2% on either side of the entered frequency. It will then search for a peak in a 2% band around six times the entered frequency to confirm its estimation.



If the RPM of the spectrum has been set using any of the described techniques, then the software normalization method will use *this* value as the 'speed', not the nominal. This particularly useful if the speed varies considerably and the spectra are complex (for example, a belt driven machine).

Advantages to Order Normalization in the spectra:

- The fundamental rotation speed is **instantly recognizable** at 1.0 order.
- **Harmonics** of the rotation speed **will be integers**.
- A **second shaft** in a gear-driven machine will have an order **equal to the gear ratio**.
- **Excitation frequencies**, such as gear mesh and pump vane pass, are readily recognized because their **order is equal to the number of elements**.
- **Bearing tones will be non-integer**, often the only major non-integer components.
- Sidebands around bearing tones will be easily recognized because they will be at the tone order ± 1, ±2, etc.
- Most important: Because machine speed is almost never exactly the same from test to test, the peaks in the spectrum will not be at the same frequencies, and the spectra cannot be averaged. **Normalized spectra have the peaks at the same frequencies from test to test, and they can be averaged without smearing**.

Machine Faults and Spectrum Analysis

Every machinery fault produces a unique type of vibration signal. When these signals are displayed in the vibration spectrum, a pattern will appear that is characteristic of that fault. When you learn how to recognize these particular patterns and relate them to their causes, you will be doing machine fault diagnosis. This pattern recognition is one of the key parts of predictive maintenance. Understanding forcing frequencies is the first step to understanding machine diagnostics. We will then begin to study the most basic of machine faults and their tell-tale vibration signatures that we can use to diagnose them.

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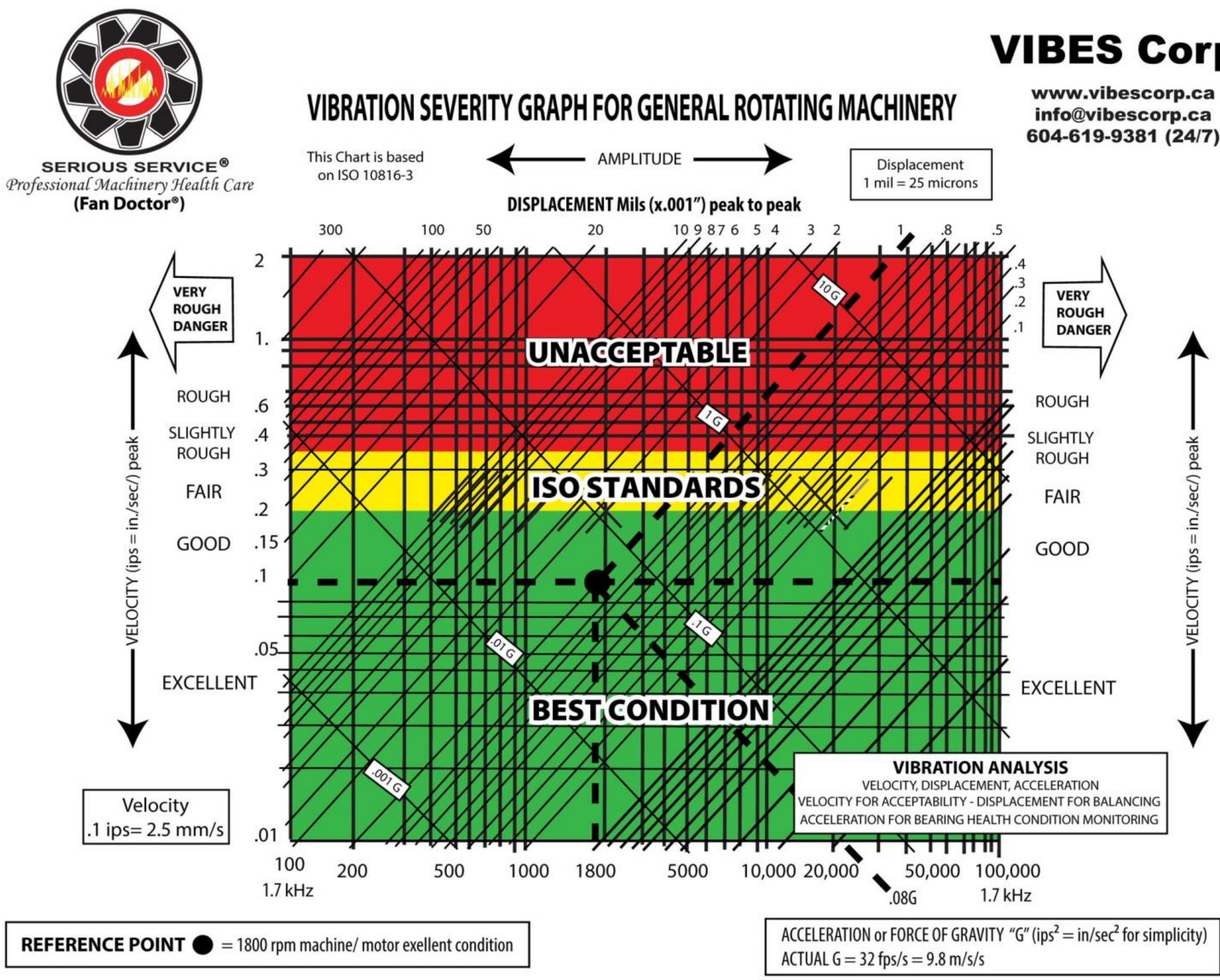

Note: the yellow area on chart represents issues that often can't be resolved due to time and cost.

