PCB PIEZOTRONICS INC.
MTS SYSTEMS CORPORATION

# PIEZOELECTRIC SENSOR FUNDAMENTALS

PCB Piezotronics Inc.

Università di Trieste
May 2018

# Agenda

- PCB® History
- Piezoelectric Theory
- Introduction to Piezoelectric Sensors
  - Structures
  - Parameters of interest
- ICP® vs. Charge
- Frequency response
- Amplitude range, sensitivity and resolution
- Cabling

# *Who is PCB?*

- First, the name:

**PCB Piezotronics, Inc.**

PCB = measure of unit charge (PicoCoulomB)

Piezo = “Greek” term to Squeeze or Stress

Tronics = addition of electronics

# Who is PCB Piezotronics?

For almost 50 years PCB® has been dedicated to the development of sensor technology and serving the needs of test and measurement professionals worldwide.

AEROSPACE & DEFENSE
A PCB PIEZOTRONICS DIV.

AUTOMOTIVE SENSORS
A PCB PIEZOTRONICS DIV.

PCB PIEZOTRONICS INC.
TEST & MEASUREMENT PRODUCTS

LARSON DAVIS
A PCB PIEZOTRONICS DIV.

IMI SENSORS
A PCB PIEZOTRONICS DIV.

THE MODAL SHOP
A PCB GROUP CO.

PCB Group Inc. was acquired by MTS Systems Corporation in July 2016.

# Global Network

PCB PIEZOTRONICS INC.
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PCB operations are supported by a network of international offices and distributors in all the major technology centers around the world.

- 🟢 **Corporate HQ/Campus – Depew, New York, USA**
- 🟡 **PCB US Operations**
- 🔴 **International Offices: France, Germany, Italy, UK, Sweden, China, Japan**
- 🔵 **Major Distributors**

# What we do ...

PCB® specializes in research & development (R&D), manufacturing and sales of piezoelectric, piezoresistive, MEMs, strain gage, and capacitive-based sensors and related instrumentation

- Vibration Sensors
- Pressure Sensors
- Force & Strain Sensors
- Load & Torque Sensors
- Microphones
- Signal Conditioners
- MEMs Accelerometers
- Fastener Instrumentation
- Noise & Vibration Dosimeters
- Sound Level Meters

ICP® is a registered trademark of PCB Group

# Facilities and Capabilities

PCB continually invests in people, advanced manufacturing capabilities, and state of the art facilities.

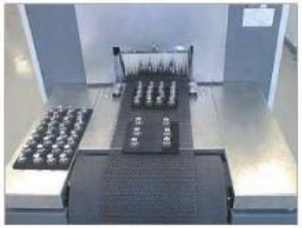
PCB PIEZOTRONICS
Depew, NY


High Volume Production


R&D and Custom Production


Micro Electronics


Laser Welding


Hermetic Connectors


Firing Piezo Ceramics at 1250 °C

PCB Machining Solutions
Depew, NY
*Specializing in precision machined components for industrial, medical, aerospace, and defense applications.*


Robotic Modular Machining Cell

PCB PIEZOTRONICS
of North Carolina, Inc.
Roanoke, NC

# *Focus Through the Years*

- **ICP®** Technology
    - **ICP®** = Integrated Circuit-Piezoelectric
    - Sensors that contain micro electronic circuitry
- Focus on pressure, force, vibration, and acoustic instrumentation for use in:

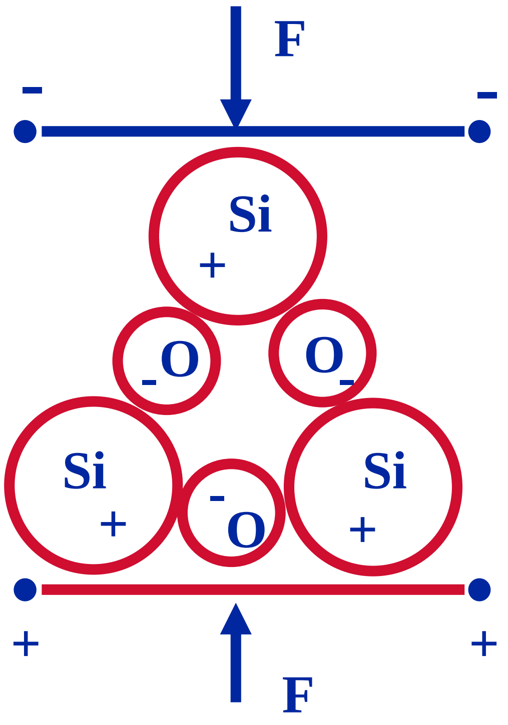
  Dynamic Applications

# Sensing Materials

- PCB products are robust instruments that incorporate a crystal as a sensing element.
- Three (3) main types of piezoelectric materials used by PCB today:
  - Quartz Crystals
  - Polycrystalline Ceramics
  - Tourmaline (High frequency blast sensors)

# *The Piezoelectric Effect*

- Resulting force produces a strain on the crystal causing charge to accumulate on opposing surfaces.



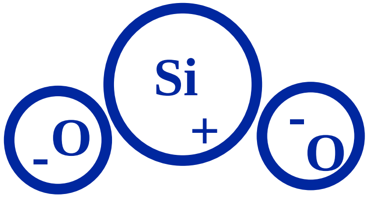
**QUARTZ CRYSTAL**

# Qualities of Crystals Important for Sensors

- Stability -- negligible aging effect
- High stiffness -- imparts high frequency response and long life
- High strength -- ruggedness, long life, high range capability in small size
- High output -- clean signal, good resolution
- Temperature insensitivity and wide range
- No capacitance change with temperature (especially for voltage mode sensors with built-in electronics)
- Economical

# Quartz Crystals

- Single Crystal made of $SiO_2$ molecules
- Found naturally in the Earth



  - Evolves over millions of years
  - Most is of poor quality useful as jewelry only

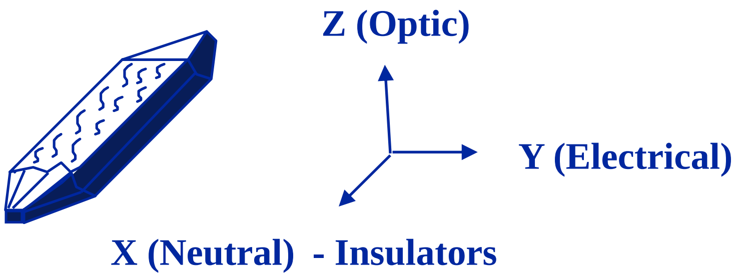
- Artificially grown under high pressure and temperature in large autoclaves
  - Very high quality
  - Takes approximately 1 month

# Quartz Crystals

- Advantages
  - Naturally Piezoelectric
    - Excellent long term repeatability
  - Non-pyroelectric
    - Work well in thermally active environments up to 316° C
  - Low Temperature Coefficient
    - Little deviation over wide temperature range
  - High Stiffness
    - Extremely linear when statically preloaded (typically internally) - shock applications

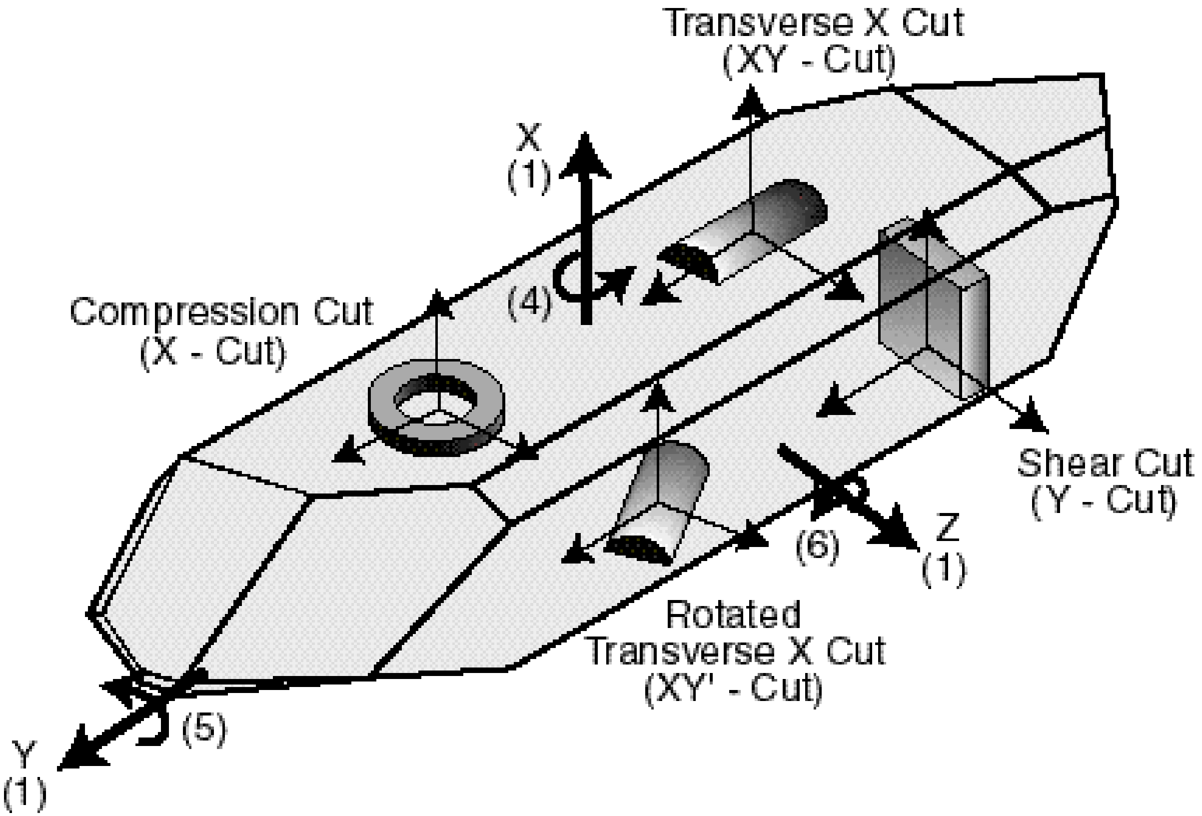
# *Quartz Crystals*

- Disadvantages
  - Limited Temperature Range
    - » Non-piezoelectric above 650 F (343 C)
  - Low Charge Output (pC)
    - » Not effective in low-noise, charge-amplified systems
  - Limited Geometry
    - » Can only cut crystal in certain number of ways and still remain piezoelectric



