Beginning Vibration Analysis with Basic Fundamentals

By: Jack Peters

VIBRATION ANALYSIS HARDWARE

Introduction

Understanding the basics and fundamentals of vibration analysis are very important in forming a solid background to analyze problems on rotating machinery.

Switching between time and frequency is a common tool used for analysis. Because the frequency spectrum is derived from the data in the time domain, the relationship between time and frequency is very important. Units of acceleration, velocity, and displacement are typical. Additional terms such as peak-peak, peak, and rms. are often used. Switching units correctly, and keeping terms straight is a must.

As much as possible, this training will follow the criteria as established by the Vibration Institute.

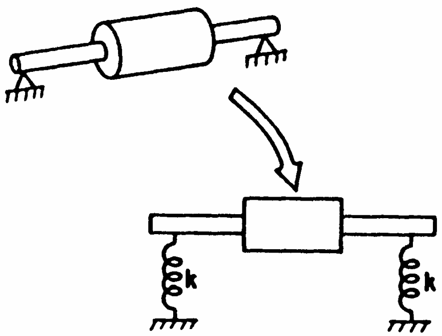
Mass & Stiffness

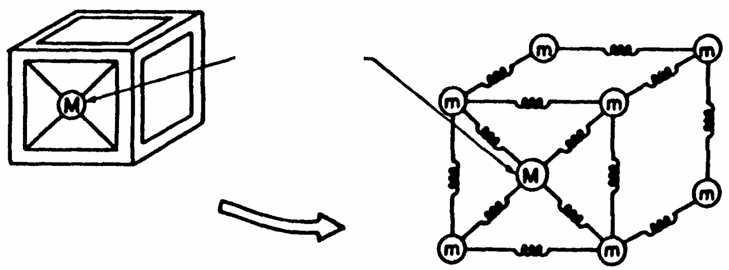
All machines can be broken down into two specific categories.

Mass & Stiffness

Mass is represented by an object that wants to move or rotate.

Stiffness is represented by springs or constraints of that movement.





Mass & Stiffness

$$f_n = 1/2\pi \sqrt{k/m}$$

Where:

f_n = natural frequency (Hz)

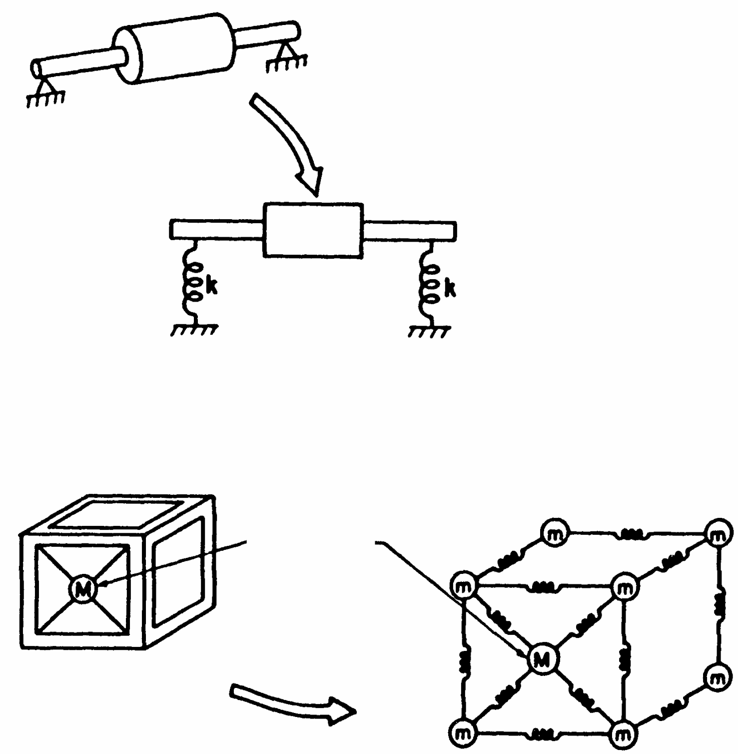
k = stiffness (lb/in)

m = mass

mass = weight/gravity

weight (lb)

gravity (386.1 in/sec^2)



Concept !

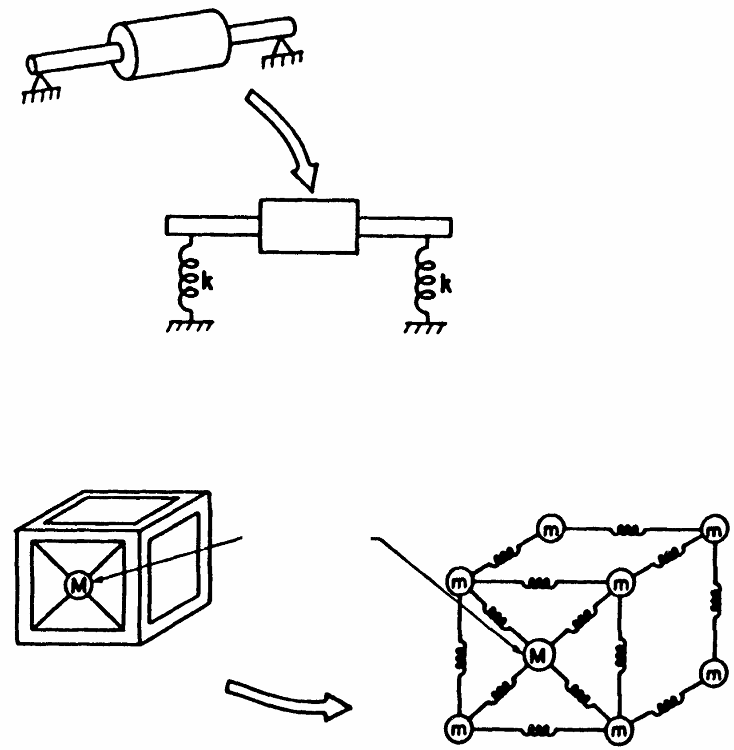
$$f_n = 1/2\pi \sqrt{k/m}$$

If k increases

Then f increases

If k decreases

Then f decreases



Concept !

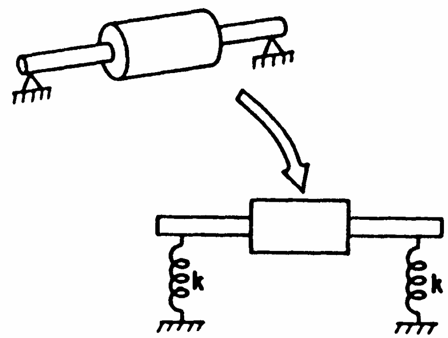
$$f_n = 1/2\pi\sqrt{k/m}$$

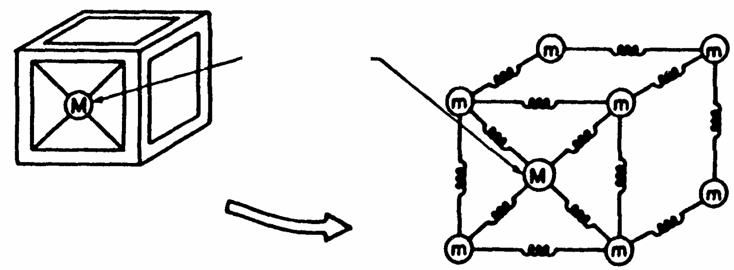
If m increases

Then f decreases

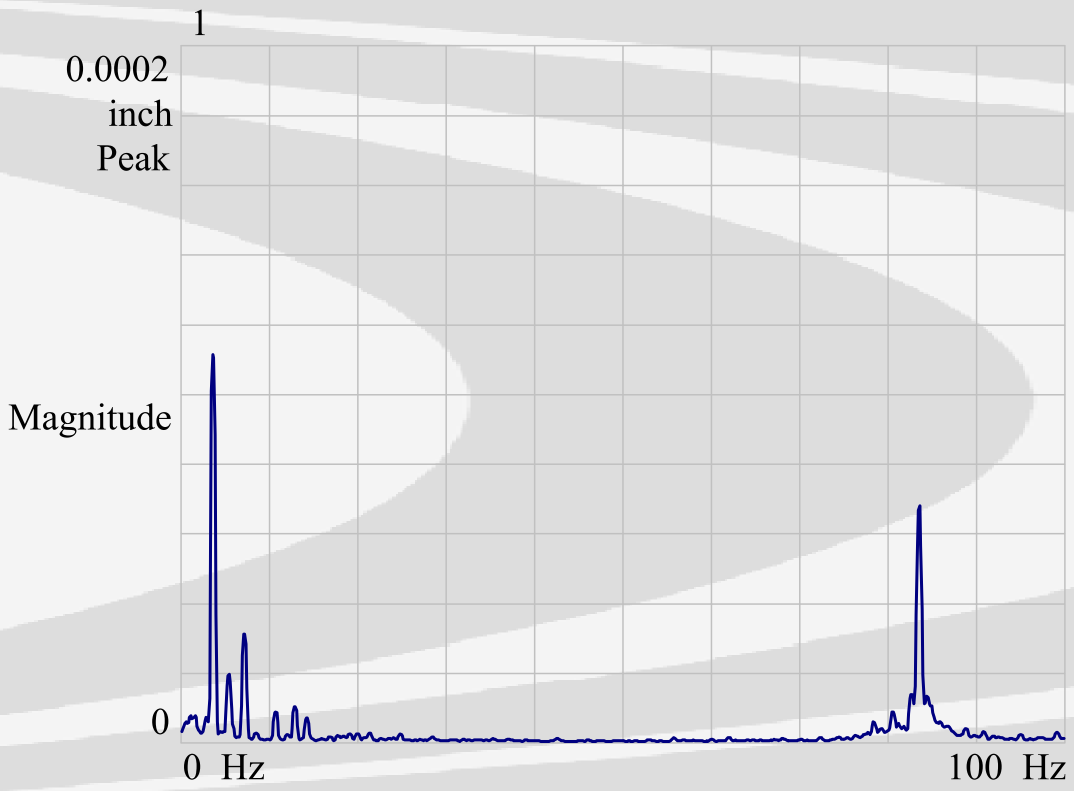
If m decreases

Then f increases

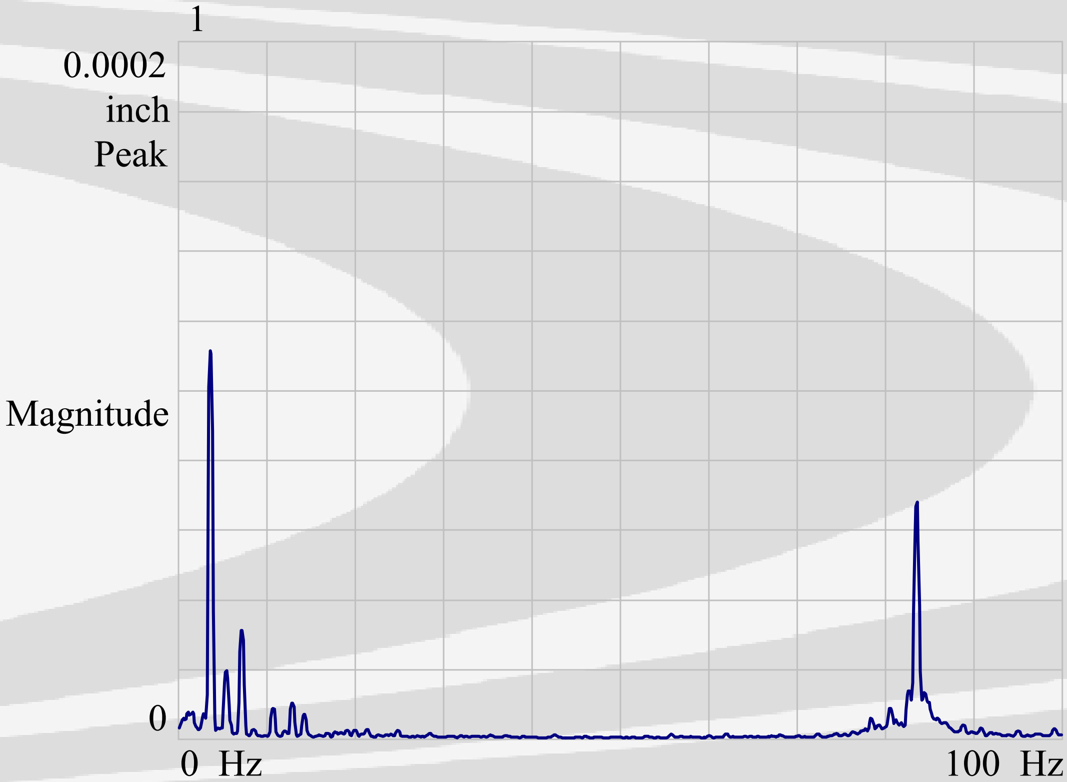




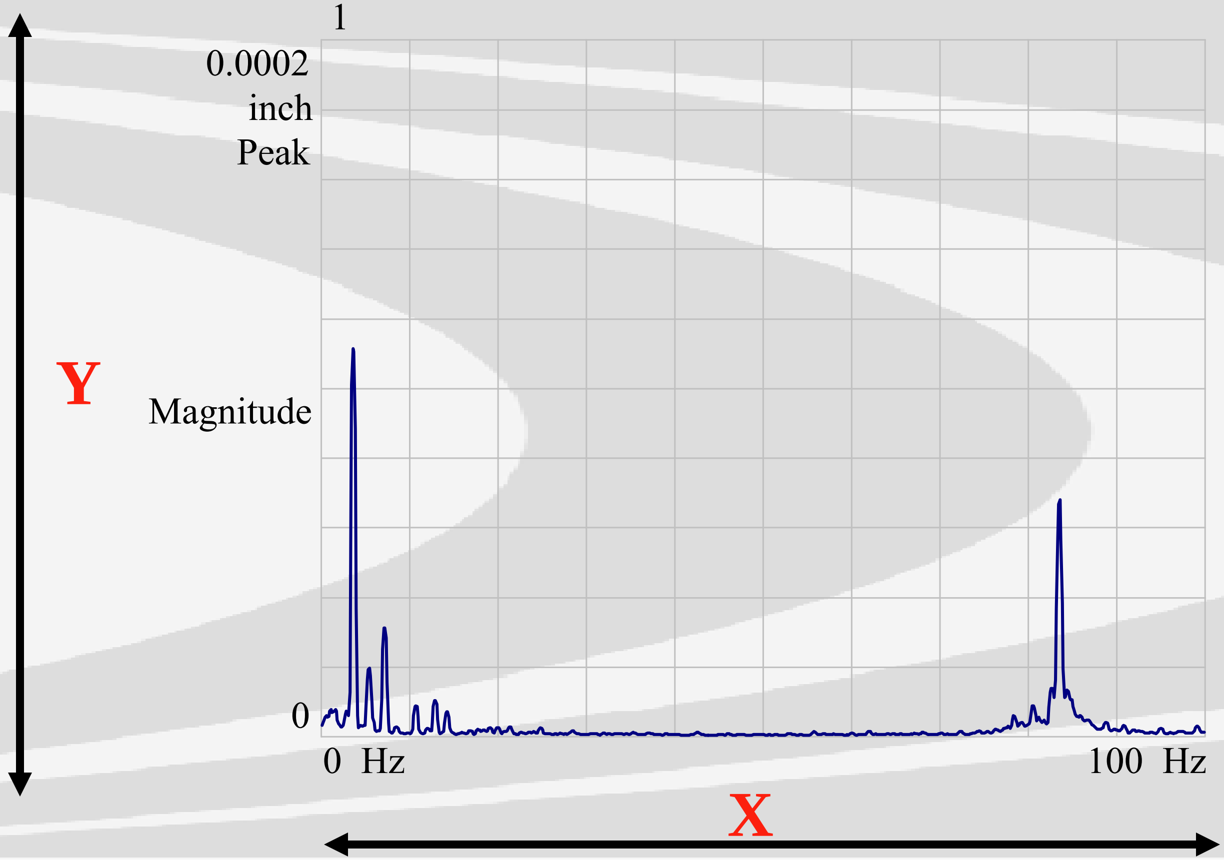
What's This ?



