Piezoelectric accelerometer design

Piezoelectric transducers

Quartz and piezoceramics

Mechanical design

Charge amplification

Design trade-offs

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Piezoelectric transducers

- What does piezoelectric mean?
- What is a transducer?
- What is a sensor?
- What is an accelerometer?

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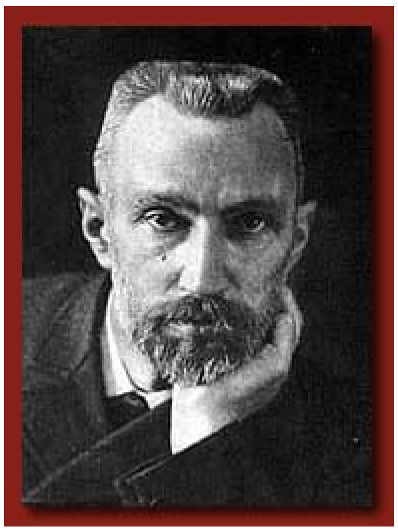
What does piezoelectric mean?

- **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(▯-)tē\ ***noun*** [ISV] (1883)
: electricity or electric polarity due to pressure esp. in a crystalline substance (as quartz)

What is a transducer?

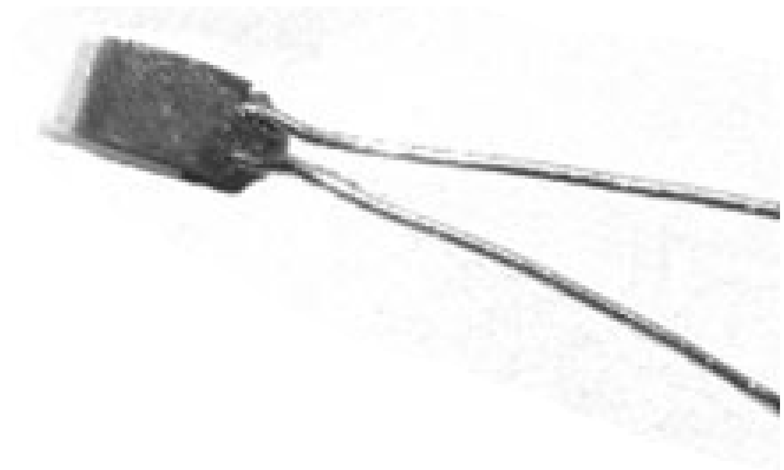
A device that converts energy

Mechanical

↑ ↓

Electrical

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

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What is an accelerometer?

- A sensor that measures **acceleration**
- Based on Newton's second law of motion
- The acceleration of an object as produced by a 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, $F = m\ a$

Accelerometer materials: quartz and PZT

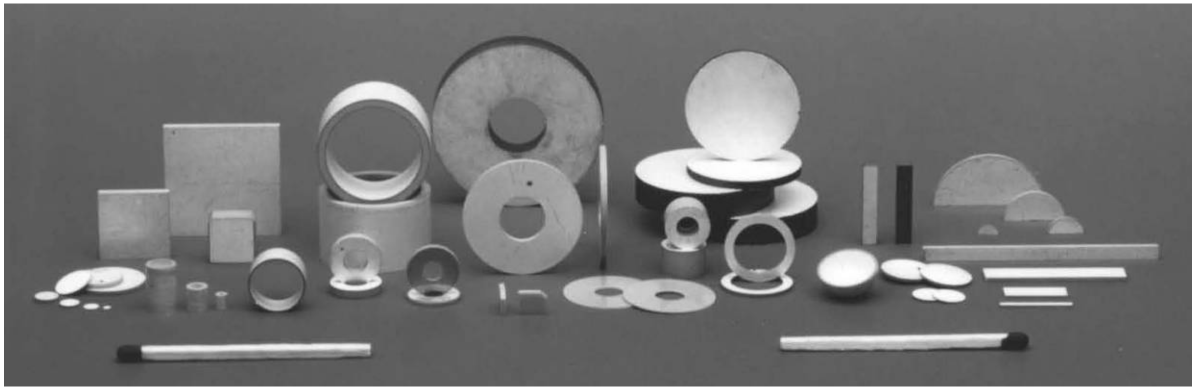
- Quartz and PZT are piezoelectric material
- Squeeze them and they produce electric current
- Apply electric current and they change shape

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

Ferroelectric materials

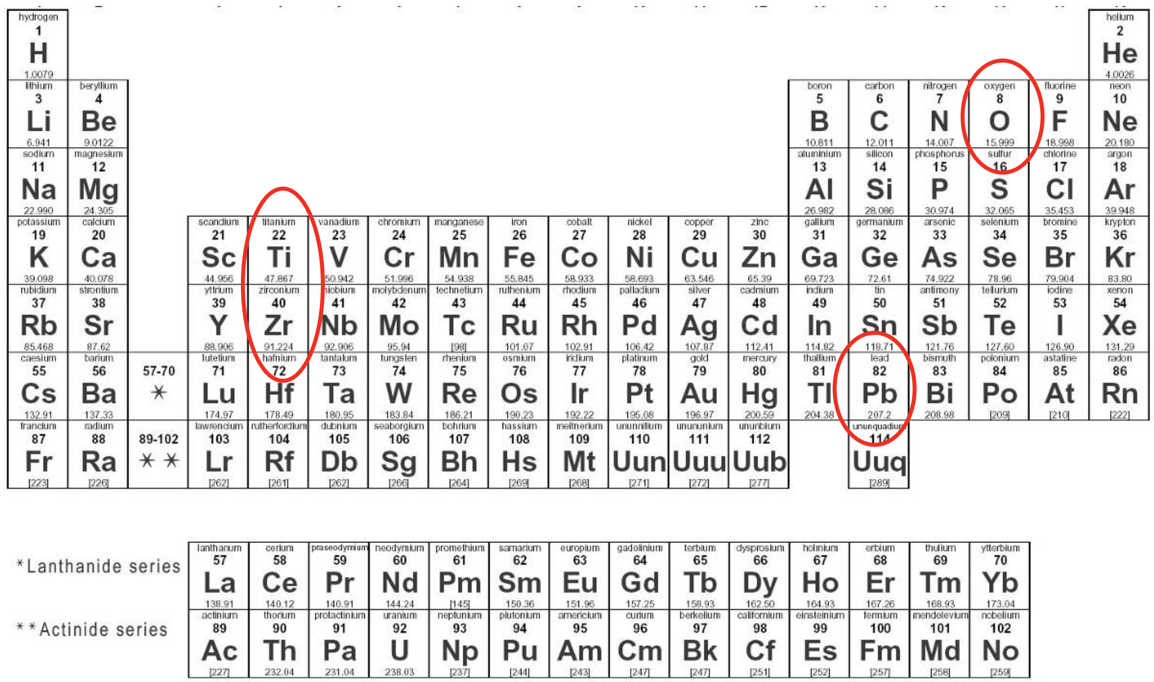
- A group of ceramic materials
- Found to have the ability to become “magnets”
- Some can be made into piezoelectric ceramic
- Lead-Zirconate-Titanate (PZT) is the piezoceramic used in most industrial transducers



Ferroperm piezoceramics

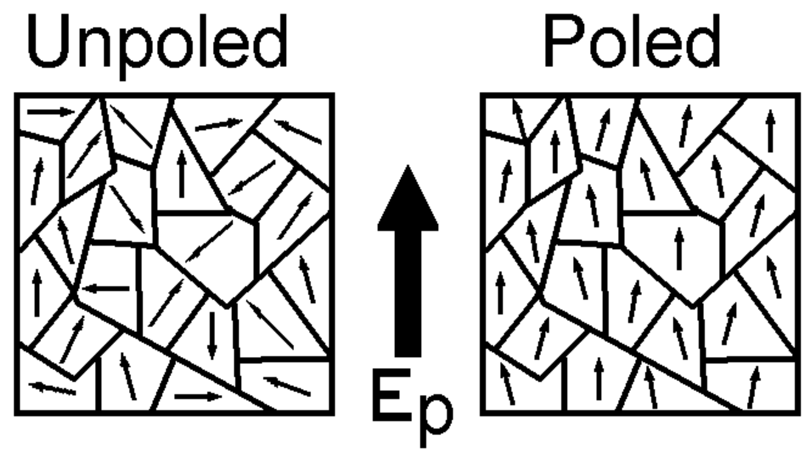
Lead-Zirconate-Titanate

- Lead: Atomic Symbol **Pb** (latin **Pl**um**b**um)
- Zirconate: A Zirconium Oxide (ZrO_2), Zirconium symbol **Zr** (mineral **Zir**con)
- Titanate: A Titanium Oxide (TiO_2), Titanium symbol **Ti** (greek **Ti**tanos)
- Resulting in **P Z T**



