CONNECTION TECHNOLOGY CENTER, INC.

BEGINNING VIBRATION ANALYSIS

WITH

BASIC FUNDAMENTALS

INTRODUCTION

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

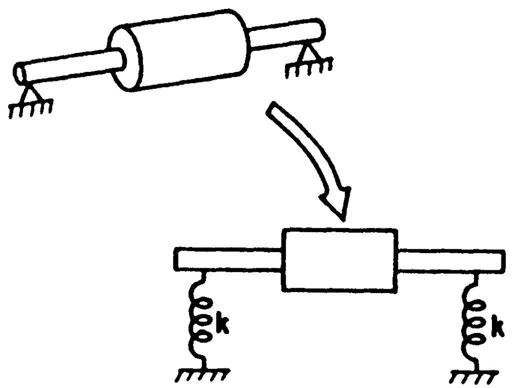
Switching between time and frequency is a common tool used for analysis. Because the frequency spectrum is derived from the data in the time domain, the relationship between time and frequency is very important. Units of acceleration, velocity, and displacement are typical. Additional terms such as peak-peak,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

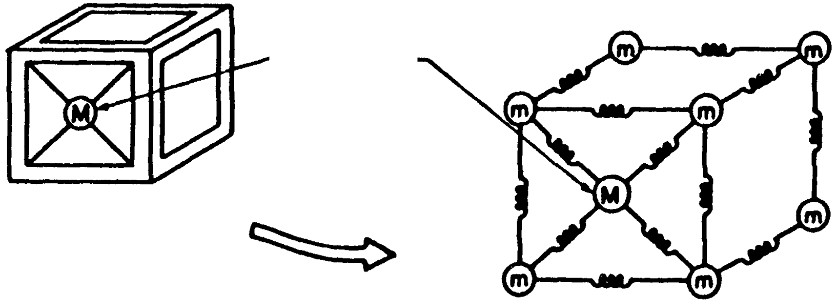
As much as possible, this training will follow the criteria as established by the Vibration Institute.

MASS AND STIFFNESS – WHAT IS IT?

All machines can be broken down into two specific categories:

- **MASS** *is represented by an object that wants to move or rotate*
- **STIFFNESS** *is represented by springs or constraints of that movement*



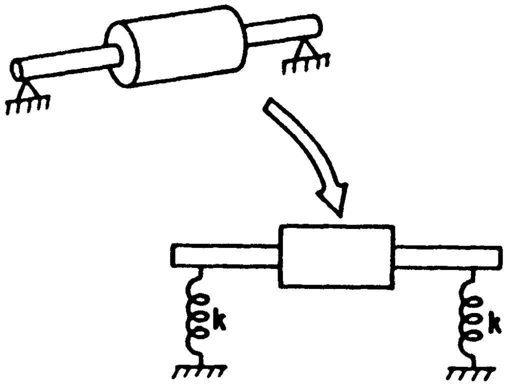


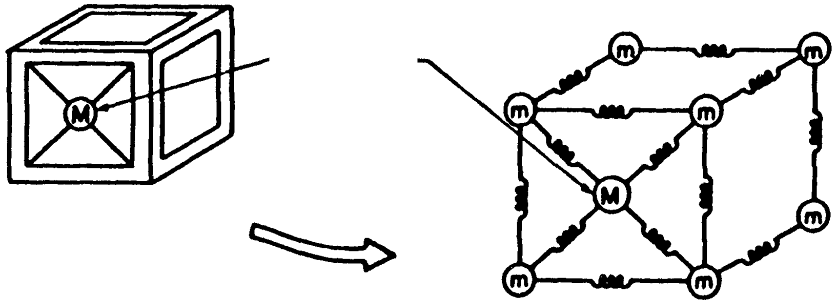
MASS AND STIFFNESS – WHAT IS IT?

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

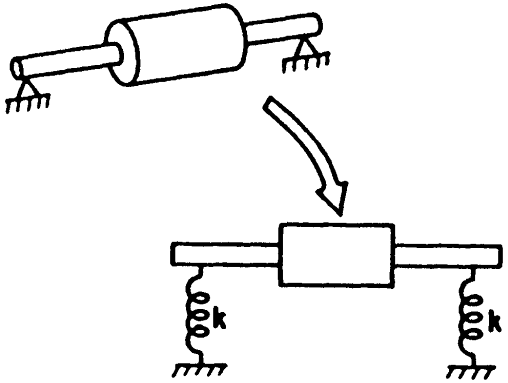
Where:

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



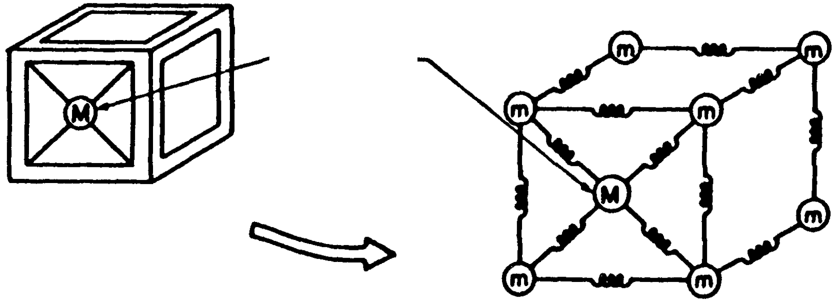


MASS AND STIFFNESS - UNDERSTANDING THE CONCEPT



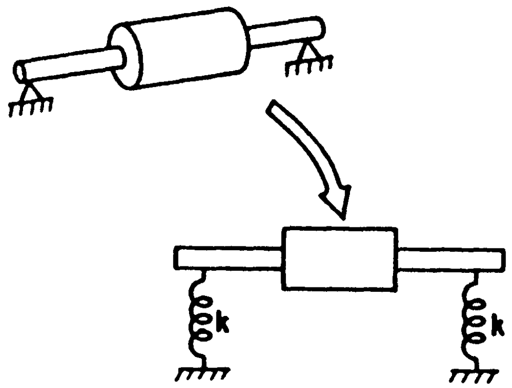
$$f_n = 1/2\Pi\sqrt{k/m}$$

- If **k increases**, then **f increases**
- **If k decreases**, then **f decreases**

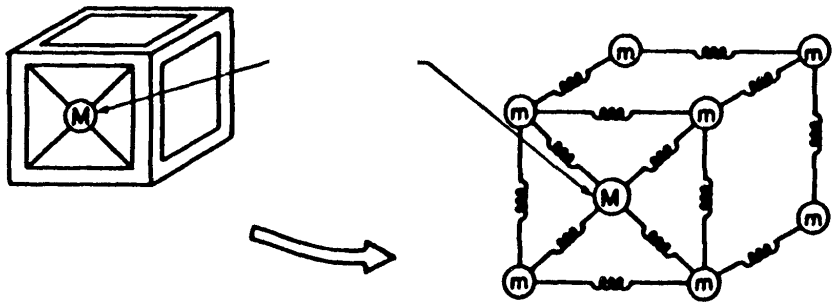


MASS AND STIFFNESS - UNDERSTANDING THE CONCEPT

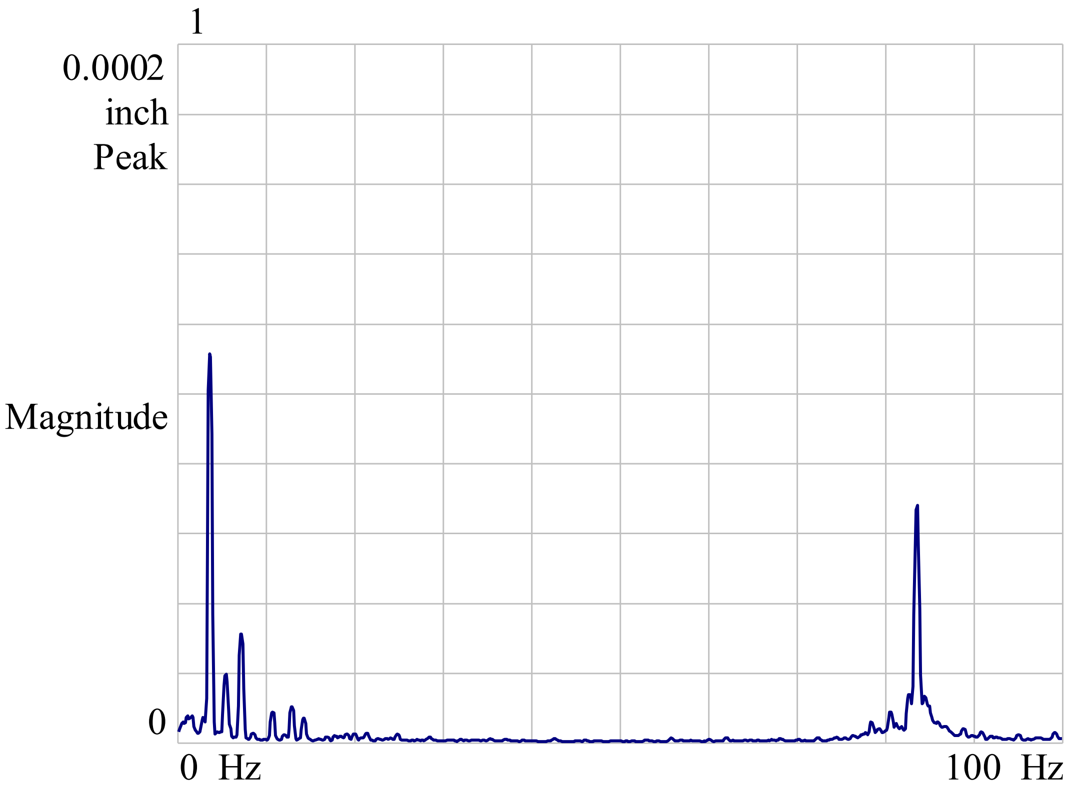
$$f_n = 1/2\Pi\sqrt{k/m}$$



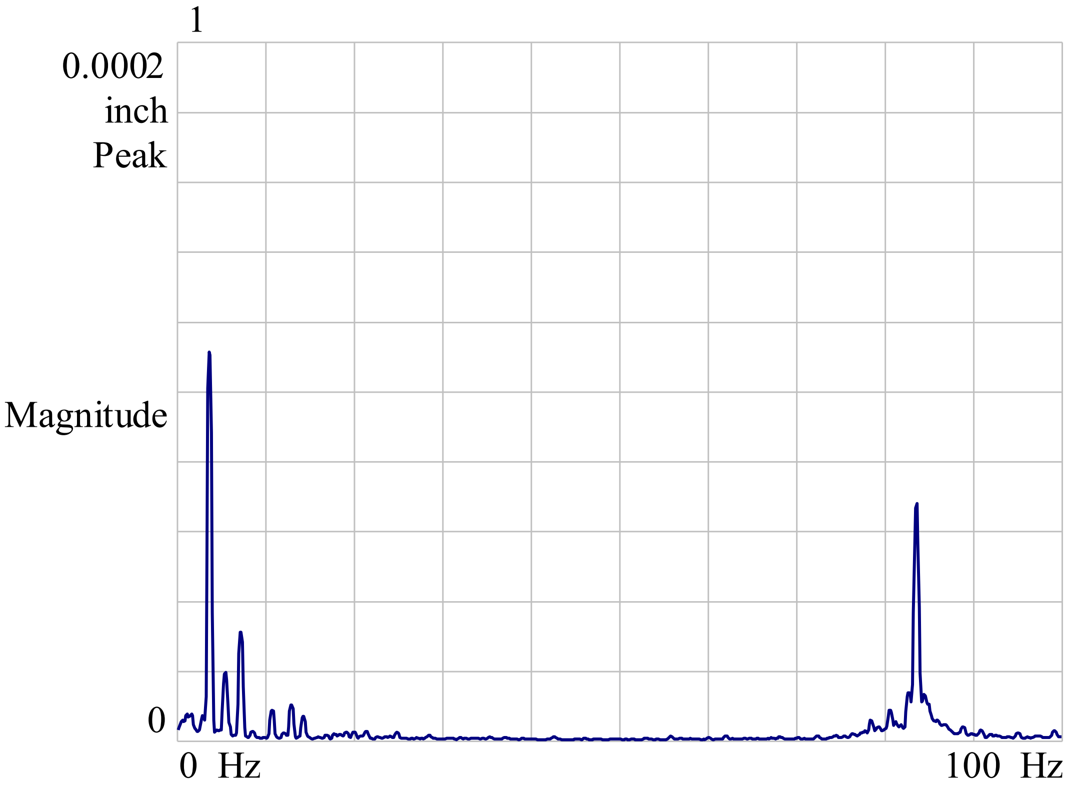
- ❑ If **m increases**, then **f decreases**
- ❑ If **m decreases**, then **f increases**



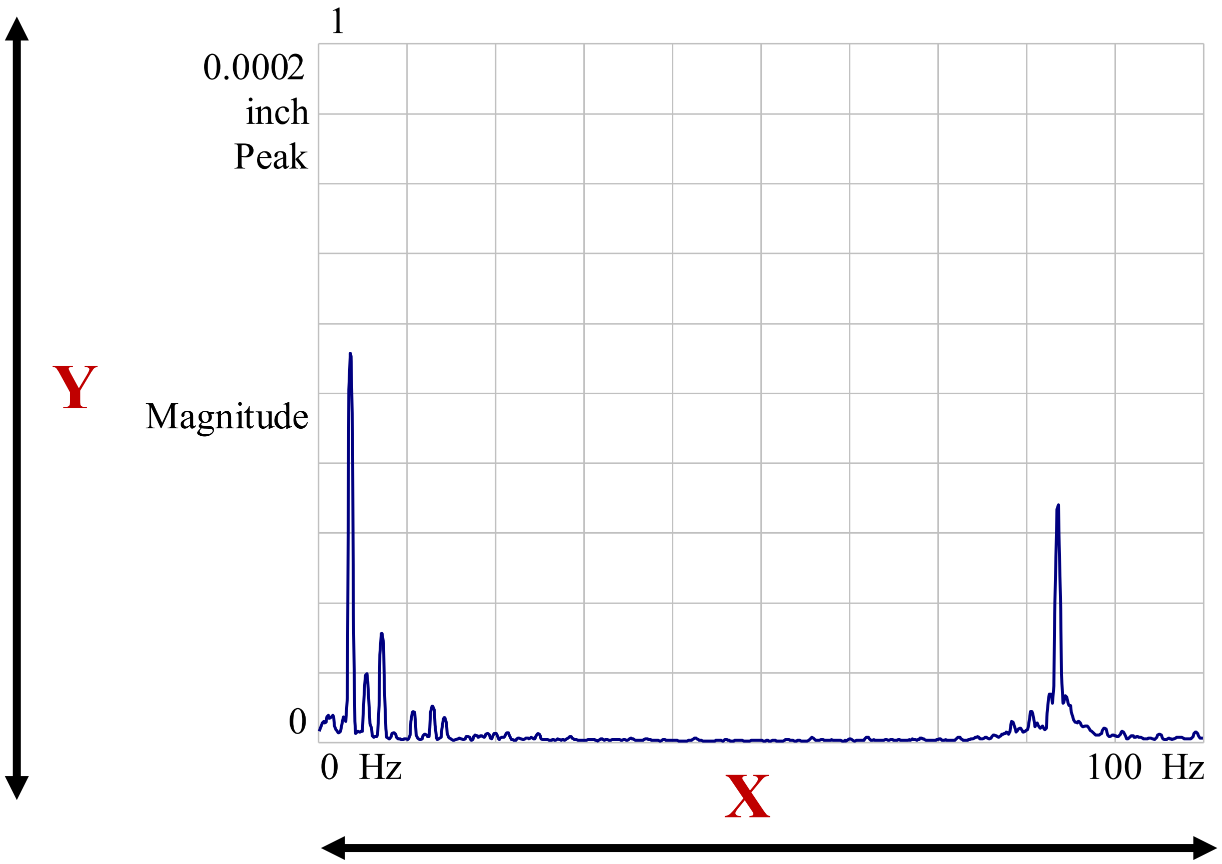
SPECTRUM – WHAT IS IT?