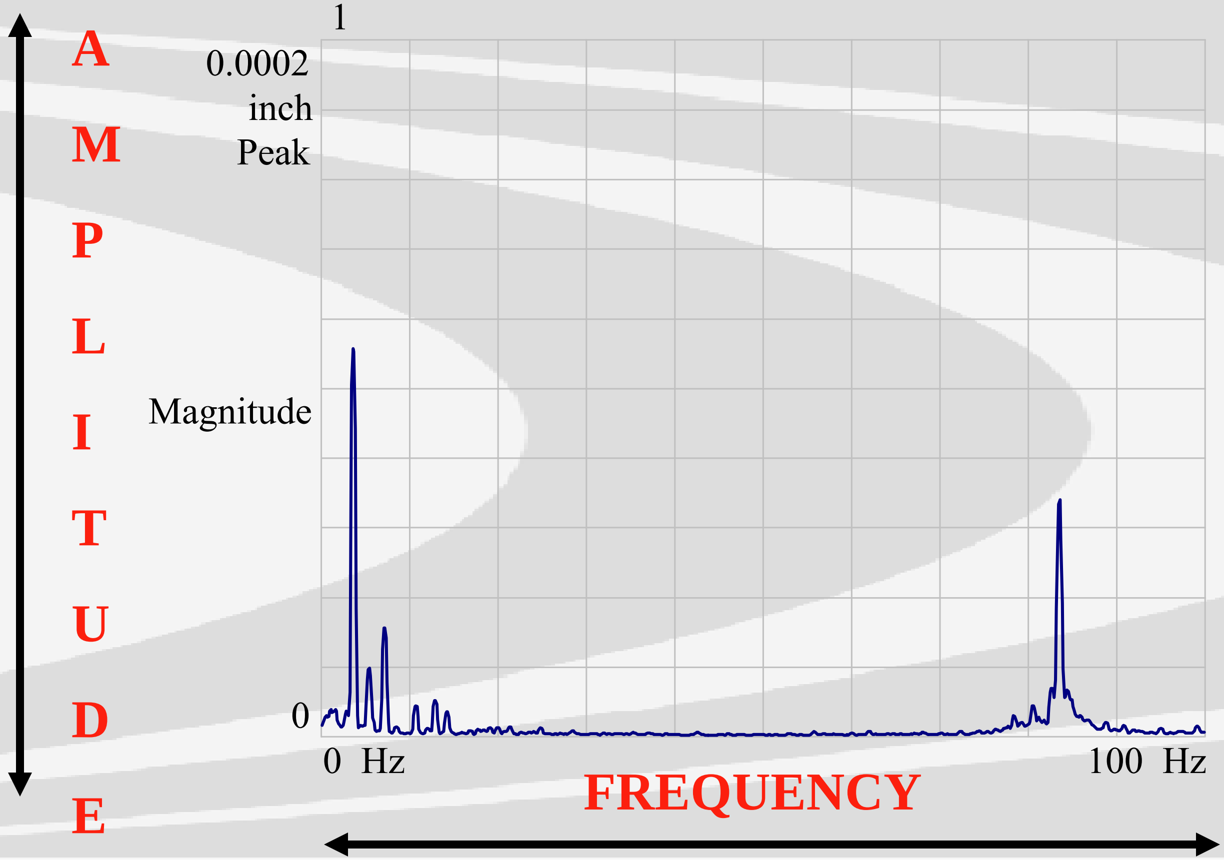
FFT, Frequency Spectrum, Power Spectrum



Scaling X & Y



Scaling X & Y


A
M
P
L
I
T
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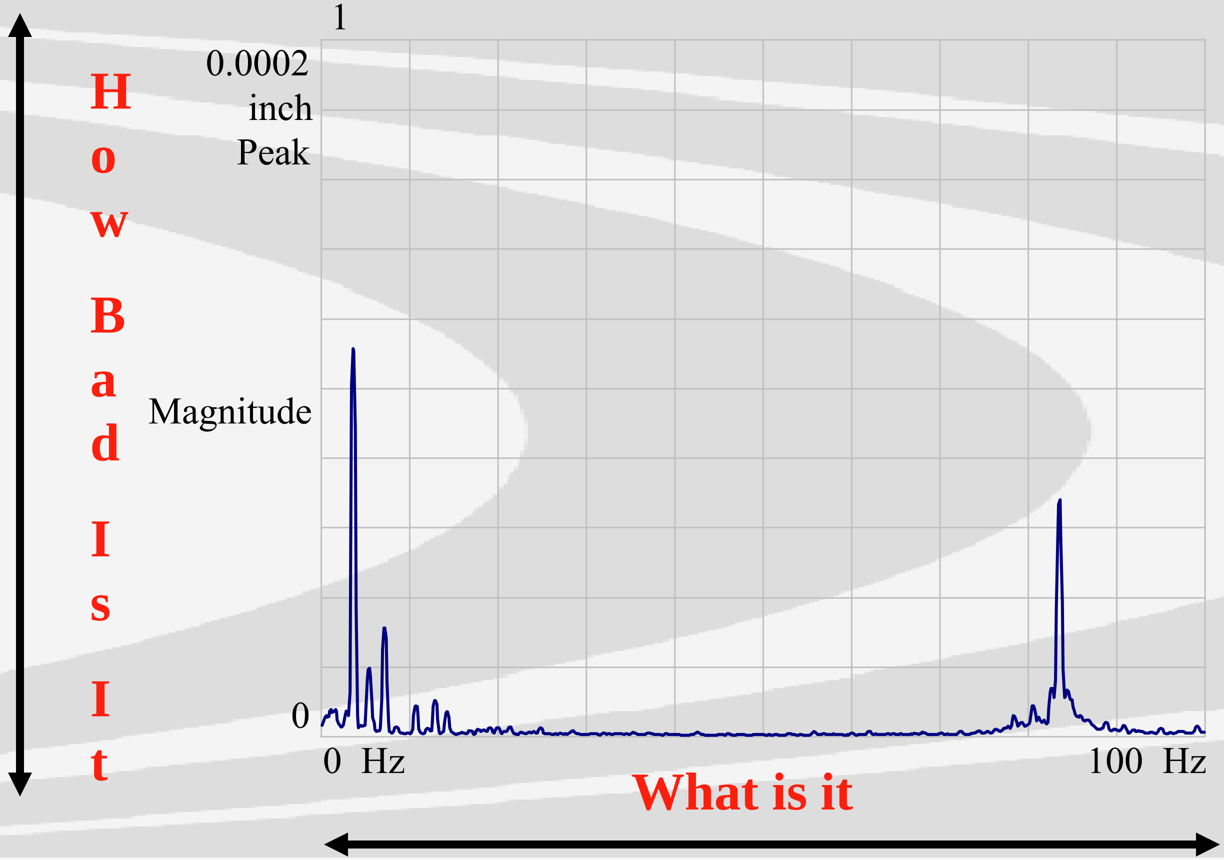
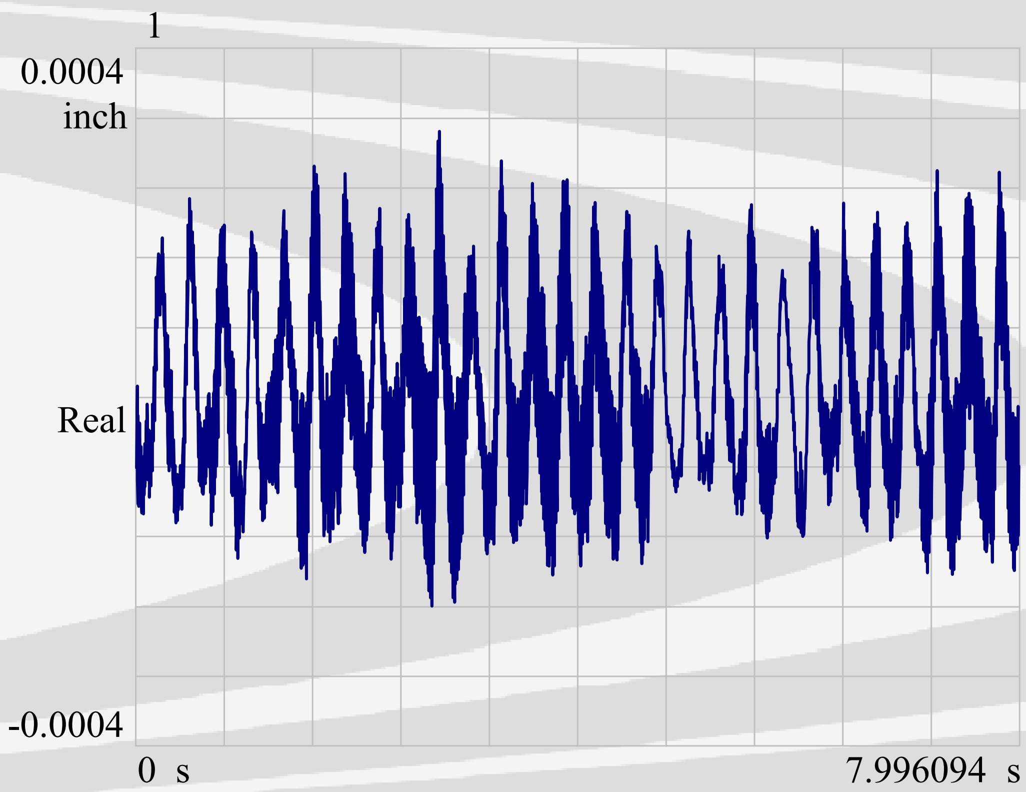
D
E
1
0.0002
inch
Peak
Magnitude
0
0 Hz
100 Hz
FREQUENCY

Spectrum

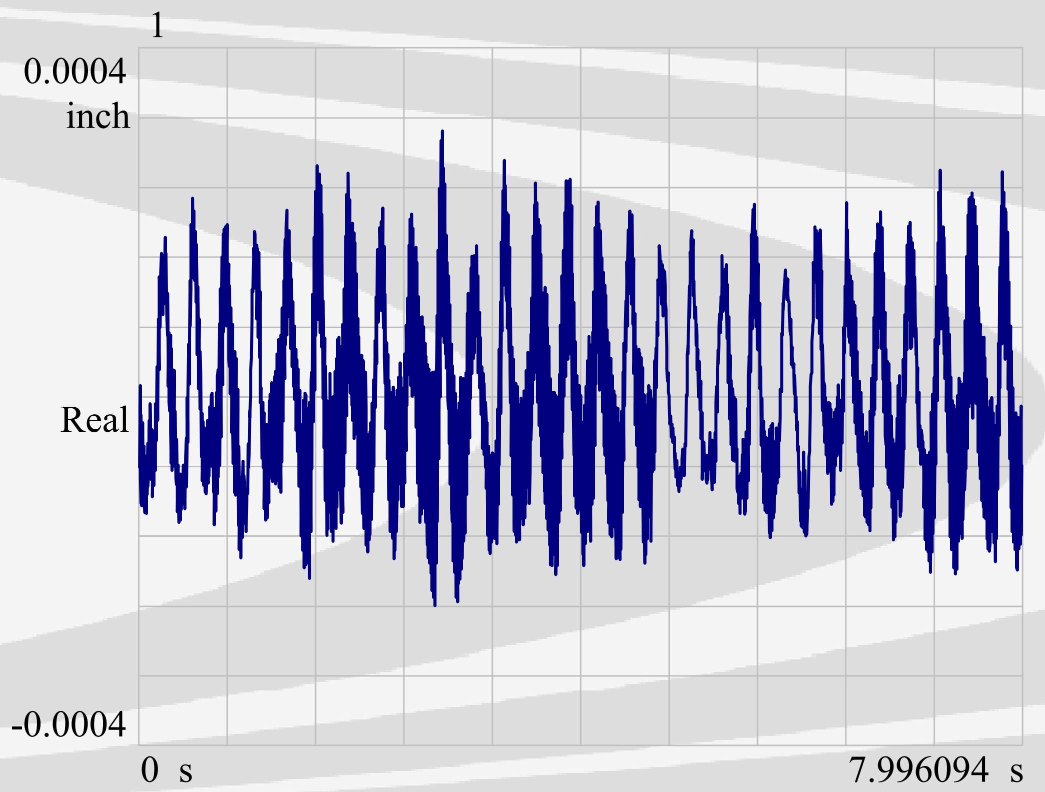
Scaling X & Y



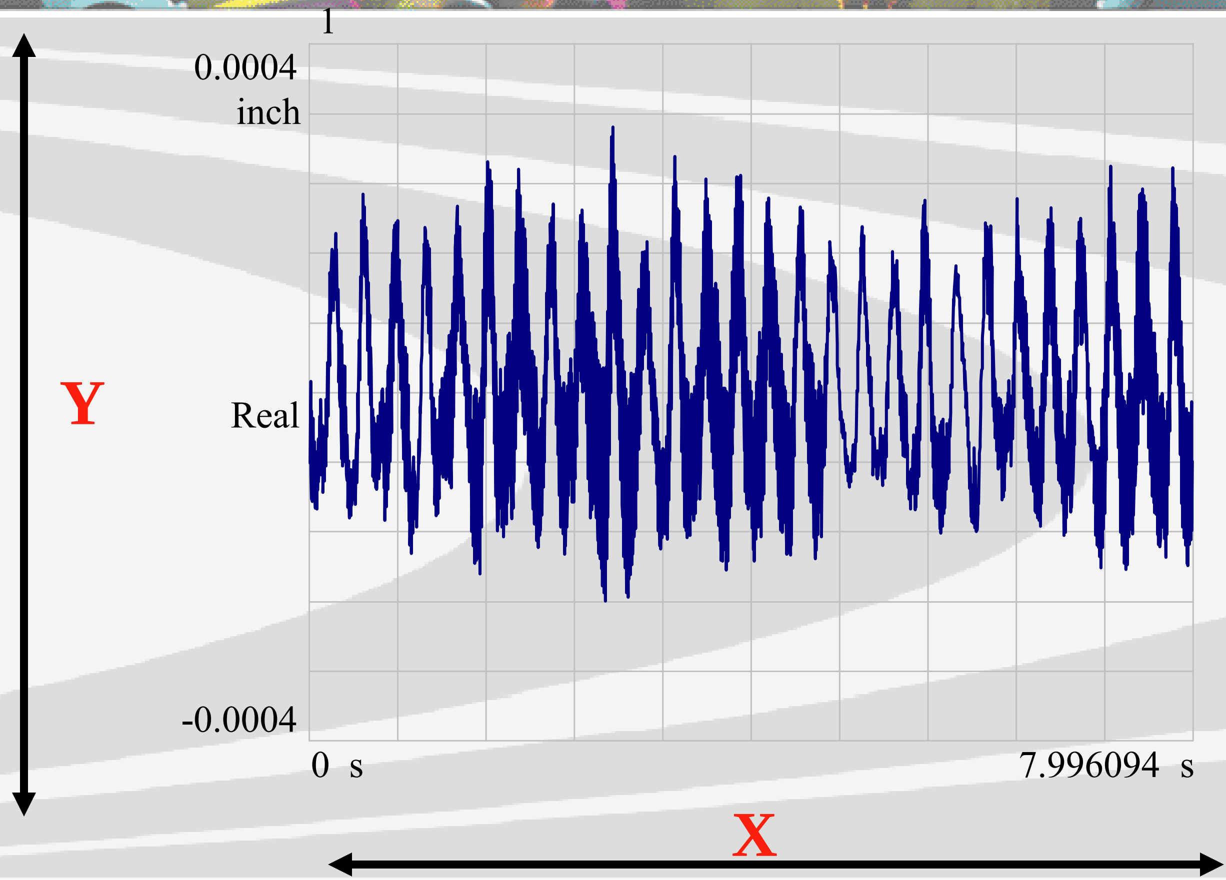
What’s That ?



