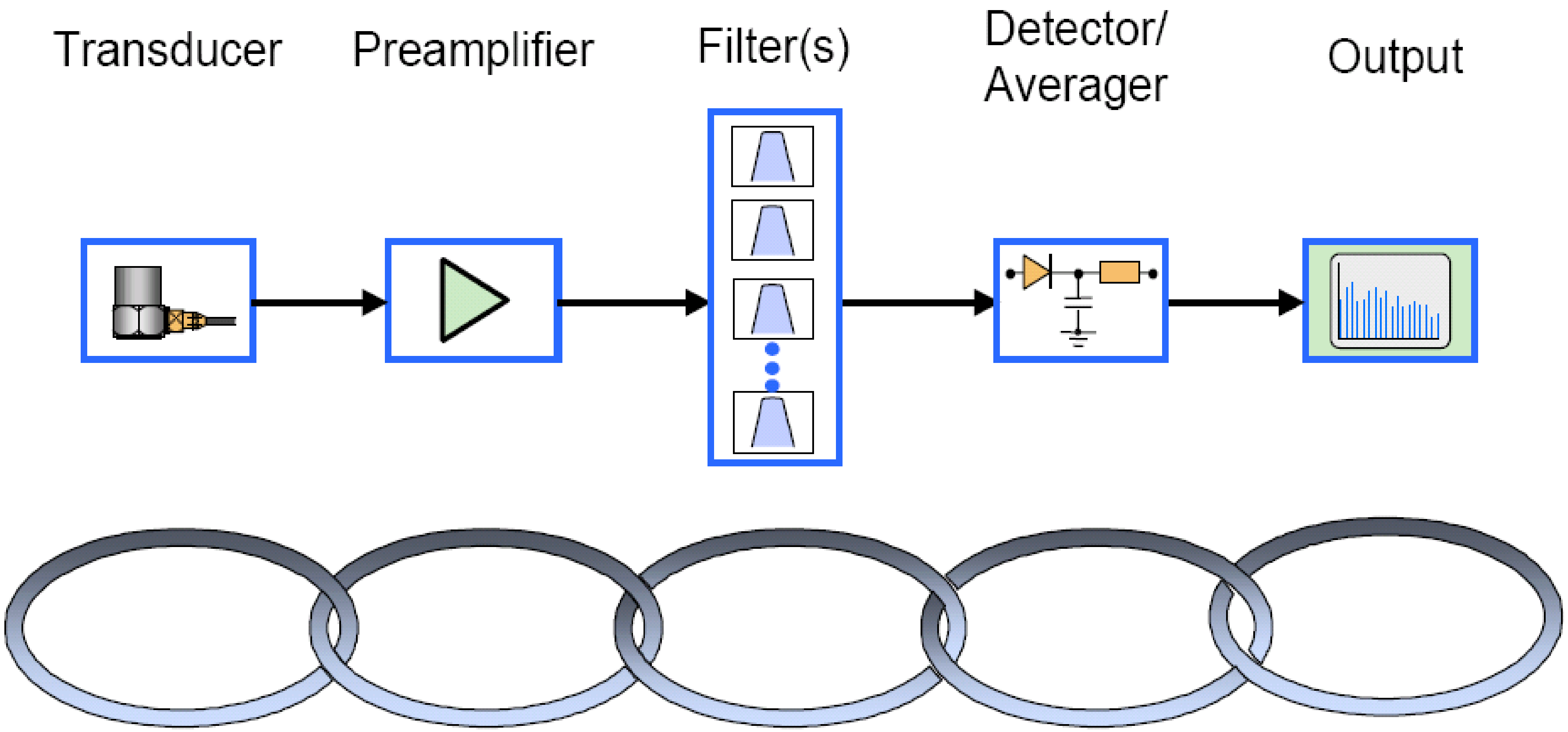
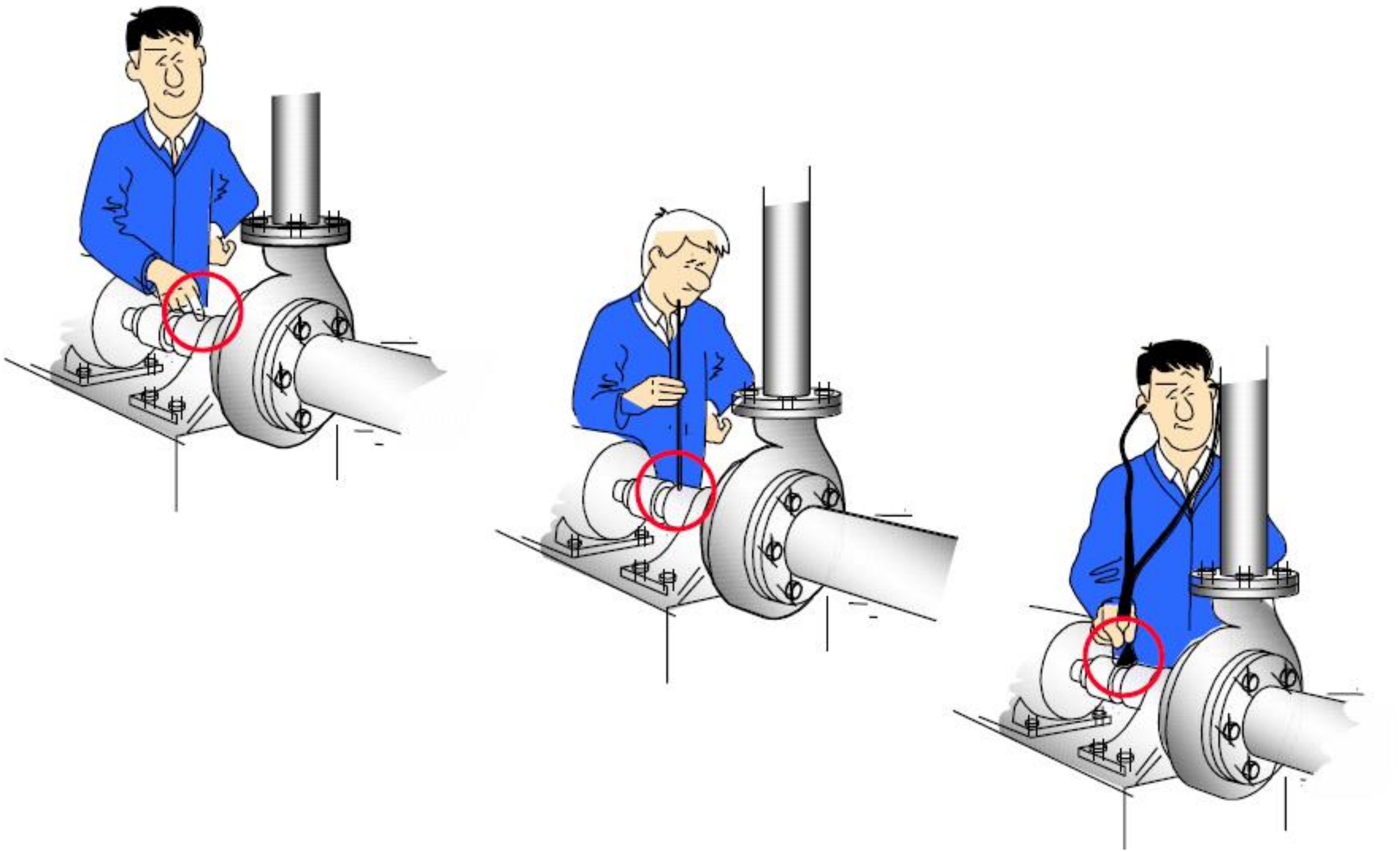
Vibration Measurement Using Accelerometers

