Instrumentation for Condition Monitoring

Measurement of Displacement, Acceleration and Vibration

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Vibration - 1

Introduction and definition of Measurands

Measurement of Displacement, Acceleration and Vibration

- Measurement of:
  - Displacement
  - Acceleration
  - Vibration
- Practical Devices
  - LVDT sensor
  - Eddy current proximity probe
  - Piezoelectric Accelerometer

Measurement of Vibration

- To determine the vibration of a machine component we can measure:
  - Displacement,
  - Velocity,
  - Acceleration.
- and integrate or differentiate accordingly.

- Vibrations are very commonly encountered in machinery operation, and therefore measurement of the accelerations associated with such vibrations is extremely important in industrial environments.

- The peak accelerations involved in such vibrations can be of 100 *g* or more in magnitude.

Vibrations normally consist of linear harmonic motion which can be expressed mathematically as:

$$x(t) = X_0 \sin(\omega t) \qquad (1)$$

where x(t) is the displacement from the equilibrium position at any general point in time, X_0 is the peak displacement from the equilibrium position, and ω is the angular frequency of the oscillations.

By differentiating Equation (1) with respect to time, an expression for the velocity v(t) of the vibrating body at any general point in time is obtained as:

$$v(t) = -\omega X_0 \cos(\omega t) \qquad (2)$$

- Differentiating Equation (2) again with respect to time, we obtain an expression for the acceleration, α, of the body at any general point in time as:

$$\alpha(t) = -\omega^2 X_0 \sin(\omega t) \qquad (3)$$

Inspection of Equation (3) shows that the peak acceleration is given by:

$$\alpha = \omega^2 X_0 \qquad (4)$$

This square law relationship between peak acceleration and oscillation frequency is the reason why high values of acceleration occur during relatively low-frequency oscillations.

Engineering Units

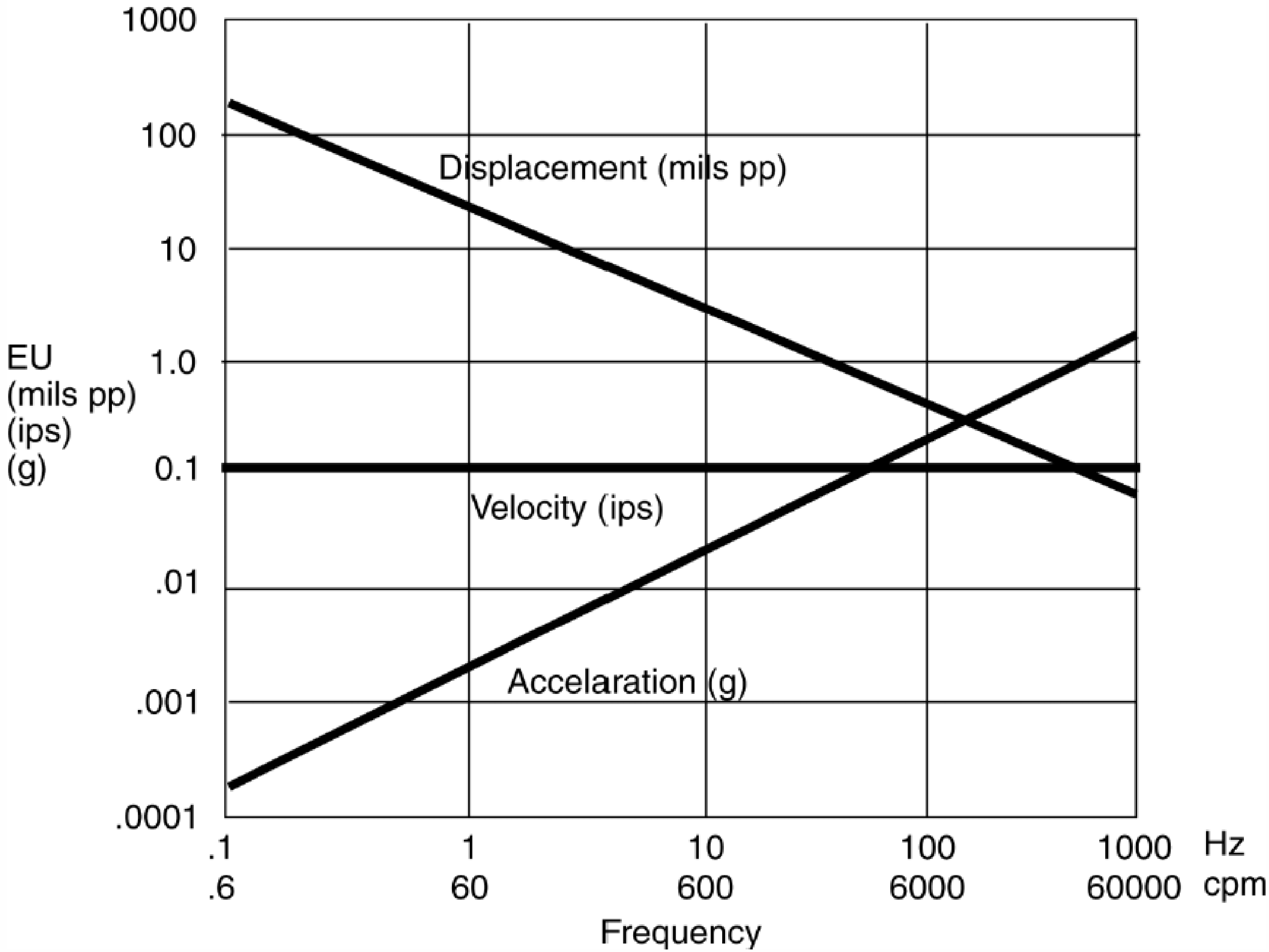
Measurements of vibration can be:

- Peak to peak (pp)
- Amplitude
- Root mean square (rms)

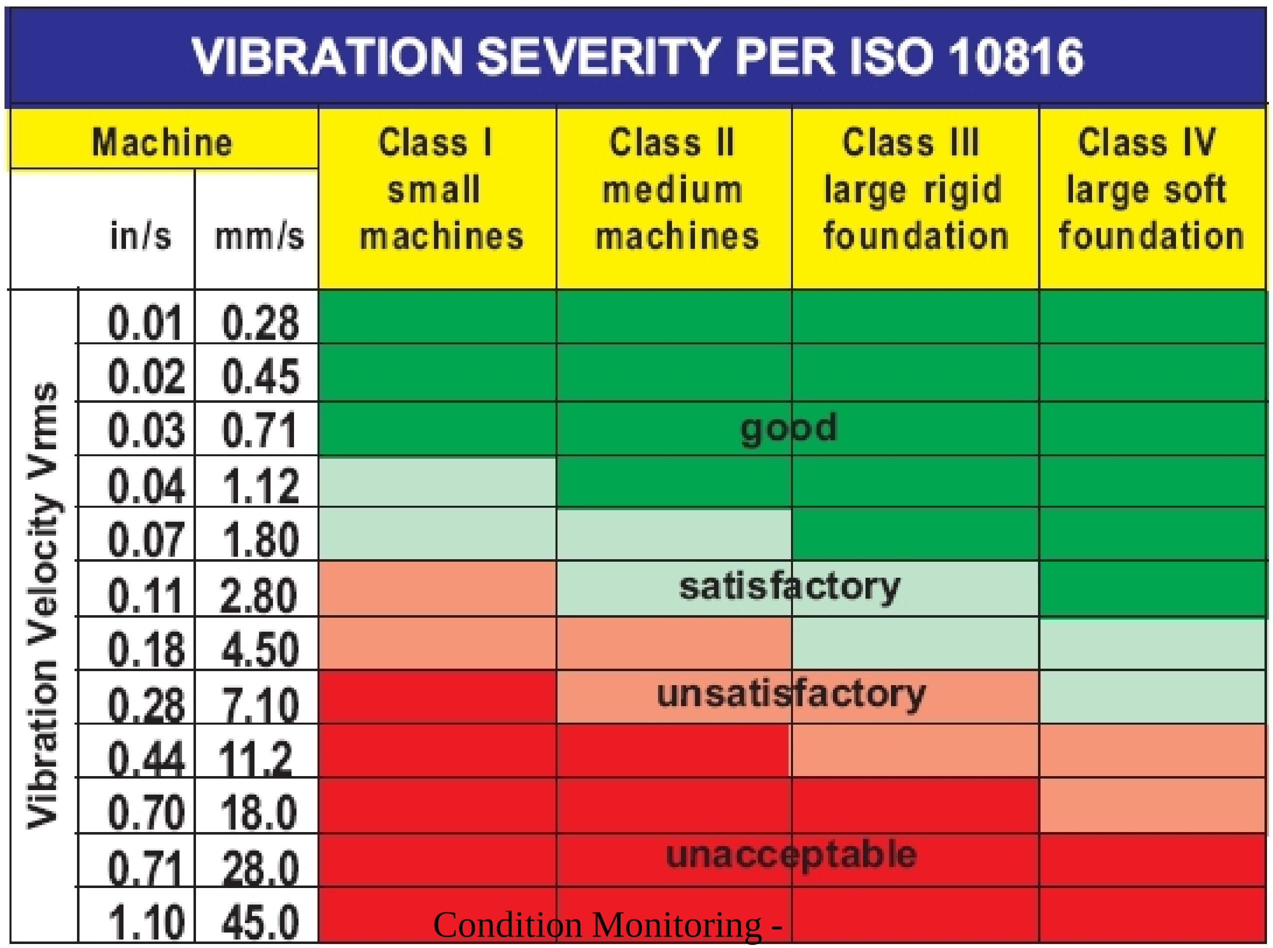
Units can be metric or American.

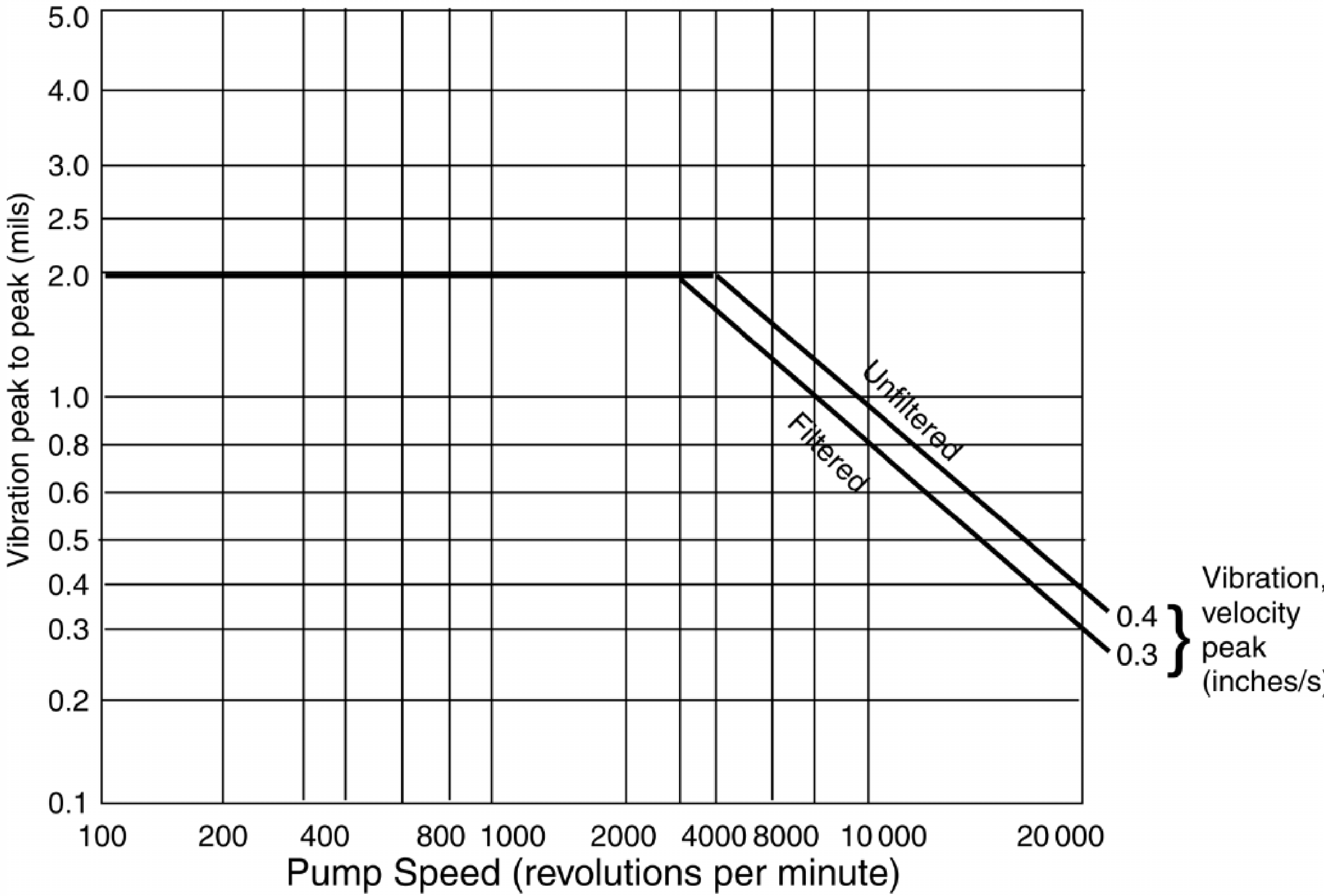
- mils = 1/1000 of an inch
- Inches/sec (ips)
- g (9.81 ms^{-2})
- Hz
- Cycles per minute (cpm)

Displacement, Velocity and Acceleration at constant Velocity



ISO 2372 (10816)