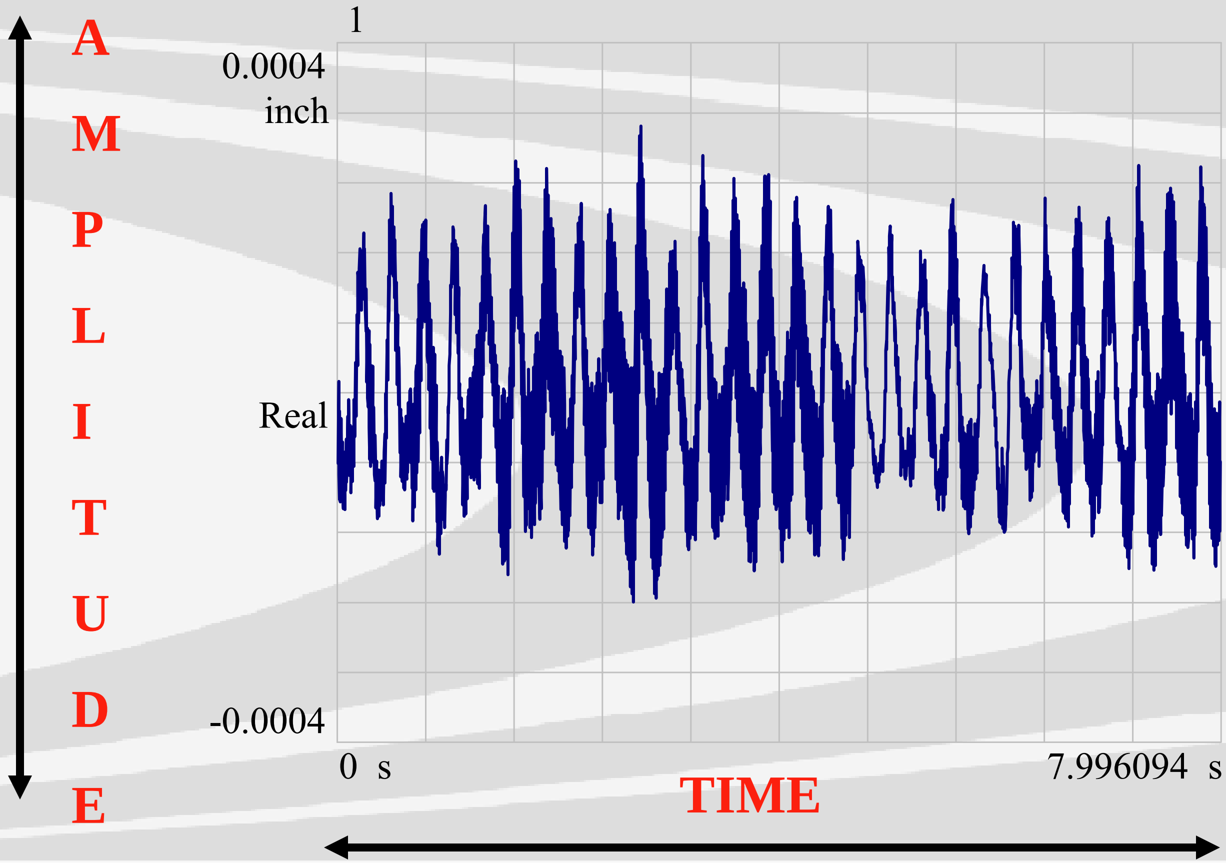
Time Waveform



Scaling X & Y

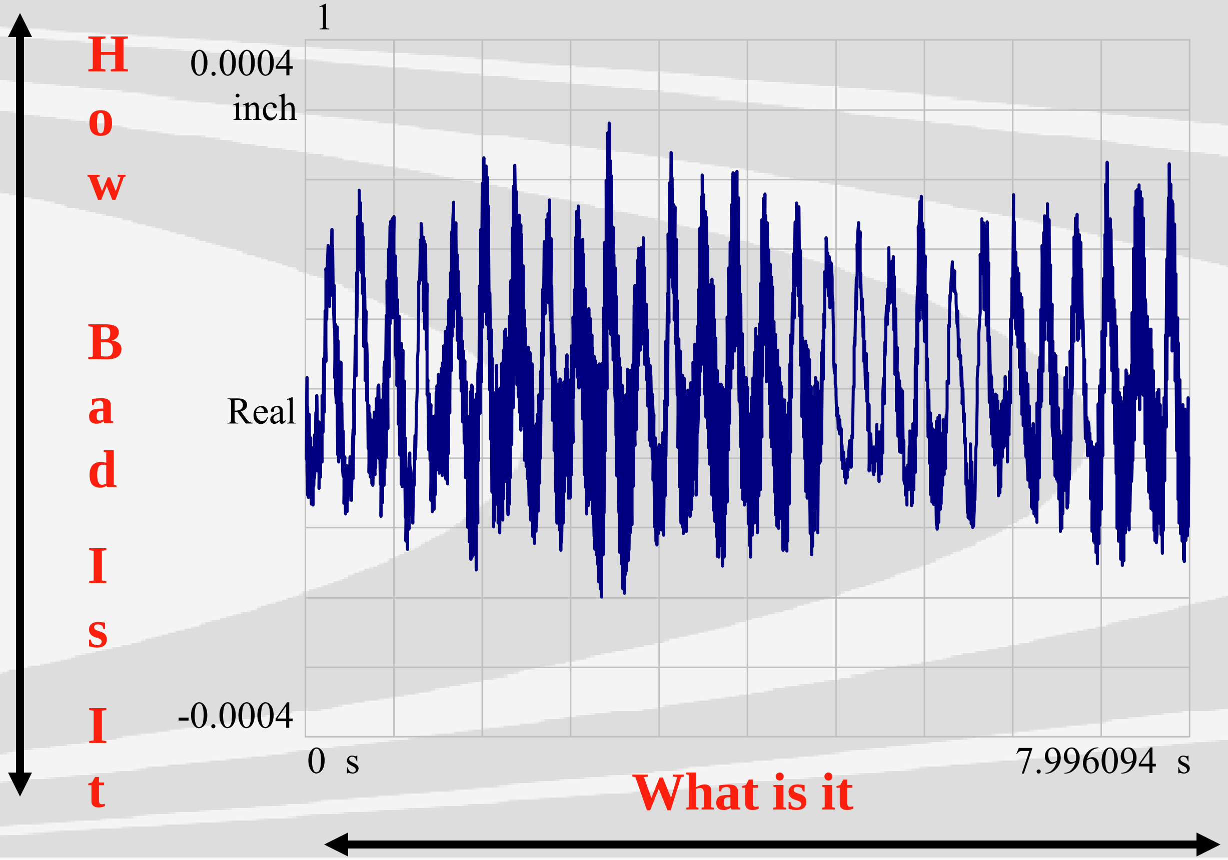


Scaling X & Y



Time Waveform

Scaling X & Y



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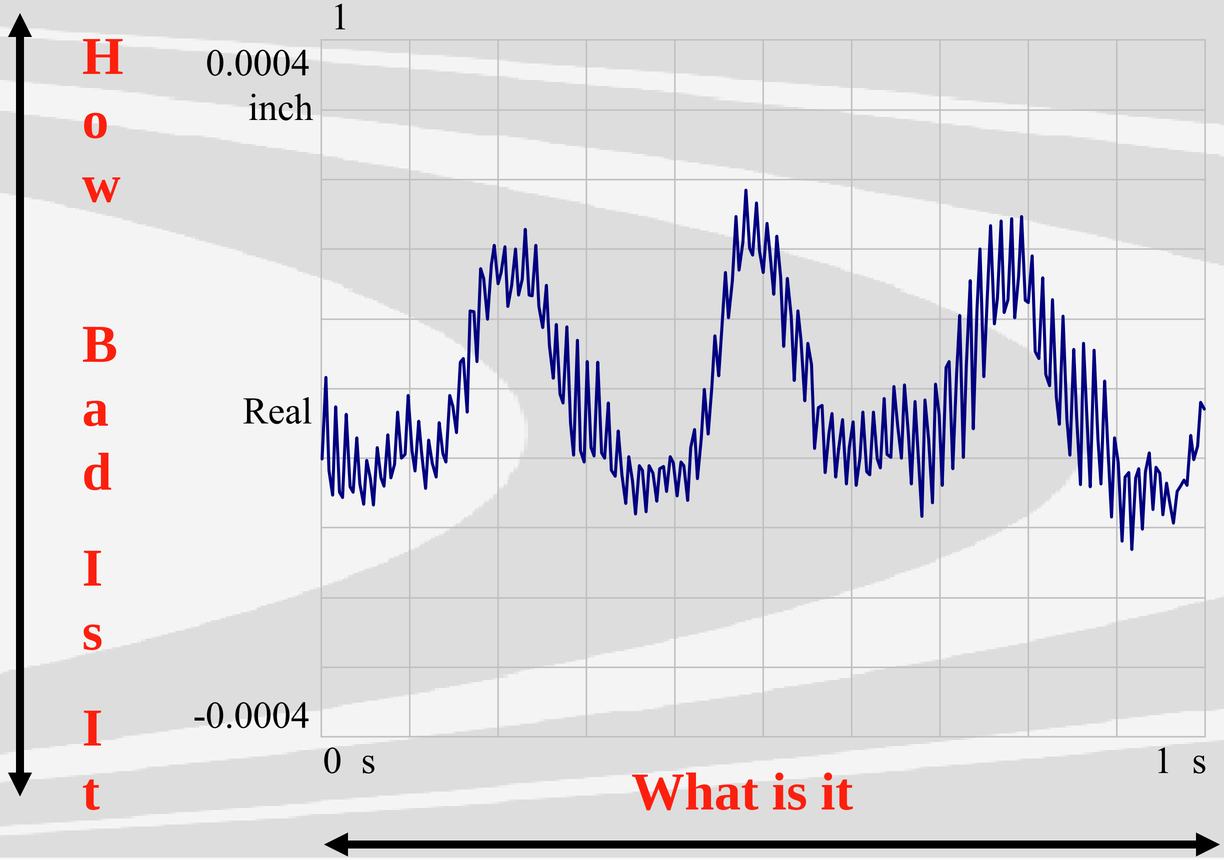
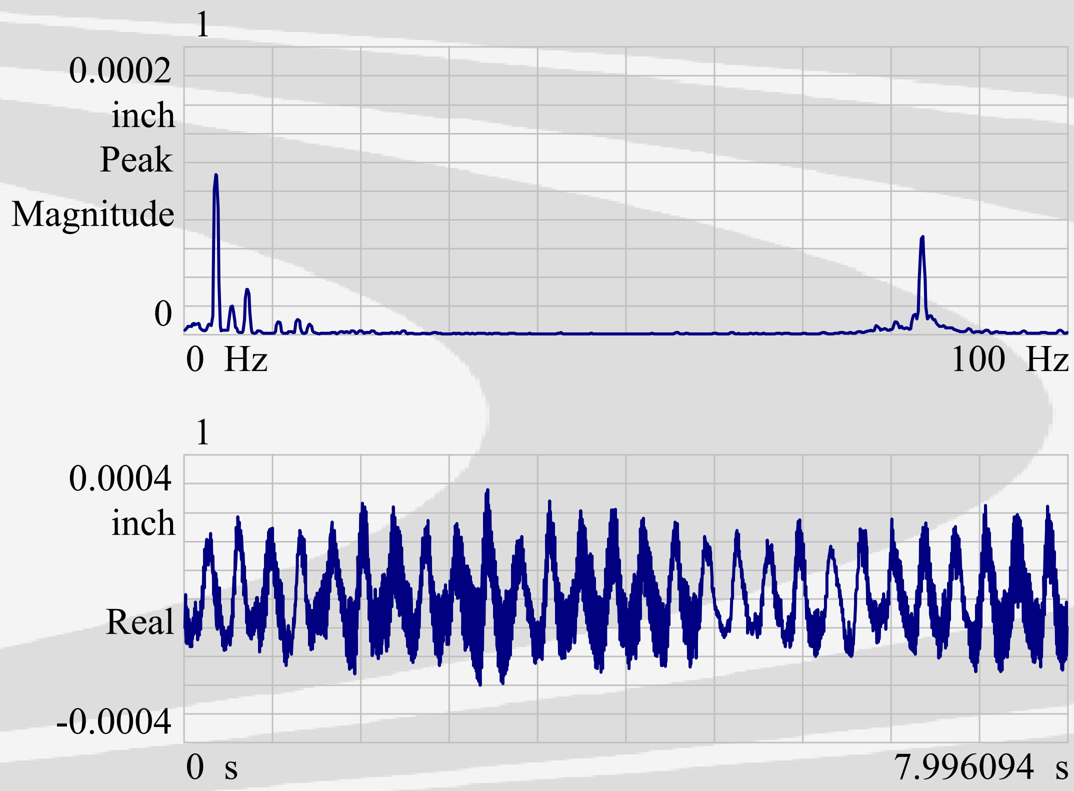
VIBRATION ANALYSIS HARDWARE

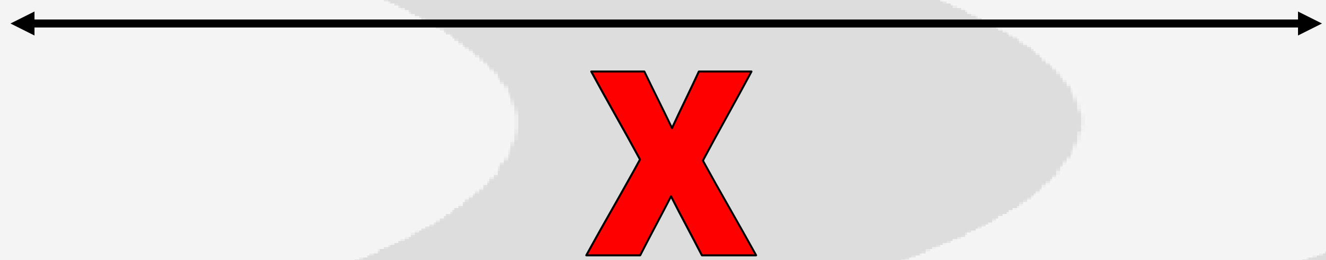
Scaling X & Y



Double Trouble



The X Scale



Hertz (Hz)

One Hertz (Hz) is equal to 1 cycle / second

It is the most common term used in vibration analysis to describe the frequency of a disturbance.

Never forget the 1 cycle / second relationship !

Traditional vibration analysis quite often expresses frequency in terms of cycle / minute (cpm). This is because many pieces of process equipment have running speeds related to revolutions / minute (rpm).

60 cpm = 1 cps = 1 Hz

Relationship with Time

The frequency domain is an expression of amplitude and individual frequencies.

A single frequency can be related to time.

$$F_{(Hz)} = 1 / T_{(s)}$$

The inverse of this is also true for a single frequency.

$$T_{(s)} = 1 / F_{(Hz)}$$

Keep in mind that the time domain is an expression of amplitude and multiple frequencies.

Concept !

If: F = 1/T and T = 1/F

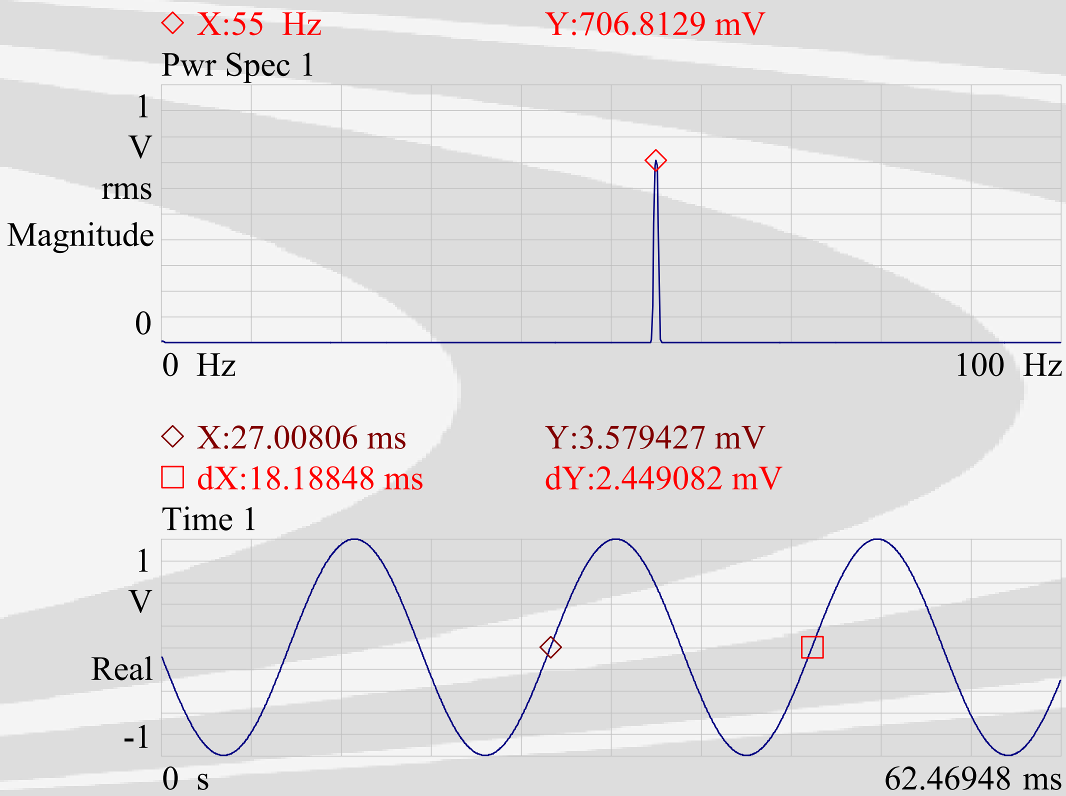
Then: FT = 1

Concept !

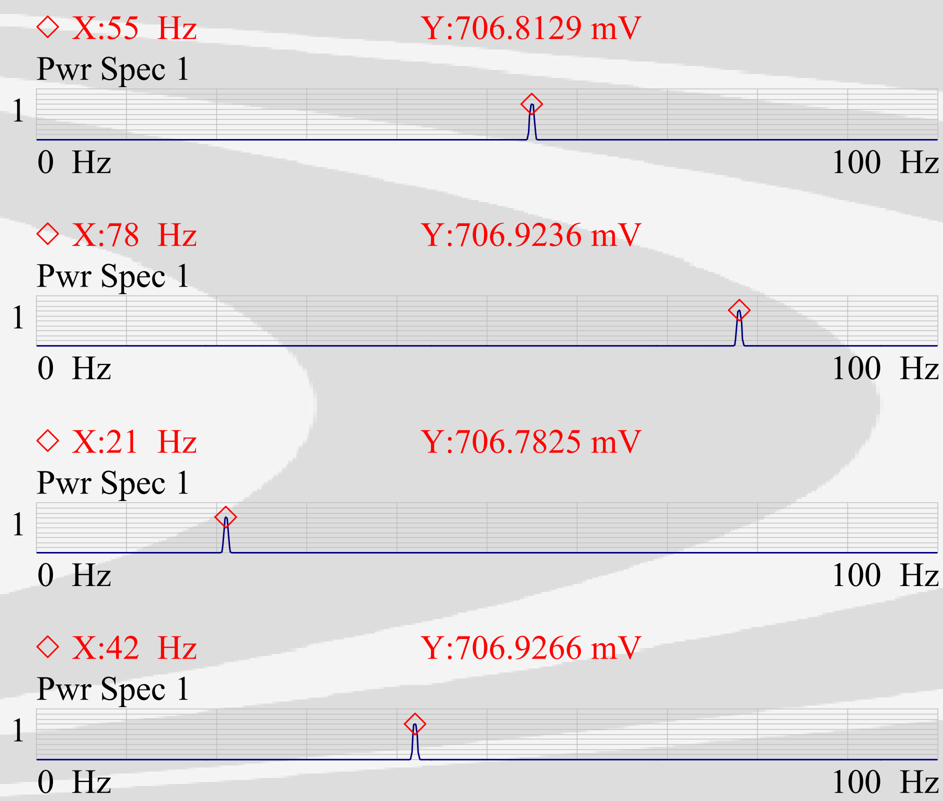
FT = 1

If:	**F increases**
Then:	**T decreases**
If:	**T increases**
Then:	**F decreases**

