CTC

UNIVERSITY

LEVEL 1, LESSON 1

BEGINNING VIBRATION ANALYSIS WITH BASIC FUNDAMENTALS

Introduction

Understanding the basics of vibration analysis is essential 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 criteria established by the Vibration Institute.

Mass And Stiffness – What Is It?

All machines can be broken down into two categories:

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

Stiffness
is represented by springs or constraints of that movement

Mass And Stiffness – What Is It?

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

- F_n = natural frequency (Hz)
- **k** = stiffness (lb/in)
- **m** = mass
- **mass** = weight (lb)/gravity (386.1 in/sec^2)

Mass And Stiffness – Understanding The Concept

If k increases, then f increases

If k decreases, then f decreases

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

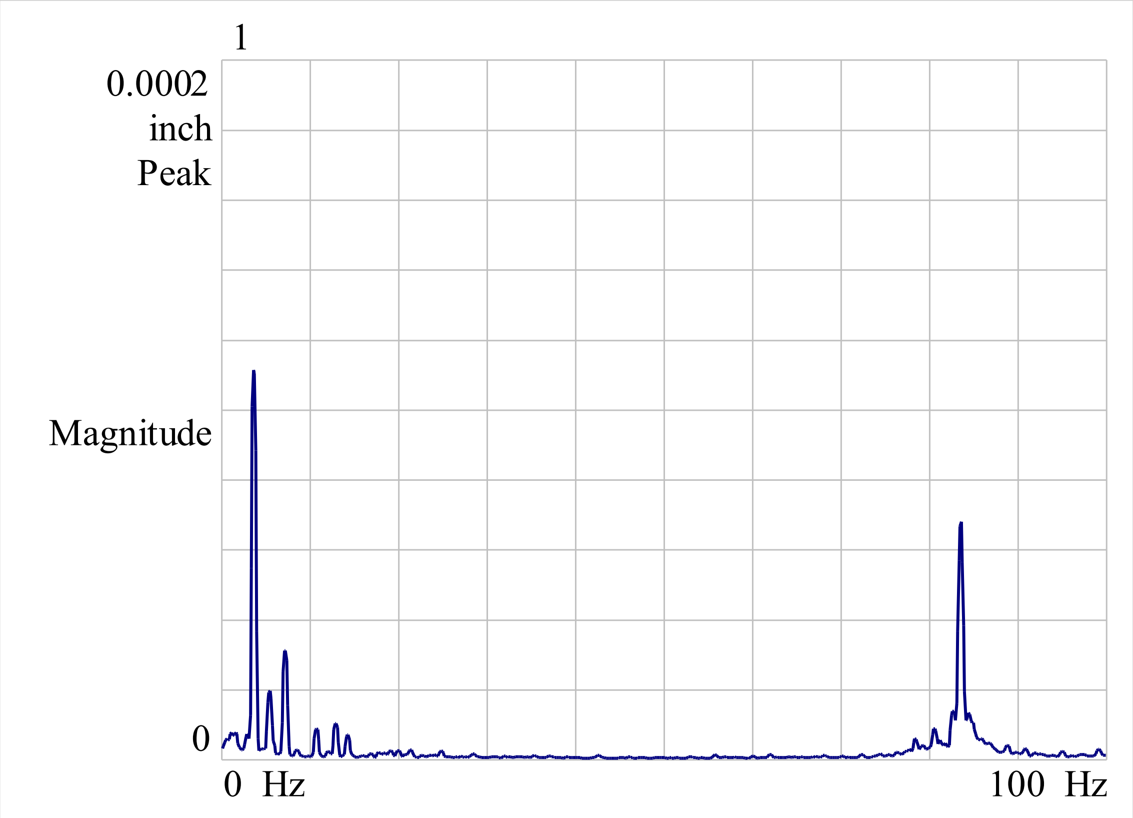
Mass And Stiffness – Understanding The Concept

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

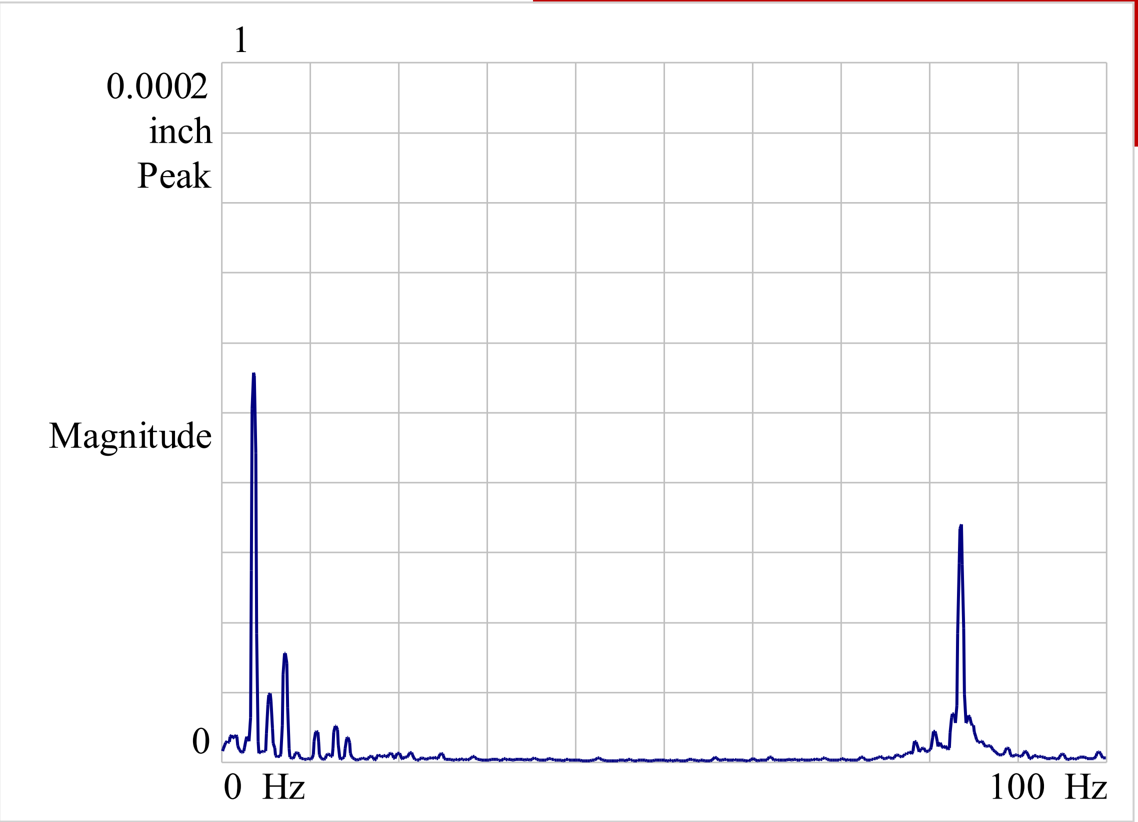
If **m** increases, then **f** decreases

If **m** decreases, then **f** increases

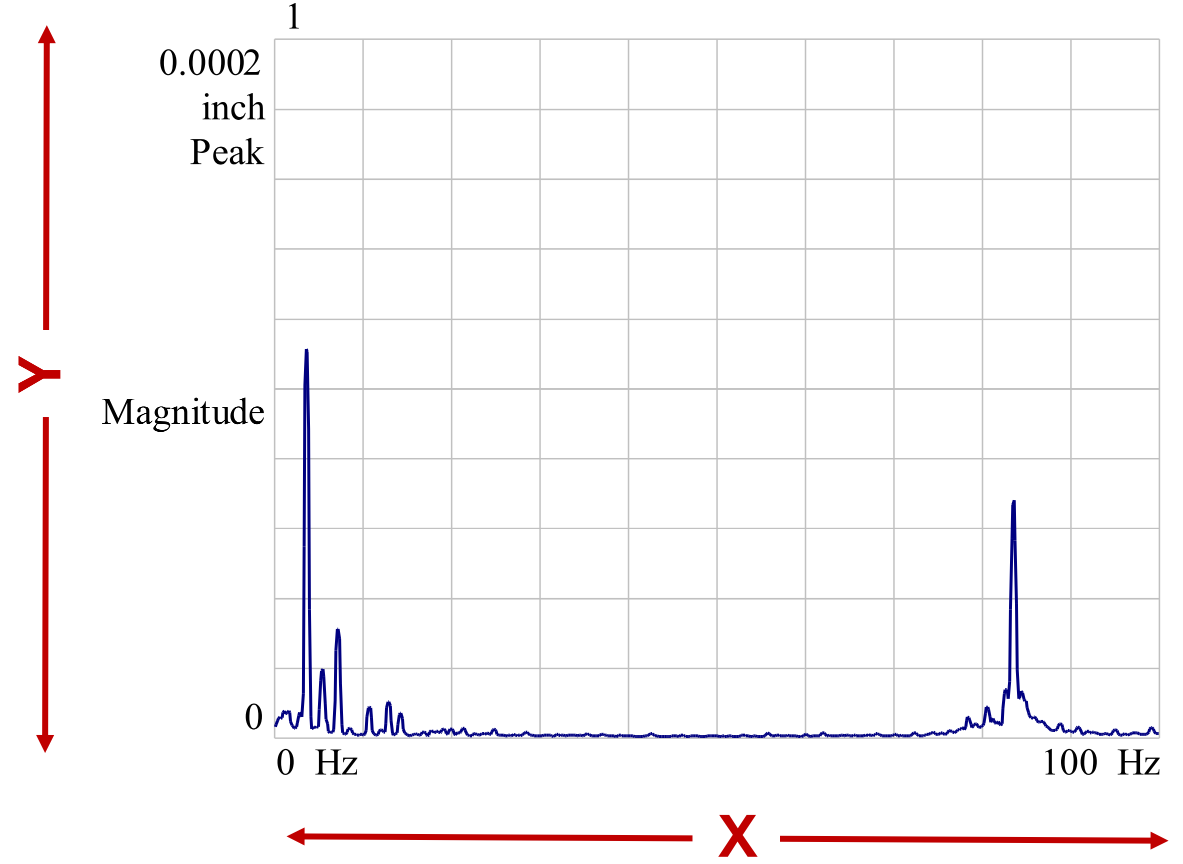
Spectrum – What Is It?



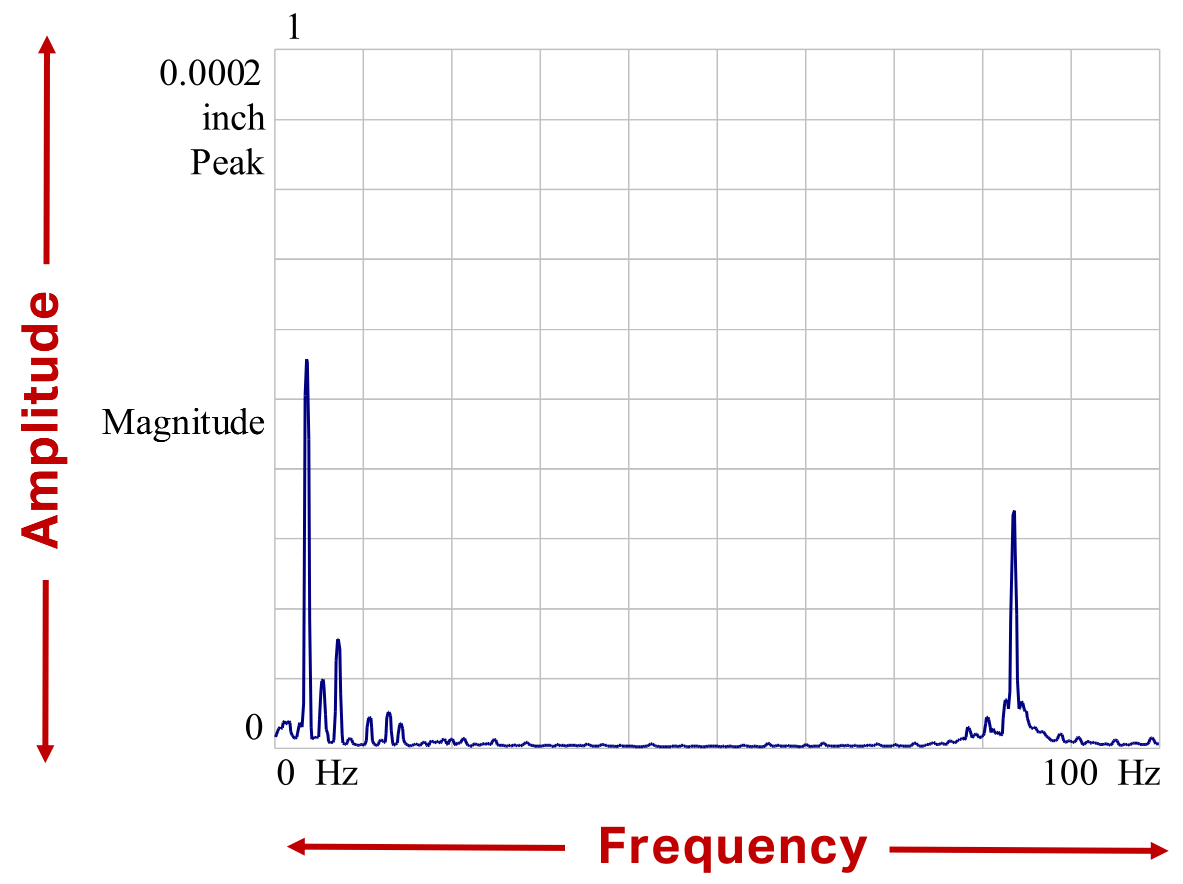
FFT, Frequency Spectrum, And Power Spectrum