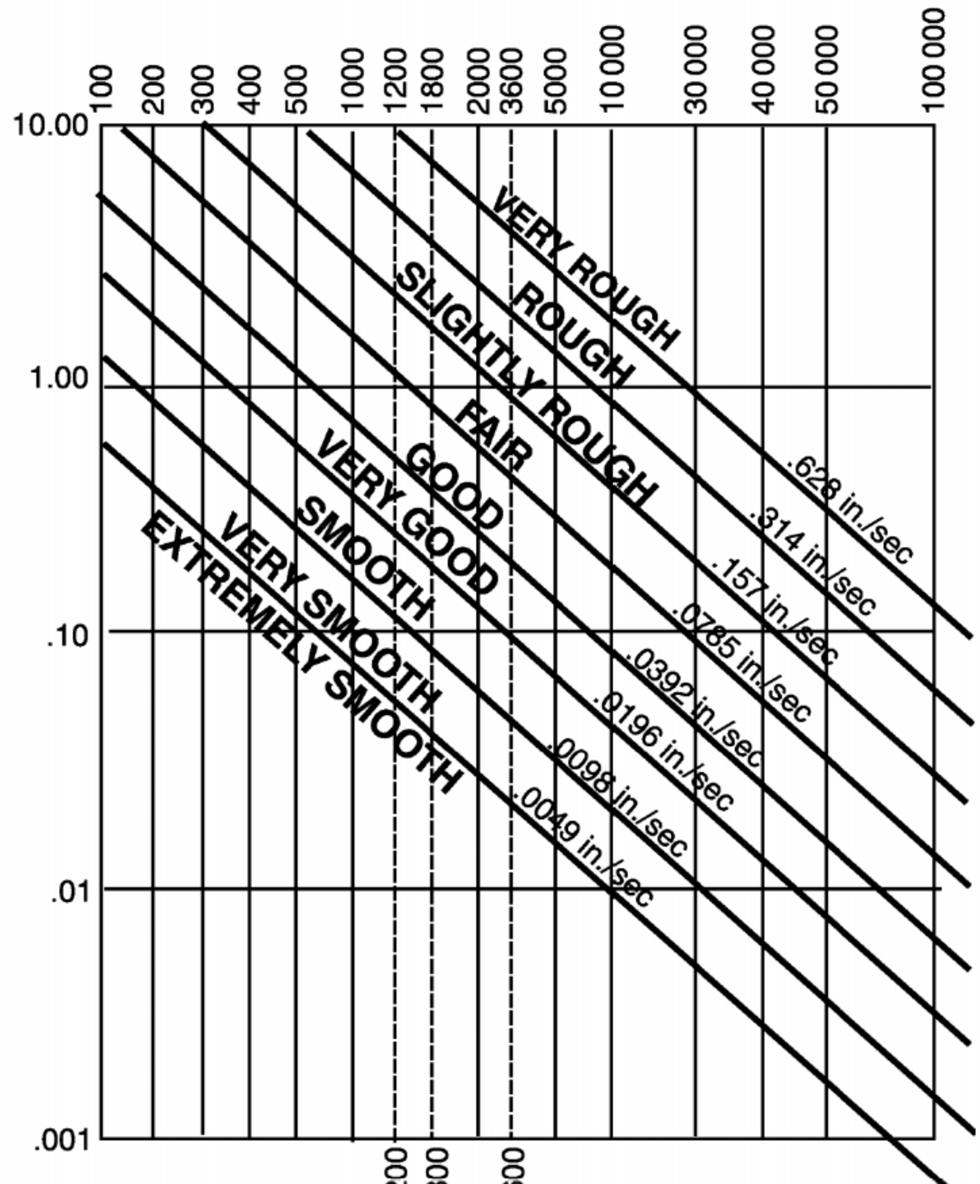




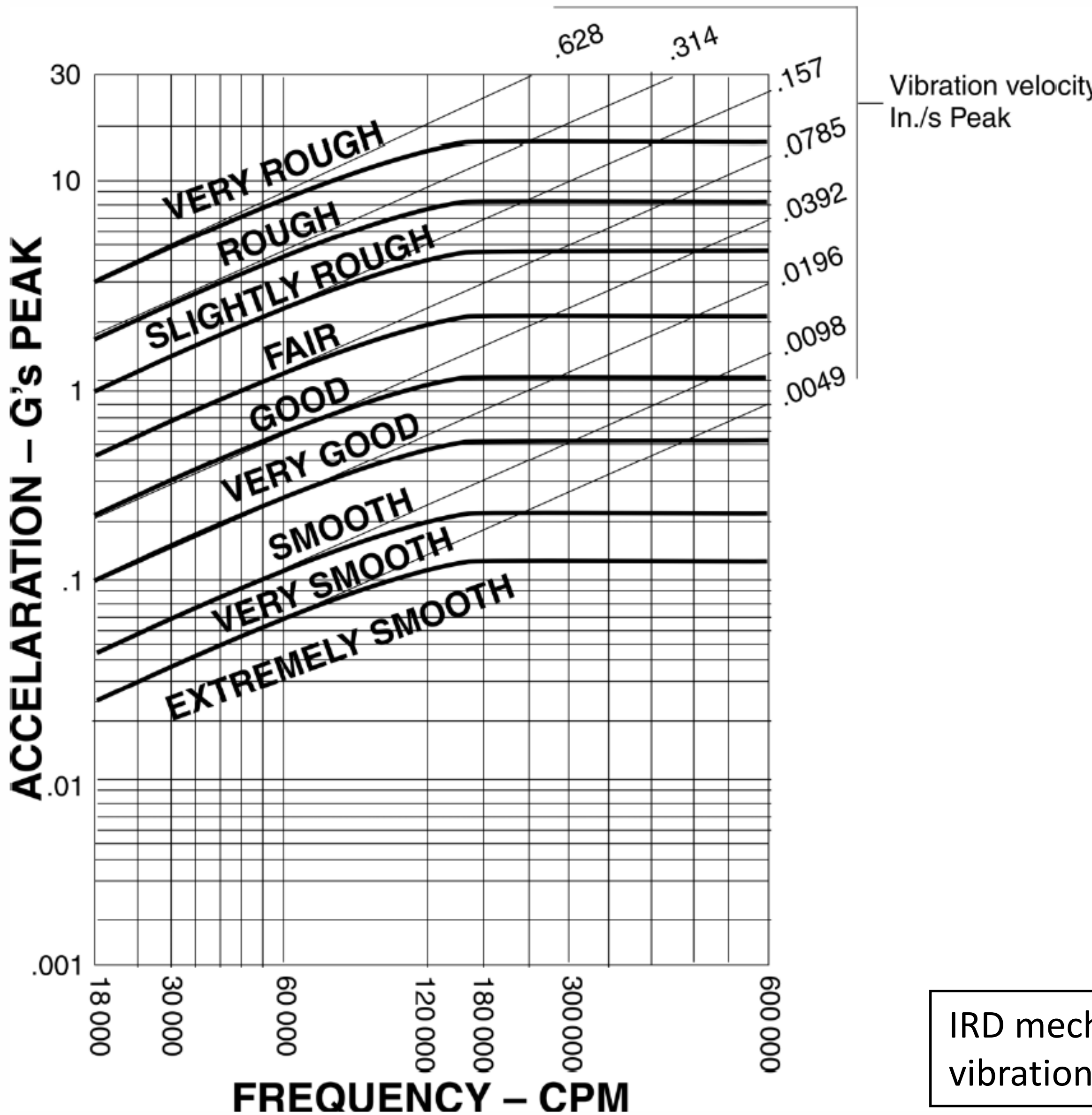
Shaft vibration limits (sleeve bearings)