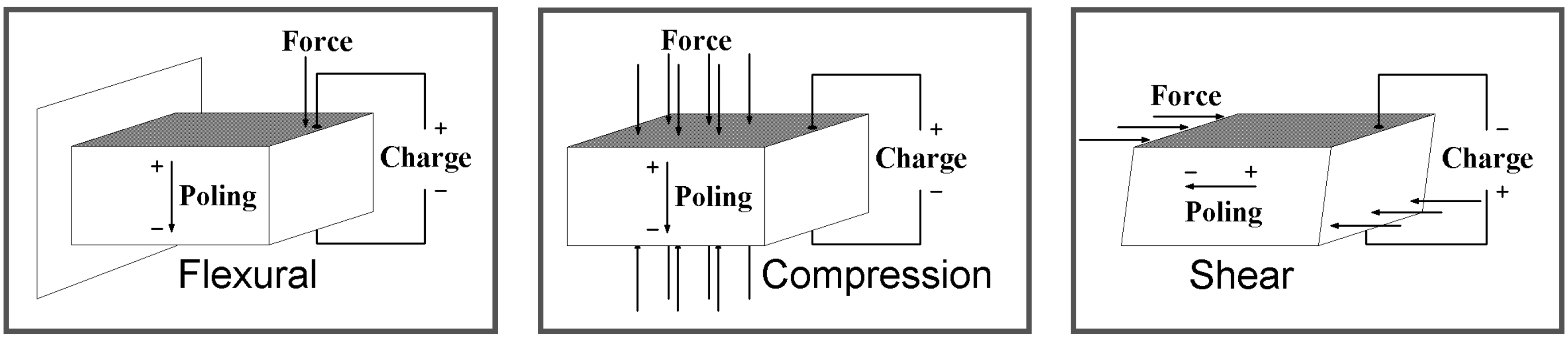
Poling

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



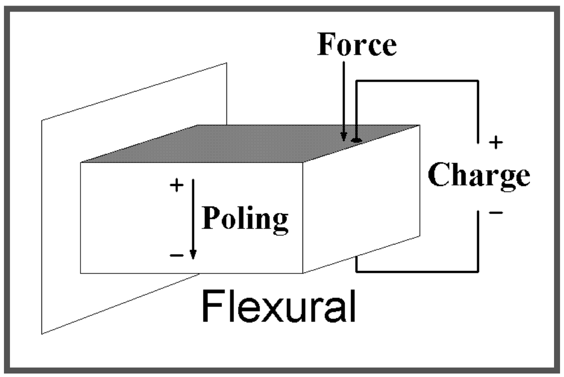
PZT must be poled for final use

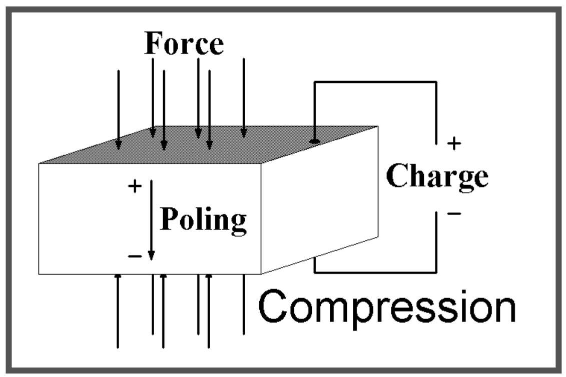
- Poling method and direction is specific for the intended use
- Polarity is important

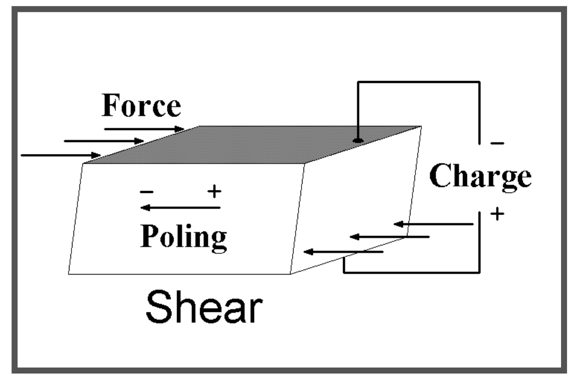


What is the pyroelectric effect?

- 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





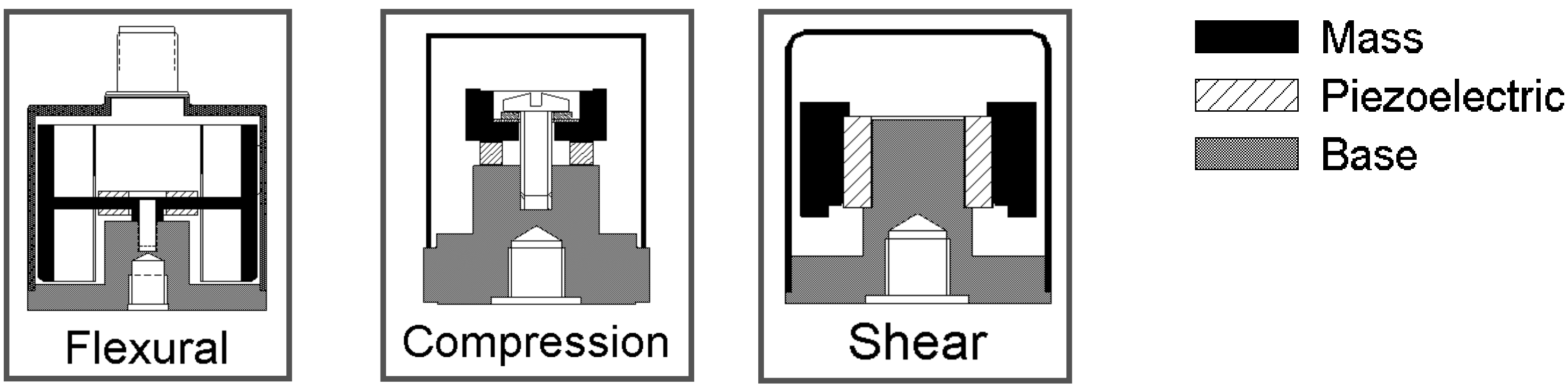


Mechanical design

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

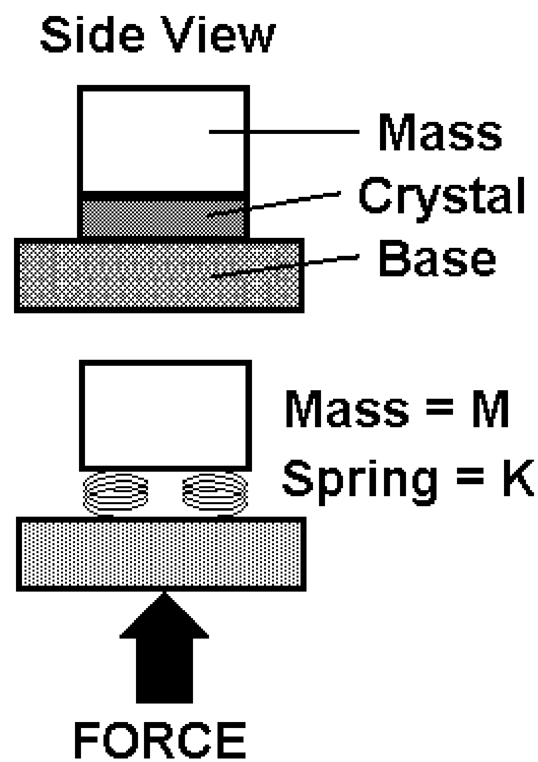
Base, PZT, and mass

- Base mounts to machine
- PZT mounts on the base
- Mass mounts on the PZT
- F = m a
- Acceleration output