# Polarity

Determined by the alignment of crystals in the sensor element



# *Ceramic Crystals*

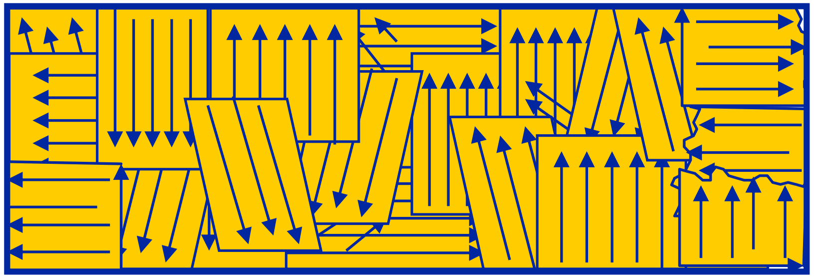
- Man-made material
- Lead-Zirconate Titanate, Barium Titanate, Lead Metaniobate
- Polycrystalline structure
  - Naturally isotropic (physical and electrical properties the same in all directions)
  - Naturally non-piezoelectric
  - Becomes piezoelectric through high voltage process known as“Poling”

# Ceramic Crystals

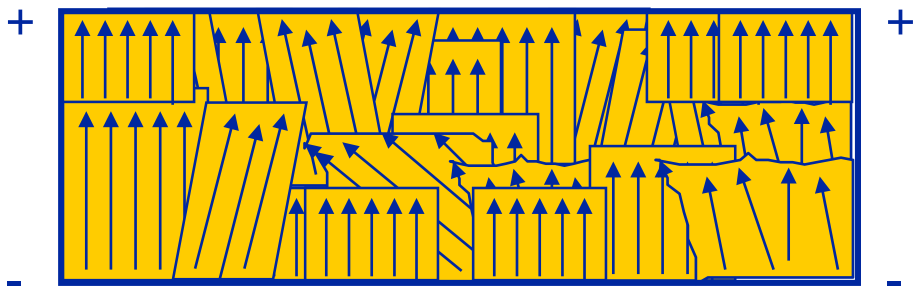
### *Polarization Process (poling)*

- An extremely high voltage placed on the polycrystalline ceramic causes the dipoles to align themselves.

BEFORE POLING



AFTER POLING

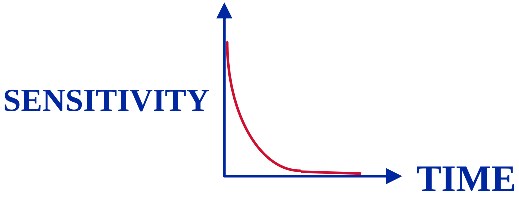


# Ceramic Crystals

- Advantages
  - High Charge Output (pC)
    - Excellent for use with tests requiring high sensitivity and/or low-noise, charge-amplified systems
  - Unlimited Geometry
    - "Poling" occurs after shaping
    - Versatility for different sensor designs: plates, annular tubes, cones, etc…
  - High Temperature Range
    - Operating temperatures: >540°C (>1000° F)

# Ceramic Crystals

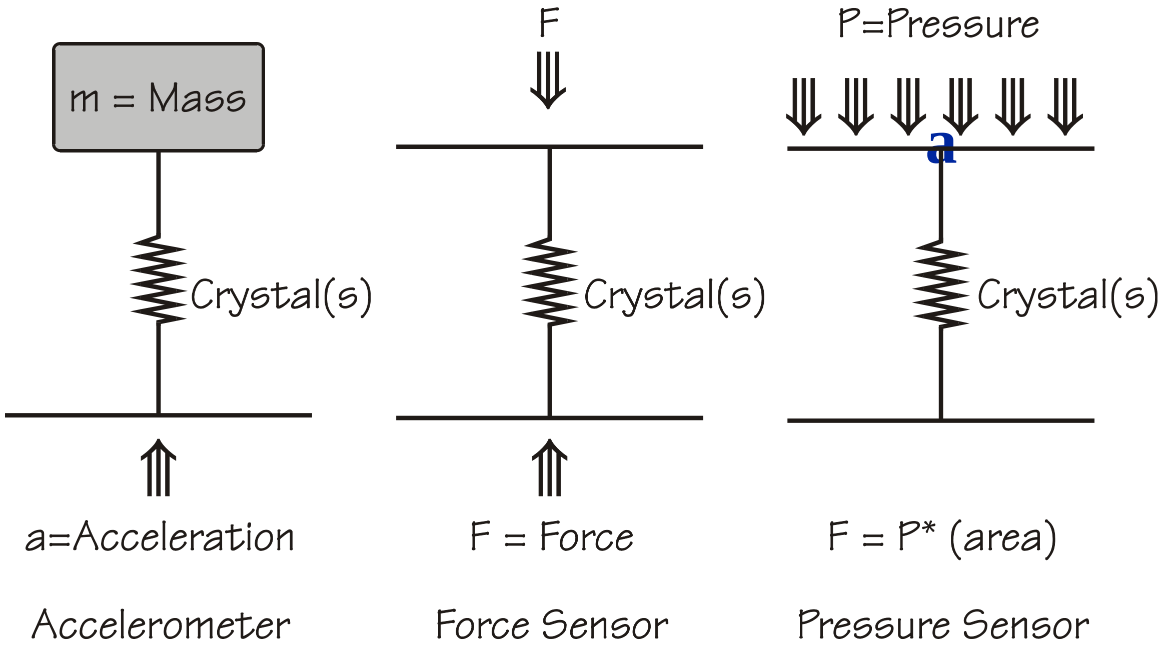
- Disadvantages
  - Pyroelectric
    - Unwanted output generated by a thermal input
  - High temperature coefficient
    - Electrical properties are dependent on temperature
  - Artificially Polarized - unstable
    - Exhibit temporary/permanent changes under large mechanical, thermal or electrical shock
    - Electrical characteristics change over time



# Sensor Structure

- A Single Degree of Freedom System
- Governed by Newton's Law of Motion:

  $F = m\ a$



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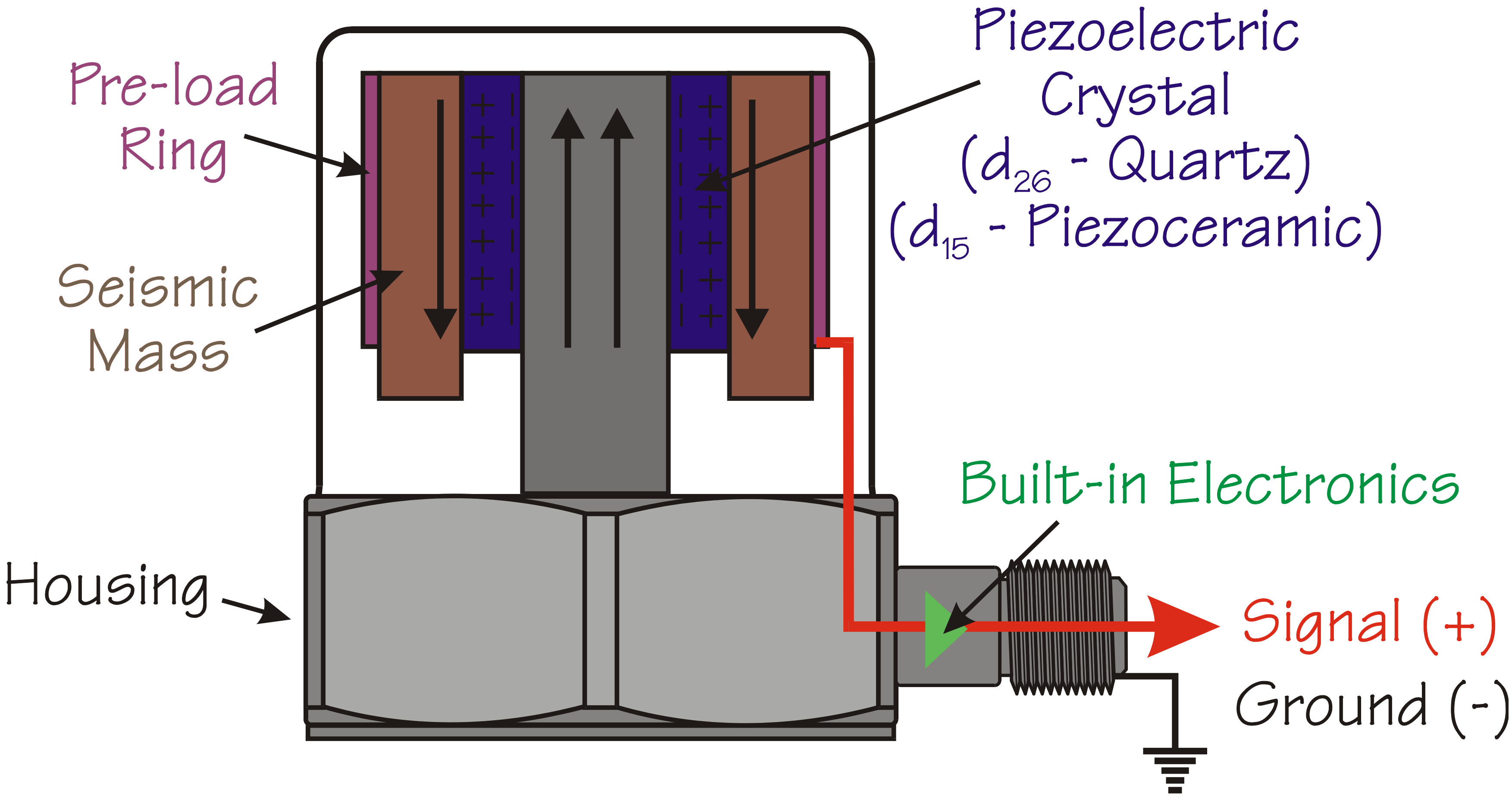
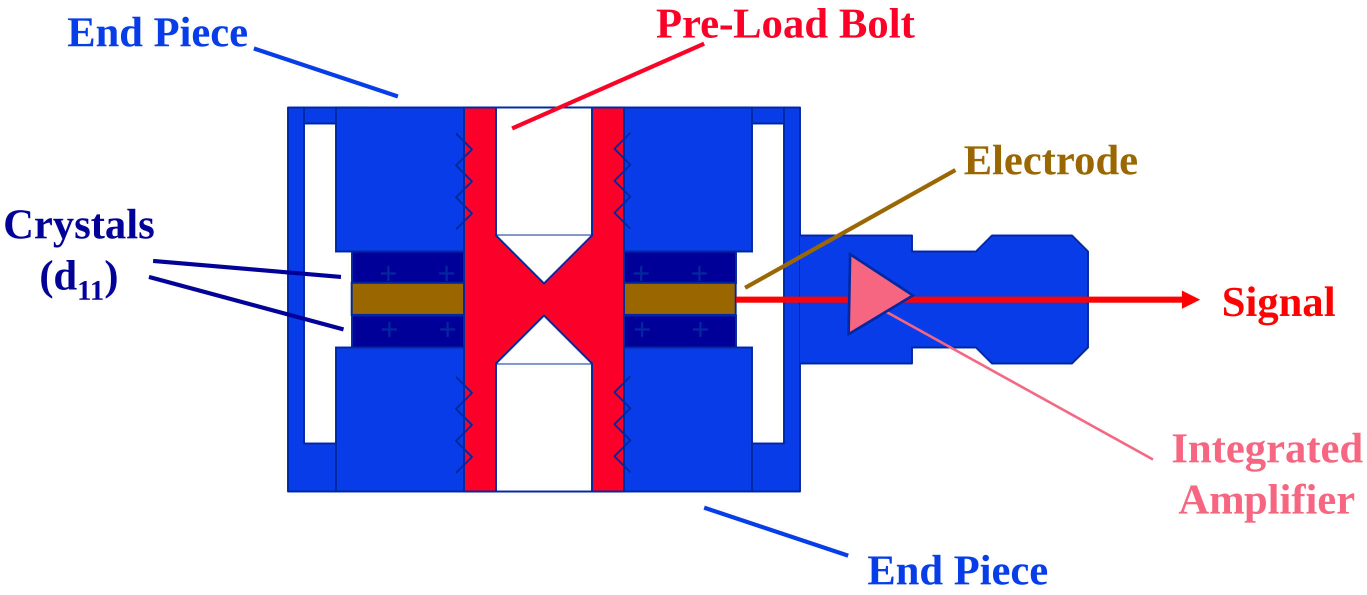
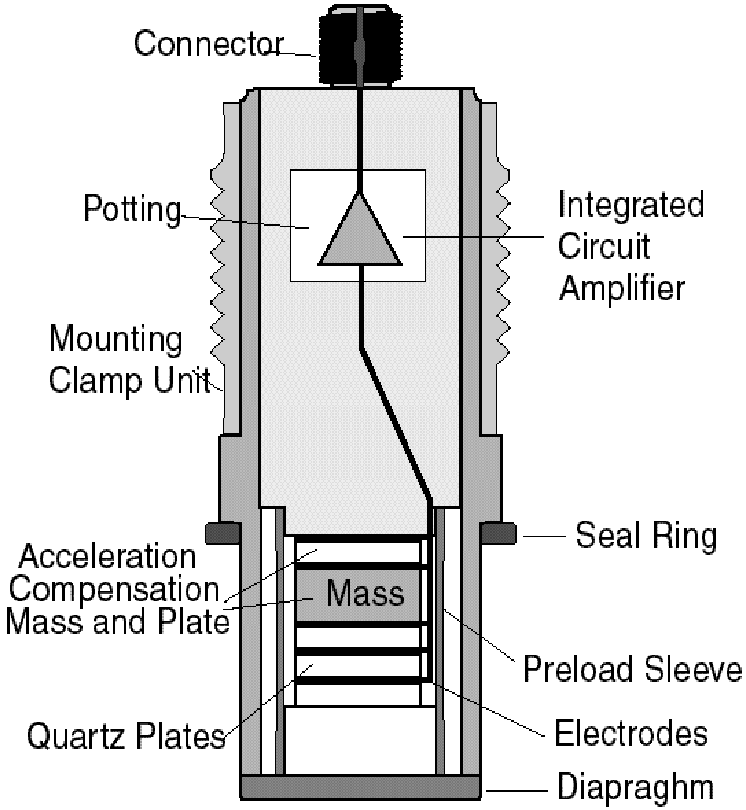
# Accelerometer, Shear Mode



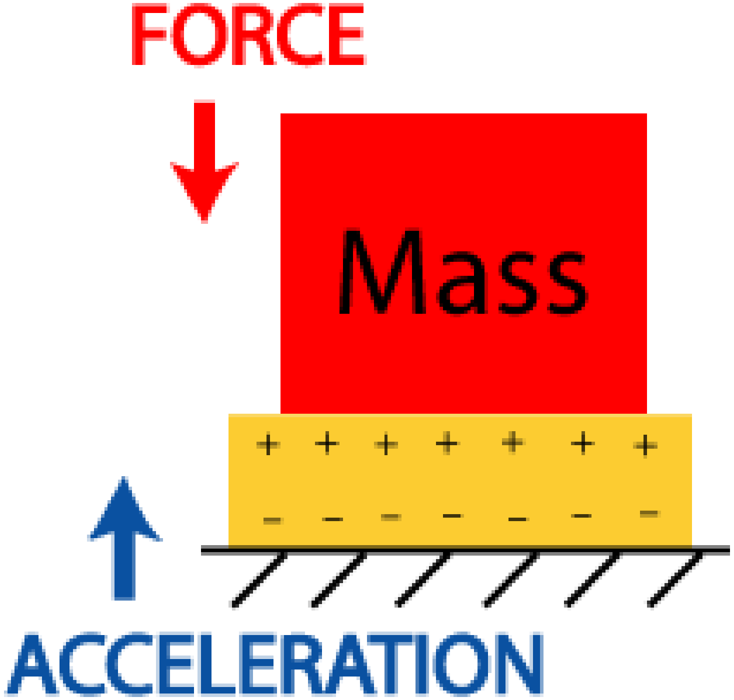
# *Force Sensor (208 style)*



# Pressure Sensor

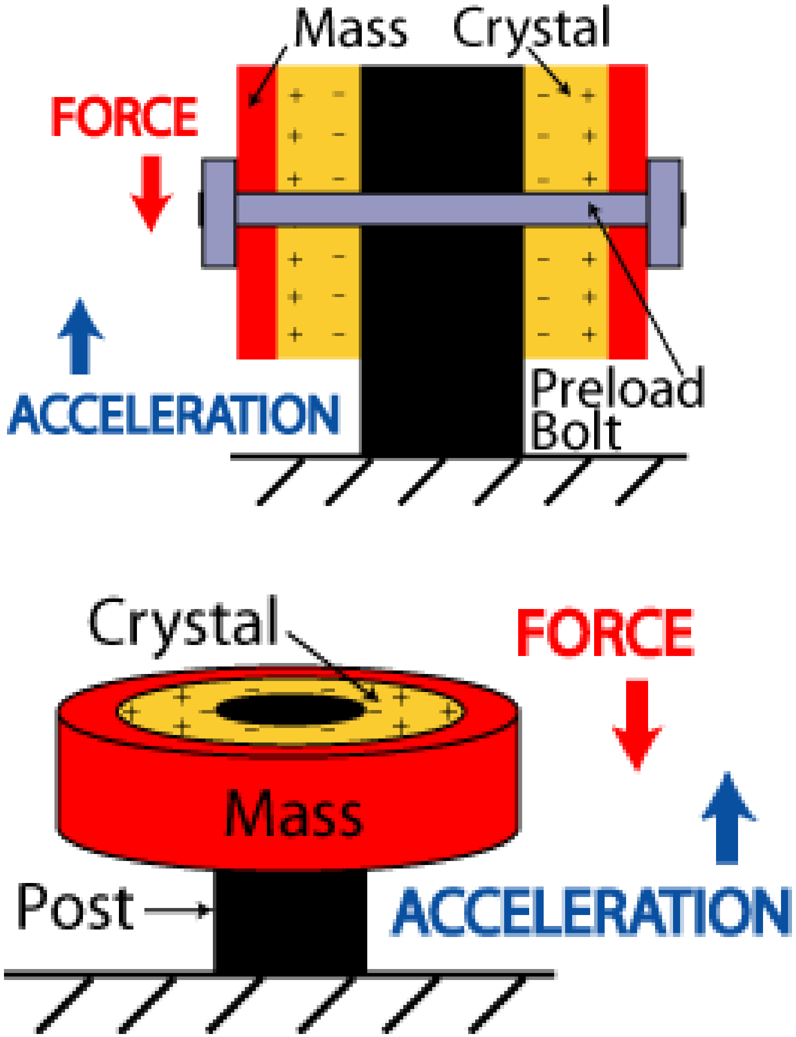


# Compression Design



The Compression design (or compression mode) offers the advantage of few parts and high stiffness leading to a high frequency range. This design tends to be more susceptible to base strain and thermal transient effects since the crystal is in intimate contact with the base of the housing. Any strain or expansion/contraction influences to the base are easily transmitted to the crystal, which can then respond with an output that is not due to acceleration and is therefore error. As a result, compression designs are not recommended for use on metal panels, which may bend, or in thermally unstable environments.