Vibration Limits: API-610 centrifugal pumps in refinery service

General Machinery Vibration Severity Chart



IRD mechanalysis vibration standard

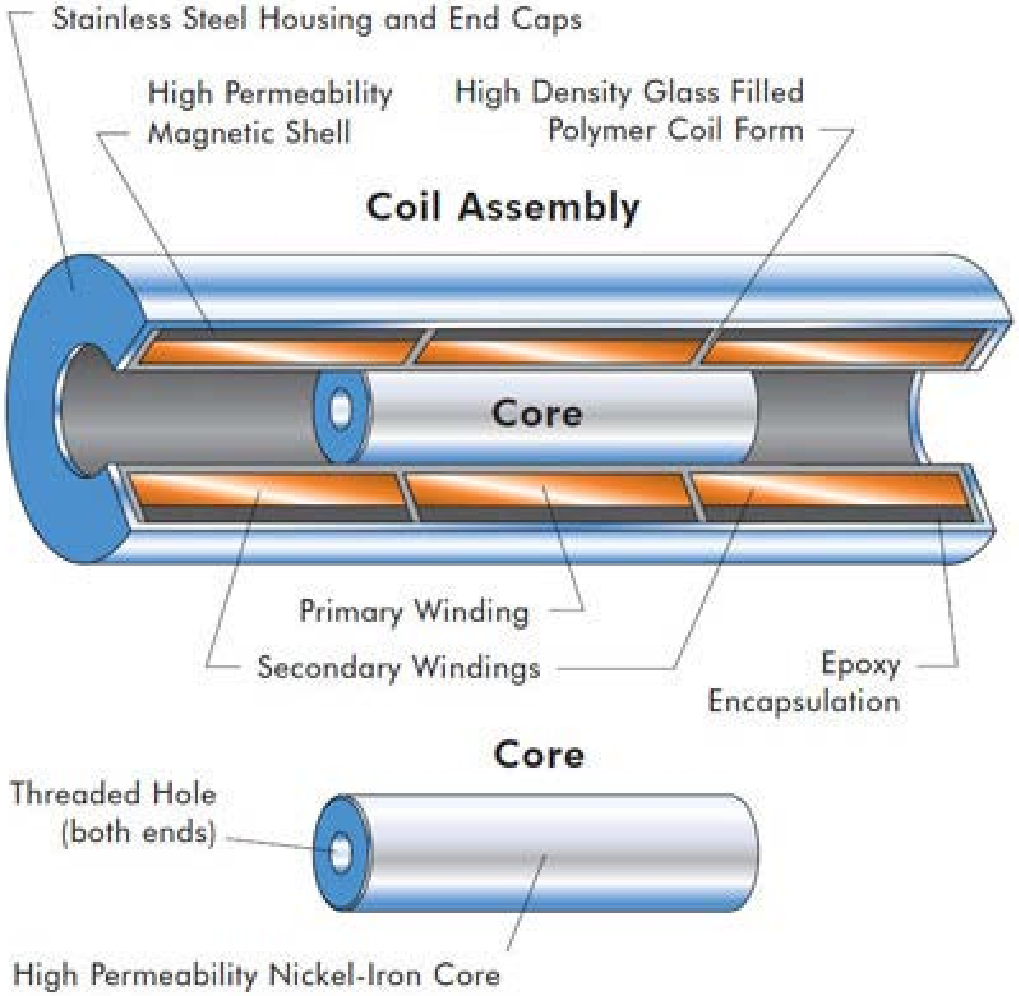


IRD mechanalysis vibration standard

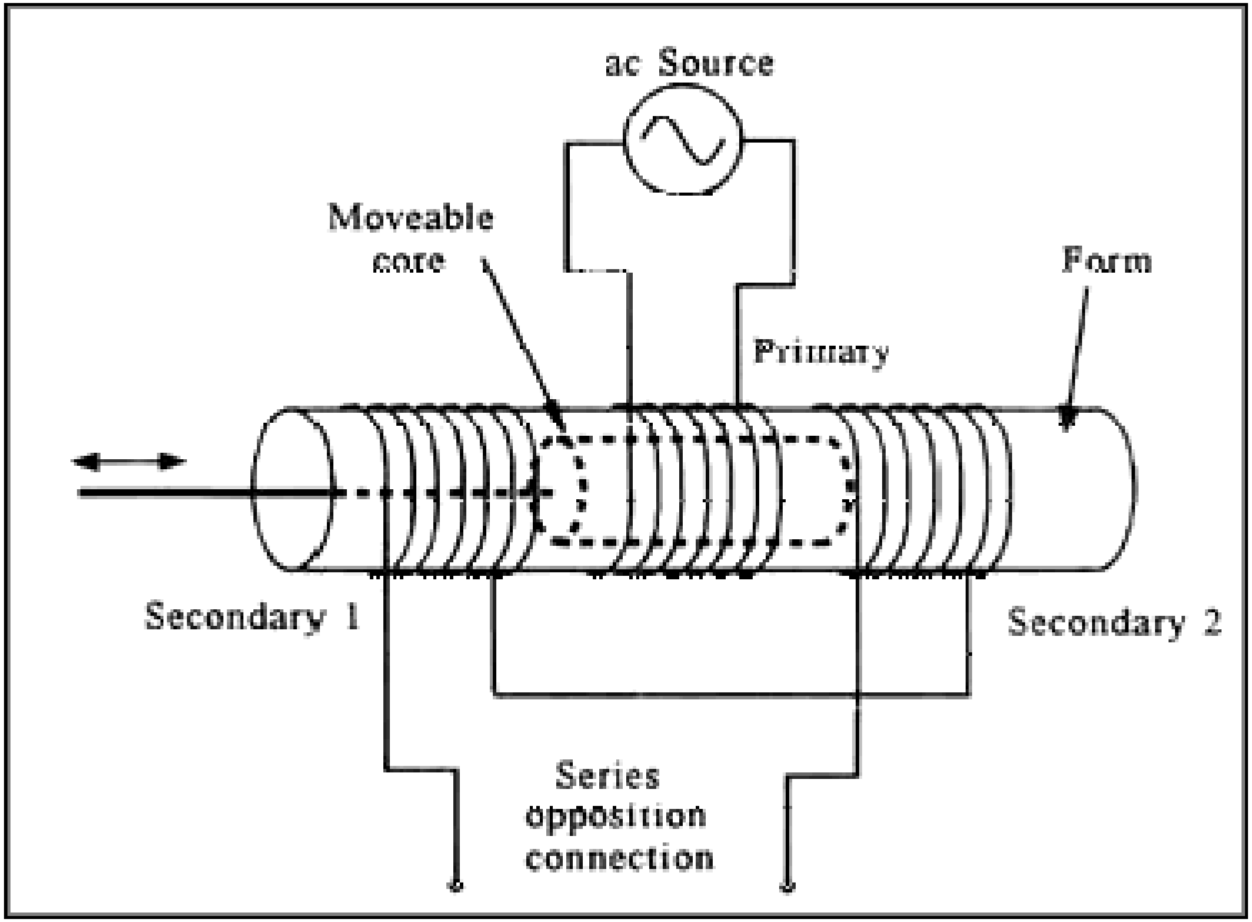
Vibration - 2

Measurement of Displacement

Linear Variable Differential Transducer



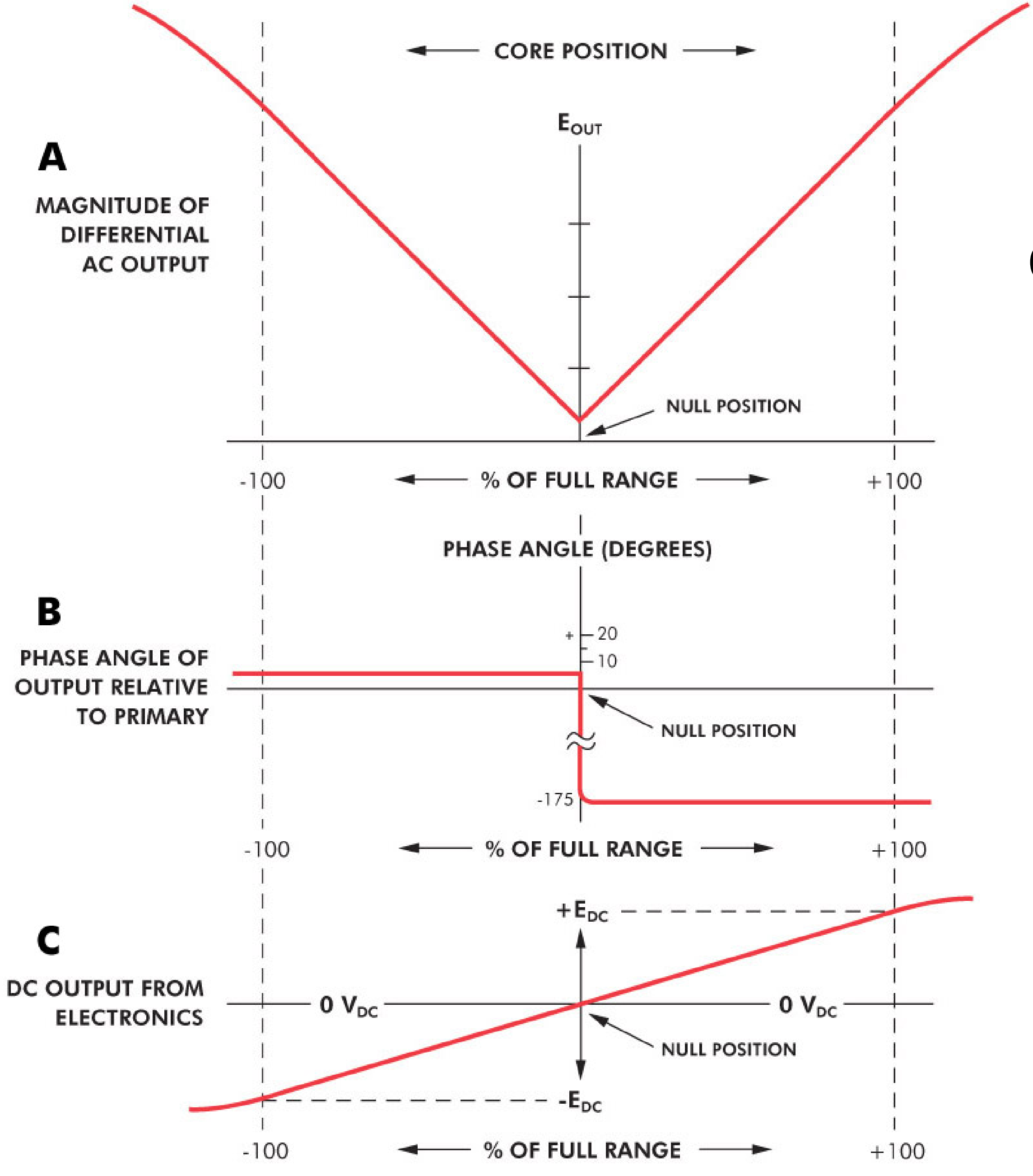
Linear Variable Differential Transducer



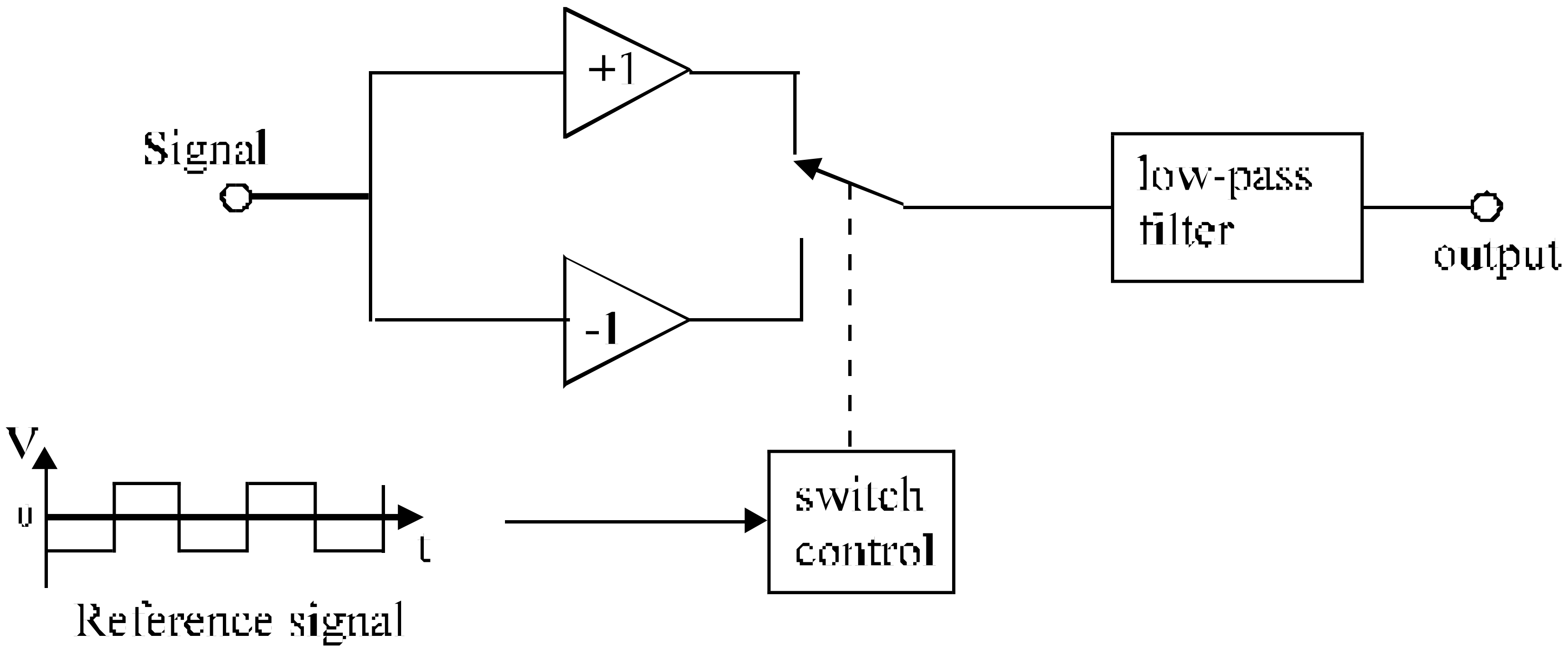
Linear Variable Differential Transducer

- Basically a transformer with 1 primary and 2 secondary windings on a tubular ferromagnetic former.
- Moveable non-magnetic plunger with ferromagnetic armature at the end.
- secondary coils connected in series oppostition to each other.
- Primary winding energised with $V_s \sim f_s$ Hz
- Output = $V_{out}\sin(2\pi f_s t + \phi) = V_1 - V_2$
- When $V_1 > V_2$ V_{out} *in phase* with V_s $\phi = 0^0$
- When $V_1 < V_2$ V_{out} *out of phase* with V_s $\phi = 180^0$
- Use phase sensitive demodulator and low pass filter to recover DC characteristic.

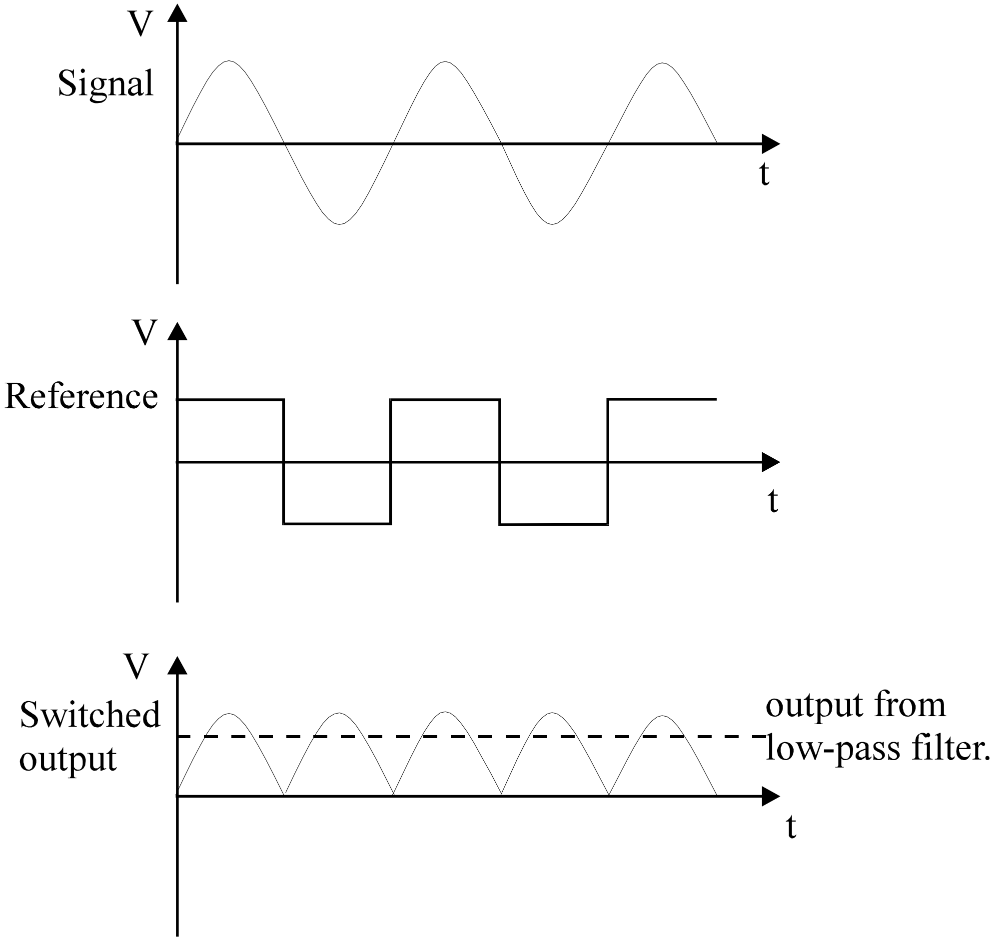
AC and DC characteristics of LVDT



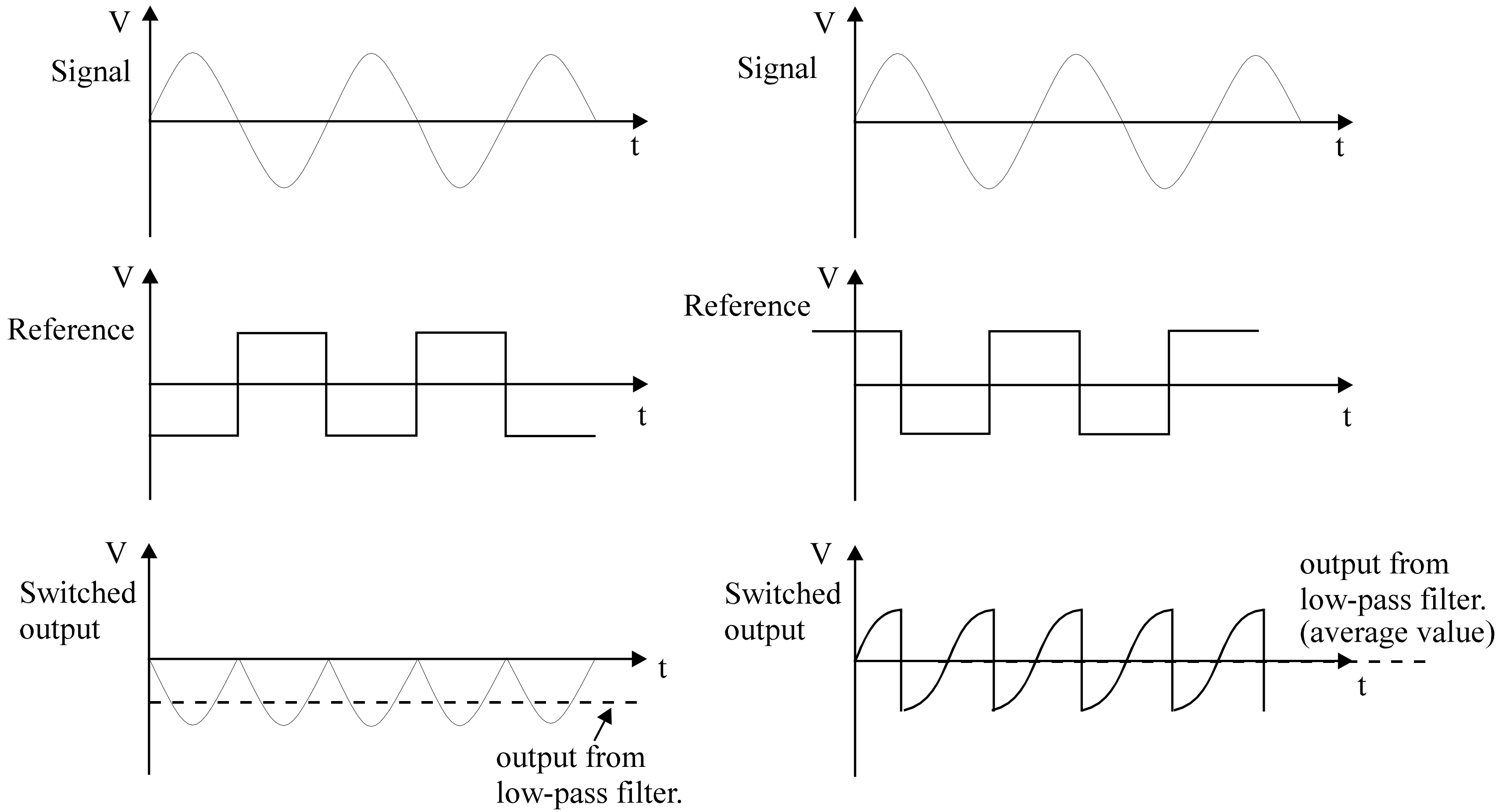
Phase Sensitive Detection Circuit



Action of PSD circuit



Action of PSD circuit



Rotating Shaft Displacement

- This is an important topic in condition monitoring.
- Use 2 displacement sensors oriented at 90 deg.
- Produce ‘orbital’ plots of shaft displacement.