Mechanical stack

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

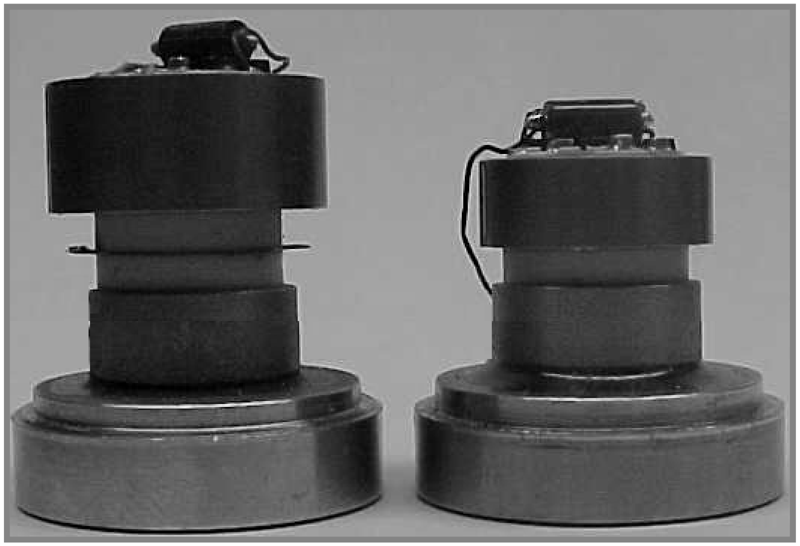


$$F_n \propto \sqrt{\frac{K}{M}}$$

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 the noise level

793L vs. 793



15 kHz vs. 25 kHz

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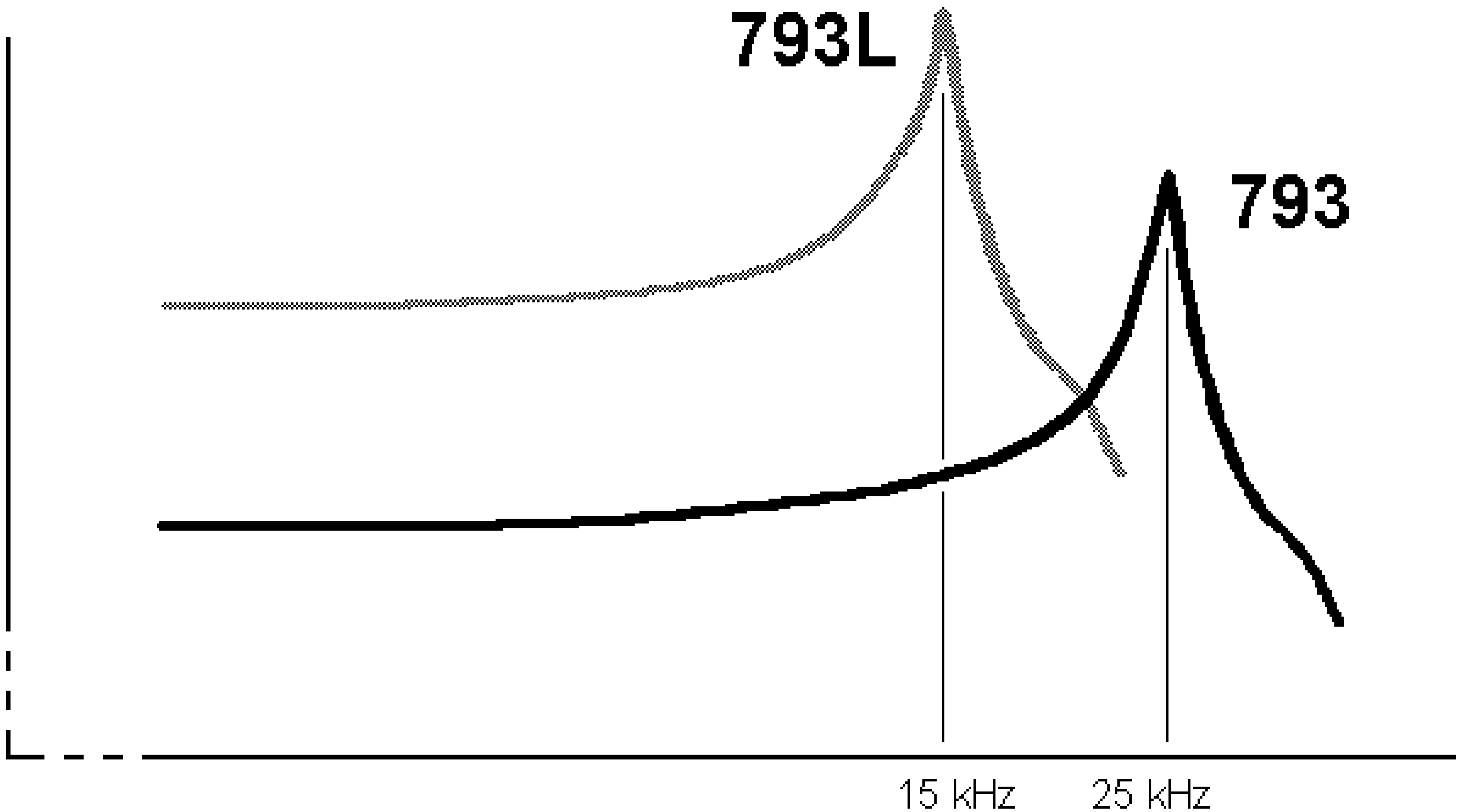
Mechanical design factors

Increased mass also increases sensitivity, but lowers the useful upper frequency



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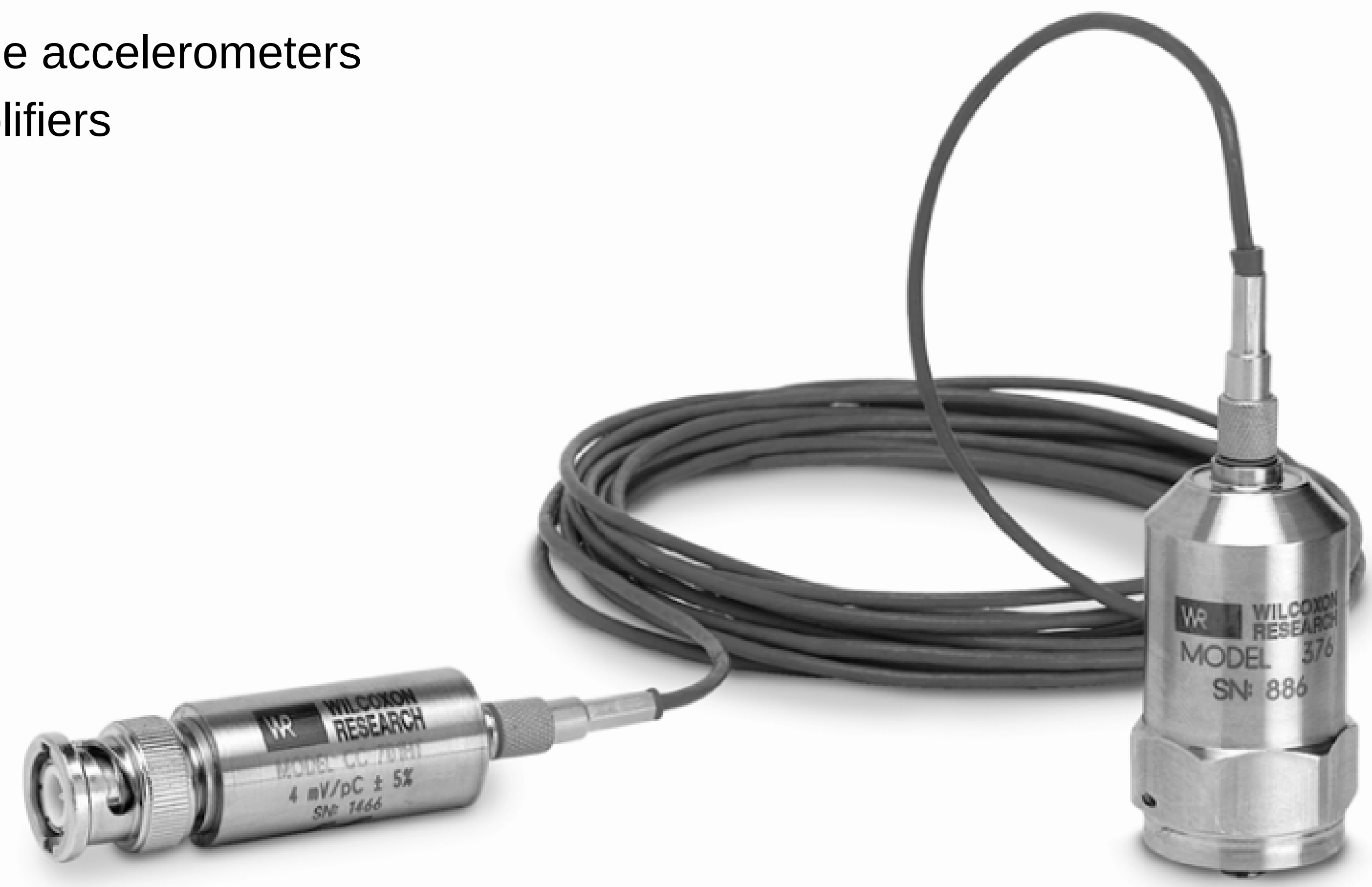
Charge amplification