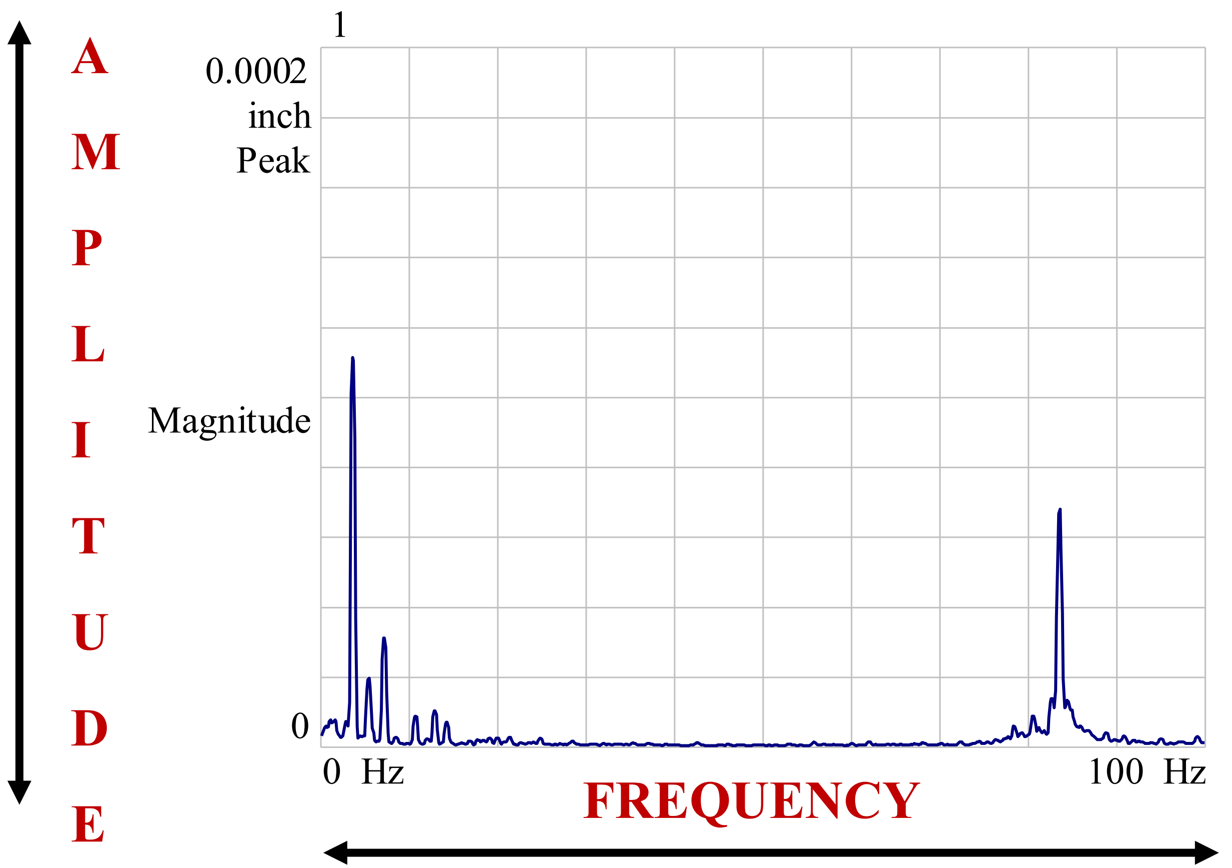
FFT, FREQUENCY SPECTRUM, POWER SPECTRUM



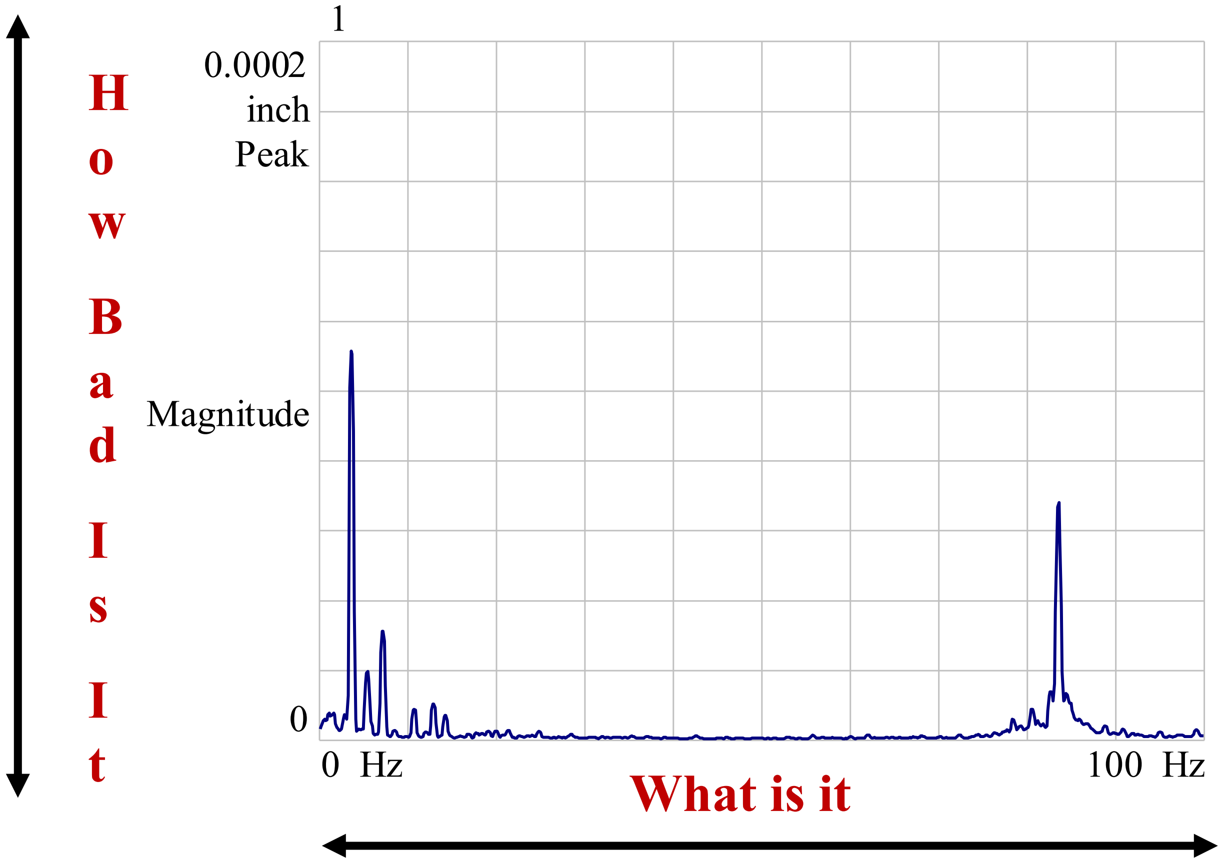
SPECTURM - SCALING X AND Y



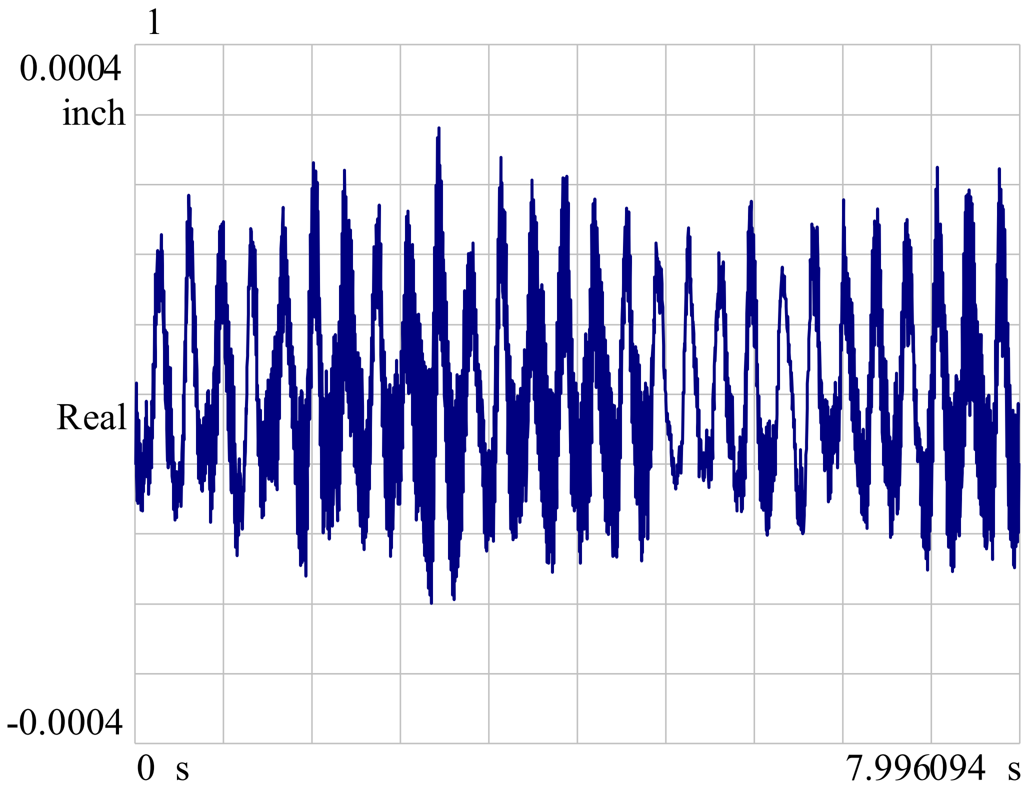
SPECTRUM - SCALING X AND Y



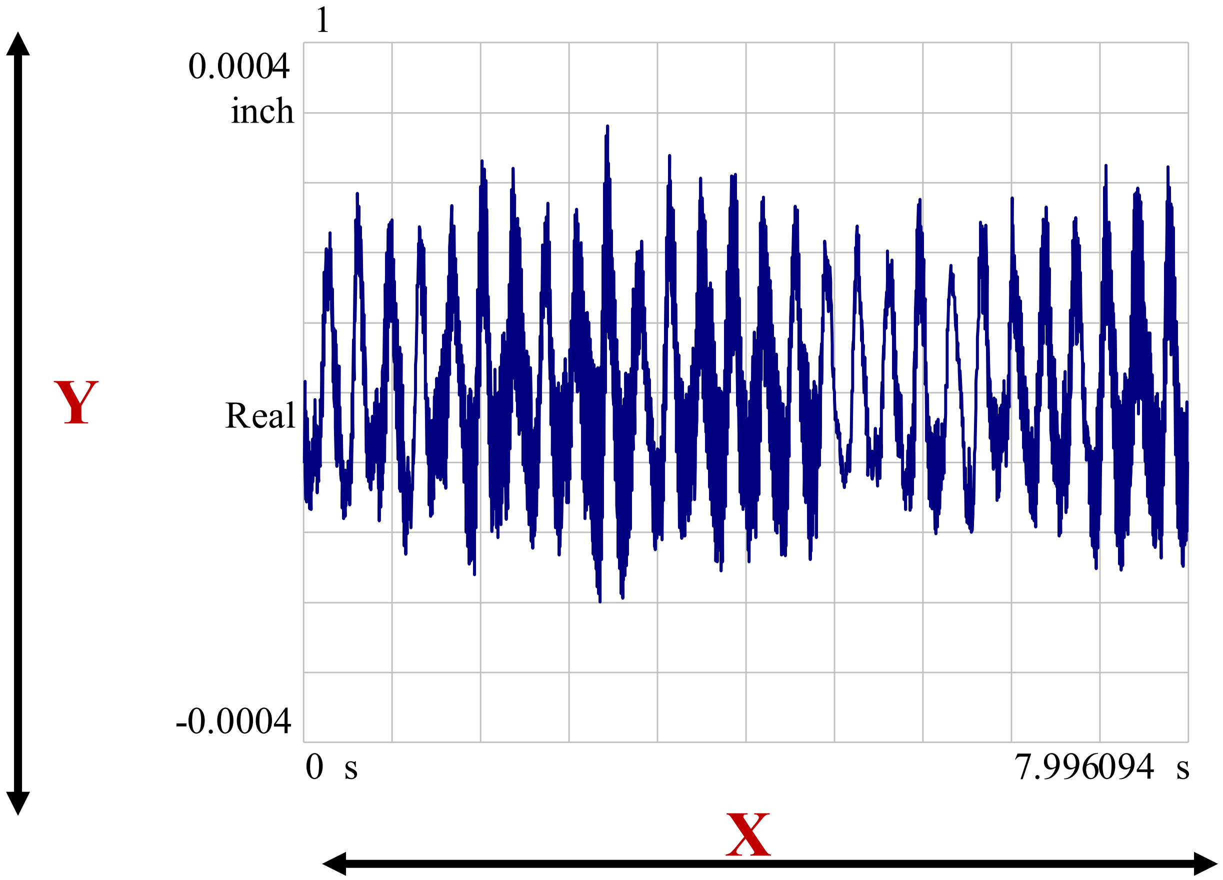
SPECTRUM - SCALING X AND Y



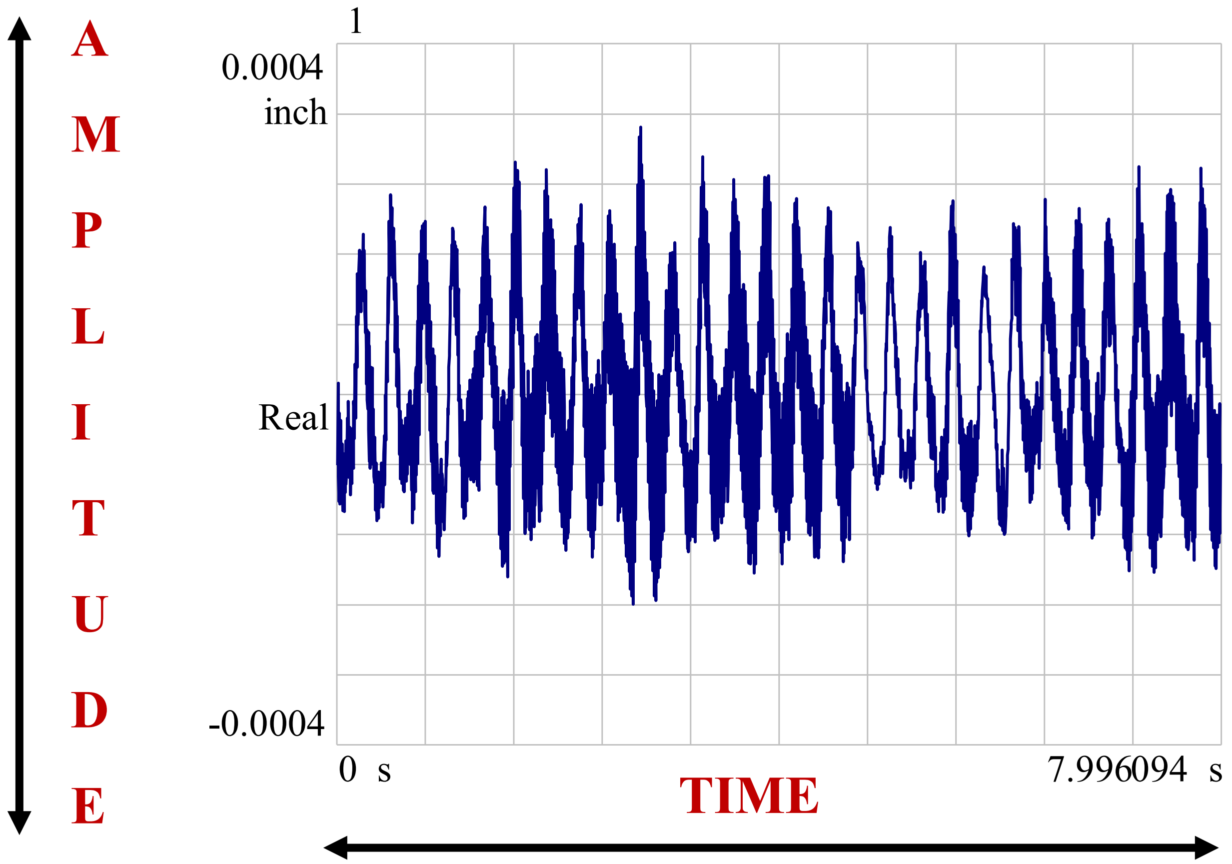
TIME WAVEFORM – WHAT IS IT?