Rotating Shaft Displacement

Applications of Shaft Monitoring

- **Journal bearing machines:**
  - **Centrifugal pumps**
  - **Turbo compressors**
  - **Steam turbines**
  - **Fans and blowers**
  - **Gear boxes**
  - **Generators**
  - **Electric motors**

Typical Probe Mounting

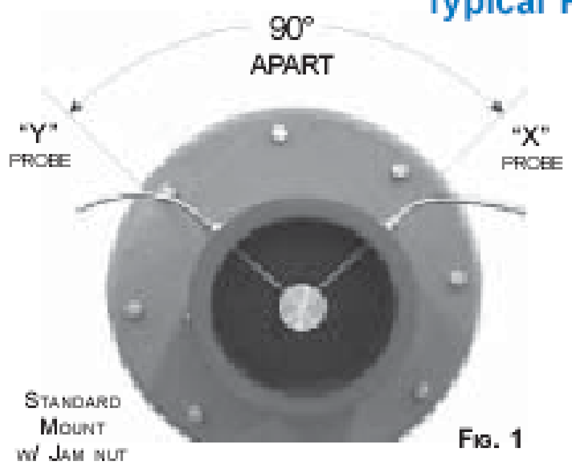


FIG. 1

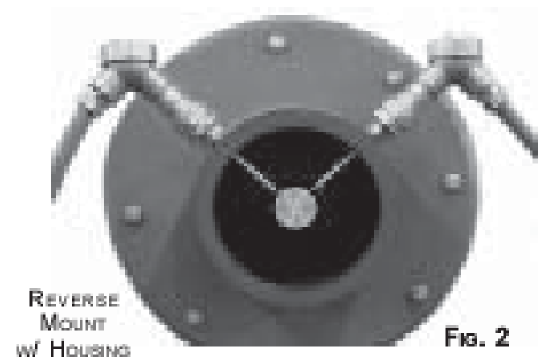
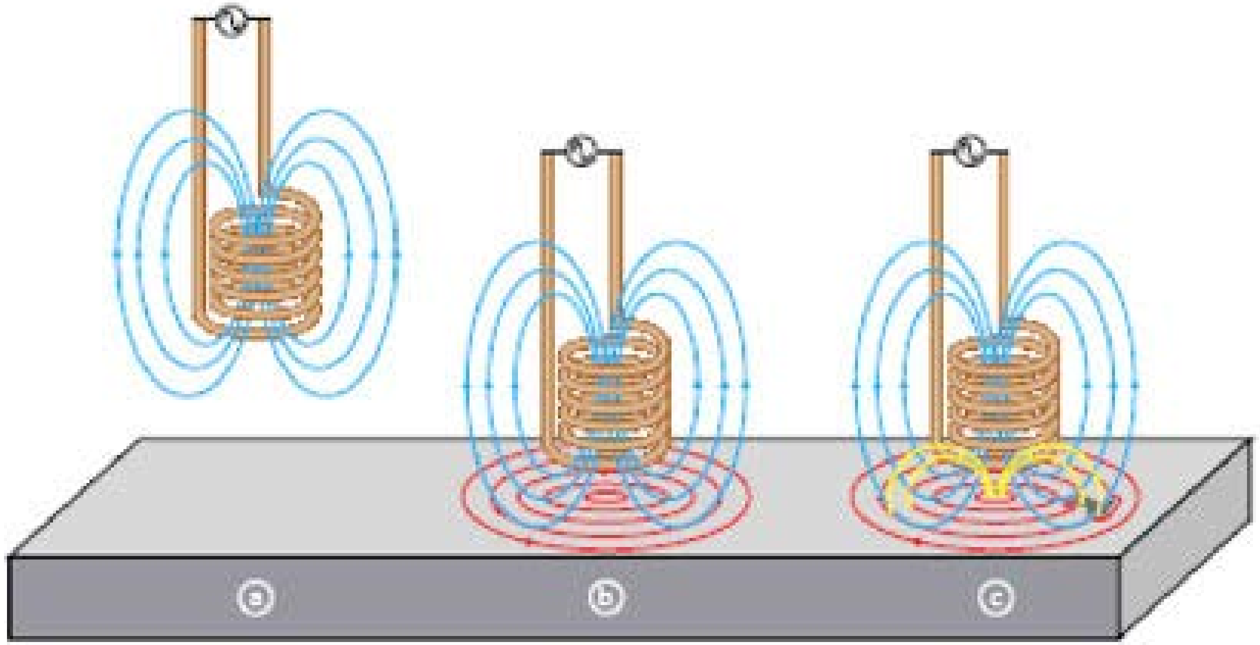


FIG. 2

Eddy Current Probe

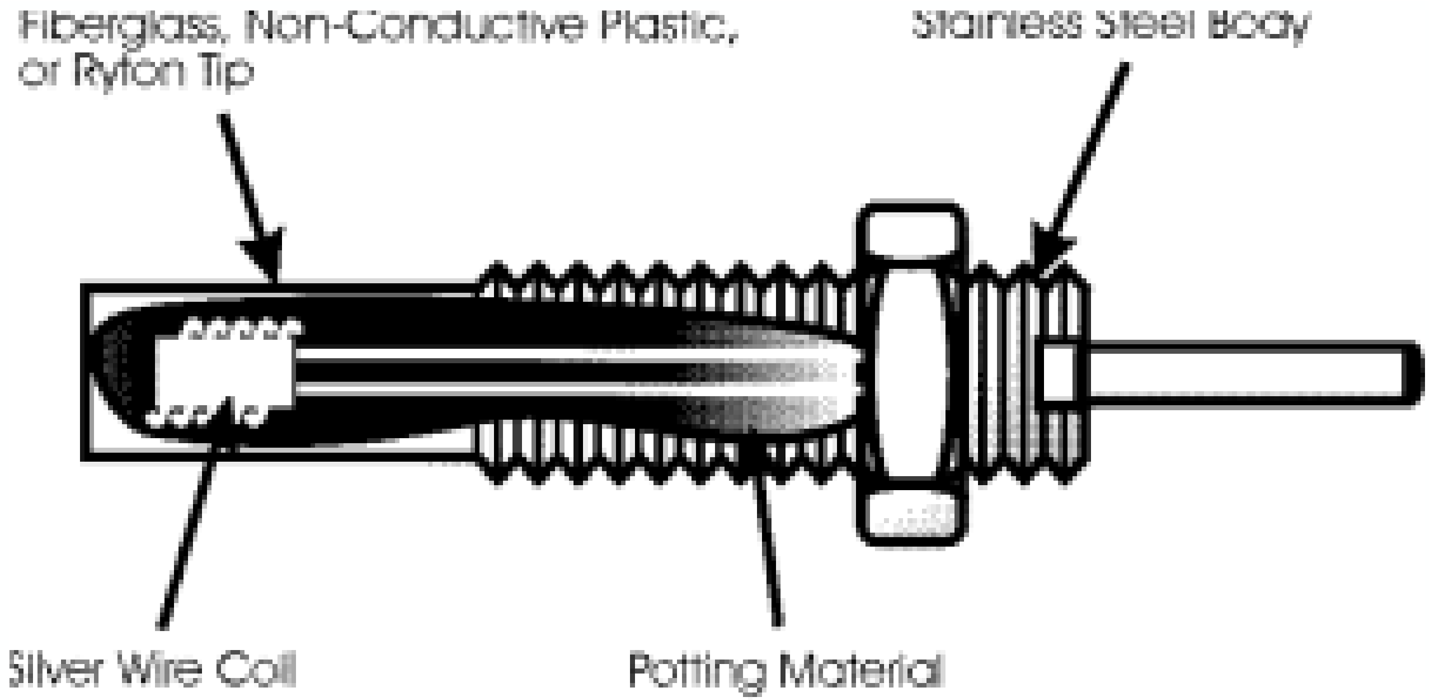


a—The alternating current flowing through the coil at a chosen frequency generates a magnetic field around the coil.

b—When the coil is placed close to an electrically conductive material, eddy current is induced in the material.

c—If a flaw in the conductive material disturbs the eddy current circulation, the magnetic coupling with the probe is changed and a defect signal can be read by measuring the coil impedance variation.

Eddy Current Probe Fabrication

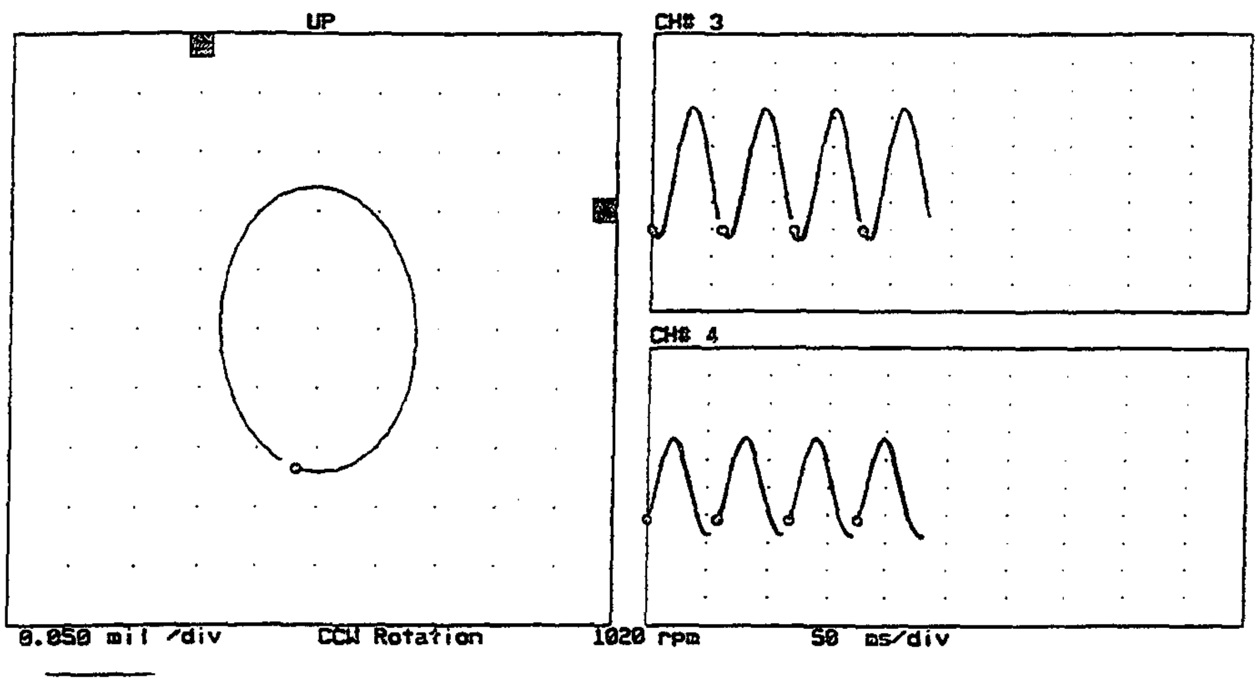


Eddy Current Probe - How It Works

- Three matched components - Driver, probe and extension cable
- Voltage applied to the Driver causes an RF signal to be generated
- Signal is transmitted to the probe by the extension cable
- Coil inside probe tip serves as an antenna and radiates high frequency energy into free space
- Any conductive material within the field absorbs energy and causes output of probe to decrease proportional to gap distance

Rotating Shaft Displacement

Figure 3-3 Shaft Displacement Waveform and Orbit (courtesy: Peter Bradshaw)



Eddy Current Displacement Probe

Figure 3–5 Typical Eddy-Current Displacement Probe Sensitivity Calibration Curve

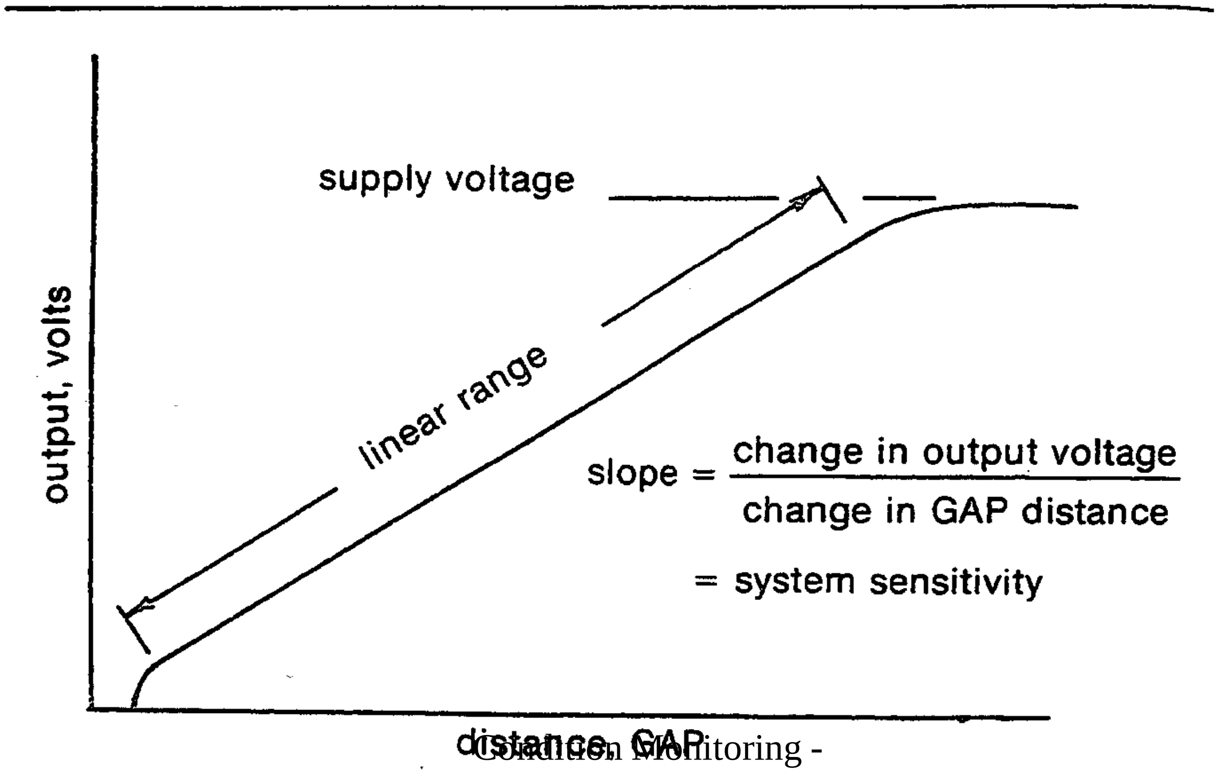


FIG. 1A.

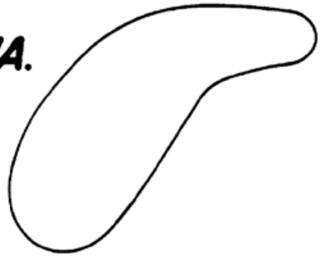


FIG. 1B.

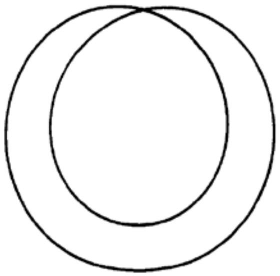


FIG. 1C.

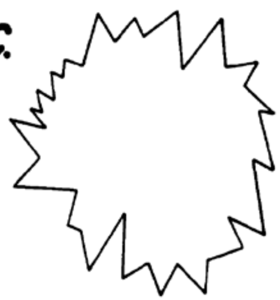


FIG. 1D.

Examples of some typical orbit plots which are produced by defects in equipment are illustrated in Figs. 1A-1D.

A typical example of an orbit plot associated with a severe case of misalignment is illustrated in Fig. 1A.

An example of an orbit plot produced by oil whirl or oil whip in a sleeve bearing is illustrated in Fig. 1B.

The spiked circle illustrated in Fig. 1C is an example of the orbit plot produced by a rub, while the plot illustrated in Fig. 1D is an example of a bent or unbalanced shaft.

Depending upon the location of the rub, the form of misalignment or cause of the unbalanced shaft, the orientation and extent of deviation from a circle may change.

