



# Piezoelectric accelerometer design

- Piezoelectric transducers
- Quartz and piezoceramics
- Mechanical design
- Charge amplification
- Design trade-offs

The information contained in this document is the property of Wilcoxon Research, Inc. and is proprietary and/or copyright material. This information and this document may not be used without the express authorization of Wilcoxon Research, Inc. Any unauthorized use or disclosure may be unlawful.

Information contained in this document is subject to U.S. Export Control regulations, specifically the International Traffic in Arms Regulations and / or Export Administration Regulations. Each recipient of this document is responsible for ensuring that transfer or use of any information contained in this document complies with all relevant International Traffic in Arms Regulations and / or Export Administration Regulations.

**MEGGITT**

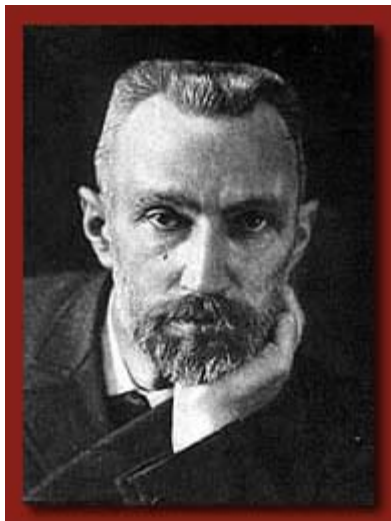
## Piezoelectric transducers

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



## What does piezoelectric mean?

- ▶ **Electricity**, produced by
- ▶ **Pressure**, applied to a
- ▶ **Crystalline** substance



Pierre Curie

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

**pi•e•zo•elec•tric•i•ty** \-ˌlek-ˈtri-s(ɪ)-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

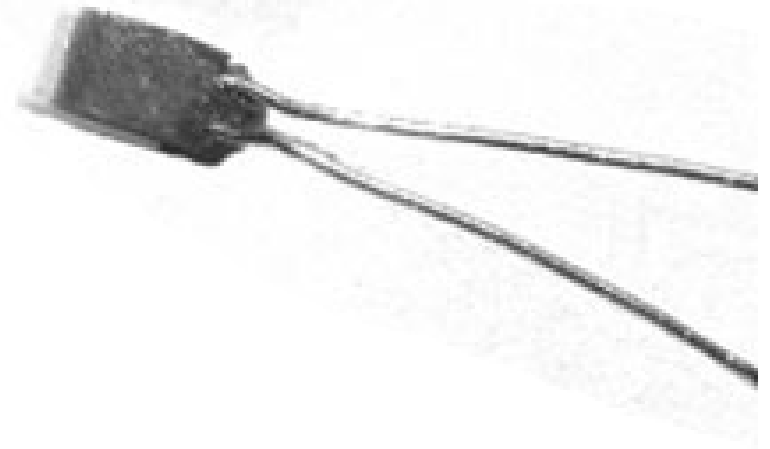


Electrical



## 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



## 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

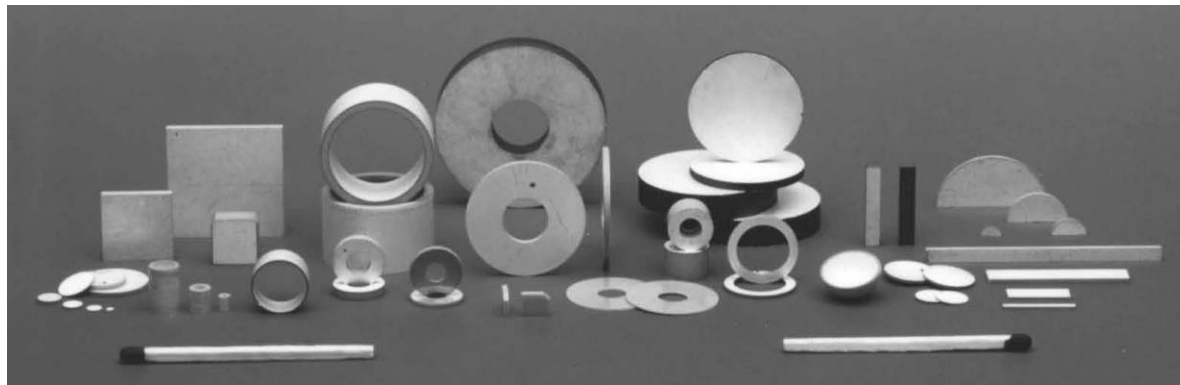
- ▶ Is a “natural” piezoelectric material
- ▶ Never loses piezoelectric properties
- ▶ Modern quartz transducer crystals are grown, not mined
- ▶ Is not as quantum efficient as ferromagnetic piezoelectric material





## 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 **Plumbum**)
- Zirconate: A Zirconium Oxide ( $ZrO_2$ ), Zirconium symbol **Zr** (mineral **Zircon**)
- Titanate: A Titanium Oxide ( $TiO_2$ ), Titanium symbol **Ti** (greek **Titanos**)
- Resulting in **P Z T**

hydrogen 1 H 1.0079																	helium 2 He 4.0026						
lithium 3 Li 6.941	beryllium 4 Be 9.0122																	boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305																	aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80						
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29						
cesium 55 Cs 132.91	barium 56 Ba 137.33	* 57-70	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04	radon 86 Rn						
francium 87 Fr [223]	radium 88 Ra [226]	* * 89-102	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]	astatine 85 At	radon 86 Rn					
			lutetium 71 Lu [175]	hafnium 72 Hf [178]	tantalum 73 Ta [181]	tungsten 74 W [184]	rhenium 75 Re [187]	osmium 76 Os [190]	iridium 77 Ir [192]	platinum 78 Pt [195]	gold 79 Au [197]	mercury 80 Hg [200]	thallium 81 Tl [204]	lead 82 Pb [207]	bismuth 83 Bi [209]	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]					
			unnilium 110 Uun	ununium 111 Uuu	unbinium 112 Uub			ununium 110 Uun	ununium 111 Uuu	unbinium 112 Uub			ununium 110 Uun	ununium 111 Uuu	unbinium 112 Uub			ununium 110 Uun	ununium 111 Uuu	unbinium 112 Uub			

\* Lanthanide series

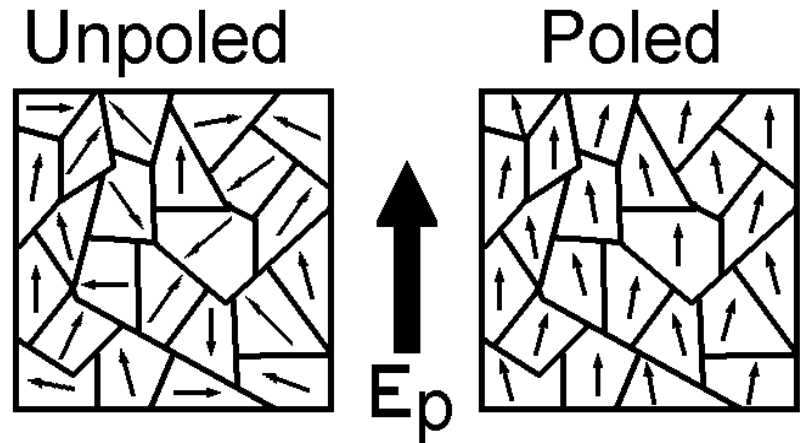
lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
---------------------------------	------------------------------	------------------------------------	---------------------------------	---------------------------------	--------------------------------	--------------------------------	----------------------------------	-------------------------------	----------------------------------	-------------------------------	------------------------------	-------------------------------	---------------------------------

\* \* Actinide series

actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]
-------------------------------	-------------------------------	------------------------------------	------------------------------	--------------------------------	--------------------------------	--------------------------------	-----------------------------	--------------------------------	----------------------------------	----------------------------------	-------------------------------	-----------------------------------	--------------------------------