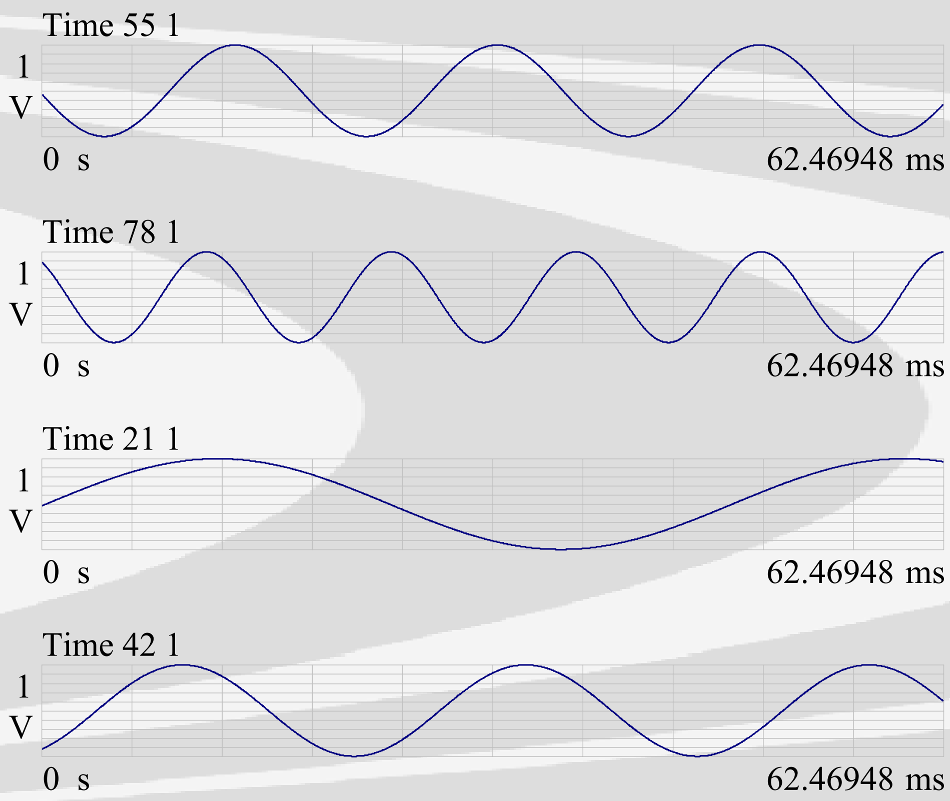
Single Frequency



Multiple Frequencies

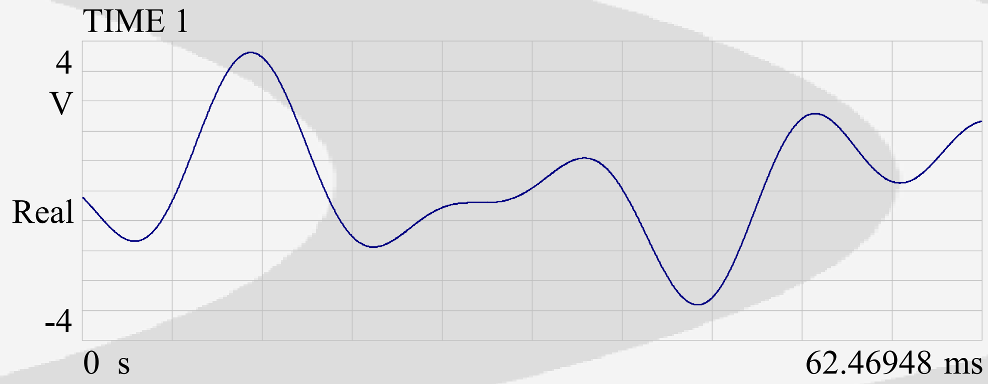


Multiple Time

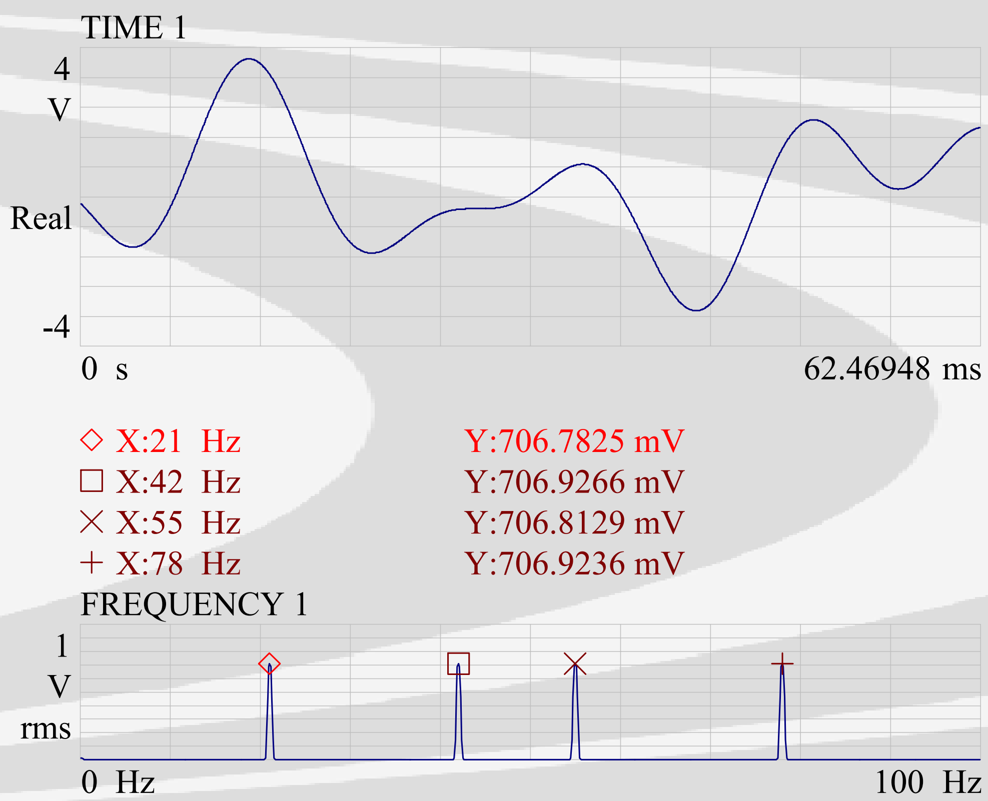


Real Life Time

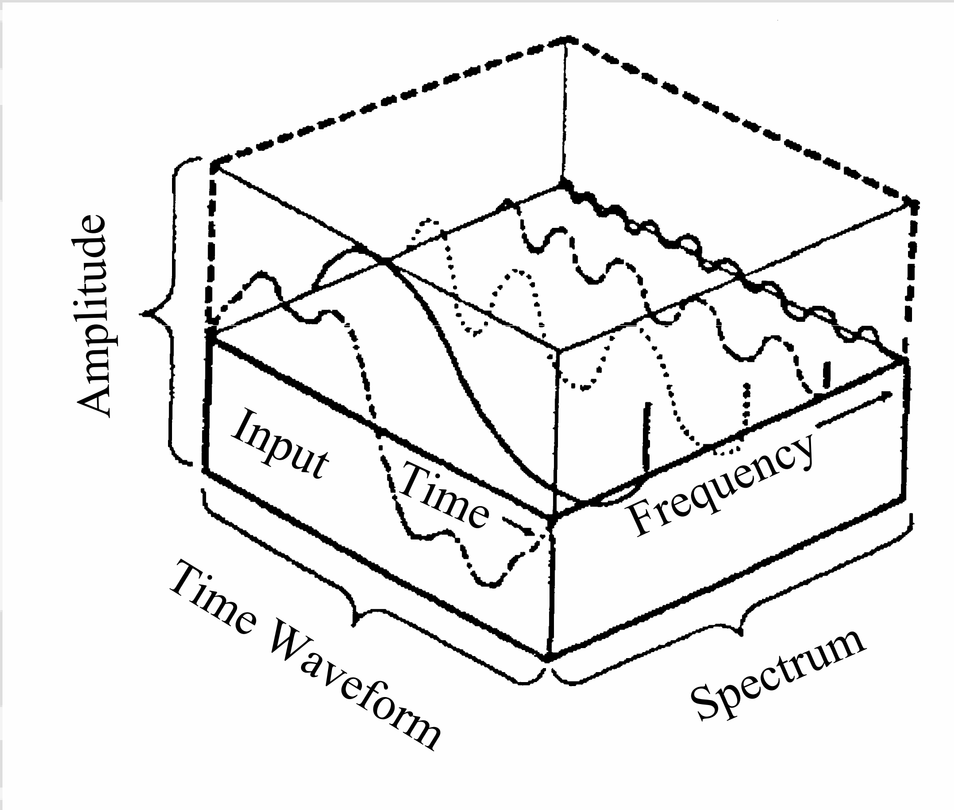
55 + 78 + 21 + 42 = Trouble !



Frequency Spectrum



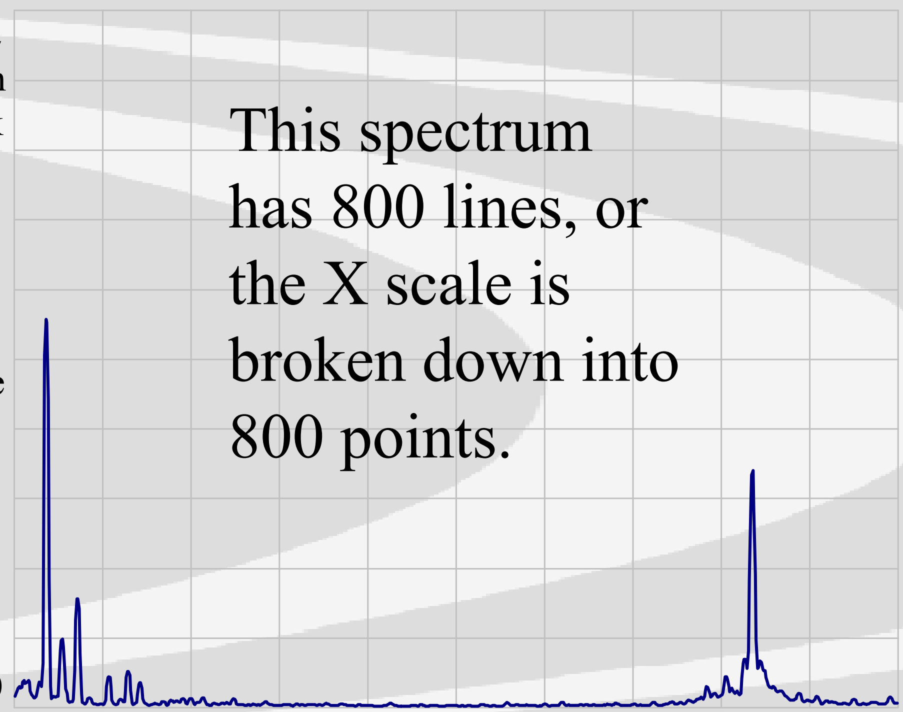
The Most Copied Slide in the History of Vibration Analysis !



Lines of Resolution

The FFT always has a defined number of lines of resolution.

100, 200, 400, 800, 1600, and 3200 lines are common choices.

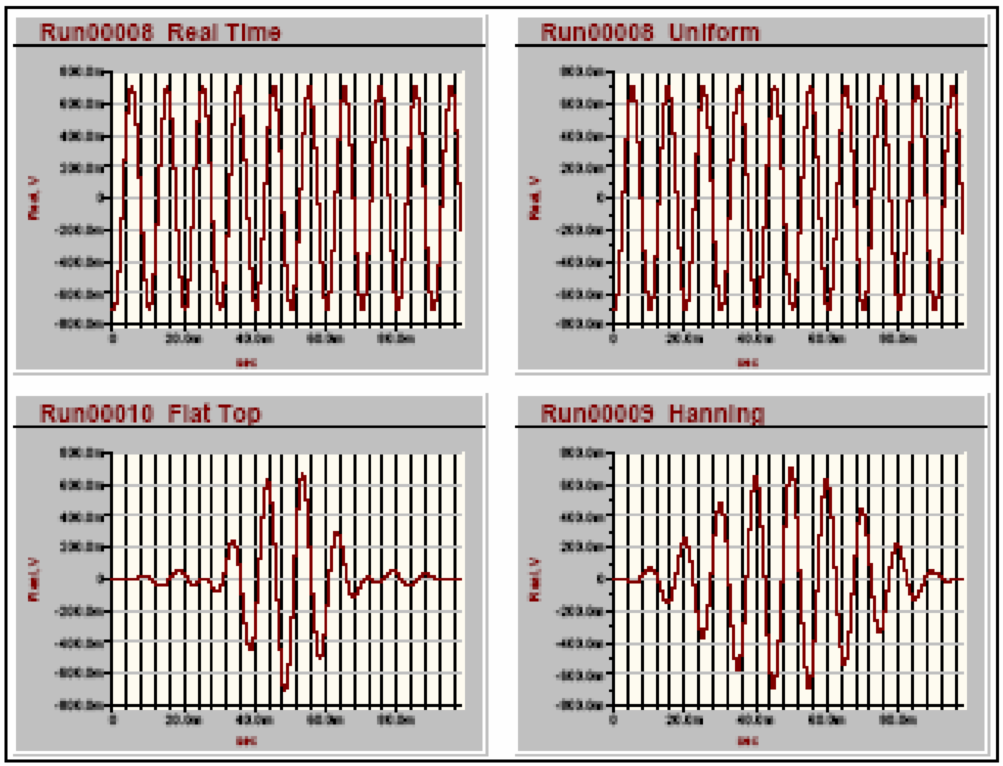


This spectrum has 800 lines, or the X scale is broken down into 800 points.

Filter Windows

- Window filters are applied to the time waveform data to simulate data that starts and stops at zero.
- They will cause errors in the time waveform and frequency spectrum.
- We still like window filters !

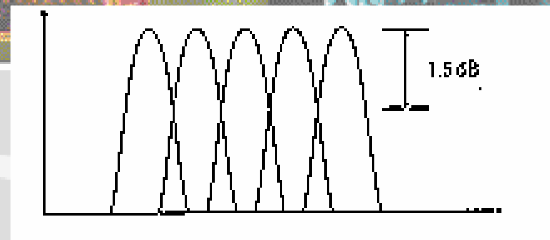
Window Comparisons



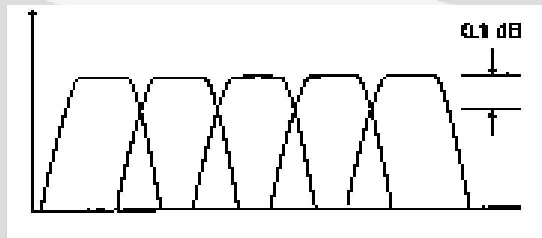
Filter Windows

- **Hanning (Frequency)**
- **Flat Top (Amplitude)**
- **Uniform (No Window)**
- **Force Exponential**
  (Frequency Response)
- **Force/Expo Set-up**

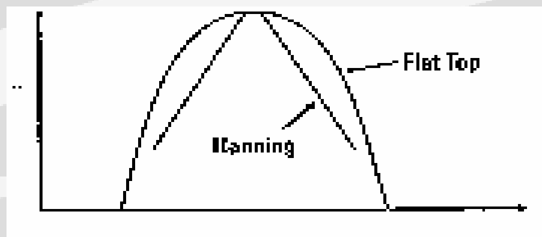
Window functions courtesy of Agilent
"The Fundamentals of Signal Analysis"
Application Note #AN 243



Hanning 16% Amplitude Error



Flat Top 1% Amplitude Error



Filter Windows

- Use the Hanning Window for normal vibration monitoring (Frequency)
- Use the Flat Top Window for calibration and accuracy (Amplitude)
- Use the Uniform Window for bump testing and resonance checks (No Window)

Minimum Derived Hz

The minimum derived frequency is determined by:

Frequency Span / Number of Analyzer Lines (data points)

The frequency span is calculated as the ending frequency minus the starting frequency.

The number of analyzer lines depends on the analyzer and how the operator has set it up.

Example: 0 - 400 Hz using 800 lines

Answer = (400 - 0) / 800 = 0.5 Hz / Line

Bandwidth

The Bandwidth can be defined by:

(Frequency Span / Analyzer Lines) Window Function

Uniform Window Function = 1.0

Hanning Window Function = 1.5

Flat Top Window Function = 3.5

Note: More discussion later on window functions for the analyzer !

Example: 0 - 400 Hz using 800 Lines & Hanning Window

Answer = (400 / 800) 1.5 = 0.75 Hz / Line

Resolution

The frequency resolution is defined in the following manner:

2 (Frequency Span / Analyzer Lines) Window Function

or

Resolution = 2 (Bandwidth)

Example: 0 - 400 Hz using 800 Lines & Hanning Window

Answer = 2 (400 / 800) 1.5 = 1.5 Hz / Line

Using Resolution

The student wishes to measure two frequency disturbances that are very close together.

Frequency #1 = 29.5 Hz.

Frequency #2 = 30 Hz.

The instructor suggests a hanning window and 800 lines.

What frequency span is required to accurately measure these two frequency disturbances ?

Using Resolution

Resolution = 30 - 29.5 = 0.5 Hz / Line

Resolution = 2 (Bandwidth)

BW = (Frequency Span / Analyzer Lines) Window Function

Resolution = 2 (Frequency Span / 800) 1.5

0.5 = 2 (Frequency Span / 800) 1.5

0.5 = 3 (Frequency Span) / 800

400 = 3 (Frequency Span)

133 Hz = Frequency Span

Data Sampling Time

Data sampling time is the amount of time required to take one record or sample of data. It is dependent on the frequency span and the number of analyzer lines being used.

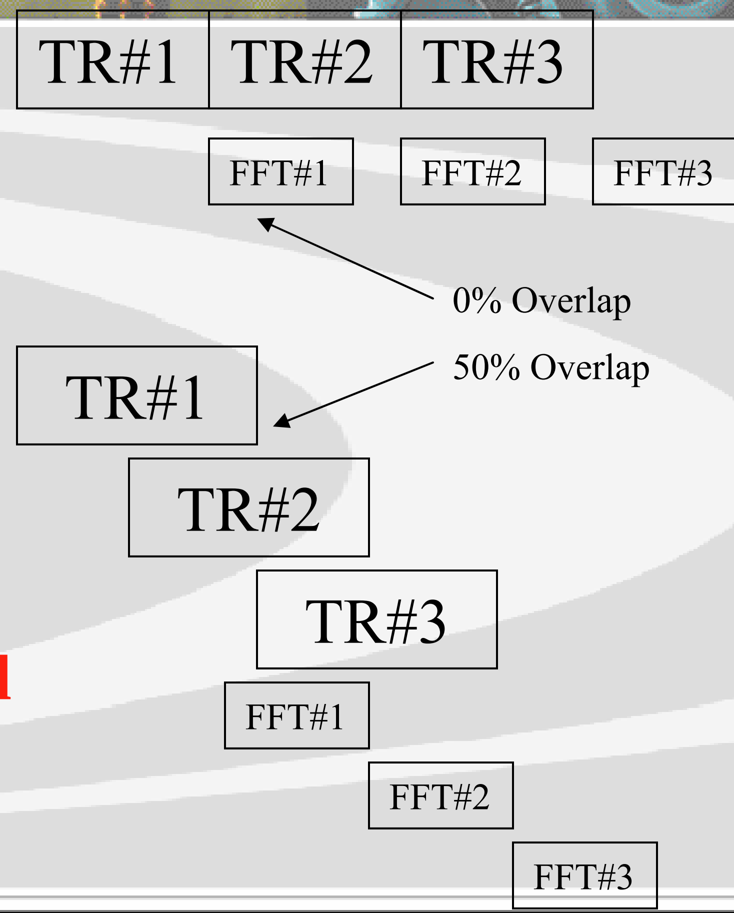
$$T_{Sample} = N_{lines} / F_{span}$$

Using 400 lines with a 800 Hz frequency span will require:

400 / 800 = 0.5 seconds

Average & Overlap

- **Average - On**
- **Overlap Percent - 50%**



How long will it take for 10 averages at 75% overlap using a 800 line analyzer and a 200 Hz frequency span?