Eddy Current Probe Installation

Figure 3-8 Adapter to Permit Probe Replacement Without Interrupting Operation

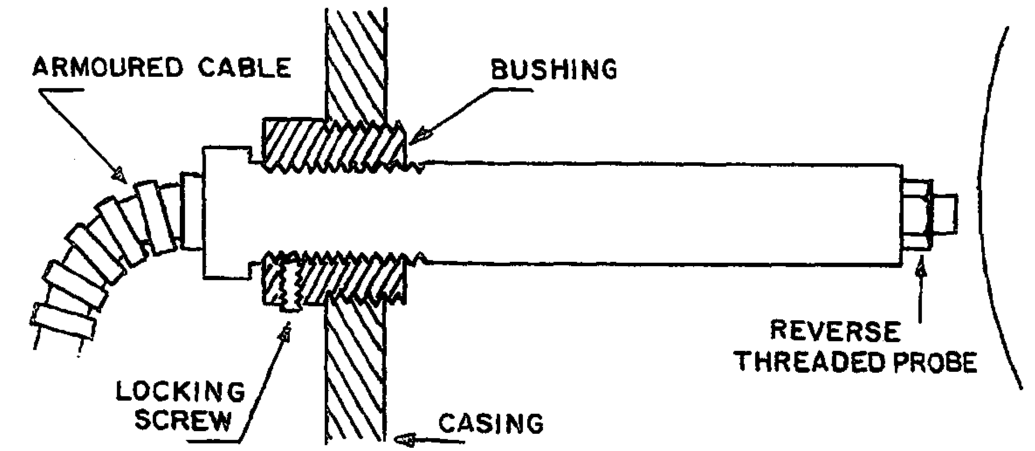
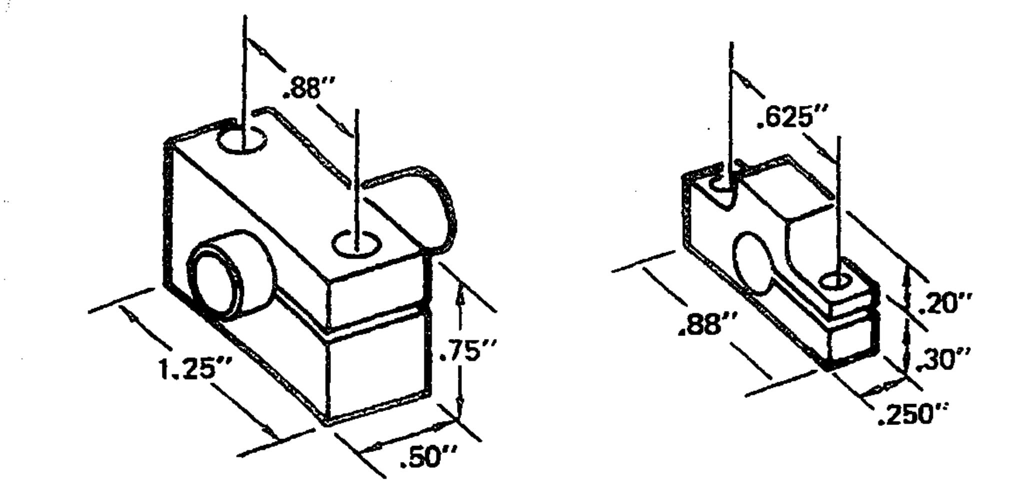
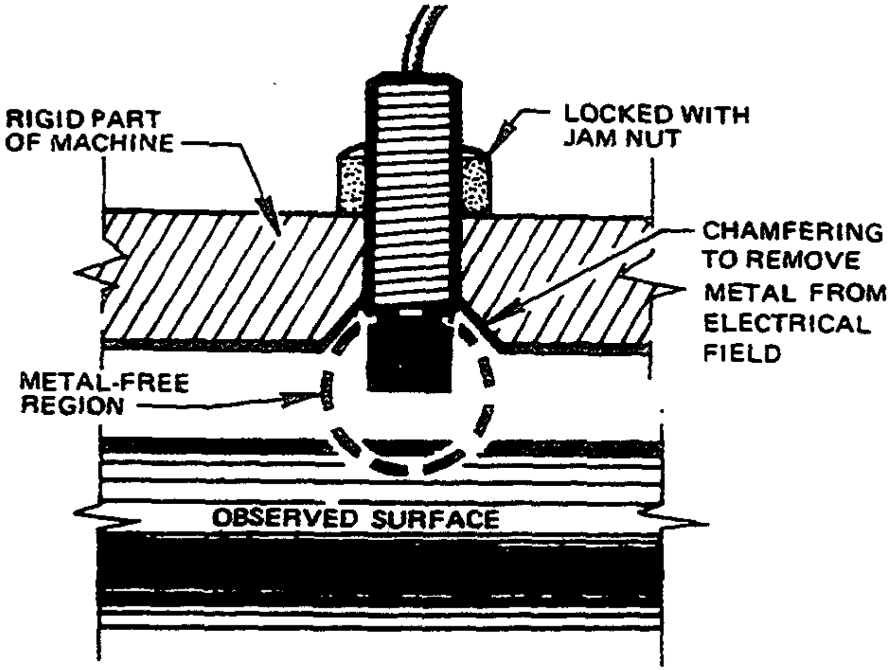


Figure 3-9 Typical Internal Probe Mounts



Eddy Current Probe Installation

Figure 3–10 Non-Contract Probe Tips Must Not Be Shaded by **Adjacent Material**



Probe and Bridge Circuit

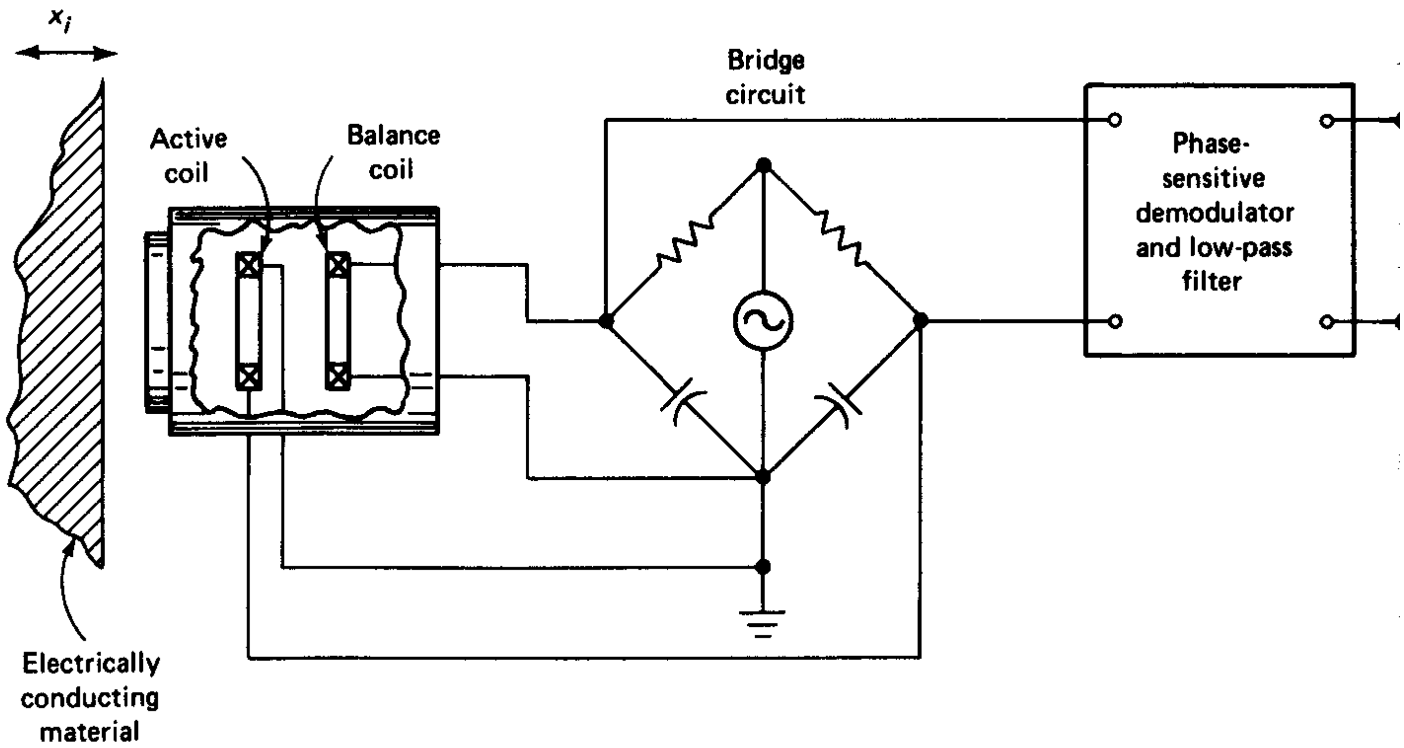


Figure 4.31 Eddy-current noncontacting transducer.

Effect of Target Material on Skin Depth at 1 MHz

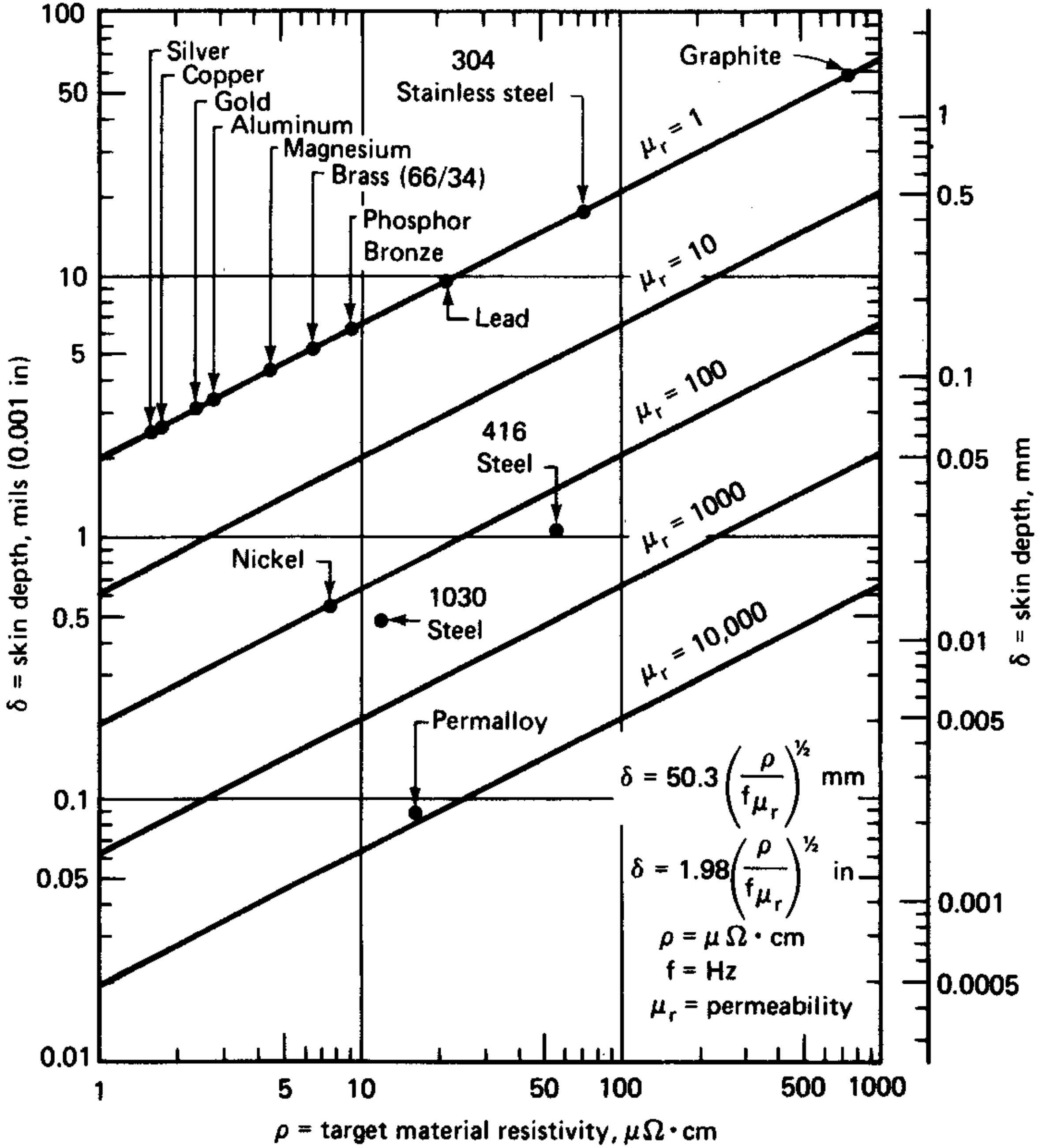


Figure 4.32 Target-material effect on eddy-current transducer.