Correct Use and Selection
Presented by
Guy Rickard

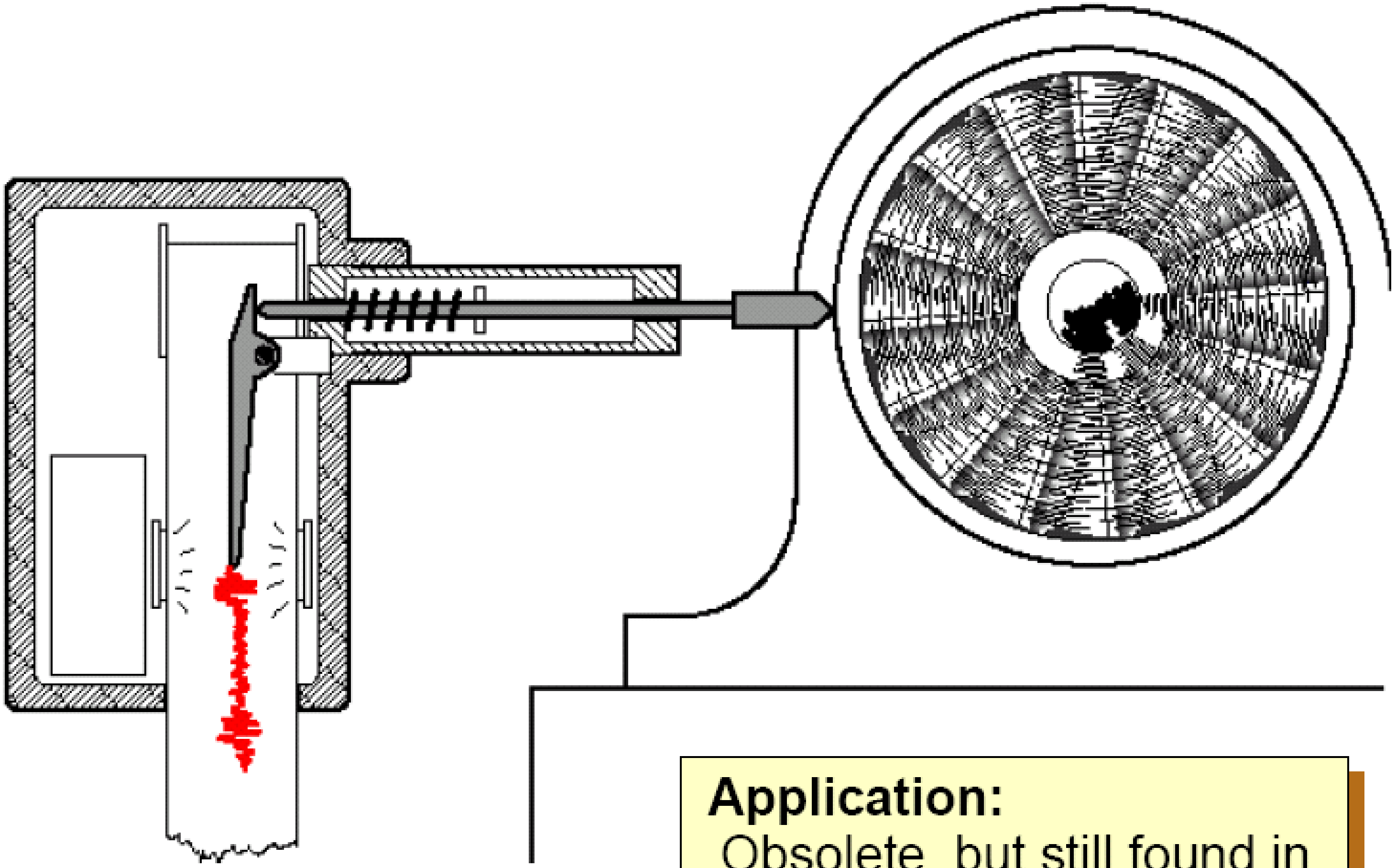
The Measurement Chain



Early Methods of Vibration Measurement