75% Overlap ?

- 10 Averages
- 75% Overlap
- 800 Lines
- 200 Hz

Average #1 = 800 / 200

Average #1 = 4 seconds

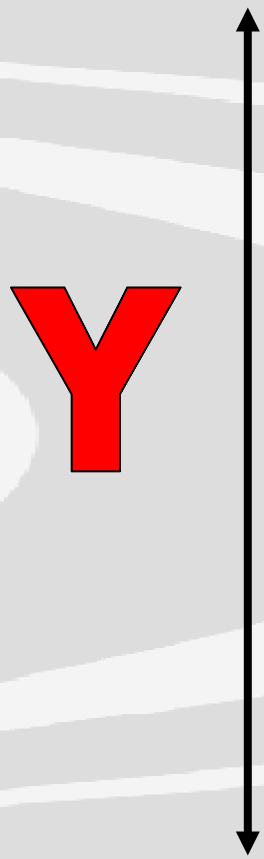
Average #2 - #10 = (4 x 0.25)

Average #2 - #10 = 1 second each

Total time = 4 + (1 x 9)

Total time = 13 seconds

The Y Scale



Amplitude

The “Y” scale provides the amplitude value for each signal or frequency.

Default units for the “Y” scale are **volts RMS**.

Volts is an **E**ngineering **U**nit (**EU**).

RMS is one of three suffixes meant to confuse you !

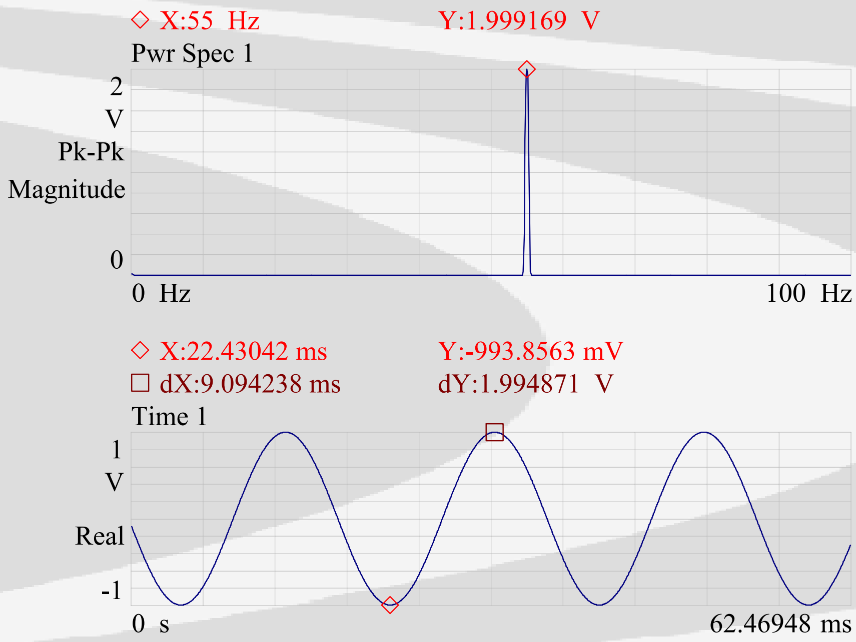
The other two are:

(Peak) and (**Peak - Peak**)

Pk-Pk (Peak - Peak)

The Peak - Peak value is expressed from the peak to peak amplitude.

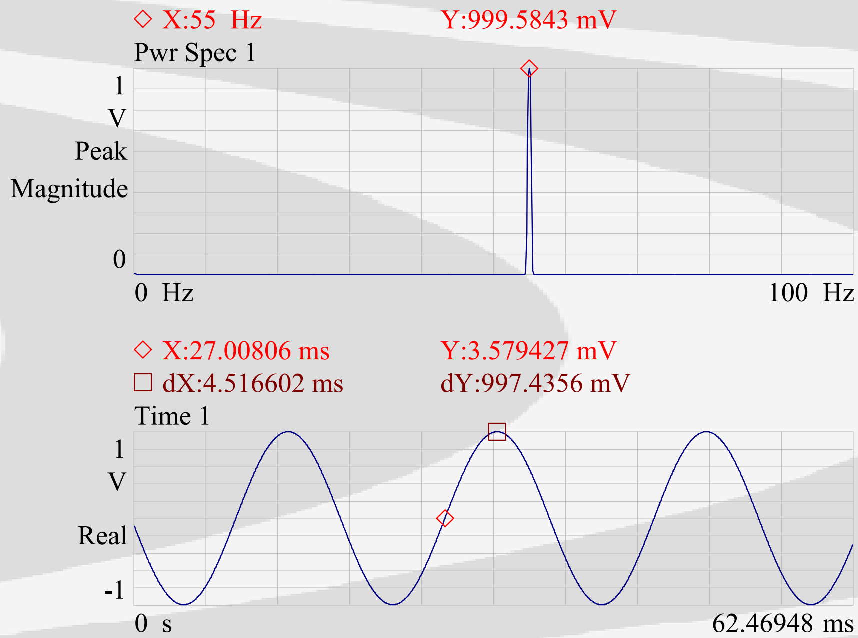
The spectrum value uses the suffix “Pk-Pk” to denote this.



Pk (Peak)

The time wave has not changed. The Peak value is expressed from zero to the peak amplitude.

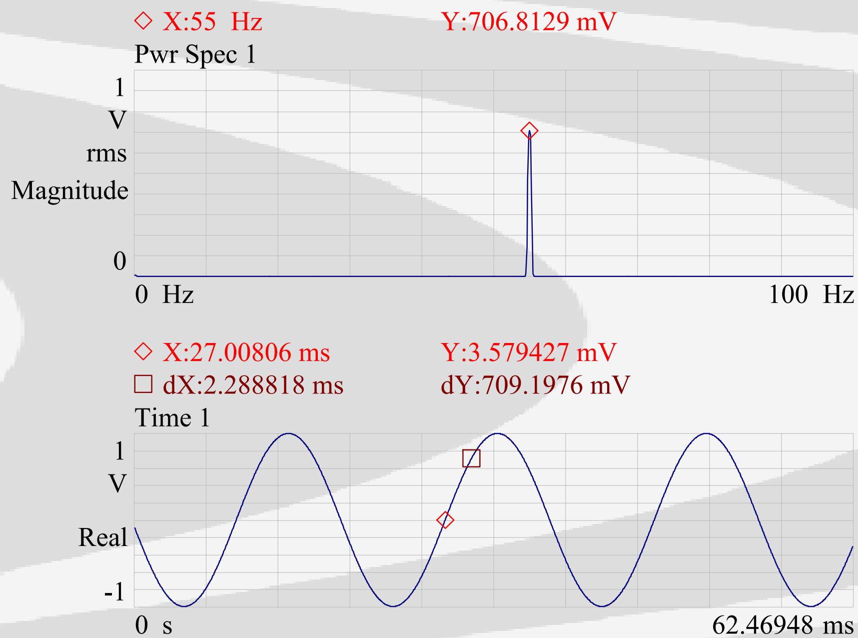
The spectrum value uses the suffix “Peak” to denote this.



RMS (Root Mean Square)

The time wave has not changed. The RMS value is expressed from zero to 70.7% of the peak amplitude.

The spectrum value uses the suffix "RMS" to denote this.

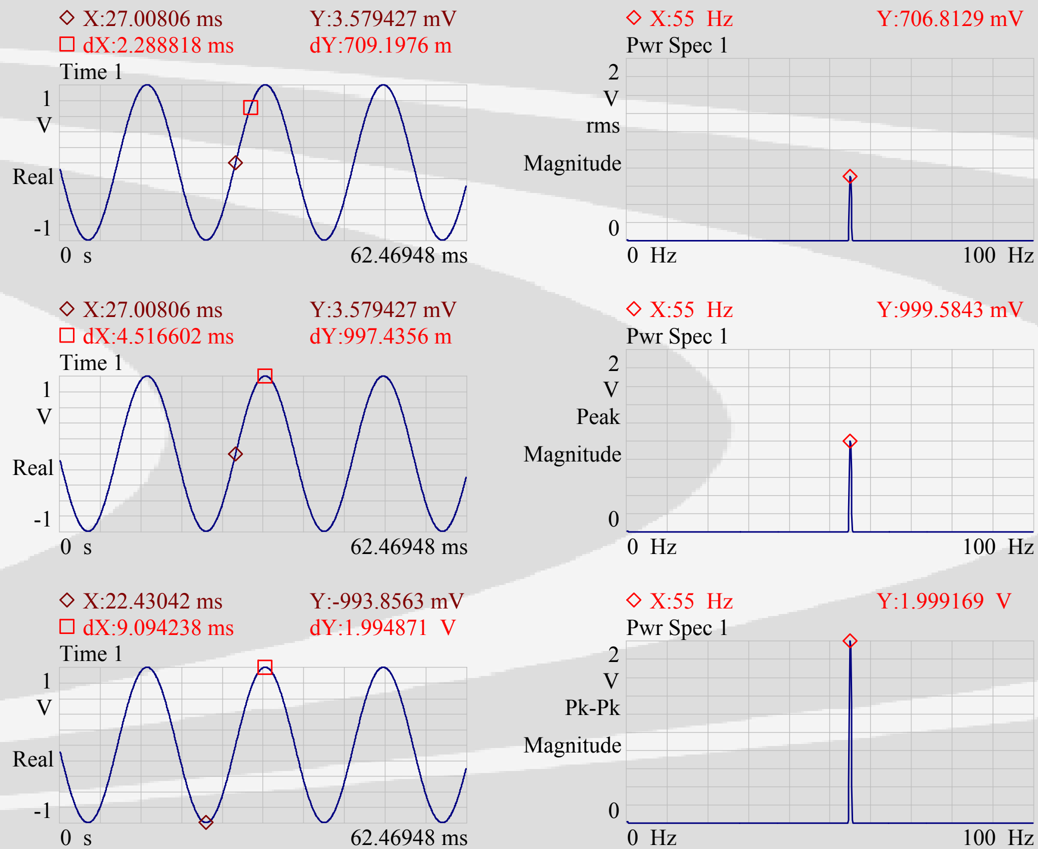


Suffix Comparison

RMS

Peak

Peak - Peak



Changing Suffixes

Many times it is necessary to change between suffixes.

Pk-Pk / 2 = Peak

Peak x 0.707 = RMS

RMS x 1.414 = Peak

Peak x 2 = Pk-Pk

Standard Suffixes

Now that we have learned all about the three standard suffixes that might possibly confuse the "Y" scale values, **what is the standard ?**

Vibration Institute:

Displacement = mils Peak - Peak

Velocity = in/s Peak or rms..

Acceleration = g's Peak or rms..

Note: 1 mil = 0.001 inches

Engineering Units (EU)

Engineering units are used to give meaning to the amplitude of the measurement.

Instead of the default "volts", it is possible to incorporate a unit proportional to volts that will have greater meaning to the user.

Examples:	**100 mV / g**	**20 mV / Pa**
	1 V / in/s	**200 mV / mil**
	50 mV / psi	**10 mV / fpm**
	33 mV / %	**10 mV / V**

EU's the Hard Way

Sometimes we forget to use EU's, or just don't understand how to set up the analyzer.

There is no immediate need to panic if ????

You know what the EU is for the sensor you are using.

Example: An accelerometer outputs 100 mV / g and there is a 10 mV peak in the frequency spectrum.

What is the amplitude in g's ?

Answer = 10 mV / 100 mV = 0.1 g

The Big Three EU's

Acceleration

Velocity

Displacement

Converting the Big 3

In many cases we are confronted with Acceleration, Velocity, or Displacement, but are not happy with it.

Maybe we have taken the measurement in acceleration, but the model calls for displacement.

Maybe we have taken the data in displacement, but the manufacturer quoted the equipment specifications in velocity.

How do we change between these EU's ?

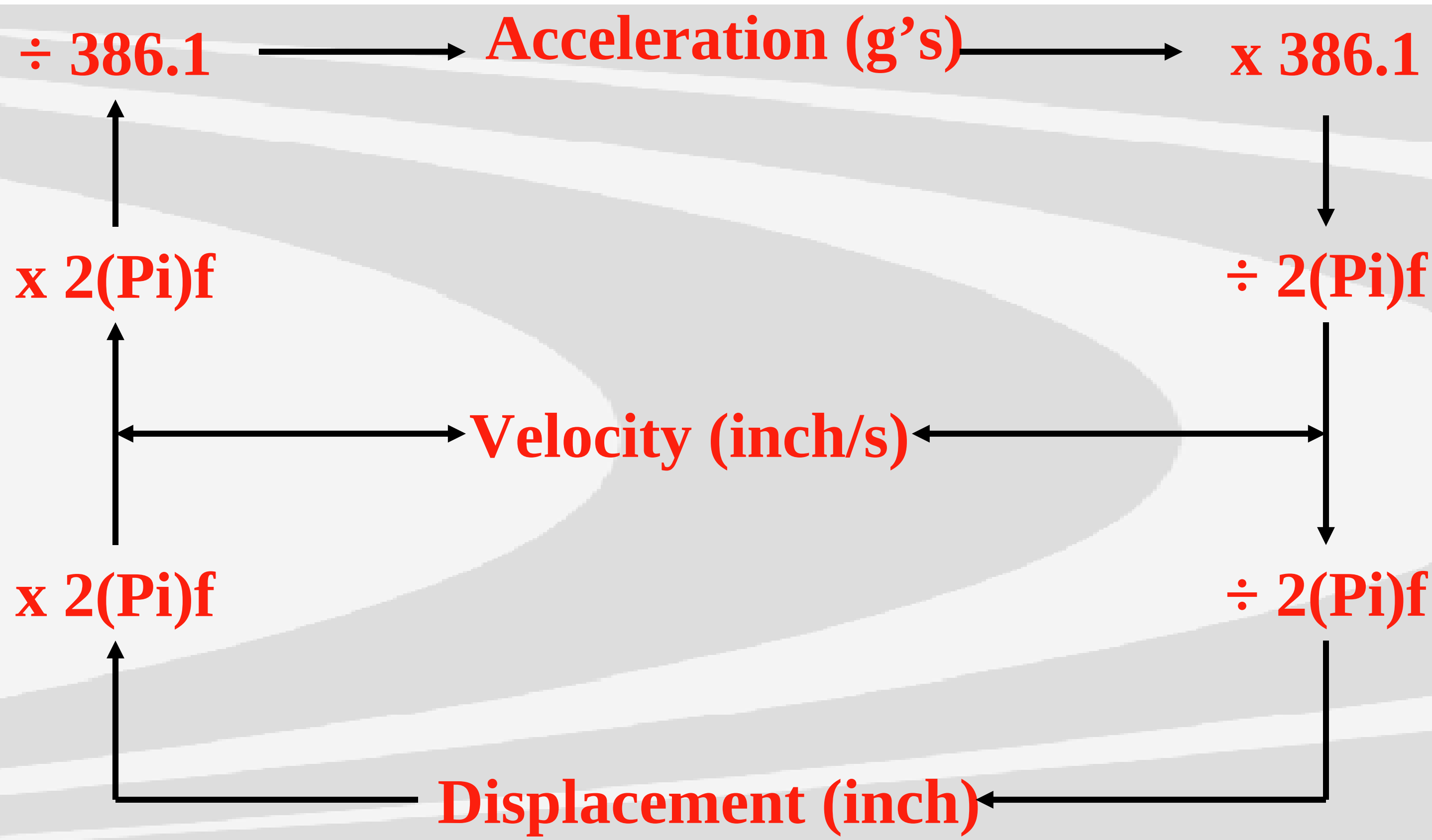
386.1 What ?

$$1g = 32.2 \text{ feet/second}^2$$

$$\frac{32.2 \text{ feet}}{\text{second}^2} \times \frac{12 \text{ inches}}{\text{foot}}$$

$$\frac{386.1 \text{ inches/second}^2}{g}$$

Go With The Flow I



Metric Go With The Flow I

÷ 9807 → Acceleration (g's) → x 9807

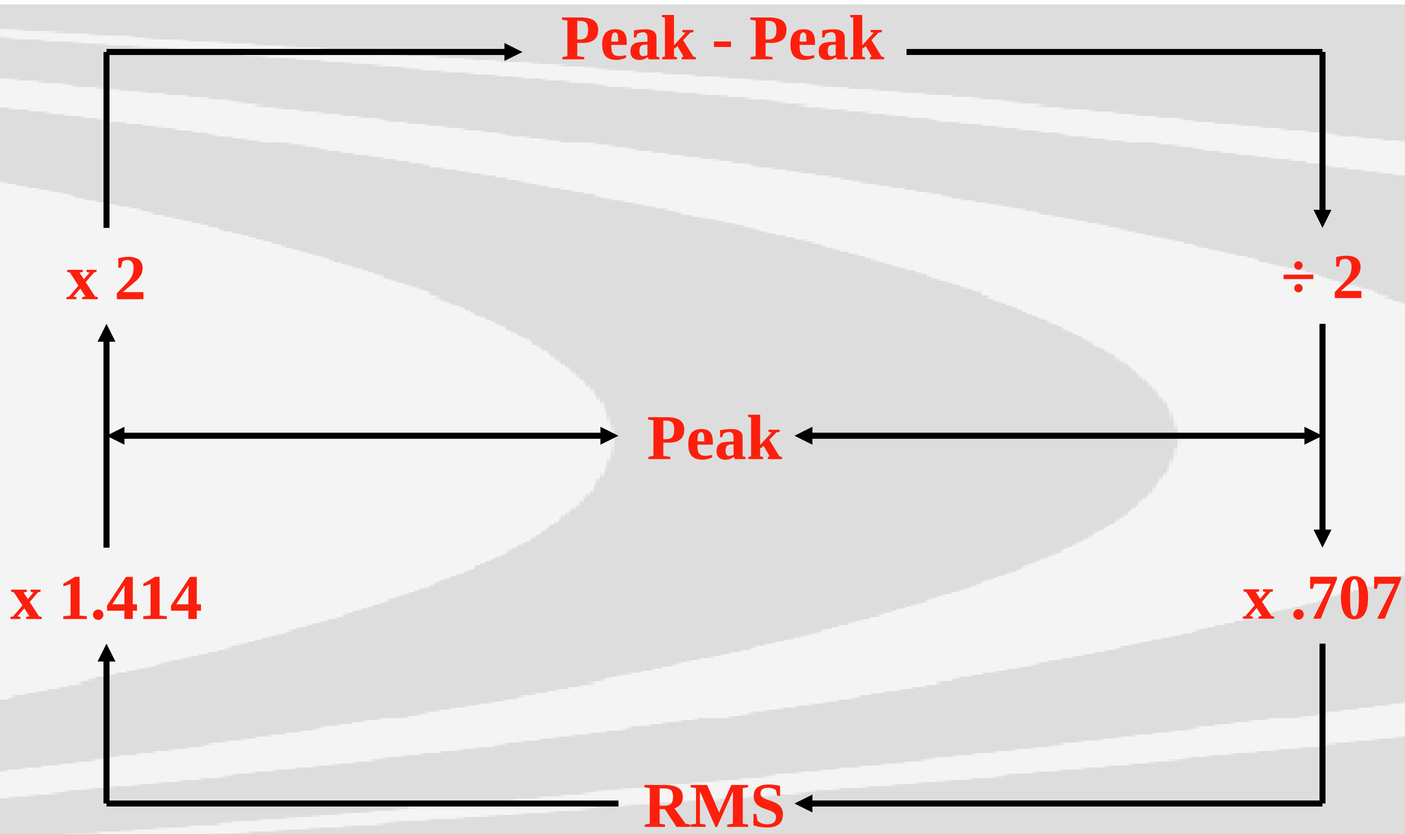
x 2(Pi)f ↑ ↓ ÷ 2(Pi)f

Velocity (mm/s)

x 2(Pi)f ↑ ↓ ÷ 2(Pi)f

Displacement (mm)

Go With The Flow II



Doing the Math Units

There is a 0.5 g vibration at 25 Hz.

