Piezoelectric accelerometer design

Piezoelectric transducers

Quartz and piezoceramics

Mechanical design

Charge amplification

Design trade-offs

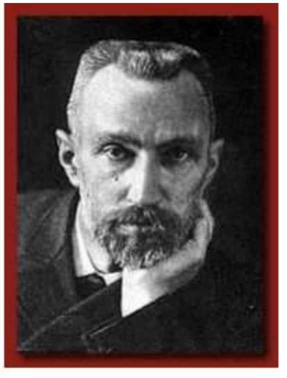
Wilcoxon SENSING TECHNOLOGIES

Industrial accelerometer design, 2009

- **Piezoelectric transducers**
  - What does piezoelectric mean
  - What is a transducer
  - What is a sensor
  - What is an accelerometer

Industrial accelerometer design, 2009

- **What does piezoelectric mean**
  - Electricity, produced by
  - Pressure, applied to a
  - Crystaline substance



Pierre Curie

piezo- *combining form* [Gk *piezein* to press; perh. akin to Skt *pīḍayati* he squeezes]
: pressure <*piezo*meter>

pi•e•zo•elec•tric•i•ty \-ˌlek-ˈtri-s(ə-)tē\ ***noun***
[ISV] (1883)
: electricity or electric polarity due to pressure esp. in a crystalline substance (as quartz)

Industrial accelerometer design, 2009

- **What is a transducer**
  - A device that converts energy

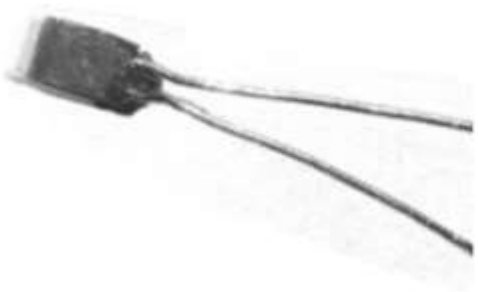
Mechanical

↑ ↓

Electrica

Industrial accelerometer design, 2009

- **What is a sensor**
  - A sensor is a transducer that is used to "sense" a mechanical property and produce a proportional electrical signal
  - RTD, LVDT, strain gages, thermocouples and accelerometers are examples of some common sensors



Industrial accelerometer design, 2009

- **What is an accelerometer**
  - A sensor is a that measures **acceleration**
  - Based on Newton's second law of motion
  - The acceleration of an object as produced by net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object
  - Or, mathematically, $F = m\,a$

Industrial accelerometer design, 2009

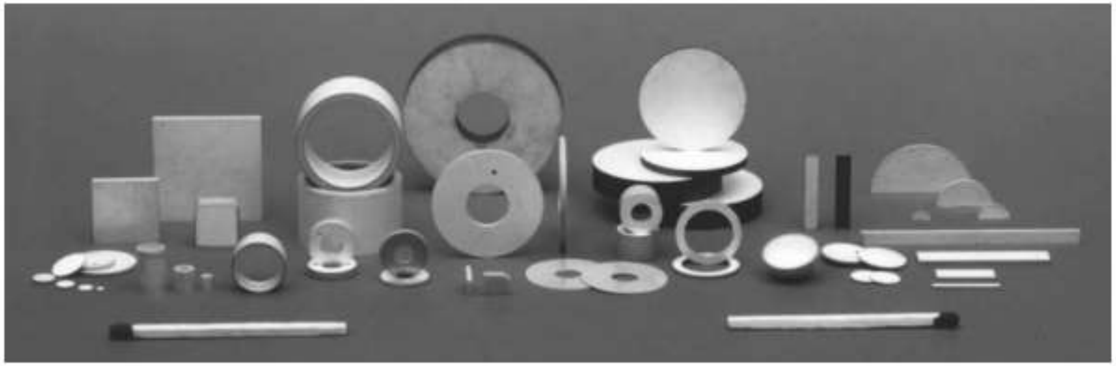
- **Accelerometer materials: quartz and PZT**
  - Quartz and PZT are piezoelectric materials
  - Squeeze them and they produce electric current
  - Apply electric current and they change shape

Industrial accelerometer design, 2009

- **Quartz**
  - Is a “natural” piezoelectric material
  - Never loses piezoelectric properties
  - Modern quartz transducer crystals are grown, not mined
  - Is not as quantum efficient as ferromagnetic piezoelectric material

Industrial accelerometer design, 2009

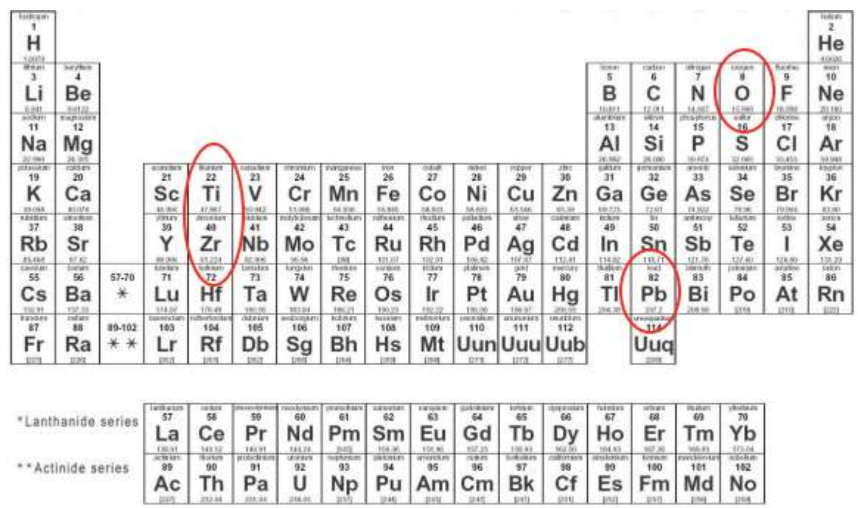
- **Ferroelectric materials**
  - A group of ceramic materials
  - Found to have the ability to become “magnets”
  - Some can be made into piezoelectric ceramic
  - Lead-Zirconate-Titanate (PZT) is the piezoceramic used in most industrial transducers