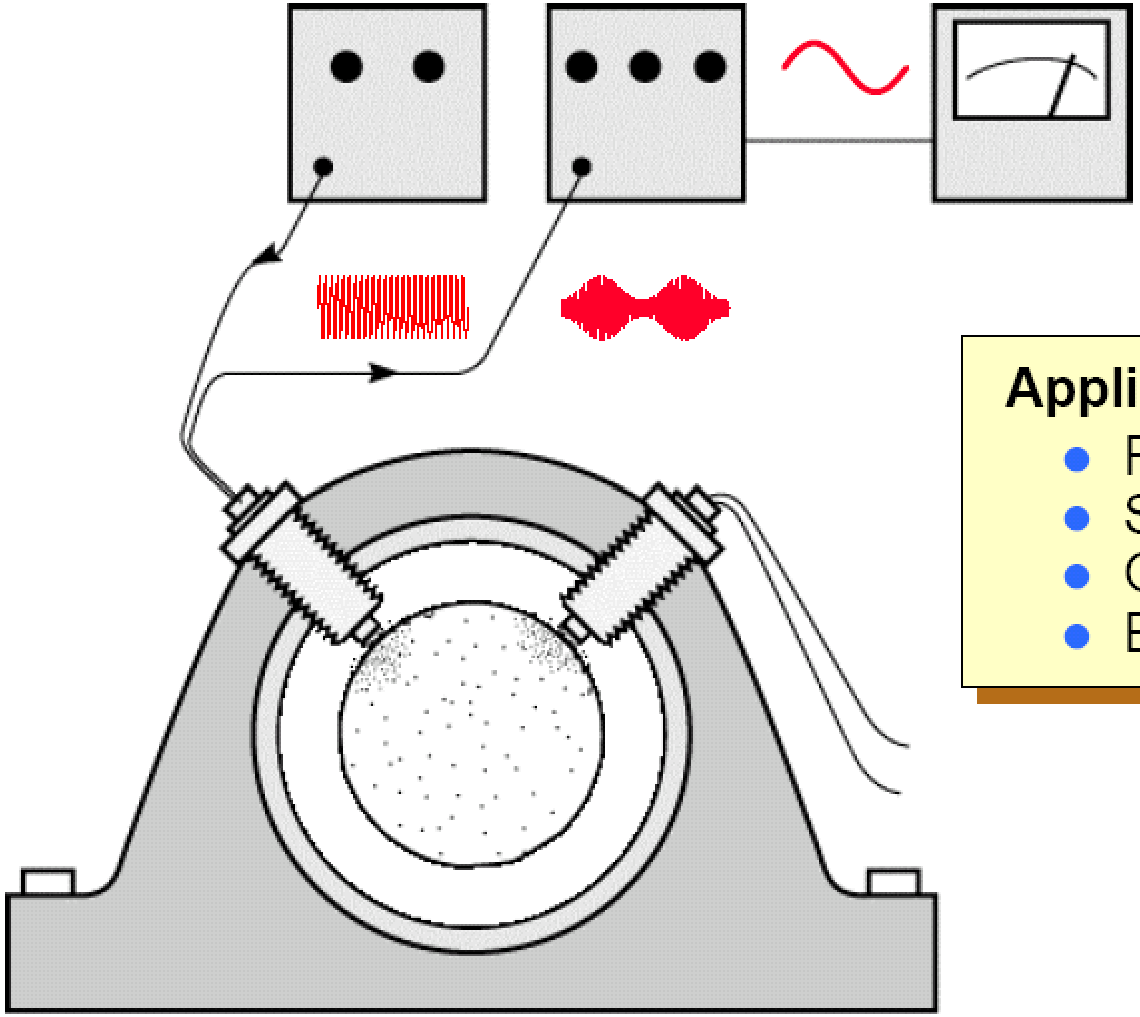


Mechanical Lever



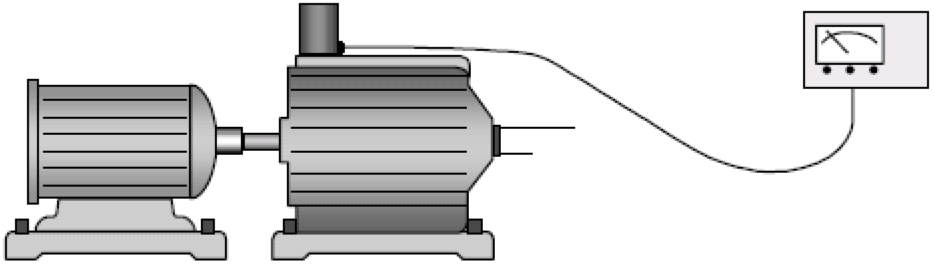
Application:
Obsolete, but still found in a few old power stations