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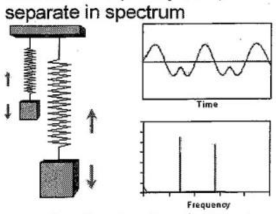
Basic Vibration Theory

Time vs. Frequency Analysis

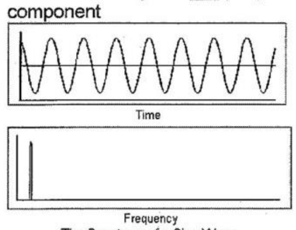
Individual frequency components are separate in spectrum



Time Domain vs Frequency Domain

Rule 1 for Frequency Analysis

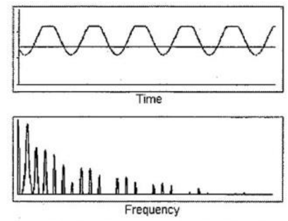
A sine wave only has one frequency component



The Spectrum of a Sine Wave

Rule 2 for Frequency Analysis

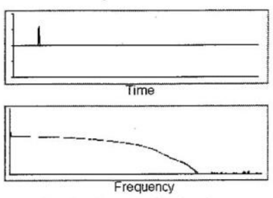
Periodic signals in machinery produce Harmonics



The Spectrum of a Periodic Signal

Rule 3 for Frequency Analysis

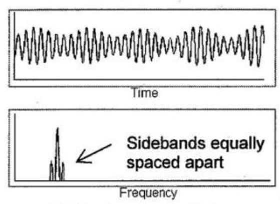
An impulse or random noise produces a continuous spectrum



The Spectrum of a Short Impulse

Rule 4 for Frequency Analysis

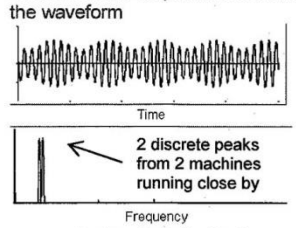
Amplitude Modulation produces Sidebands (e.g. gear fault)



The Spectrum of an Amplitude Modulated Wave Form

Rule 5 for Frequency Analysis

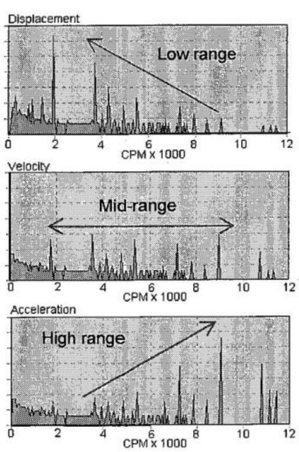
Beats look like amplitude modulation in the waveform



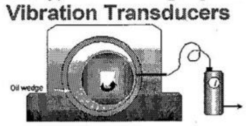
Spectrum of a Beating Signal

Presentation of Data

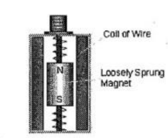
Each curve below contains the same information! Select the units for the flattest curve – provides the most visual information. Displacement (distance from a reference point) is used for low speeds. Velocity (rate of change of displacement) is the most commonly used for machine diagnostic work. Acceleration (rate of change of velocity) is used for high-speeds.



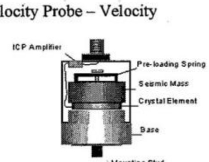
Vibration Transducers



Proximity Probe Displacement



Velocity Probe – Velocity

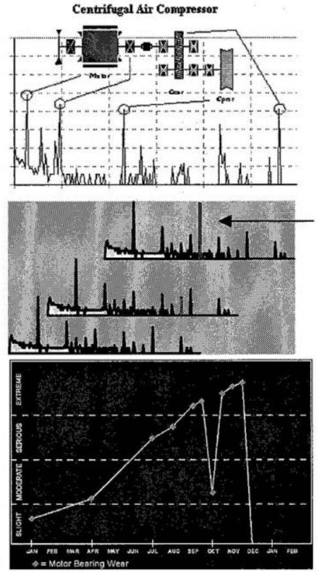


Accelerometer Acceleration

Vibration Analysis – 3 Step Process

1. **Identify Peaks**: Relationship to machine component
2. **Trend Amplitude of Peak**: Severity of machine fault
3. **Repair Priority**: Based on fault severity

Centrifugal Air Compressor



Bearing Fault grows

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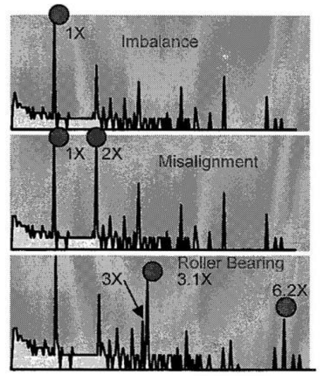
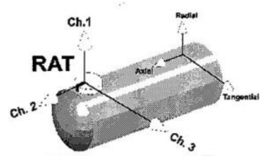
Simplified Diagnostic Chart