Ferroperm piezoceramics

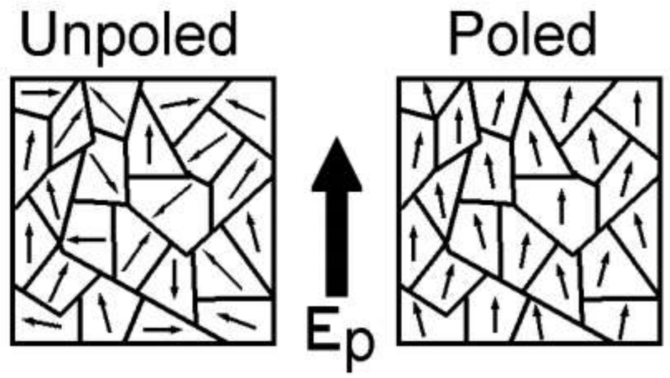
Industrial accelerometer design, 2009

- **Lead-Zirconate-Titanate**
  - Lead: Atomic symbol **Pb** (latin **P**lum**b**um)
  - Zirconate: A Zirconium Oxide (ZrO_2), Zirconium symbol **Zr** (mineral **Zir**con)
  - Titanate: A Titanium Oxide (TiO_2), Titanium symbol **Ti** (greek Titanos)
  - Resulting in **PZT**



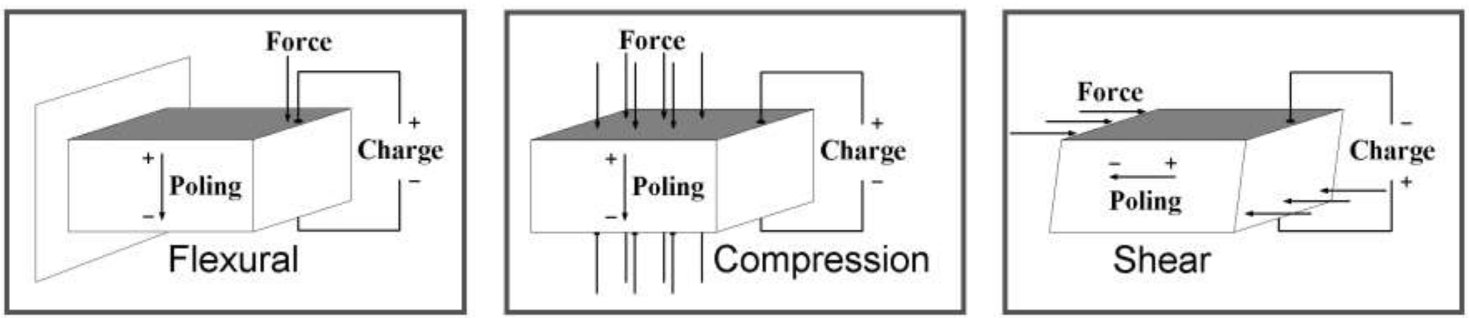
Industrial accelerometer design, 2009

- **Poling**
  - The process of making a ceramic become piezoelectric
  - Apply electrodes
  - Connect to DC voltage
  - Leave connected for time
  - Results in “aligned” crystal matrix



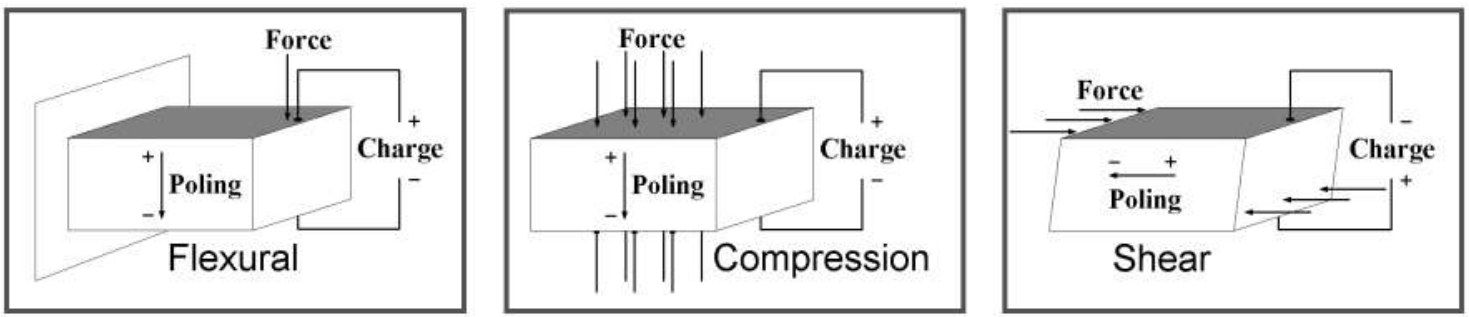
Industrial accelerometer design, 2009

- **PZT must be poled for final use**
  - Poling method and direction is specific for the intended use
  - Polarity is important



Industrial accelerometer design, 2009

- **What is the pyroelectric effect**
  - Piezoceramic crystals that are poled in the axis of use will have a pyroelectric output
  - Flexural and compression designs exhibit pyroelectric output
  - However, it usually appears as a very low frequency signal, below 0.5 Hz

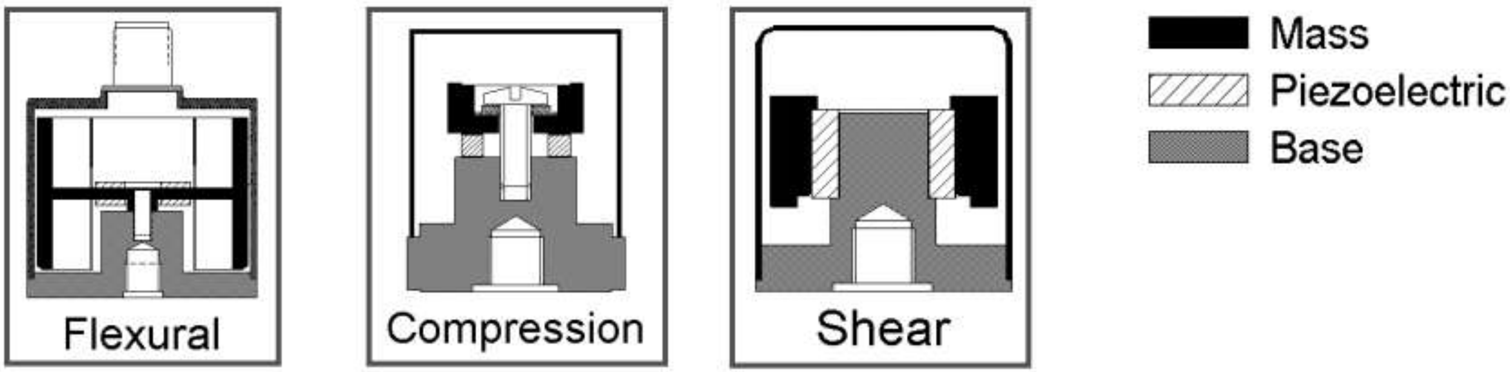


Industrial accelerometer design, 2009

- **Mechanical design**
  - Base, PZT and mass
  - Mechanical stack
  - Mechanical design factors