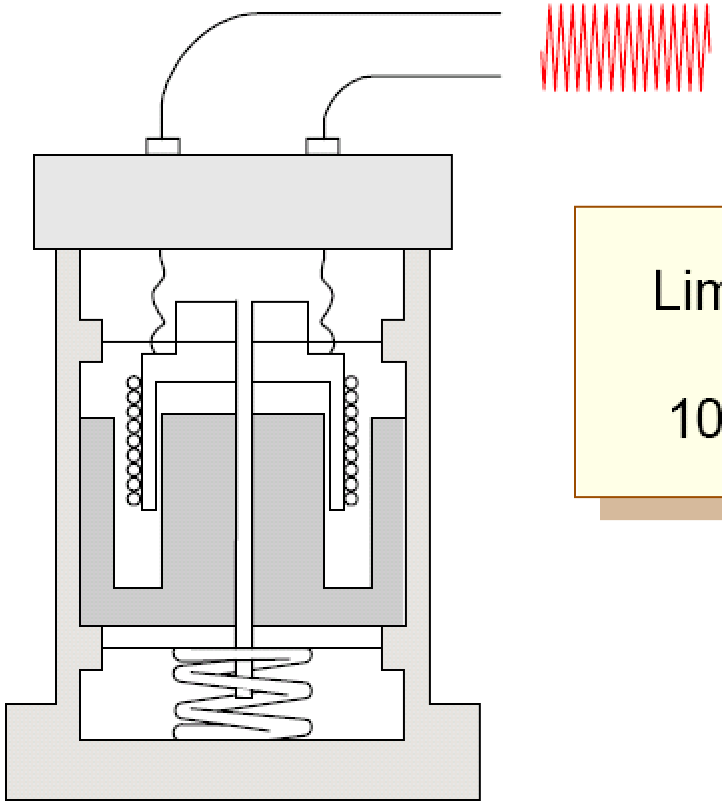
Eddy Current Proximity Probes



Applications:
- Relative motion
- Shaft eccentricity
- Oil film thickness
- Etc.

Velocity Pickups

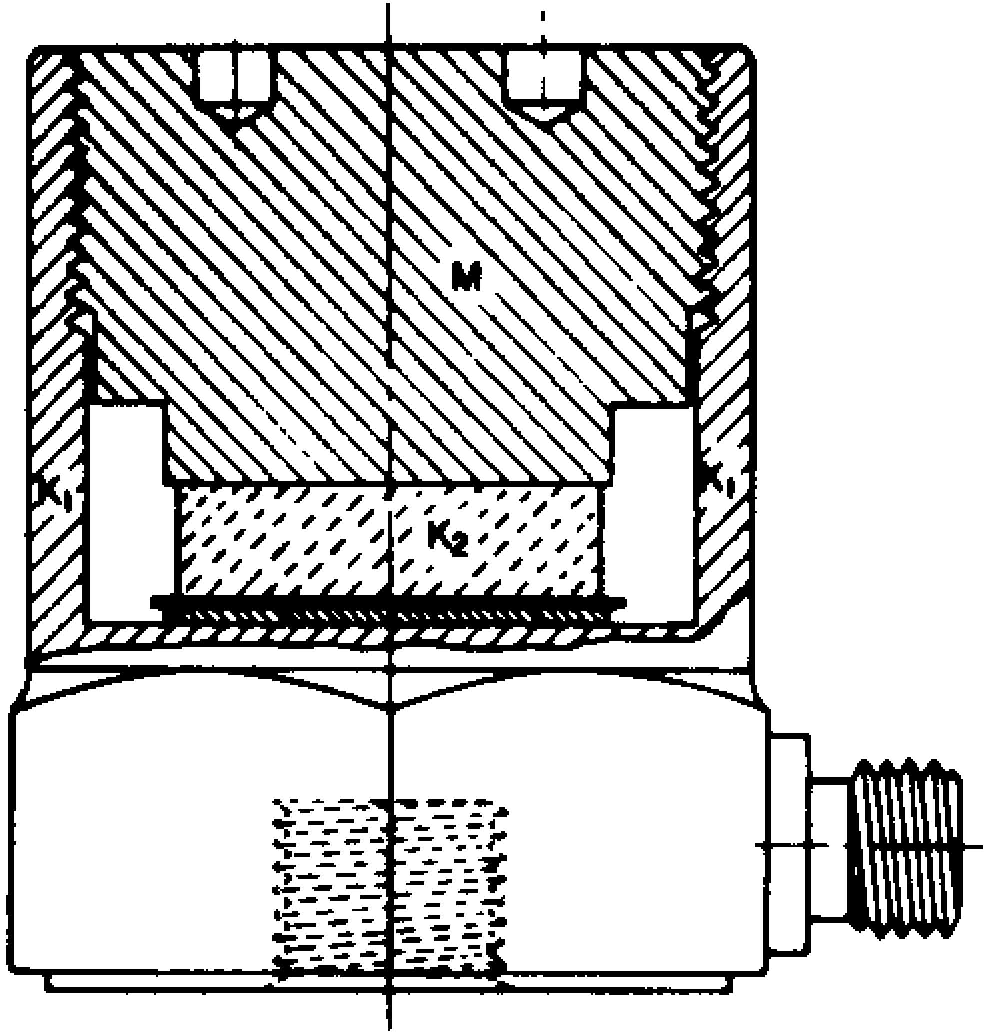




$e = Blv$

Limited frequency range:
$10 < f < 1000$ Hz

Piezoelectric Accelerometer



Vibration Measurement and Analysis

Why use an accelerometer to measure vibration and shock events?

They have many advantages over other types of vibration transducer:

- Small size
- Light weight
- Wide bandwidth
- Convenient mounting method

Are all accelerometers suitable for all types of vibration and shock testing? No!!!