Vibration Source	Exciting Freq.	Dominant Axes	Comments
Imbalance, Supported	1X	R & T	Most common
Imbalance, Overhung	1X	A, R, T	Axial deflection
Bent or bowed shaft	1X	A, R, T	Mimic imbalance
Parallel misalignment	2X	R & T	Both sides of coupling
Angular misalignment	1X	A	Both sides of coupling
Combination	1X, 2X	A, R, T	Most common
Coupling Wear	3X	any, all	Both sides of coupling
Rolling Bearing	Non Integer	R, T, A	With harmonics, 1X sidebands, noise floor
Shaft Looseness And Journal Bearing	1X and Harmonics	R, T, A	High 4X – 15X
Foundation flexibility	1X	T	T > R by 6 dB
Motor Lamination	MB	R, T, A	120 Hz sidebands (twice line freq.)
Unbalanced Phase	120 Hz	R, T, A	Twice line freq
Fan or Pump wear	PV or FB	R, T, A	Vane or blade pass freq. and harmonics
Cavitation	Noise	R, T, A	Hump of random high freq. noise 20X – 50X





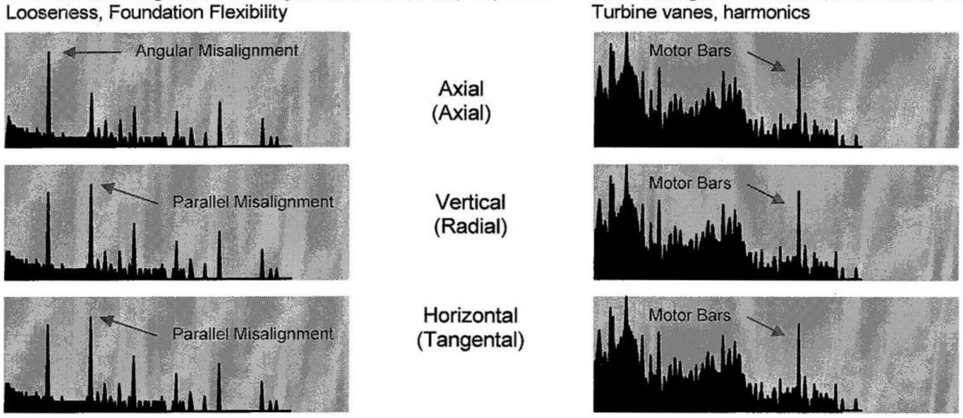
3 Axes of Data
Horizontal Shaft:
Radial = Vertical
Tangental = Horiz.

2 Frequency Ranges
Low Range = 0-10 Orders of shaft rotation
High Range = 0-100 Orders of shaft rotation

3 Axis and 2 Frequency Ranges

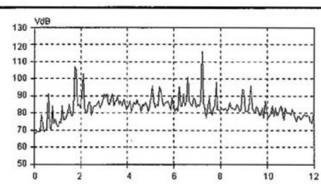
Low Range Data
Imbalance, Misalignment, Bearings, Fan blades, Pump Impeller, Looseness, Foundation Flexibility

High Range Data
First bearing fault indication, Motor Bars, Gear Mesh, Turbine vanes, harmonics

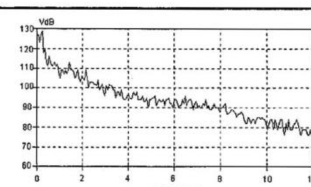


Data Validity

Bad Data comes from:
- Improper test conditions
- Wrong machine tested
- Sensor amplifier problem
- Incorrect orientation



Loose Sensor (magnet mount)



Overheated sensor (ski slope)

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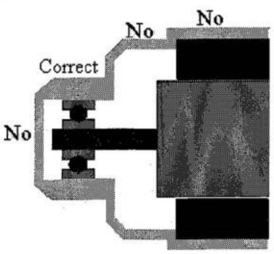
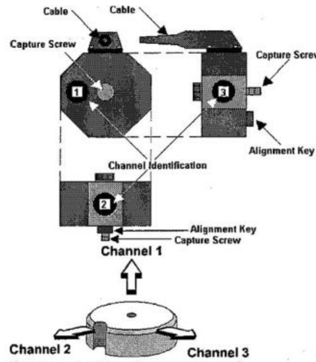