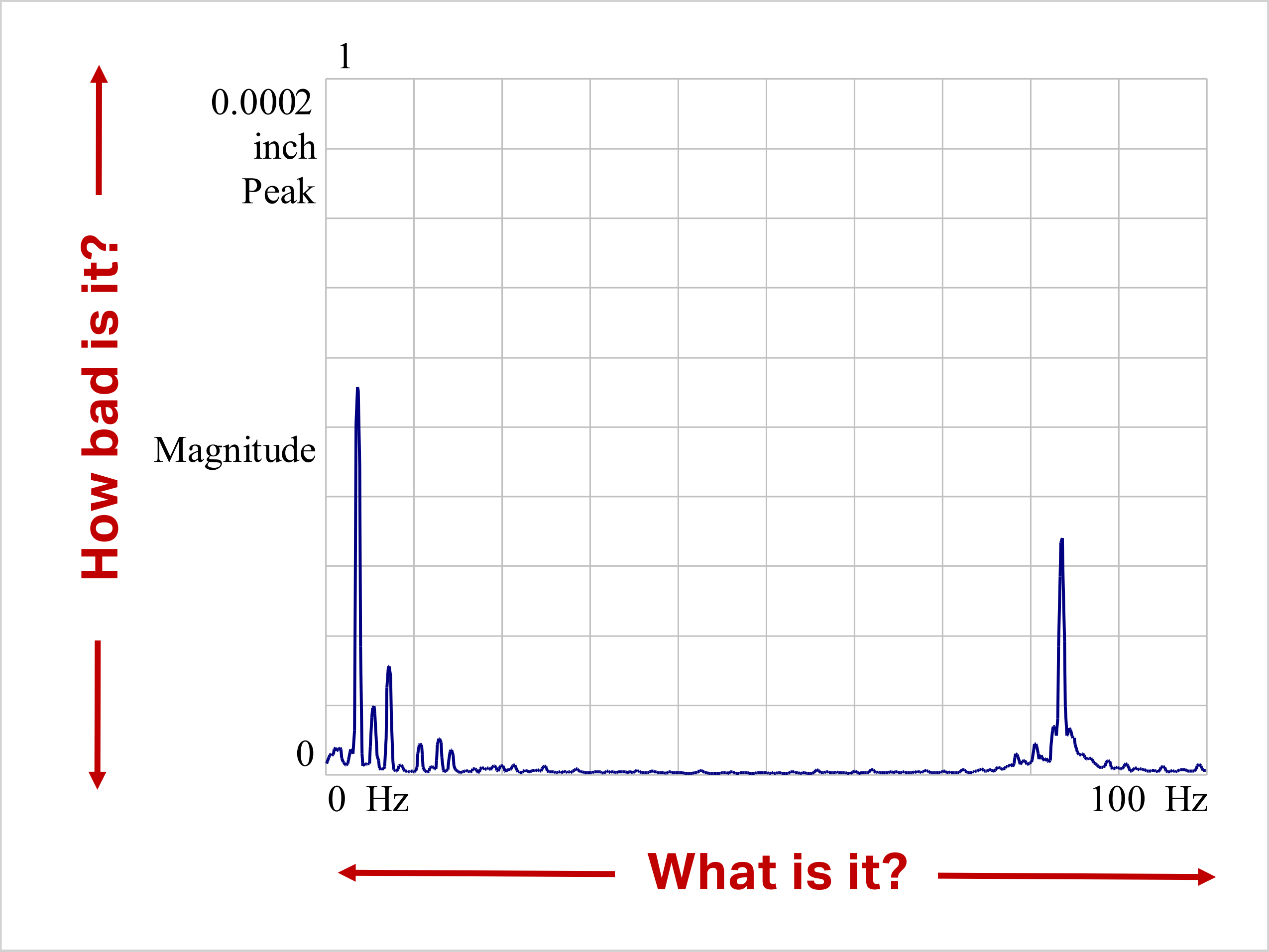
Spectrum – Scaling X And Y



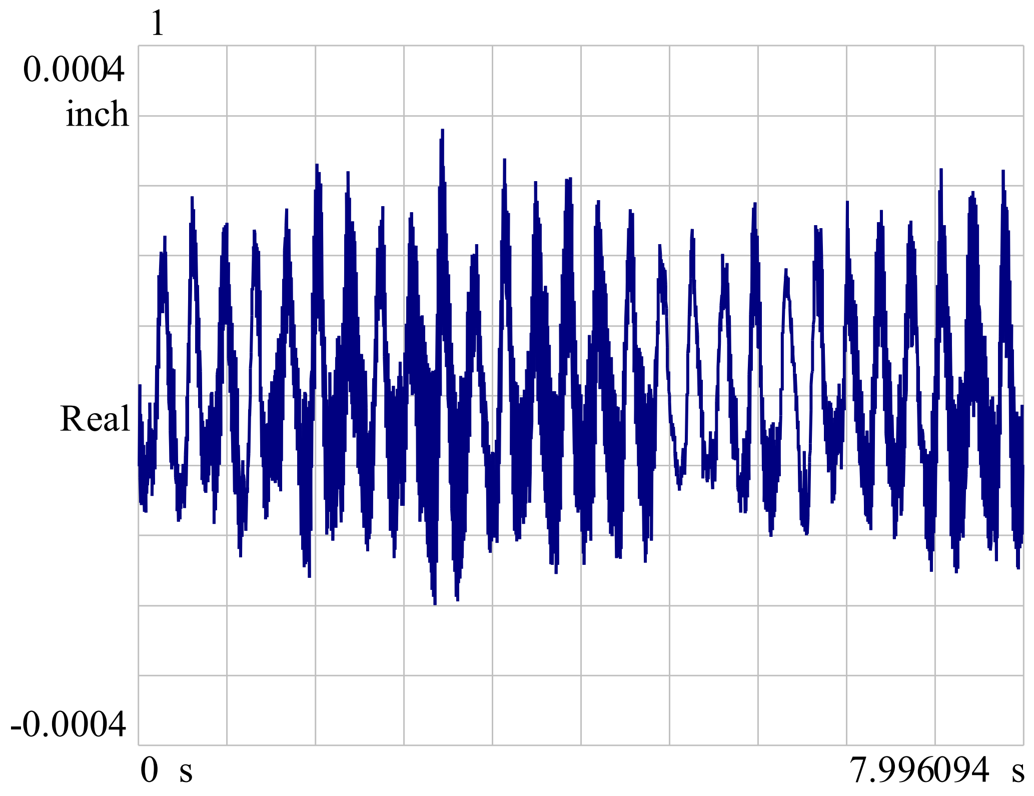
Spectrum – Scaling X And Y



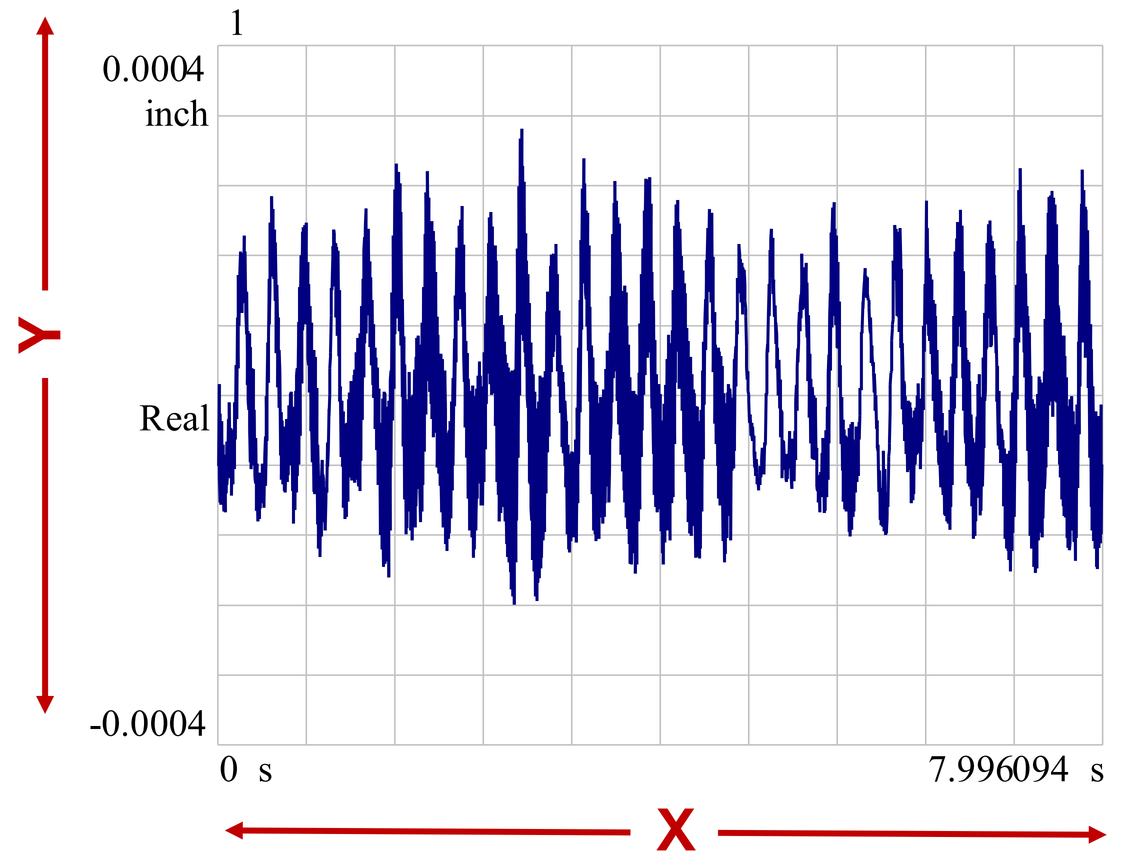
Spectrum – Scaling X And Y



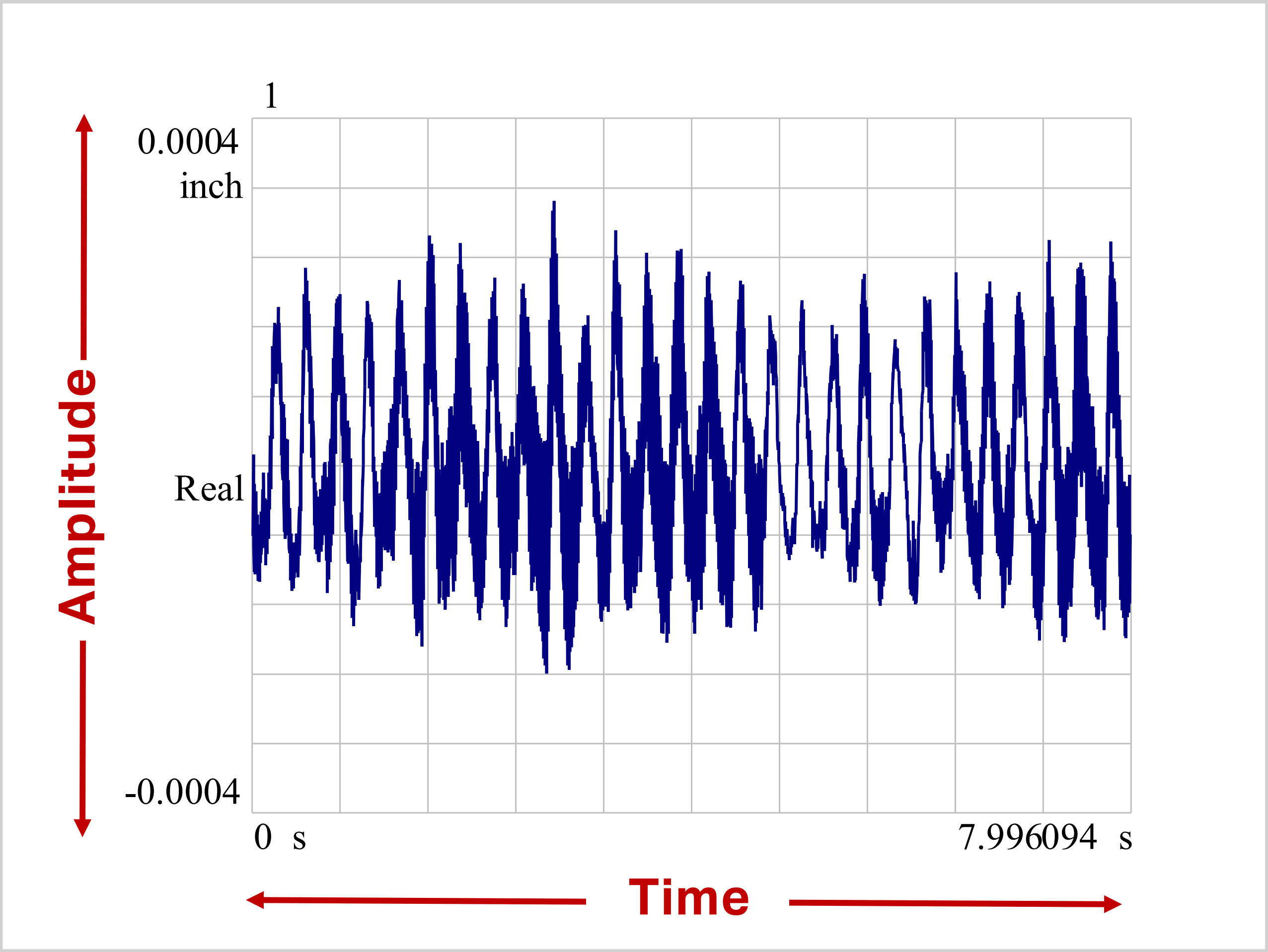
Time Waveform – What Is It?



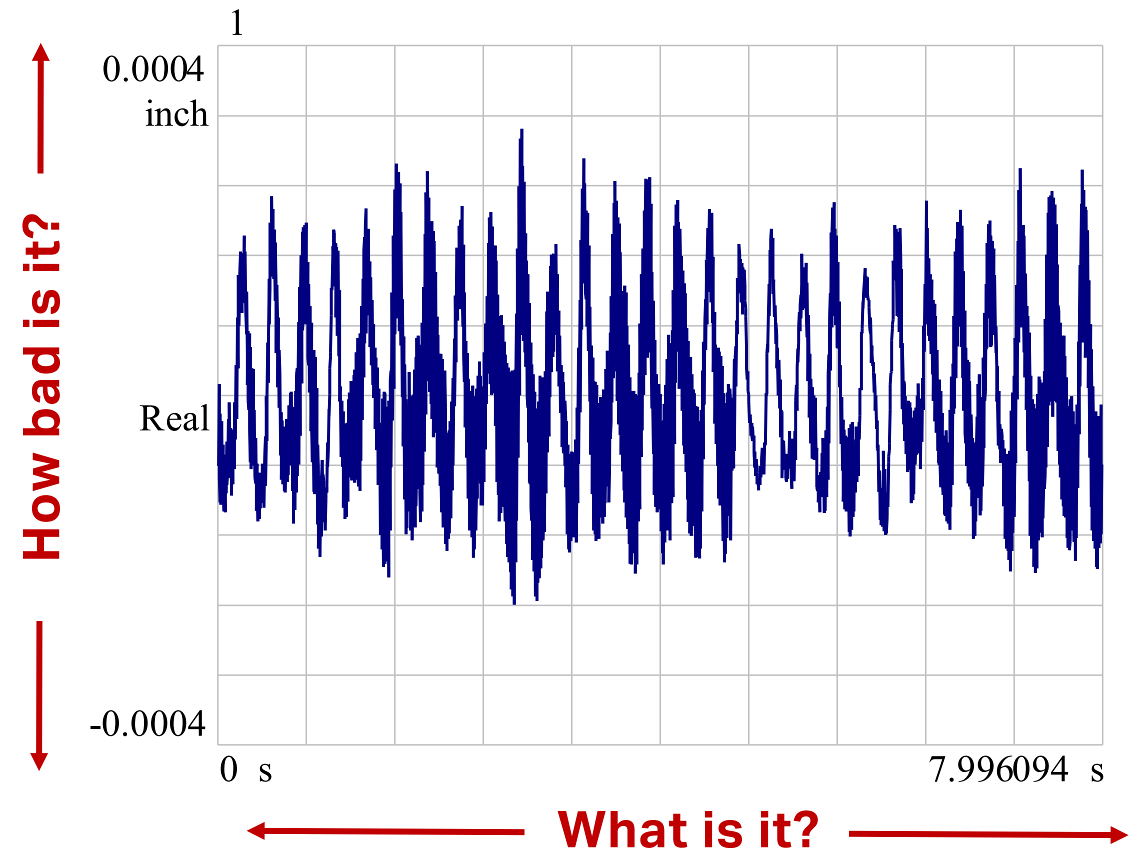
Time Waveform – Scaling X And Y



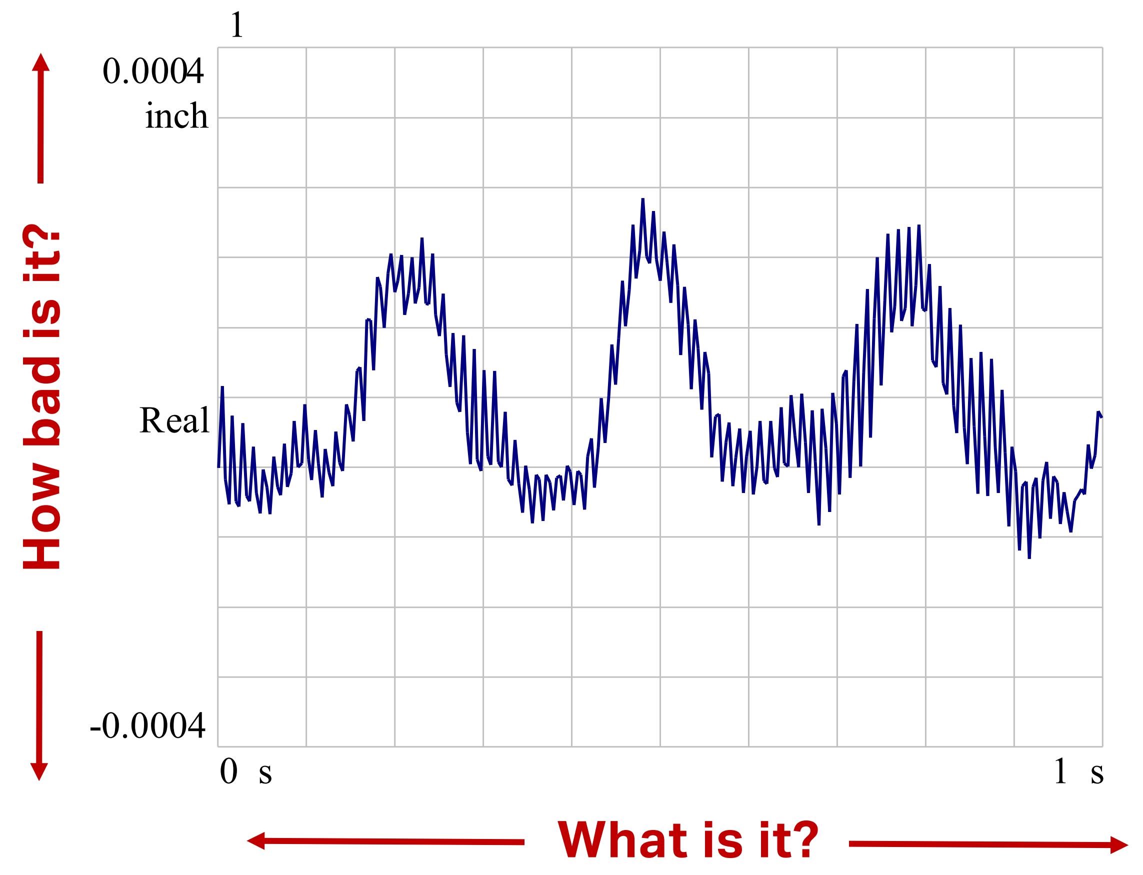
Time Waveform – Scaling X And Y



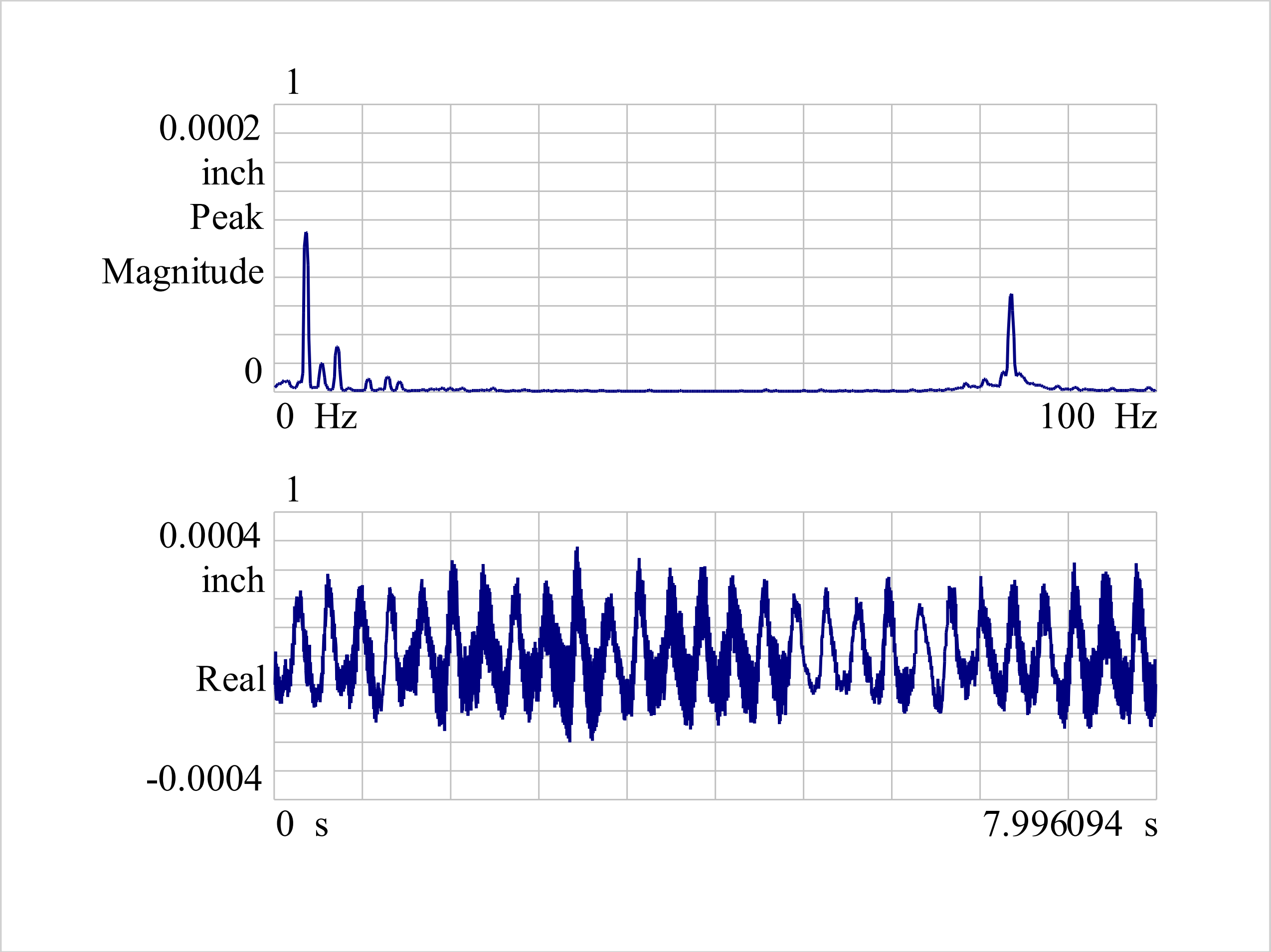
Time Waveform – Scaling X And Y



Time Waveform – Scaling X And Y



Time And Frequency – Double Trouble



The X Scale

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
- 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).

$$60\ cpm = 1\ cps = 1\ Hz$$

The X Scale – 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 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