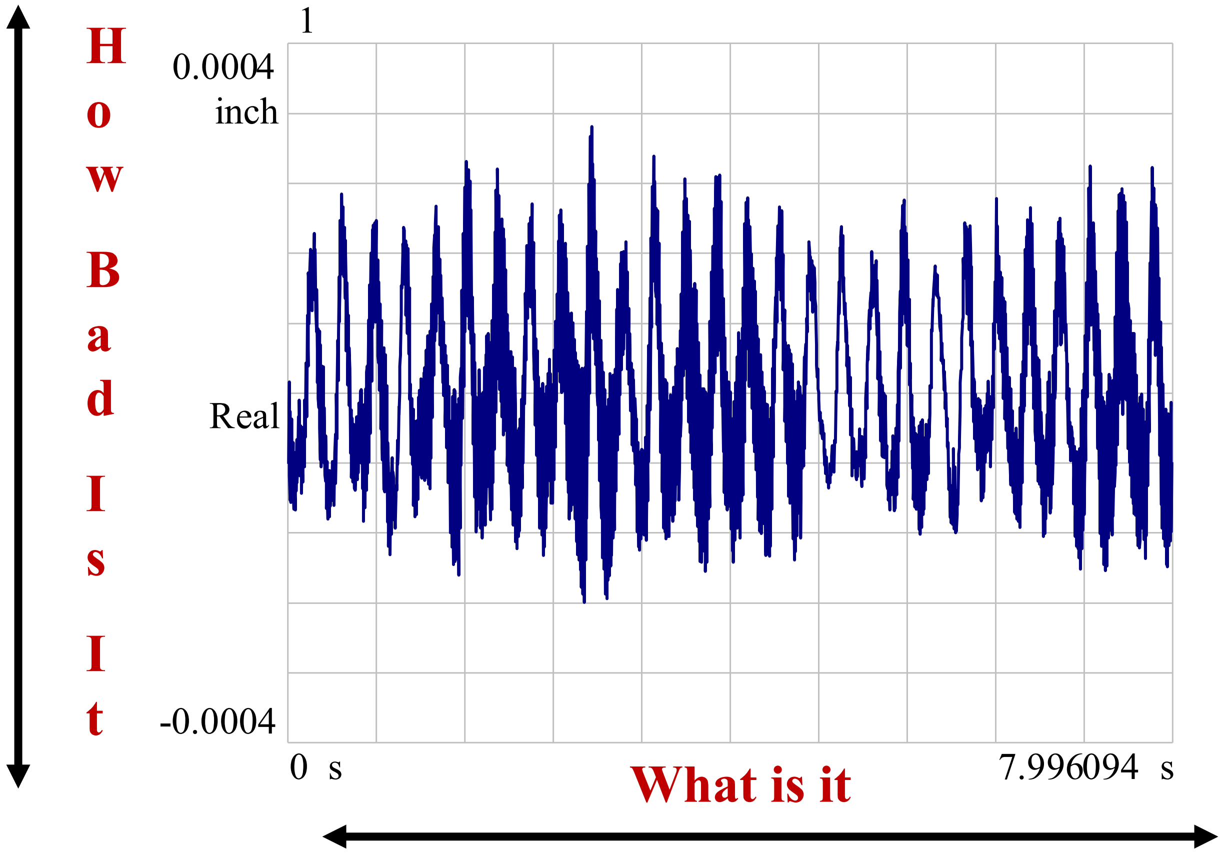
TIME WAVEFORM – SCALING X AND Y



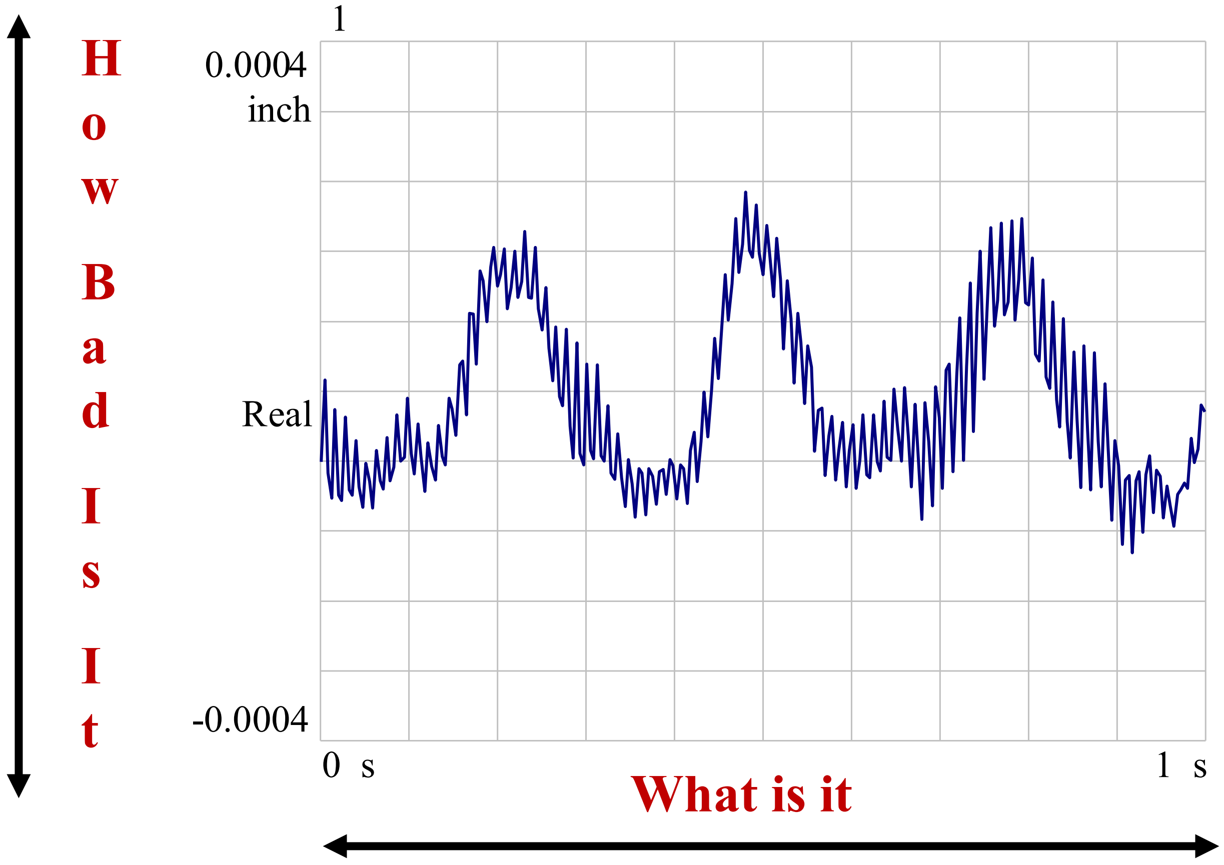
TIME WAVEFORM – SCALING X AND Y



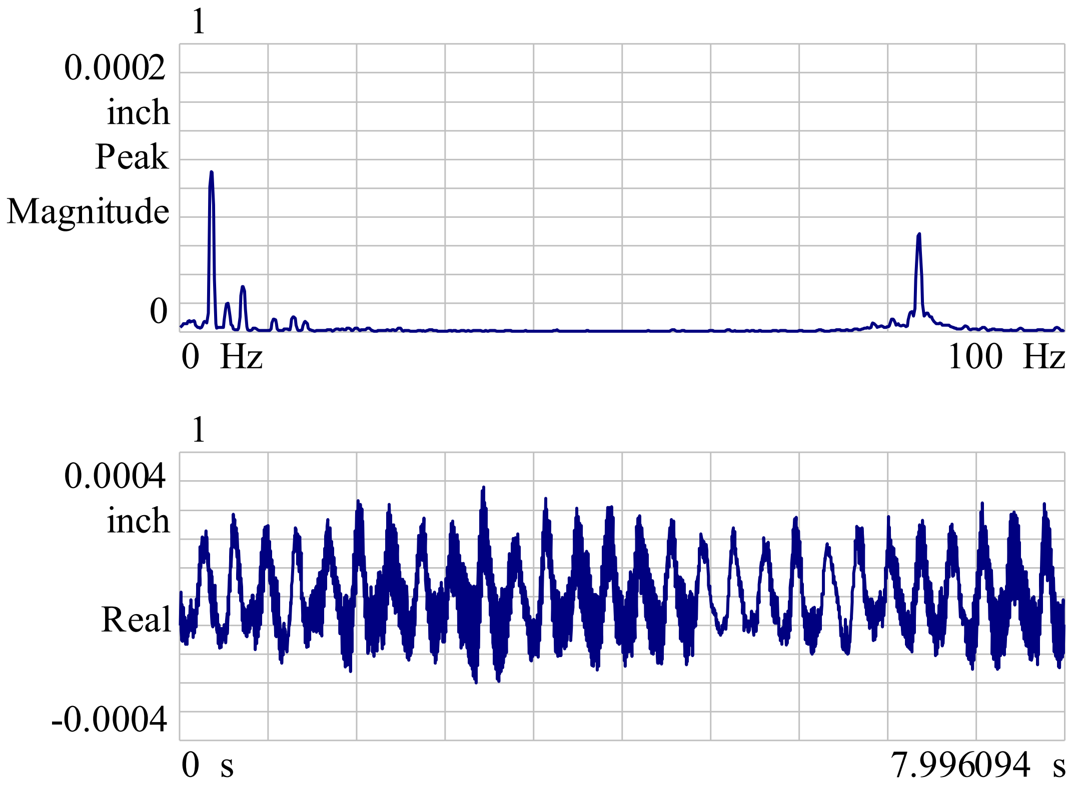
TIME WAVEFORM – SCALING X AND Y



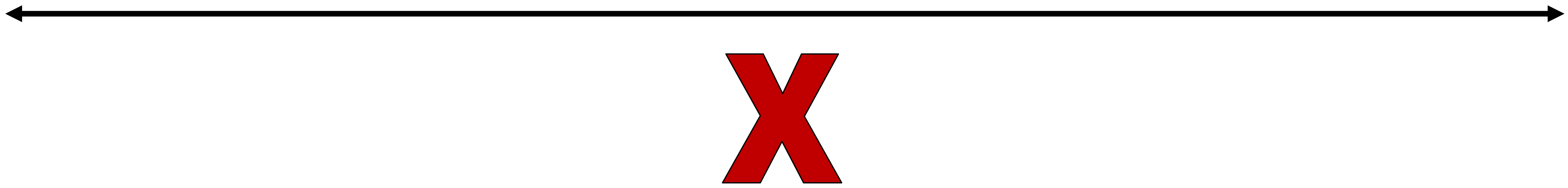
TIME WAVEFORM – SCALING X AND Y



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.

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

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 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.

THE X SCALE – UNDERSTANDING THE CONCEPT

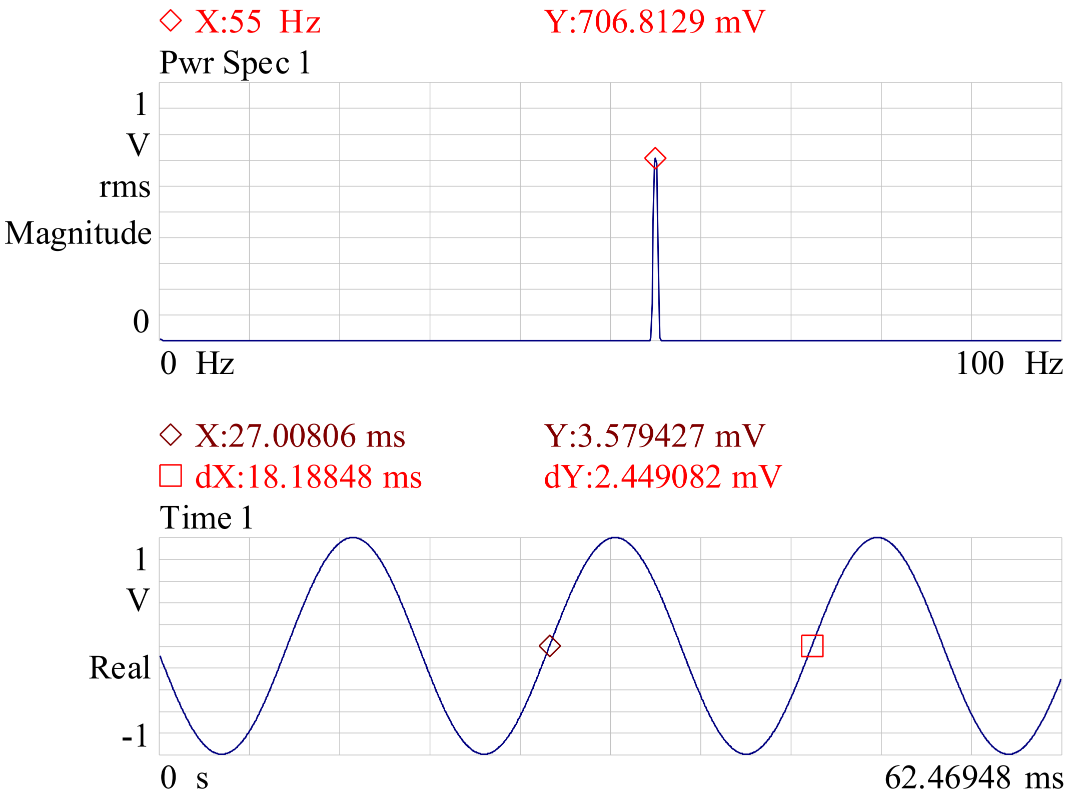
- If **F = 1/T** and **T = 1/F**, then **FT = 1**

THE X SCALE – UNDERSTANDING THE CONCEPT

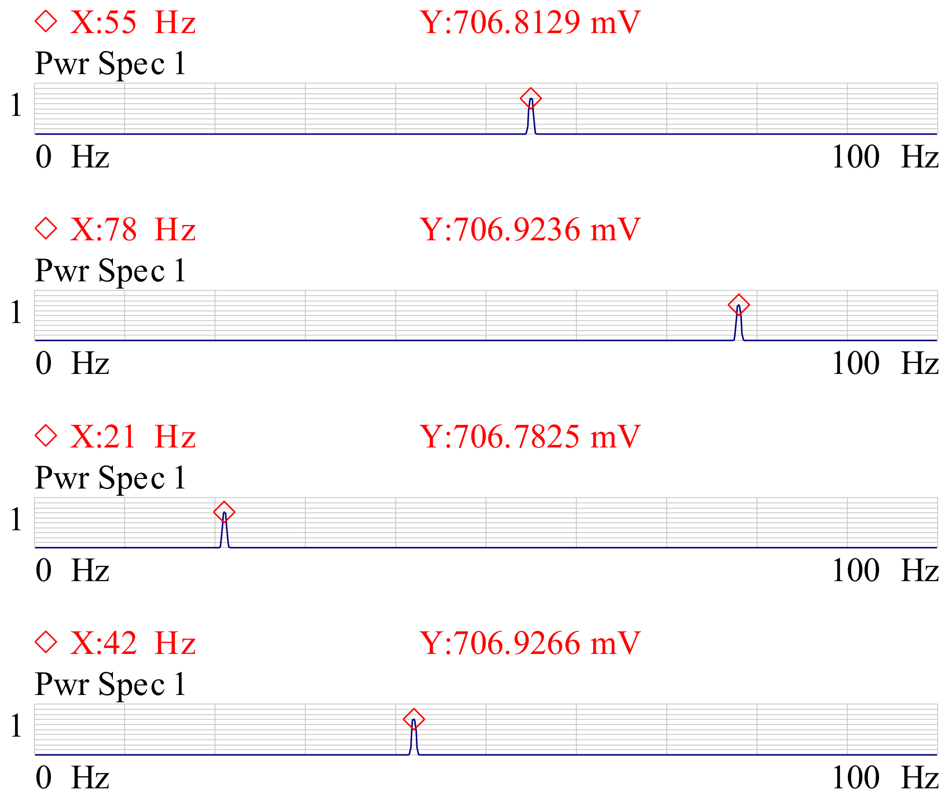
FT = 1

- If **F increases**, then **T decreases**
- If **T increases**, then **F decreases**