Accelerometer Location

Selecting Test Locations

1. Transmission Path
2. Frequency Response
3. Repeatability

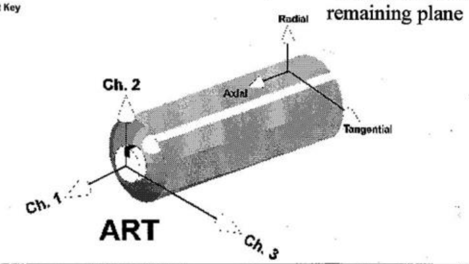


Sensor attachment pad

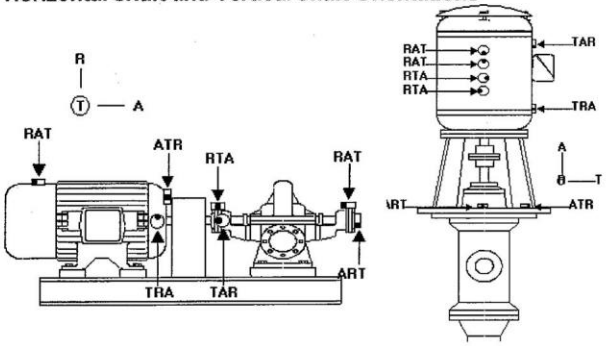
Selecting Orientations

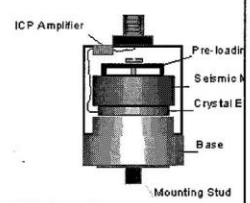
1-2-3	1-2-3
RAT	VAH
ART	AVH
TRA	HVA

- Sensor #1 is in line with captive screw
- Sensor #2 is in line with alignment pin
- Sensor #3 is in the remaining plane

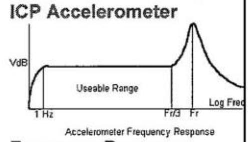


Horizontal shaft and Vertical shaft Orientations





ICP Accelerometer



Frequency Response

Maintenance Types:

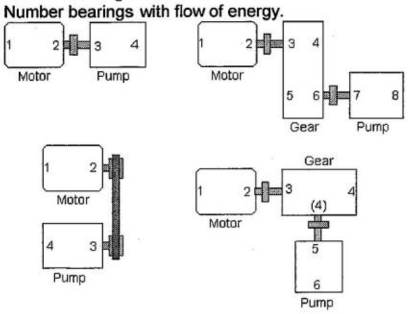
Reactive – Run to Failure
Preventive – Calendar based
Predictive – Condition based
Proactive – Root Cause Analysis

Keys to a Successful Program:

- Complete & repeatable data
- Get Answers, not just Data
- First rate support & training
- Distribute information to planners and managers

Sensor Location Numbering

Start numbering from driver free end.
Number bearings with flow of energy.



Sensor Location Numbering

Maintenance Planning

Extreme Faults – Shutdown machine for immediate repairs to avoid catastrophic failure
Serious Faults – Schedule normal repairs for planned outage or maintenance period
Moderate Faults – Increase frequency of collection / Review parts availability
Slight Faults – Monitor machine
Retest following maintenance – Verify maintenance performed correctly

Vibration Severity Considerations

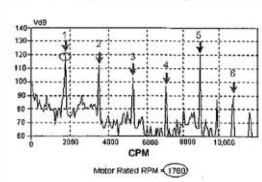
Harmonics – fault getting worse; looseness
Side-bands – modulation by another signal
Elevated noise floor – increase in background
Multiple symptoms – confirming evidence

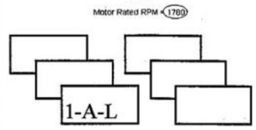
Sidebands in machine data

Roller bearing – 1X sidebands
Gear wear – 1X sidebands
Motor Bars – 120 Hz sidebands

Analyze Data

1. Find 1X peak and harmonics
2. Identify forcing frequencies
3. Identify machine faults – Imbalance, Misalignment, Bearings, Looseness
4. Compare data between axis / ranges
5. Compare data to baseline
6. Compare data to other like machines
7. Compare data to previous data





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VdB to IPS

VdB	ips peak	VdB	ips peak	VdB	ips peak
60	.0006	90	.018	120	.56
62	.0007	92	.022	122	.70
64	.0009	94	.028	124	.88
66	.0011	96	.035	126	1.1
68	.0014	98	.044	128	1.4
70	.0018	100	.056	130	1.8
72	.0022	102	.070	132	2.2
74	.0028	104	.088	134	2.8
76	.0035	106	.11	136	3.5
78	.0044	108	.14	138	4.4
80	.0056	110	.18	140	5.6
82	.0070	112	.22	142	7.0
84	.0088	114	.28	144	8.8
86	.011	116	.35	146	11.1
88	.014	118	.44	148	14.0

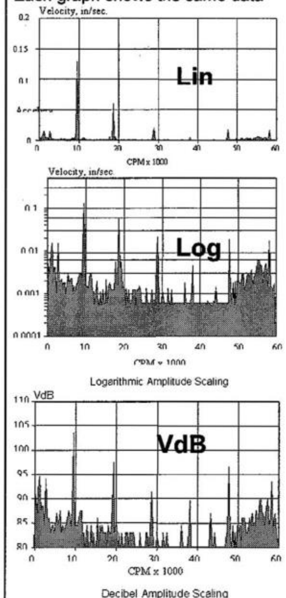
Log to Linear

dB Change	Linear Level Ratio
0	1
3	1.4
6	2
10	3.1
12	4
18	8
20	10

Analyze data with all of the tools available. Get familiar with both linear and log amplitude scales to optimize analysis. Use both CPM and Order Normalized frequency analysis