Accelerometer Technologies

- Piezoelectric
  - Can measure dynamic events only such as vibration, short duration shock pulses, pressure fluctuations
  - High temperature capability 260, 480, 650, 760 deg C
- Piezoresistive & Variable Capacitance (Silicon)
  - Can measure static and dynamic events - i.e. constant acceleration on centrifuge, long duration shock events
  - Max. temperature typically 125 deg C

Accelerometer Technologies

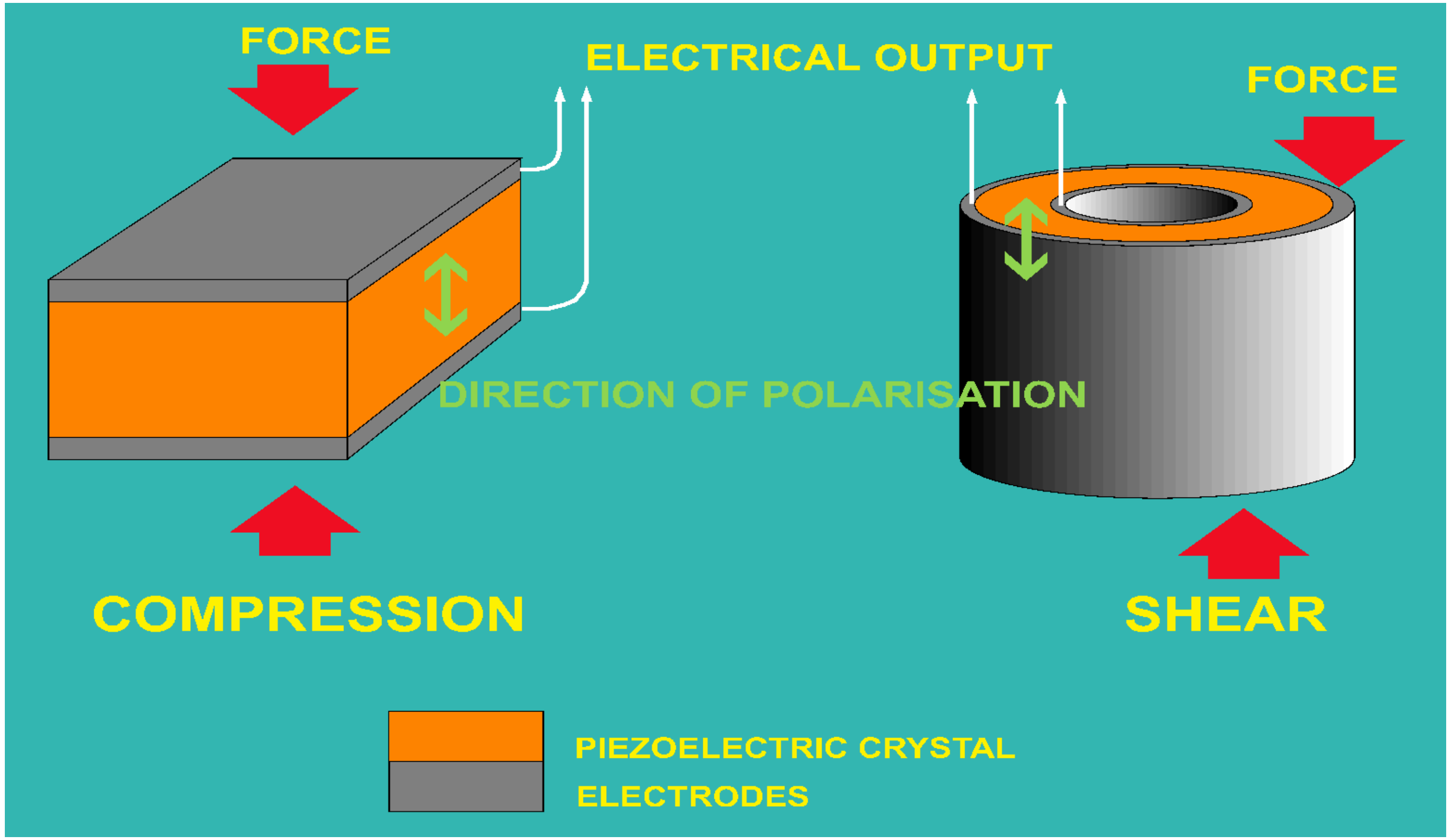
Types of Piezoelectric accelerometer

- **Standard Piezoelectric charge output accelerometer**
  - Self generating high impedance output
  - Requires charge amplifier to condition signal
  - High temperature capability – up to 760 deg C

- **IEPE (Integral Electronics piezoelectric accelerometer)**
  - Low impedance voltage output
  - Needs to be powered by external constant current power source
  - Output can be fed directly into most frequency analysers / data loggers etc
  - TEDS capability available on some models

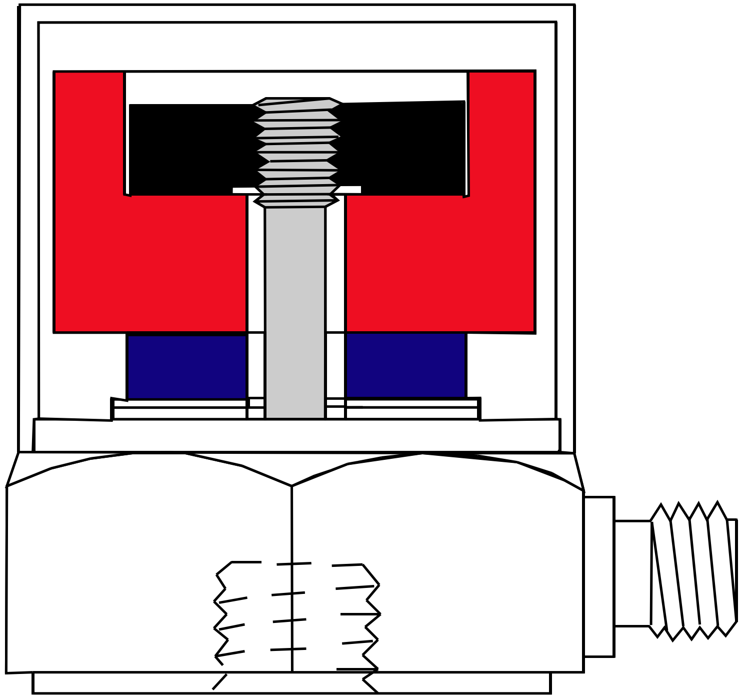
Principles of Operation

Piezoelectric Accelerometers



Principles of Operation

Piezoelectric Accelerometers



- Single Ended Compression
  - – Rugged
  - – High Output
  - – High Frequency
  - – Small, Lightweight.