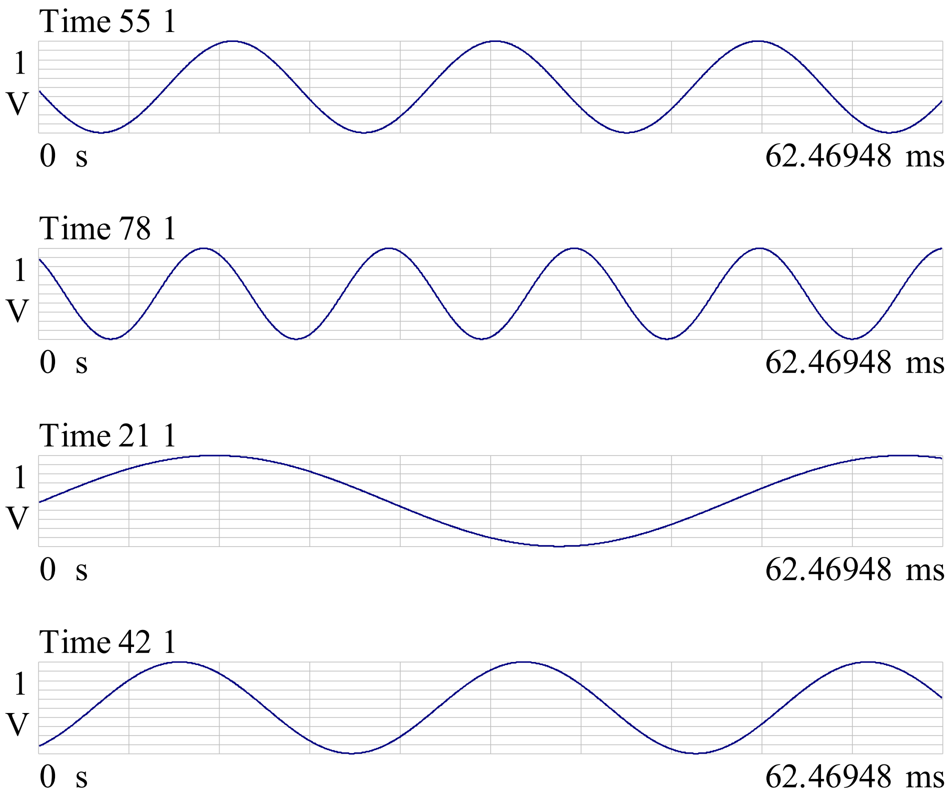
THE X SCALE – SINGLE FREQUENCY



THE X SCALE – MULTIPLE FREQUENCIES

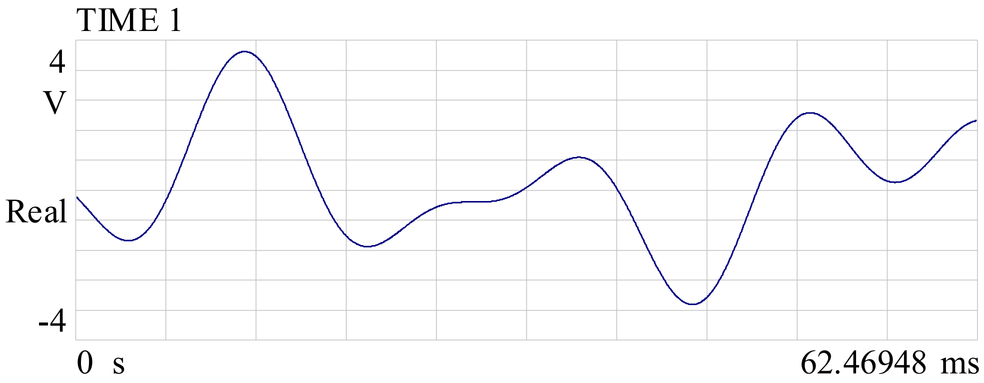


THE X SCALE – MULTIPLE TIME

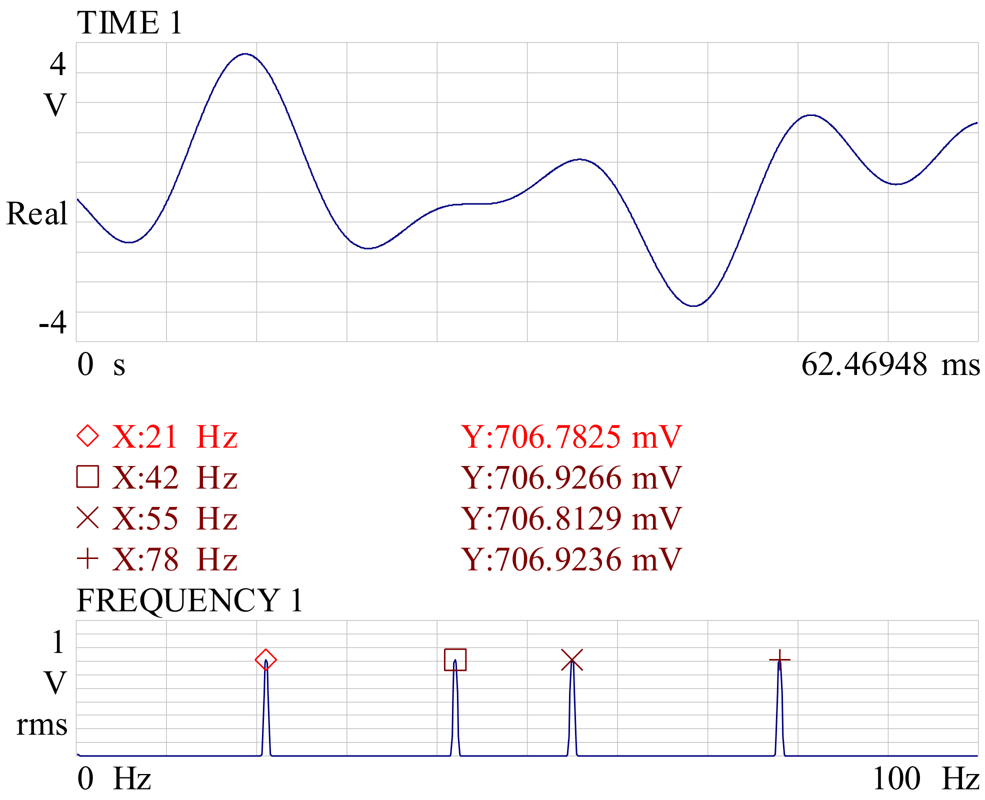


THE X SCALE – REAL LIFE TIME

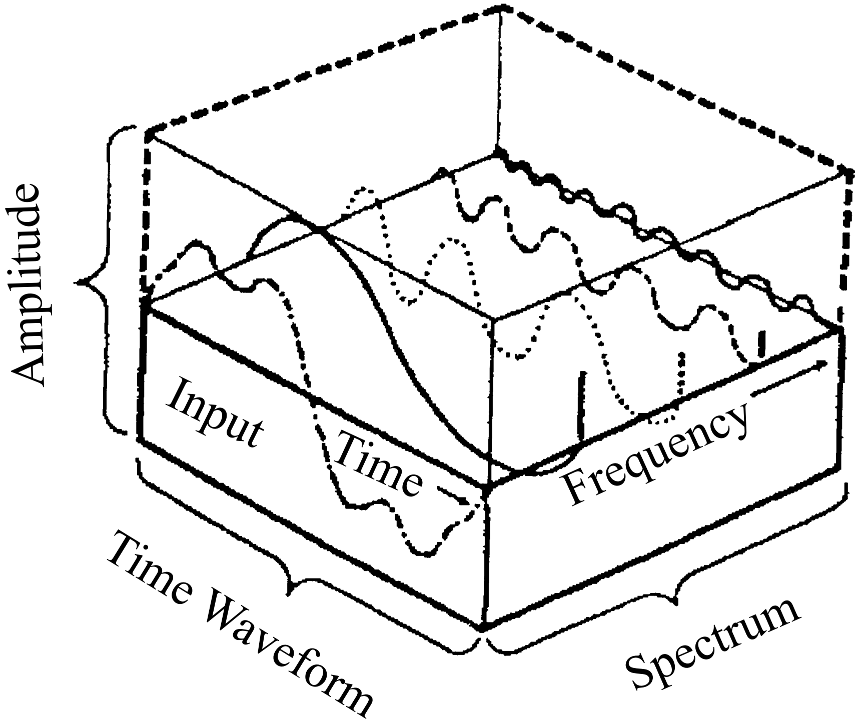
55 + 78 + 21 + 42 = Trouble !



THE X SCALE – FREQUENCY SPECTRUM



THE X SCALE –
THE MOST COPIED SLIDE IN THE HISTORY OF VIBRATION ANALYSIS!

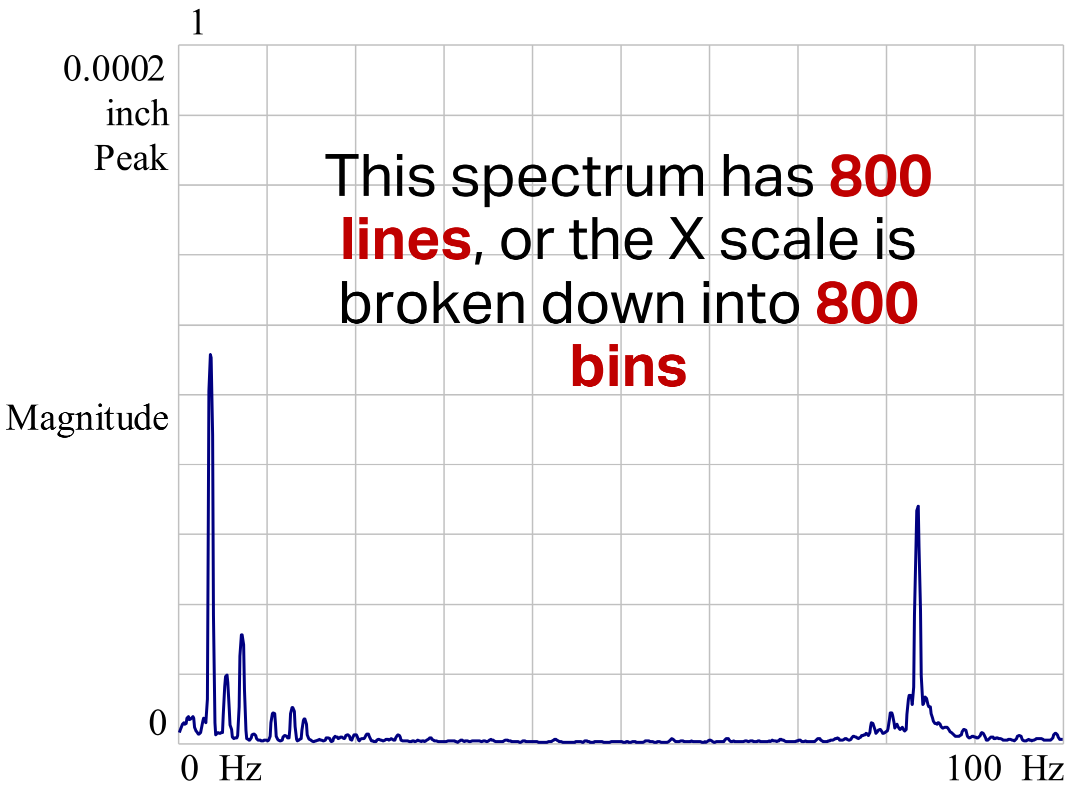


THE X SCALE – LINES OR BINS

The **FFT** always has
a defined number of lines or bins.

The following are common choices:

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



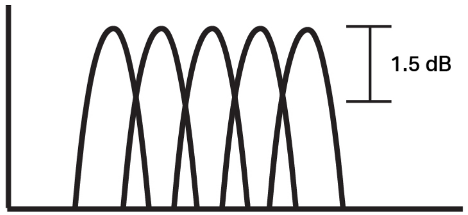
THE X SCALE – FILTER WINDOWS

WINDOW FILTERS *are applied to the time waveform data to simulate data that starts and stops at zero.*

- ❑ Window filters will cause errors in the time waveform and frequency spectrum
- ❑ We still like window filters!

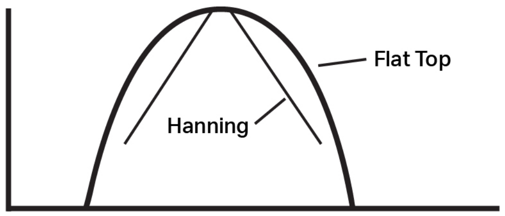
THE X SCALE – FILTER WINDOWS

- **Hanning** (frequency)
- **Flat Top** (amplitude)
- **Uniform** (no window)
- **Force Exponential** (frequency response)
- **Force / Expo Set-up**



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

- 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)

THE X SCALE – LRF

The **Lowest Resolvable 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**

THE X SCALE – BANDWITH

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 = 3.8

- ❑ *Example:* **0 - 400 Hz using 800 Lines & Hanning Window**
- ❑ *Answer:* **(400 / 800) 1.5 = 0.75 Hz / Line**

Note:

Later in the presentation we'll discuss window functions for the analyzer!

THE X SCALE – 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**

THE X SCALE – 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 ?

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.

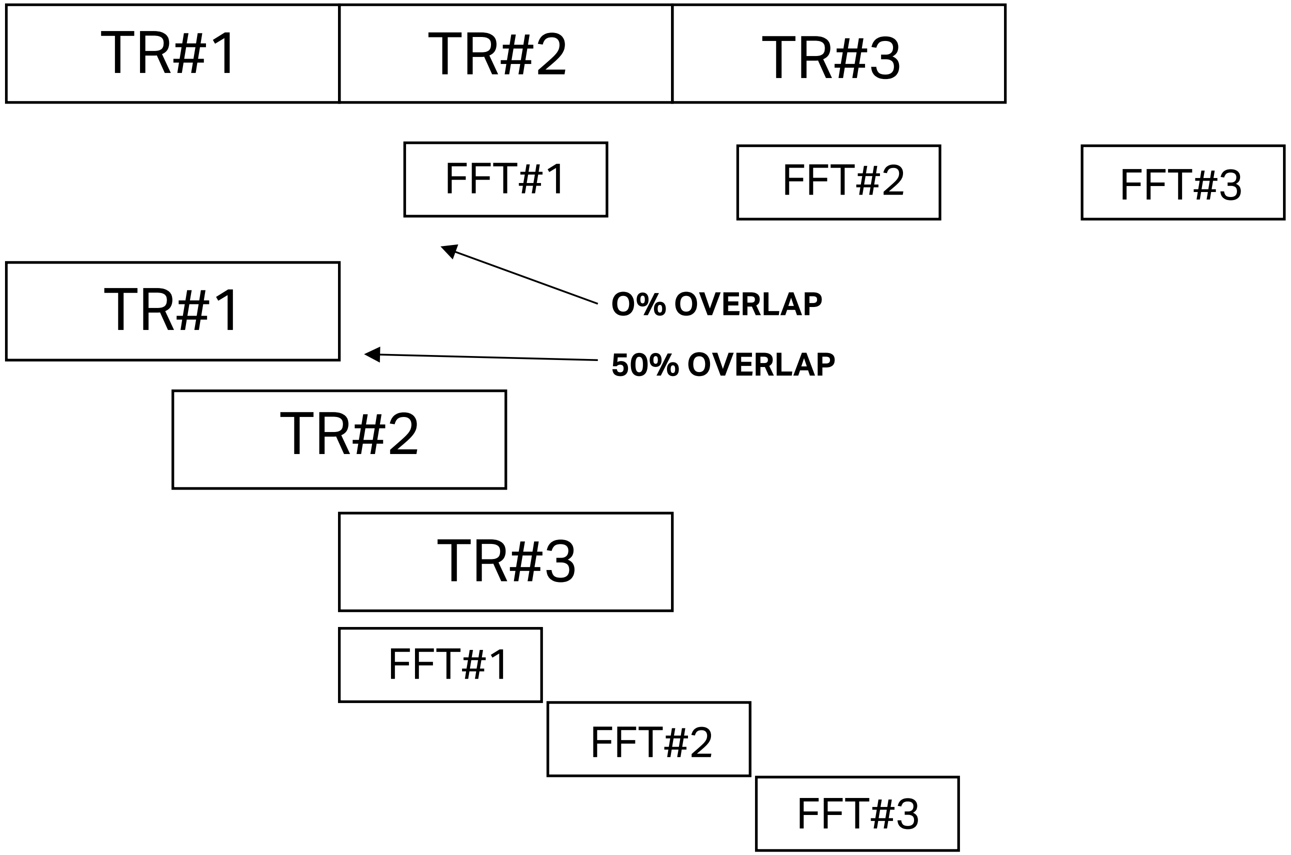
$$T_{Sample} = N_{lines} / F_{span}$$

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

400 / 800 = 0.5 seconds

THE X SCALE – AVERAGE AND 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?

THE X SCALE – 75% OVERLAP?

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

Average #1 = 800 / 200

Average #1 = 4 seconds

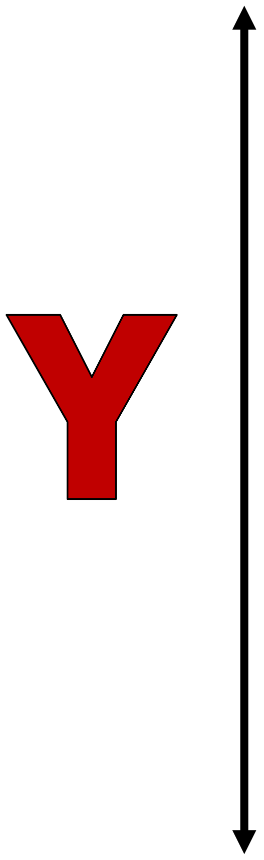
Average #2 - #10 = (4 x 0.25)

Average #2 - #10 = 1 second each

Total time = 4 + (1 x 9)

Total time = 13 seconds

THE Y SCALE



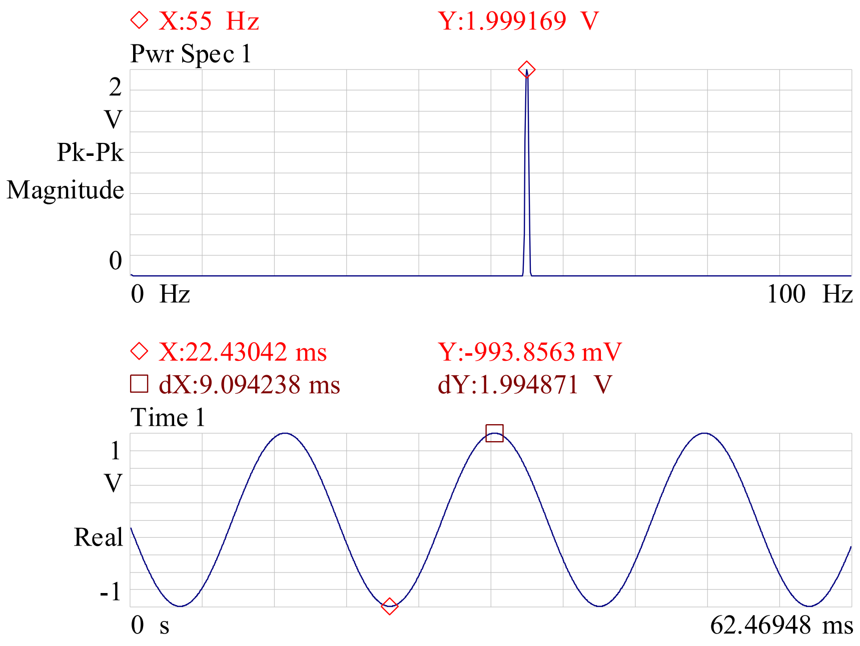
THE Y SCALE – AMPLITUDE

- 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 three suffixes meant to confuse you!
- The other two are **(Peak)** and **(Peak - Peak)**

THE Y SCALE – PK-PK (PEAK – PEAK)

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

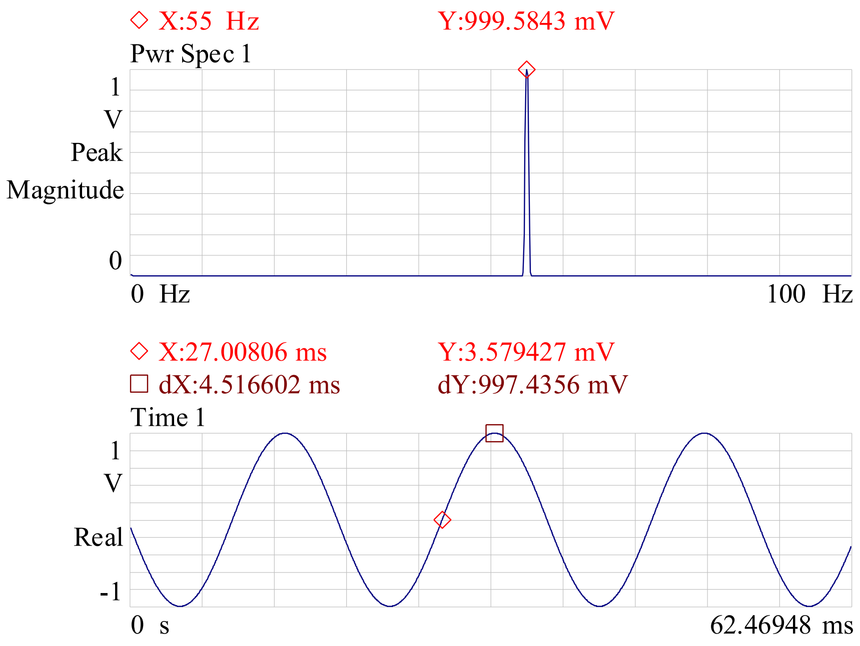
The **spectrum value uses the suffix “Pk-Pk”** to denote this.