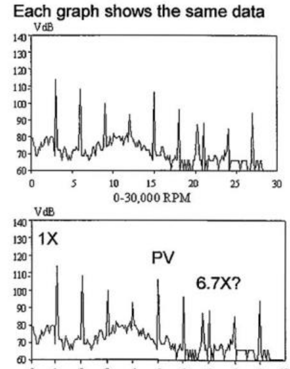
Amplitude levels –

Each graph shows the same data



Frequency Analysis – CPM vs. Orders

Each graph shows the same data

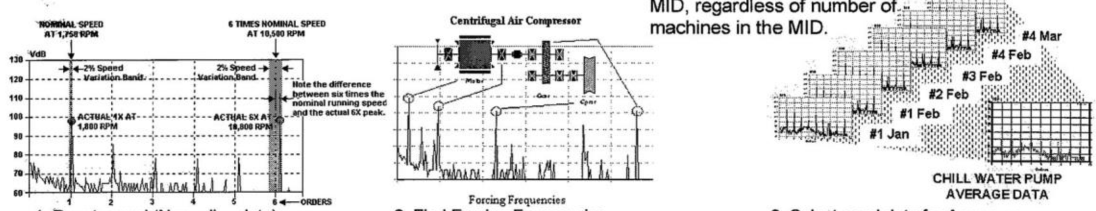


Order Normalized data is easier to quickly identify shaft vibration and components associated with shaft

Log data allows viewing small peaks and large peaks on the same graph without rescaling of data. VdB scaling eliminates decimals.

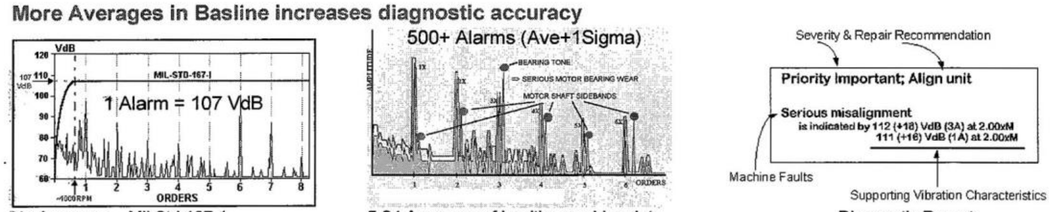
Fine-tune Program

There is one average record per MID, regardless of number of machines in the MID.



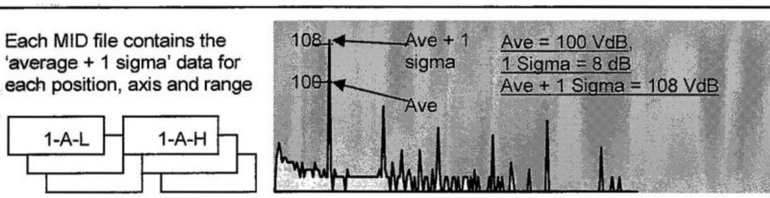
1. Reset speed (Normalize data) 2. Find Forcing Frequencies 3. Select good data for Averages

More Averages in Basline increases diagnostic accuracy



No Averages – Mil Std 167-1 5-24 Averages of healthy machine data Diagnostic Report

Each MID file contains the 'average + 1 sigma' data for each position, axis and range



6 Healthy sets of data,
1X spectral peak =
1-104 VdB 4-100 VdB
2-102 VdB 5-98 VdB
3-100 VdB 6-96 VdB

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Vibration Sources Identification Guide

CAUSE	FREQUENCY	AMPLITUDE	PHASE	COMMENTS
Unbalance	1 x RPM	Highest in Radial Direction-Proportional to Unbalance	Single Mark (Steady)	A common cause of vibration.
Defective Anti-Friction Bearings	Very High-Often From 10 to 100 x RPM	Use Velocity	Unstable	Velocity readings are highest at defective bearing. As failure approaches, the amplitude of the velocity signal will increase and its frequency will decrease. Cage frequency is approximately 0.6 x RPM x number elements.
Misalignment of Coupling or Bearing	1, 2 or 3 x RPM	High Axial Axial 50% or more of Radial	Often 2, Sometimes 1 or 3	Use phase analysis to determine relative movement of machine or bearings. Use a dial indicator if possible. Often diagnosed as a bent shaft. Can be caused by misalignment of V belts.
Sleeve Bearing	1 x RPM	Not Large Use Displacement Mode Up to 6000 CPM	Single Reference Mark	May appear to be unbalanced. Shaft and bearing amplitude should be taken. If shaft vibration is larger than the bearing, vibration amplitude indicates clearance.
Bent Shaft	1 or 2 x RPM	High Axial	1 or 2	Similar to misalignment. Use phase analysis.
Defective Gears	High No. Gear Teeth x RPM	Radial	Unsteady	Use velocity measurement. Often affected by misalignment. Generally accompanied by side band frequency. Pitting, scuffing and fractures are often caused by torsional vibrations. Frequency sometimes as high as 1 million CPM or more.
Mechanical Looseness	2 x RPM Sometimes 1 x RPM	Proportional to Looseness	1 or 2	Check movement of mounting bolts in relation to the machine base. Difference between base and machine indicates amount of looseness.
Defective Drive Belts	1 or 2 x Belt Speed	Erratic	Use Strobe to Freeze Belt in OSC Mode	Calculate the belt RPM using: $\text{Belt RPM} = \frac{\text{Pulley Diameter x 3.141}}{\text{Belt Length}} \text{ x Pulley RPM}$ Look for cracks, hard spots, soft spots or lumps. Loose belt. Changes with belt tension.
Electrical	1 or 2 x Line Frequency (3600 or 7200 CPM for 60Hz Power) May appear at 1 x RPM	Usually Low	1 or 2 Marks Sometimes Slipping	Looks like mechanical unbalance until power is removed. Then drops dramatically.
Oil Whip	45 - 55% RPM	Radial Unsteady	Unstable	Caused by excessive clearance in sleeve bearings or by underloaded bearings. Will change with viscosity of oil (temperature).
Hydraulic-Aerodynamic	No. Blades or Vanes x RPM	Erratic	Unsteady	May excite resonance problems.
Beat Frequency	Near 1 x RPM	Variable at Beat Rate	Rotates at Beat Frequency	Caused by two machines, mounted on same base, running at close to same RPM.
Resonance	Specific Critical Speeds	High	Single Reference Mark	Phase will shift 180° going through resonance (90° at resonance). Amplitude will peak at resonance. Resonance in frame can be removed by changing rotor operating speed or by changing the stiffness of the structure.