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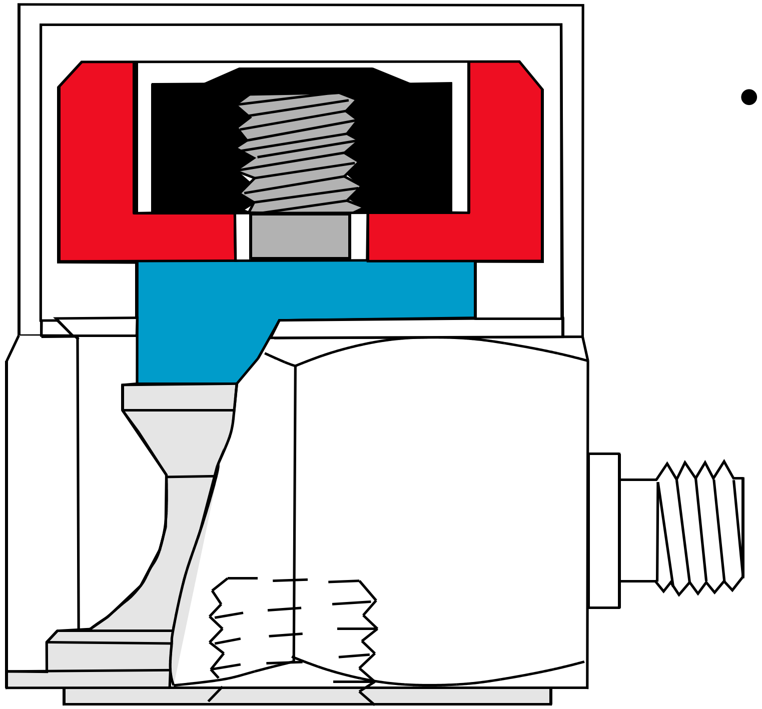
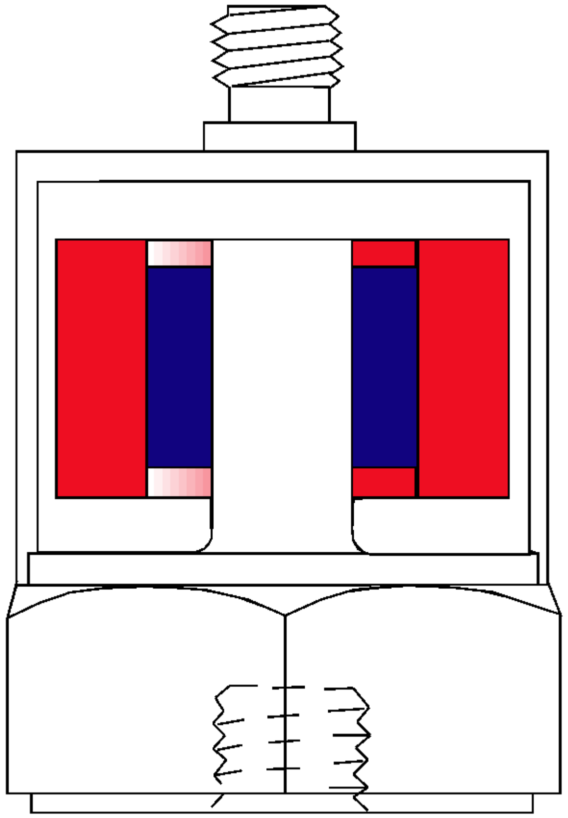
Piezoelectric Accelerometers



- ISOBASE®
  - – Better mechanical isolation
  - – Lower base strain sensitivity
  - – Lower thermal transient sensitivity.

Piezoelectric Accelerometers

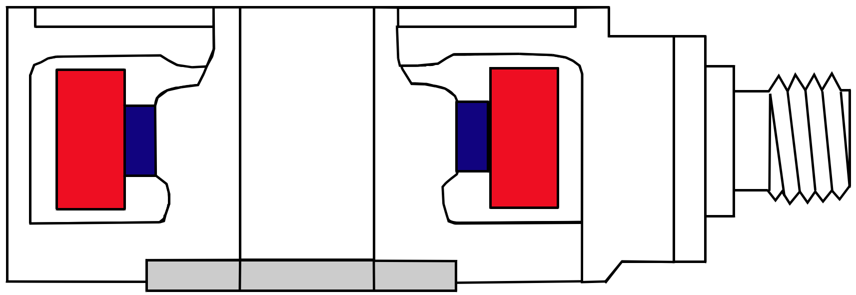


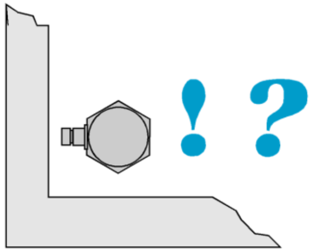
- Annular Shear
  - – Low base strain Sensitivity
  - – Low thermal transient sensitivity
  - – Small, Lightweight – miniature designs only 0.2g in weight.