- Charge mode accelerometers
- Charge amplifiers



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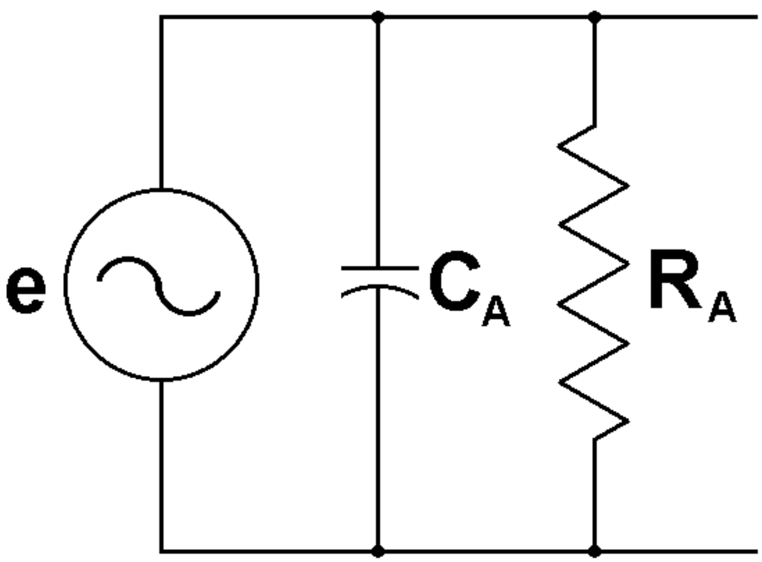
Charge-mode accelerometers



Basic equation:

V = Q / C

where

Q = charge produced

C = sensor capacitance

V = voltage output

R is leakage and affects the low-frequency response

Charge amplifiers

C_i is the input capacitance of the amplifier

R_i is the input resistance of the amplifier

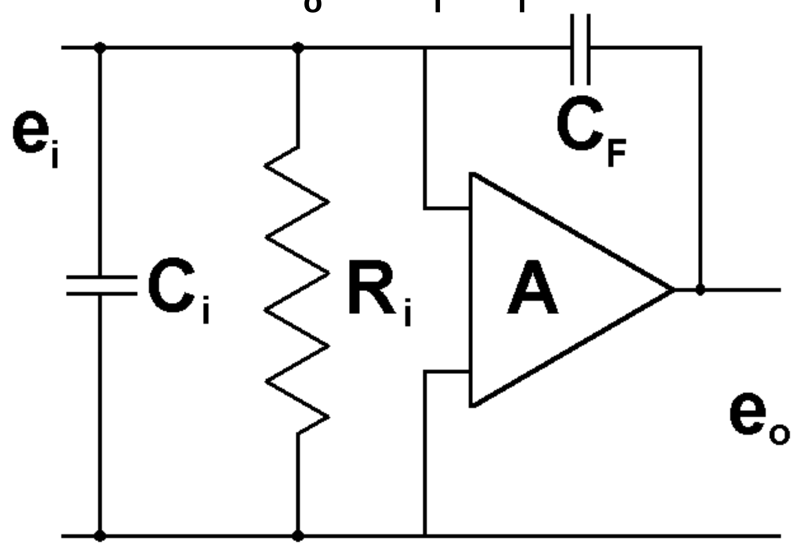
C_f is the feedback element of the amplifier

A is the amplifier

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

Basic equation of gain

$$e_o = - e_i / C_f$$



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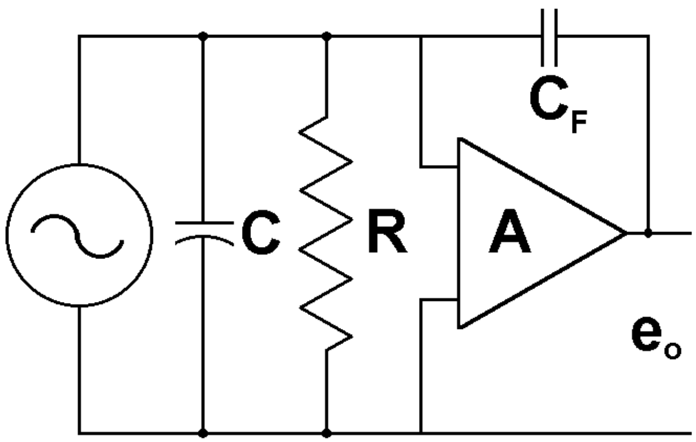
Charge amplification inside the sensor

- Basis for all IEPE sensors
- Cable length is then not an issue for most applications

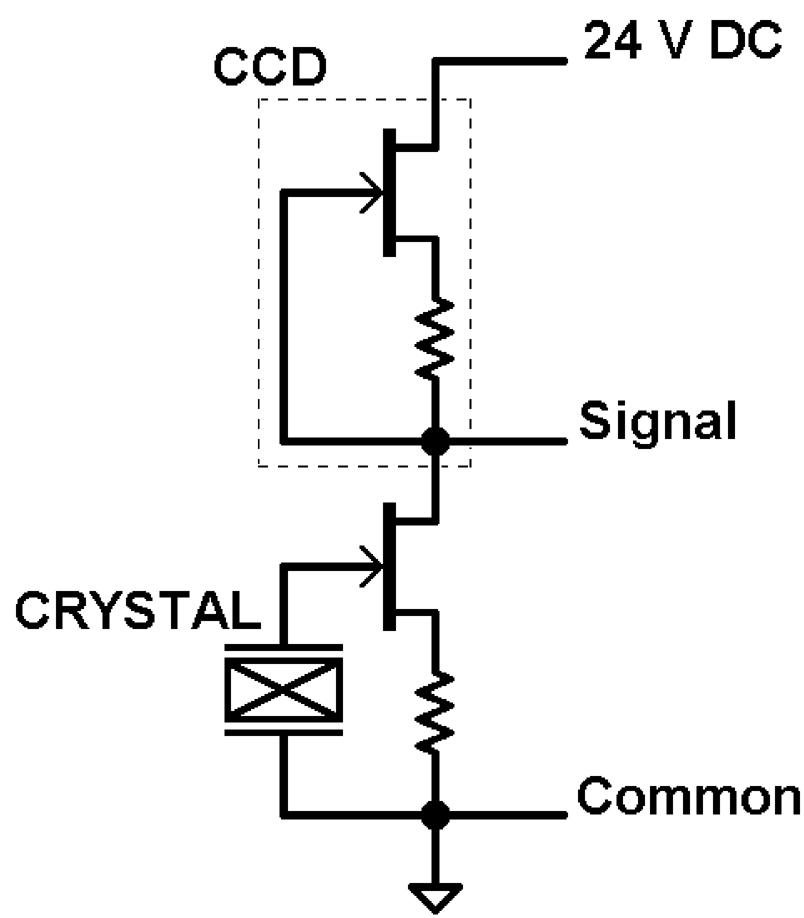


Design trade-offs

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

Signal and power on two wires

- Basis for all IEPE sensors
- Circuit was pioneered by Kistler Instruments in the 1960's



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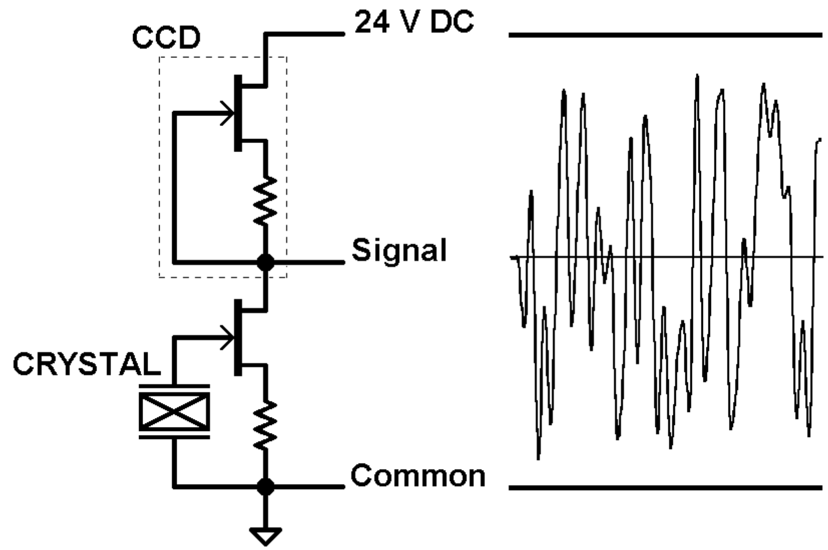
Internal amplifier produces BOV