The X Scale – Understanding The Concept

If $F = 1/T$ and $T = 1/F$, then $FT = 1$

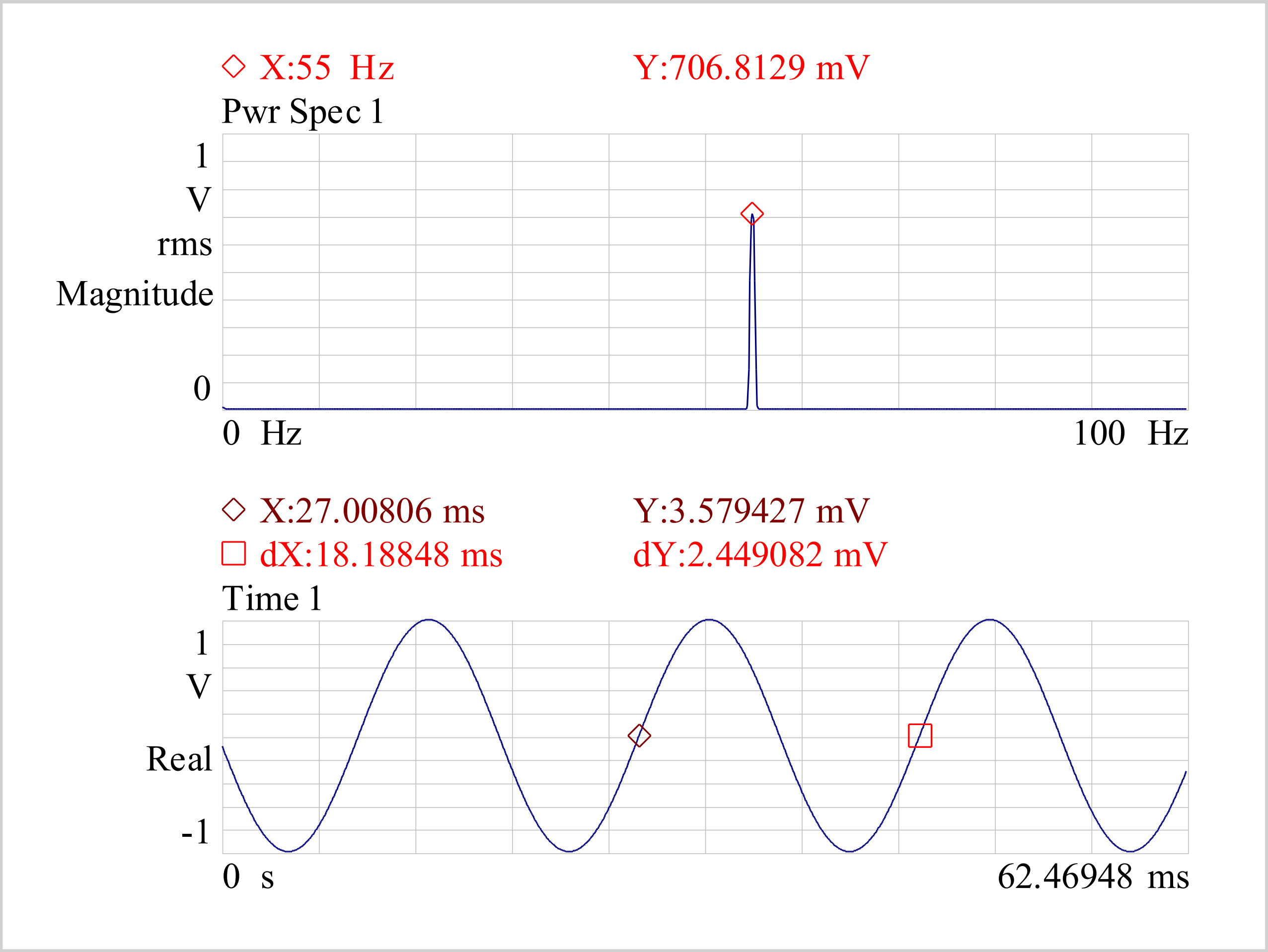
The X Scale – Understanding The Concept

If F increases, then T decreases

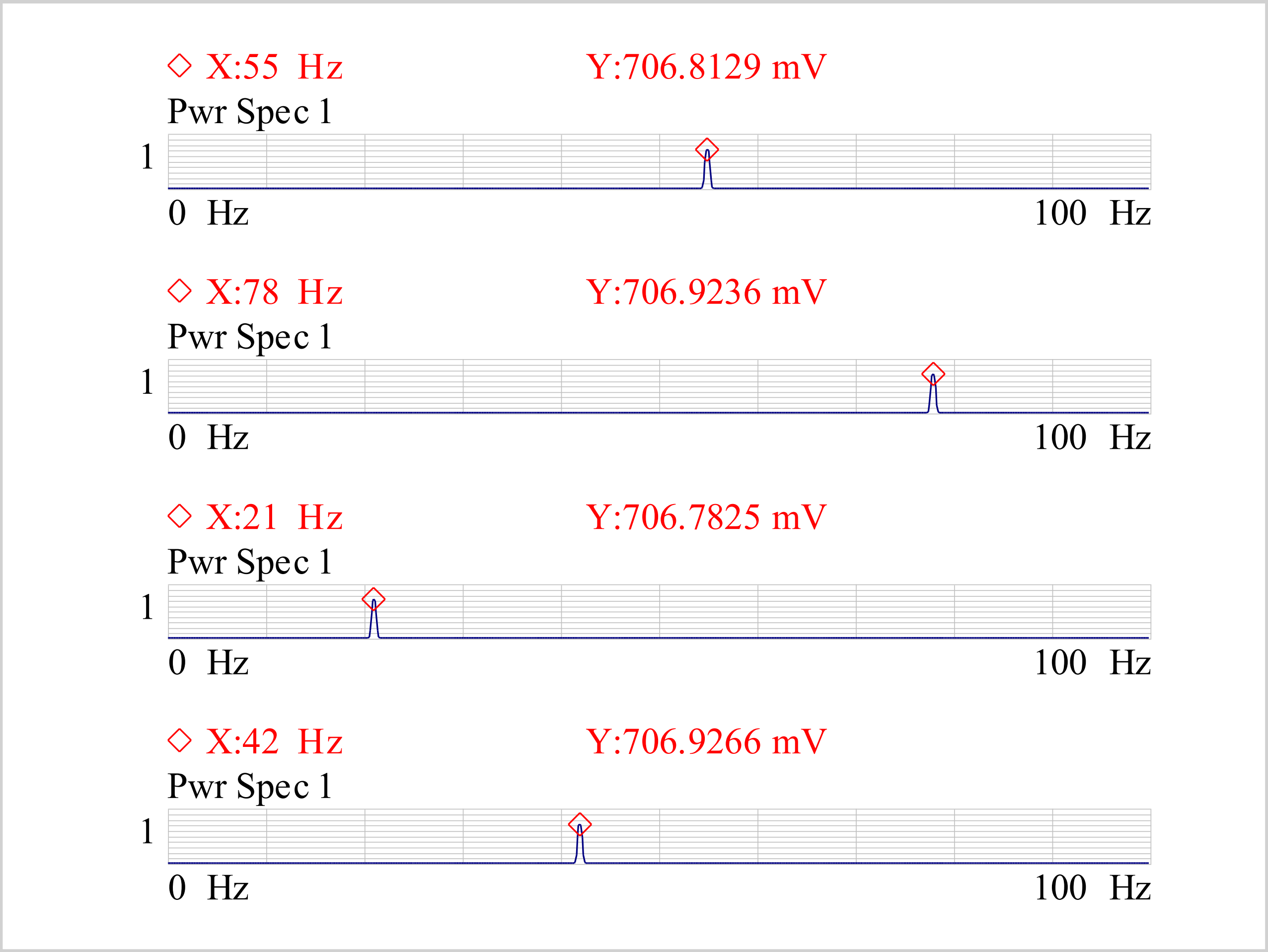
If T increases, then F decreases

$$FT = 1$$

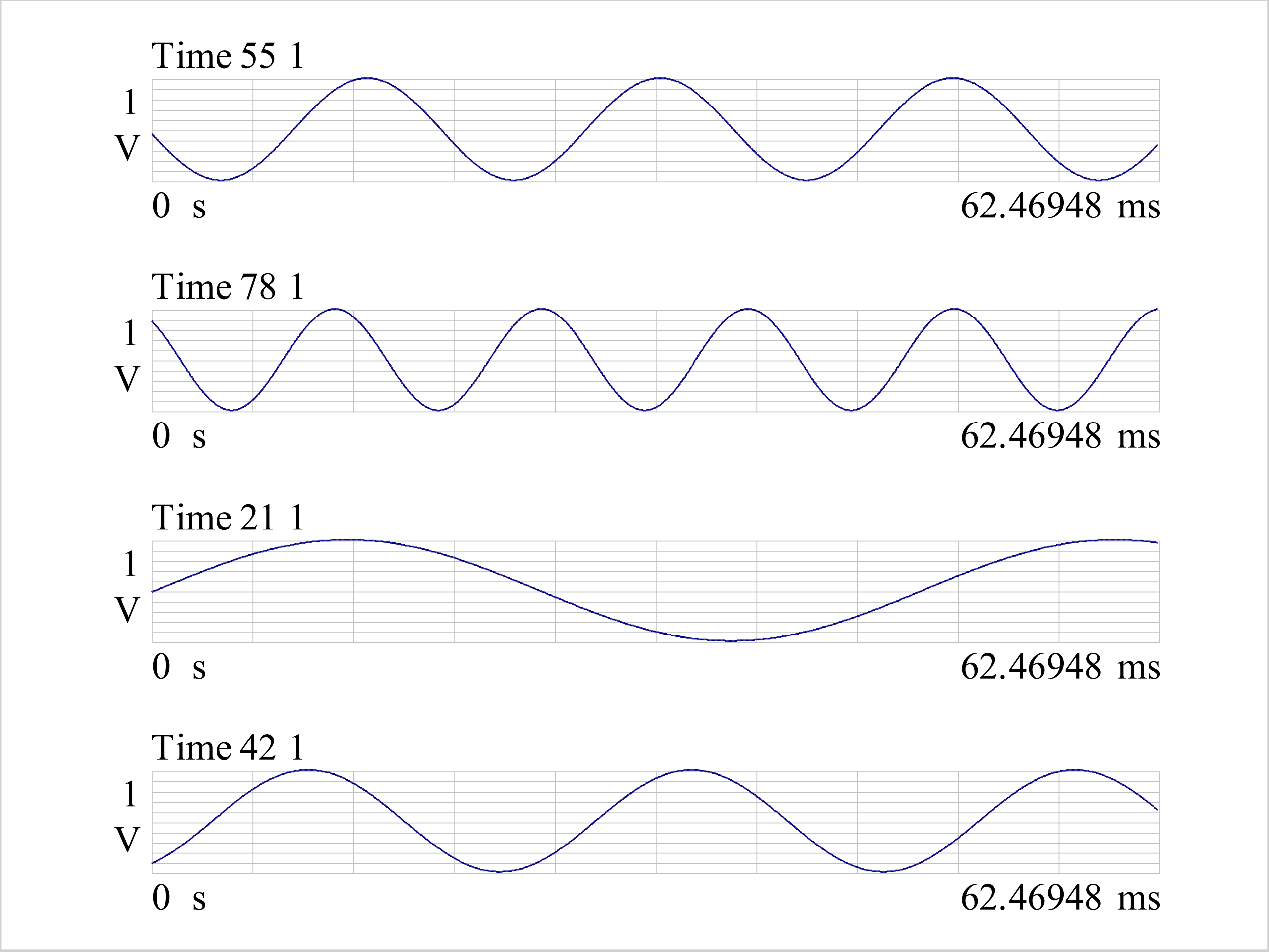
The X Scale – Single Frequency



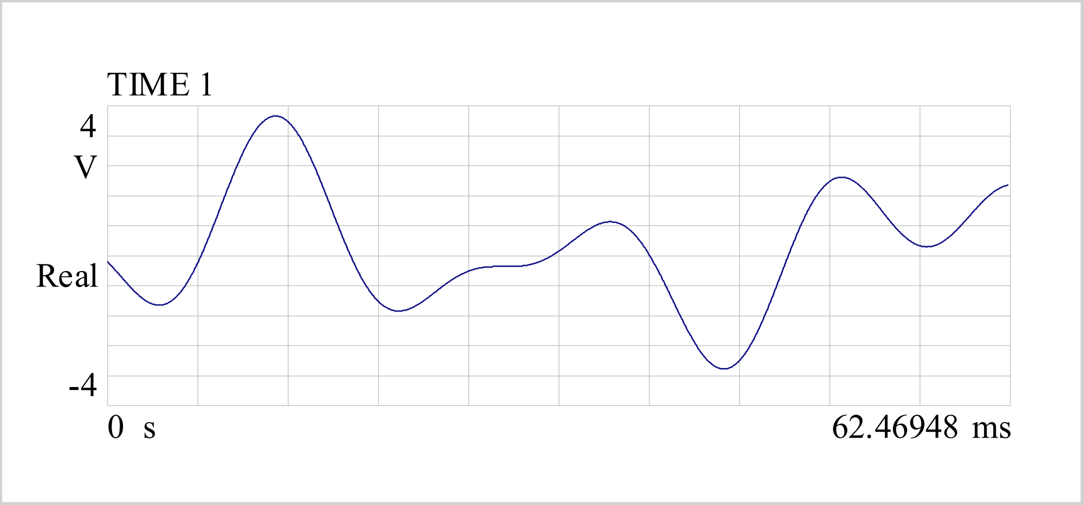
The X Scale – Multiple Frequencies



The X Scale – Multiple Time

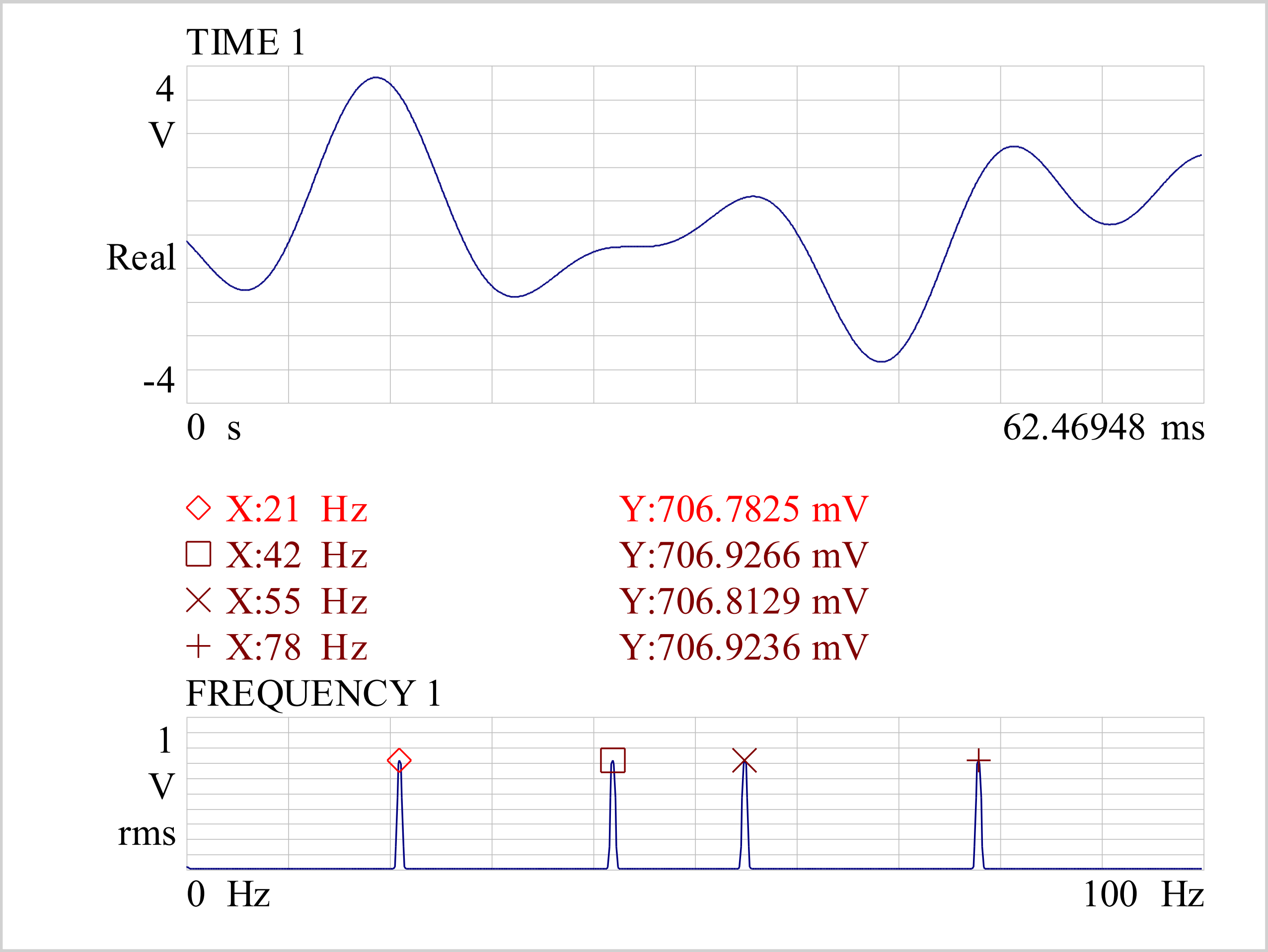


The X Scale – Real Life Time

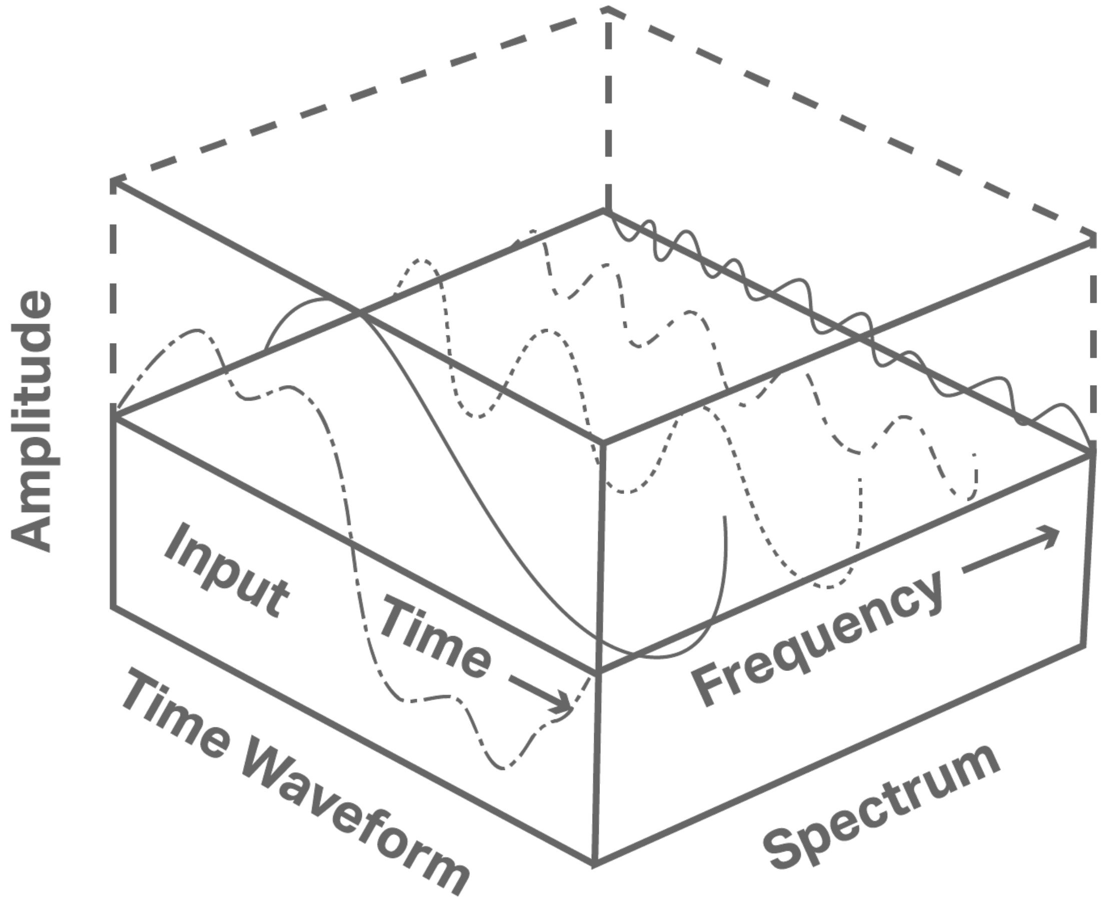


$$55 + 78 + 21 + 42 = \text{Trouble!}$$

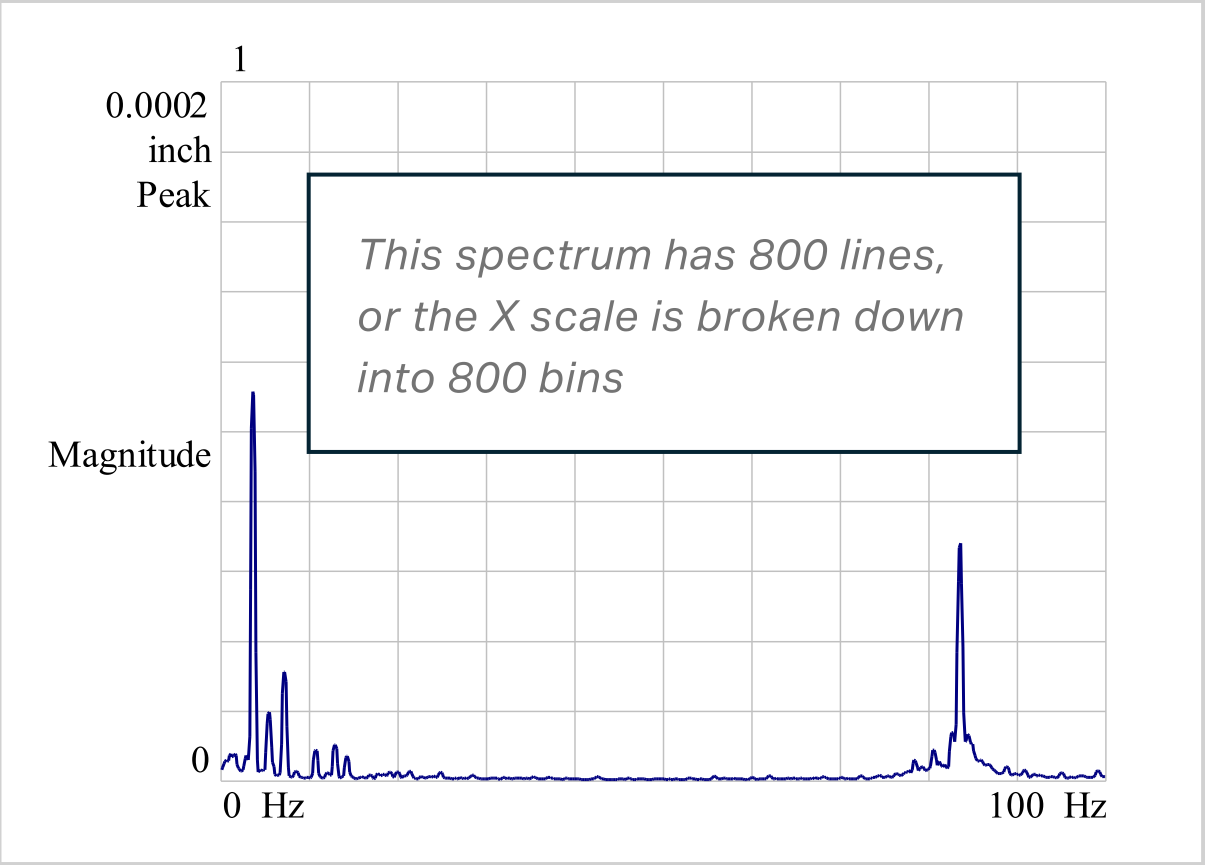
The X Scale – Frequency Spectrum



The X Scale –
The Most Copied Slide In The History Of Vibration Analysis!



The X Scale – Lines Or Bins



The FFT always has a defined number of lines or bins. Common choices include:

- 100 lines
- 200 lines
- 400 lines
- 800 lines
- 1600 lines
- 3200 lines

The X Scale – Filter Windows

Hanning (frequency)

Flat Top (amplitude)

Uniform (no window)

Force Exponential (frequency response)

Force / Expo Setup

types of filter windows

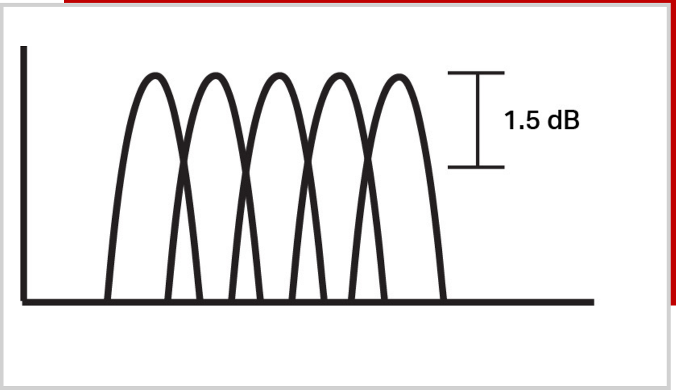
Window Filters are applied to the time waveform data to simulate data that starts and stops at 0

They will cause errors in the time waveform and frequency spectrum

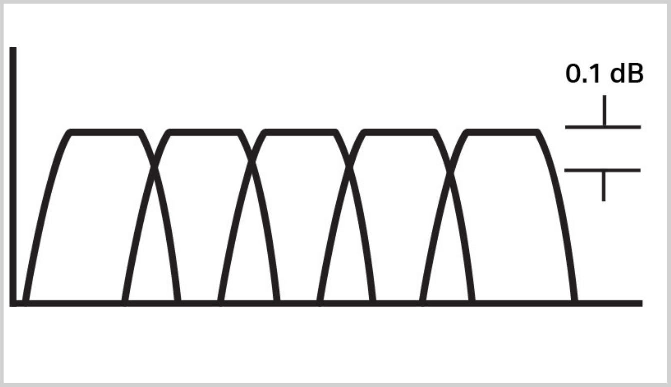
We still like window filters!

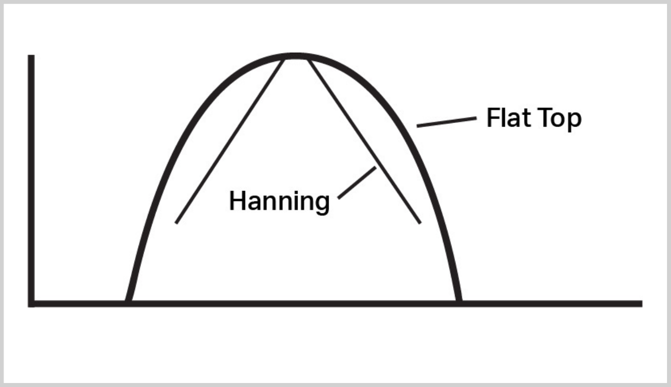
The X Scale – Filter Windows

Hanning 16% amplitude error



Flat top 1% amplitude error





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

The X Scale – Filter Windows

Hanning (frequency) — Used for normal vibration monitoring

Flat Top (amplitude) — Used for calibration and accuracy

Uniform (no window) — Used for bump testing and resonance checks

The X Scale – Lowest Resolvable Frequency (LRF)