THE Y SCALE – PK (PEAK)

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

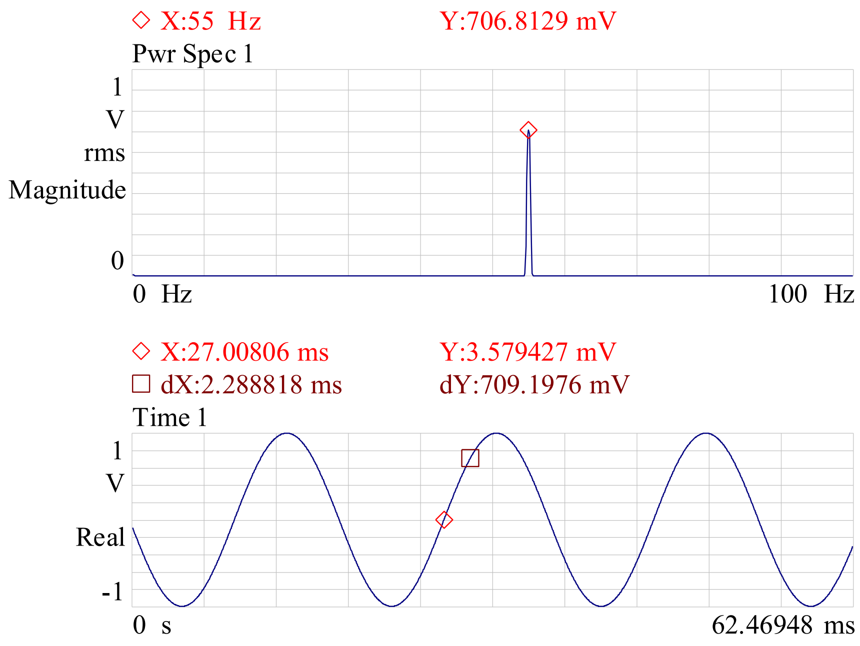
The **spectrum value uses the suffix "Peak"** to denote this.



THE Y SCALE – RMS (ROOT MEAN SQUARE)

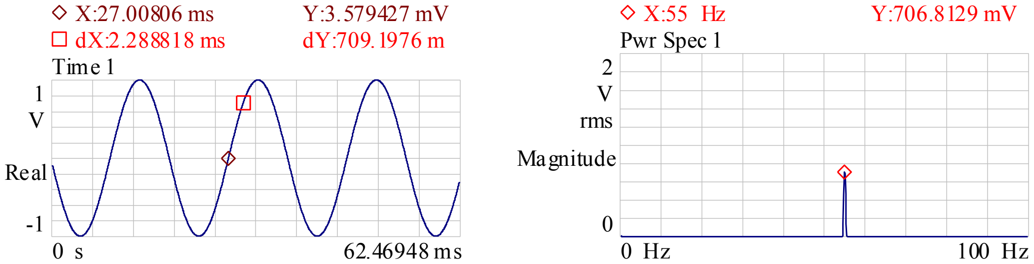
The time wave has not changed. The **RMS value** is expressed from zero to 70.7% of the peak amplitude.

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

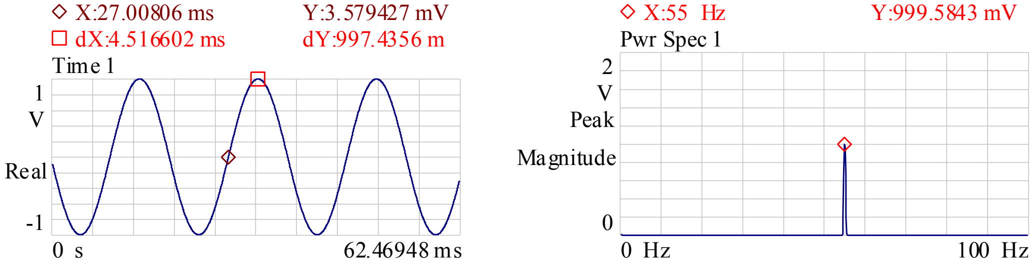


THE Y SCALE – SUFFIX COMPARISON

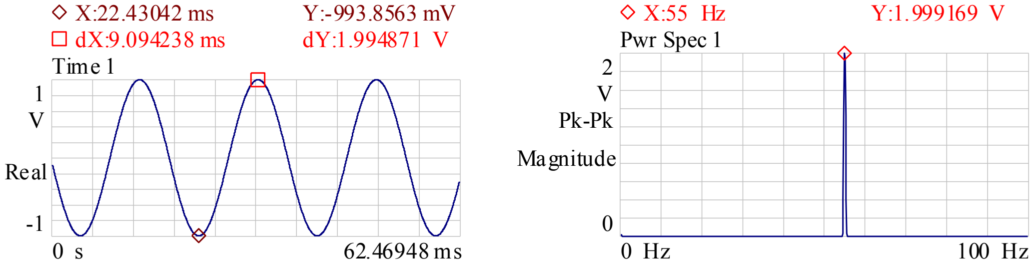
RMS



PEAK (PK)



PEAK - PEAK (PK - PK)



THE Y SCALE – 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**

THE Y SCALE – 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

THE Y SCALE – 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**

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 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 Y SCALE – THE BIG THREE EUs

- Acceleration
- Velocity
- Displacement

THE Y SCALE – CONVERTING THE BIG THREE

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?

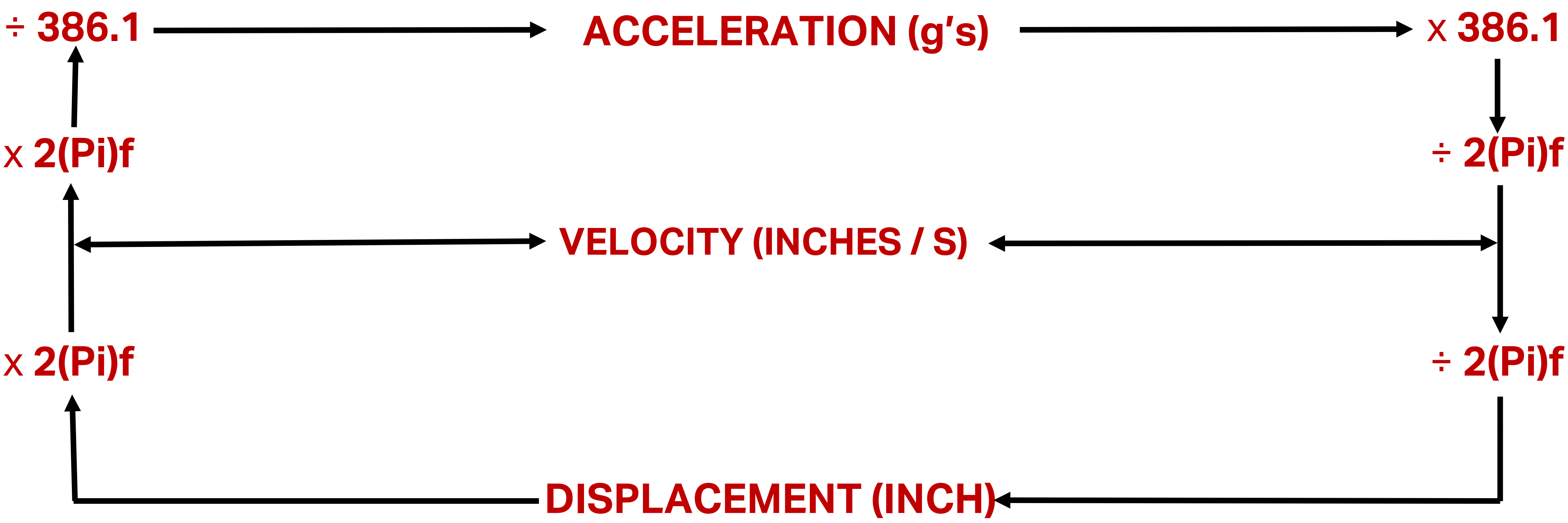
THE Y SCALE – 386.1 WHAT?

1g = 32.2 feet / second^2

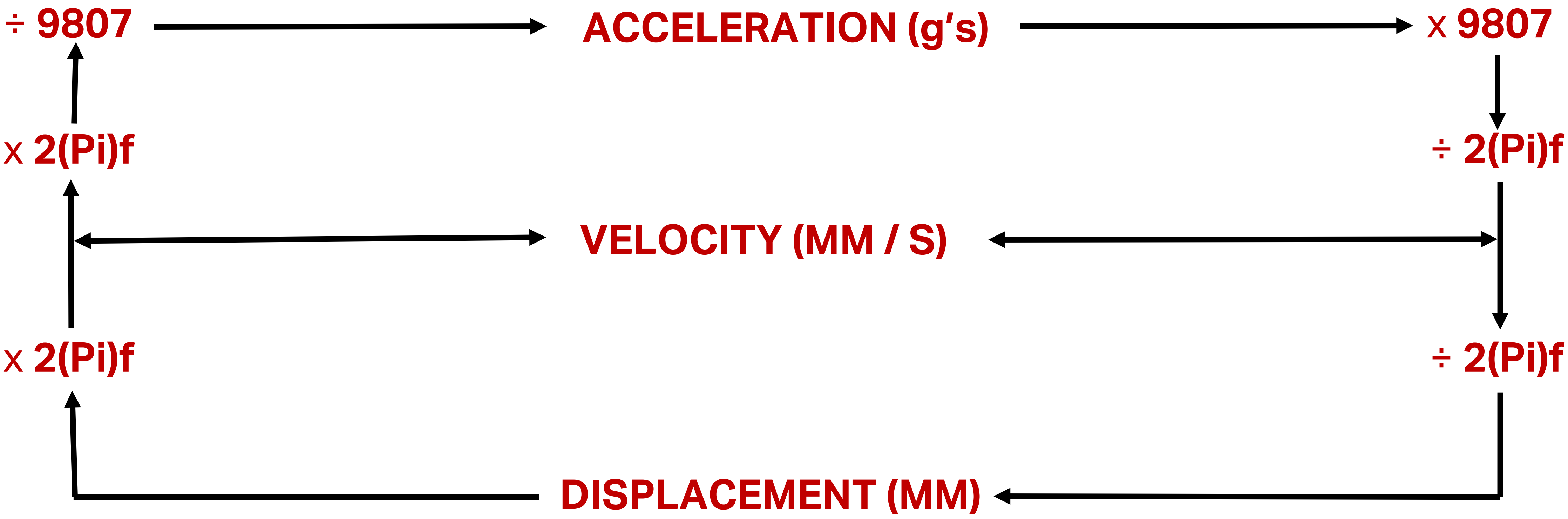
$$\frac{32.2 \text{ feet}}{\text{second}^2} \times \frac{12 \text{ inches}}{\text{foot}}$$

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

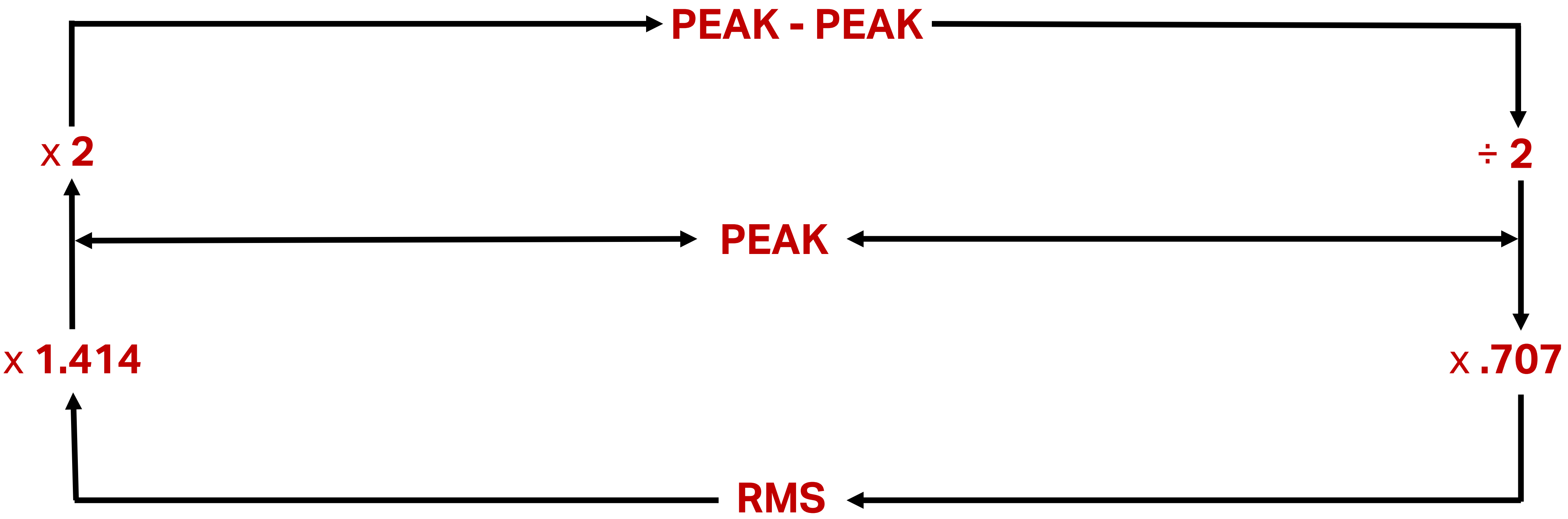
THE Y SCALE – GO WITH THE FLOW I



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?

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

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

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

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

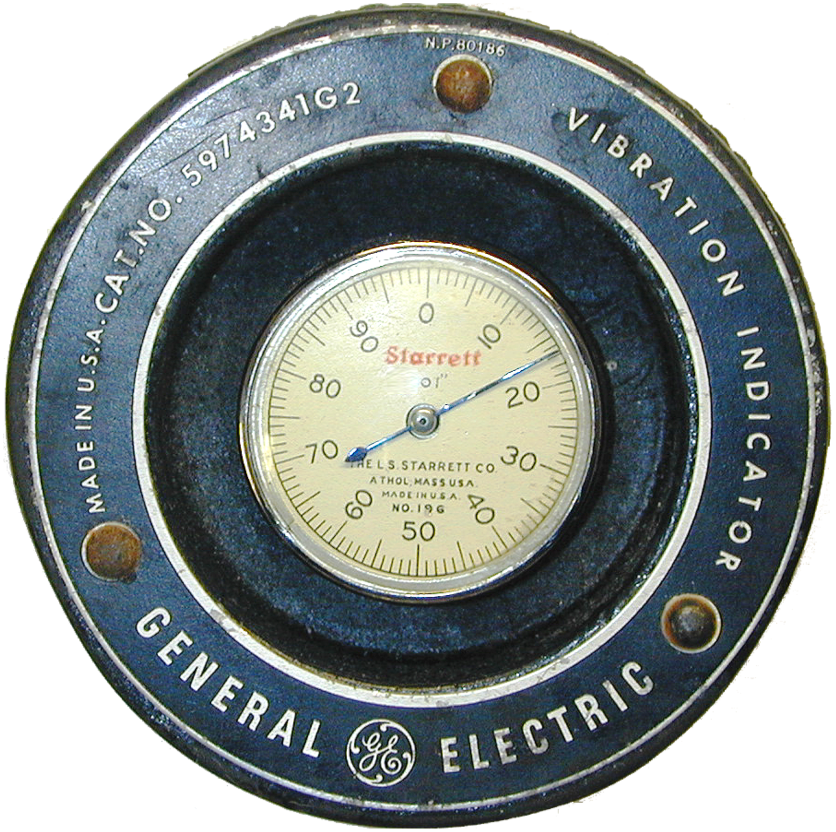
= (g x 386.1) / (2 Pi x F)2

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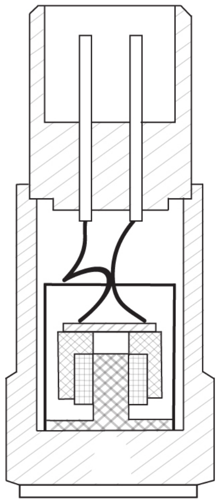
MADE IN U.S.A. CAT. NO. 5974341G2
VIBRATION INDICATOR
GENERAL ELECTRIC
Starrett
.01"
THE L.S. STARRETT CO.
ATHOL, MASS. U.S.A.
MADE IN U.S.A.
NO. 196