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

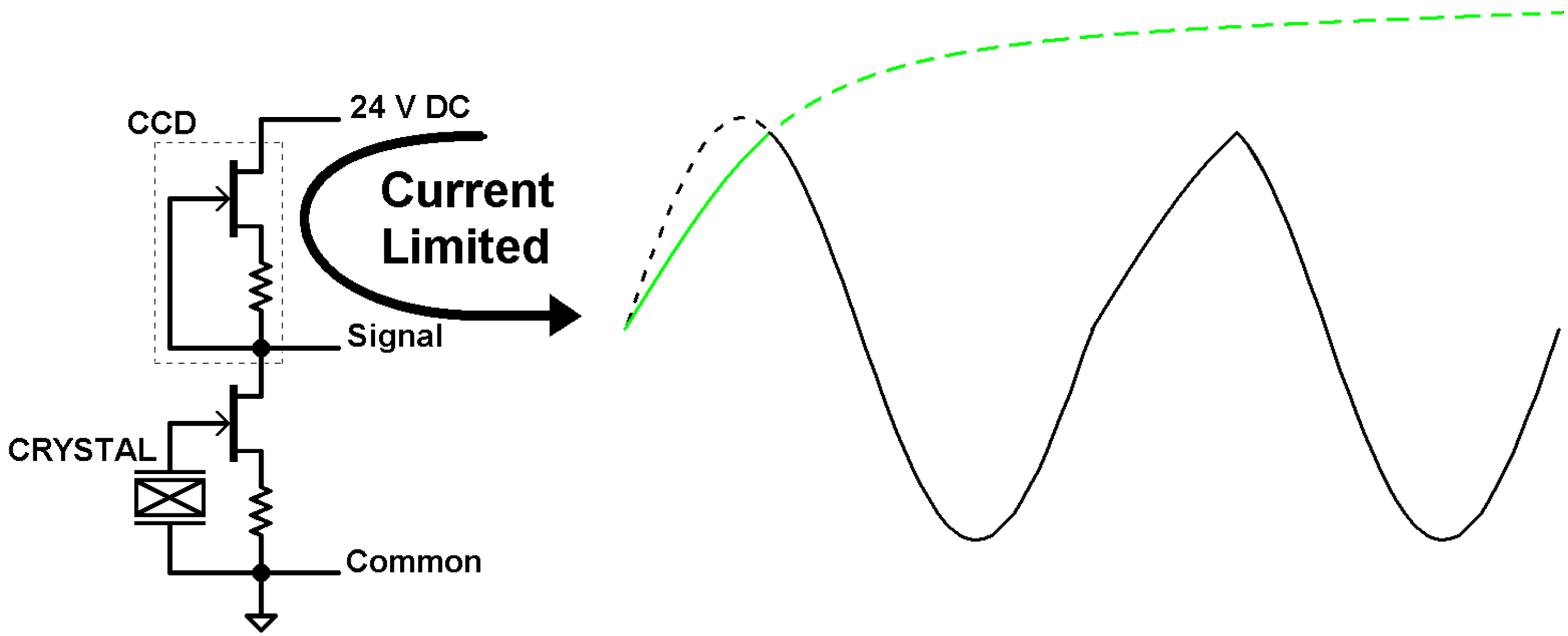


Cable length limits

- Long cables connected to IEPE sensors cause signal distortion of the "positive-going" signal
- It is a "slew rate" limitation of the signal
- This results in harmonic distortion and false harmonic signals