What is the velocity ?

$$\frac{\dfrac{0.5g \times \dfrac{386.1\ \text{inches}}{\text{second}^2}}{g}}{2\pi \times \dfrac{25\ \text{cycles}}{\text{second}}}$$

$$\frac{0.5g \times 386.1\ \text{inches}}{g \quad \text{second}^2} \times \frac{1\ \text{second}}{2\pi \times 25\ \text{cycles}}$$

$$\frac{0.5 \times 386.1\ \text{inches}}{\dfrac{2\pi}{\text{cycle}} \times 25\ \text{cycles second}}$$

1.23 inches/second

Acceleration - Velocity

Example: Find the equivalent peak velocity for a 25 Hz vibration at 7 mg RMS ?

= (g x 386.1) / (2 Pi x F)

= (0.007 x 386.1) / (6.28 x 25)

= 0.017 inches / second RMS

Answer = 0.017 x 1.414 = 0.024 inches / second Pk

Velocity - Displacement

Example: Find the equivalent pk-pk displacement for a 25 Hz vibration at 0.024 in/s Pk ?

= Velocity / (2 Pi x F)

= 0.024 / (6.28 x 25)

= 0.000153 inches Pk

Answer = 0.000153 x 2 = 0.000306 inches Pk-Pk

Acceleration - Displacement

Example: Find the equivalent Pk-Pk displacement for a 52 Hz vibration at 15 mg RMS ?

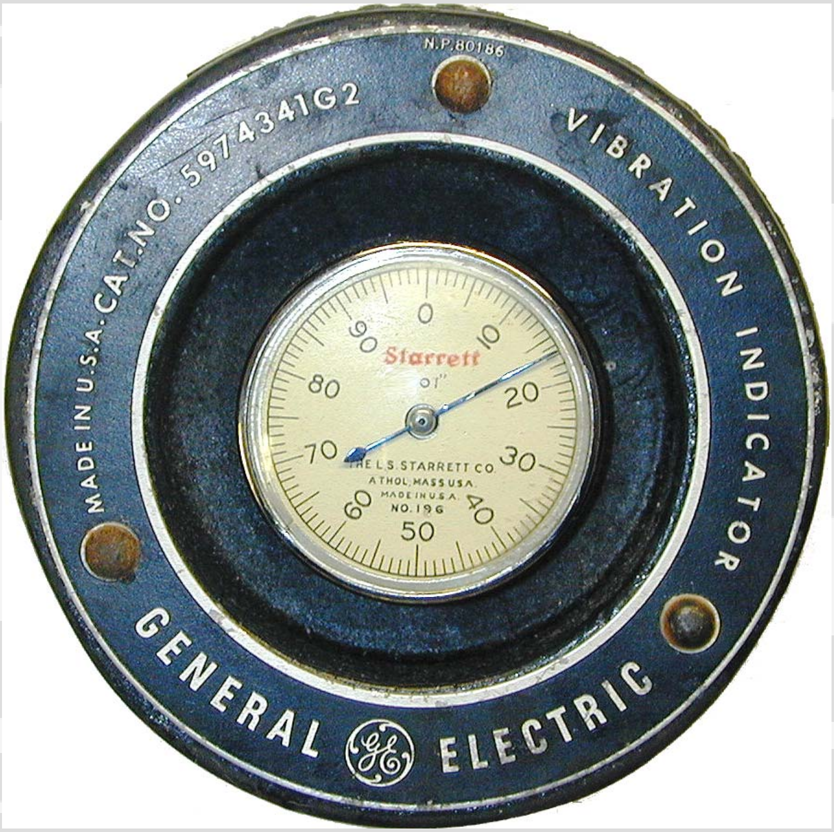
$$= (g \times 386.1) / (2 \text{ Pi} \times F)^2$$

$$= (0.015 \times 386.1) / (6.28 \times 52)^2$$

$$= 0.000054 \text{ inches RMS}$$

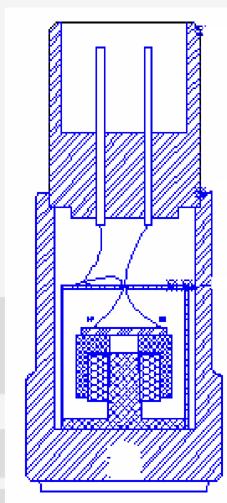
Answer = (0.000054 x 1.414) 2 = 0.000154 inches Pk-Pk

Sensors


N.P. 80186
MADE IN U.S.A. CAT. NO. 5974341G2
VIBRATION INDICATOR
GENERAL ELECTRIC
Starrett
.01"
THE L.S. STARRETT CO.
ATHOL, MASS U.S.A.
MADE IN U.S.A.
NO. 196

Accelerometers

- Integrated Circuit
  - Electronics inside
  - Industrial
- Charge Mode
  - Charge Amplifier
  - Test & Measurement



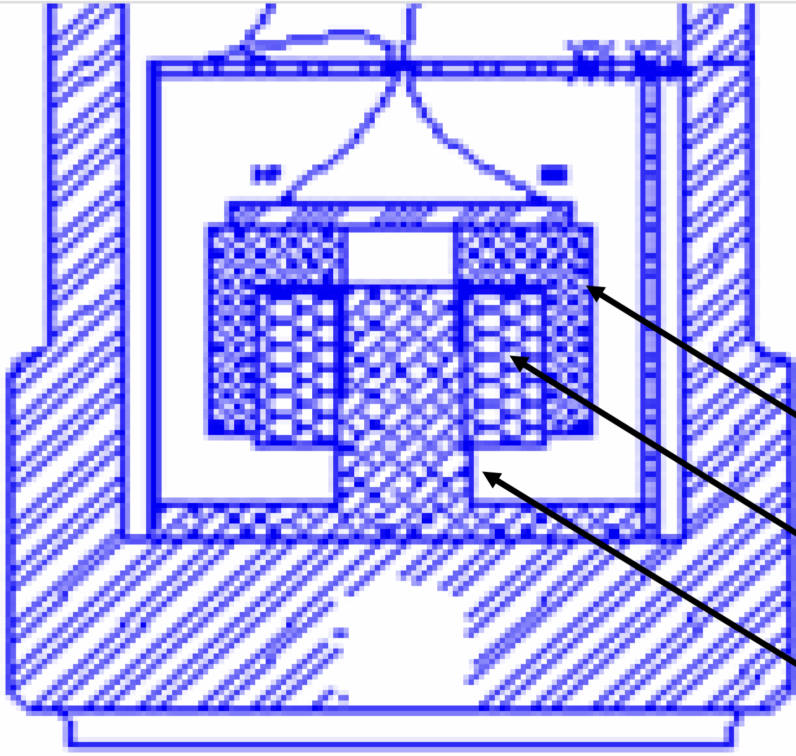
Accelerometer Advantages

- Measures casing vibration
- Measures absolute motion
- Can integrate to Velocity output
- Easy to mount
- Large range of frequency response
- Available in many configurations

Accelerometer Disadvantages

- Does not measure shaft vibration
- Sensitive to mounting techniques and surface conditions
- Difficult to perform calibration check
- Double integration to displacement often causes low frequency noise
- One accelerometer does not fit all applications

Mass & Charge



Relative movement between post & mass creates shear in ceramic producing charge.

Mass

Ceramic/Quartz

Post

Accelerometer Parameters

Performance Suited for Application

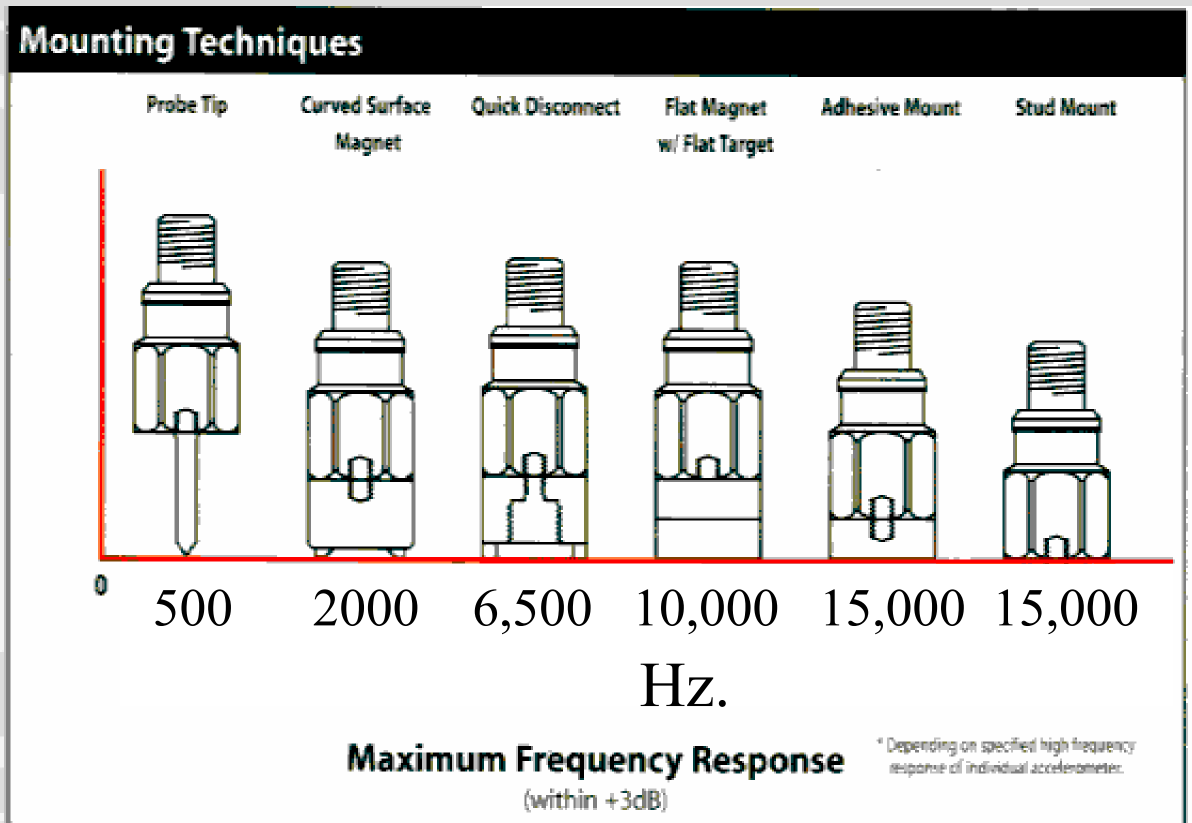
Sensitivity (mV/g)

Frequency Response of target (f span)

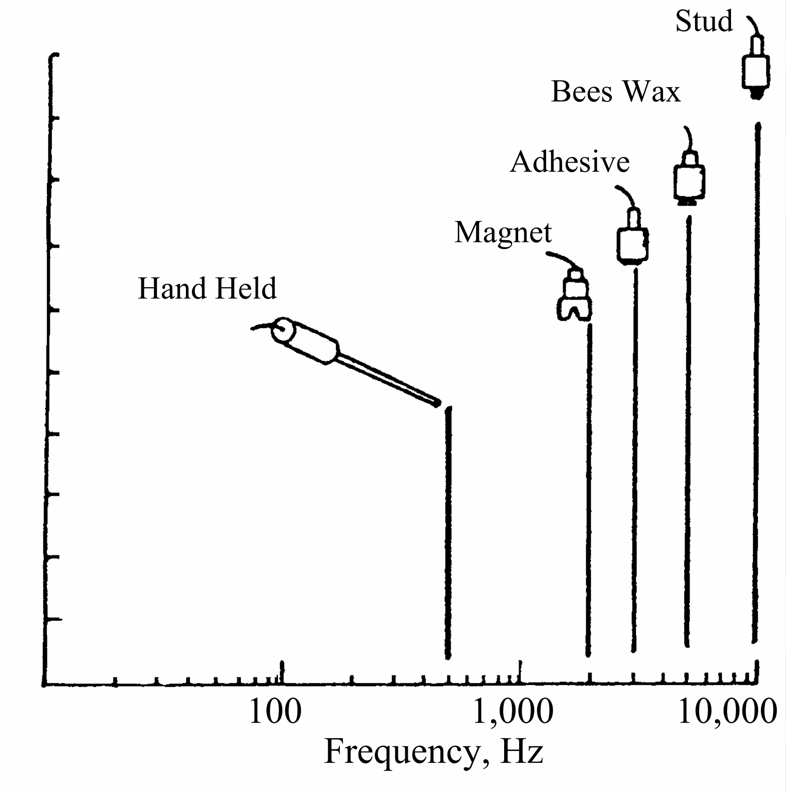
Dynamic Range of target (g level)

Part Number	AC102-1B
Performance Specifications	***English***
Sensitivity +/-10%	100 mV/g
Frequency Response	
±3 dB	30-900,000 CPM
±10%	60-360,000 CPM
±5%	102-240,000 CPM
Dynamic Range	±50 g peak

Mounting the Accelerometer



Realistic Mounting

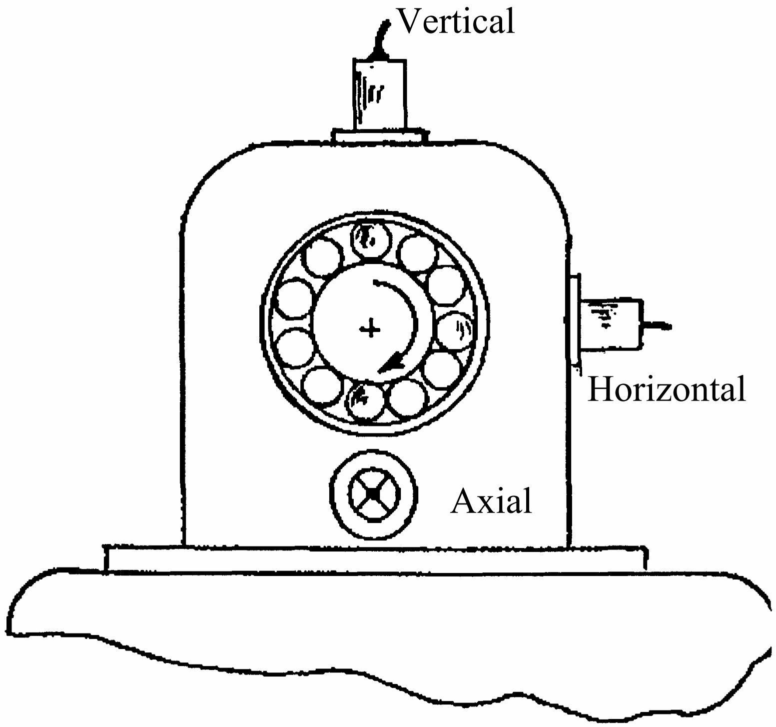


In the real world, mounting might not be as good as the manufacturer had in the lab !

What happened to the high frequency ?