Vibration - 3

Accelerometers

Seismic Accelerometer

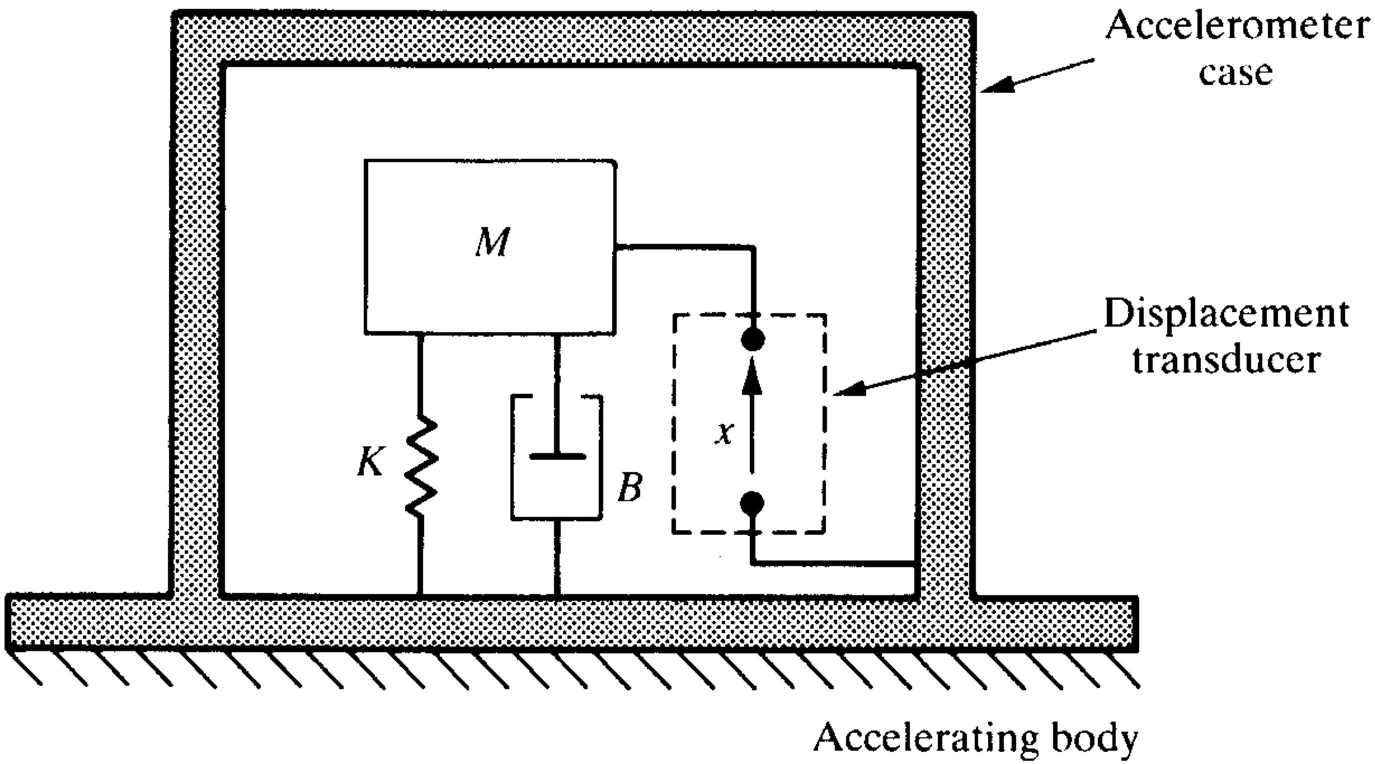


Figure 18.1 Structure of an accelerometer

The accelerometer is rigidly fastened to the body undergoing acceleration. Any acceleration of the body causes a force, F_a, on the mass, M, given by:

$$F_a = Ma$$

This force is opposed by the restraining effect, F_s, of a spring with spring constant K, and the net result is that the mass is displaced by a distance x from its starting position such that:

$$F_s = Kx$$

In the steady state, when the mass inside is accelerating at the same rate as the case of the accelerometer, $F_a = F_s$ and so:

$$Kx = Ma \text{ or } a = (K/M)x$$

We include a damping term proportional to the velocity

$$F_d = B\ dx/dt$$

The equation of motion is now

$$Kx + B\ dx/dt = M\ d^2x/dt^2$$

Which is often written in the form

$$d^2x/dt^2 - 2\ \omega_n\ \xi\ dx/dt - \omega_n^2\ x = 0$$

Where ω_n the natural frequency and ξ (ksi) the damping ratio are given by:

$\omega_n = \sqrt{(K/M)}$ and $\xi = B/2\sqrt{(KM)}$

(ξ = 'Xi' it is the Greek 'x' as in xylophone)

Frequency Response of a Second Order Transducer Showing Resonance and Damping Effects

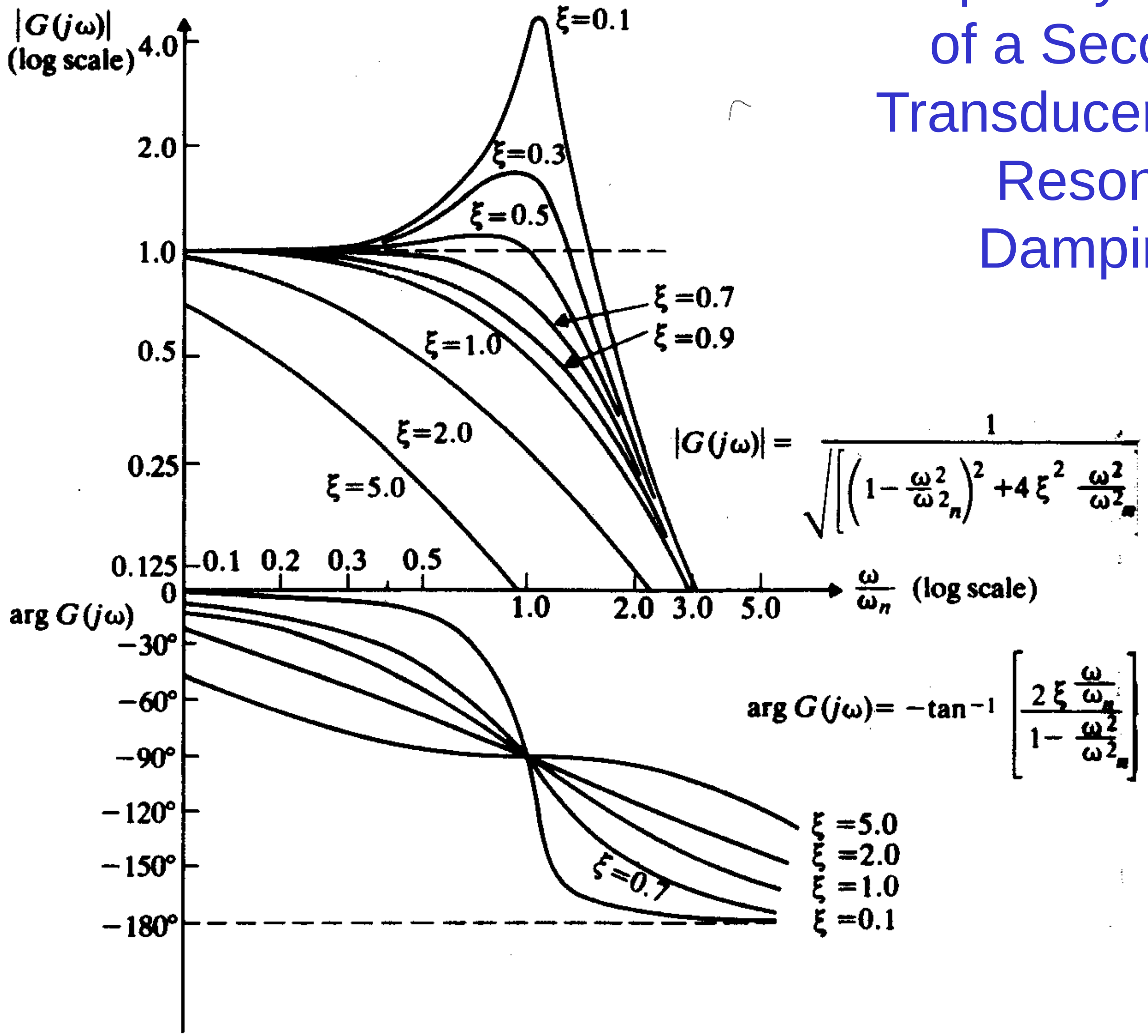


Fig. 4.10 **Frequency response characteristics of second order element with:**

Piezoelectric Accelerometer

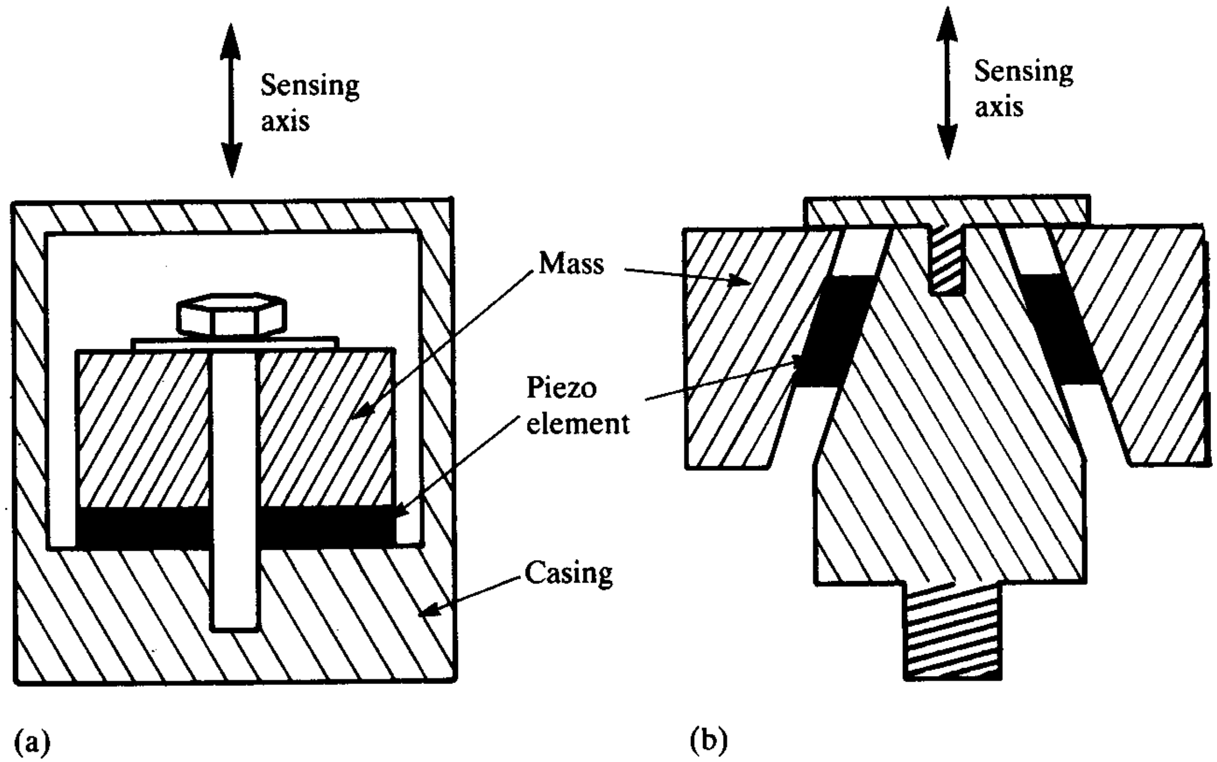


Fig. 8.16 Piezoelectric accelerometers
(a) Compression mode
(b) Shear mode (after Purdy[11])

Piezoelectric effect:

- Crystal (e.g. Quartz) cut so as to have parallel faces with plated electrodes.
- Apply compressive force.
- Charges of opposite polarity appear on the faces.
- Amount of charge depends on the force applied (within a limited range).
- Polarity depends on direction of crystal axis.

$$x = \frac{1}{k} F$$

x = displacement

k = crystal stiffness

F = force

and $q = Kx$

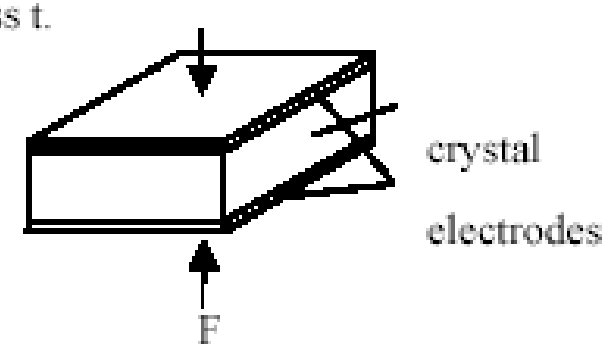
K: constant - $q \propto x$

$$\Rightarrow q = \frac{K}{k} F = dF$$

d: charge sensitivity to force (coulombs.newtons^{-1})

- metal electrodes are deposited on opposite faces of the crystal to produce a capacitor ⇒ can measure q.
  e.g. rectangular block of crystal of thickness t.

$$C = \frac{\varepsilon_0 \varepsilon A}{t}$$



output voltage $V = Q/C$

Output of Piezoelectric Accelerometer

- Charge sensitivity to force: $q = dF$
- Newton's law: $F = Ma$
- PZT is a capacitor: $V = q/C$
- Hence $V = dMa/C$
- Sensitivity (V/a) = dM/C volts $m^{-1}s^{2}$
- 0r 9.81 dM/C volts g^{-1}

Piezoelectric Materials

	Material	Charge Sensitivity α $pC.N^{-1}$	Dielectric Constant ε	Young's Modulus $E \times 10^9\ Nm^{-2}$
Natural	Quartz	2.3	4.5	80
	Tourmaline	1.9, 2.4	6.6	160
Piezoelectric Ceramic	Lead Zirconate-Titanate	265	1500	79
	Lead Metaniobate	80	250	47

Problems with bare PZT

- Total capacitance of system C’ is combination of PZT crystal+cable+scope input
- System sensitivity proportional to 1/C’
- Low frequency cut off of system response given by $1/\tau = 1/RC'$
- Solve these problems using so-called ‘charge amplifier’
- silly name, doesn’t amplify charge, rather, it provides v_{out} proportional to q_{in}