SENSORS – ACCELEROMETERS

Integrated Circuit

- ❑ Electronics inside
- ❑ Industrial



Charge Mode

- ❑ Charge amplifier
- ❑ Test and measurement

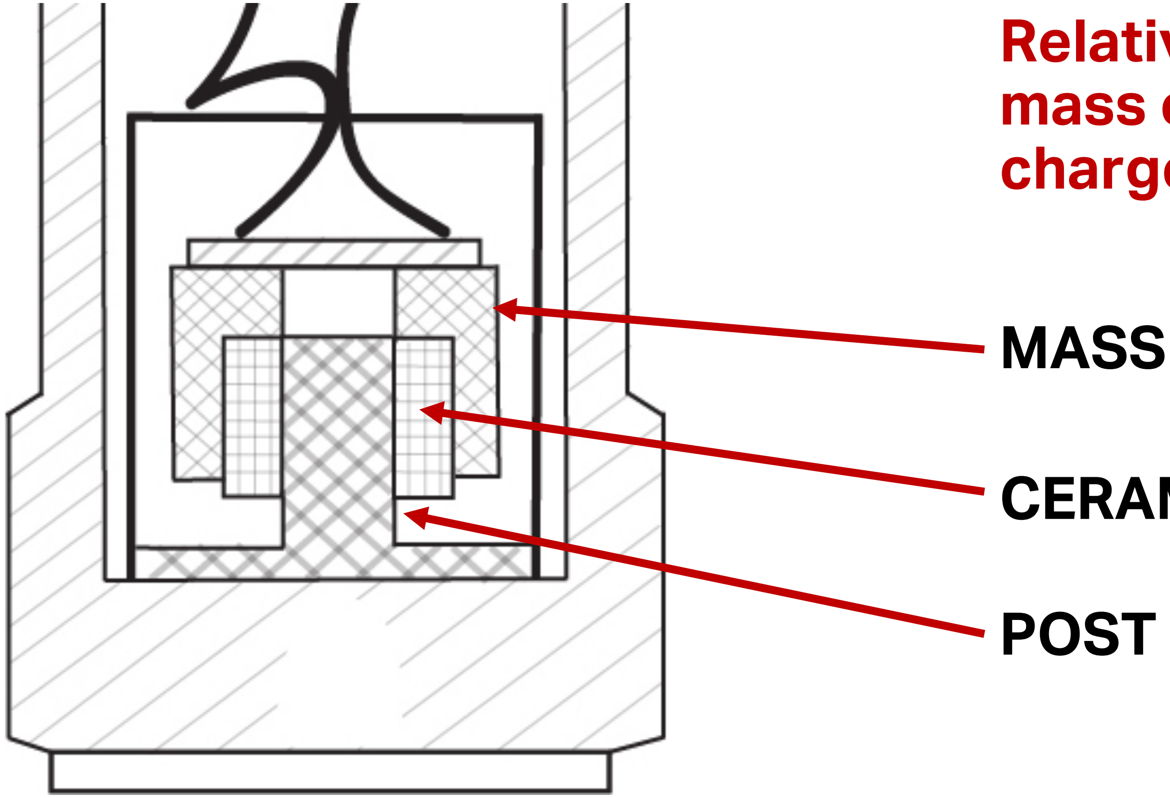
SENSORS – ACCELEROMETER ADVANTAGES

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

SENSORS – 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

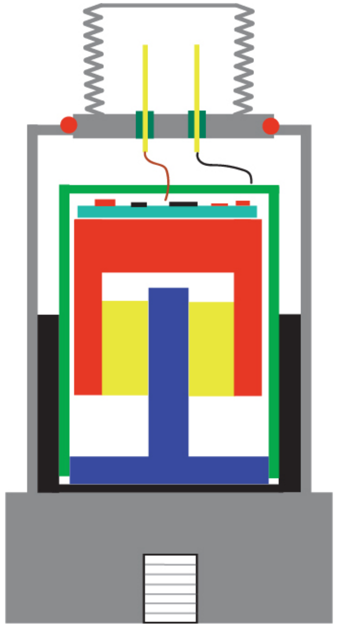
SENSORS – MASS AND CHARGE



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

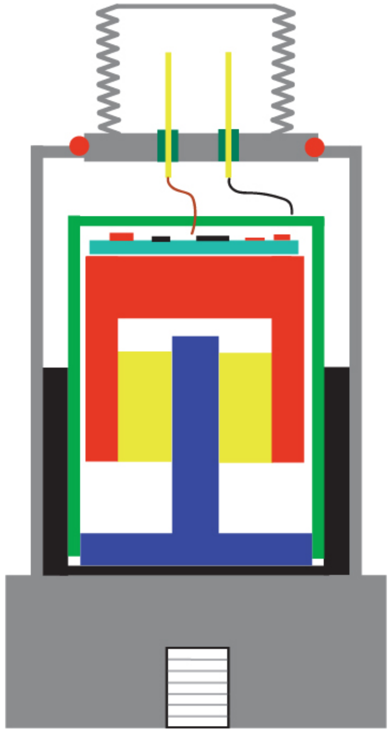
SENSORS – ACCELEROMETER CONSTRUCTION

- Faraday shield
- Insulating material
- Stainless Steel 316L housing with ¼-28 threaded mounting
- 2, 3,or 4 pin military connector



- Hermetically sealed welded seam
- PC Board
- Mass
- PZT ceramic
- Pedestal (post)

SENSORS – ACCELEROMETER OPERATION



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

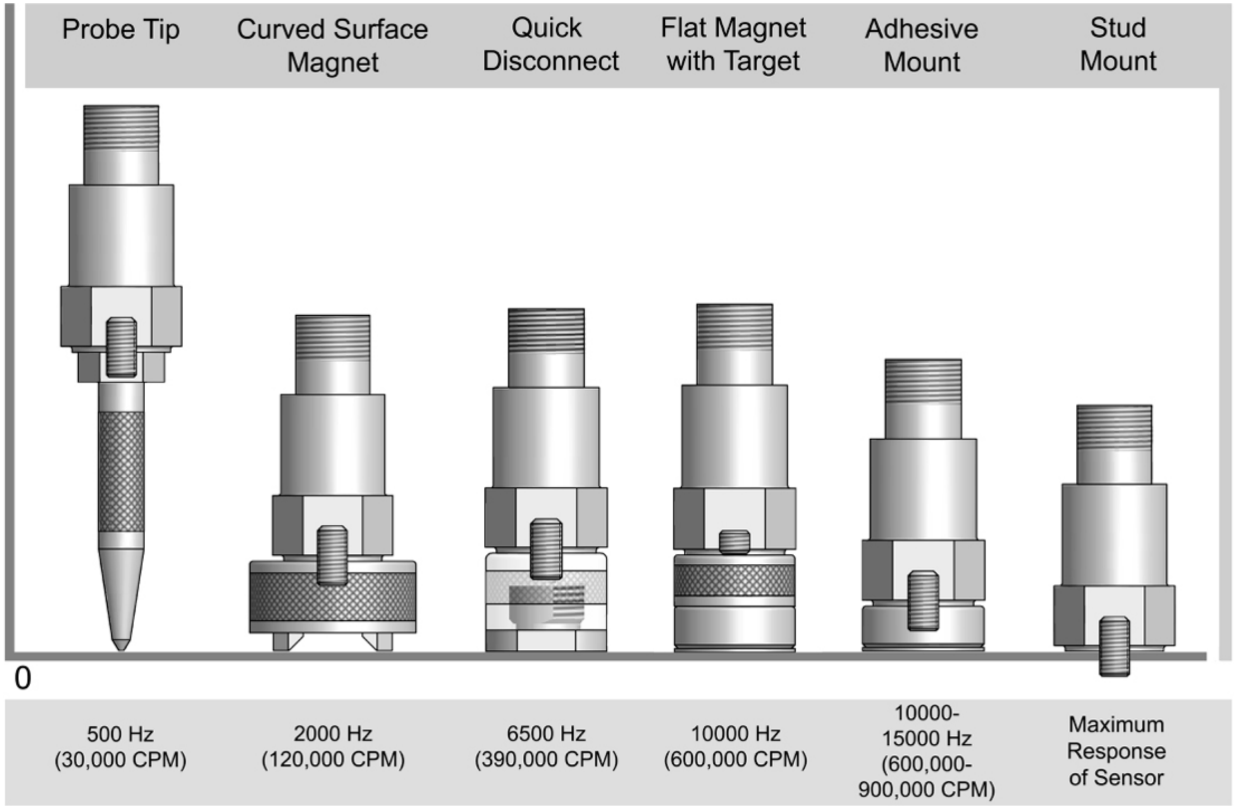
SENSORS – ACCELEROMETER PARAMETERS

Performance suited for application

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

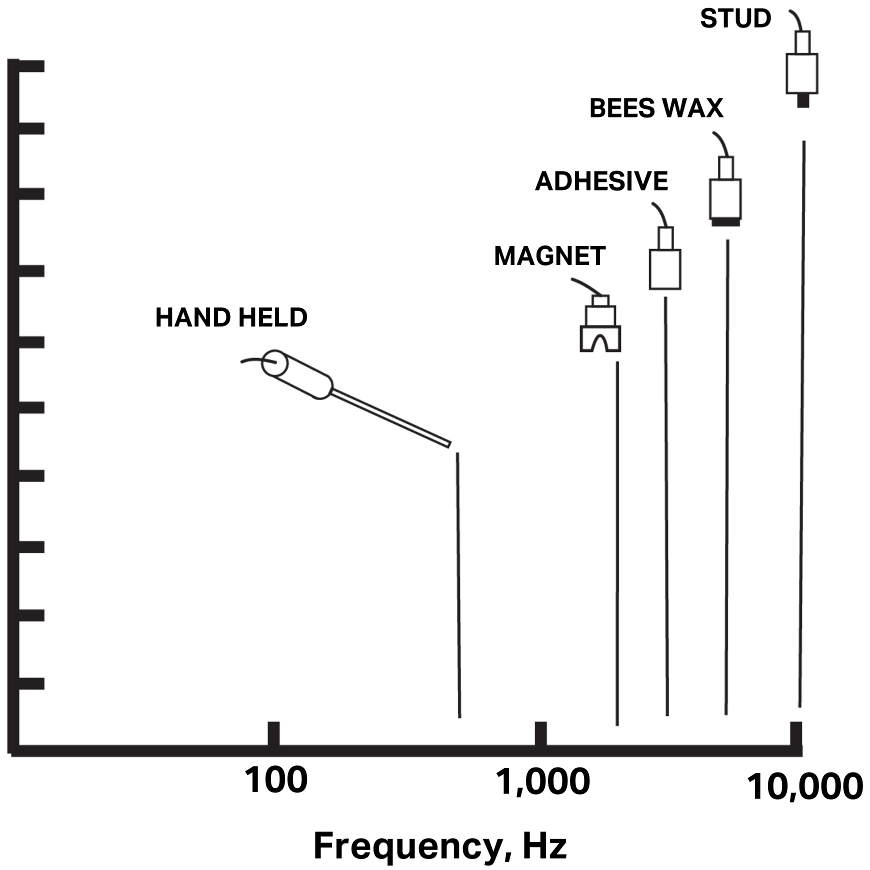
PART NUMBER: AC102-1B	
Performance Specifications	***English***
Sensitivity +/- 10%	100 mV/g
Frequency Response	
± 3 dB	30-900,000 CPM
± 10%	60-360,000 CPM
± 5%	102-240,000 CPM
Dynamic Range	± 50 g peak

SENSORS – MOUNTING THE ACCELEROMETER



Maximum Frequency Response
(within ±3dB)
**depending on specified high frequency response of individual sensors*

SENSORS – REALISTIC MOUNTING

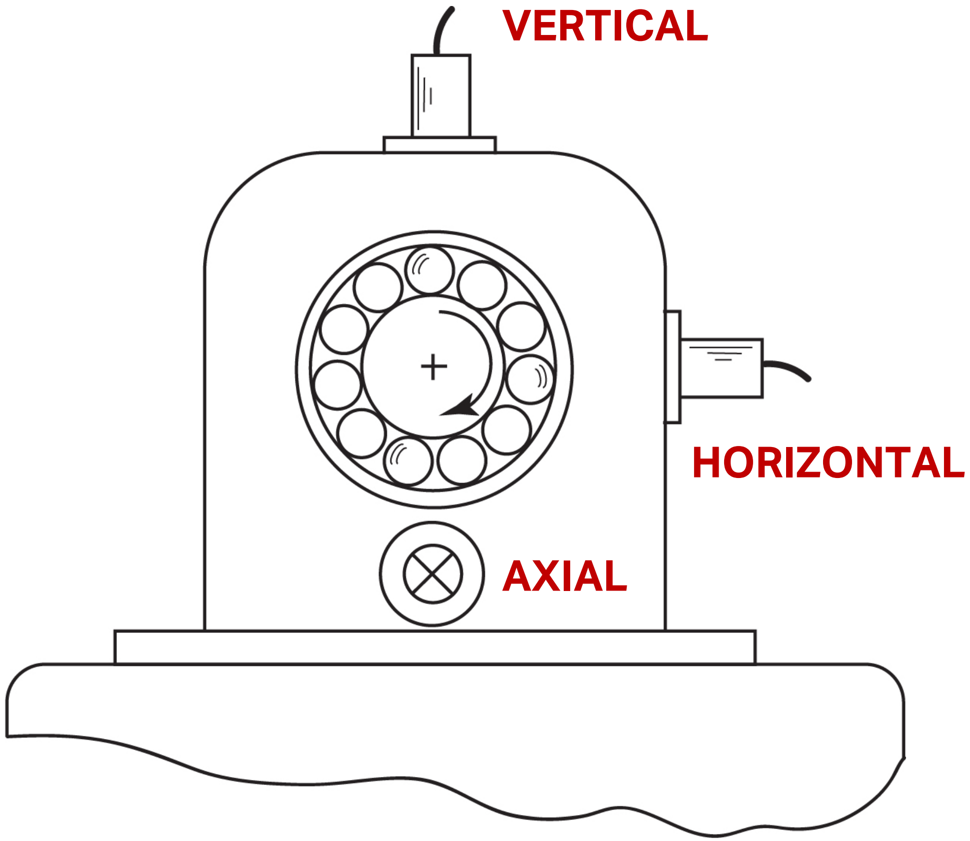


In the real world, mounting might not be as good as the manufacturer had in the lab!

What happened to the high frequency?

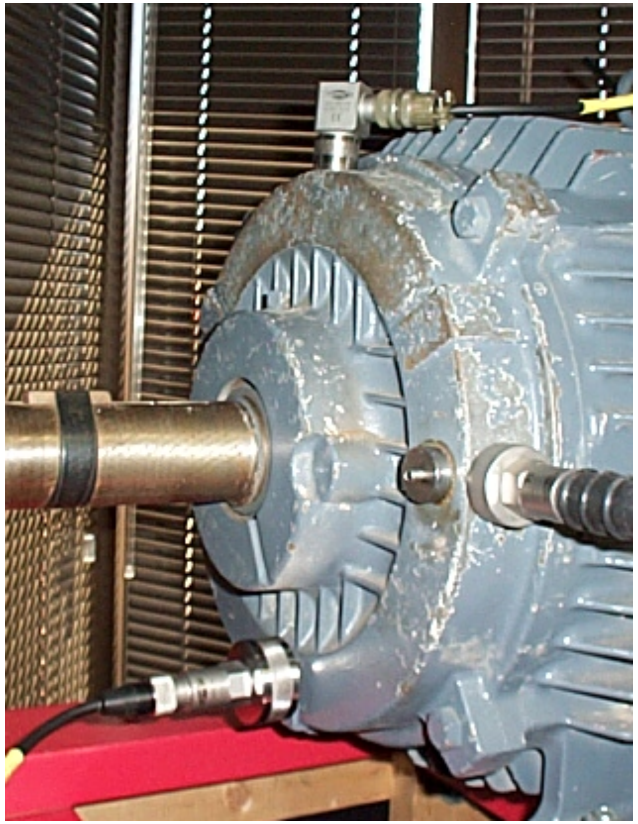
SENSORS – MOUNTING LOCATION

- ❑ Load zone
- ❑ Radial
  - ❑ Vertical
  - ❑ Horizontal
- ❑ Axial



SENSORS – MOUNTING LOCATION

- ❑ Load zone
- ❑ Radial
  - ❑ Vertical
  - ❑ Horizontal
- ❑ Axial



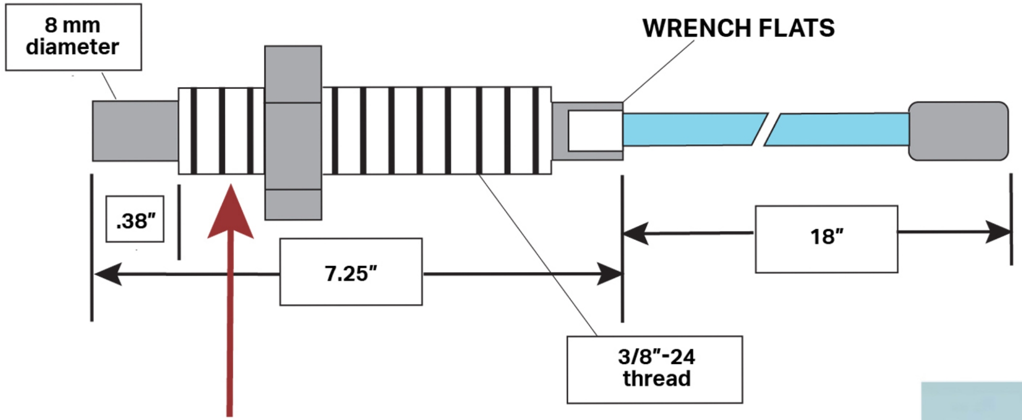
SENSORS – ACCELEROMETER ALARMS

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

SENSORS – PROXIMITY PROBES



DS1811-38-038-725-1

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

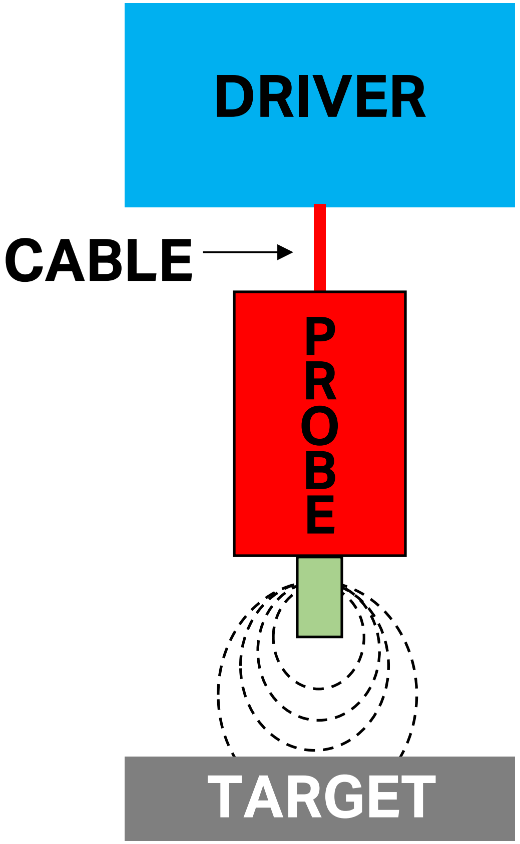
DS1590

Proximity Probe Driver

DSCB1000-450-C200

Extension Cable assembly with SMA Connector and spade lugs, 4.5 m long (14.5 ft)

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 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.