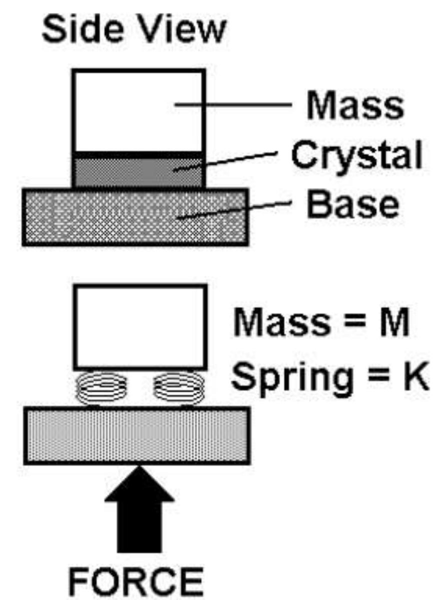
Industrial accelerometer design, 2009

- **Base, PZT and mass**
  - Base mounts to machine
  - PZT mounts on base
  - Mass mounts on PZT
  - F = m a
  - Acceleration output



Industrial accelerometer design, 2009

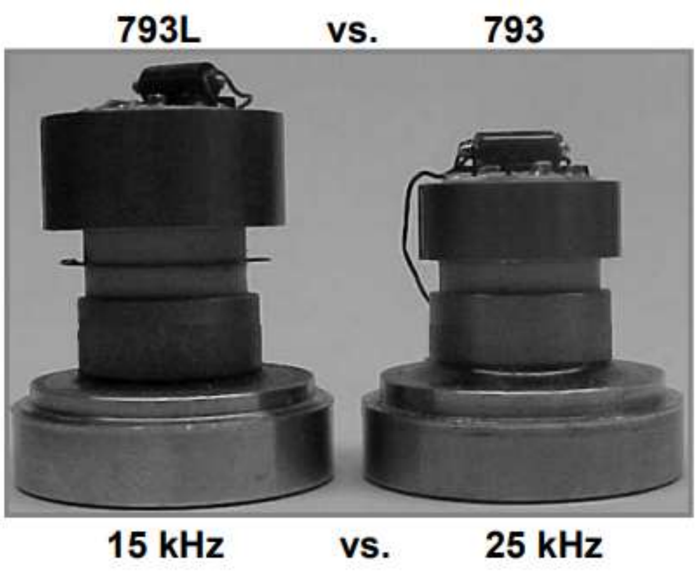
- **Mechanical stack**
  - The resonant frequency of an accelerometer stack is a function of the mechanical properties of the materials and the design style



$$F_n \propto \sqrt{\frac{K}{M}}$$

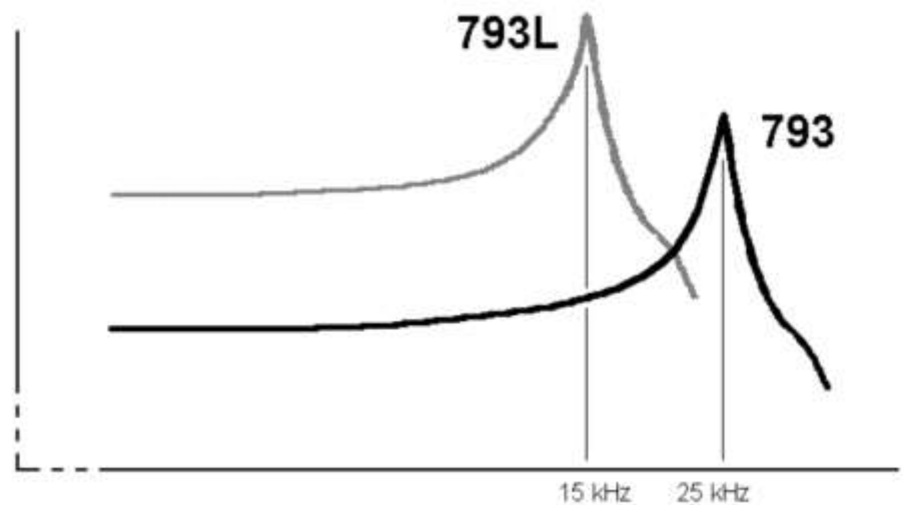
Industrial accelerometer design, 2009

- **Mechanical design factors**
  - Increase mass to increase output
  - Increase number of ‘crystals’ to increase output
  - Doing either will reduce the resonant frequency
  - A special bonus is also a reduction in noise level



Industrial accelerometer design, 2009

- **Mechanical design factors**
  - Increase mass also increases sensitivity, but lowers useful upper frequency

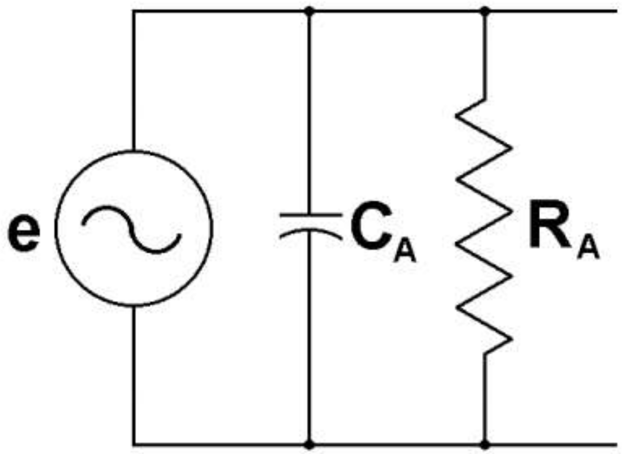


Industrial accelerometer design, 2009

- **Charge amplification**
  - Charge mode accelerometers
  - Charge amplifiers

Industrial accelerometer design, 2009

- ## Charge-mode accelerometers



Basic equation:

V = Q / C

where

Q = charge produced

C = sensor capacitance

V = voltage output

R is leakage and affects the low-frequency response

Industrial accelerometer design, 2009

- ## Charge amplifiers

C_i is the input capacitance of the amplifier

R_i is the input resistance of the amplifier

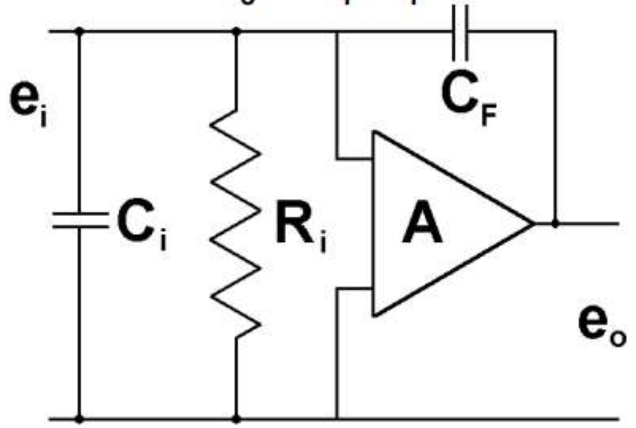
C_f is the feedback element of the amplifier

A is the amplifier

Keeping the resistance between conductors near 100 megohms is critical to operation

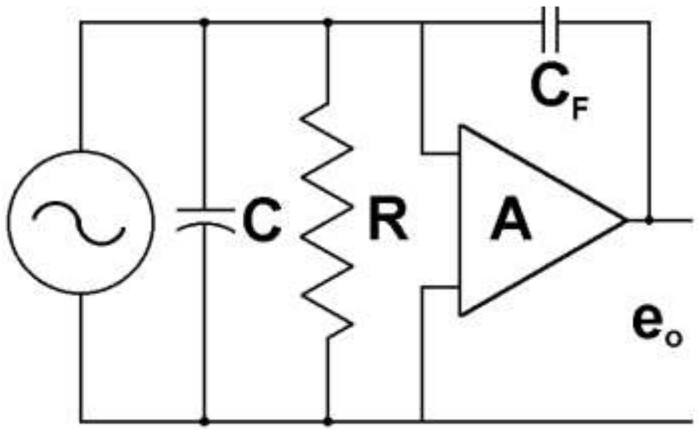
Basic equation of gain

$e_o = - e_i / C_f$



Industrial accelerometer design, 2009

- **Charge amplification inside the sensor**
  - Basis for all IEPE sensors
  - Cable length is then not an issue for most applications

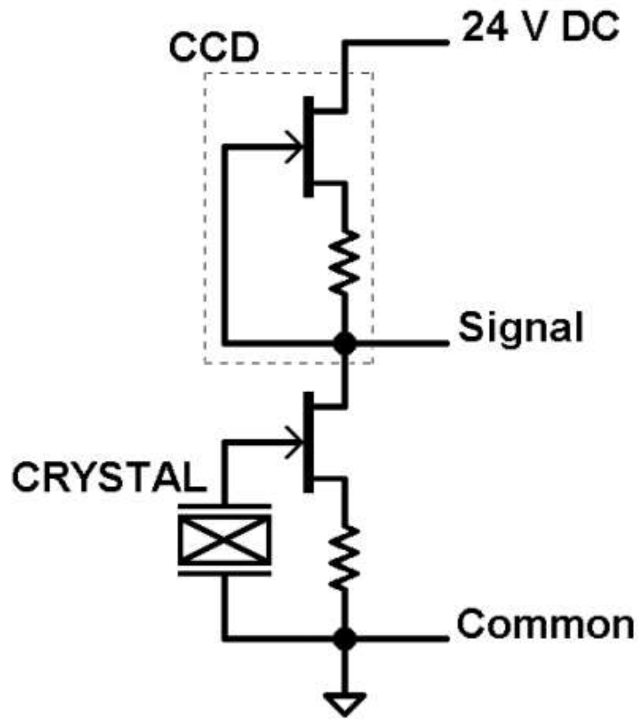


Industrial accelerometer design, 2009

- **Design trade-offs**
  - Power
  - Cable length limits
  - CCD limits
  - Discharge time-constraint
  - Sensitivity
  - Frequency response
  - Mounted resonant frequency response
  - Noise
  - Low frequency measurements
  - Operational range

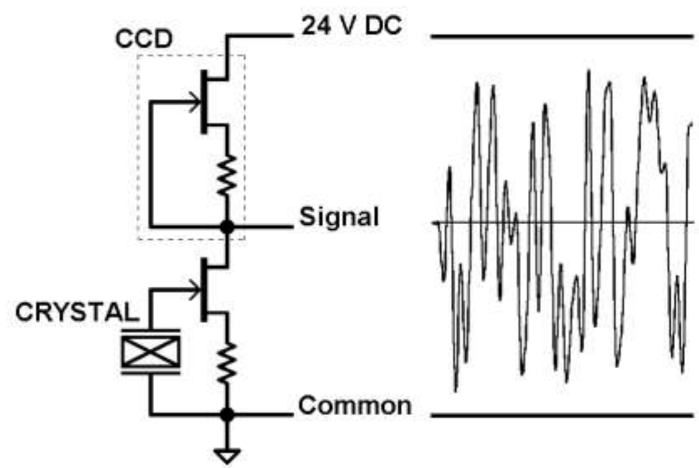
Industrial accelerometer design, 2009

- **Signal and power on two wires**
  - Basis for all IEPE sensors
  - Circuit was pioneered by Kistler Instruments in the 1960's



Industrial accelerometer design, 2009

- **Internal amplifier produces BOV**
  - Constant-current diode powers sensor
  - DC voltage appears at sensor terminals
  - Vibration signal is superimposed on the DC voltage
  - Allows long cables