Charge Amplifier for PZT Accelerometer

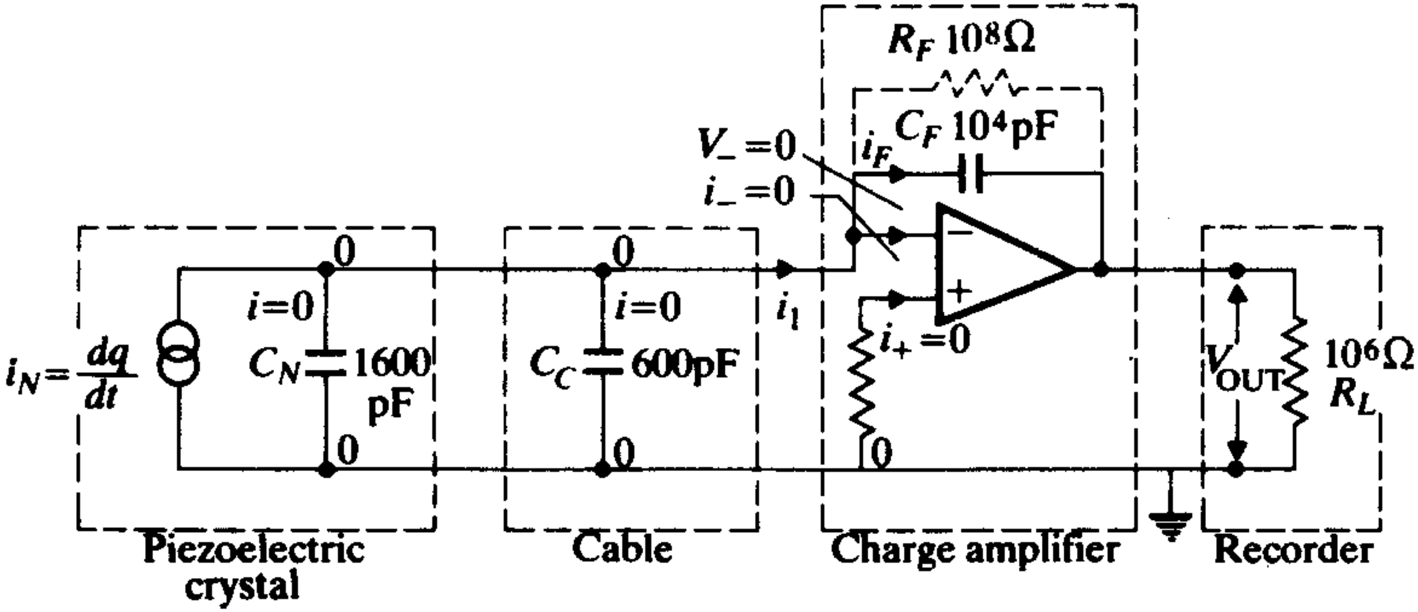
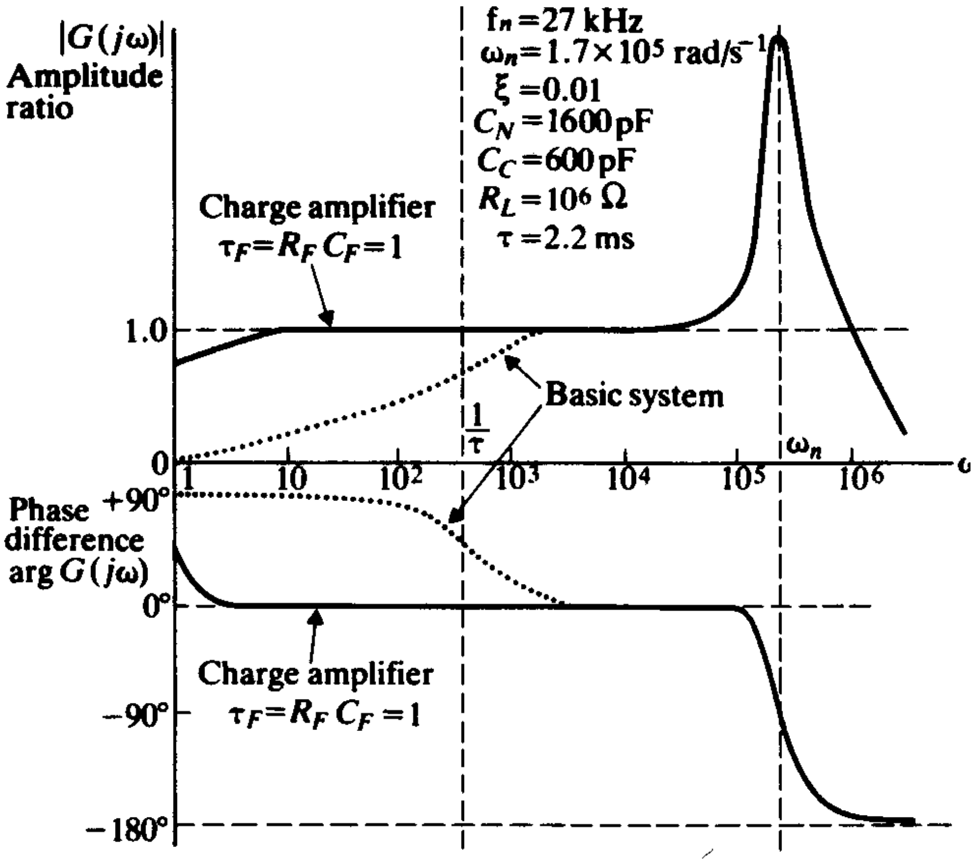


Fig. 8.15 Approximate frequency response characteristics and equivalent circuit for piezo-electric measurement system

Charge Amplifier for PZT Accelerometer

- System sensitivity now $v = -q/C_f$
- Low frequency time constant now $\tau = R_f C_f$

Accelerometer Frequency Response



Vibration - 4

Practical Considerations

Accelerometer Selection Considerations

- Frequency Range
- Minimum vibration amplitude
- Maximum vibration amplitude
- Operating temperature range
- Environment (fluids, gases, chemicals)
- Mounting method
- Physical constraints
- Intrinsic safety certifications

Frequency Range Considerations

What is the minimum and maximum frequency to be measured?

Some examples for estimating maximum frequency to be measured.

- Roller Element Bearings - 20 to 40 times the shaft RPM
- Journal Bearings - 10 to 20 times the shaft RPM
- Gear Boxes - 3.5 times the gear mesh
- Electric Motors - 3.5 times the rotor bar frequency, or 3.5 times the line current frequency
- Pumps & Fans - 3.5 times the blade pass frequency

Minimum Vibration Amplitude

- This is rarely a consideration for industrial applications except for very low frequency measurements.
- The minimum amplitude vibration should generate a signal at least 5 times the amplifier noise present at that frequency.

Maximum Vibration Amplitude

- Maximum possible vibration must not “overload” the sensor amplifier
- The sensor sensitivity should provide sufficient voltage output without creating distortion due to amplifier overload

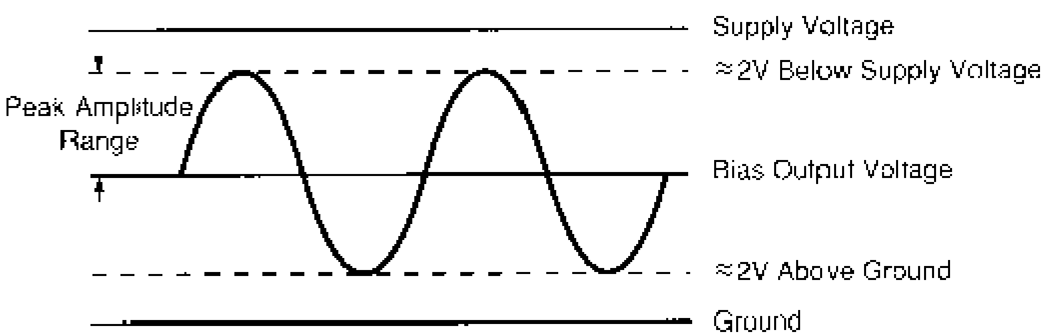


Figure 4. Range of Linear Operation

Operating Temperature Range

- The storage temperature is the same as the specified operating temperature.
- Higher input power current adversely affects maximum operating temperature (4mA maximum is recommended for high temperature)
- Low temperatures for industrial applications rarely go below -50°C

Environmental Considerations

- 316L Stainless steel, Viton®, and Teflon® can withstand most industrial environments.
- Hermetically sealed sensors and splash proof cables, or sensors with integral cables rated to IP68 should be used in " wet" environments.

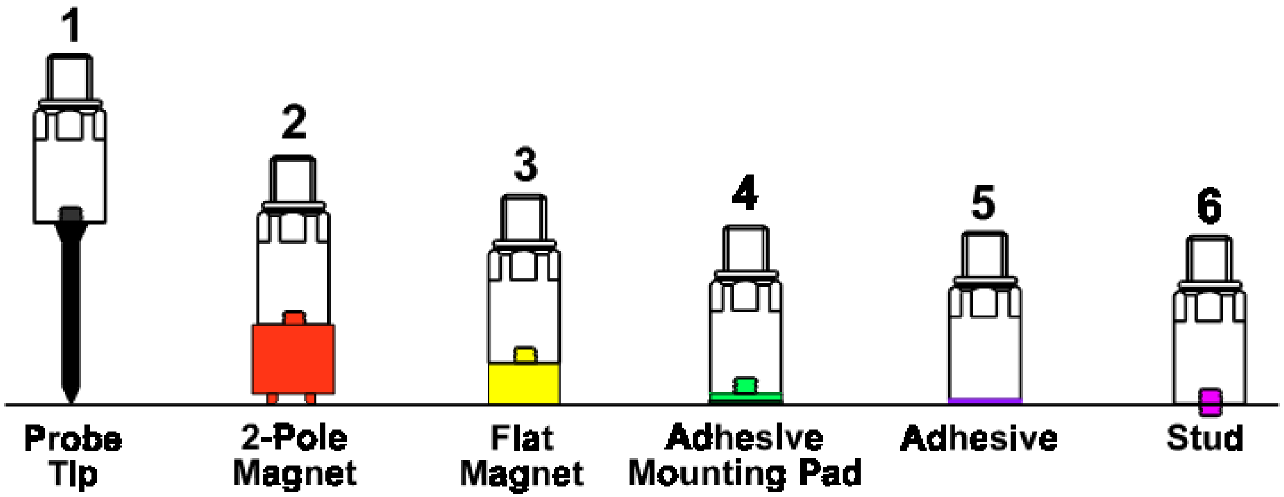
Mounting Considerations & Physical Constraints

- How will the sensor be mounted?
  stud, epoxy, quicklink, magnet
- Is there sufficient room to mount the sensor?
- Side exit or top exit connector required?

Mounting Considerations

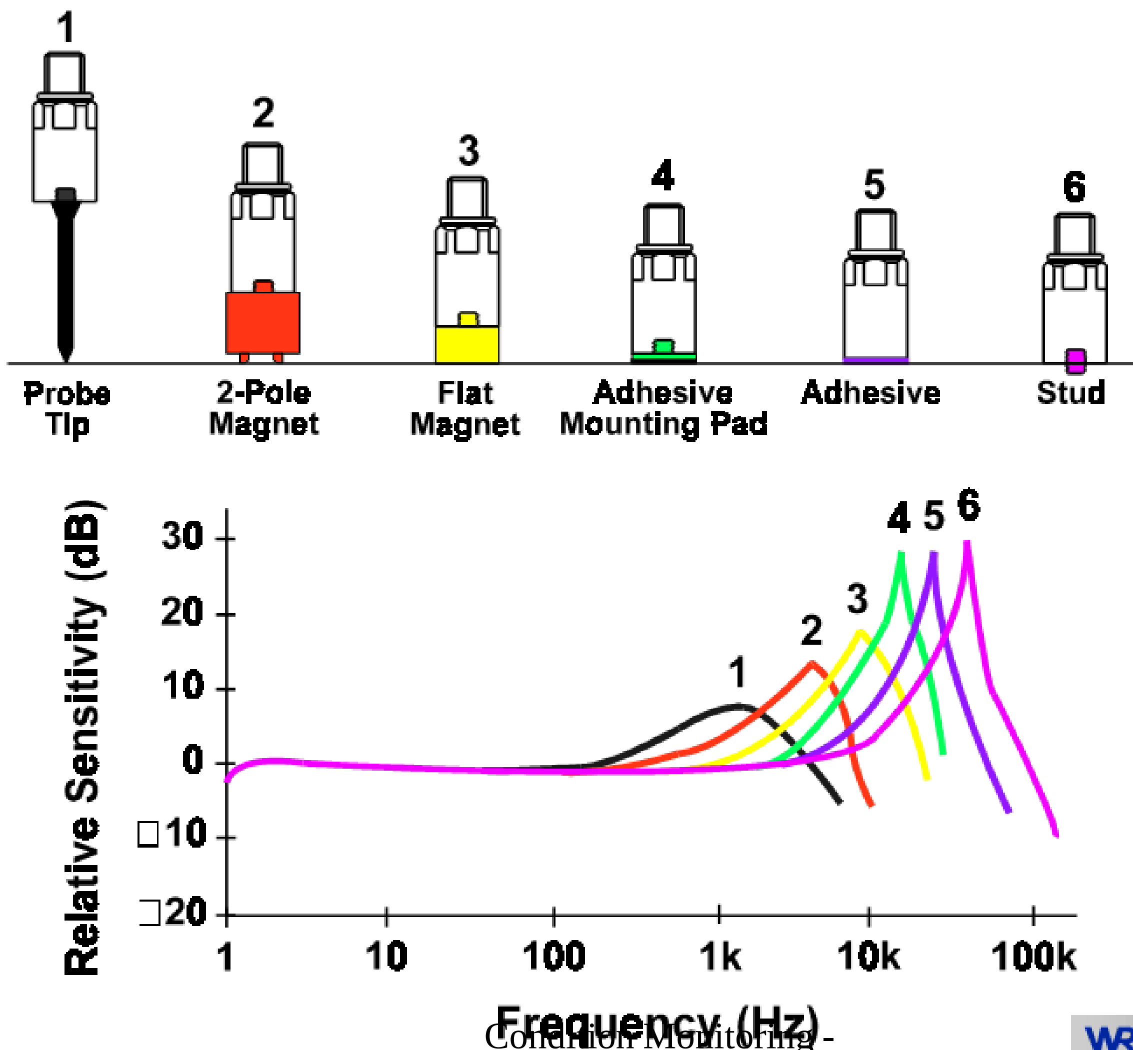
- Is the location for monitoring in a safe, accessible location?
- Can the accelerometer be permanently mounted?
  - Can the machine be faced properly?
- Mounting location
  - Where is the best location?
  - Are there obstacles?
- What are the frequencies of interest?

Accelerometer Mounting



- Hardware Selection
- Mounting Location
- Surface Preparation
- Mounting Resonance's

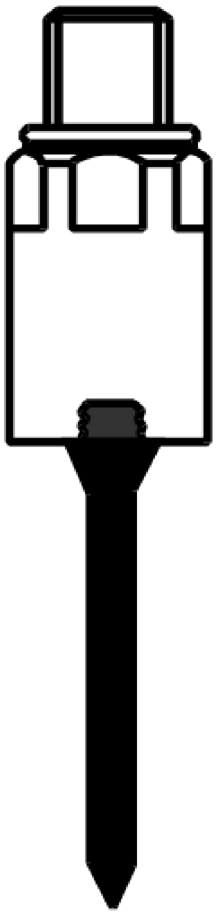
Mounting Technique Determines the Mounted Resonance



Condition Monitoring - instrumentation

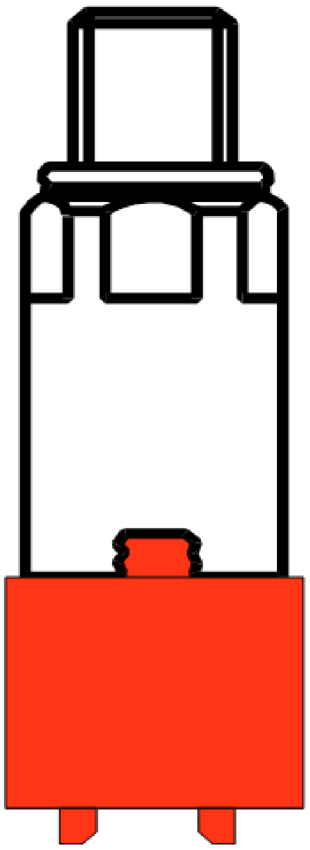
Probe Tips

- Use on difficult to reach areas and aluminum motor frames
- Do not use for measurements less than 10 Hz
- Mounted Resonance
  800 - 1500 Hz



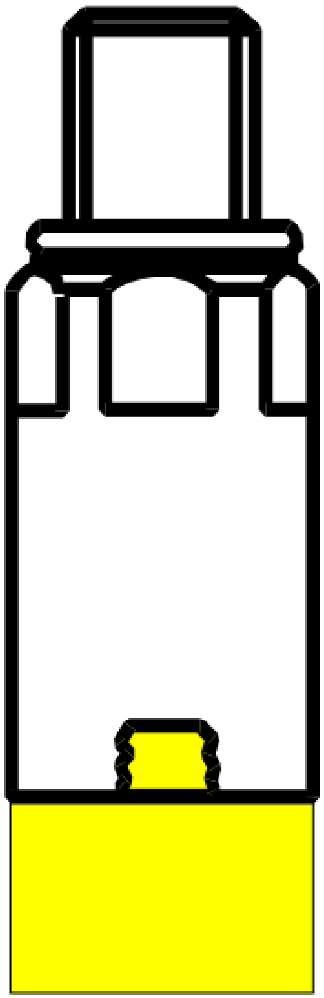
Magnets for Curved Surfaces

- Use on irregular and curved surfaces
- Magnet made of Alnico 5
- Includes 1/4-28 Stud
- Mounted Resonance 3000 to 7000 Hz