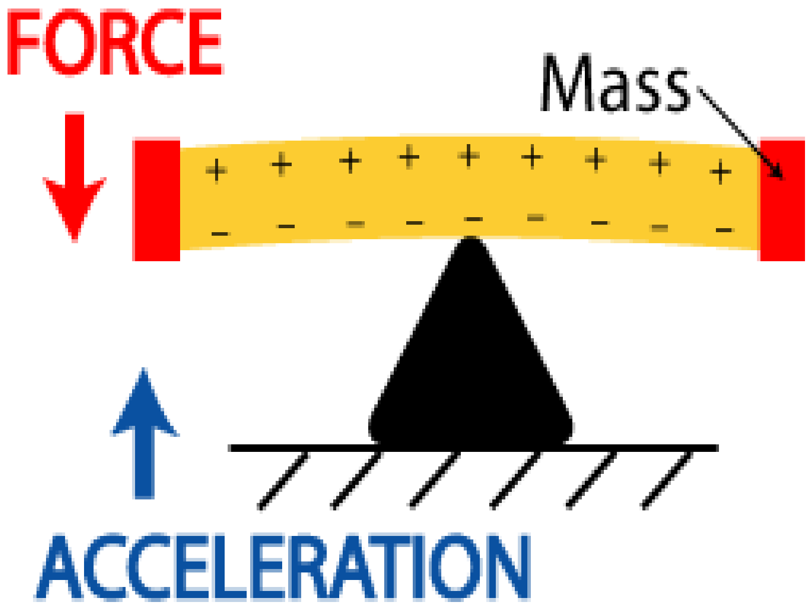
# Shear Design



Planar shear designs (using crystal plates) and annular shear designs (using a ring shaped crystal) are prevalent.

With each style, the crystal is clamped between a center post and outer mass. The more mass that is attached, the more shear force is applied to the crystal for a given acceleration. The accelerometer structure is rigid, affording a high frequency range and since the crystal is not in intimate contact with the base, strain and thermal transient effects are minimized.

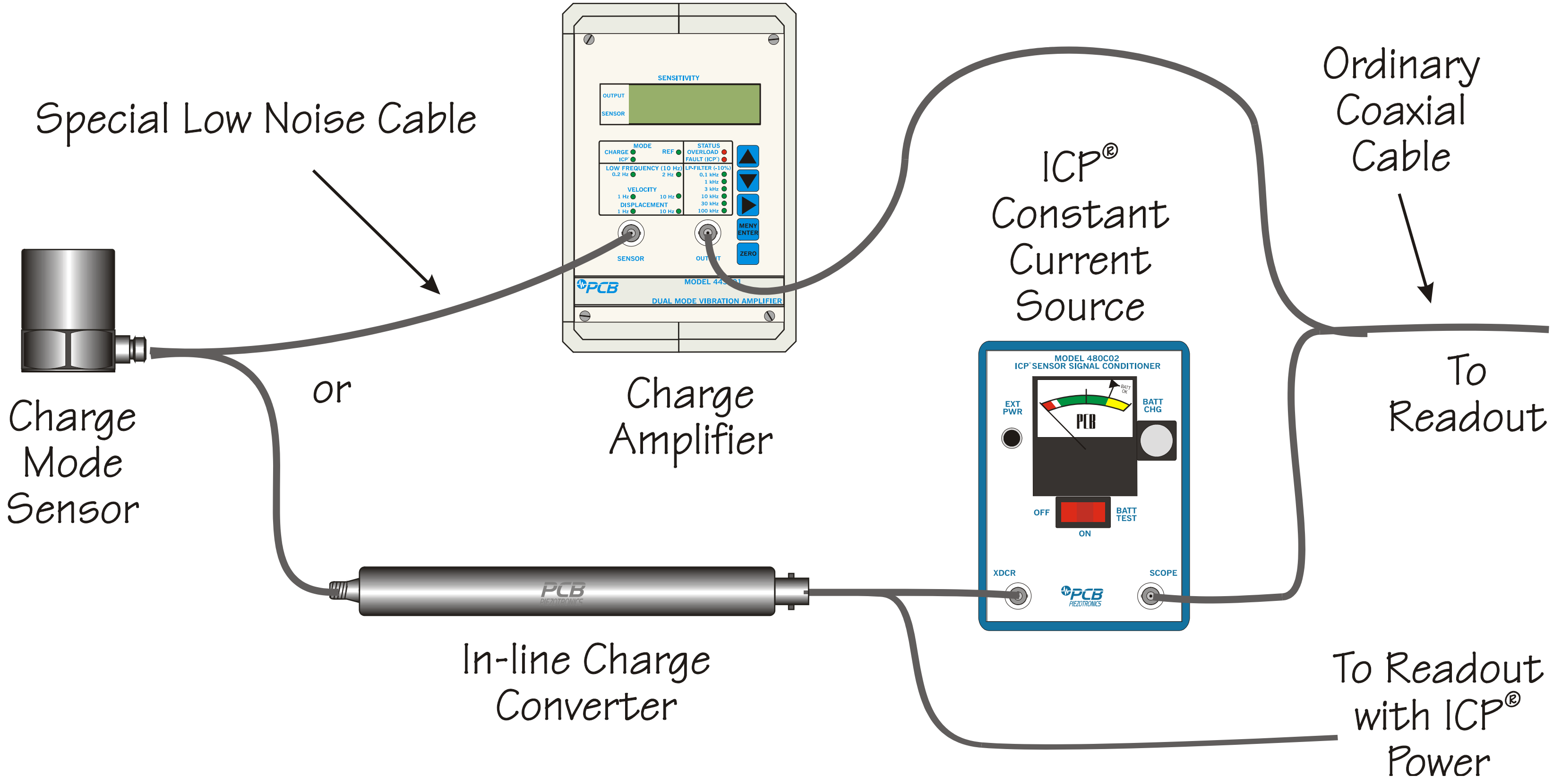
# Flexural Design



Flexural designs offer the ability to generate exceptionally high output signals since the crystal is subjected to high stress levels. These designs use crystal plates that are rectangular or disc shaped. The bending of the crystal can occur as the result of the crystal's own mass in opposition to acceleration, or to enhance bending, additional weight may be clamped or bonded to the crystal. Flexural mode accelerometers are less stiff when compared to compression or shear designs, providing them with a limited frequency range. Also, since the crystal is subjected to high stress levels, they are more easily damaged than other types if exposed to excessive shock or vibration.

# Charge Mode System

- System Schematic



Special Low Noise Cable

Charge Mode Sensor

or

Charge Amplifier

ICP® Constant Current Source

Ordinary Coaxial Cable

To Readout

In-line Charge Converter

To Readout with ICP® Power

# Charge Mode System

- Characteristics
  - High temperature range (540 C / 1000 F )
  - Amplitude range, low frequency limit, and signal normalization can be adjusted at the charge amplifier
  - High output impedance signal
    - Requires low noise cable easily corrupted by EMI and RFI
    - Often requires expensive charge amplifiers and low-noise cables
    - All high impedance components must be kept dry and clean to maintain high insulation resistance
    - Signal/noise limited by cable length
    - Difficult to use in contaminated environments

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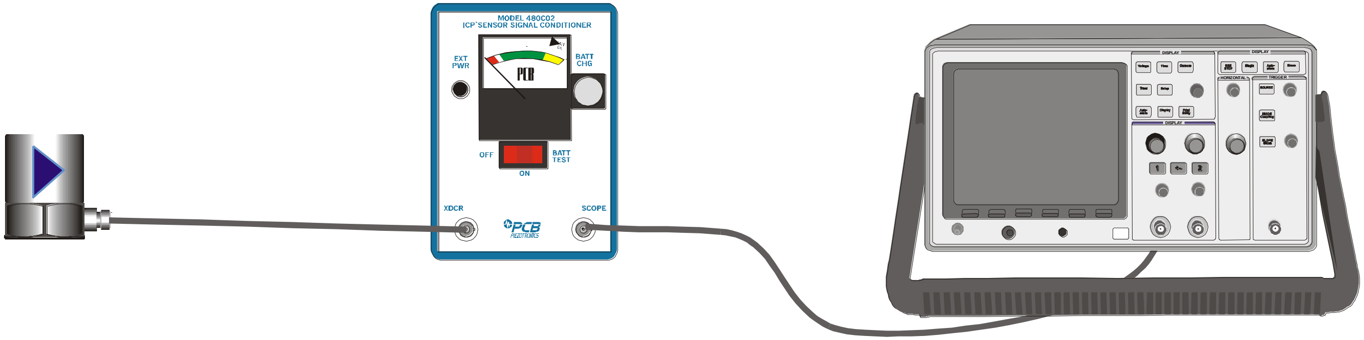
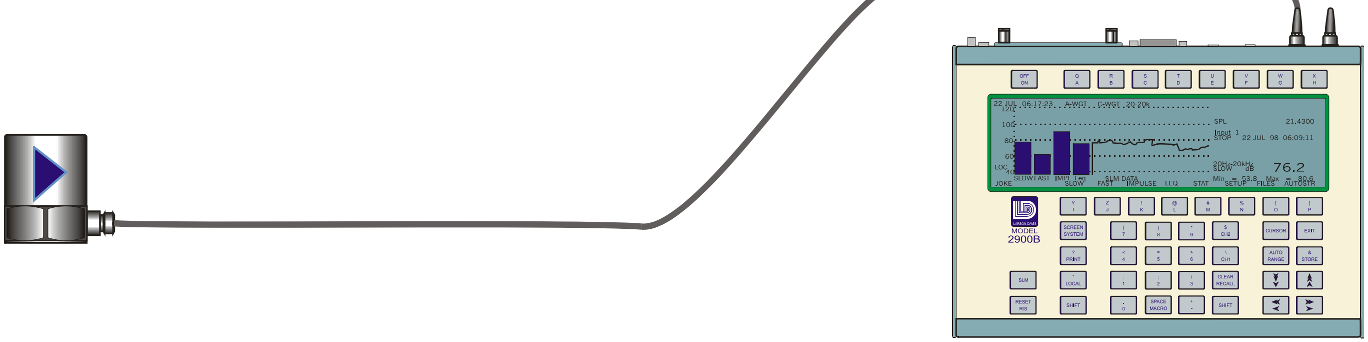
# ICP® Mode System