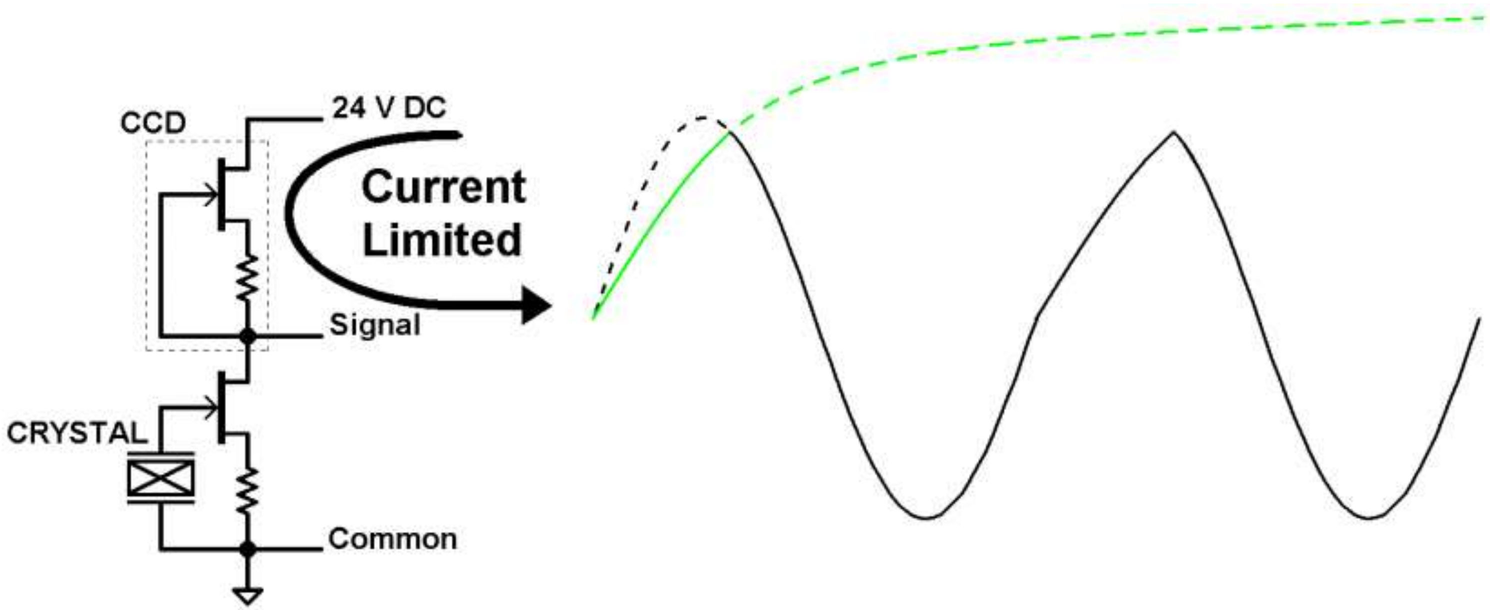


Industrial accelerometer design, 2009

- **Cable length limits**
  - Long cables connected to IEPE sensors cause signal distortion of the “positive-going” signal
  - It is a “slew rate” limitation to the signal
  - Results in harmonic distortion and false harmonic signals

Industrial accelerometer design, 2009

- **CDC limits current on positive cycles**
  - Constant-current diode limits cable charging current

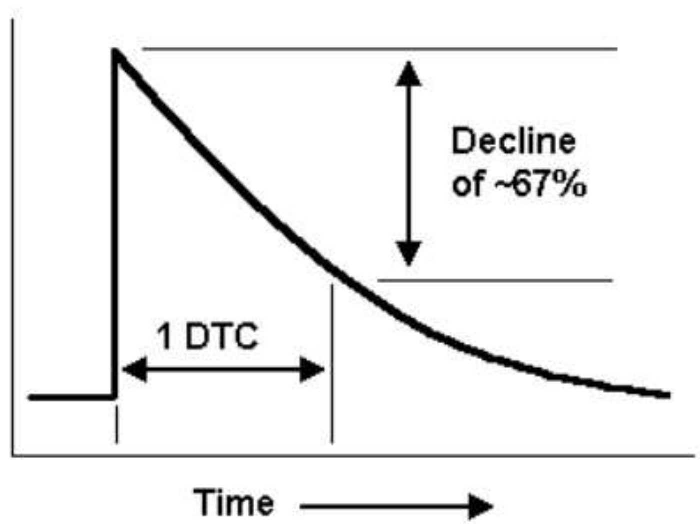


Industrial accelerometer design, 2009

- **Discharge time-constant**
  - Definition: Time it takes a signal to decline to ~67% pf the peak value of a transient
  - Directly related to the low frequency response of 3 dB point

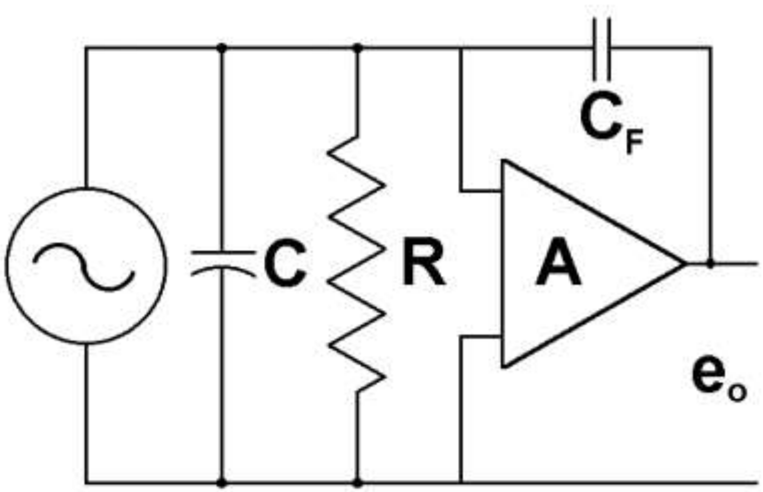
$$DTC = RC$$

$$LF = \frac{1}{2\pi RC}$$



Industrial accelerometer design, 2009

- **Sensitivity**
  - C_f determines sensitivity
  - IEPE accelerometers can be tuned for a specific sensitivity



Industrial accelerometer design, 2009

- **Sensitivity can change of PZT over time**

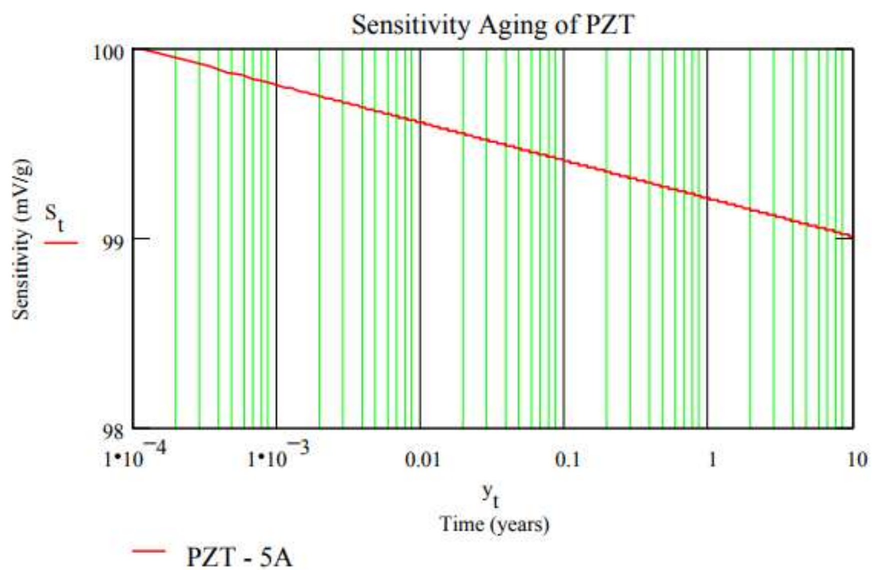
$$S(t) = S_0 \cdot [1 - 0.002 \cdot log(t)]$$