The lowest resolvable frequency (LFR) 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 it set up

Example:

0 – 400 Hz using 800 lines

Answer:

(400 – 0)/800 = 0.5 Hz/line

The X Scale – Bandwidth

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 = 3.8

Example:

0 – 400 Hz using 800 lines and Hanning Window

Answer:

(400/800) 1.5 = 0.75 Hz/Line

The X Scale – Resolution

The frequency resolution can be defined as:

2 (Frequency Span/Analyzer Lines) Window Function

or

Resolution = 2 (Bandwidth)

Example:
0 – 400 Hz using 800 lines and Hanning Window

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

The X Scale – Using Resolution

A 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?

The X Scale – 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

The X Scale – Data Sampling Time

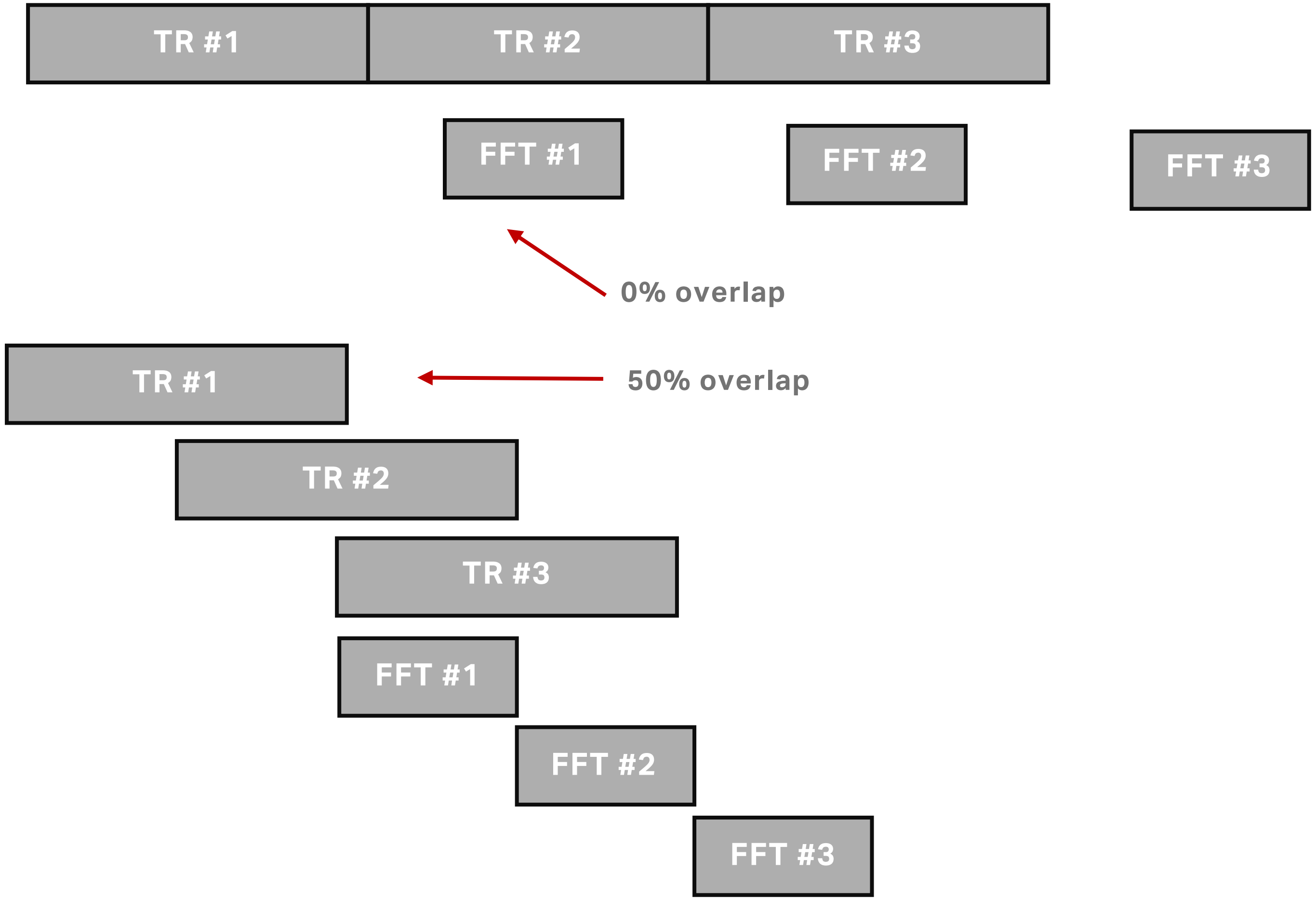
- Data sampling time is the amount of time required to take one record or sample of data
- It is dependent on the frequency span and the number of analyzer lines being used
- Using **400 lines** with an **800 Hz** frequency span will require:
  400/800 = 0.5 seconds

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

The X Scale – Average And Overlap

Average: On

Overlap Percent: 50%



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

The X Scale – 75% Overlap?

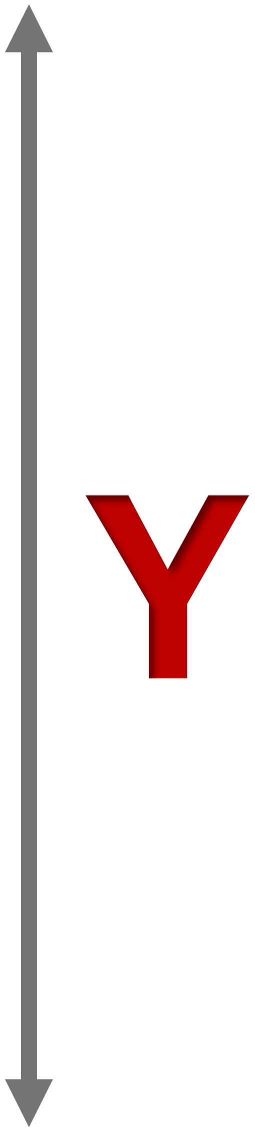
- 10 averages
- 75% overlap
- 800 lines
- 200 Hz

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



The Y Scale – Amplitude

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

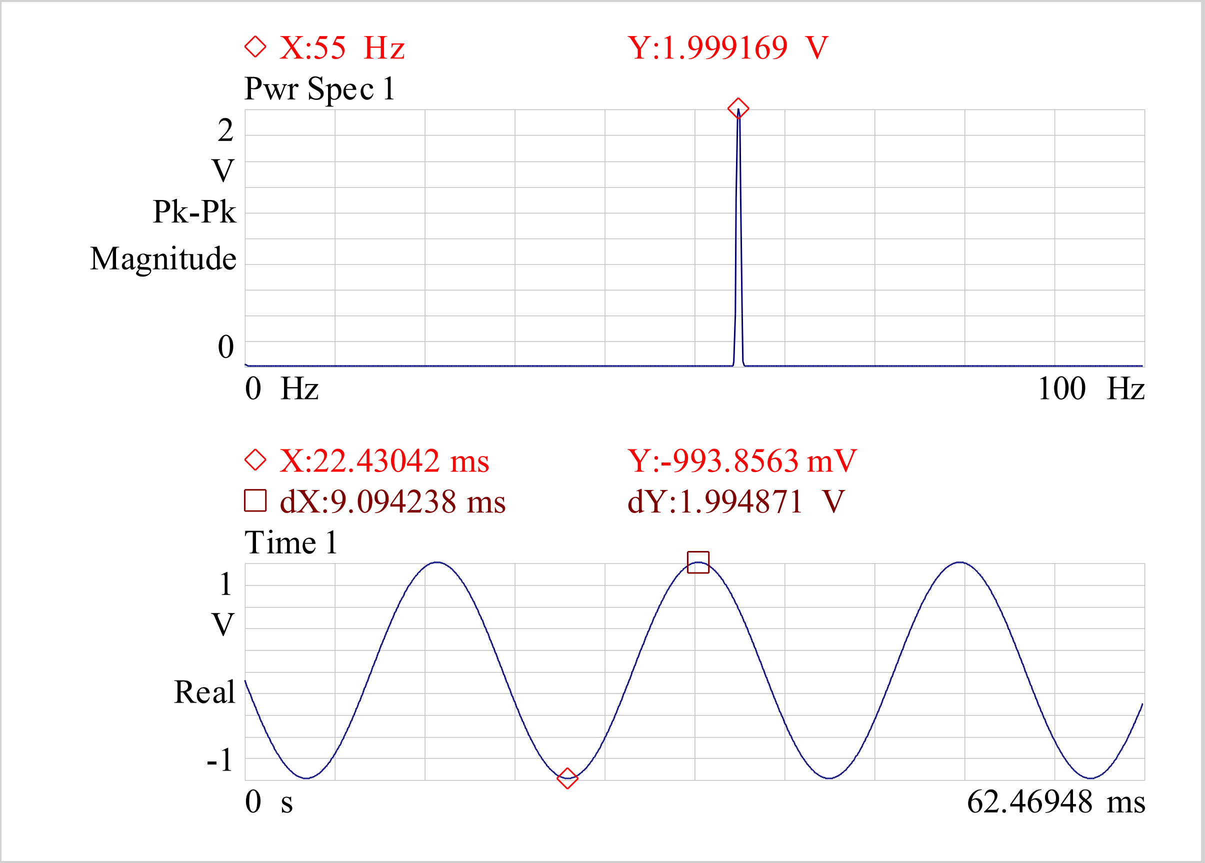
Default units for the Y scale are volts RMS

Volts is an Engineering Unit (EU)

RMS is one of the three suffixes meant to confuse you

The others are Peak and Peak - Peak

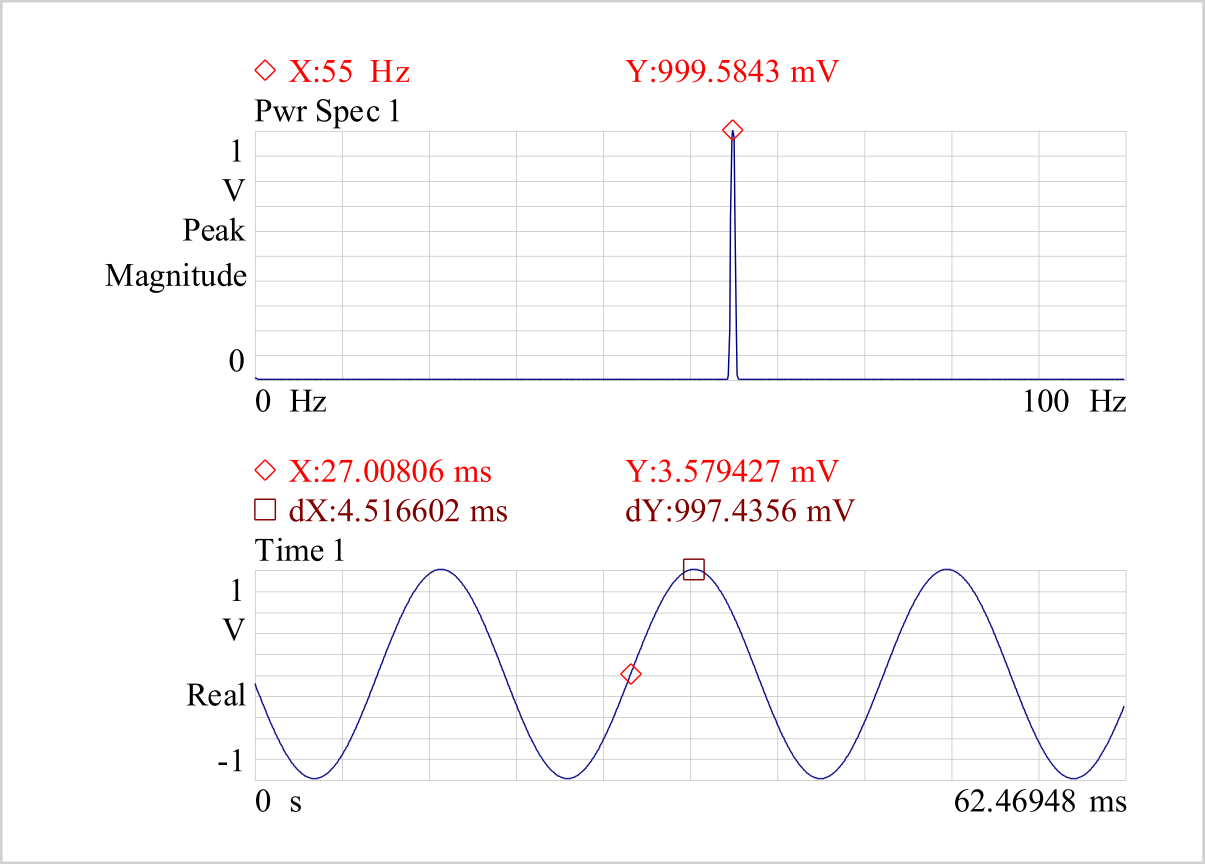
The Y Scale – PK-PK (Peak – Peak)