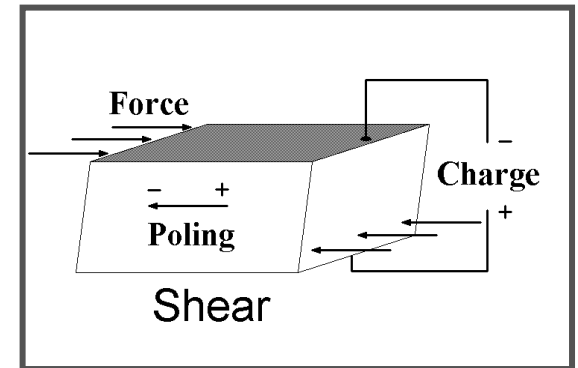
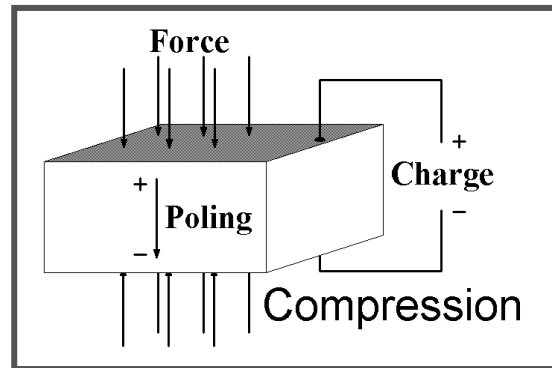
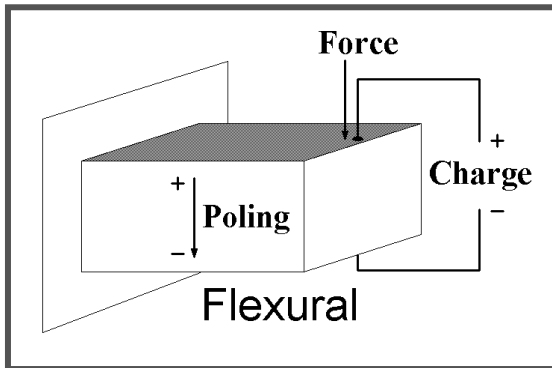
## Poling

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



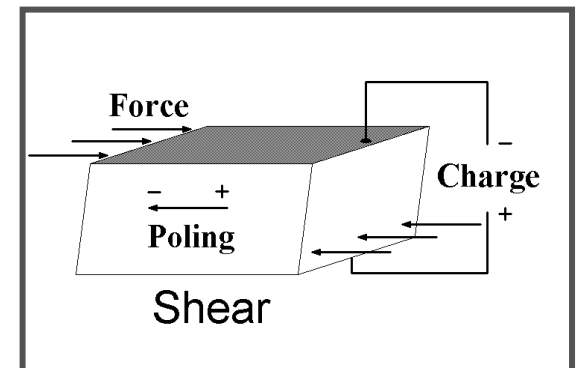
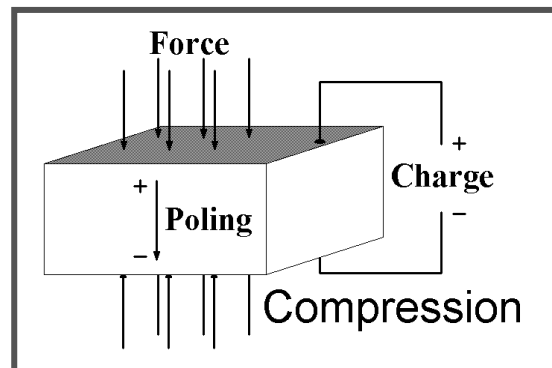
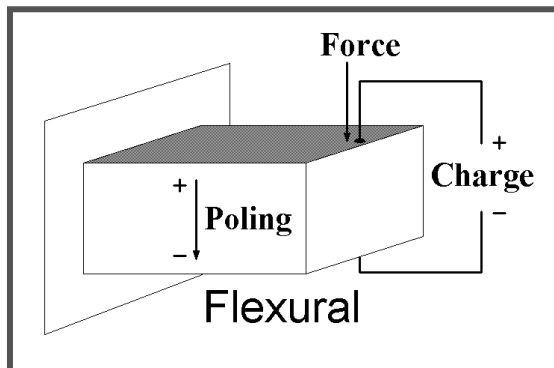
## PZT must be poled for final use

- ▶ 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



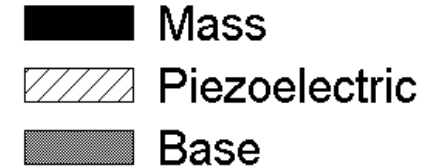
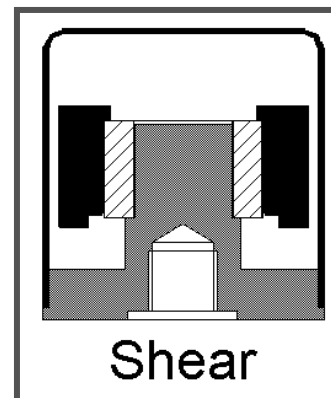
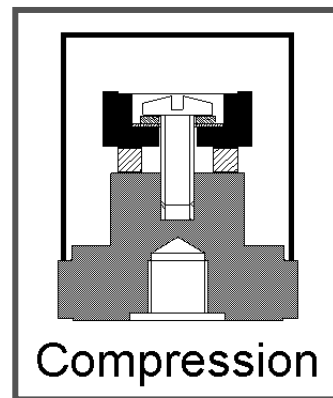
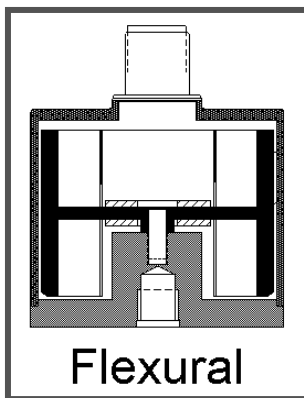
## Mechanical design

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



## Base, PZT, and mass

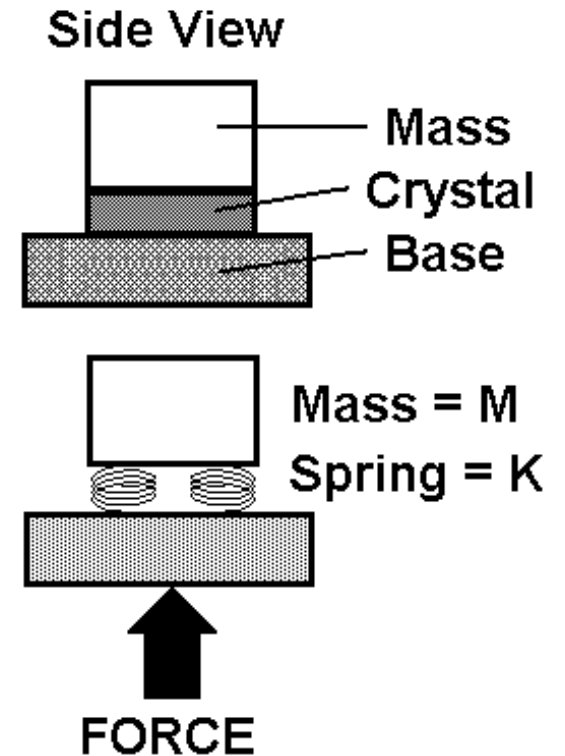
- ▶ Base mounts to machine
- ▶ PZT mounts on the base
- ▶ Mass mounts on the PZT
- ▶  $F = m a$
- ▶ Acceleration output