S(t) is the resulting sensitivity

S_o is the original calibration sensitivity

t, time, is measured in hours

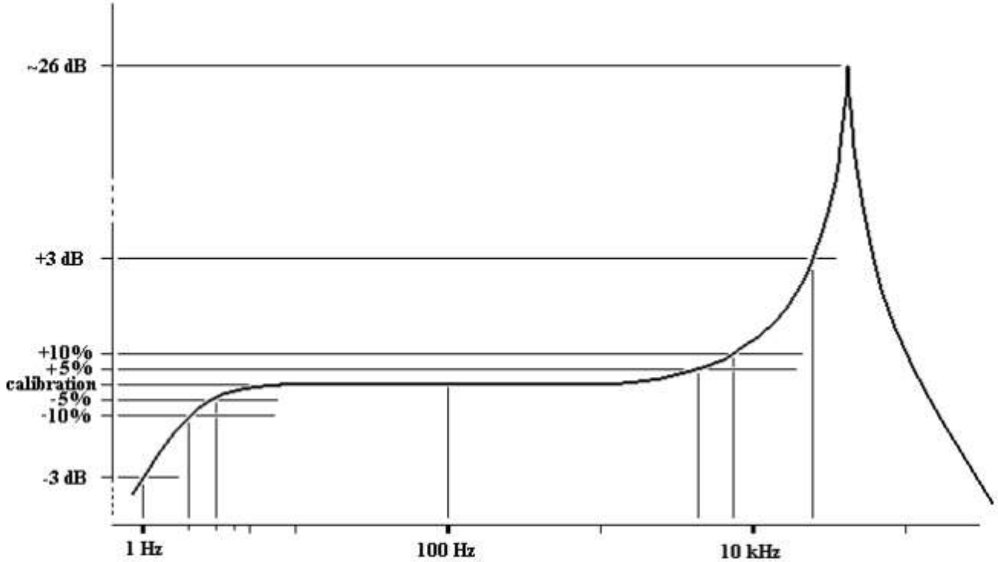
Pre-aged crystals will lose no more than 1% of sensitivity in ten years



Industrial accelerometer design, 2009

- **Accelerometer frequency response example (786A)**

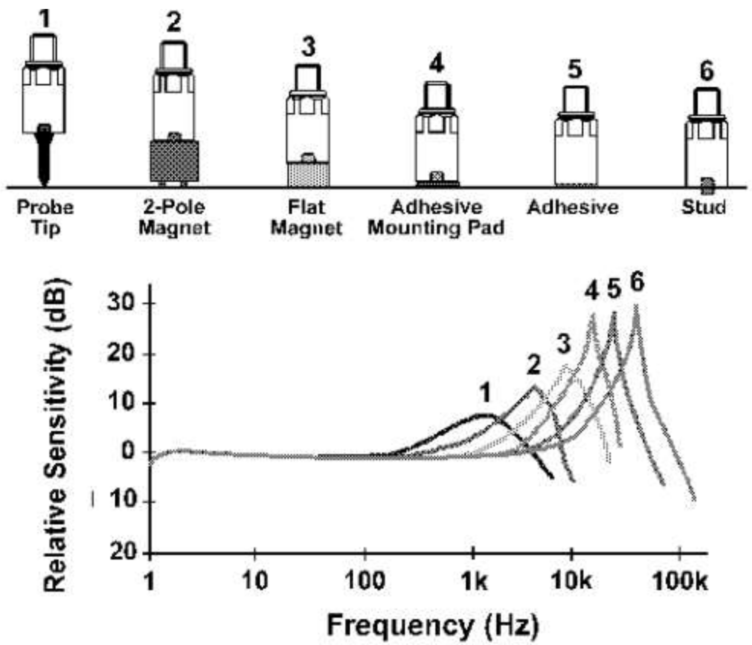
± 5% ....3 - 5,000 Hz
±10% ....1 - 9,000 Hz
± 3 dB ....0.5 - 14,000 Hz



Industrial accelerometer design, 2009

- ## Mounted resonant frequency

  786A resonance frequency = 30 kHz

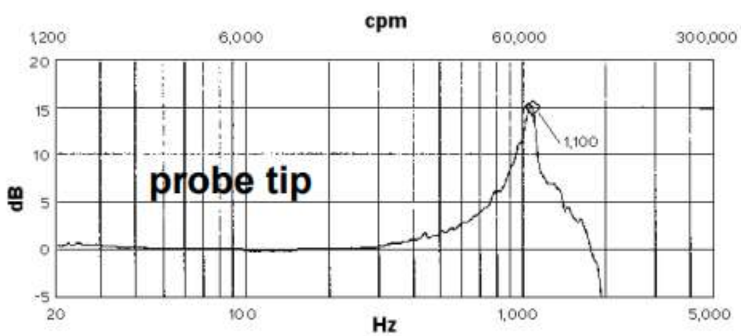


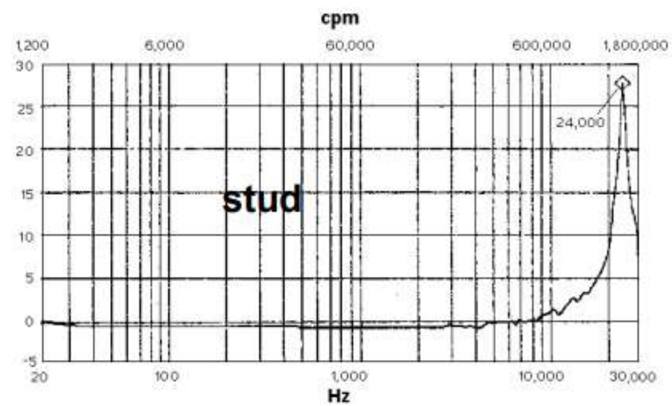
– Specification datasheet identifies resonant frequency of the ideal mounting condition, e.g. stud mounting