There are several additional detailed articles that identify more complicated vibration sources at www.vibescorp.ca titled:

1) LEARN ABOUT VIBRATION VOLUME 1: BASIC UNDERSTANDING OF MACHINERY VIBRATION

2) LEARN ABOUT VIBRATION VOLUME 2: ADVANCED VIBRATION ANALYSIS

3) LEARN ABOUT ELECTRICALLY INDUCED BEARING DAMAGE & SHAFT CURRENTS

4) FAILURE PREVENTION OF VARIABLE AND CONTROLLABLE PITCH IN MOTION AXIAL FANS

SERIOUS SERVICE®
Professional Machinery Health Care
(Fan Doctor®)

VIBES Corp®

Est. 1967

Vibration **I**ndustrial **B**alancing & **E**quipment **S**ervices, Corporation

720 - 999 W. Broadway, Vancouver, BC V5Z 1K5

www.vibescorp.ca email: info@vibescorp.ca

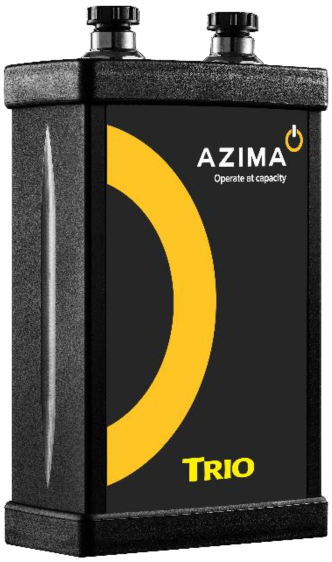
Phone: 604 - 619 - 9381 (24/7)

This is the equipment Vibes Corp has been using for 15 years with good results

COMPLYWORKS ContractorCheck Alcumus Avetta

Vendor Compliant for Property Owners, Management Firms of Commercial Buildings, Hospitals, Industrial Sites, & Infra-Structure Facilities

POWERFUL, ERGONOMIC, AND SAFE MACHINE DATA AQCUISITION WITH THE TRIO® BRAND FIELD ANALYZERS



TRIO C-Series

COMMERCIAL INDUSTRIAL VIBRATION DATA COLLECTOR / FIELD ANALYZER

- ✓ Modular system with rugged IP-65 rated Windows 10 tablet PC
- ✓ 8” and 10” screen size options available
- ✓ Full-day, hot-swappable battery, standard-life or extended-life

TRIO H-Series

HAZLOC-RATED VIBRATION DATA COLLECTOR / FIELD ANALYZER

- ✓ Modular system with Class 1, Division 2 HAZLOC approvals
- ✓ 9”, Ultra-rugged Windows 10 tablet PC
- ✓ Extra-long battery life, optional Snap-back battery packs

TRIO Feature Highlights

- ✓ Modular, Bluetooth® connectivity, separates tablet from instrumentation
- ✓ 4 simultaneous channels of data plus dedicated tachometer channel
- ✓ Capactive touchscreen, sunlight readable, brilliant screen resolution
- ✓ Safest vibration device on the market

TRIO Model Options

- ✓ ExpertALERT™ / Collector X applications for full automated diagnostic functions
- ✓ ViewALERT™ / Collector application for simple in field data collection
- ✓ ALERT RTA™ - Real-time Analyzer application for advanced troubleshooting
- ✓ ALERT™ Multi-plane Balance application for multi-plane, multi-speed balance

CHOOSE THE PERFECT HARDWARE DESIGN SUITED FOR YOU

TRIO C8-Series

TRIO C10-Series

TRIO H8-Series

TOTAL TRIO®

BRAUN, BRAINS AND BEAUTY

TOTAL TRIO IS A COMPLETE PACKAGE INCLUSION

Total TRIO ensures your equipment is operational, hardware and software is up-to-date, and technical and analytical support is there if needed.