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

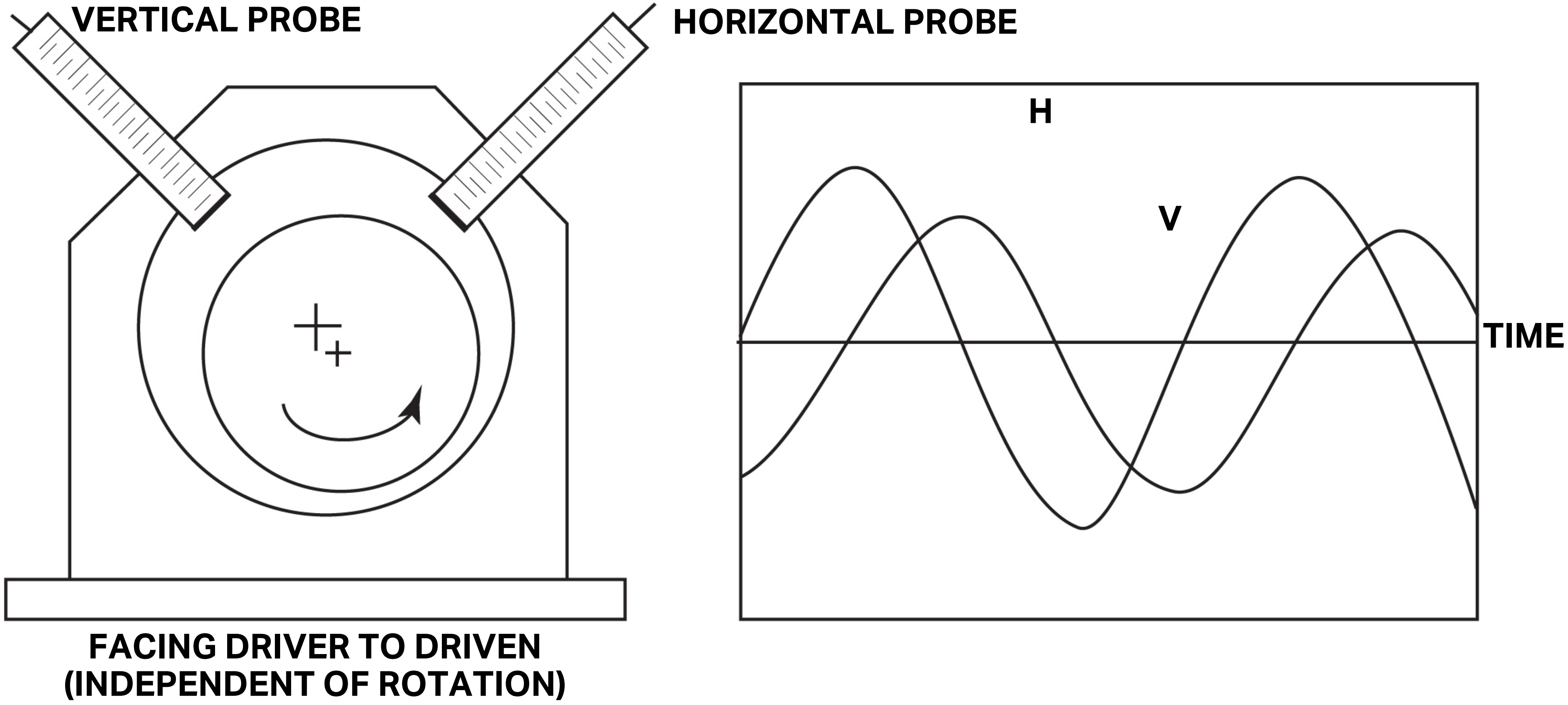
SENSORS – PROXIMITY PROBE ADVANTAGES

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

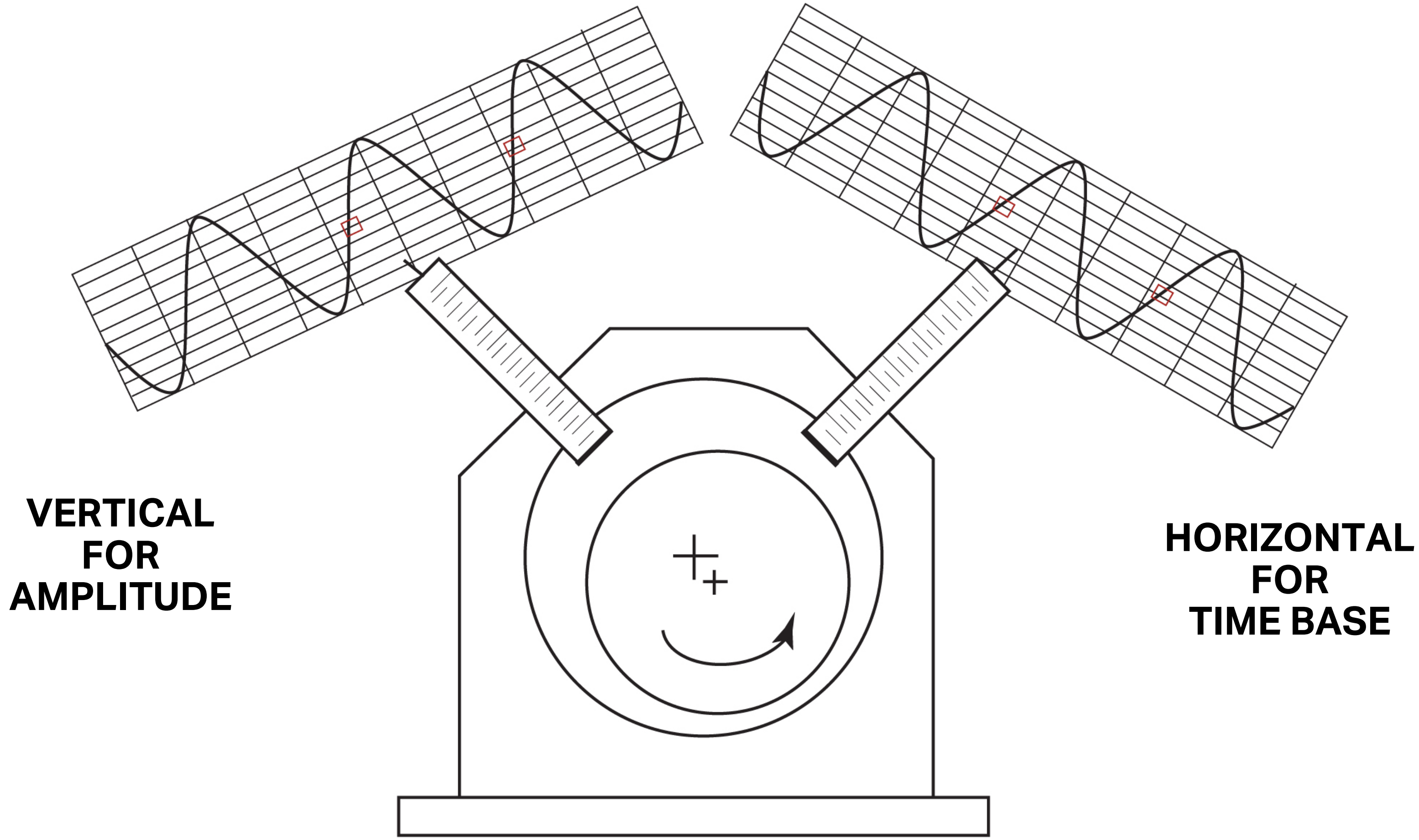
SENSORS – PROXIMITY PROBE DISVANTAGES

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

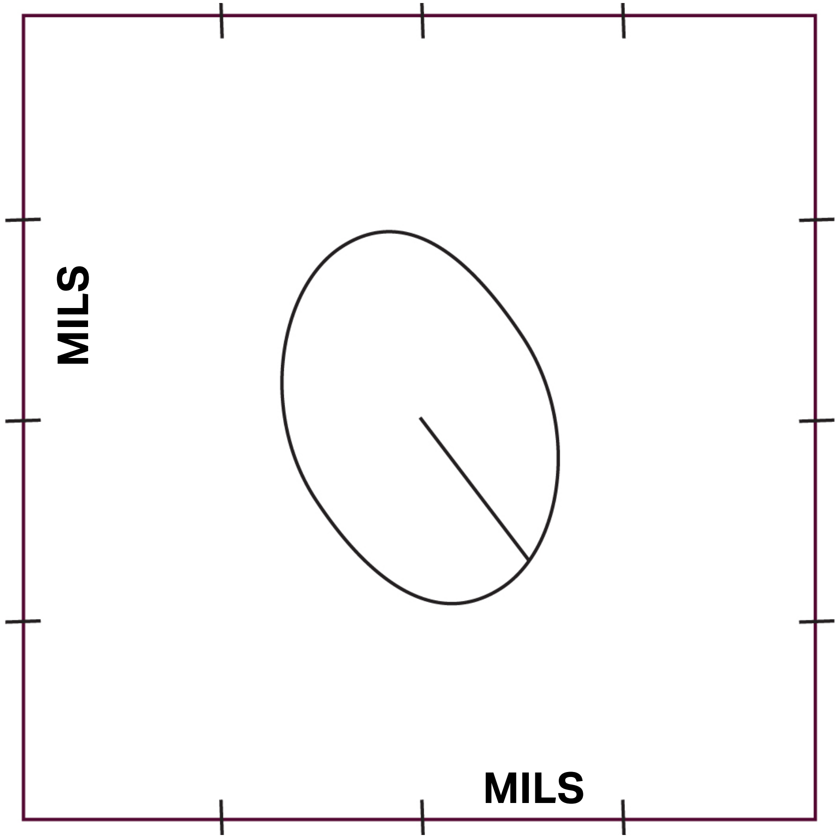
SENSORS – TYPICAL MOUNTING

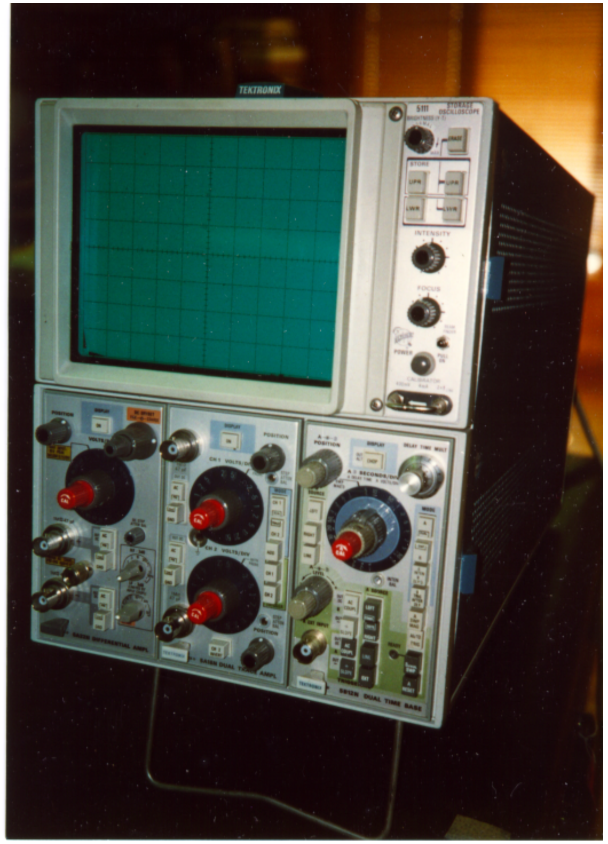


SENSORS – LOOKING AT ORBITS

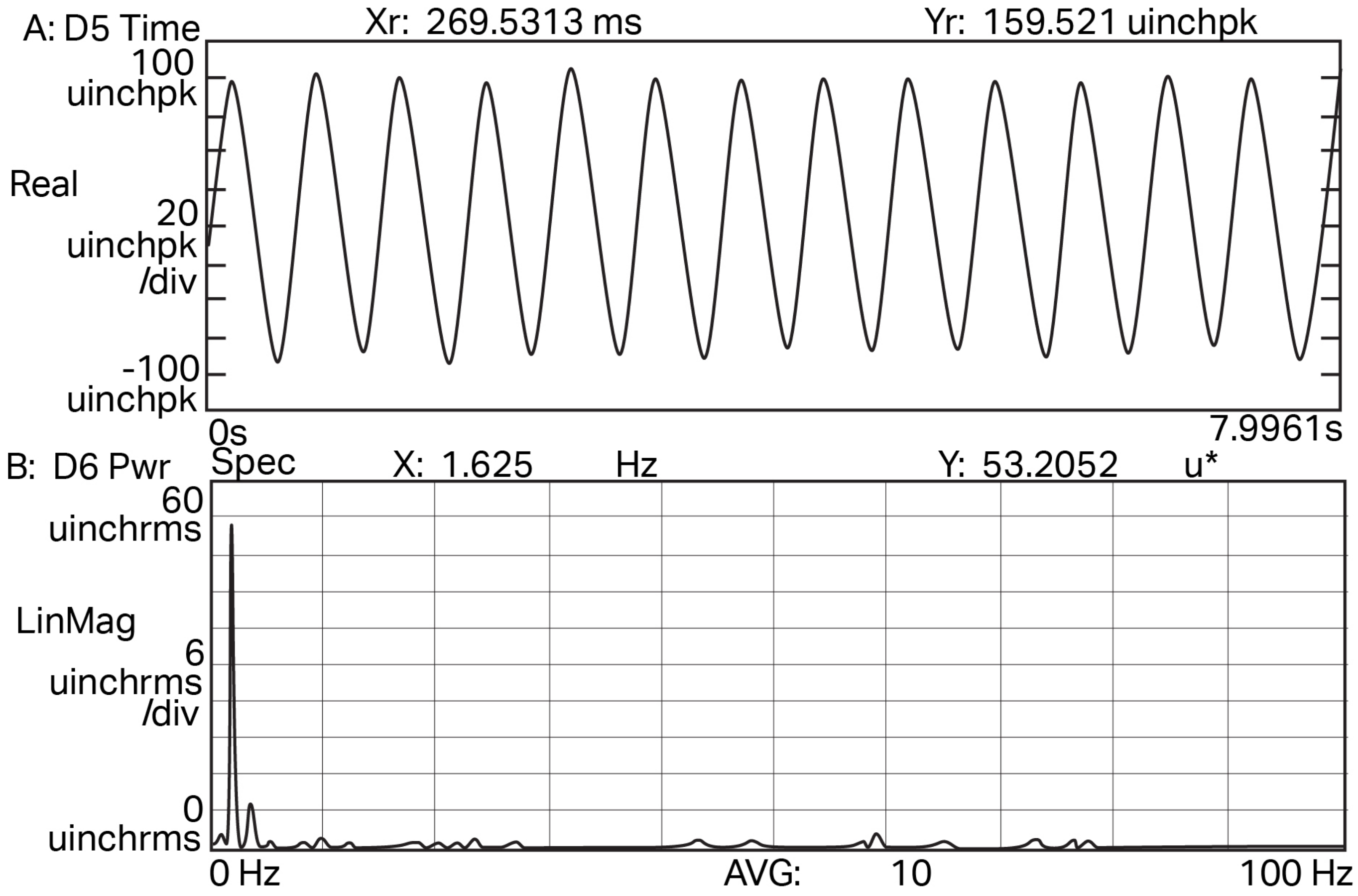


SENSORS – THE ORBIT DISPLAY

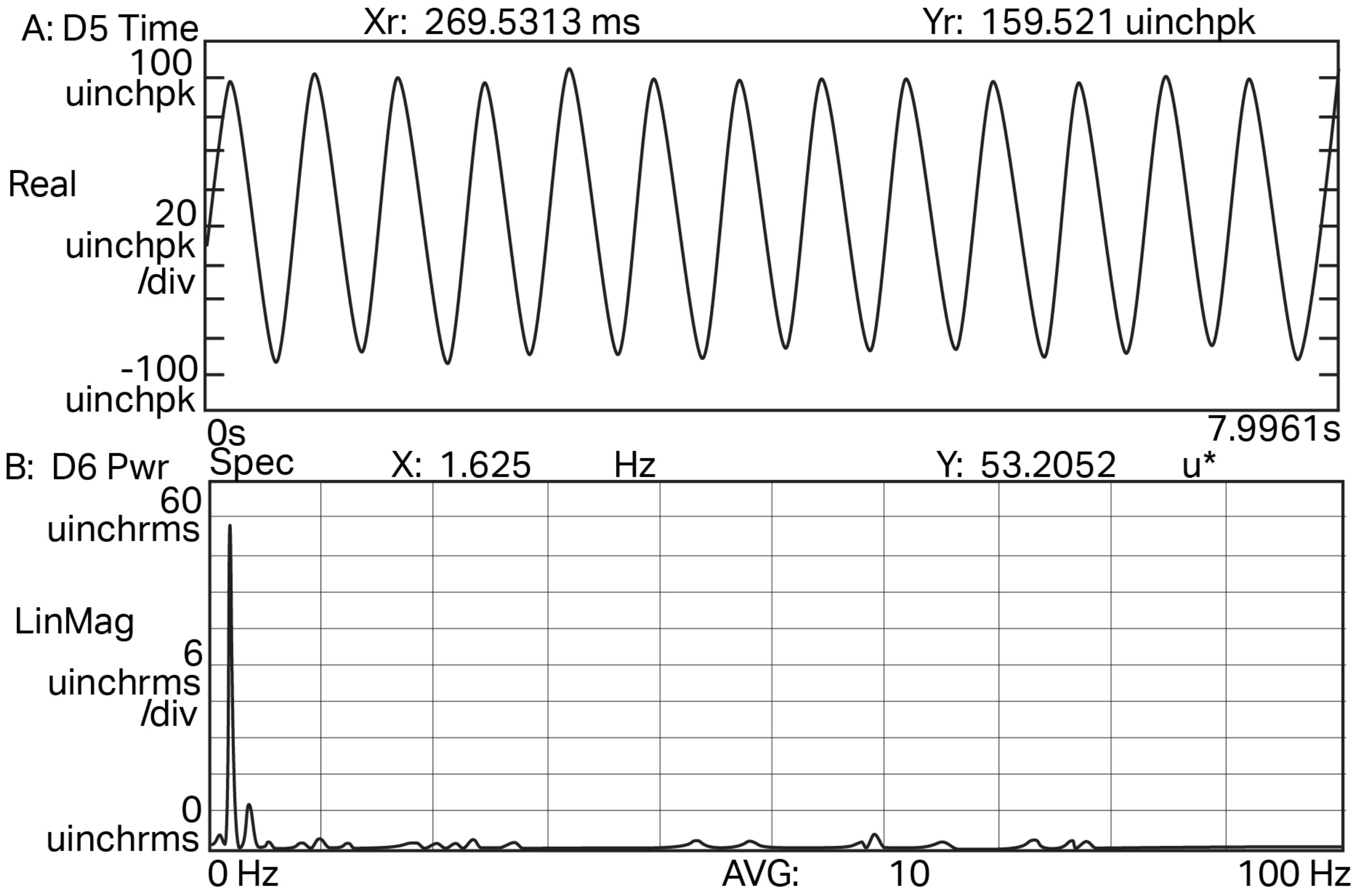


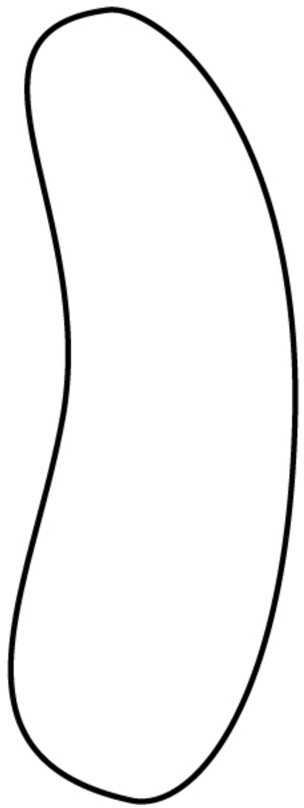


SENSORS – UNBALANCE

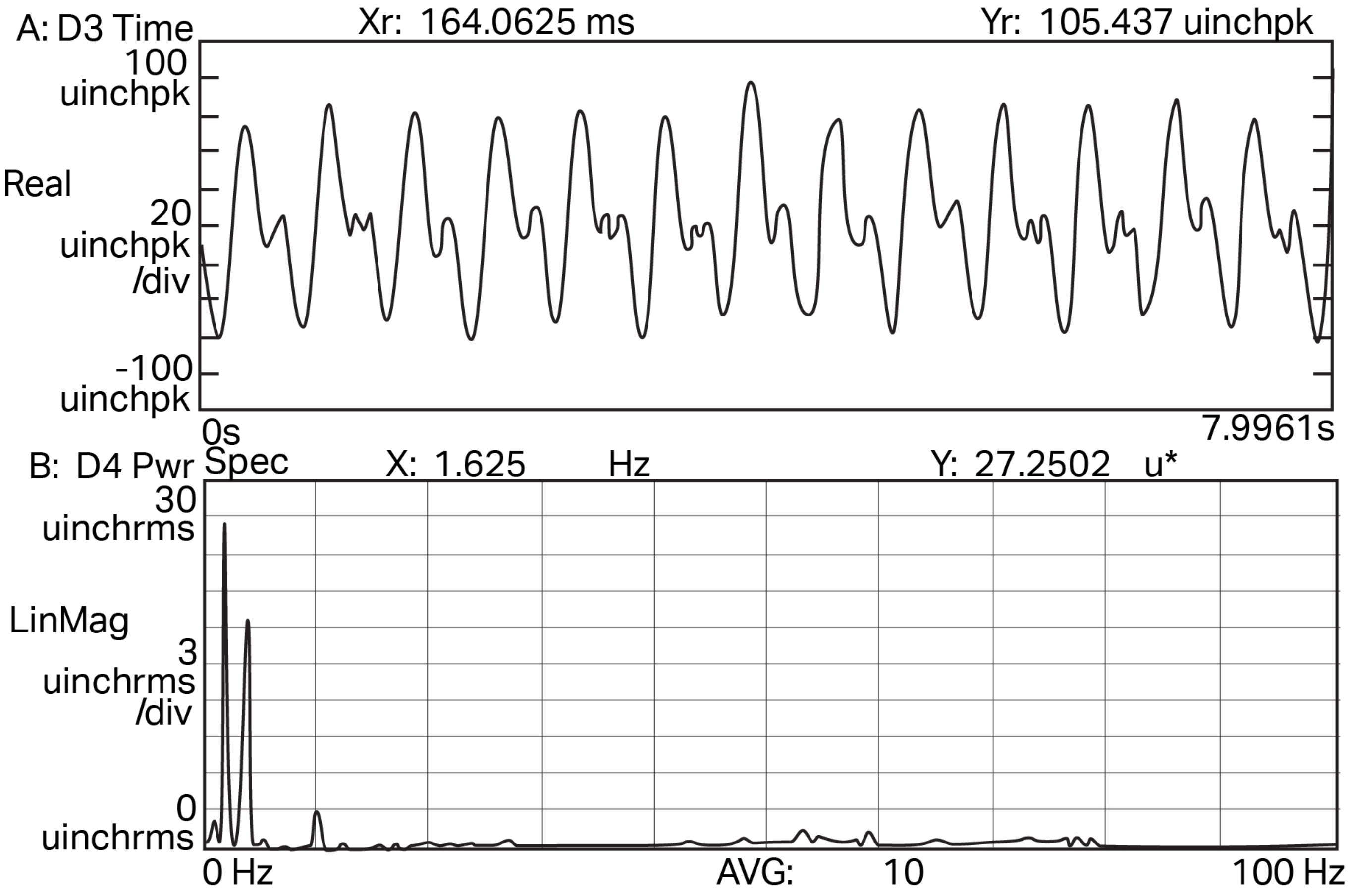


SENSORS – UNBALANCE WITH ORBIT

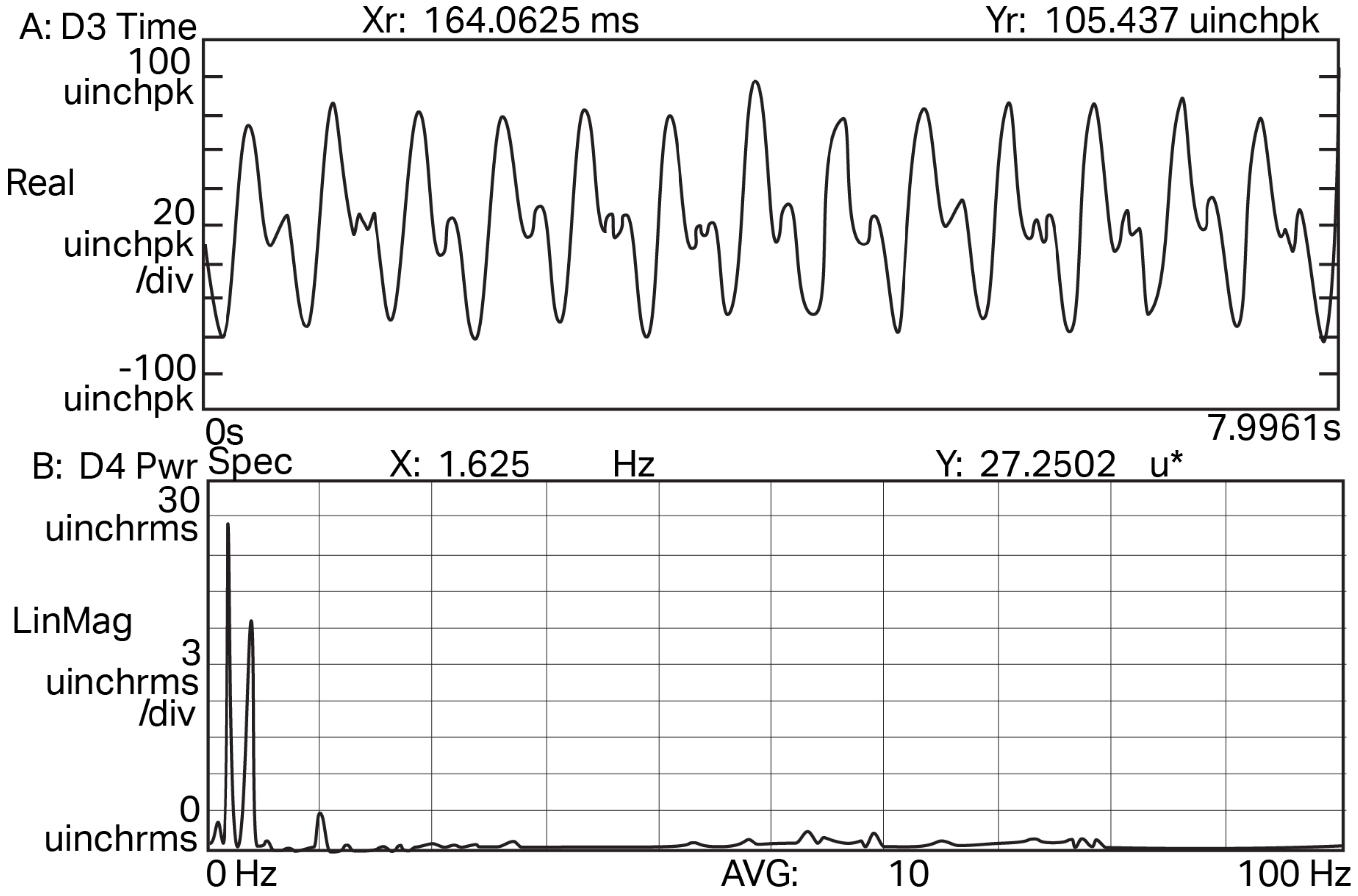


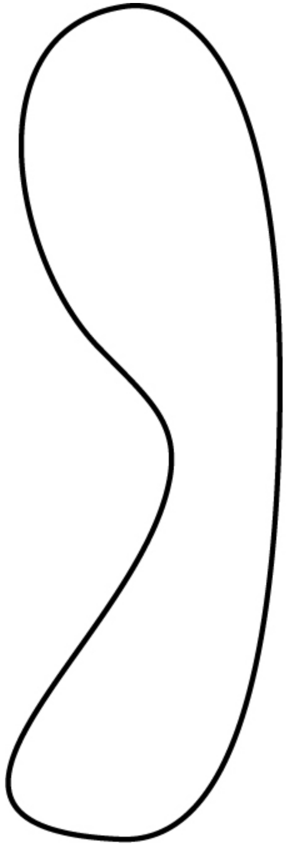