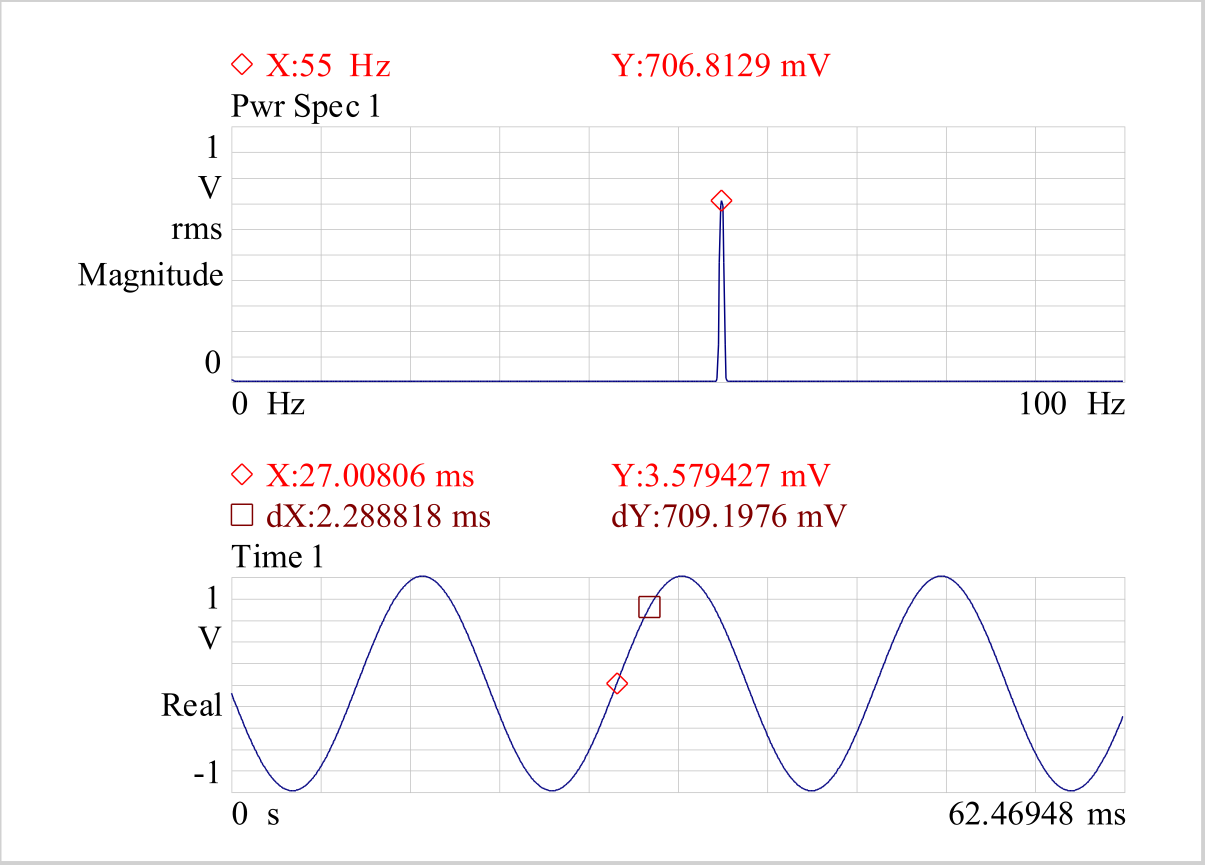
- The Peak – Peak value is expressed from the peak to peak amplitude
- The spectrum value uses the suffix Pk-Pk to denote this

The Y Scale – 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



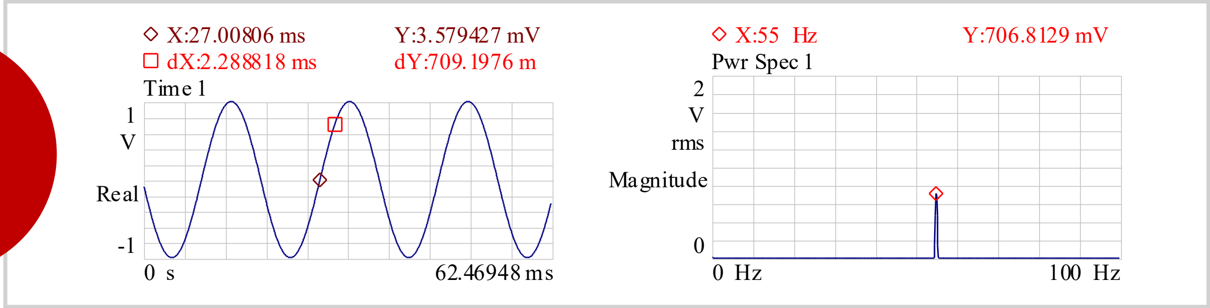
The Y Scale – RMS (Root Mean Square)



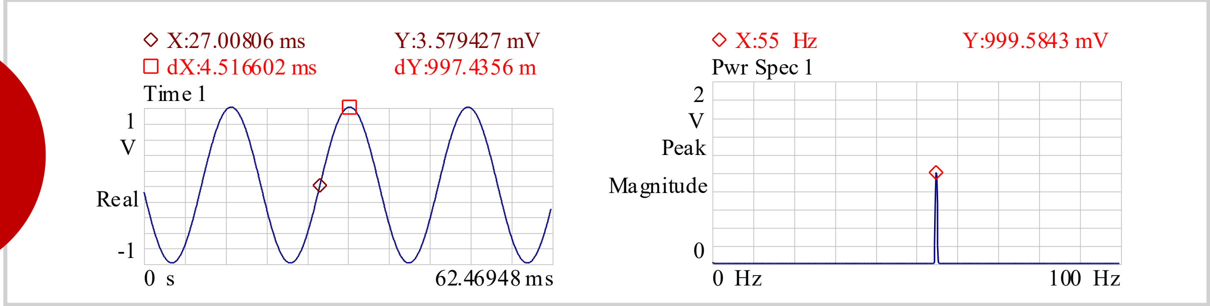
- The time wave has not changed
- The RMS value is expressed from zero to 70.7% of the peak amplitude
- The spectrum value uses the suffix RMS to denote this

The Y Scale – Suffix Comparison

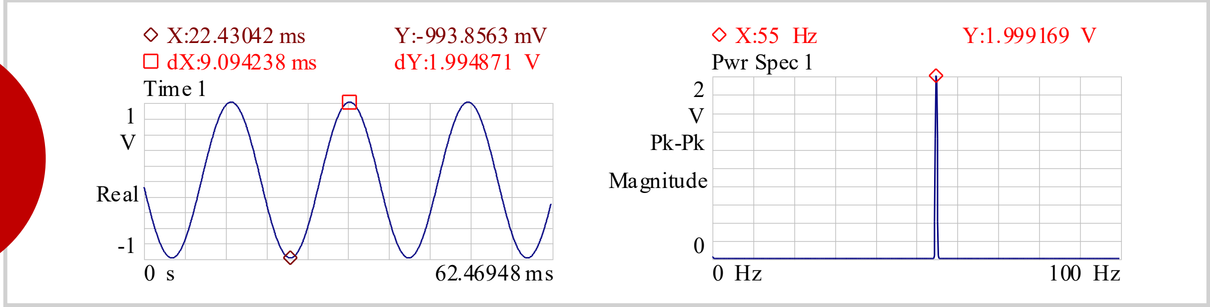
RMS



PK



PK-PK



The Y Scale – Changing Suffixes

It is often necessary to change between suffixes:

Pk-Pk /2 = Peak

Peak x 0.707 = RMS

RMS x 1.414 = Peak

Peak x 2 = Pk-Pk

The Y Scale – Standard Suffixes

Now that we've learned about the three standard suffixes that may 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 in.

The Y Scale – Engineering Units

100 mV/g

20 mV/Pa

1 V/in/sec

200 mV/mil

50 mV/psi

10 mV/fpm

33 mV/%

10 mV/V

- Engineering units likes these 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

The Y Scale – EUs The Hard Way

- Sometimes we forget to use EUs, 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're 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 Y Scale –
The Three Big EUs

- Acceleration
- Velocity
- Displacement

CTC

The Y Scale –
Converting The Big Three EUs

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 EUs?

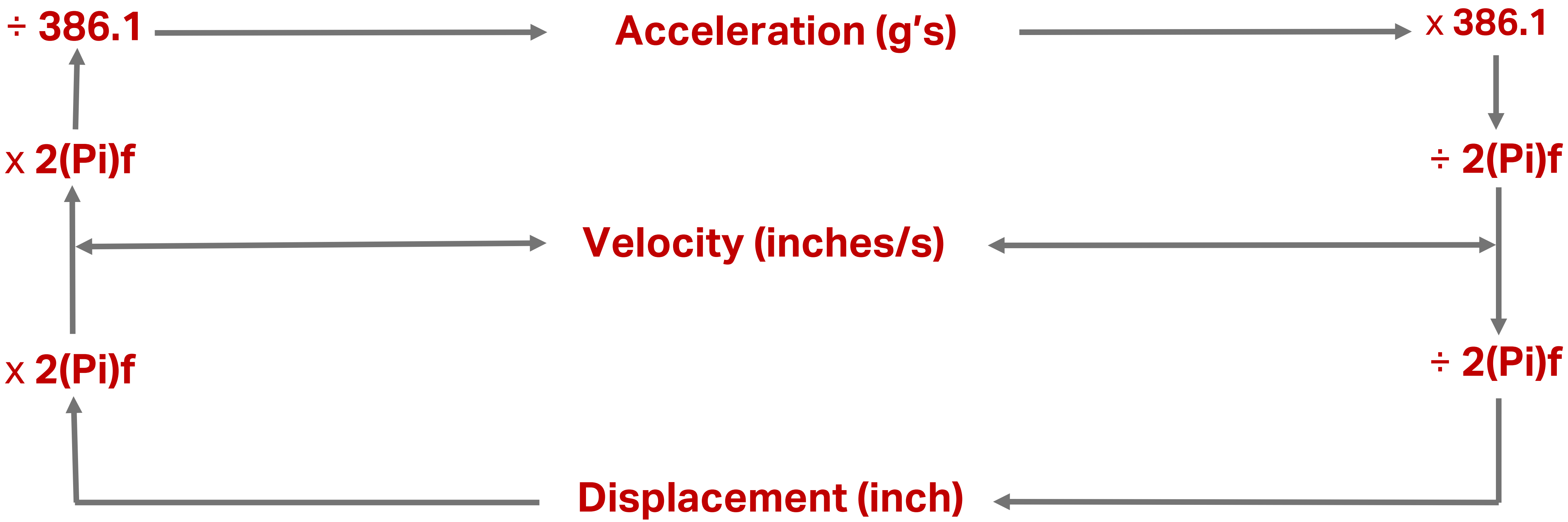
The Y Scale – 386.1 What?

$$1\ g = \frac{32.22\ ft.}{second^2}$$

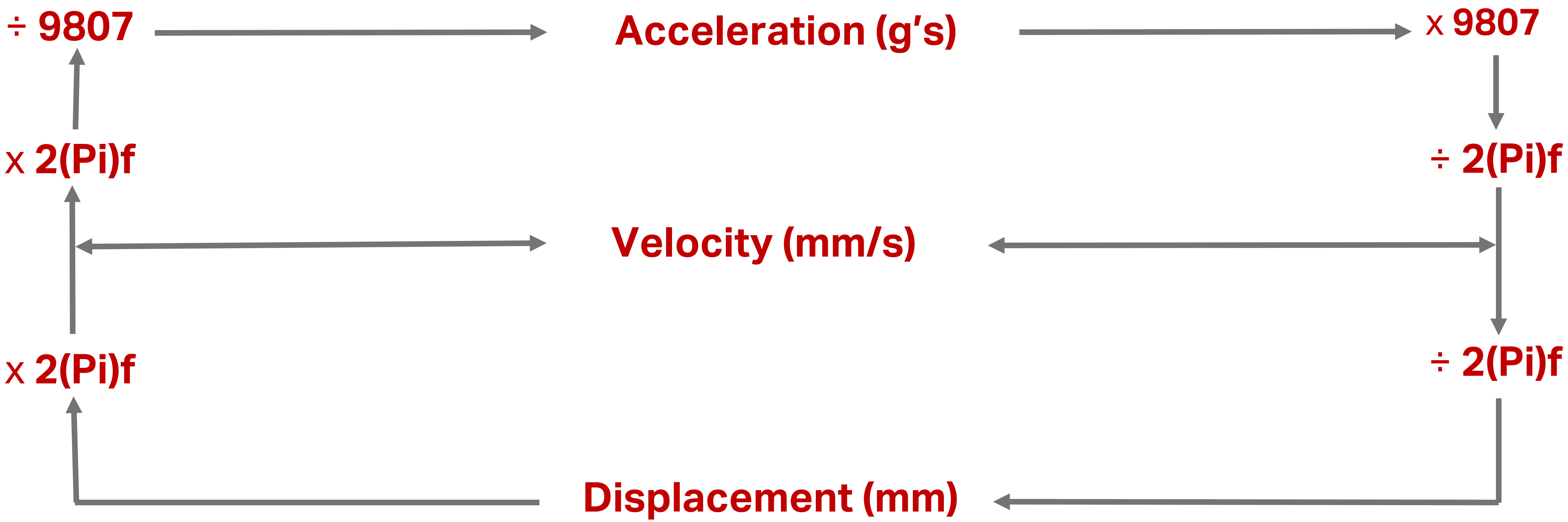
$$\frac{32.22\ ft.}{second^2} \times \frac{12\ in.}{foot}$$

$$\frac{386.1\ in/second^2}{g}$$

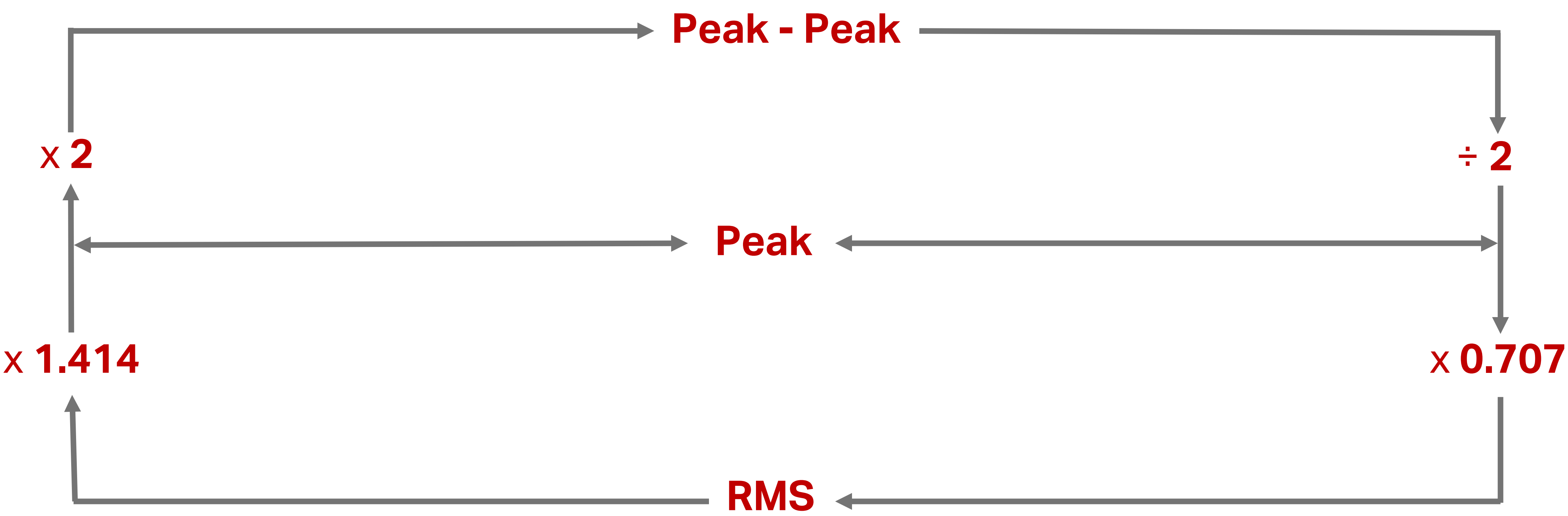
The Y Scale –
Go With The Flow I



The Y Scale –
Metric Go With The Flow I



The Y Scale –
Go With The Flow II



The Y Scale – Doing The Math Units

There is a 0.5 g vibration at 25 Hz

What is the velocity?

$$\frac{0.5\ g\ x\ 386.1\ inches\ second^2/g}{2\pi\ x\ 25\ cycles/second}$$

$$\frac{0.5\ g\ x\ 386.1\ inches}{g/second^2}\ x\ \frac{1\ second}{2\pi\ x\ 25\ cycles}$$

$$\frac{0.5\ g\ x\ 386.1\ inches}{2\pi\ x\ 25\ cycles\ second\ cycle}$$

$$1.23\ inches/second$$

The Y Scale – 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

The Y Scale –
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

The Y Scale –
Acceleration - Displacement

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

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

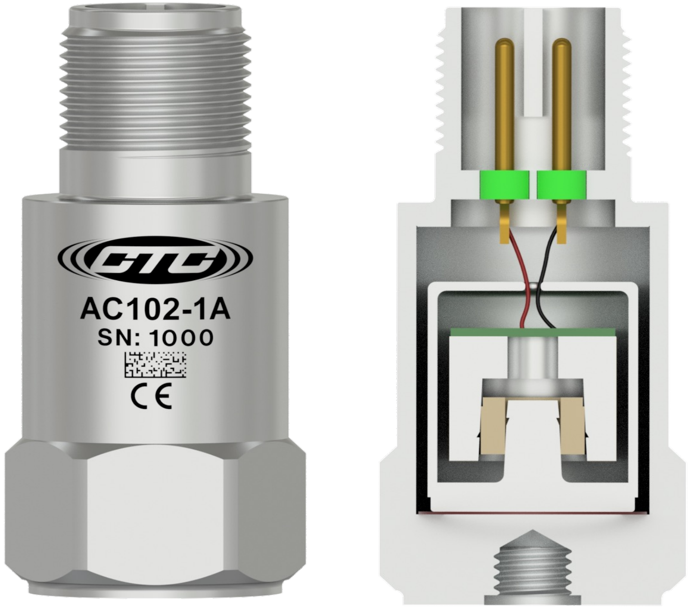
= (0.015 x 386.1)/(6.28 x 52)2

= 0.000054 inches RMS

Answer:

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

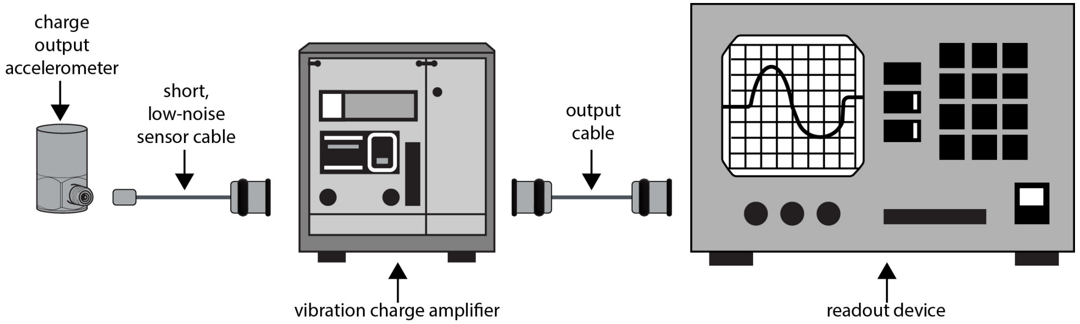
Sensors –
Integrated Circuit Accelerometers