## Mechanical stack

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

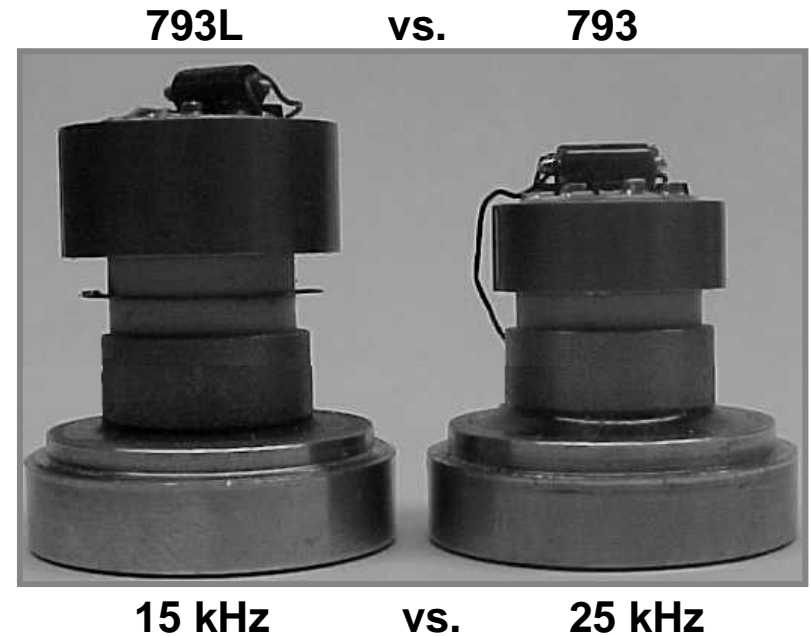
$$F_n \propto \sqrt{\frac{K}{M}}$$





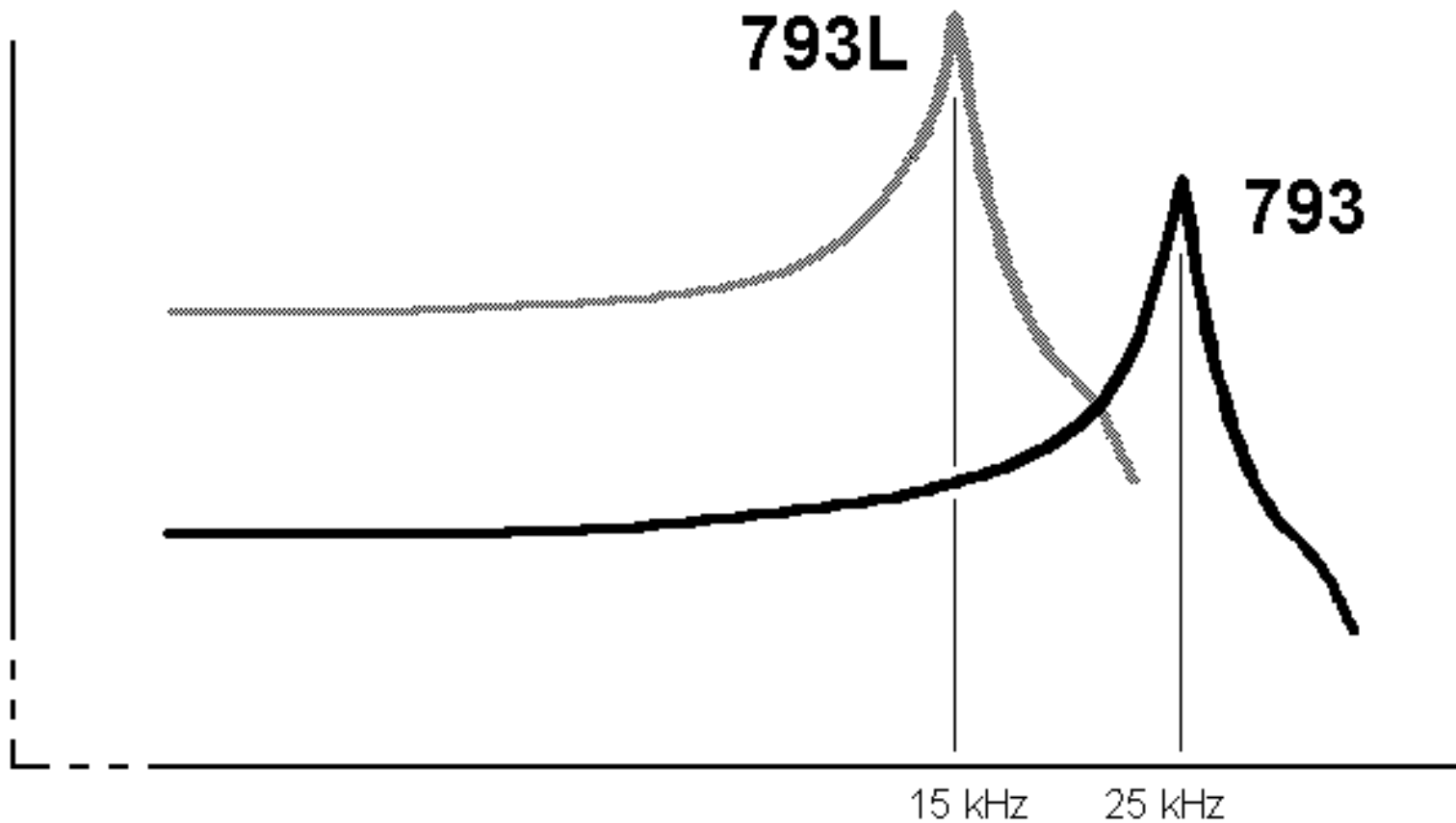
## Mechanical design factors

- ▶ 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



## Mechanical design factors

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

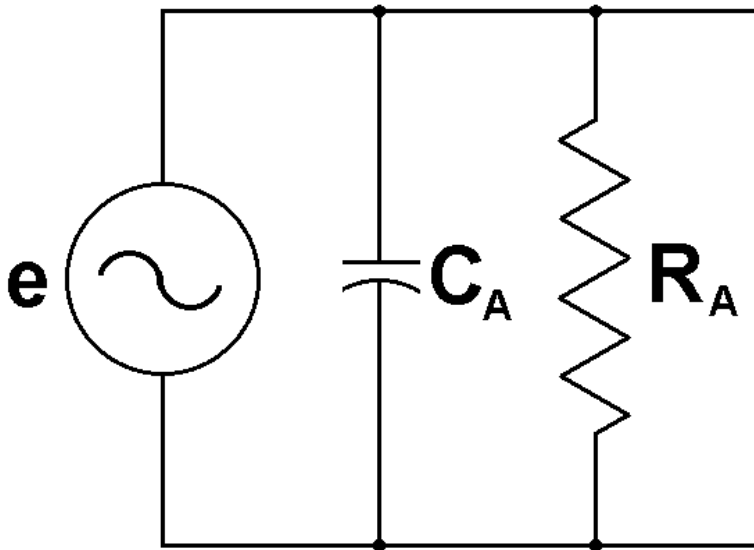


## Charge amplification

- ▶ Charge mode accelerometers
- ▶ Charge amplifiers



## 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

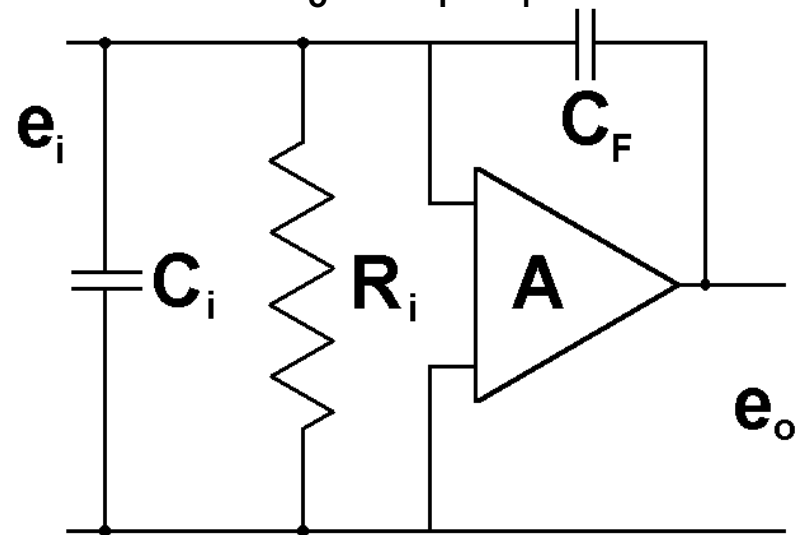
$C_f$  is the feedback element of the amplifier