CCD limits the current on positive cycles

The constant-current diode limits the cable charging current

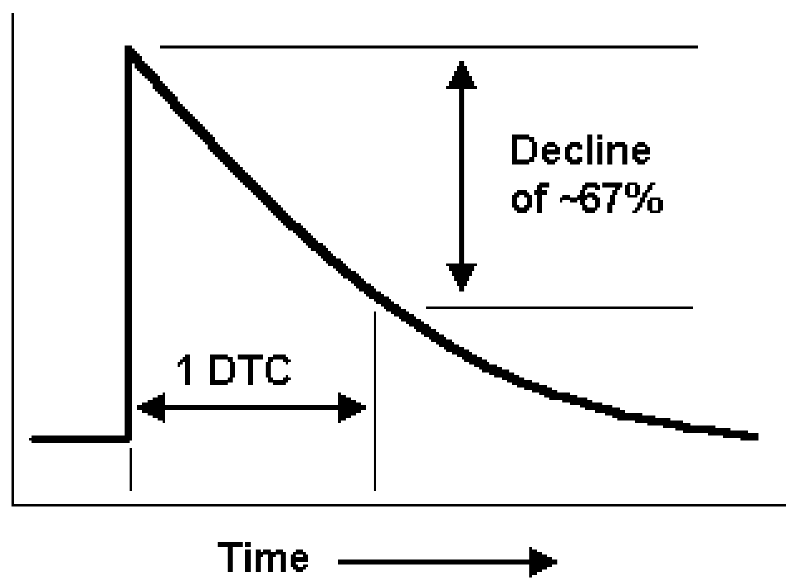


Discharge time-constant

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

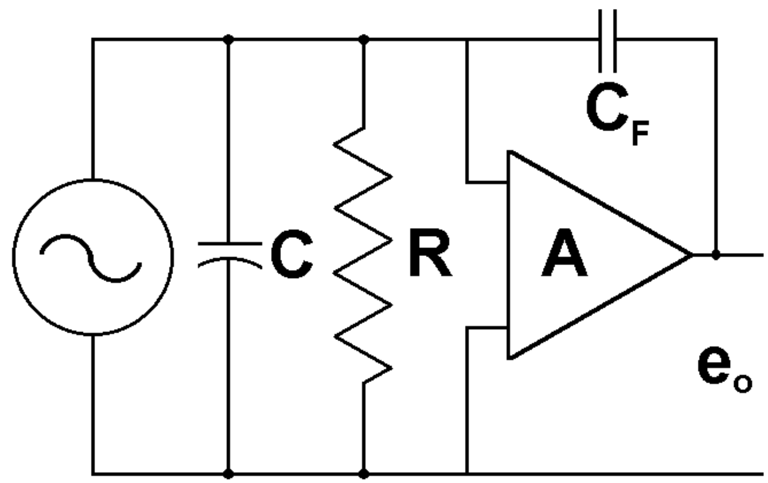
$$DTC = RC$$

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



Sensitivity

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



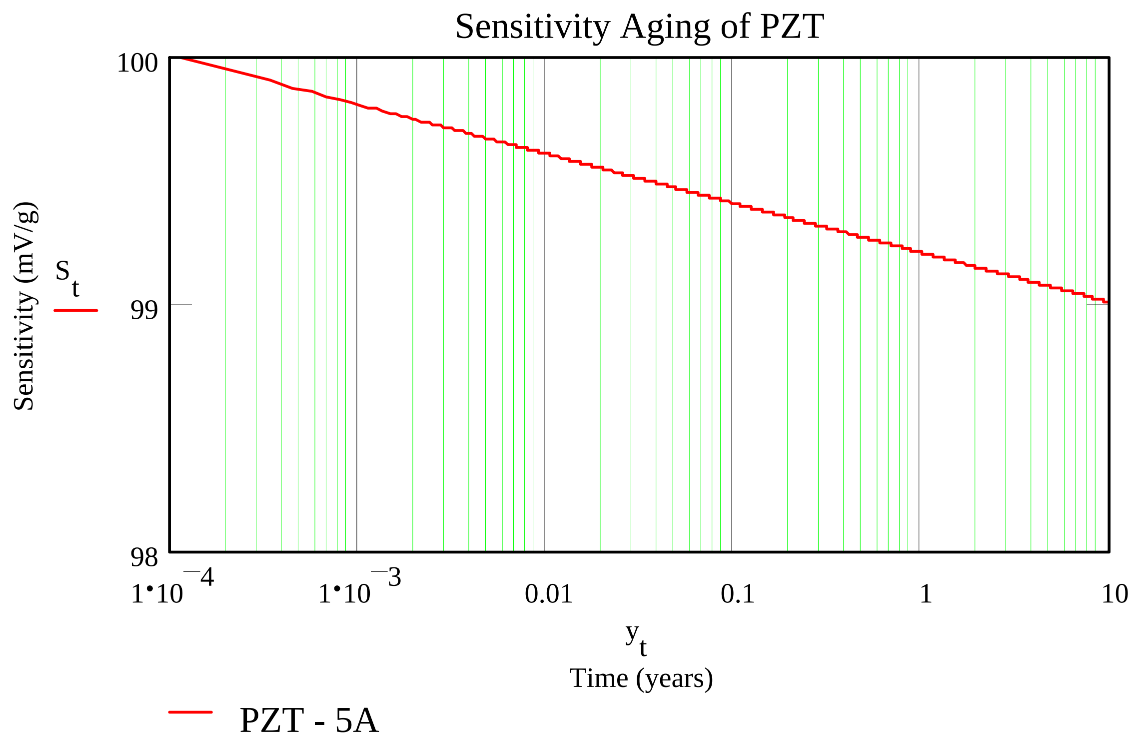
Sensitivity change of PZT over time

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

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

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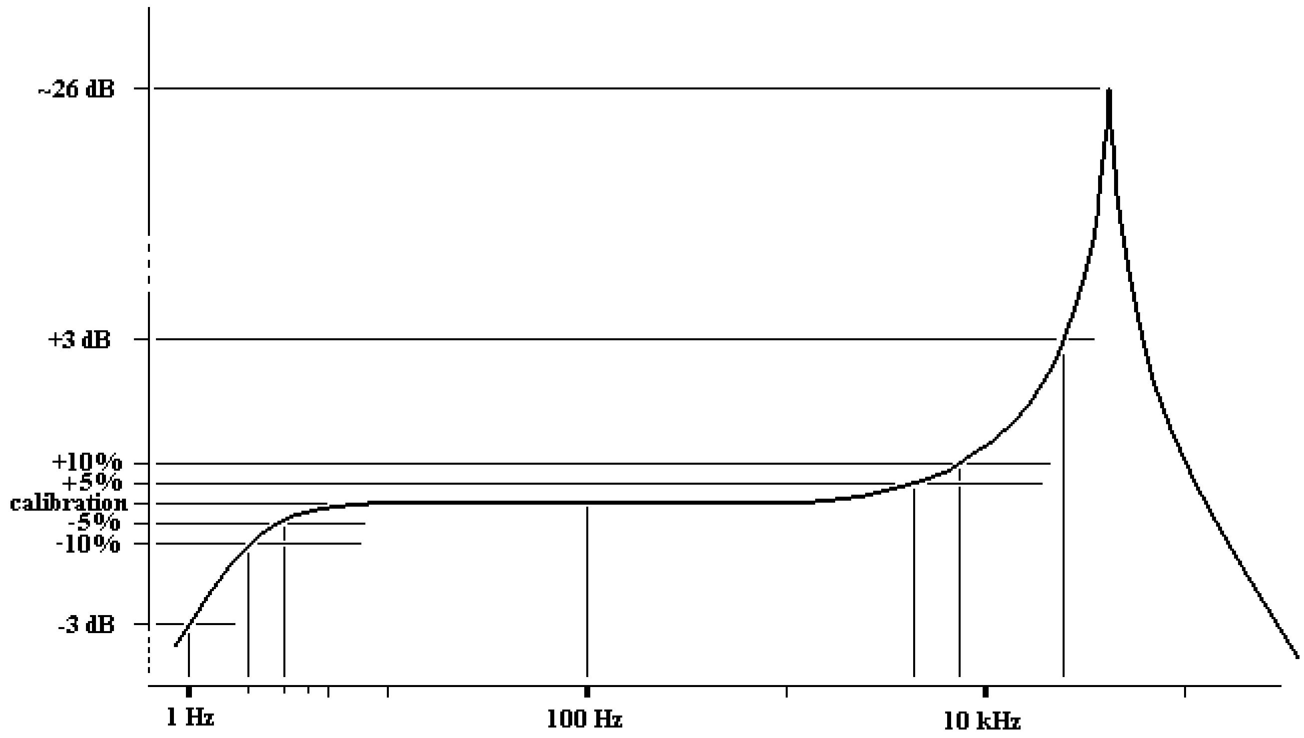
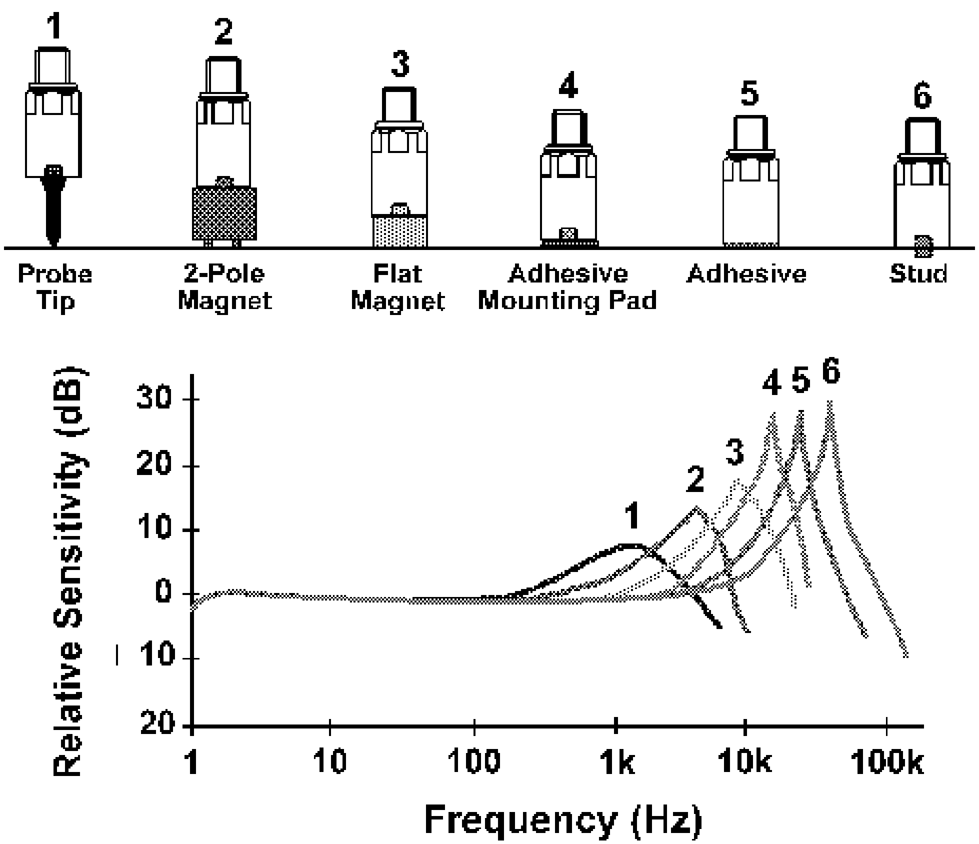
Accelerometer frequency response example (786A)