Mounting Location

- Load Zone
- Radial
  - ✓Vertical
  - ✓Horizontal
- Axial



Mounting Location

- Load Zone
- Radial
  - ✓Vertical
  - ✓Horizontal
- Axial

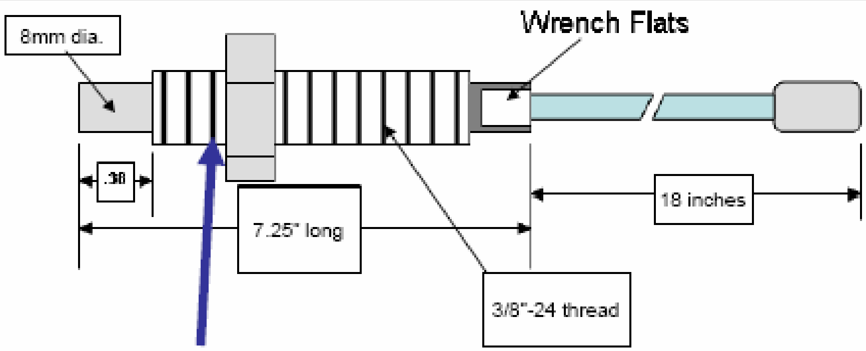
Accelerometer Alarms

Machine Condition	Velocity Limit	
	rms	peak
Acceptance of new or repaired equipment	< 0.08	< 0.16
Unrestricted operation (normal)	< 0.12	< 0.24
Surveillance	0.12 - 0.28	0.24 - 0.7
Unsuitable for Operation	> 0.28	> 0.7

Note #1: The rms velocity (in/sec) is the band power or band energy calculated in the frequency spectrum.

Note #2: The peak velocity (in/sec) is the largest positive or negative peak measured in the time waveform.

Proximity Probes



DS1811-38-038-725-1

Proximity Probe with 8mm tip, 100mil range w/18" integral cable and SMA connector

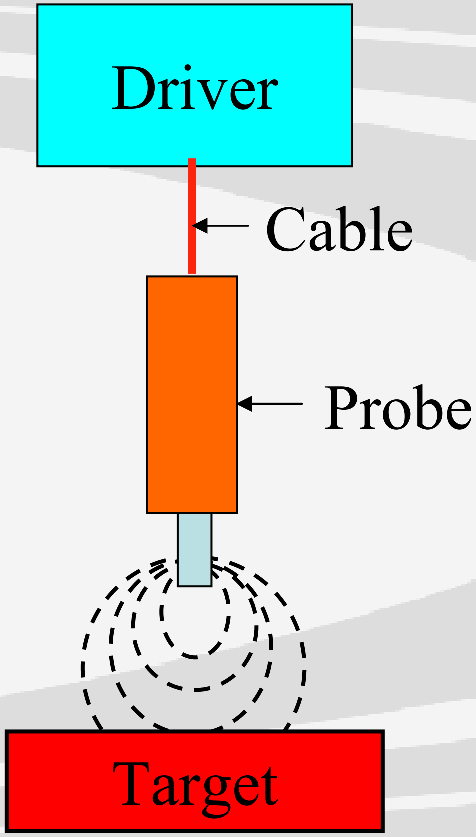
DS1590

Proximity Probe Driver

DSCB1000-450-C200

Extension cable assembly with SMA Connector and spade lugs, 4.5 meters Long (14 ½ feet).

Proximity Probe Theory



The tip of the probe broadcasts a radio frequency signal into the surrounding area as a magnetic field.

If a conductive target intercepts the magnetic field, eddy currents are generated on the surface of the target, and power is drained from the radio frequency signal.

As the power varies with target movement in the radio frequency field, the output voltage of the driver also varies.

A small dc voltage indicates that the target is close to the probe tip.

A large dc voltage indicates that the target is far away from the probe tip.

The variation of dc voltage is the dynamic signal indicating the vibration or displacement.

Output Values

- Typical
  - 100 mv/mil
  - 200 mv/mil
- Depends on probe, cable (length), and driver.
- Target material varies output.

Calibration Examples

Copper	380 mV/mil
Aluminum	370 mV/mil
Brass	330 mV/mil
Tungsten Carbide	290 mV/mil
Stainless Steel	250 mV/mil
Steel 4140, 4340	200 mV/mil

Based on typical output sensitivity of 200 mV/mil.

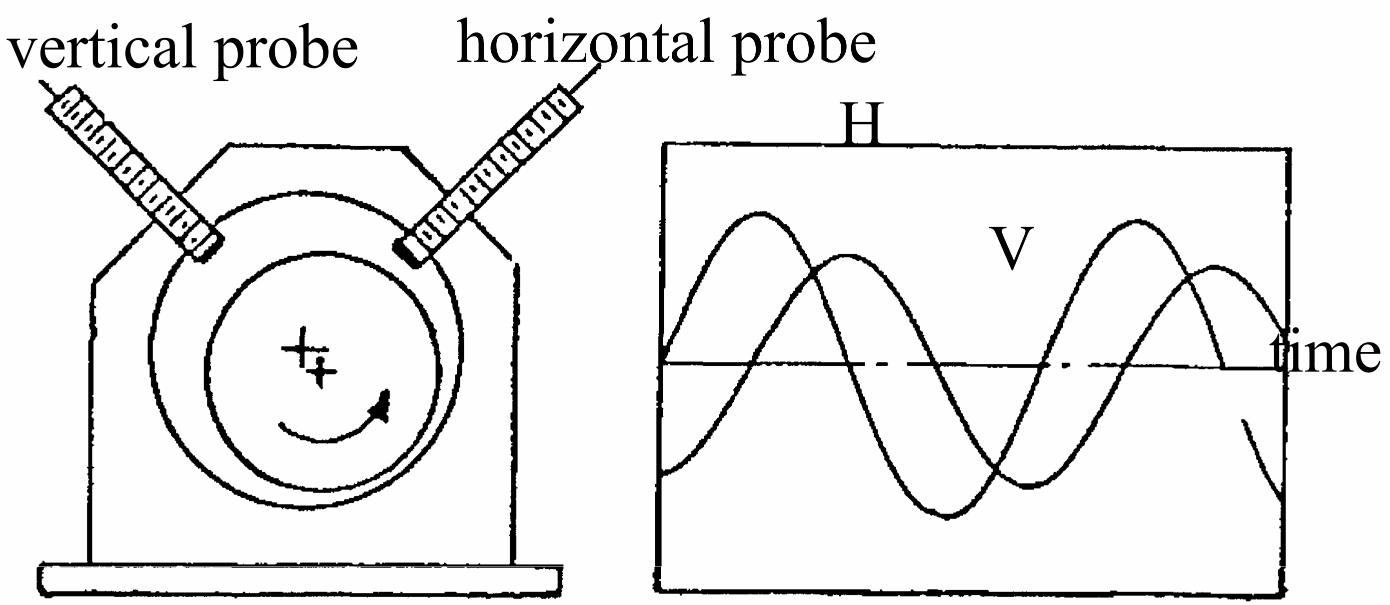
Proximity Probes - Advantages

- Non-contact
- Measure shaft dynamic motion
- Measure shaft static position (gap)
- Flat frequency response dc – 1KHz
- Simple calibration
- Suitable for harsh environments

Proximity Probes - Disadvantages

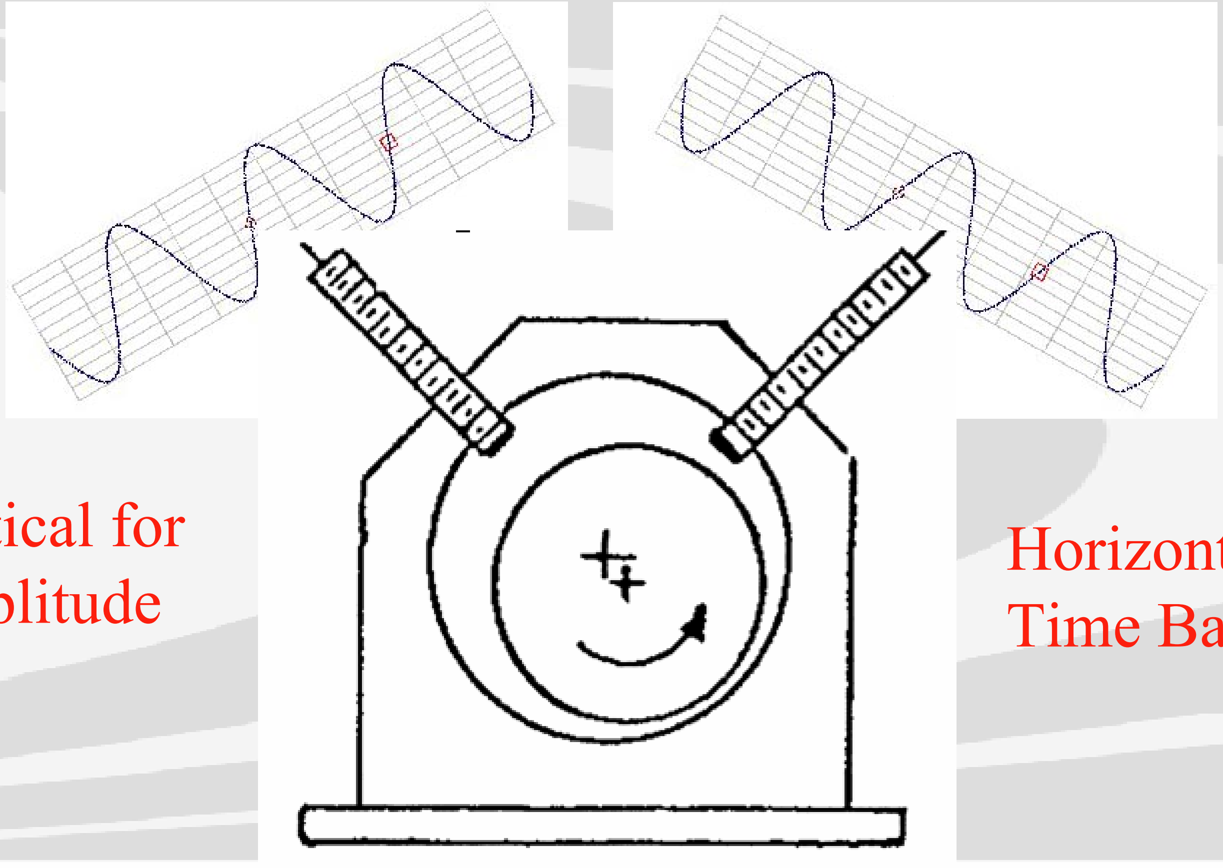
- Probe can move (vibrate)
- Doesn’t work on all metals
- Plated shafts may give false measurement
- Measures nicks & tool marks in shaft
- Must be replaced as a unit (probe, cable & driver)
- Must have relief at sensing tip from surrounding metal

Typical Mounting



Facing Driver to Driven
(independent of rotation)