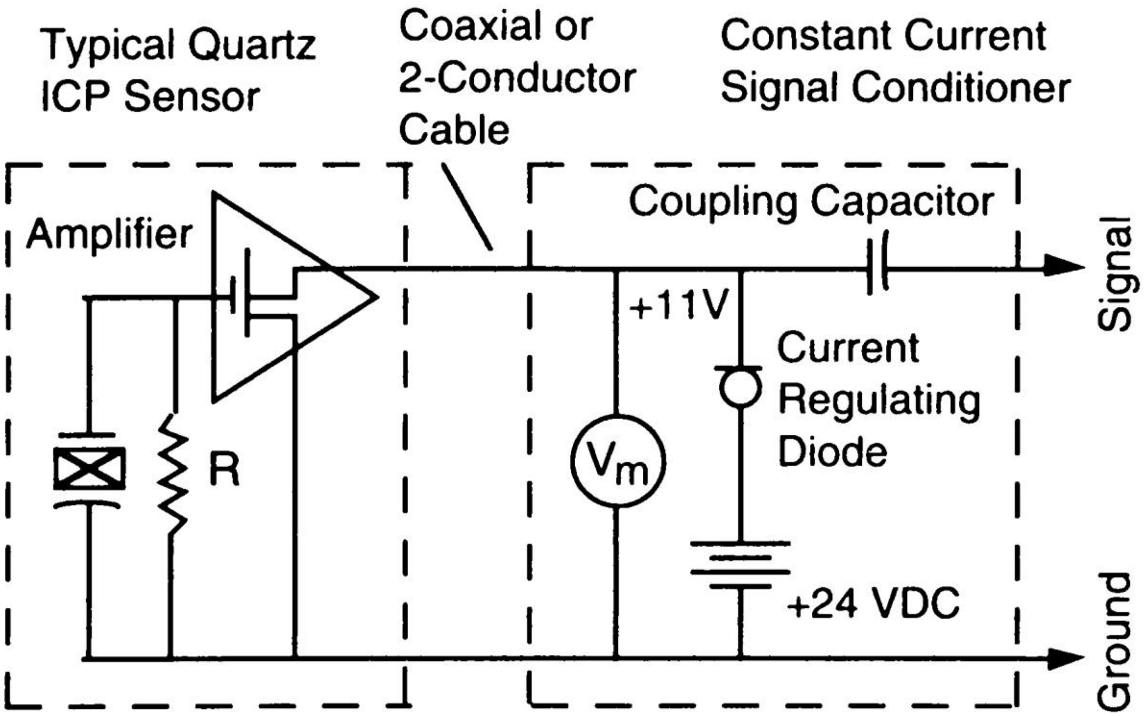
- Connected via ICP® power supply/signal conditioner to readout



- Sent directly to readout device supplying constant current power (now common in analyzers)



# ICP® Mode System



# ICP® Mode System

- Characteristics
  - Simplified Operation
  - Contain built-in electronics
    - » Low output impedance
      - High impedance circuitry protected
      - Operates over standard coaxial cable
      - Signal can be transmitted through harsh environments without loss in signal quality
    - » Two-wire operation from inexpensive constant current source
    - » Direct operation into readout equipment incorporating constant current power
    - » Fixed sensitivity, and discharge time constant

# Impedance Conversion

- Both systems convert the high impedance output of the crystal to a low impedance time-varying voltage output with a field effect transistor (mosfet or jfet)
- Impedance conversion closest to the crystal reduces capacitive loading on the fet and provides the best signal to noise ratio
- ICP® sensors, by converting the signal within the sensor minimize noise, seal all high impedance circuitry inside the sensor, and allow the use of long, low-cost, <u>ordinary</u> coaxial cable

# ICP® Advantages

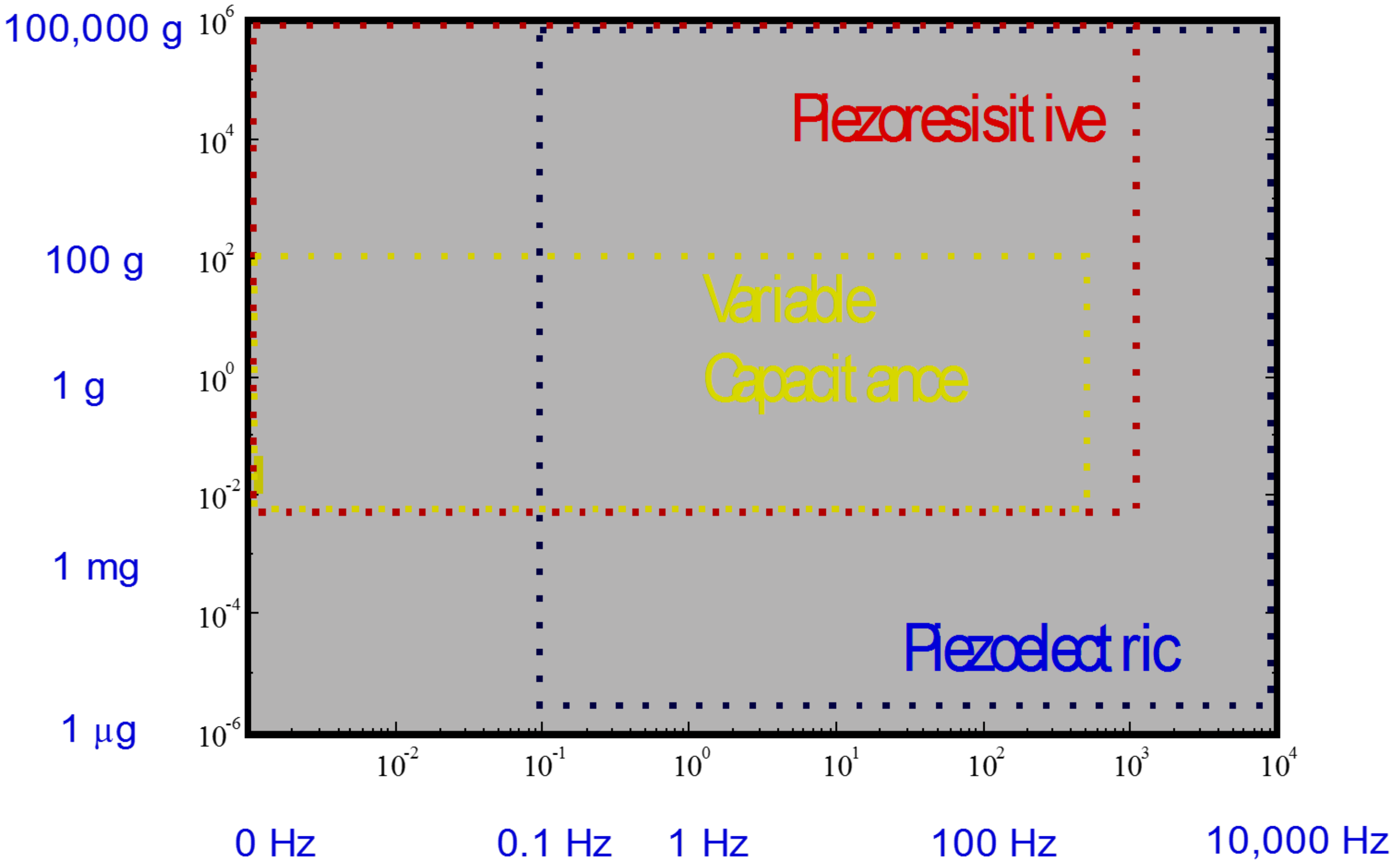
- Eliminates costly charge amplifiers and low-noise cables
- Long life ruggedness
- Use standard electronic hardware and cables
- Lower set-up and maintenance costs
- Less possibility of damage because of large overrange capability (model dependent)

# *Applications of ICP® and Charge Systems*

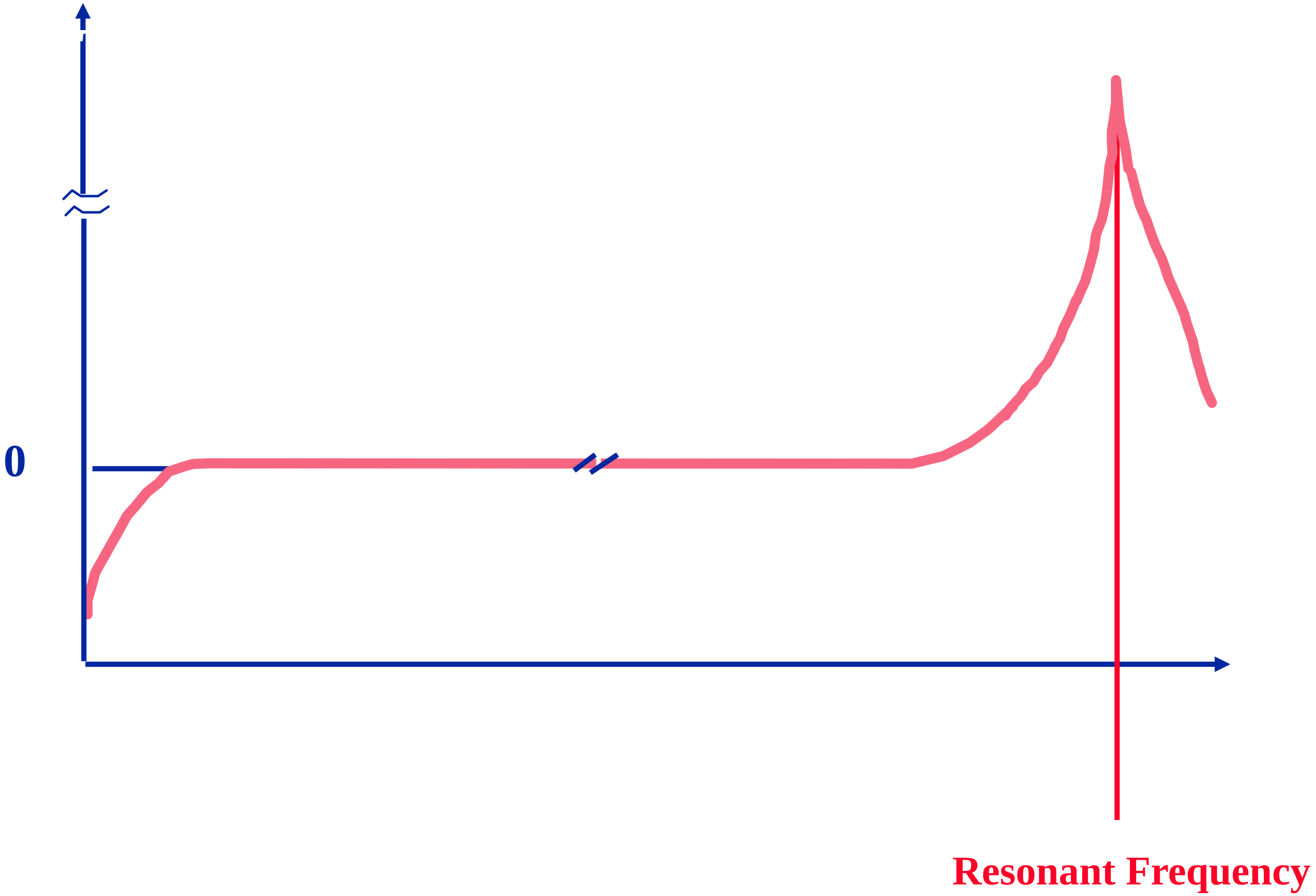
- Charge Mode
  - High Temperature Testing
    - Engine Studies, Steam Pipe Vibration, Gas Turbine Monitoring
  - High Frequency SHOCK applications
- ICP® Sensors
  - Almost Everything Else
    - Modal Analysis, Cryogenic, Shock, Machinery Monitoring, Seismic, High Frequency, Structural Testing, Flight Testing, Underwater, Human Vibration, Package Testing