Integrated circuit accelerometers are designed for industrial applications and have the electronics inside the sensor case, as shown here

Sensors – Charge Mode Accelerometers

Charge mode accelerometers utilize an external charge amplifier (as shown here) and are often used in test and measurement applications



Sensors – Accelerometer Pros And Cons

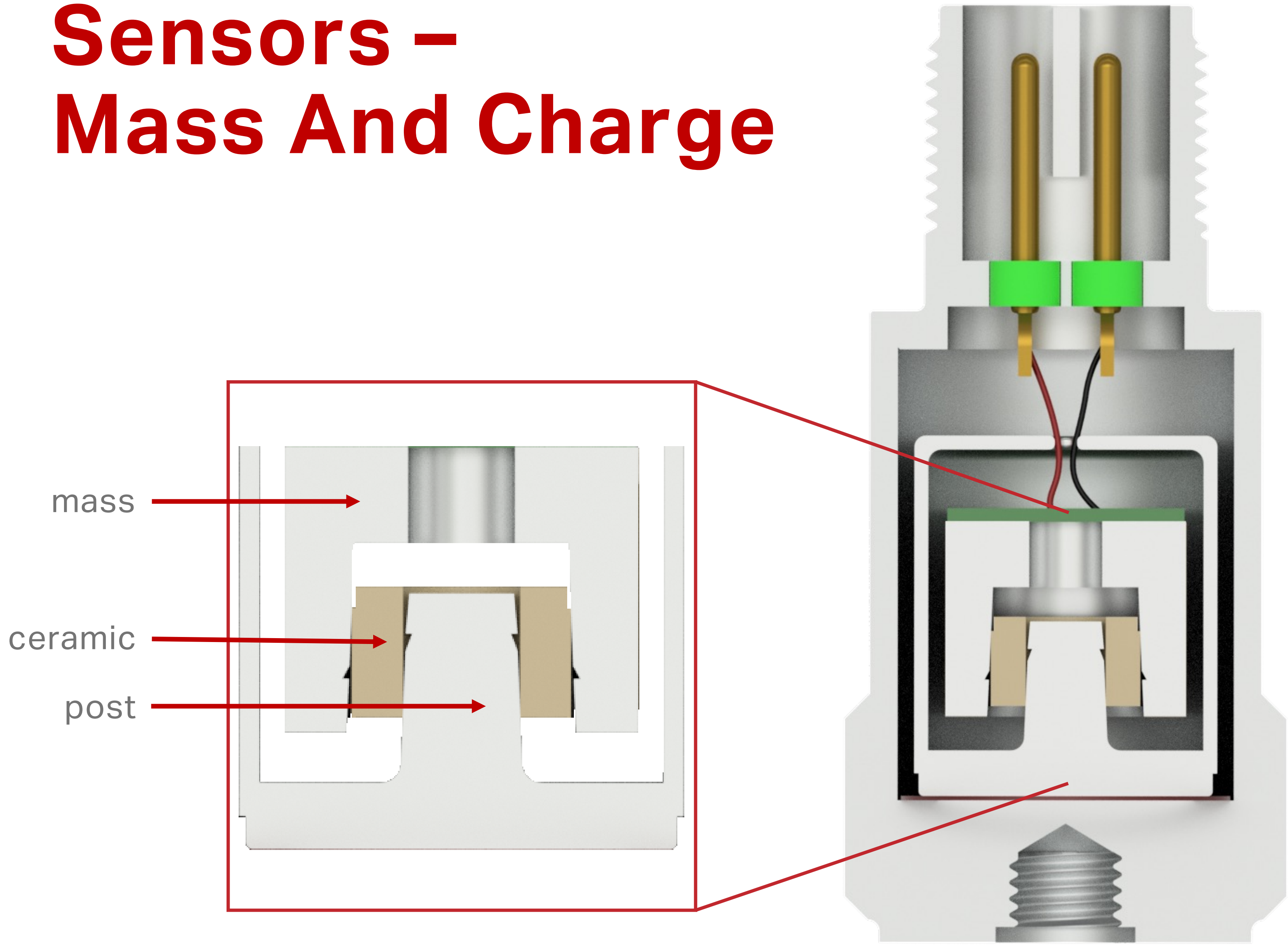
Pros

- Measures casing vibration
- Measures absolute motion
- Integrates to velocity output
- Easy to mount
- Large range of frequency responses
- Many available configurations

Cons

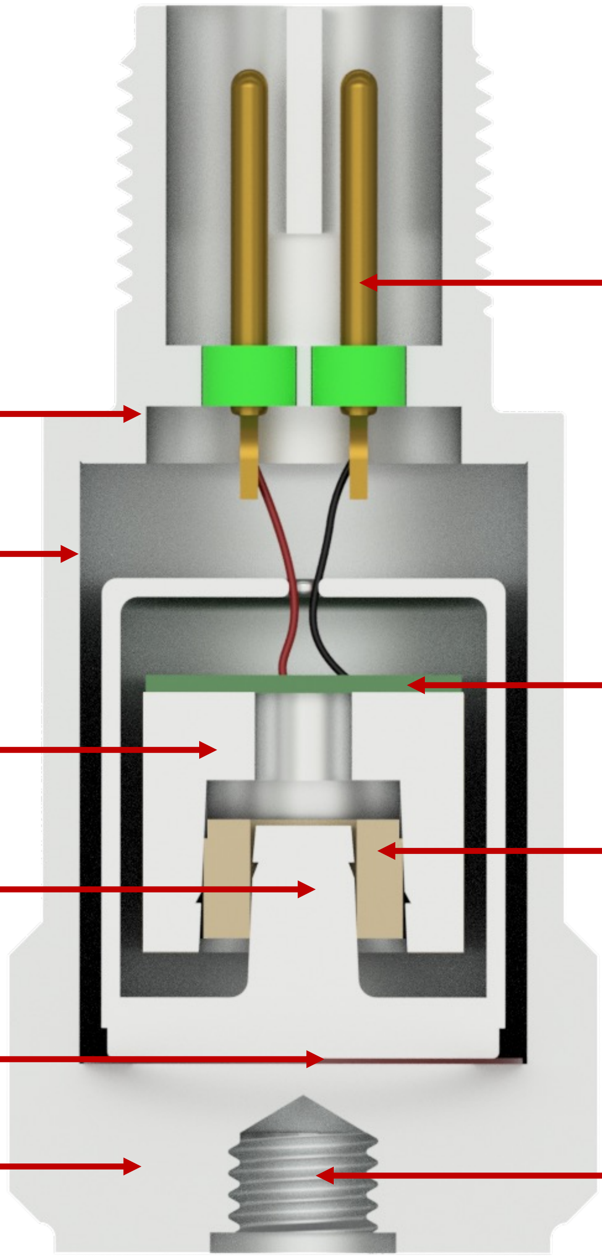
- Does not measure shaft vibration
- Sensitive to mounting techniques and surface conditions
- Difficult to perform calibration check
- Double integration to displacement often causes low frequency noise
- One accelerometer does not fit all applications

Sensors – Mass And Charge



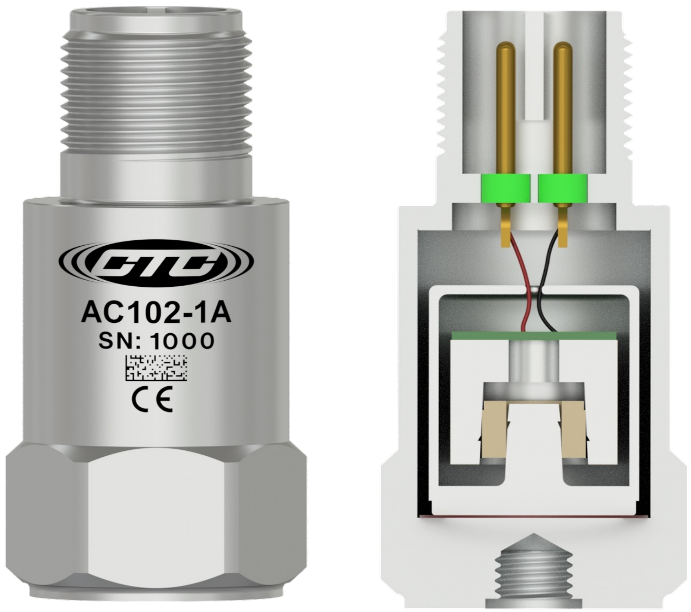
Relative movement between post and mass creates shear in ceramic producing charge

Sensors – Construction



Sensors – Accelerometer Operation

- Mass remains at rest
- PZT ceramic is in shear
- Pedestal (post) transmits vibration



Sensors – Accelerometer Parameters

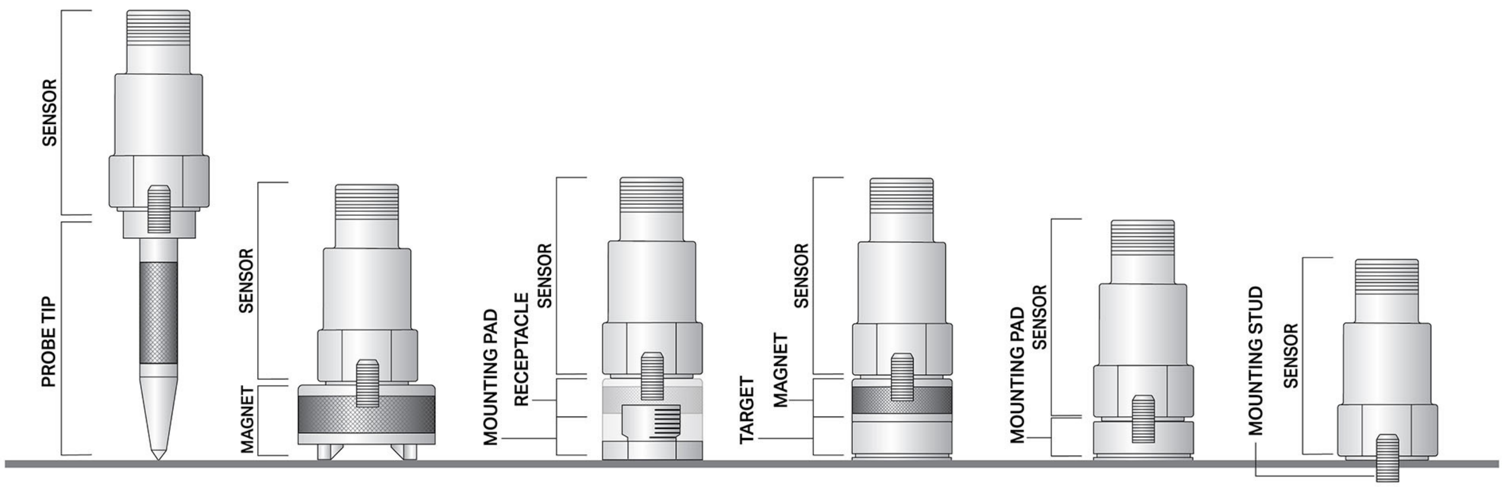
PART NUMBER: AC292-1A	
Performance Specifications	***English***
Sensitivity +/- 5%	100 mV/g
Frequency Response	
± 3 dB	18-900,000 CPM
± 10%	60-600,000 CPM
± 5%	600-300,000 CPM
Dynamic Range	± 80 g peak, *Vsource ≥ 22V, 12 V bias

Performance suited for application:

- Sensitivity (mV/g)
- Frequency response of target (f span)
- Dynamic range of target (g level)

Sensors – Mounting

PROBE TIP	CURVED SURFACE MAGNET	QUICK DISCONNECT	FLAT MAGNET WITH TARGET	ADHESIVE MOUNT	STUD MOUNT
500 Hz (30,000 CPM)	2,000 Hz (120,000 CPM)	6,500 Hz (390,000 CPM)	10,000 Hz (600,000 CPM)	10,000 - 15,000 Hz (600,000 - 900,000 CPM)	Maximum Response of Sensor



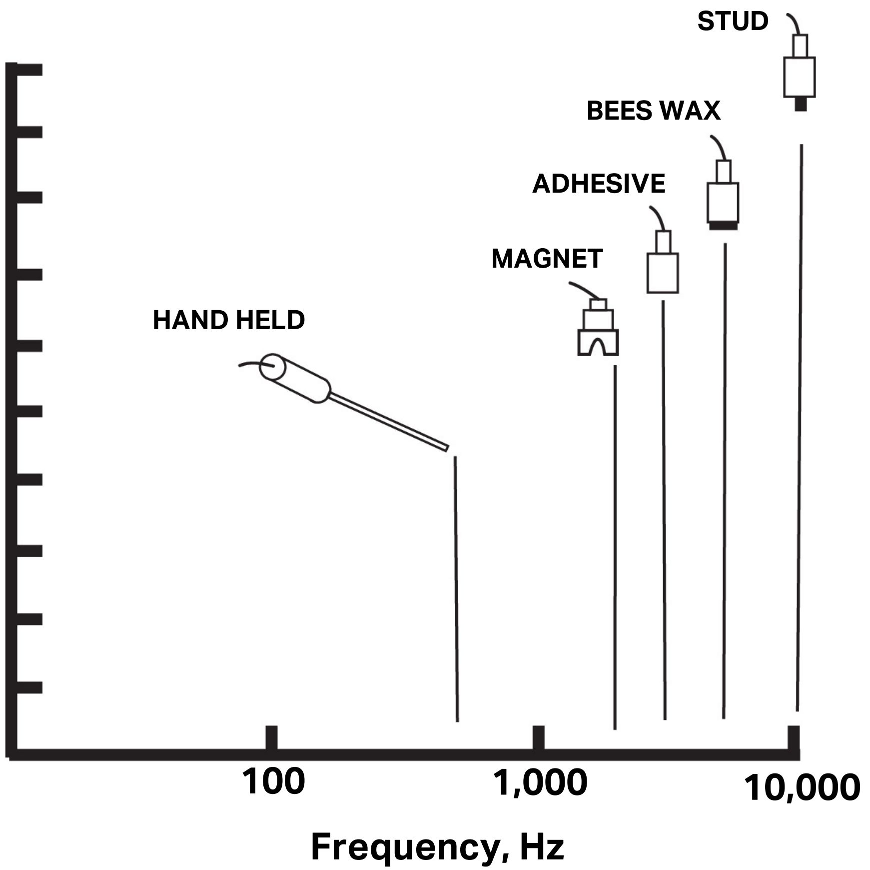
Maximum Frequency Response*
(within ±3dB)

* depending on specified high frequency response of individual sensors

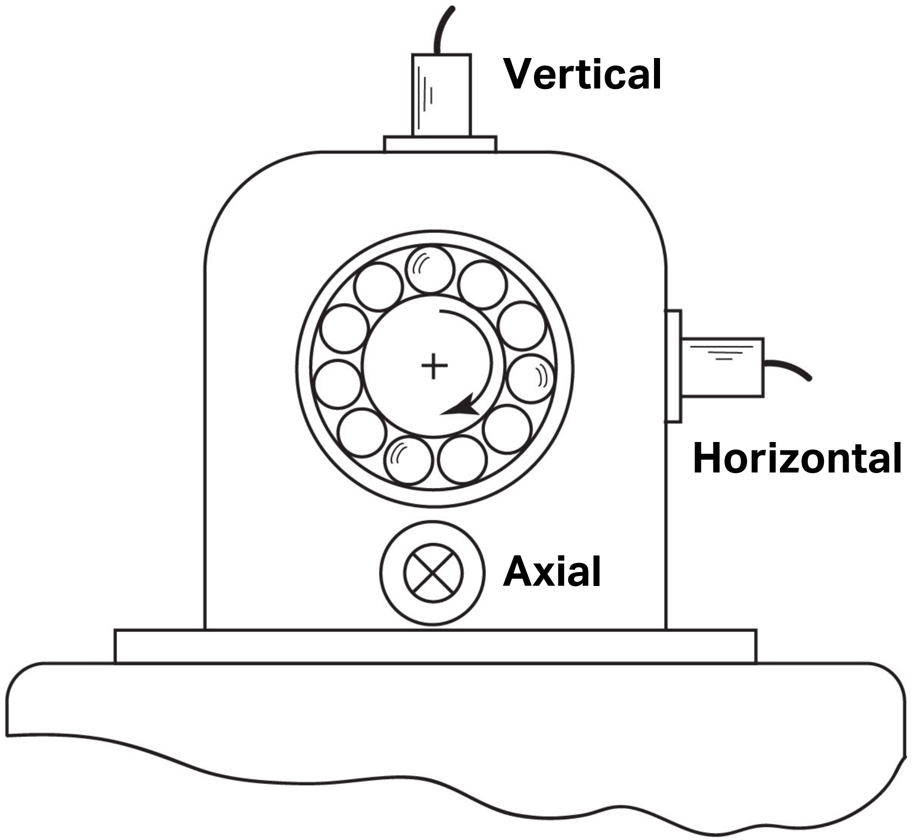
Sensors – Realistic Mounting

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

What happened to the high frequency?