$A$  is the amplifier

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

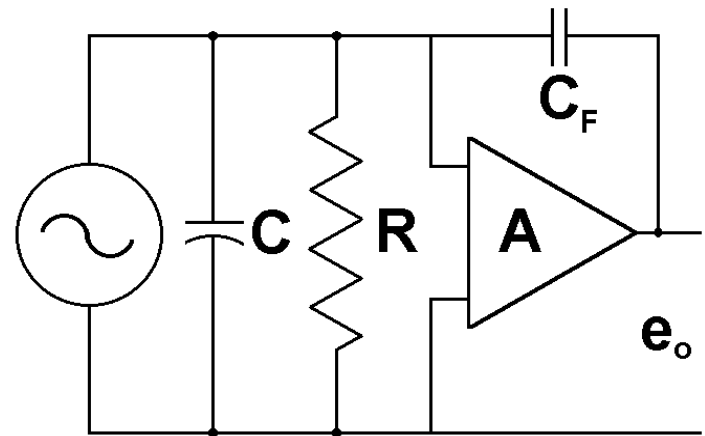
### Basic equation of gain

$$e_o = - e_i / C_f$$



## Charge amplification inside the sensor

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

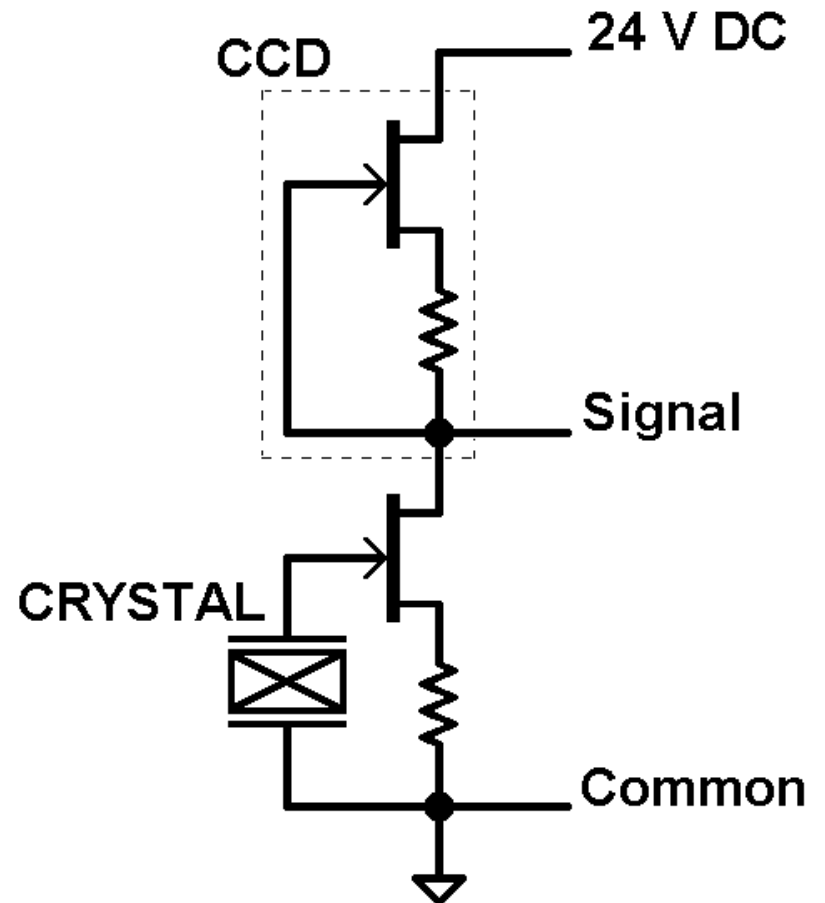


## Design trade-offs

- ▶ 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

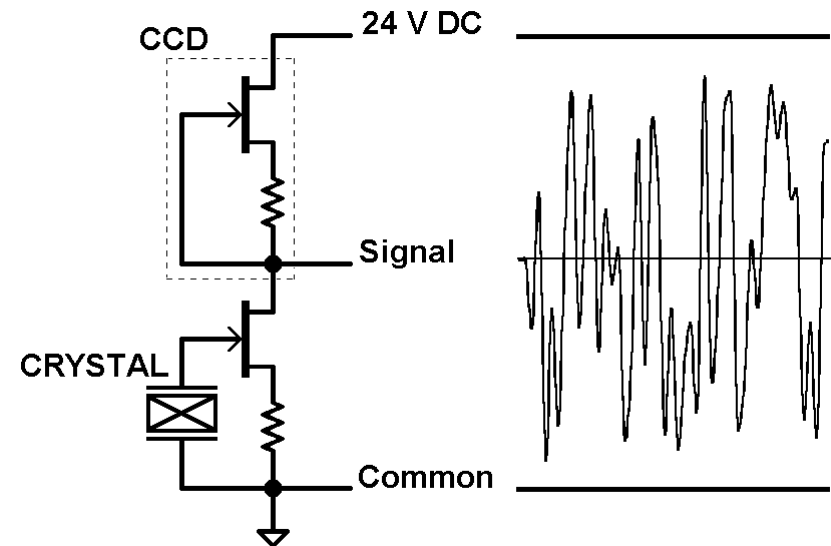
- ▶ Basis for all IEPE sensors
- ▶ Circuit was pioneered by Kistler Instruments in the 1960's