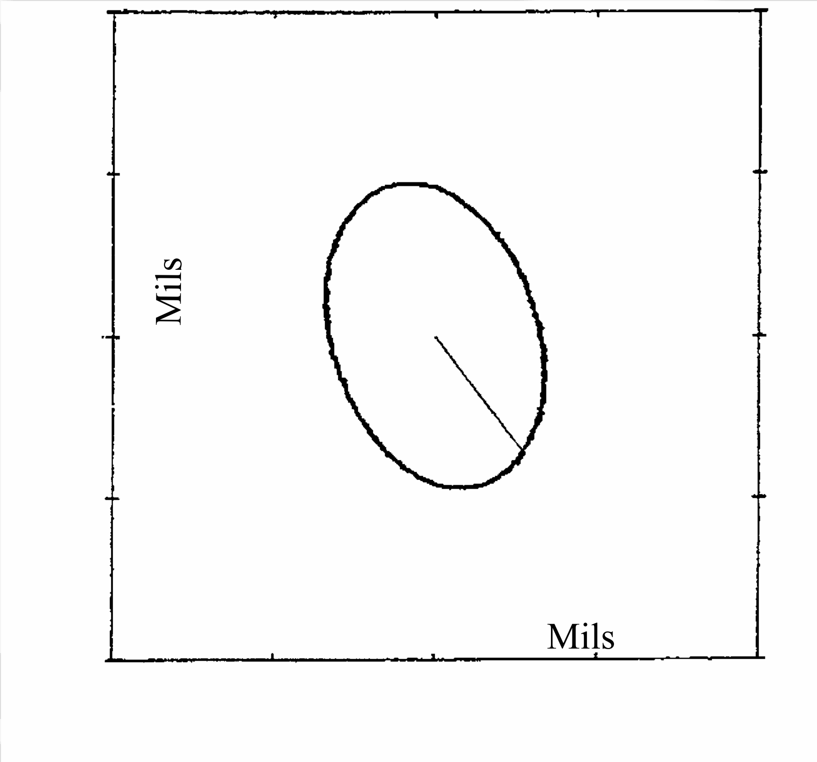
Looking at Orbits

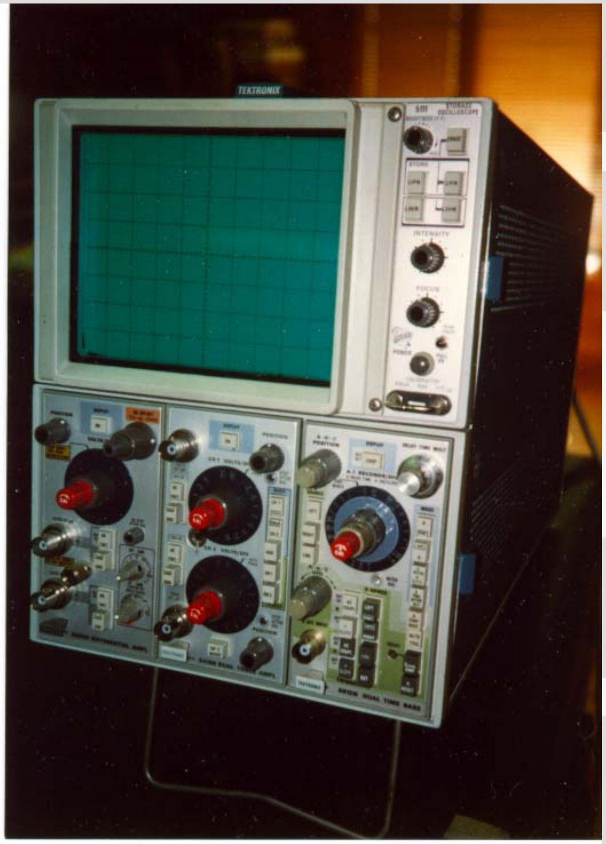


Vertical for Amplitude

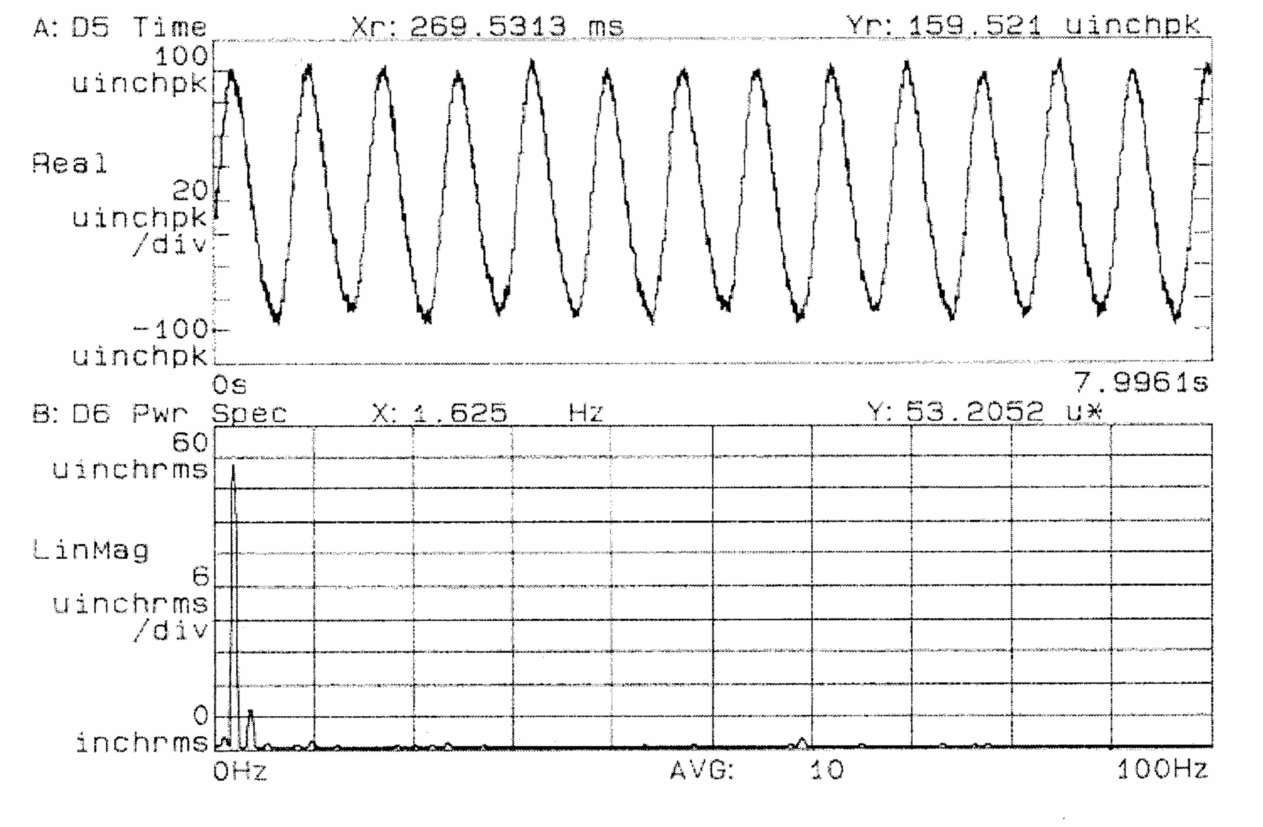
Horizontal for Time Base

The Orbit Display

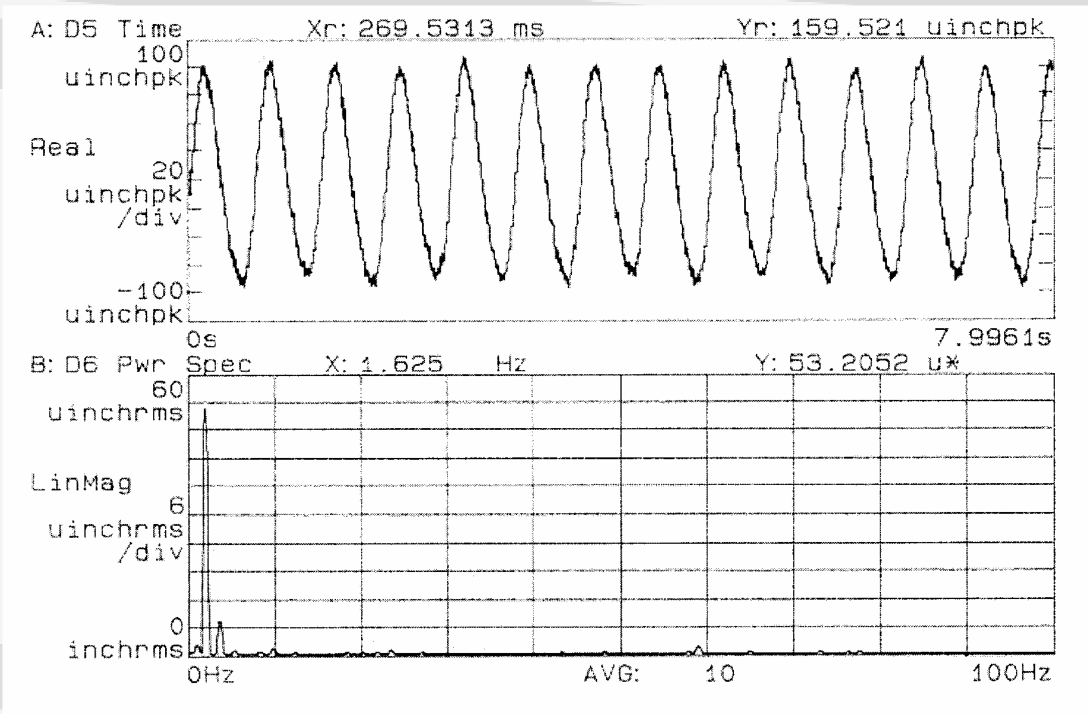


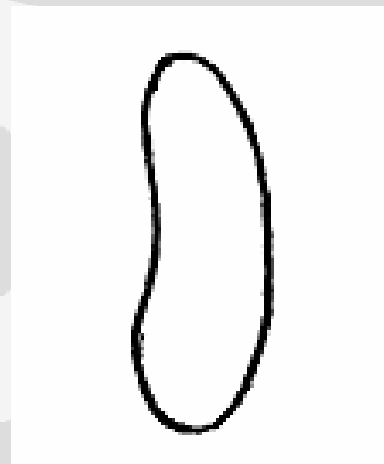


Unbalance

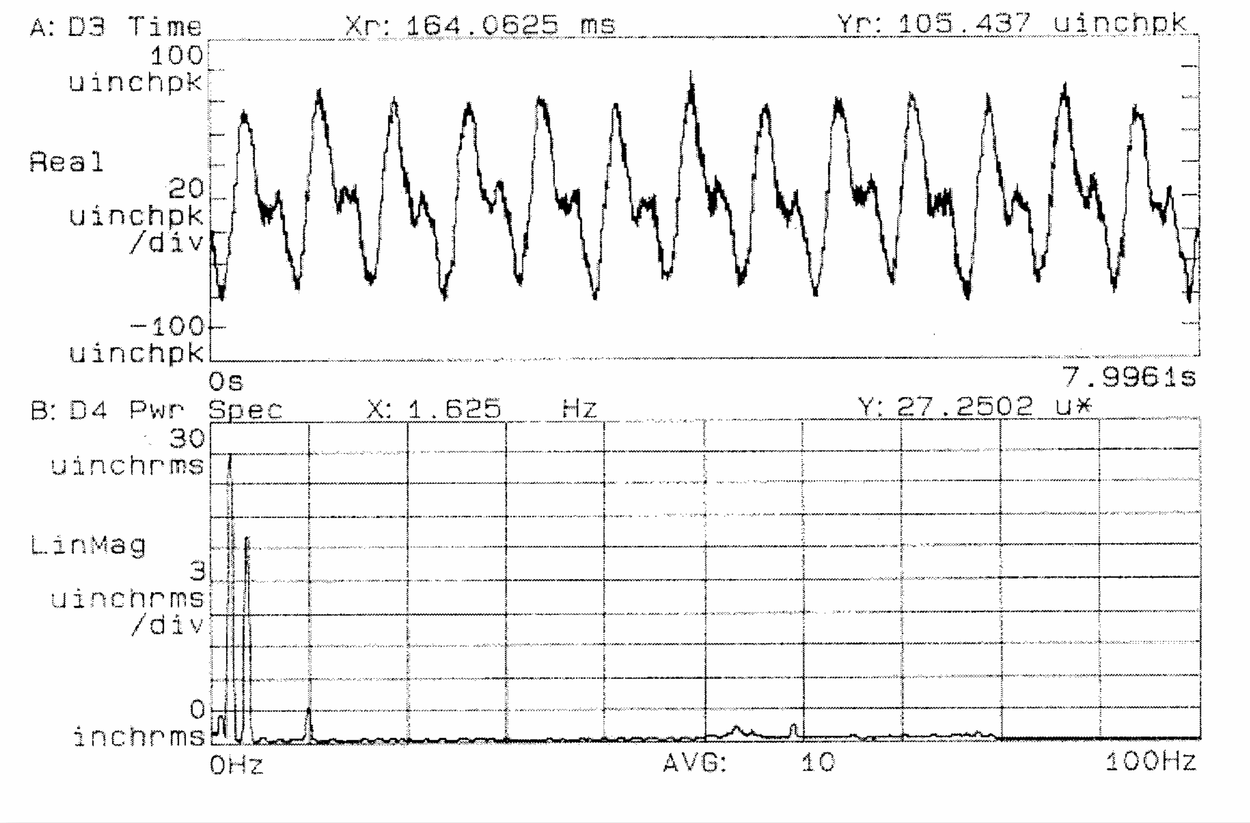

A: D5 Time
Xr: 269.5313 ms
Yr: 159.521 uinchpk
100 uinchpk
Real
20 uinchpk /div
-100 uinchpk
0s
7.9961s
B: D6 Pwr Spec
X: 1.625 Hz
Y: 53.2052 u*
60 uinchrms
LinMag
6 uinchrms /div
0 inchrms
0Hz
AVG: 10
100Hz

Unbalance with Orbit

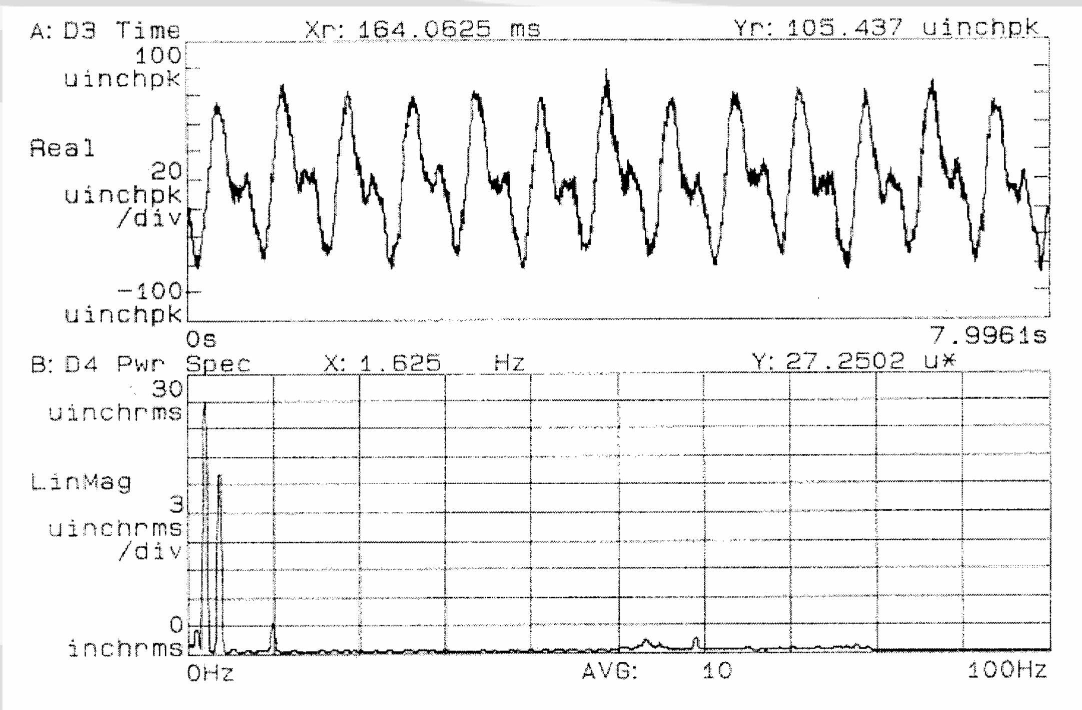


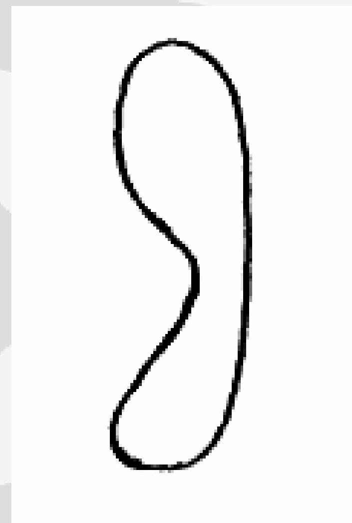


Misalignment

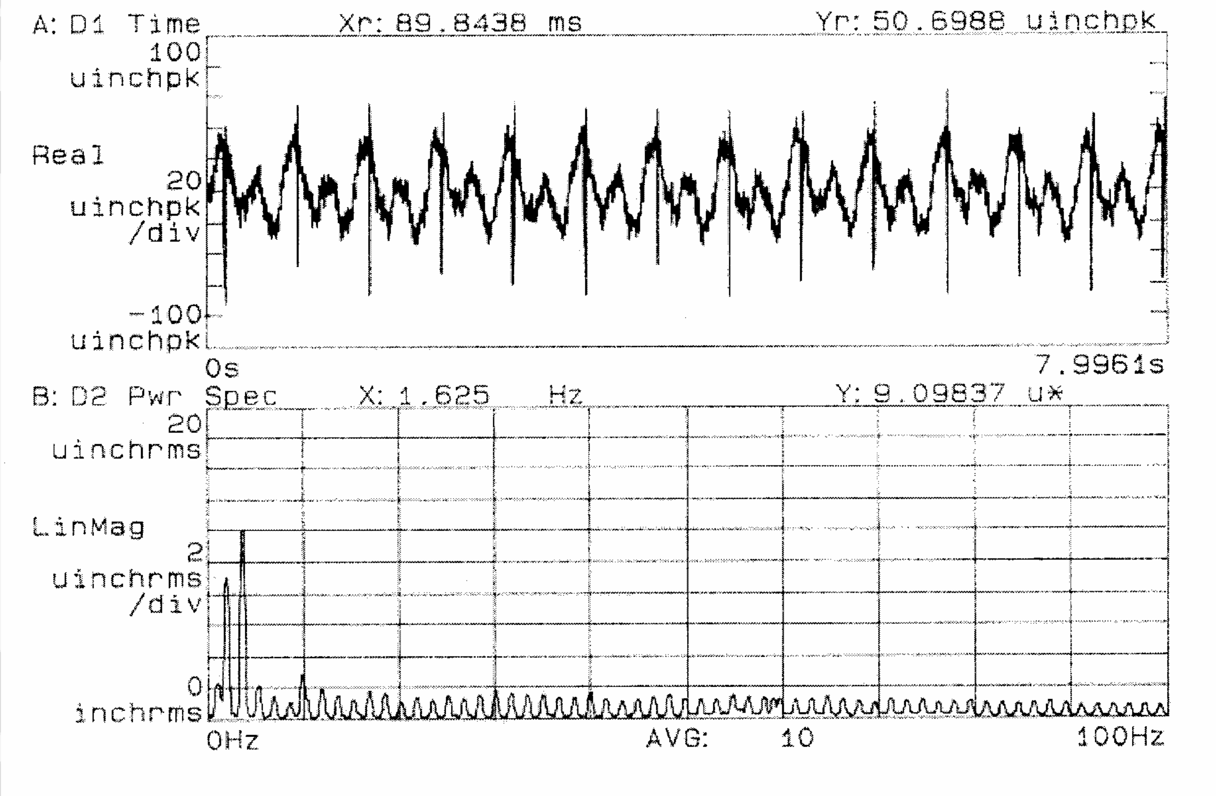


Misalignment with Orbit





And the problem is ?



Proximity Probe Alarms

Machine Condition	Allowable R/C	
	< 3,600 RPM	< 10,000 RPM
Normal	0.3	0.2
Surveillance	0.3 - 0.5	0.2 - 0.4
Planned Shutdown	0.5	0.4
Unsuitable for Operation	0.7	0.6

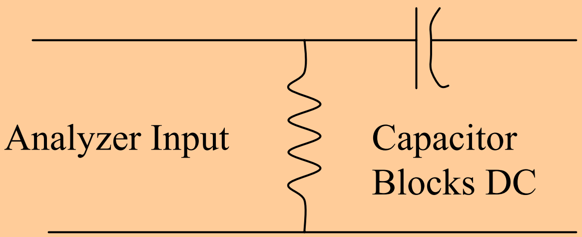
Note #1: R is the relative displacement of the shaft measured by either probe in mils peak-peak.

Note #2: C is the diametrical clearance (difference between shaft OD and journal ID) measured in mils.

Analyzer Input - Front End

- **Coupling - AC**, DC →

  AC coupling will block the DC voltage. It creates an amplitude error below 1 Hz. DC coupling has no error below 1 Hz, but the analyzer must range on the total signal amplitude.



AC Coupling Capacitor in DSA

- **Antialias Filter - On**, Off →

  Prevents frequencies that are greater than span from wrapping around in the spectrum.

If the antialias filter is turned off, at what frequency will 175 Hz. appear using a 0 - 100 Hz span, and 800 lines ?

1024/800 = 1.28

100 x 1.28 = 128 Hz

175 Hz - 128 Hz = 47 Hz.

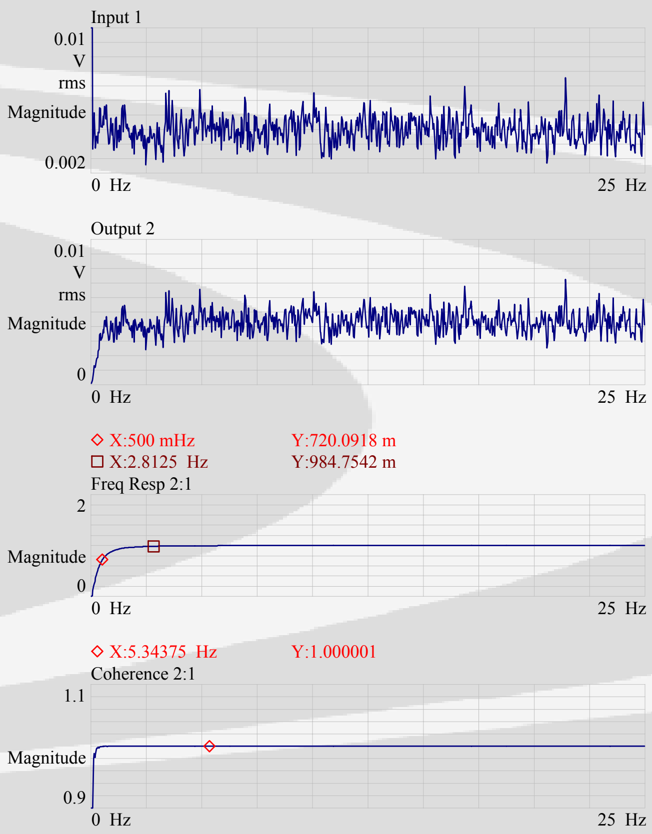
128 Hz - 47 Hz = 81 Hz

Low End Frequency Response

To the right is a typical problem with frequency response at the low end of the frequency spectrum.

This low end roll off was a result of AC coupling on CH #2 of the analyzer.

Values below 2.8 Hz are in error, and values less than 0.5 Hz should not be used.



Data Collection

MADE IN THE USA

CTC
VIBRATION ANALYSIS HARDWARE

Tape Recorders “*Insurance Policy*”

Multi-channel digital audio tape recorders.

For the Measurement that can’t get away !

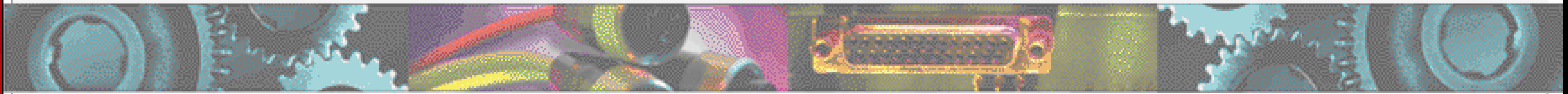
Dynamic Signal Analyzers *“Test & Measurement”*

Large PC driven solutions with multiple channels and windows based software.

Smaller portable units with 2 – 4 channel inputs and firmware operating systems.

Data Collectors *"Rotating Equipment"*

Data Collectors *"Rotating Equipment"*



- **Route Based**
- **Frequency Spectrum**
- **Time Waveform**
- **Orbits**
- **Balancing**
- **Alignment**
- **Data Analysis**
- **History**
- **Trending**
- **Download to PC**
- **Alarms**
- **"Smart" algorithms**

Bibliography

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- Eshleman, Ronald L., *Basic Machinery Vibrations,* ISBN 0-9669500-0-3
- LaRocque, Thomas, *Vibration Analysis Design, Selection, Mounting, and Installation,* Application Note, Connection Technology Center
- Agilent Technologies, *The Fundamentals of Signal Analysis,* Application note 243
- Agilent Technologies, *Effective Machinery Measurements using Dynamic Signal Analyzers,* Application note 243-1

Thank You !

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www.ctconline.com

in the "*Technical Resources*" section