With Total TRIO, the TRIO Controller is renewed every 3 years which keeps the technology always fresh.

Analysts have access to AzimaAI's domain experts to get second opinions on tough recommendations

Support will give you head-of-line for repairs and provide loaners if repair will take longer than 2 weeks.

TRIO EMBRACES THE INDUSTRIAL INTERNET OF THINGS

Total TRIO includes the WATCHMAN Data Center for database management and security. No IT capital expenses are required.

An included use license of ExpertALERT-Cloud is provided to work through AzimaAI's cloud application.

Key decision makers and program contributors can all gain insights into your PdM program through the included WATCHMAN Reliability Portal™.

HOW COULD TRIO® BE SO MUCH BETTER, YOU ASK?

Powerful User Interface

The TRIO™ line of data acquisition products includes the powerful, Windows OS industrial tablet computers. TRIO uses a robust Bluetooth® connection and includes a solid state hard drive, bright sunlight readable touch screen and Wi-Fi access allowing TRIO to communicate with your desktop or networked PCs and servers. TRIO's user interface provides you more capabilities, better ease of use, and allows you to bring your other Windows PdM and Office productivity applications into the field

Lower Cost and Flexibility of Ownership

TRIO™ recognizes that computer technology is rapidly changing. Its distributed system configuration allows the tablet PC component to be replaced or upgraded for a small fraction of the cost of replacing a traditional vibration data collector.

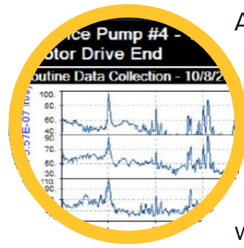
Improved Ergonomics and Safety

There is no safer vibration data collector on the market. TRIO's ergonomic design allows more efficient and safer use of the data collector around dangerous and difficult to access machinery. Machines can be tested from safe and secure distances from rotating machine locations using the integral Bluetooth® communication. Its modular design helps keep technicians hands-free and untethered from the machine for improved safety.

Collection Automation

TRIO automatically queues multiple frequency ranges of FFT, time, overall and demodulated vibration tests for a single machine location and collects X, Y and Z axis data simultaneously with a single command. You will collect more quality data in less time with TRIO.

Automated Diagnostics



ALERT provides critical machinery health information in addition to vibration data, by rapidly screening vibration measurements and applying over 6000 unique rules to identify over 1200 individual faults in a wide variety of machine types.

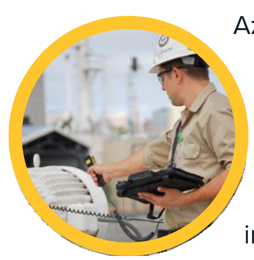
Variety of Configurations

TRIO offers several ergonomic-designed, in-field carrying options, including the convenient utility belt, shoulder-worn soft case and the shoulder strap/belt configurations. Depending on your specific use model, you can wear it, carry it or sling it over your shoulder.

TRIO™ and WATCHMAN™ Reliability Services

Our combination of TRIO and WATCHMAN Reliability Services offer a new level of efficiency and capability to the predictive maintenance market. WATCHMAN provides business level and enterprise performance metrics for transparent visibility. Advanced dashboards ensure managers and executives are informed on maintenance decisions, risks to production and readiness of operations

Proof Comes from the Field Experts



AzimaAI's WATCHMAN users prefer using the TRIO systems. They have found that route-based data collection is easier and more productive. Also, whether your predictive maintenance program is implemented in-house, outsourced or hybrid in-between, TRIO can be integrated with online and other service programs for flexibility and sustainability.

TRIO®

Machine Data Acquisition

TECHNICAL SPECIFICATIONS

Overview

- Triaxial vibration data collector system
- Industrial Windows 10 OS Tablet PC Controllers
- Wireless, Bluetooth®, IP-65 rated Data Processing Unit (TRIO DP)
- Optional HAZLOC-rated North American Class 1, Division 2
- Portal-enabled connectivity to the hosted WATCHMAN Data Center
- Handheld laser tachometer for speed and phase measurement optional
- Flexible carrying options including utility belt, should straps, courier bags, hard transit case
- Sybase 12 SQL database onboard allows full PdM database to be mobile on unit
- Database synchronization for collaboration with multiple TRIOs or analysts
- Ergonomic designs allow more efficient and safer use
- 4-plane balancing and advanced real-time analysis software options
- HX- or CX-Series includes embedded ExpertALERT onboard analysis software (no host software required)
- HA- or CA-Series includes embedded ViewALERT onboard software (Requires host system: ExpertALERT (desktop, embedded, cloud- subscription) or StandardALERT)