## 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



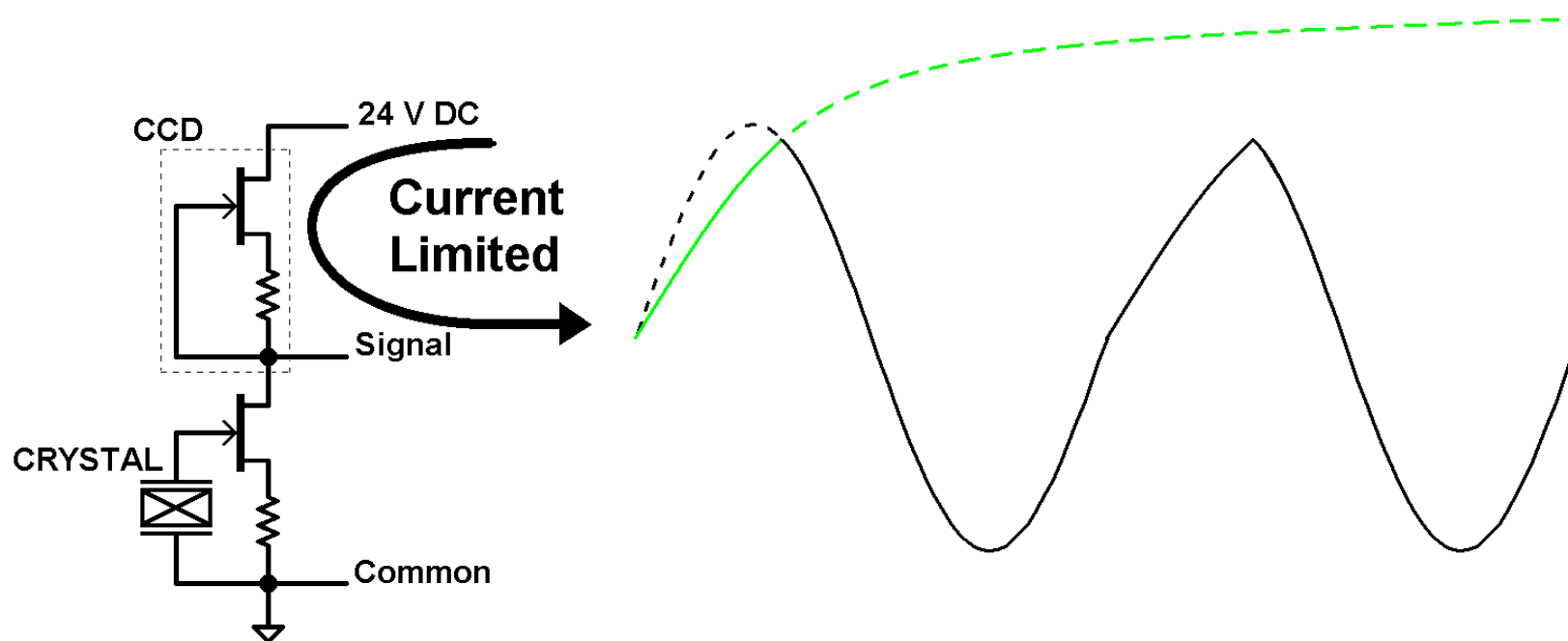
## Cable length limits

- ▶ 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

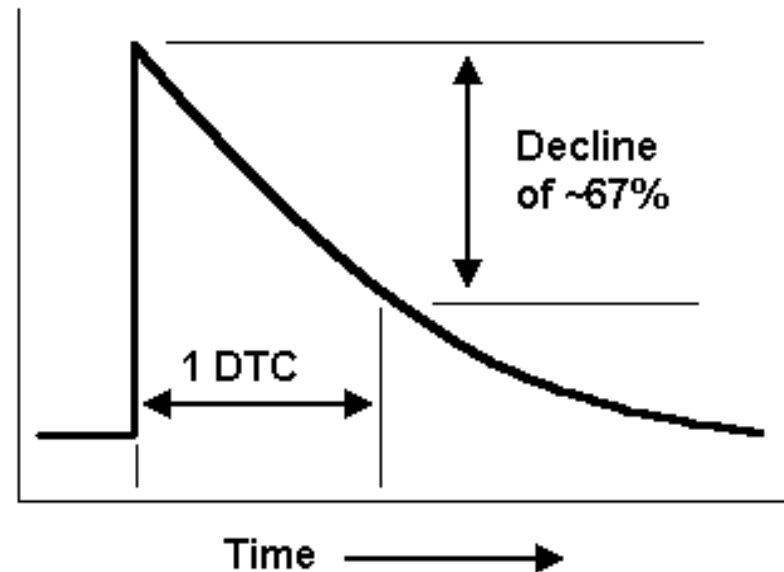


## Discharge time-constant

- ▀ 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

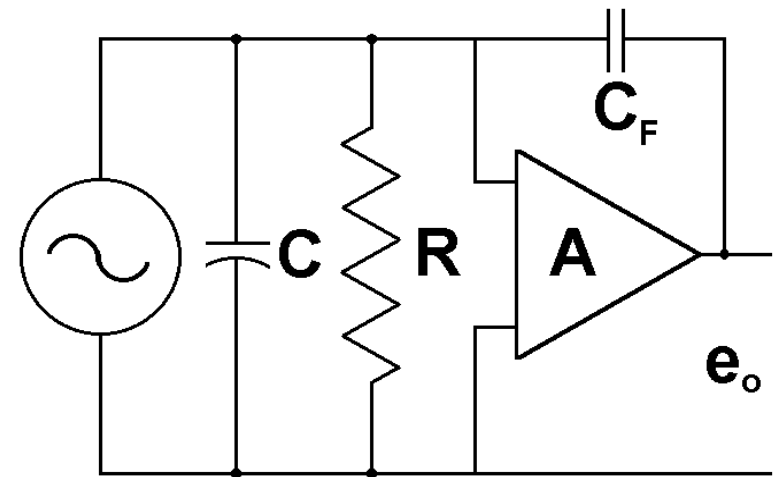
$$\text{DTC} = RC$$

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



## Sensitivity

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



## Sensitivity change of PZT over time

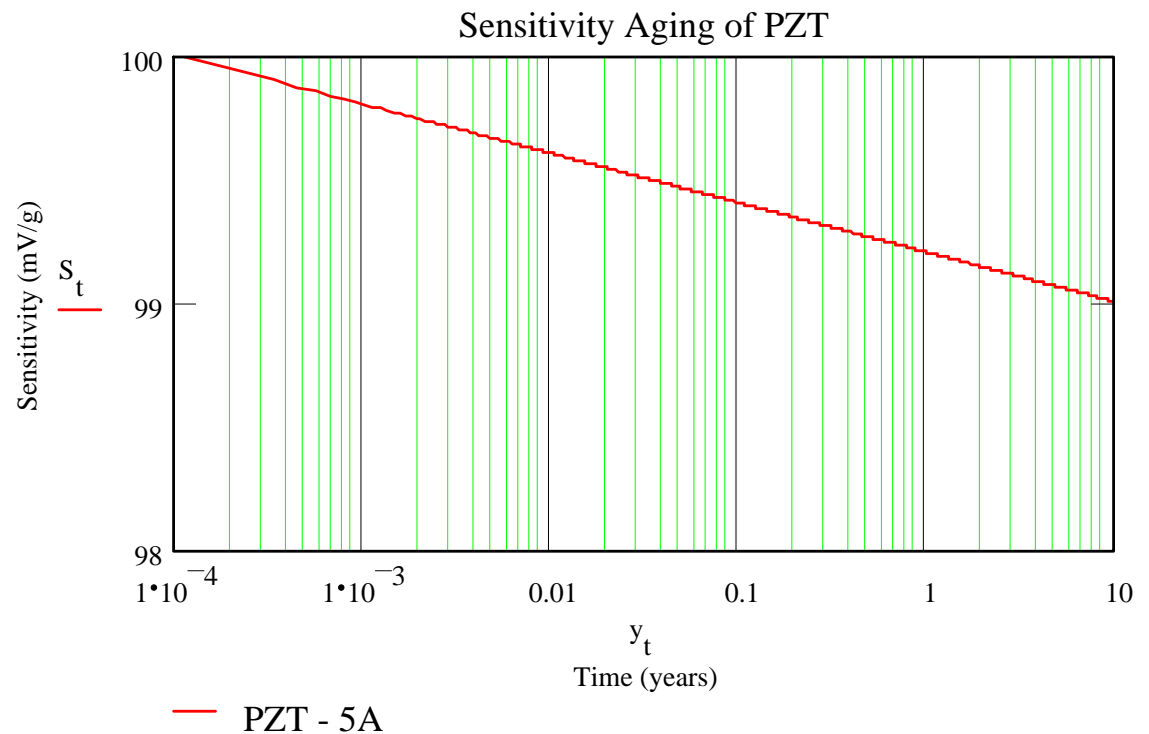
$$S(t) = S_0 \cdot [1 - 0.002 \cdot \log(t)]$$

**S(t)** is the resulting sensitivity

**S<sub>0</sub>** is the original calibration sensitivity

**t**, time, is measured in hours

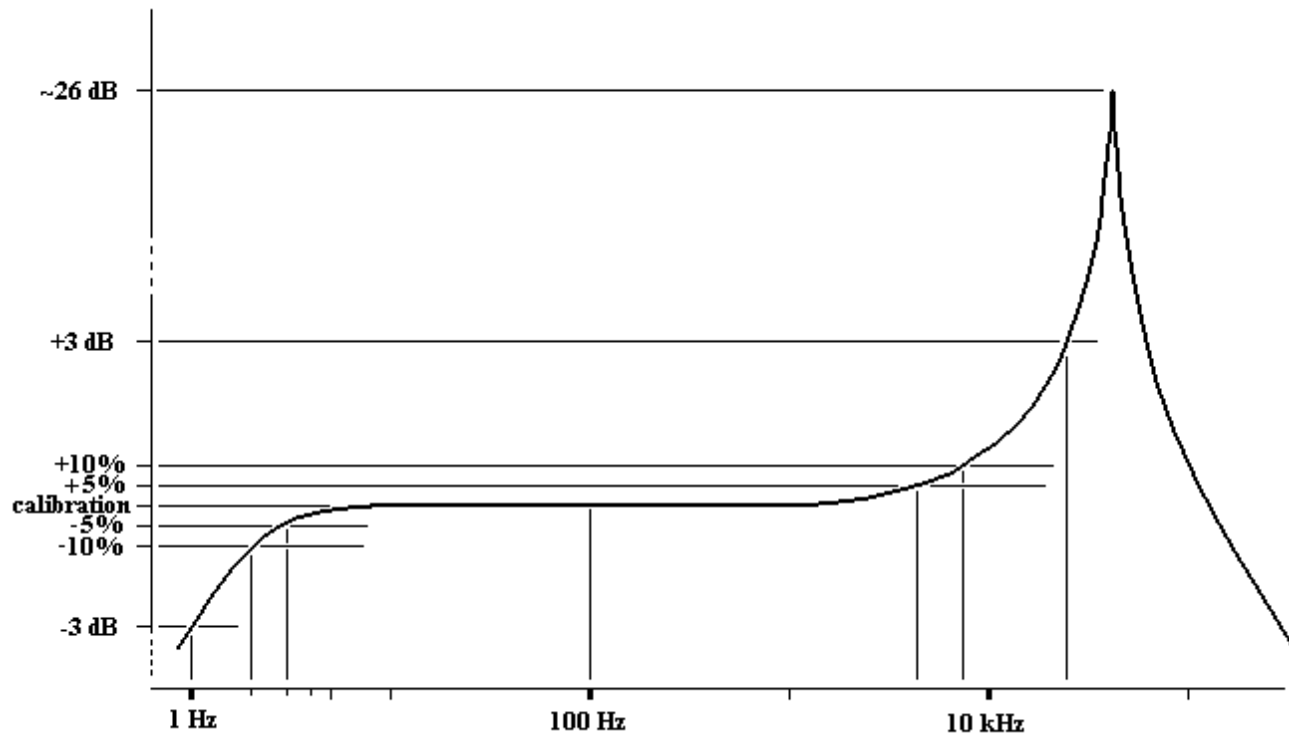
Pre-aged crystals will lose no more than 1% of sensitivity in ten years