Sensors – Mounting Location



Load Zone

Radial:
Vertical | Horizontal

Axial

Sensors – Accelerometer Alarms

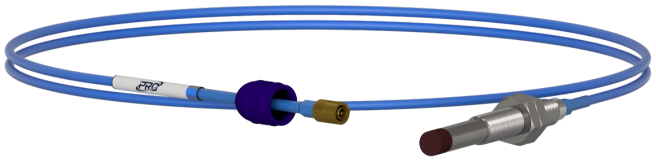
Machine Condition	Velocity Limit	
	RMS	Peak
Acceptance of new or prepared equipment	<0.08	<0.16
Unrestricted operation (normal)	<0.12	<0.24
Surveillance	0.12 – 0.28	0.24 – 0.7
Unsuitable for operation	>0.28	>0.7

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

Sensors – Proximity Probes

A complete proximity probe system consists of a probe, a driver, and an extension cable:



Probe

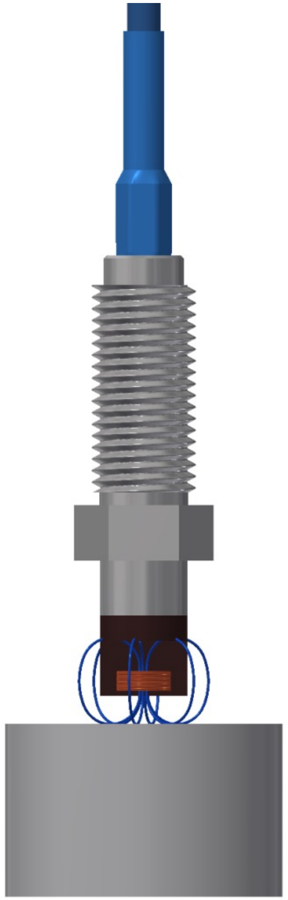
+

Driver

+

Extension Cable

Sensors – 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 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 the target is close to the probe tip
- A large DC voltage indicates the target is far away from the probe tip
- The variation of DC voltage is the dynamic signal indicating the vibration or displacement

Sensors – 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	250 mV / mil

Based on typical output sensitivity of 200 mV/mil

Sensors – Proximity Probe Pros And Cons

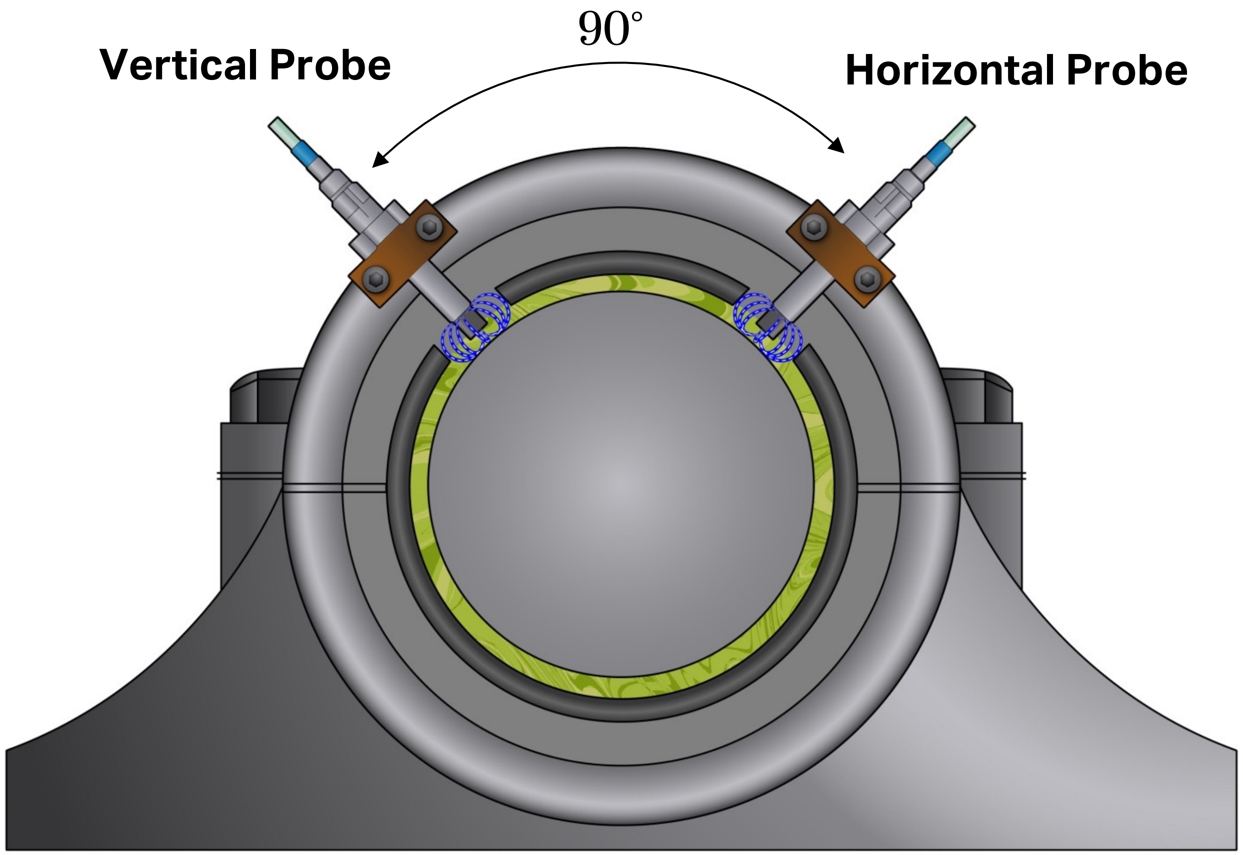
Pros

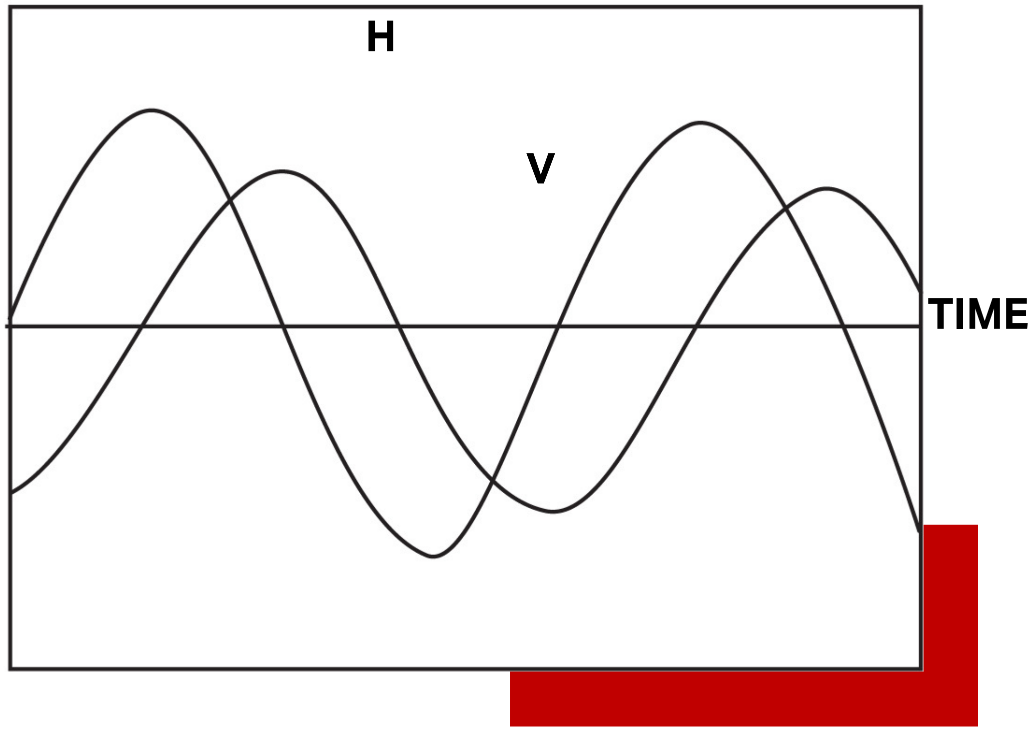
- Non-contact
- Measure shaft dynamic motion
- Measure shaft static position (gap)
- Flat frequency response DC – 1 kHz
- Simple calibration
- Suitable for harsh environments

Cons

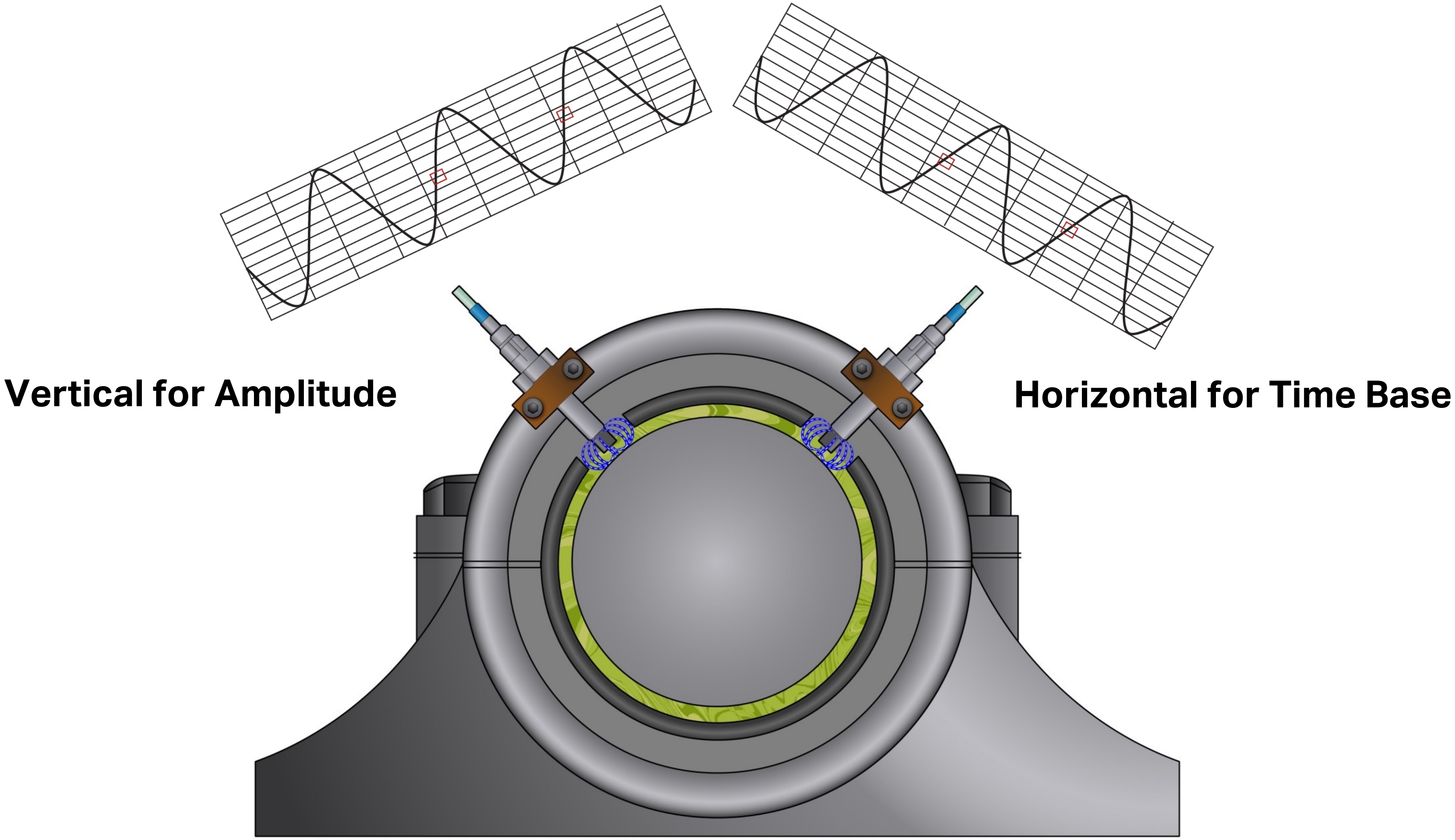
- Probe can move (vibrate)
- Doesn’t work on all metals
- Plated shafts may give false measurements
- Measures nicks and tool marks on shaft
- Must be replaced as a unit (probe, cable, and driver)
- Must have relief at sensing tip from surrounding metal