SENSORS – MISALIGNMENT

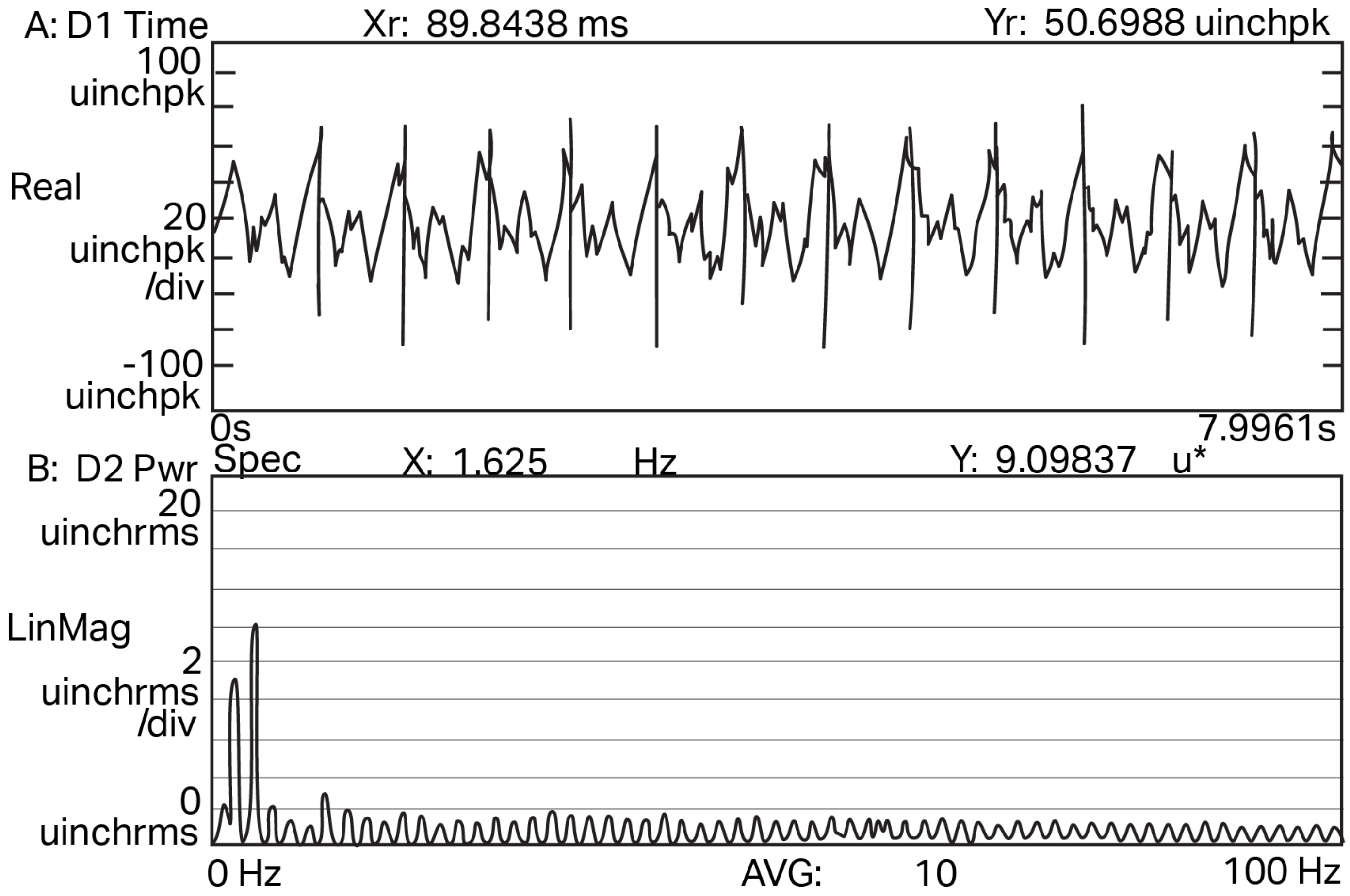


SENSORS – MISALIGNMENT WITH ORBIT





SENSORS – AND THE PROBLEM IS?



SENSORS – PROXIMITY PROBE ALARMS

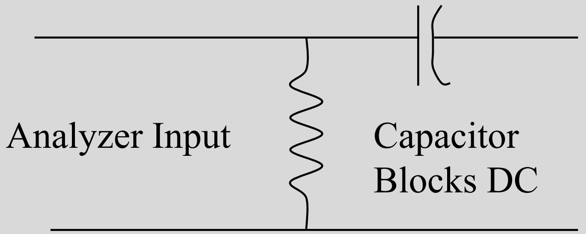
MACHINE CONDITION	ALLOWABLE R / C	
	< 3,600 RPM	< 10,000 RPM
NORMAL	0.3	0.2
SURVEILLANCE	0.3 - 0.5	0.2 - 0.4
PLANNED SHUTDOWN	0.5	0.4
UNSUITABLE FOR OPERATION	0.7	0.6

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 1Hz. 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 x 1.28 = 128 Hz

175 Hz - 128 Hz = 47 Hz.

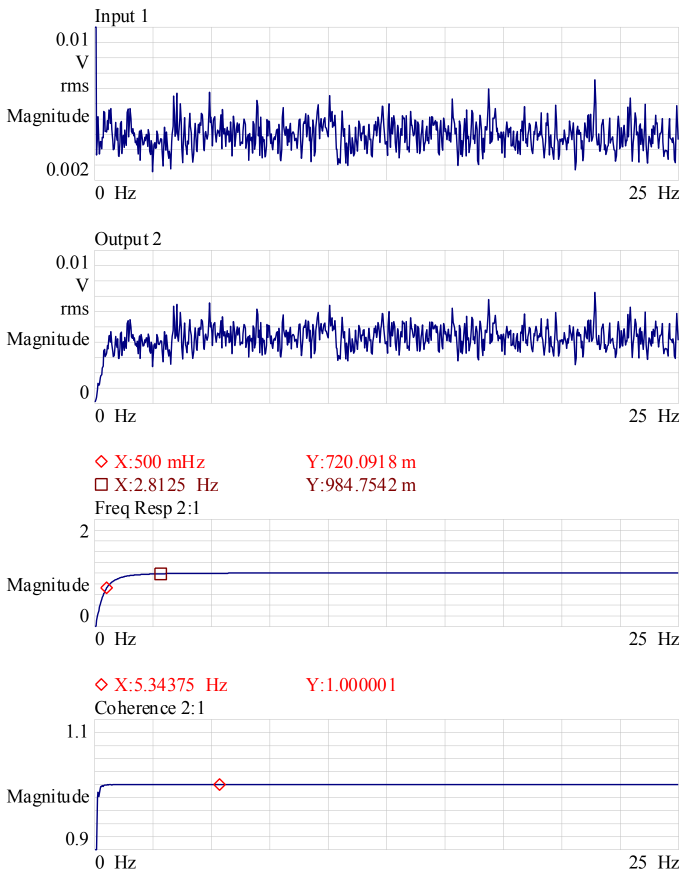
128 Hz - 47 Hz = 81 Hz

SENSORS – 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

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

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