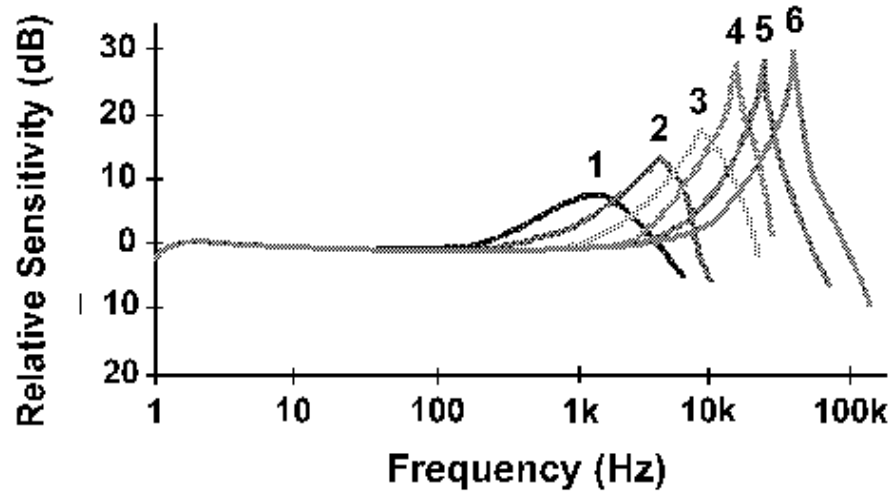
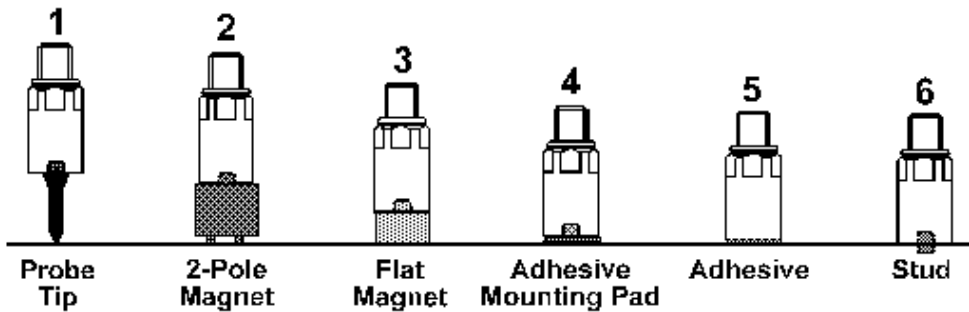
## Accelerometer frequency response example (786A)

$\pm 5\%$  ..... 3 - 5,000 Hz  
 $\pm 10\%$  ..... 1 - 9,000 Hz  
 $\pm 3 \text{ dB}$  ..... 0.5 - 14,000 Hz



# Mounted resonant frequency

786A resonance frequency .....30 kHz



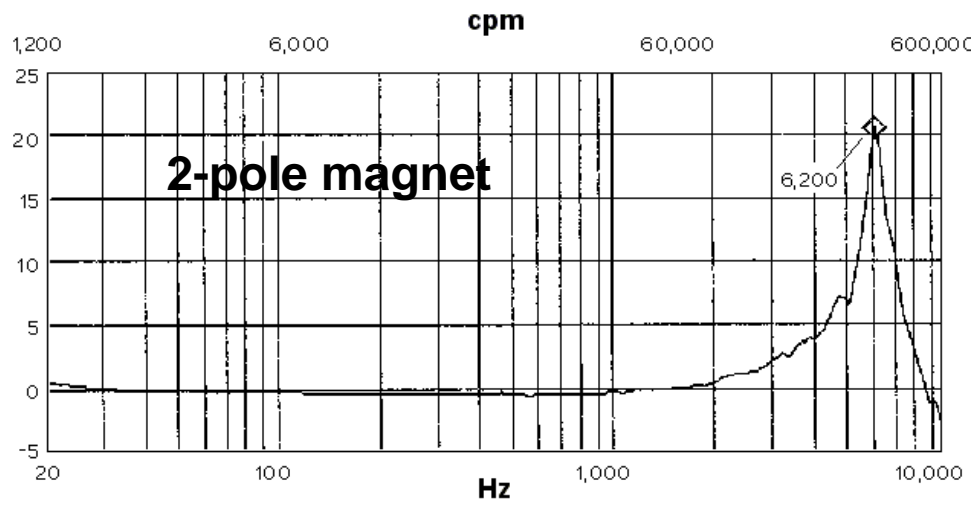
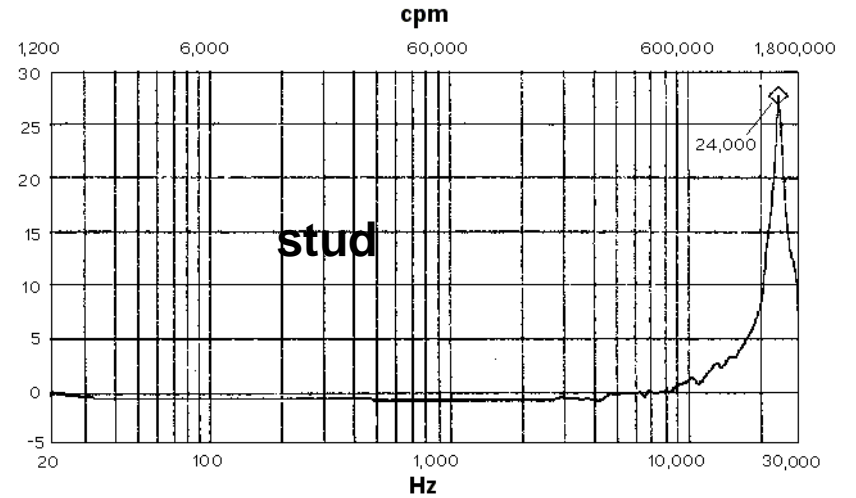
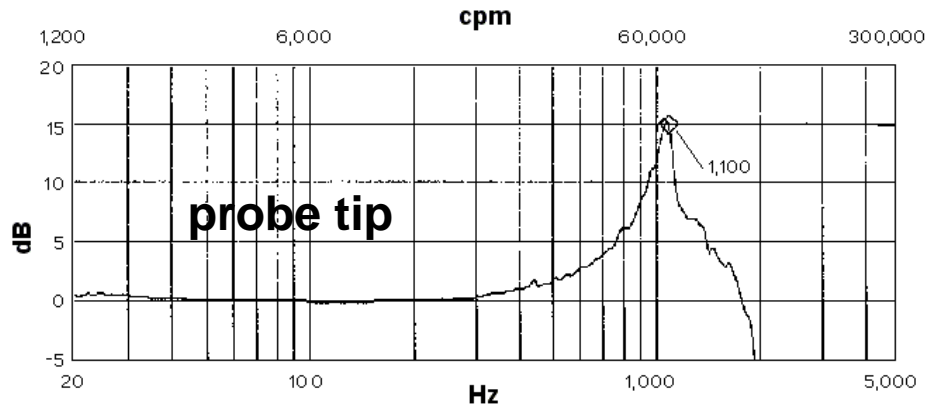
▶ The specification data sheet identifies the resonant frequency of the ideal mounting condition, i.e. - stud mounting