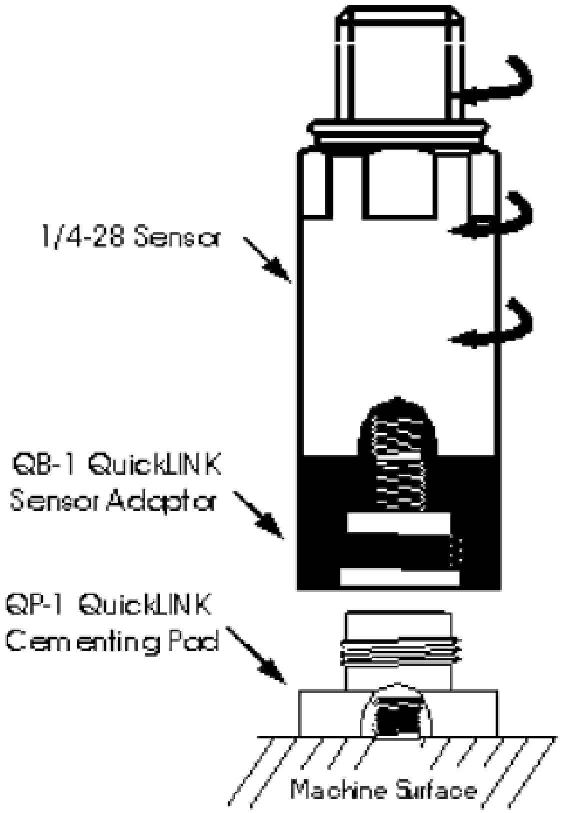
Magnets for Flat Surfaces

- Use on flat surfaces or magnet pads
- Magnet made of Rare Earth Material
- Some have an integral 1/4-28 mounting stud while others have a 1/4-28 Tapped Hole
- Other stud sizes are available
- Mounted Resonance 5000 to 10,000 Hz



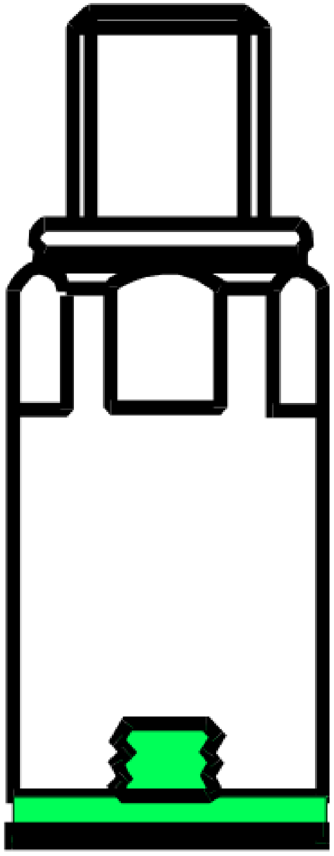
QuickLINK® Mounting Pads

- Mounts quickly like a magnet
- Uses dual lead threads for less than 1 full turn
- High mounting resonance like a stud
- Reduces cable and wrist fatigue



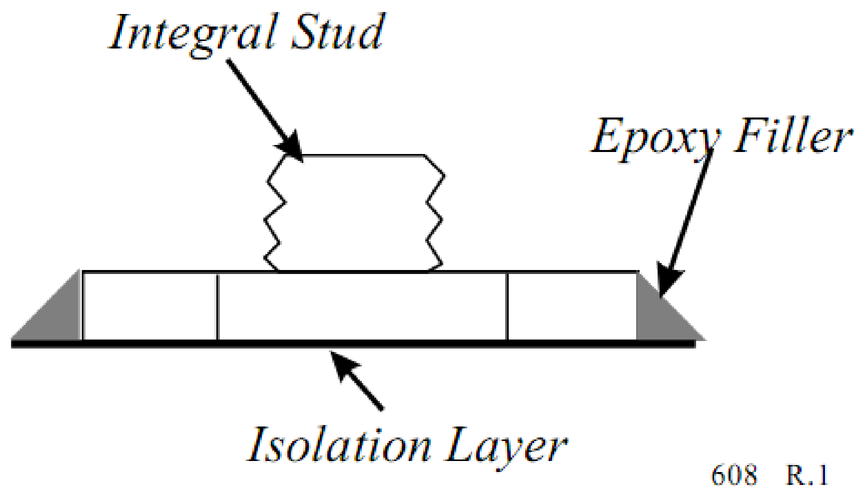
Adhesive Mounting Pads

- Provides adequate frequency response
- Pad available for most common thread sizes
- Pad available for tapped holes for use with accelerometers that use captive screws



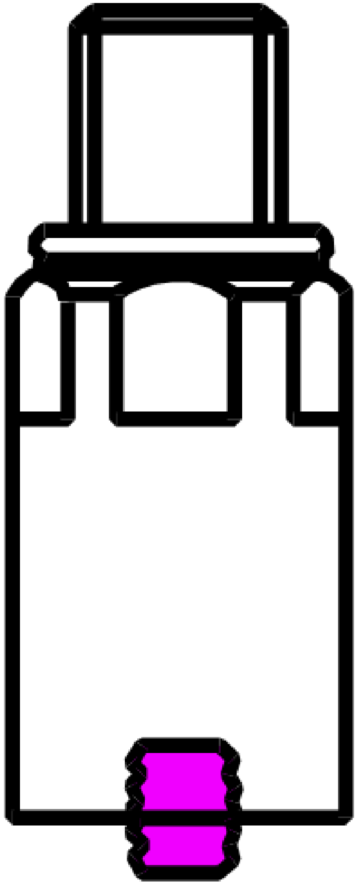
Adhesive Mounting

- Spot Face Surface
- Abrade Surface
- Clean Surface
- Use Proper Adhesive
  - VersiLock®
    406 / Cat 19
  - Loctite® Depend
  - Loctite® Liquid Metal
- Use Proper Mix Ratios



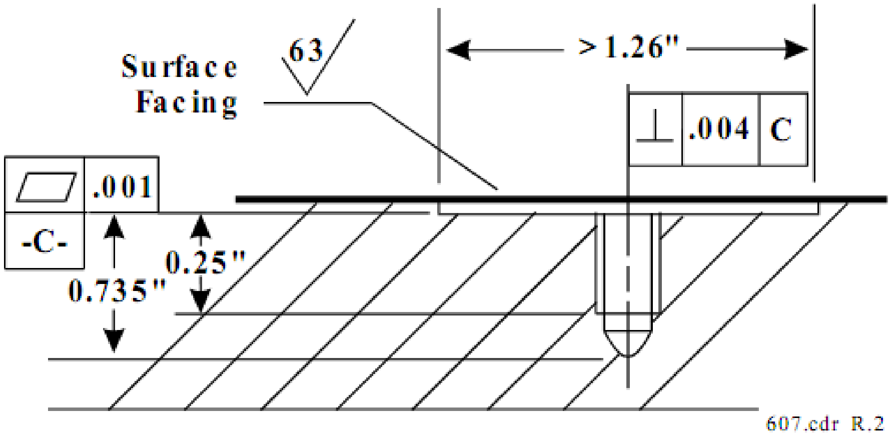
Mounting Studs

- Provides highest frequency response
- Various Stud sizes are available
- Captive Screws with are available with various mounting threads



Stud Mounting

- Tap Drill Hole to Proper Depth
- Spot Face Surface Perpendicular to Hole
- Tap Proper Threads
- Ensure Flatness, Surface Texture, and Perpendicularity



Advantages of Permanently Mounted Sensors

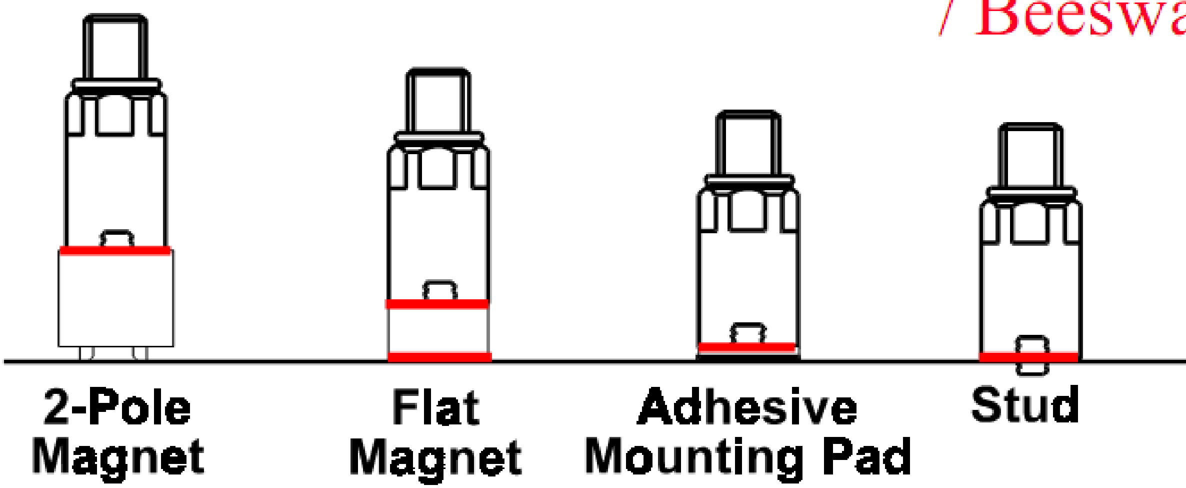
- Safety
- Convenience
- Repeatability of Data
- Faster Data Collection
- Reduces Auto Collection Errors

Coupling Fluids

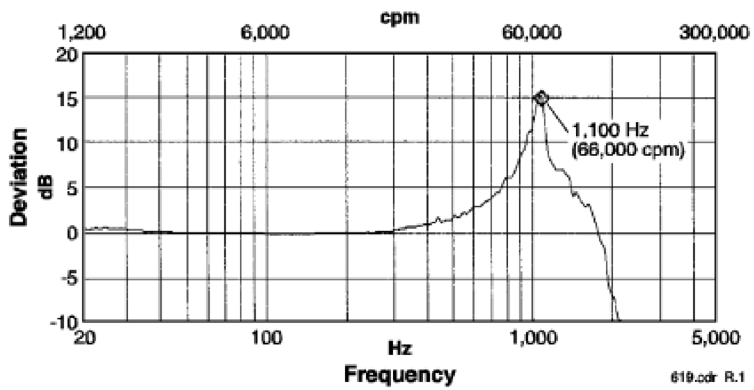
- Coupling fluids should be used between the sensor and mounting surface interfaces

Coupling fluids include:

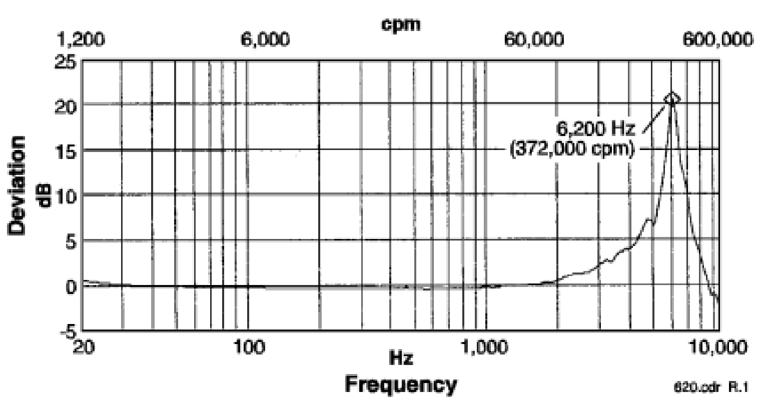
- Silicone Grease
- Oil
- Petroleum Jelly / Beeswax



Mounting Responses

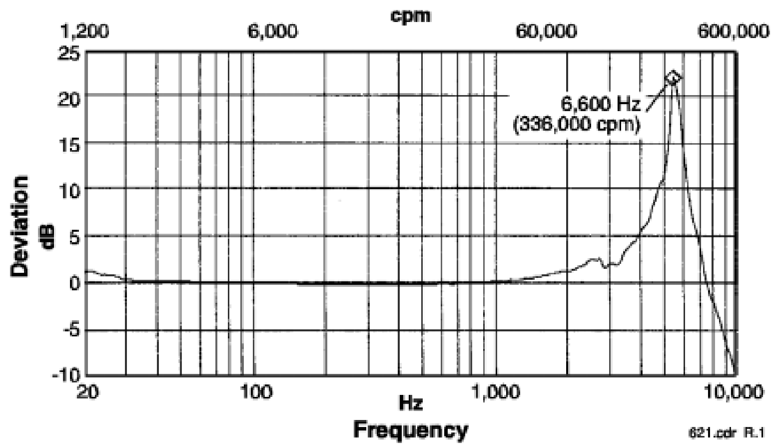


Probe Tip

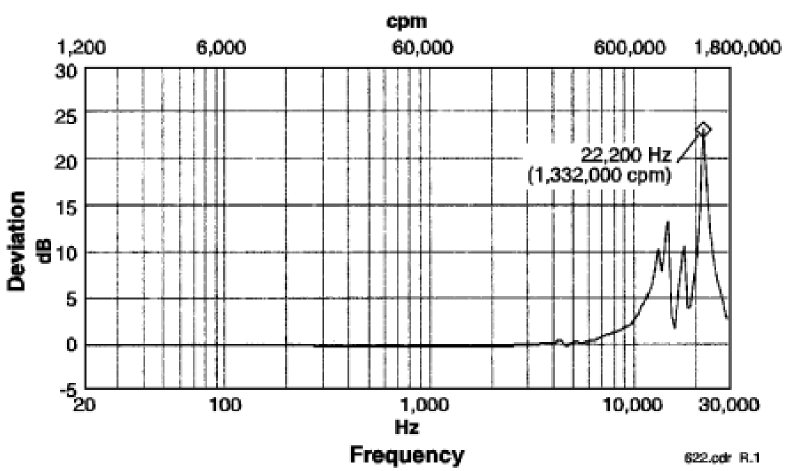


Curved Surface Magnet

Mounting Responses



Flat Magnet



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Mounting Resonance's

- Mounting Resonance's can amplify high frequency signals and increase overload
- Mounting Resonance's can appear to be severe rolling element and gear mesh faults

KNOW YOUR MOUNTING CONDITIONS!