Sensors –
Typical Proximity Probe Mounting

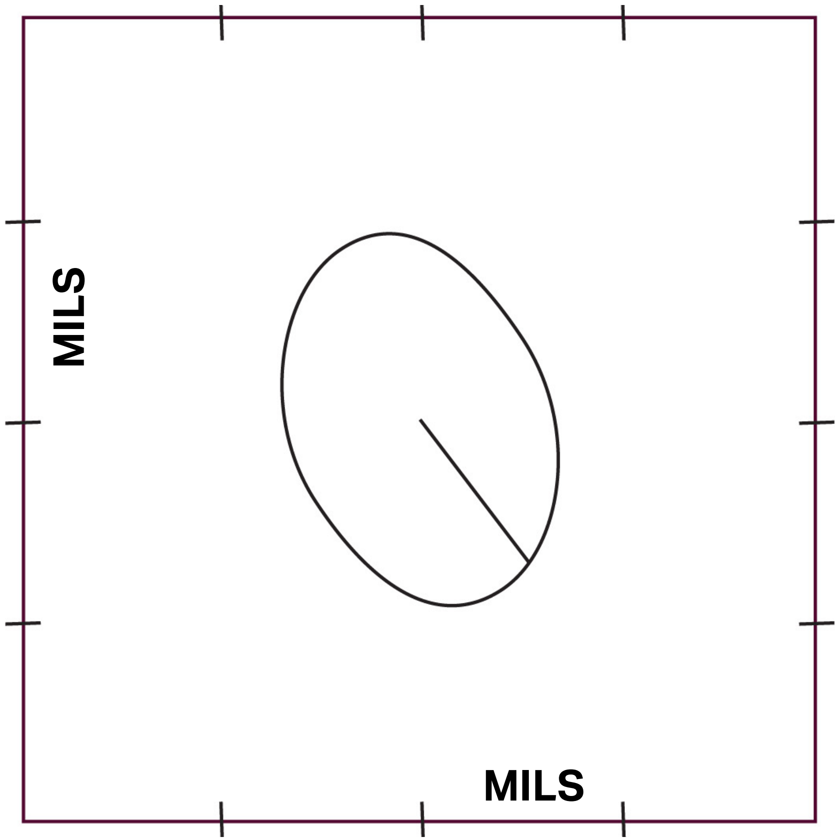


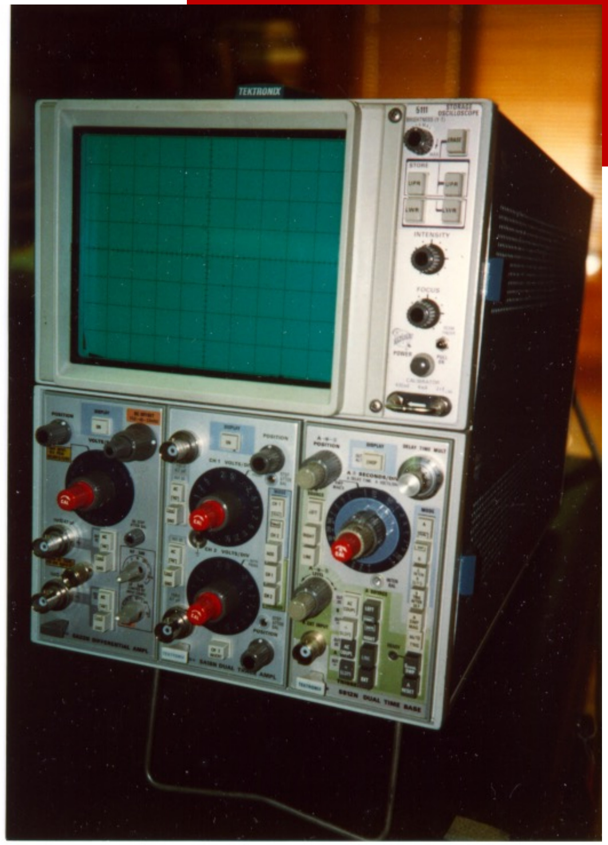


Sensors -
Looking At Orbits

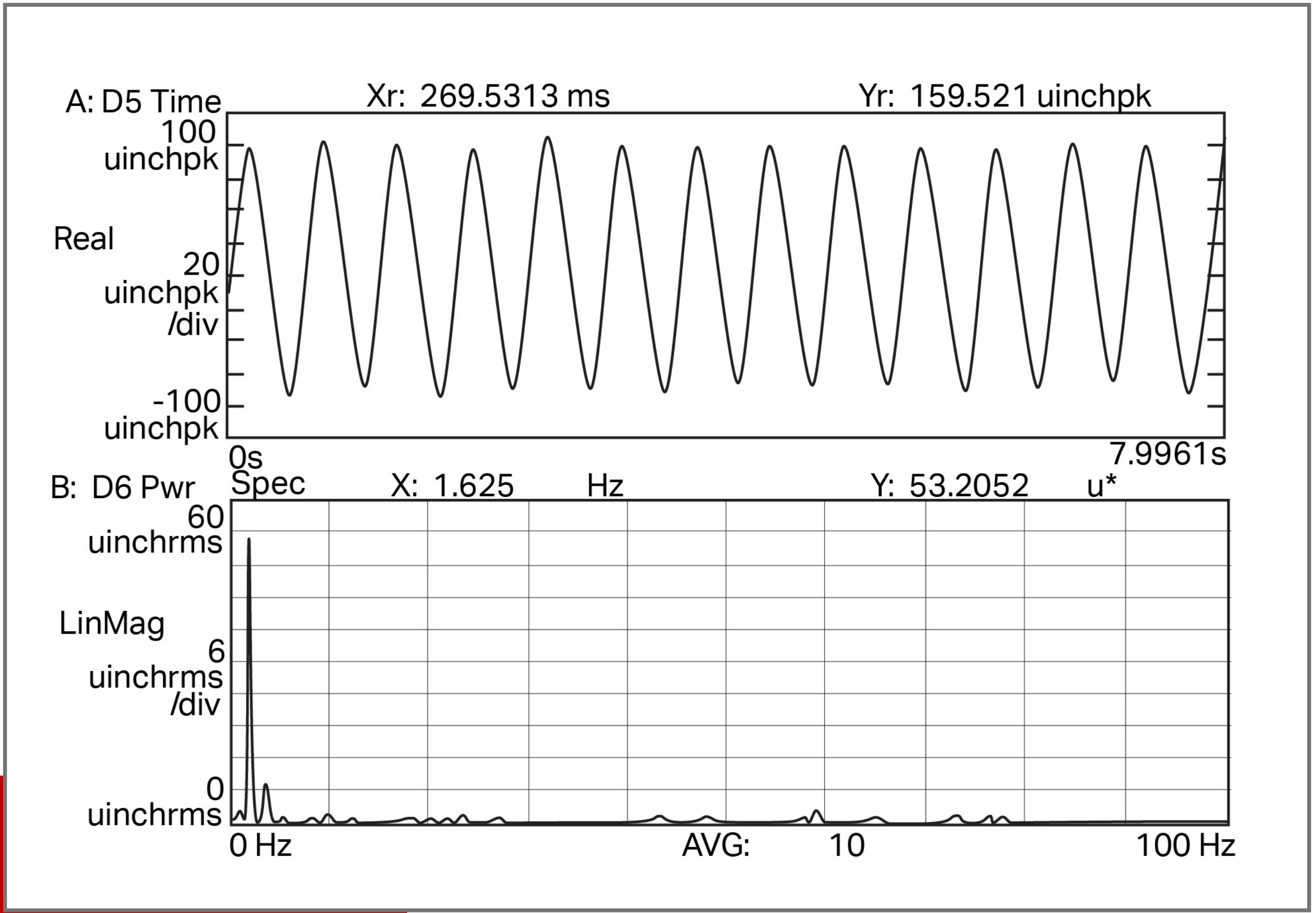


Sensors –
The Orbit Display

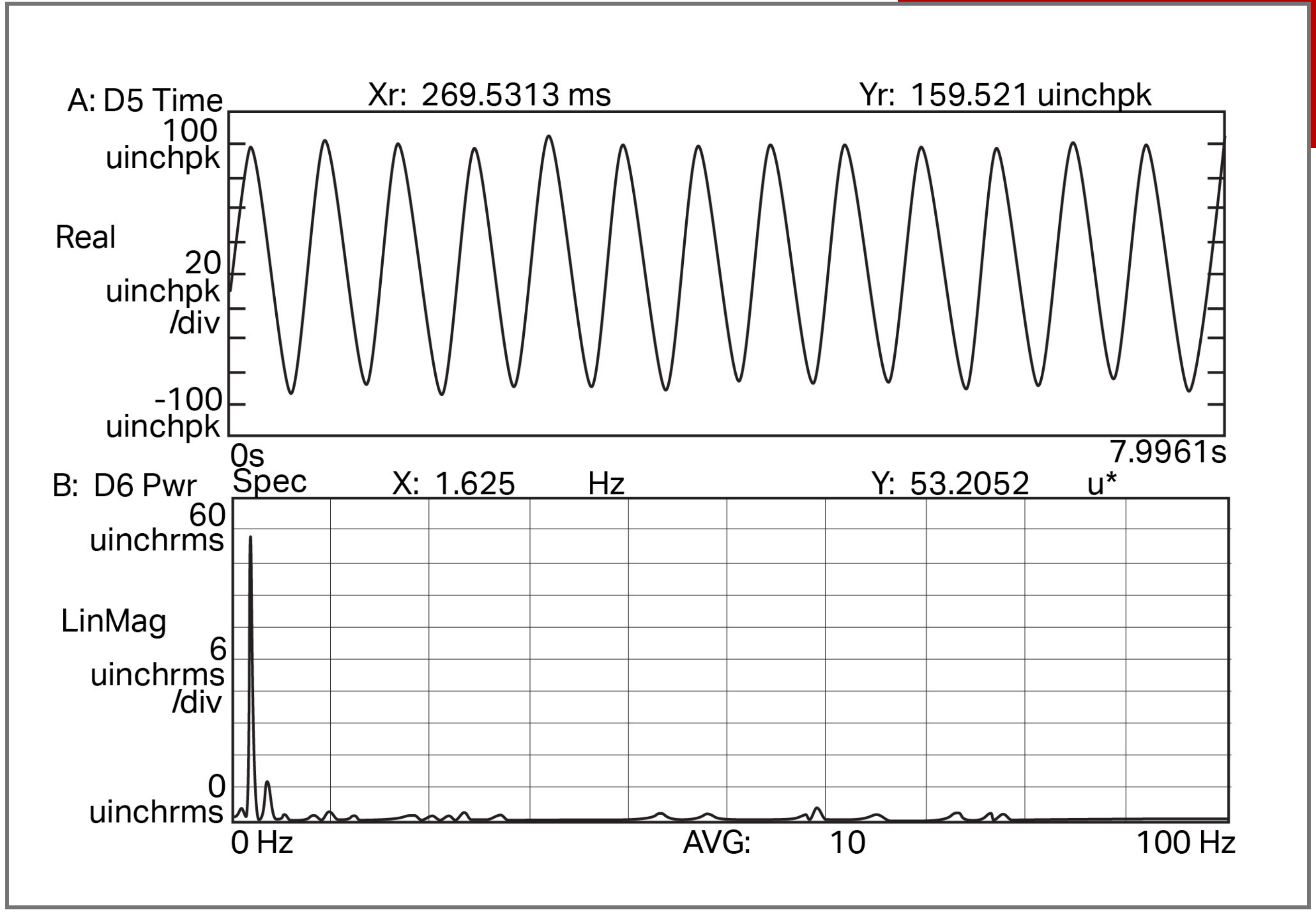


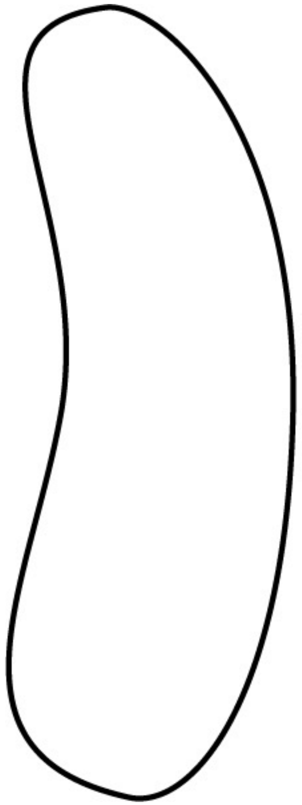


Sensors – Unbalance

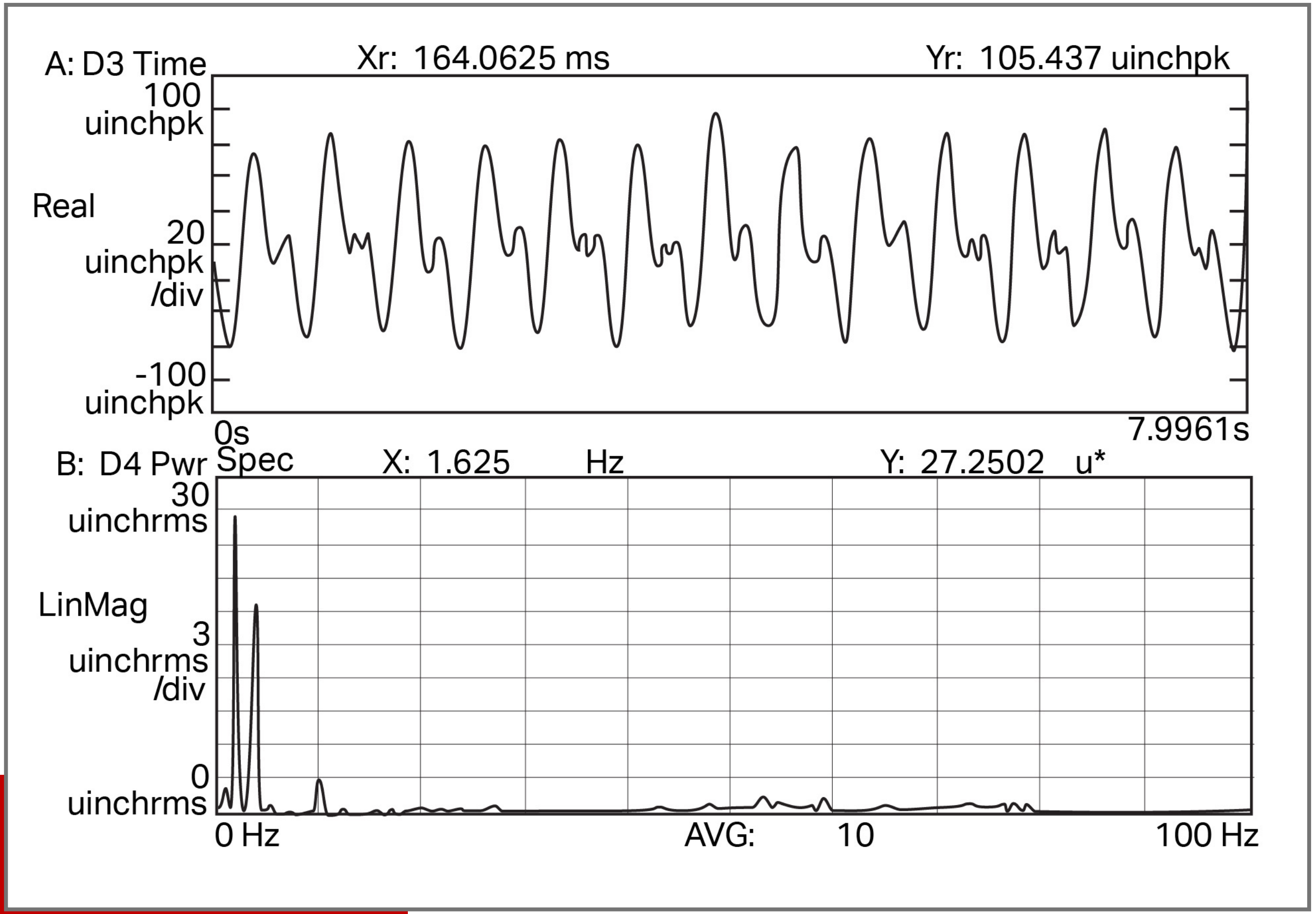


Sensors – Unbalance With Orbit

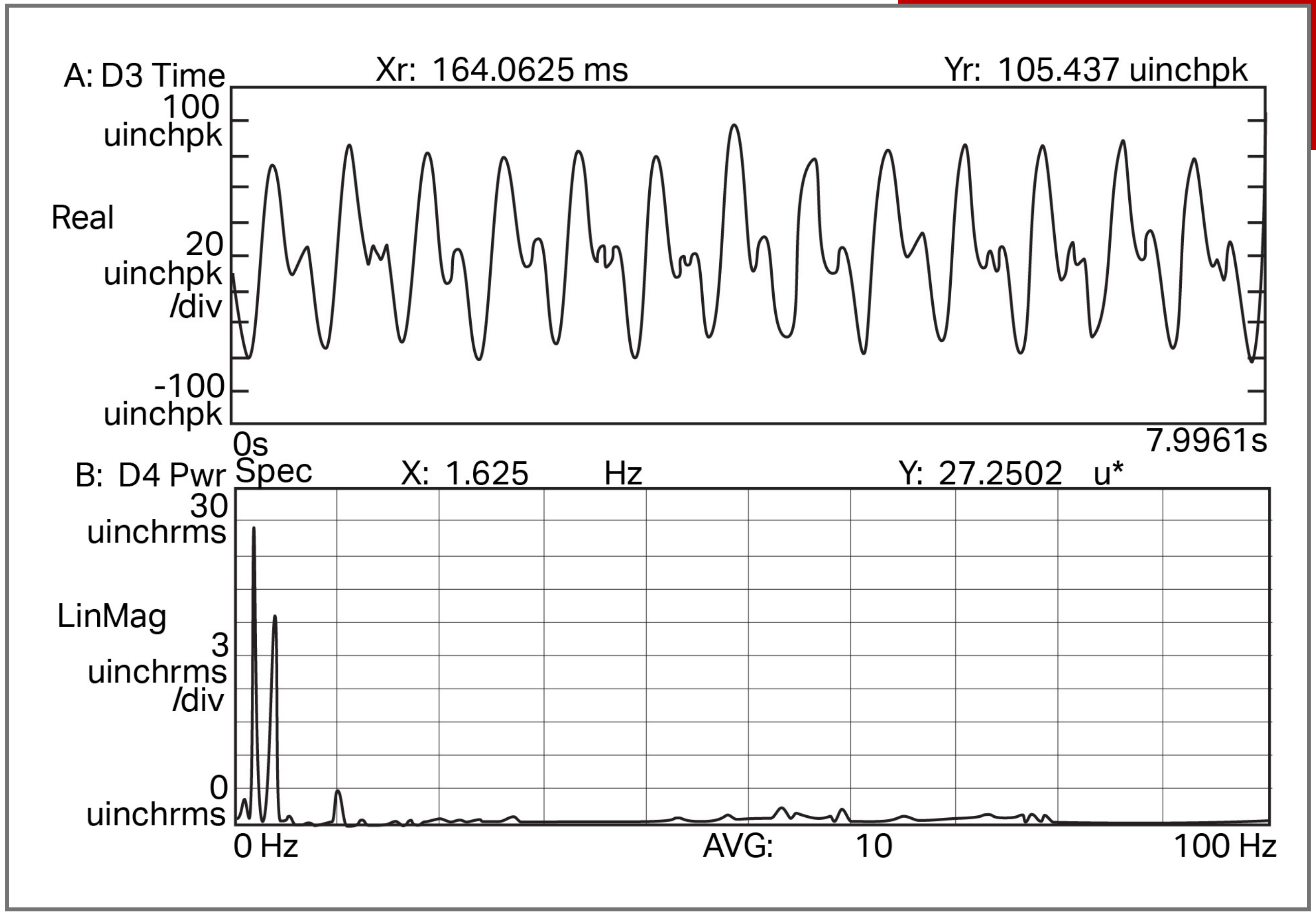


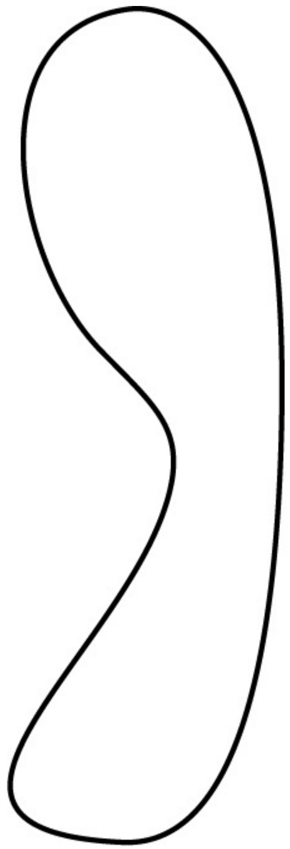


Sensors – Misalignment

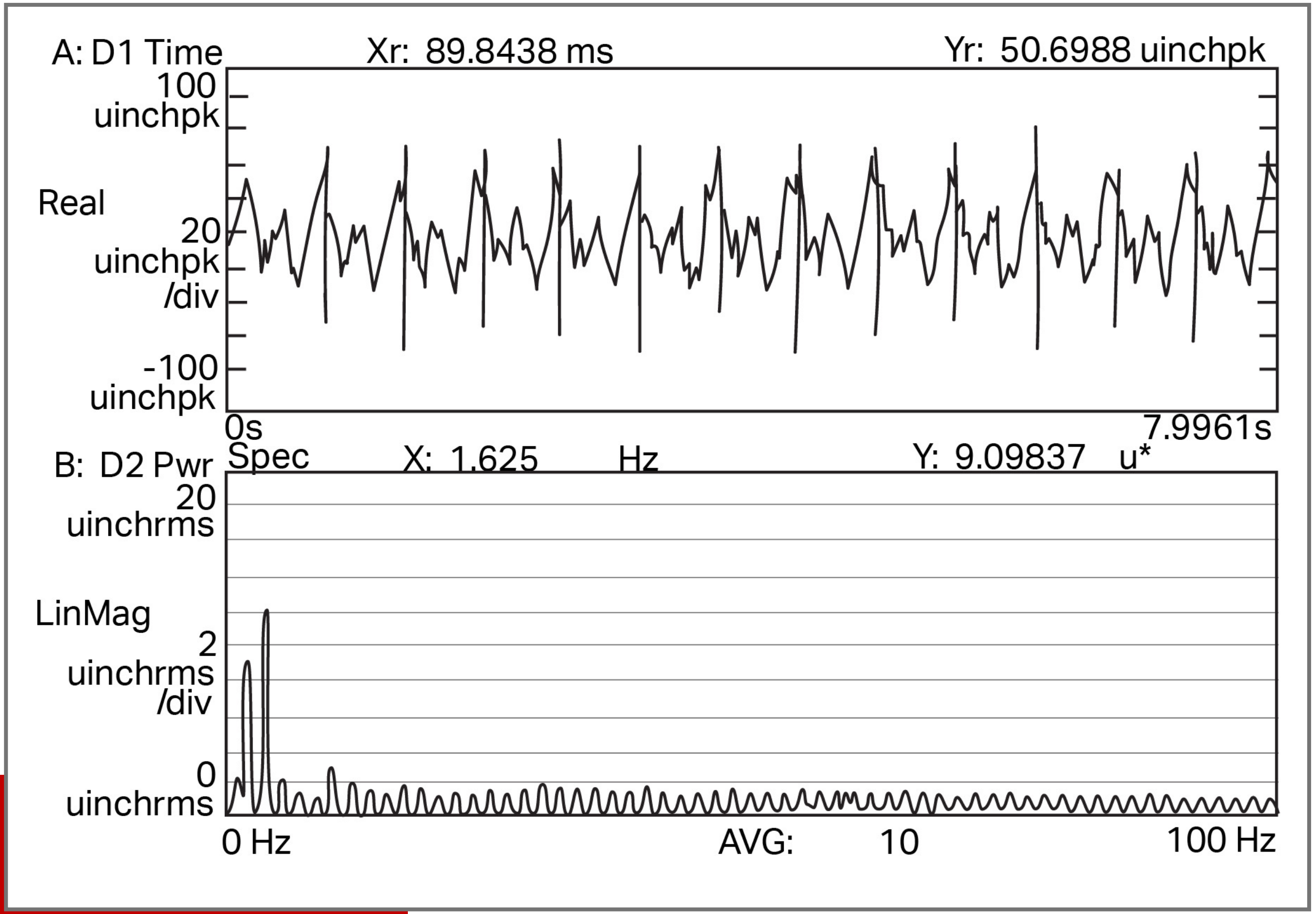


Sensors – Misalignment With Orbit





Sensors –
And The Problem Is?



Sensors – 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

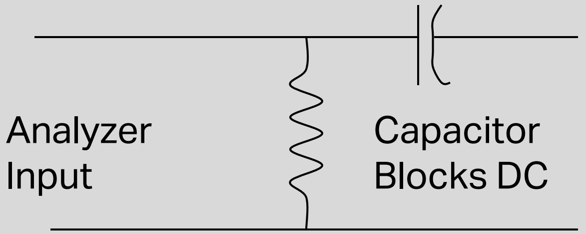
Note 1: R is the relative displacement of the shaft measured by either probe in mils Peak-Peak

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

Sensors –
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.

Antialias Filter – On, Off
Prevents frequencies that are greater than span from wrapping around in the spectrum.



AC Coupling Capacitor in DSA

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

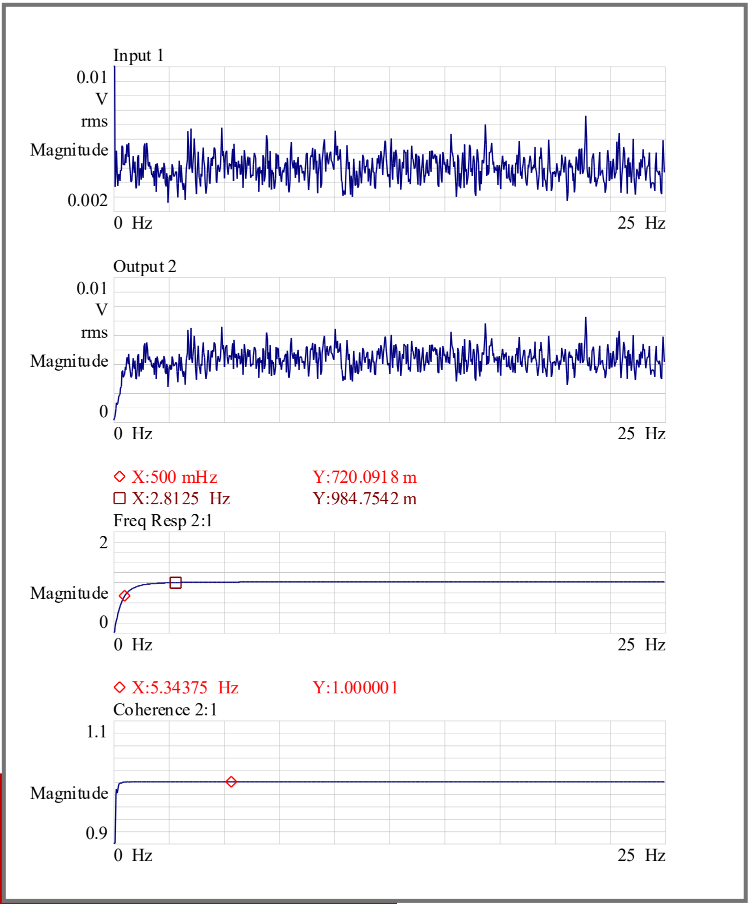
$$1024/800 = 1.28$$

$$100 \text{ x } 1.28 = 128 \text{ Hz}$$

$$175 \text{ Hz - } 128 \text{ Hz} = 47 \text{ Hz}$$

$$128 \text{ Hz - } 47 \text{ Hz} = 81 \text{ Hz}$$

Sensors – Low End Frequency Response



- To the left is a typical problem with frequency response at the low end of the frequency spectrum
- The 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

Data Collection – Data Collector Rotating Equipment

- Route based
- Frequency Spectrum
- Time waveform
- Orbits
- Balancing
- Alignment
- Data Analysis
- History
- Trending
- Download to PC
- Alarms
- 'Smart' Algorithms

Bibliography

- Eisenmann, Robert Sr. & Eisenmann, Robert Jr., Machinery Malfunction Diagnosis and Correction, ISBN 0-13-240946-1
- 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

Connect With CTC

We look forward to hearing from you

www.ctconline.com

sales@ctconline.com

(585) 924-5900

Connection Technology Center