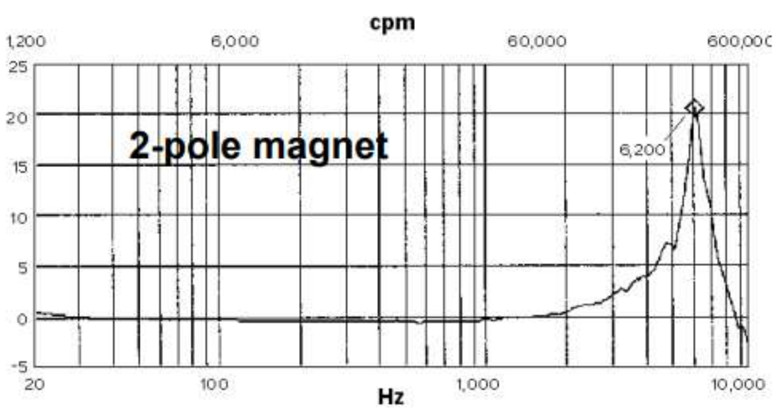
– Actual mounting conditions will affect this frequency

Industrial accelerometer design, 2009

- **Mounted resonant frequency examples**

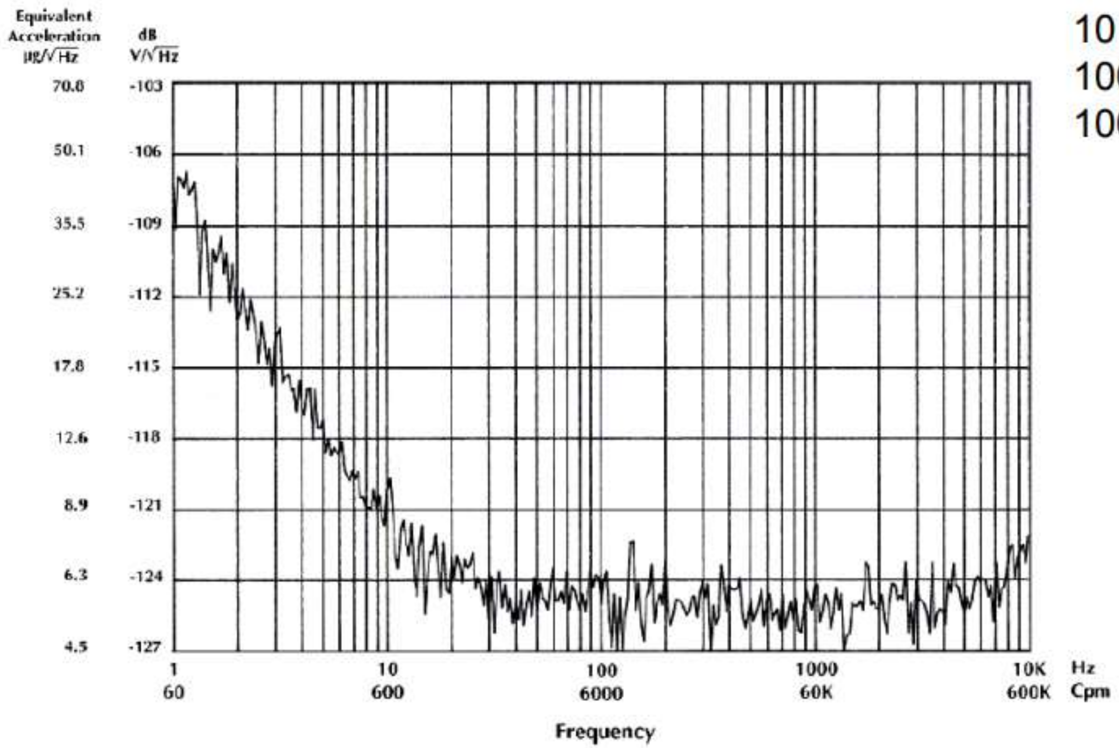






Industrial accelerometer design, 2009

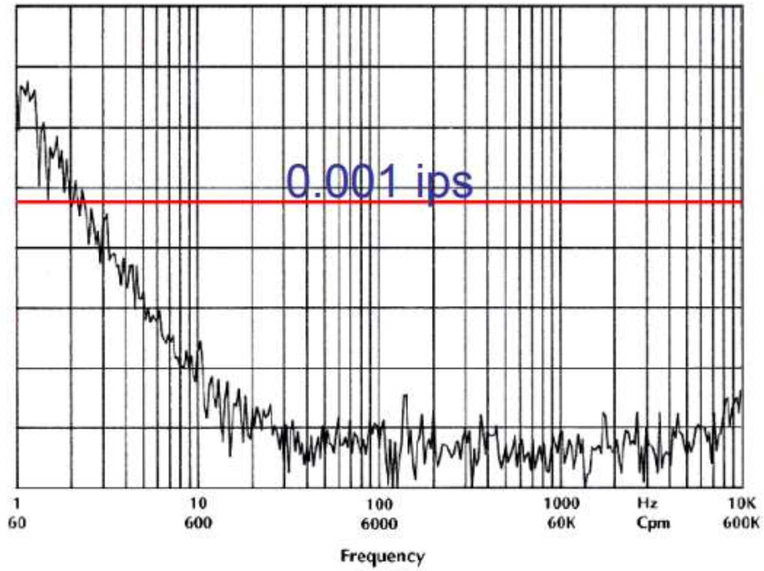
- **Electrical noise, equivalent g's**



10 Hz	8 µg/√Hz
100 Hz	5 µg/√Hz
1000 Hz	5 µg/√Hz

Industrial accelerometer design, 2009

- **Noise effect on velocity measurement**
  - In this example the noise floor of the accelerometer crosses the 0.001 ips level between 2 Hz and 3 Hz
  - While the sensor has a low frequency -3dB of 0.5 Hz, it should not be used to that low of a frequency for velocity measurements