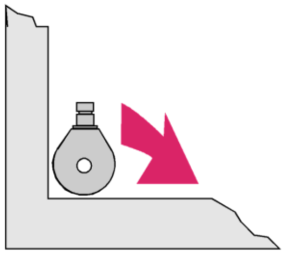
Principles of Operation

Piezoelectric Accelerometers

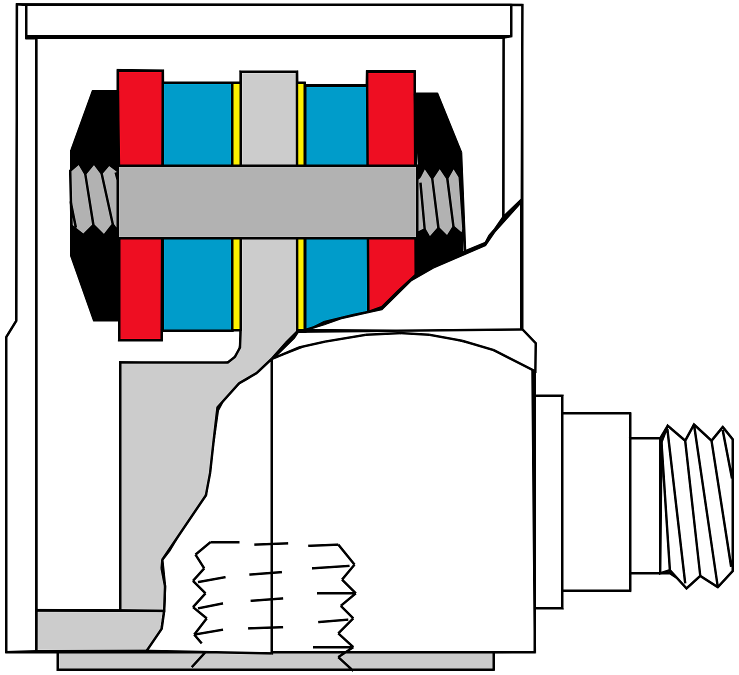
- Annular Shear
  - – Ring shape for ease of installation.







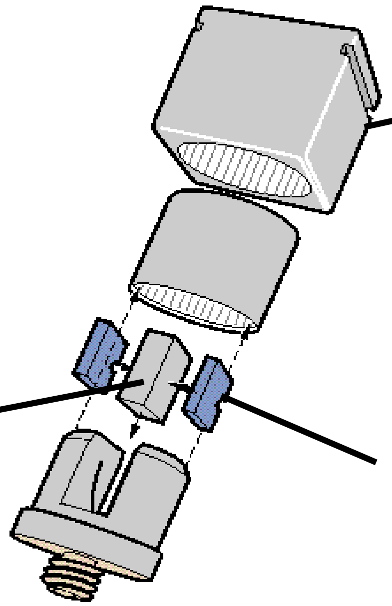
Piezoelectric Accelerometers



- ISOSHEAR ®
  - Flat Plate Shear Design
  - Lowest base strain sensitivity
  - Lowest thermal transient response
  - Temperature compensation on some units
  - High sensitivity designs - 1000pC/g

Principles of Operation

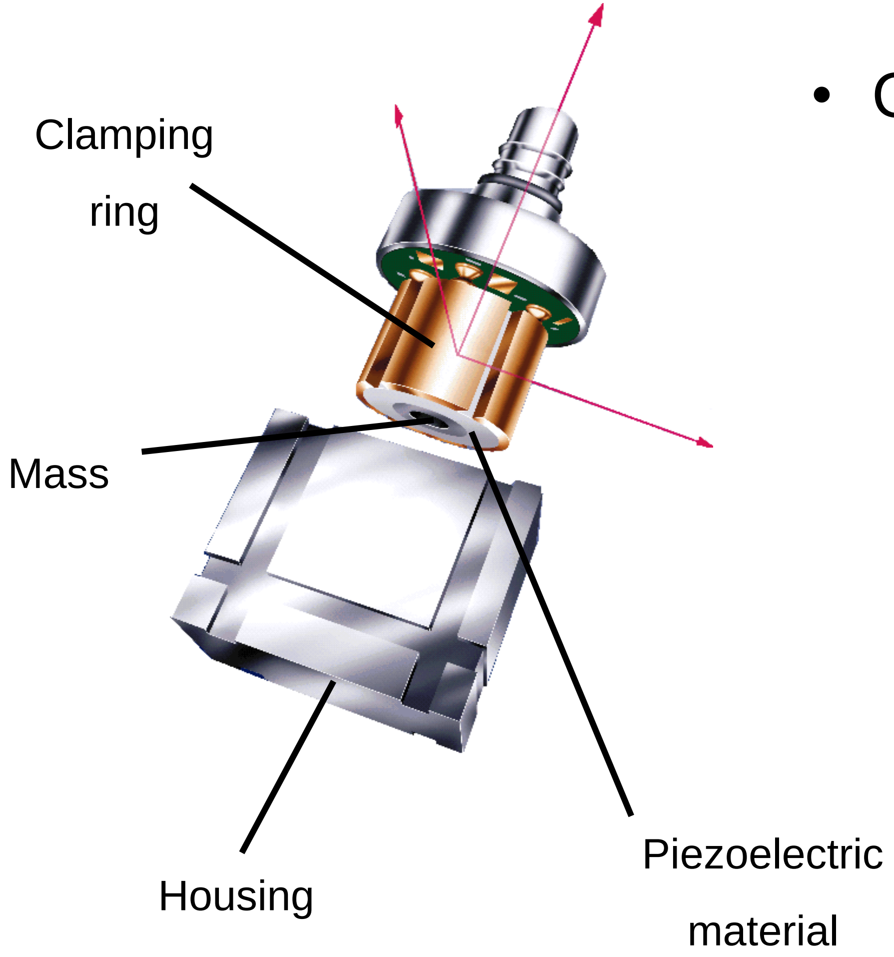
Piezoelectric Accelerometers



- ThetaShear ®
  - Two element, central mass shear design
  - Low base strain sensitivity
  - Low thermal transient response
  - Wide range of sensitivities, 10mV/g up to 1V/g
  - Slotted housing designed for mounting on quick release plastic clips