# Typical Accelerometer Ranges

## *Piezoelectric, Piezoresistive and Variable Capacitance*



# Frequency Response



# *Frequency Response*

- Sensors respond to dynamic events
  - High frequency response
    - Mechanical structure of sensor
    - Mounting plays a significant role
    - Cable driving may also affect signal
  - Low frequency response
    - Sensor Discharge Time Constant
    - System Coupling Time Constant

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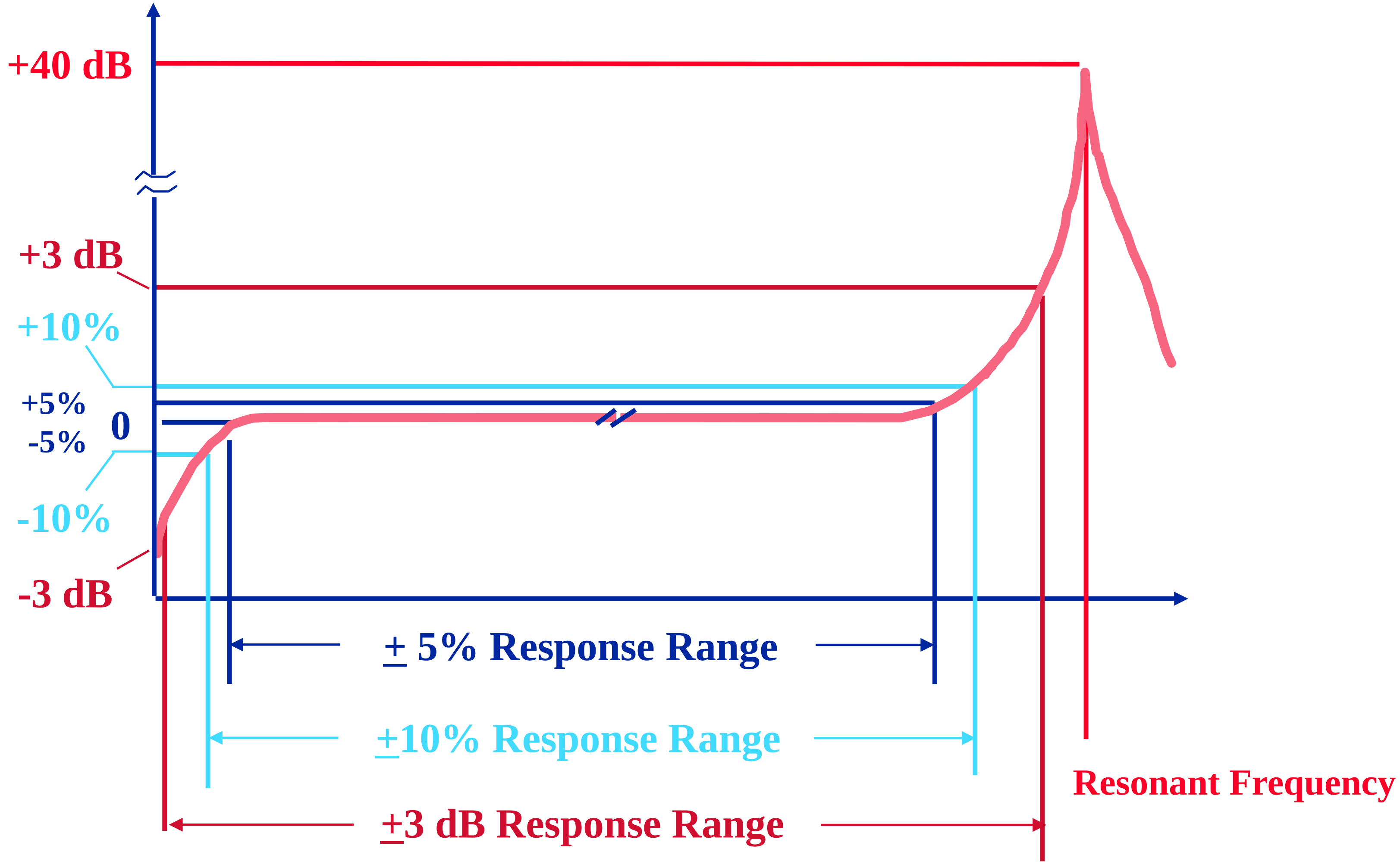
# Frequency Response (Vibration)



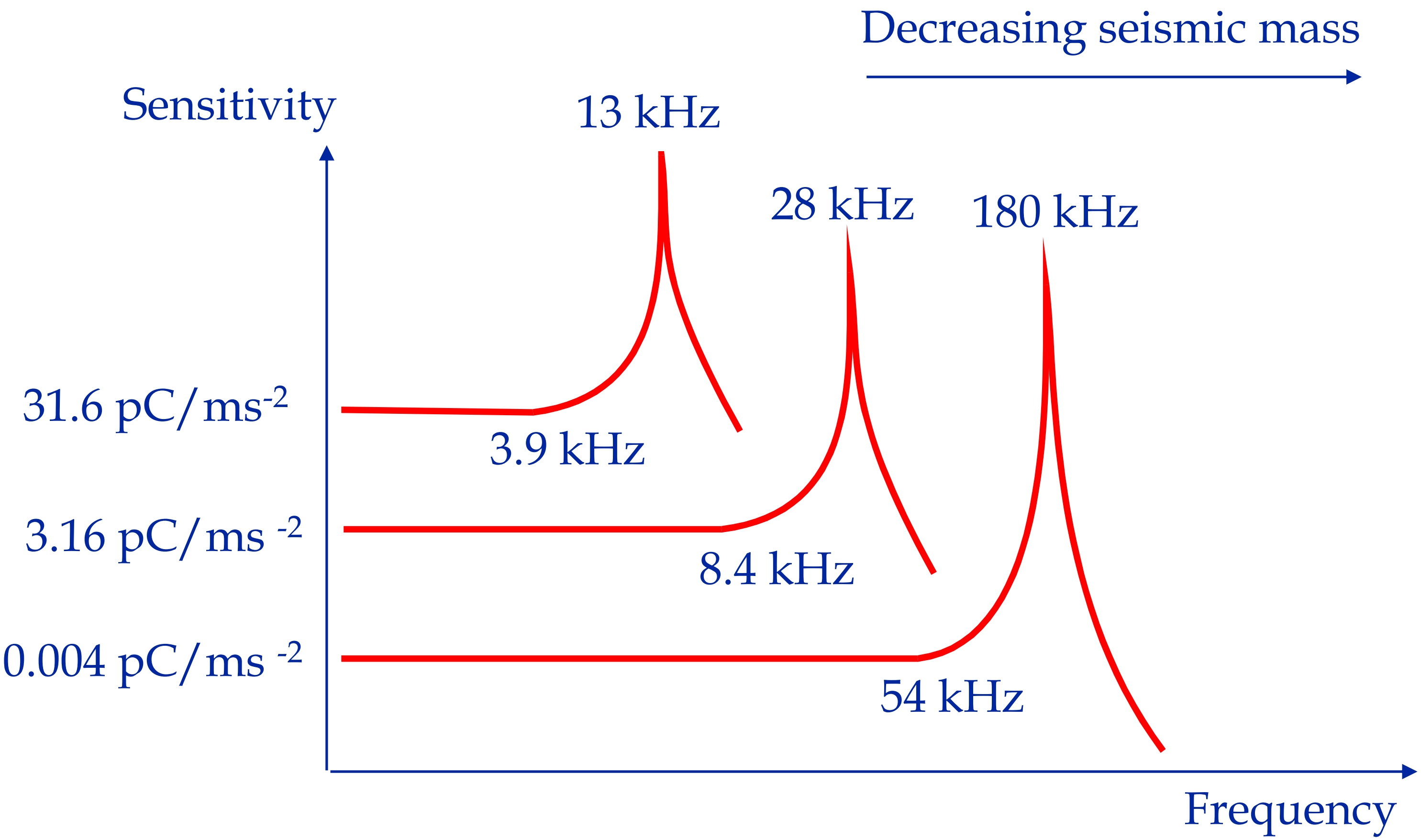
± 5% Response Range

±10% Response Range

±3 dB Response Range

Resonant Frequency

# *Accelerometer Selection*



# Range Specifications

Maximum range - The maximum shocked step input a sensor can withstand, mechanically or electrically.