ALERT™ Capabilities

- Intuitive graphical user interface that is simple to learn and operate
- Setup wizards reduce set up time and increase configuration accuracy
- Enhanced management and visualization of dynamic data
- Automated vibration data screening using narrow-band vibration techniques for early faults detection
- Automated bearing fault identification without requiring bearing make and model number
- Multi-level fault severity and prioritized repair recommendations improve repair planning
- Advanced reporting tools produce professional reports
- Included 75,000 bearing asset library and 15,000 motor asset library
- Better machine performance determination through ALERT's calculated process points feature
- Integration of multiple PdM technologies, reports, documents, spreadsheets, inspections, and data
- Online monitoring, walk-around vibration collection and operating log collection in one system
- Close loop reporting with ALERT's Event Tracker

Graphical Capabilities

- Amplitude Alarm Triggering
  - Impact Demod Spectra and Waveform
  - Overall Values
  - Spectrum
  - Waveform
- Automated Peak Locator o Harmonics
  - Order Normalization
  - Sidebands
- Average Baseline Comparison
  - Synthesized Average
  - Average plus sigma
- Bode Plot
- Bump Test
  - Equipment ON
  - Equipment OFF
- Customized Real-time Setup
- Graphical Remote Control Window
- Hotkeys & Hotspots
- Integration & Differentiation
- Long-time Data Capture
- Markers
  - Reference Cursor Delta
  - Harmonics
  - Sidebands
  - Fault Frequencies
- Nyquist Plot
- Order Tracking
- Peak Analysis and Identification Functions
- Phase Analysis
  - Cross Channel
  - Polar Phase Plot
- Run-up / Coast-down plotting o Spectral Waterfall
  - Bode-Peak & Phase
  - Peak Hold
- Spectrum
  - Single Axis
  - Triaxial
  - Double-Triax
  - Demodulation
  - Waterfall
  - Native, Integrate, Double integrated, Decibel
- Time Synchronous Averaging
- Waveform
  - Autocorrelation
  - Single Axis
  - Triaxial
  - Double-Triaxial
  - Orbit, Filtered Orbit
  - Poincare Map
  - Single Circular Graph
  - Triaxial Circular Graph
  - Waterfall with Correlation Factor
  - Native, Integrated, Double-integrated
- Long time Data Capture
- Cross Channel Phase Analysis

TRIO Data Acquisition / Processor (DP-2, DP-2H)

Inputs

- 4 simultaneous sampled, fully phase matched, ICP programmable
- Other Coupling: AC (for proximity probe connections)
- AC Input Voltage Range: +/- 10V
- AC Bandwidth: 0.5Hz to 40 kHz
- DC Bias/Gap Measurement: +/- 25V range for ICP bias voltage check and proximity probe gap measurement
- Measurements: Acceleration, velocity (by hw integration), bearing demodulation (accelerometers), and displacement (proximity probes)
- Gain Ranges: Gain steps 1, 2, 4, 10, 20, and 50
- Digital trigger input: External trigger, tachometer speed, ordered data (by phase-lock-loop)

Processing

AC MEASUREMENTS

- ADC: 24-bit sigma-delta, simultaneous on four AC channel inputs, better than 104 dB dynamic range
- Sampling Rates: 64Hz to 102.4kHz
- Bandwidth Ranges: 0.5Hz-25Hz, 0.5Hz-40kHz, protected by anti-alias filters
- Data Block Lengths: 64 to 400,000 samples
- Spectral Lines: Up to 25,600
- Noise Floor: Less than 0.2 micro-volts per root Hz from 0.5 to 1000kHz

DC MEASUREMENTS

- ADC: 16-bit multiplexed for bias voltage, process, and probe gap measurements, 0-10kHz Bandwidth

Analysis Capabilities

- Dynamic Analysis: Overall, Spectra, Waveform, Phase and Speed
- Cross-channel: Cross-power, Transform Function, Coherence, Phase and Magnitude
- Demodulation Function: Digital amplitude demodulator and Impact Demodulation for low speed detection
- Averaging: RMS, Exponential, Peak Hold, Order Tracking, Synchronous Time, and Negative Averaging
- Number of averages: 1 – 1000
- FFT Window Function: Hanning, Hamming, Rectangular, Flattop

Communications with Tablet Controller

- Wireless: Bluetooth v2.0 with EDR (1.5Mbps max)
- Wired: USB user port (includes data stream and remote power to DP)

Power

- Charging rate: 0.5A from USB PC input (4 hrs), 1.0A from USB wall power adapter (2 hrs)
- Battery life: 8 hours, continued use

Physical

- Dimensions: 6.18"x 3.62" x 1.81" (157 mm x 92 mm x 46 mm)
- Carrying options: Belt holster or courier bag
- Weight: 1.0 lb (0.45 kg)
- Operating Temperature: -10C to +60C
- Humidity: MIL-STD-810G
- Drop: 4 feet per MIL-STD-810G
- Sealing: IP-65; polycarbonate and nylon
- Compliance: CE, ETL Listed
- IP65 rated; dust tight, protected from water jet

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Professional Machinery Health Care
(Fan Doctor®)

VIBES Corp®

Est. 1967

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Vendor Compliant for Property Owners, Management Firms of Commercial Buildings, Hospitals, Industrial Sites, & Infra-Structure Facilities