▶ Actual mounting conditions will affect this frequency



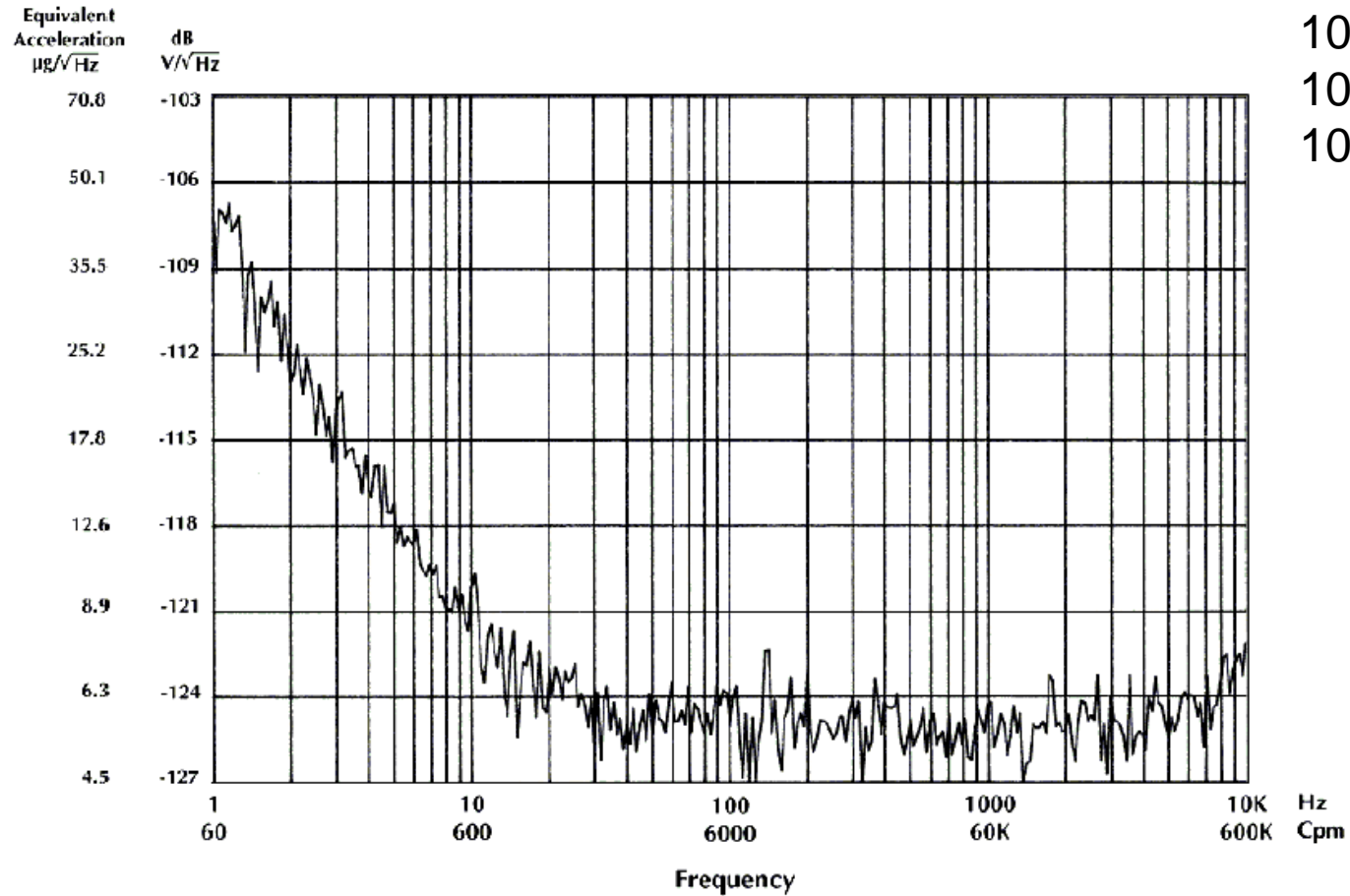


# Mounted resonant frequency examples





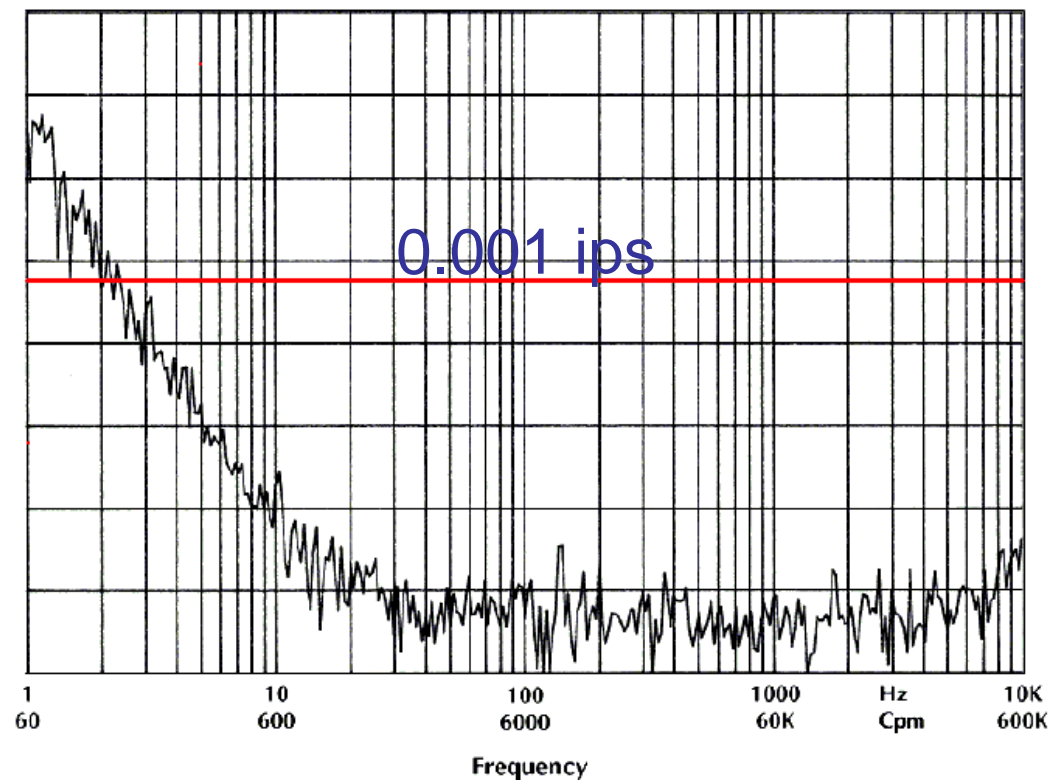
# Electrical noise, equivalent g's



10 Hz      8  $\mu\text{g}/\sqrt{\text{Hz}}$   
100 Hz     5  $\mu\text{g}/\sqrt{\text{Hz}}$   
1000 Hz    5  $\mu\text{g}/\sqrt{\text{Hz}}$