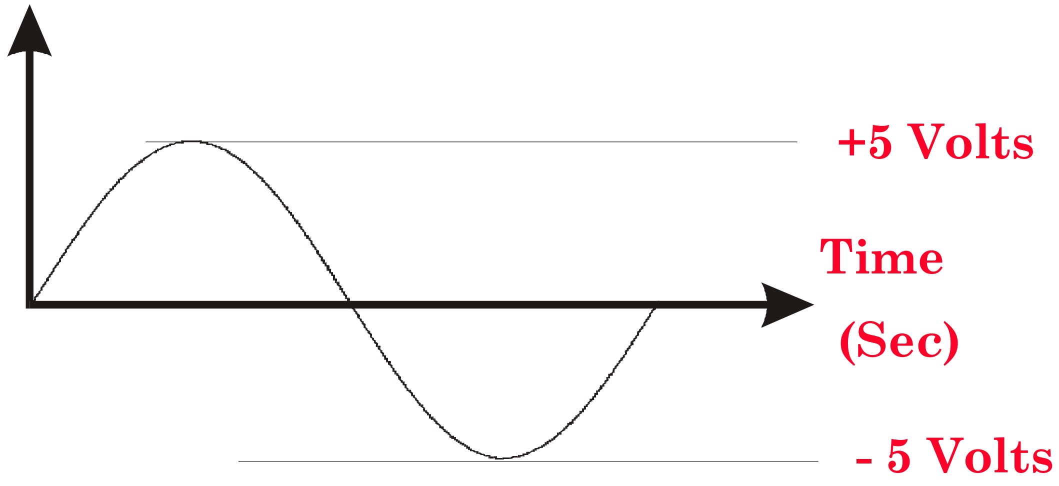
Mechanical – physical damage

- Breaking of connectors and welds
- Force, Crush the sensor
- Pressure sensors
  - ejection from port
  - Diaphram damage

- Electrical – step pressure greater than 30 volts.
  - Low range, High output sensors may contain protected circuits to prevent shock damage

# Range

- The maximum physical quantity that can be applied to the sensor maintaining the output signal to a maximum of ±5 volts.
- For the above limits the amplitude linearity is better that 1% of F.S.O.



# Range Specifications

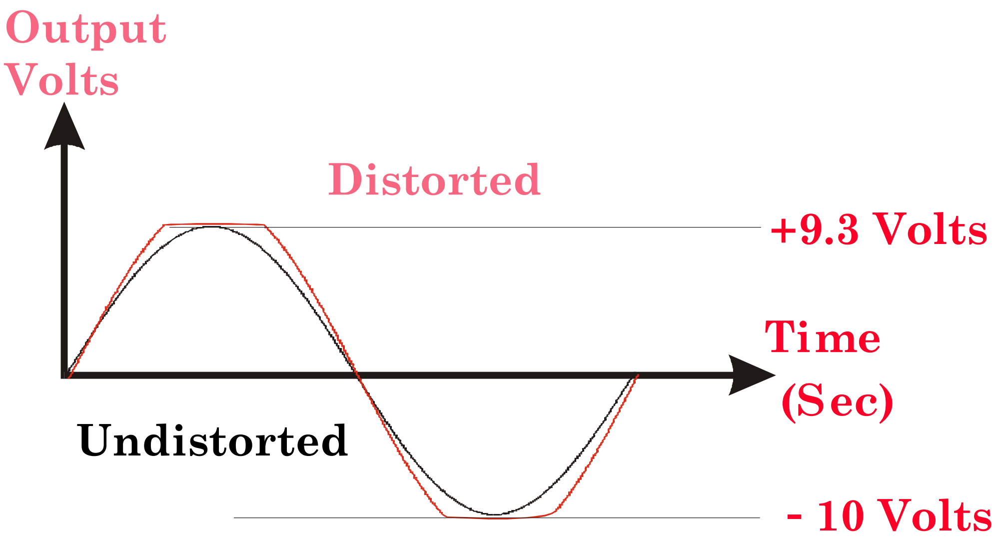
**Useful Overrange** – the maximum operating range of the sensor limited by either maximum mechanical input or electrical output

Electrical output may be limited by the supply input

In some cases, a sensors useful over range maybe the same working range specification of the sensor. This is due to characteristics of that specific sensor.

# *Over-range Capability*

- The maximum physical quantity that can be fed in the sensor input. Usually at this level of amplitude, linearity of 1% of F.S.O does not apply anymore (distortion from 5 to 10% is normal at levels above the Range specification.)



# Sensitivity

- Sensitivity partly determines the amplitude range as most sensors are specified with a +/- 5 V output
  - 100 mV/unit x +/- 50 unit = +/- 5 Volt
  - 5 mV/unit x +/- 1000 unit = +/- 5 Volt

- Typical accelerometer sensitivities include:
  - General Purpose: 10 to 100 mV/g
    - Shock: 0.01 mV/g
    - Seismic: 1 to 10 V/g
  - Force: 110mV/N to 0.011 mV/N
    500mV/lb 0.05mV/lb
  - Pressure: 0.010mV/kPa to 14.5 mV/kPa
    0.07 mV/psi to 100 mV/psi

# *Sensitivity*

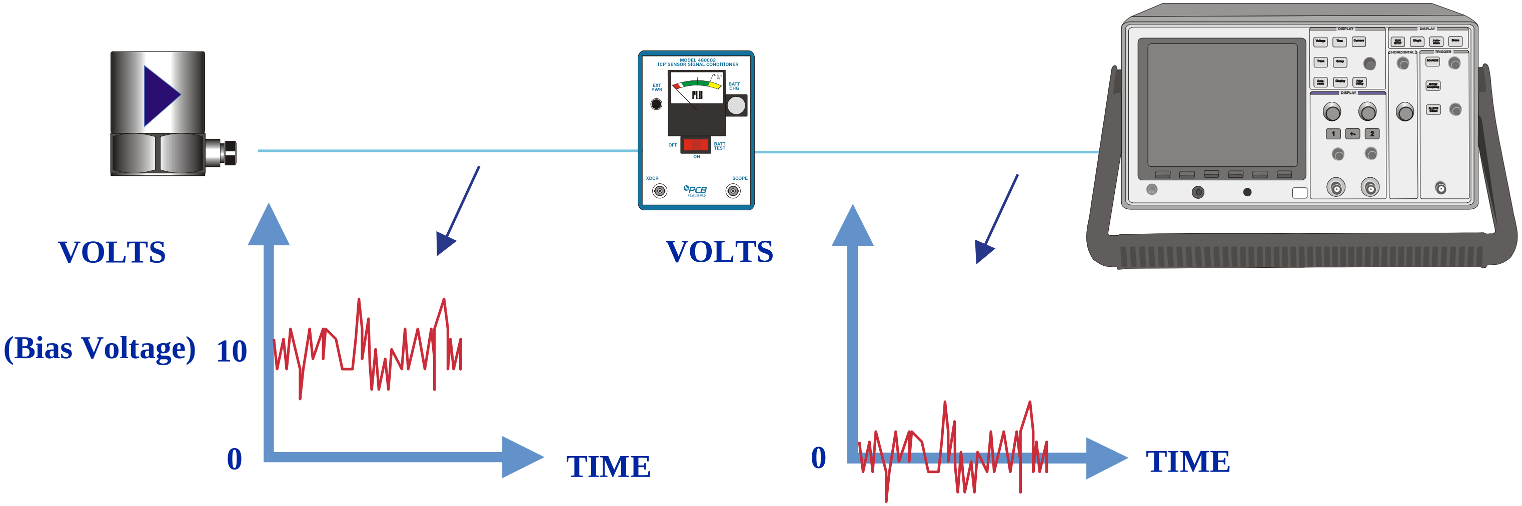
- Is sensitivity specified as, or mV/g peak, mV/g peak-peak, or mV rms?
  - Neither, it is simply mV/g
    - » We calibrate sensors at 1 g rms and; hence, read the sensor output as volts rms. (Units Cancel!)
  - How you analyze the signal will determine whether the vibration is rms or peak!
    - » If you measure the peak amplitude of the measurement signal and divide by the sensitivity, the result is g peak
    - » If you run the signal through an rms meter and divide by the sensitivity, the result is g rms.

# Bias Voltage

- In ICP® sensors, bias voltage is the voltage required to turn on the electronic circuit. It is generally in the range of 8-14 volts.
- Higher output miniature sensors may have a bias as high as 17 volts.
- Some sensors can be provided with low bias electronics with a range of 4-6 volts. ( “B” prefix to PCB models)

# Amplitude Range

- Amplitude range is dependent on:
  - Excitation Voltage
    - » Power supply voltage minus 1 Volt drop across C.C. Diode
  - Sensor Output Bias
    - » A DC voltage at the output of an ICP sensor on which an AC measurement signal is superimposed



# Amplitude Range

Amplitude Range is how much output may be obtained during a reading.