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



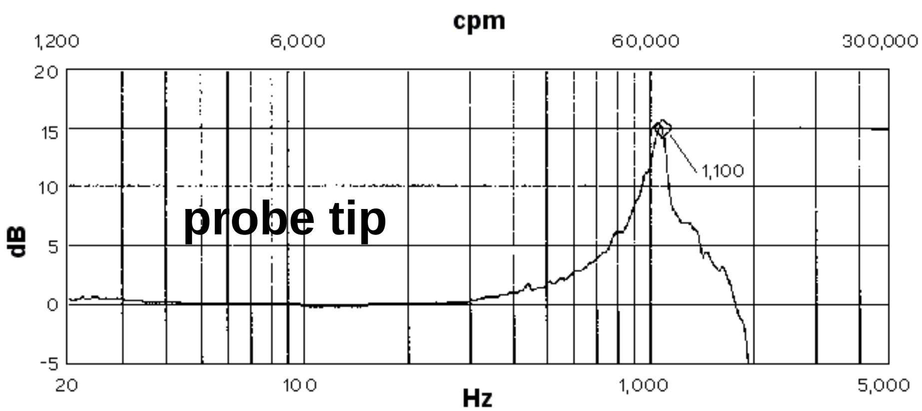
Mounted resonant frequency

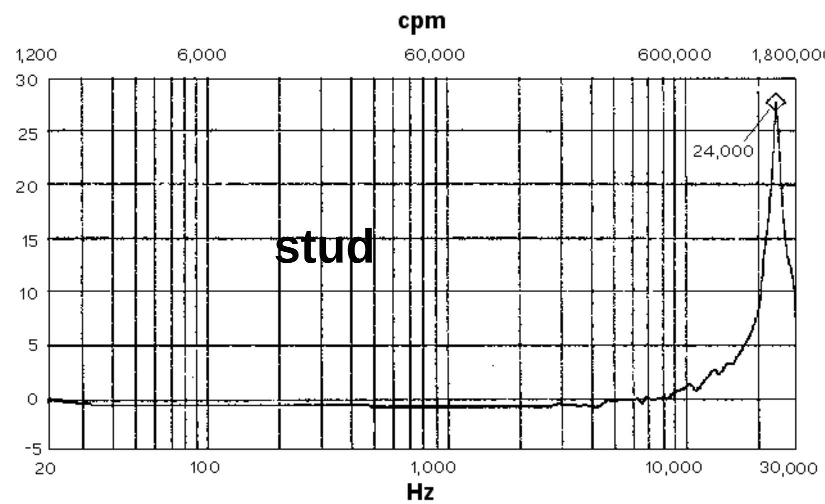
786A resonance frequency ....30 kHz

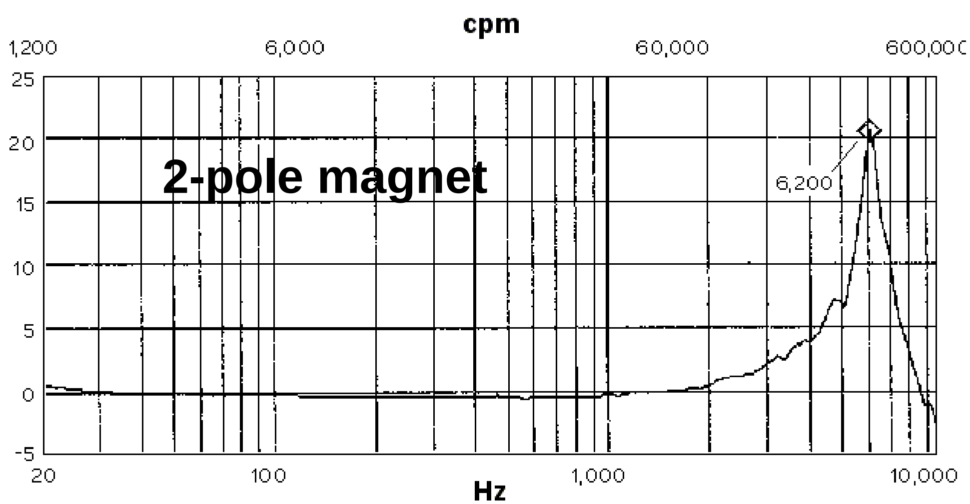


- The specification data sheet identifies the resonant frequency of the ideal mounting condition, i.e. - stud mounting
- Actual mounting conditions will affect this frequency