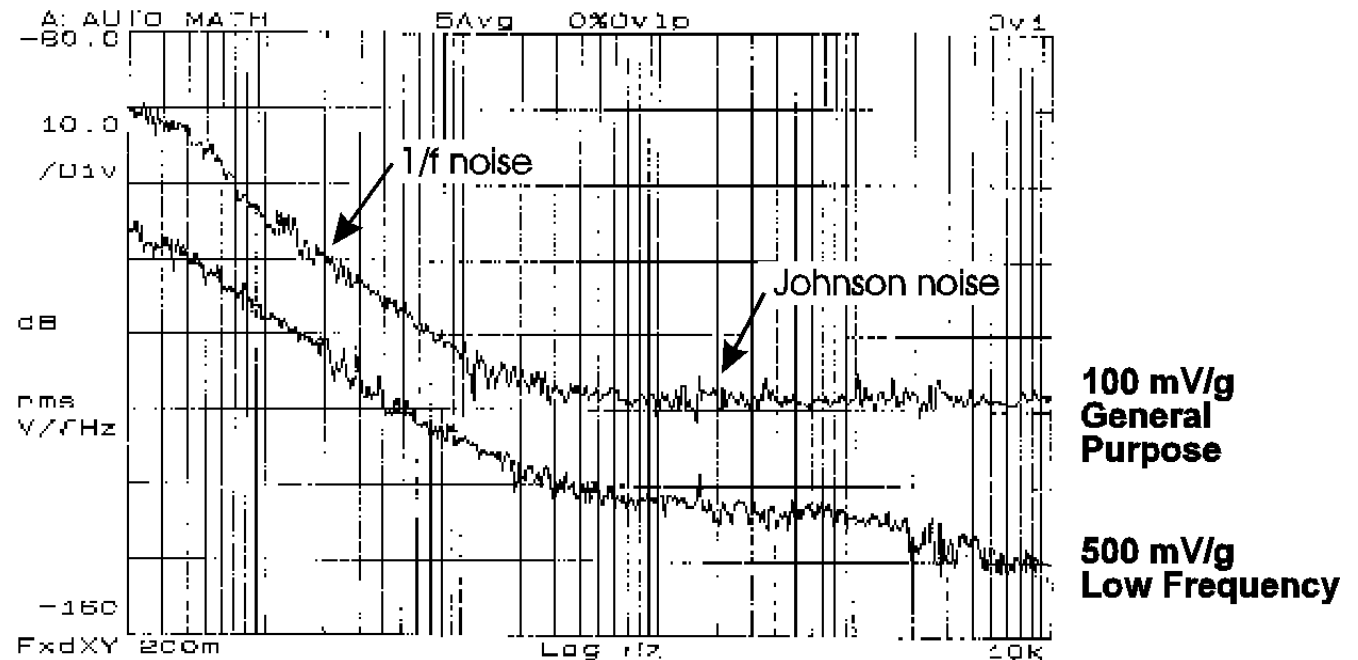
## Noise effect on velocity measurement

- ▶ 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



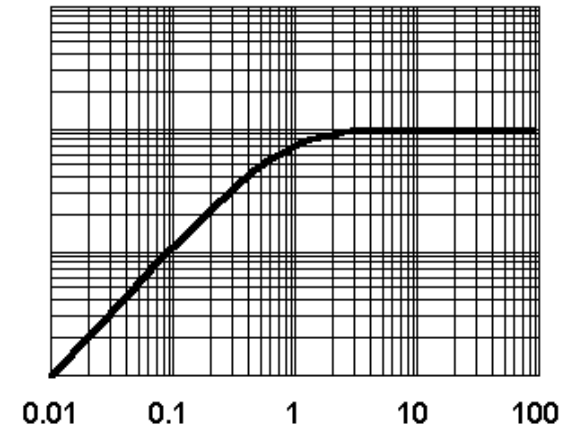
## Noise difference between accelerometers

- ▶ The low frequency accelerometer is 500 mV/g
- ▶ The low frequency accelerometer also has a much lower noise @ 10 Hz
  - ▶ 100mV/g = 8  $\mu\text{g}/\sqrt{\text{Hz}}$
  - ▶ 500mV/g = 0.4  $\mu\text{g}/\sqrt{\text{Hz}}$



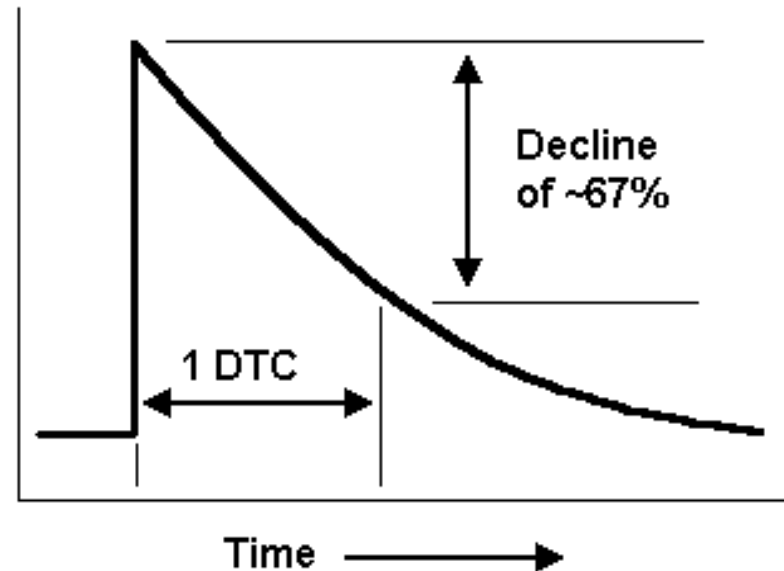
## Low frequency response is limited only by the electronics within the accelerometer

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



$$DTC = RC$$

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



## Low frequency measurements need low frequency accelerometers

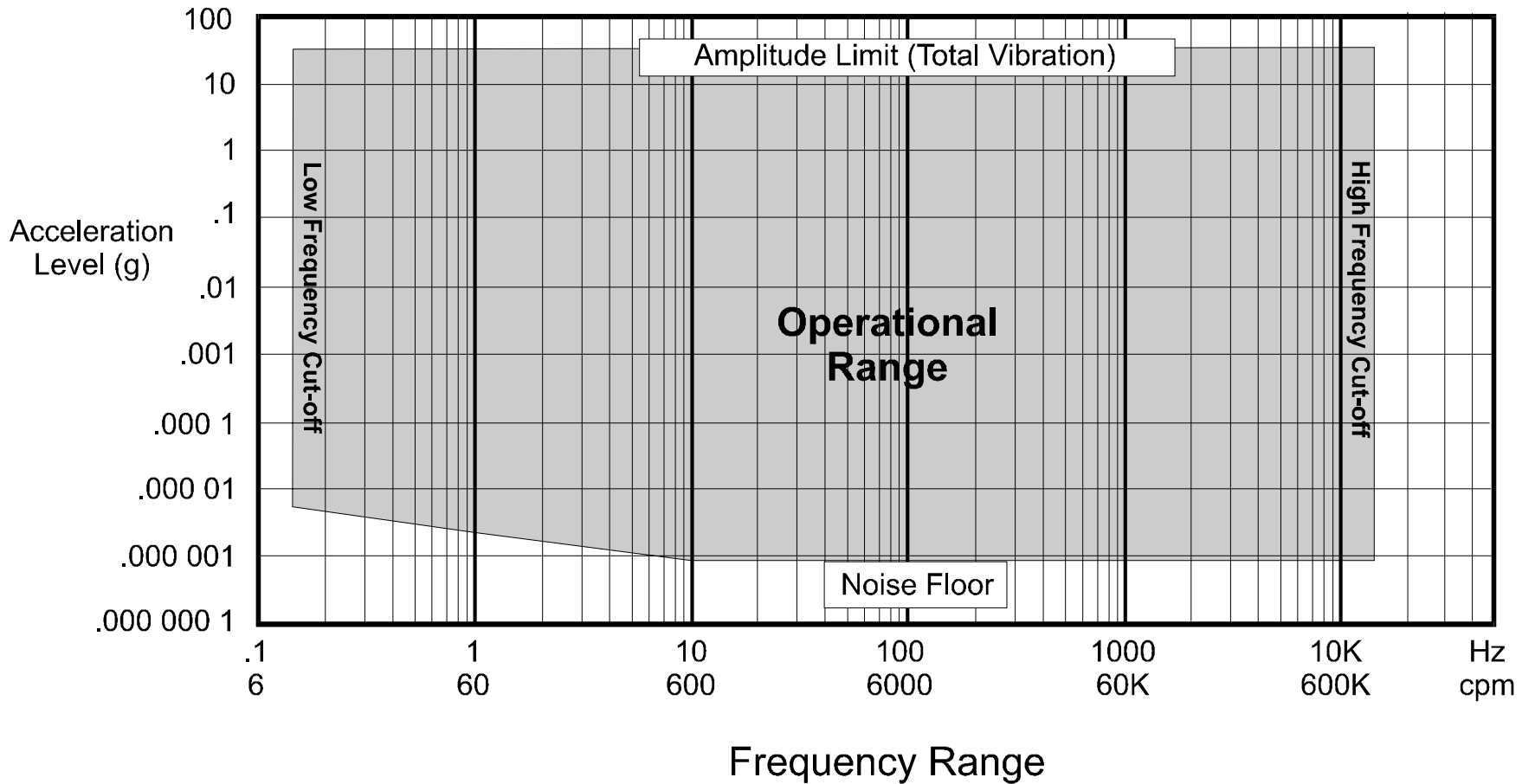
- ▶ For machines that run below 600 RPM a low frequency accelerometer should be used
- ▶ The signal is five times higher with a 500 mV/g accelerometer
- ▶ The noise can be as much as twenty times lower
- ▶ Overall improvement is a 5, 20, or 100 times better signal-to-noise ratio





# 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





## **Wilcoxon Research**

Customer service and applications support

+1 301 330 8811

wilcoxon@meggitt.com



## Industrial accelerometer design, 2009

The information contained in this document is the property of Wilcoxon Research and is proprietary and/or copyright material. This information and this document may not be used or disclosed without the express authorization of Wilcoxon Research. Any unauthorized use or disclosure may be unlawful.

The information contained in this document may be subject to the provisions of the Export Administration Act of 1979 (50 USC 2401-2420), the Export Administration Regulations promulgated thereunder (15 CFR 730-774), and the International Traffic in Arms Regulations (22 CFR 120-130). The recipient acknowledges that these statutes and regulations impose restrictions on import, export, re-export and transfer to third countries of certain categories of data, technical services and information, and that licenses from the US Department of State and/or the US Department of Commerce may be required before such data, technical services and information can be disclosed. By accepting this document, the recipient agrees to comply with all applicable governmental regulations as they relate to the import, export and re-export of information.'