Positive Swing:

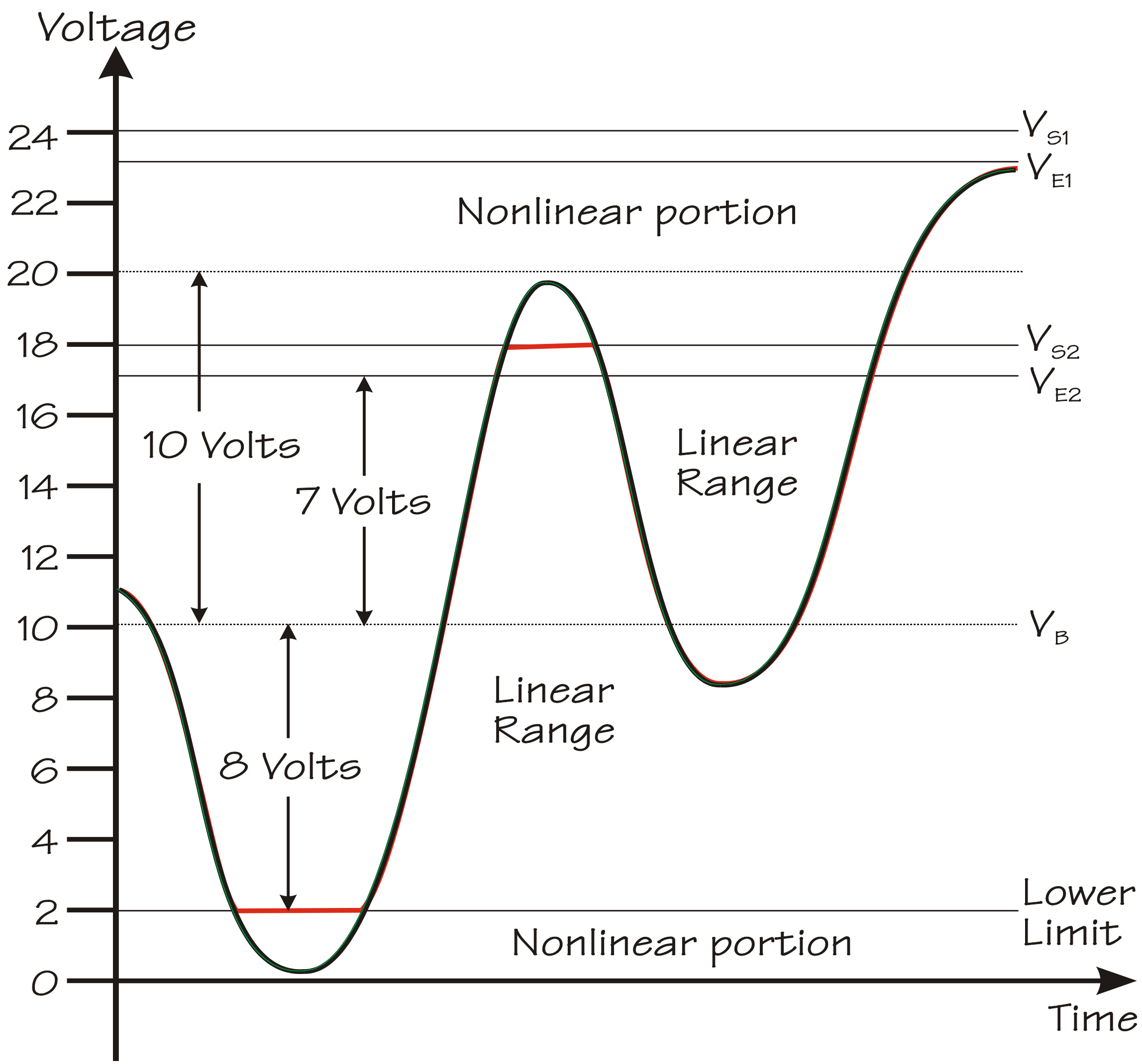
Supply Voltage – Sensor Bias Voltage – 1 Volt (for cc Diode) = Amount of positive voltage swing available

Bias Voltage is the baseline -----------------------------------

Negative Swing:

Bias Voltage – 2 Volts (readings below 2 volts may be poor) = Amount of negative voltage swing available

# Amplitude Range



- 🟦 Theoretical Measureand (Output)
- 🟥 Output Signal (18 VDC Supply)
- 🟥 Output Signal (24 VDC Supply)

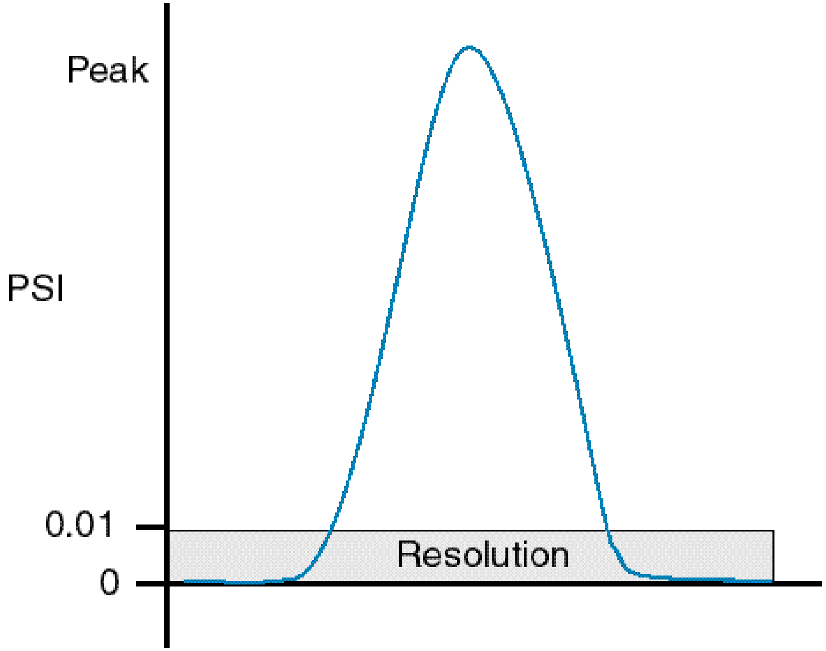
Specified amplifier range = +/- 5 Volts
Actual max. amp. range = +/- 10 Volts

# Resolution (Noise Floor)

- How low can one measure?
- Electrical characteristic
  - ICP® - Noise floor of internal electronics
  - Charge – Noise of the external charge amplifier
  - Discharge Time Constant determines low end frequency response
- For Accelerometers
  - Broadband – the average lowest level over a frequency range.
  - Spectral – The resolution at a specified frequency.

# Resolution

Suggested low level measurement is 10 times greater than resolution.



# Cabling

- The accuracy and reliability of a measurement system is no better than that of the cabling itself.

- Cabling is the weak point of the measurement system

# *Attaching Cable to Sensor*

General rules

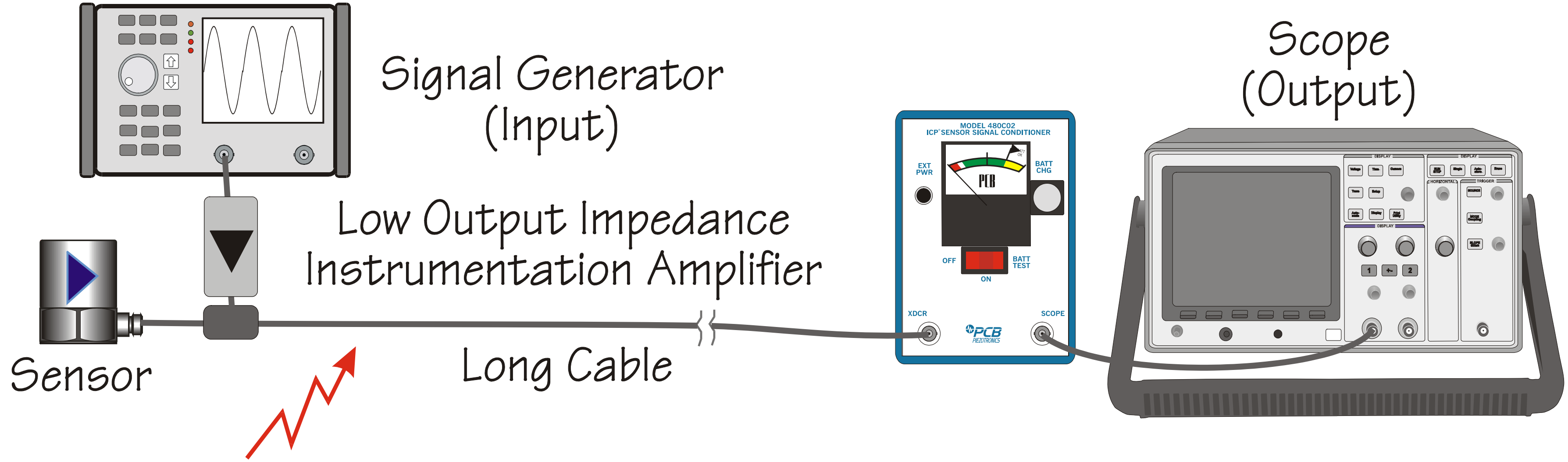
- Use serviceable thread locker on connector
- Strain relieve cable at sensor
- Secure cable to minimize motion
- “Figure 8” wrap extra cable.  Do not let it dangle.
- Use low noise cable with charge mode sensors
- Do not kink the cable
- Cross power lines at right angles
- Use twisted pair in high magnetic areas
- Screw the Cable onto Sensor. **DO NOT SPIN** Sensor onto Cable!! – You will break the cable resulting in an intermittent connection!

# *Driving Long Cables*

- What is a "long" cable run
  - To some customers, 3-meters (10-feet) is long.
  - PCB has stock cable up to 30 Meters (100 feet)
  - 480 Series signal conditioners can drive signals 60 meters (200 feet)
    - » Battery Supplies - Current within 480 Series is factory set, non-adjustable at 2mA.
    - » Line Supplies - Current within other 480 Series is factory set at 4mA. They may be adjusted to 20mA.
  - For longer lengths, adjust current within the signal conditioner

# Effect of Long Cables

- Experimentally testing long cables
  - Input/Output = 1 system O.K.
  - Input/Output < 1 add series resistance
  - Input/Output > 1 increase constant current



# *Effect of Long Cables*

- Capacitive loading of long cable runs may distort (or filter) higher frequency signals
  - $F_{max}$ = Maximum frequency (Hz)
  - C = Cable capacitance (pF)
  - V = Peak voltage output from sensor (V)
  - $I_c$ = Constant current available from power source (mA)
  - 10 = Scaling constant
  - $\pi$ = 3.14159

$$\mathbf{F\ max} = \frac{\mathbf{10^9}}{\mathbf{2\,\pi\,CV / (I - 1)}}$$

# *Effect of Long Cables*

**ASSUME:** 30 meter (100 ft. Cable)
100 pF/mtr (30 pF/ft)
+/-5 Volt Sensor Output
2 mA CC Supply

**1) CABLE CAPACITANCE:**
**C x L = 100 * 30 = 3000 pF**

**2) RATIO:**
**V / ($I_C$ - 1) = 5 / (2 - 1) = 5**

**3) MAX. FREQUENCY:**
**From Chart = 10.2 kHz**