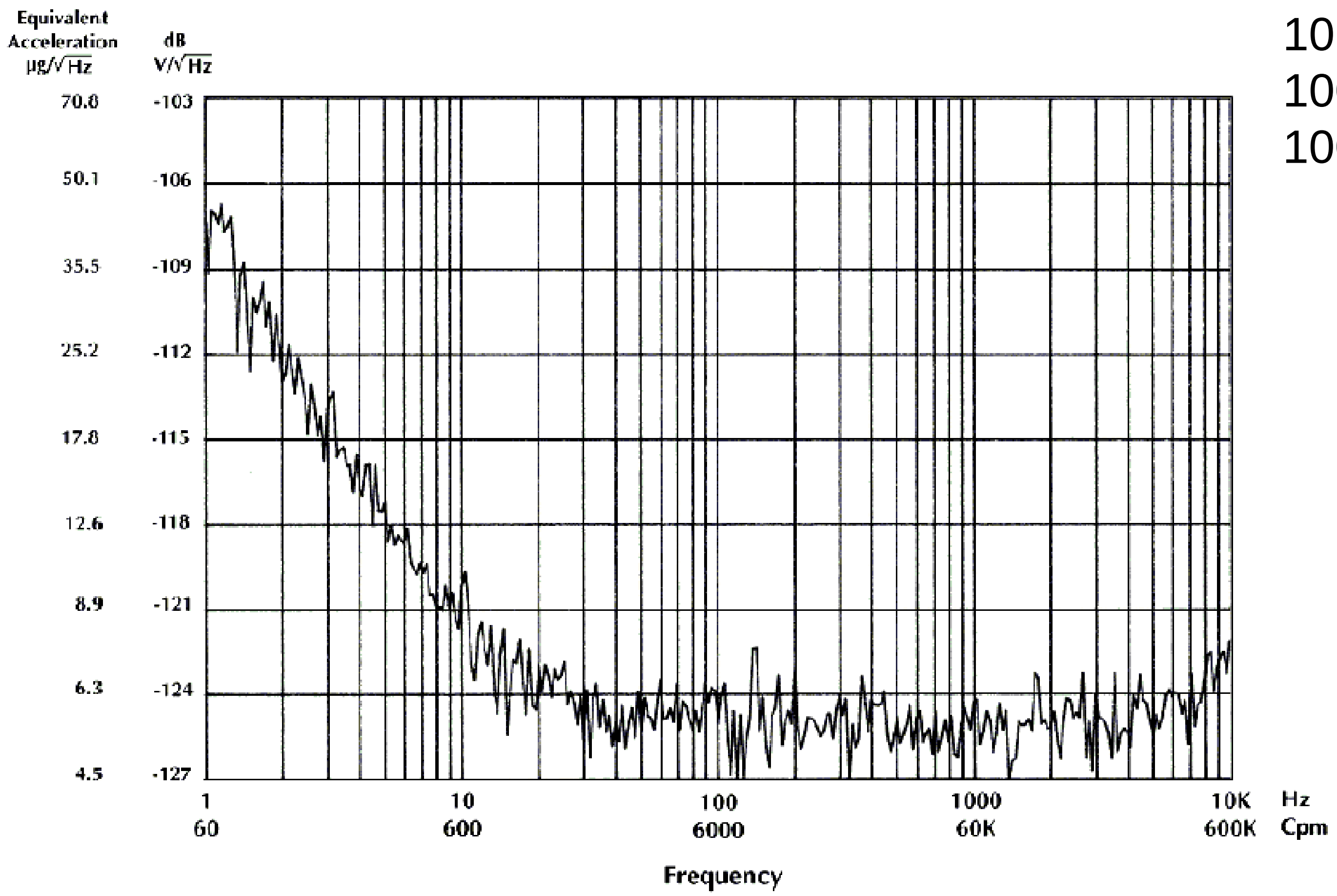
Mounted resonant frequency examples







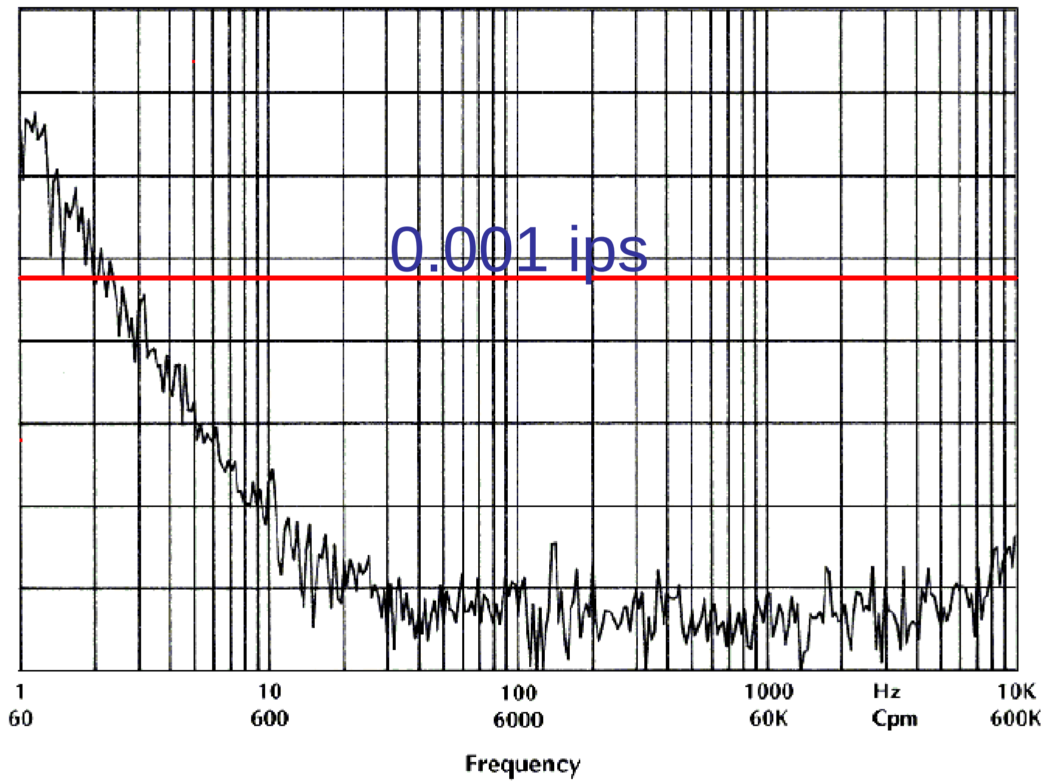
Electrical noise, equivalent g's



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

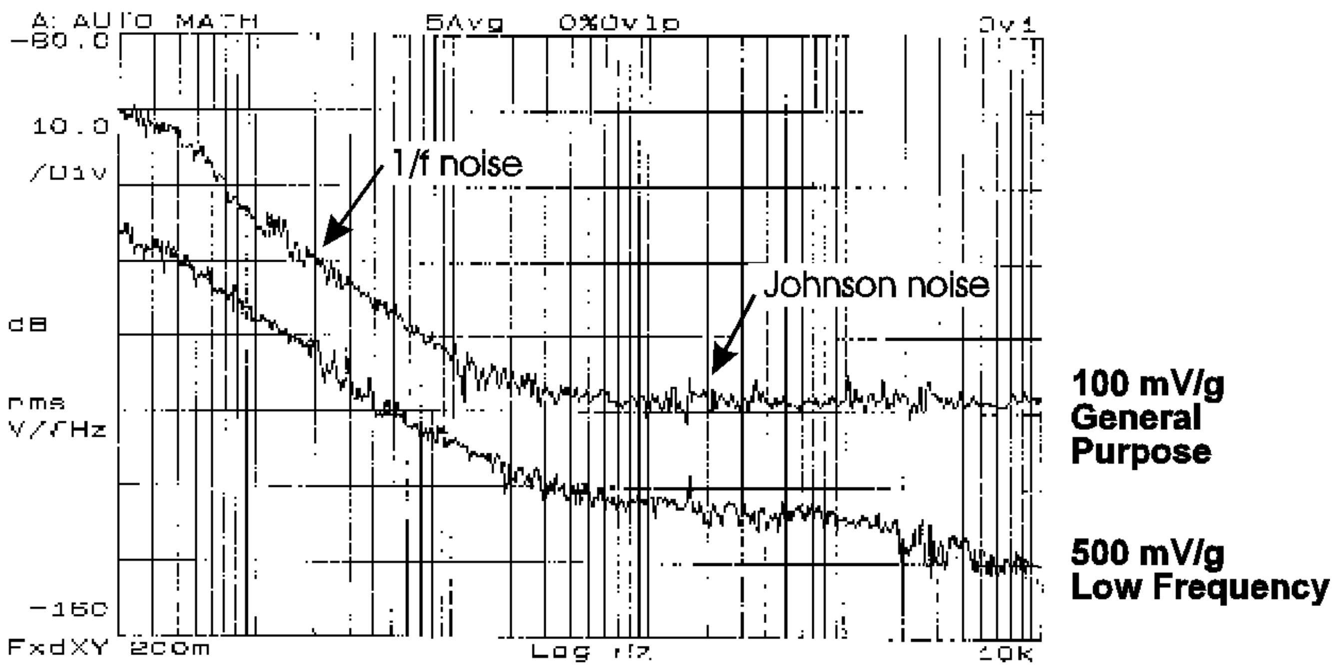
Noise effect on velocity measurement

- 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 really be used to that low of a frequency for velocity measurements



Noise difference between accelerometers

- The low frequency accelerometer is 500 mV/g
- The low frequency accelerometer also has a much lower noise @10 Hz
  - 100mV/g = 8 µg/√Hz
  - 500mV/g = 0.4 µg/√Hz



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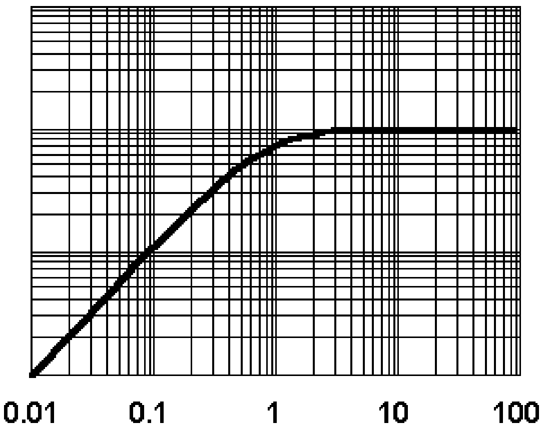
Low frequency response is limited only by the electronics within the accelerometer

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



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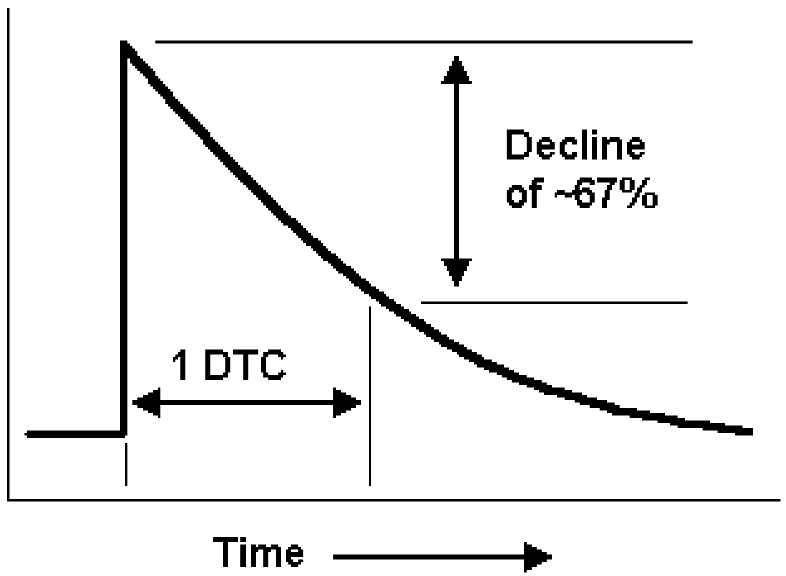

Low frequency measurements need low frequency accelerometers

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

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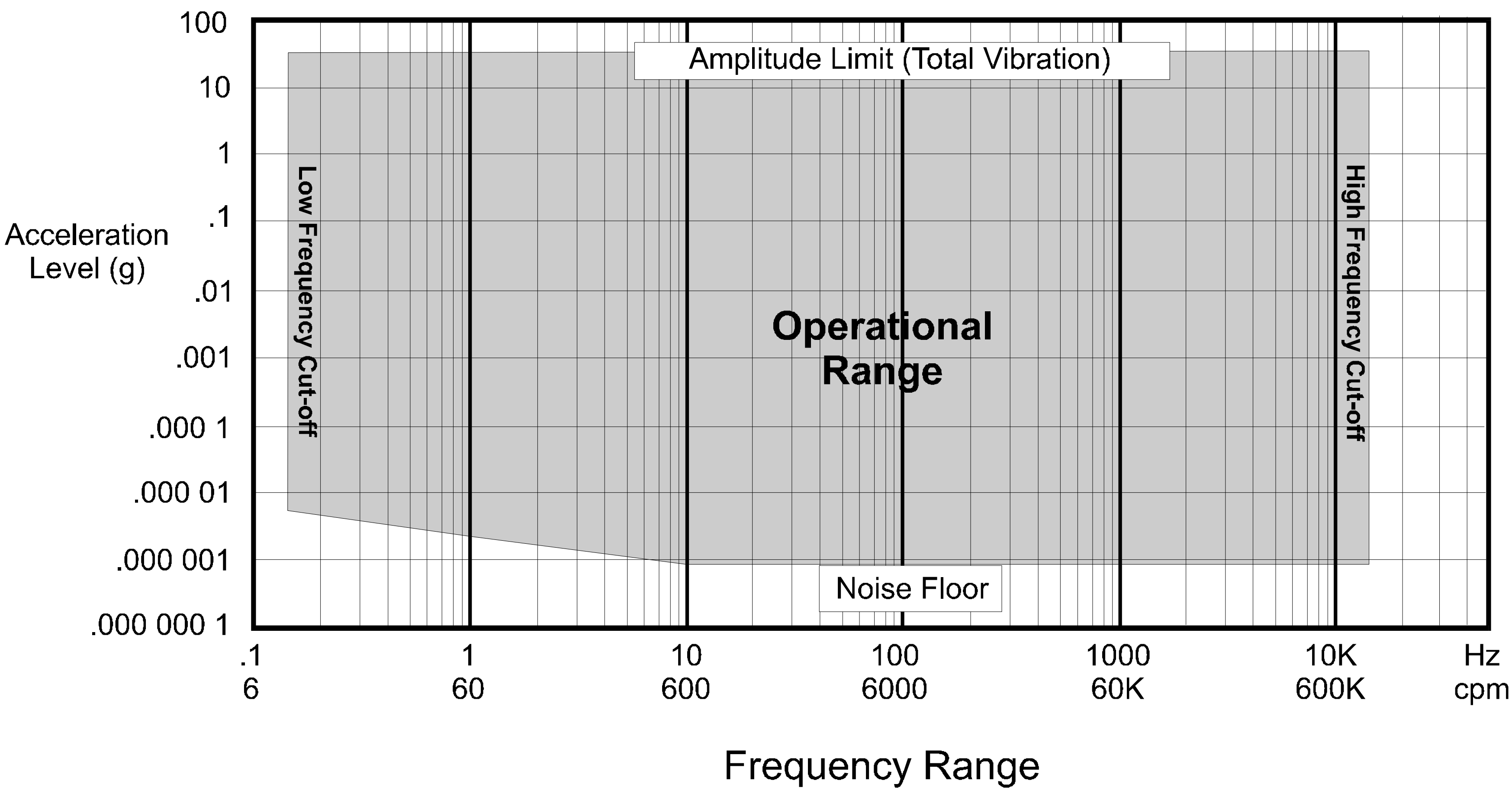
Operational range

Every change causes something else to change



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

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