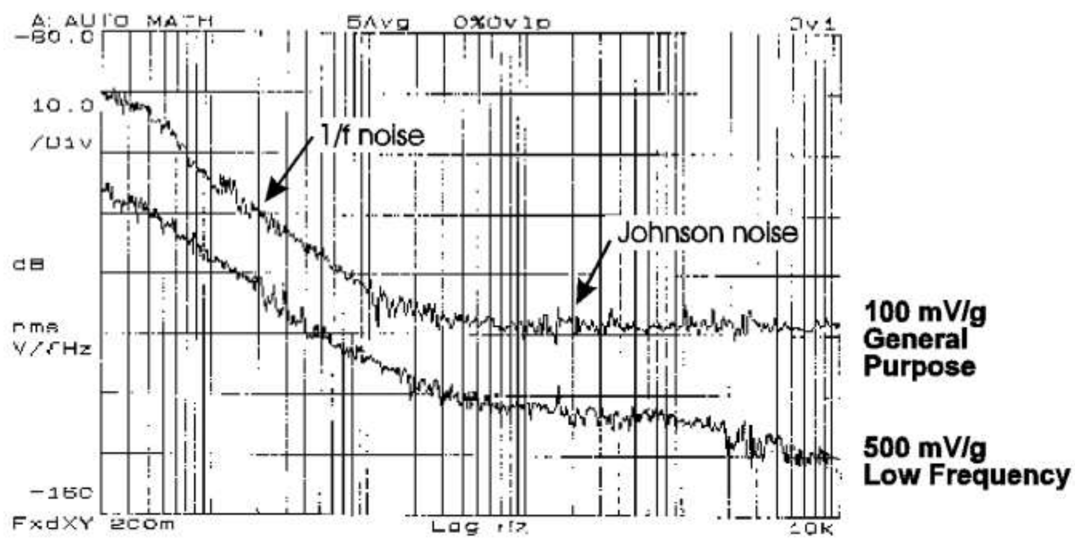


Industrial accelerometer design, 2009

- **Noise difference between accelerometers**
  - Low frequency accelerometer is 500 mV/g
  - Low frequency accelerometer also has a much lower noise @ 10 Hz

100mV/g = 8 μg/√Hz

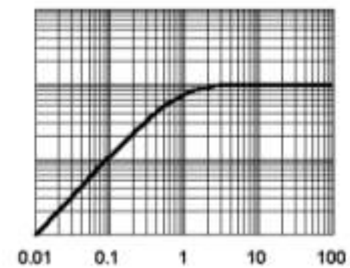
500mV/g = 0.4 μg/√Hz



Industrial accelerometer design, 2009

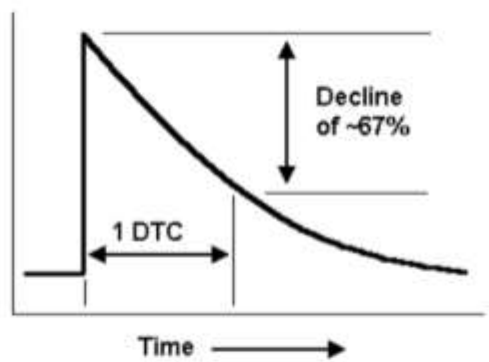
- **Low frequency response is limited only by the electronics within accelerometer**

R and **C** determine the low frequency response



$$DTC = RC$$

$$LF = \frac{1}{2\pi RC}$$

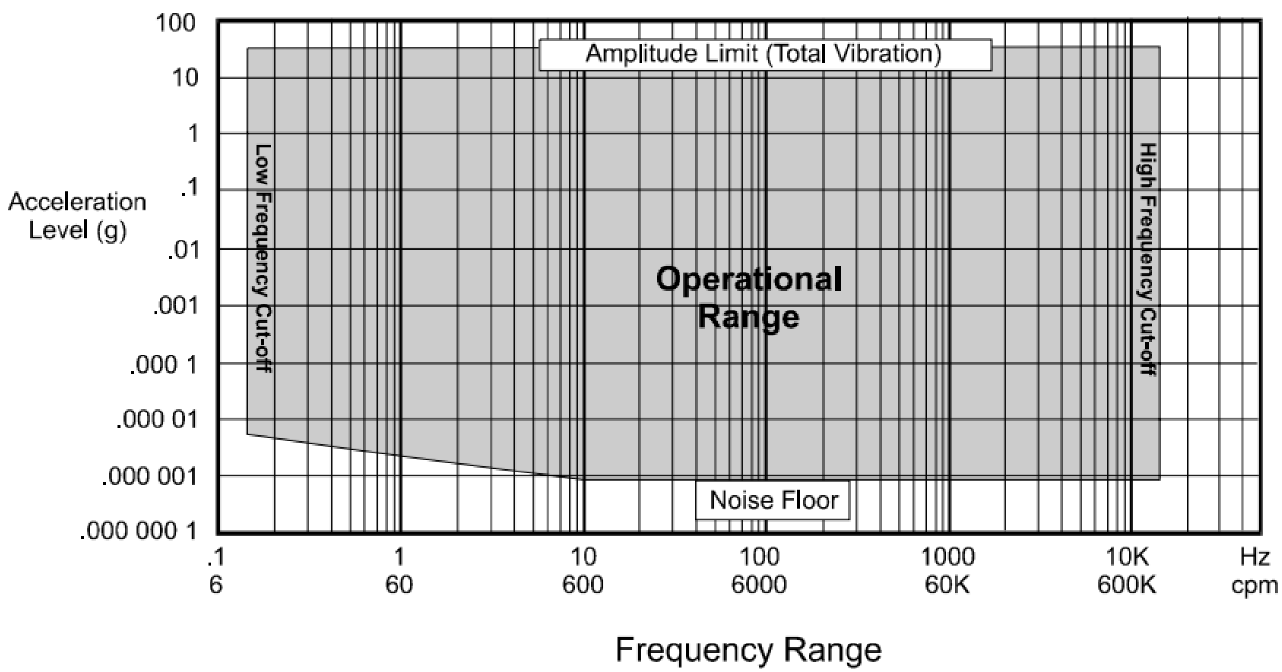


Industrial accelerometer design, 2009

- **Low frequency measurements need low frequency accelerometers**
  - For machines that run below 600 RPM, a low frequency accelerometer should be used
  - Signal is five times higher with a 500 mV/g accelerometer
  - Noise can be as much as twenty times lower
  - Overall improvement is a 5, 20 or 100 times better signal-to-noise ratio

Industrial accelerometer design, 2009

- **Operational range**
  - Every change causes something else to change



Industrial accelerometer design, 2009

- **Summary of selected trade-offs**
  – This table is a brief representation of some of the trade-offs caused by changes in characteristics of accelerometers

Specification improvement	Desired characteristic improvement	Necessary trade-off	What this means
Decrease low frequency response -3 dB point	Read lower frequencies	Increased turn-on and shock recovery time	Thermal transient effects more pronounced via base strain sensitivity
Increased high frequency response +3 dB point by higher resonant frequency	Read higher frequencies	Lower signal-to-noise ratio	Will lose ability to read smaller signal amplitudes
Decrease noise level	Read smaller amplitudes	Decreased high frequency response	Loss of higher frequency signals
Reduce sensor sensitivity	Read larger amplitudes	Lower signal-to-noise ratio	Will lose ability to read smaller signal amplitudes

Wilcoxon Sensing Technologies

For more information, please contact us:

✆ +1 (301) 330 8811
✉ info@wilcoxon.com
💻 www.wilcoxon.com