Principles of Operation

Piezoelectric Accelerometers



- Othoshear
  - Centre mass shear design
  - Low base strain sensitivity
  - Low thermal transient response
  - High sensitivity versions available, up to1V/g
  - Slotted housing designed for mounting on quick release plastic clips

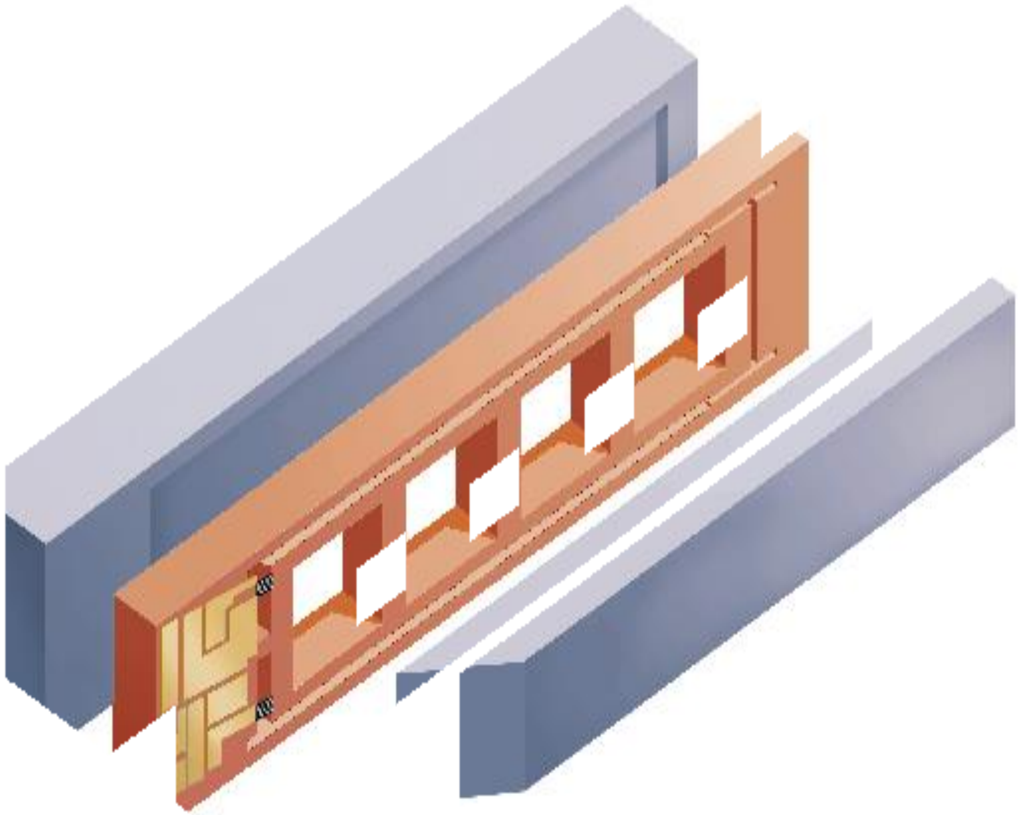
*

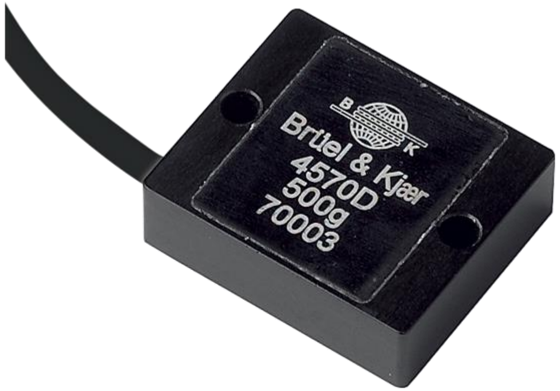
Principles of Operation

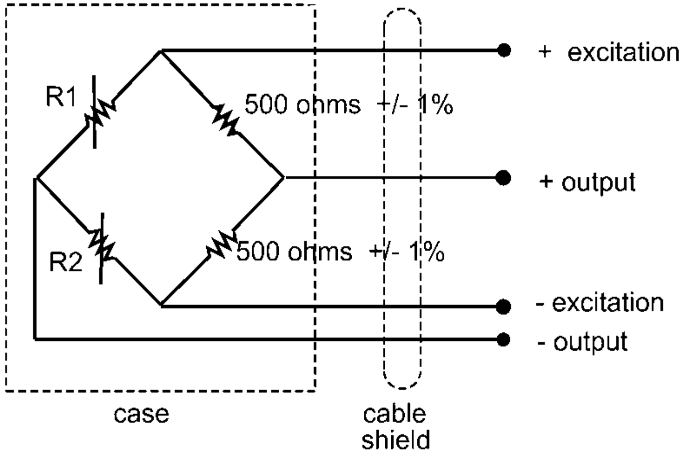
Silicon Accelerometers

- **Piezoresistive accelerometers**
  - DC response
  - Full and half bridge Wheatstone bridge strain gauge sensing elements
  - Ranges from 25 to 200,000g
  - Requires DC Differential Voltage Amplifier to condition output
- **Variable Capacitance accelerometers**
  - DC response
  - Silicon MEMS Sensing element
  - High Sensitivity
  - Ranges from 2g to 100g
  - Can be used in single ended or differential modes

Piezoresistive Accelerometers







Selection Criteria

What should I consider when selecting an accelerometer for vibration and shock measurements?

- Frequency range
  - Does the unit selected have sufficient dynamic range for the measurement in question?
- Sensitivity
  - What are the maximum and minimum acceleration levels
- Amplitude Linearity
  - Is the unit linear across the required measurement range
- Temperature range
  - What is maximum and minimum temperature that the unit will be used at?

Selection Criteria

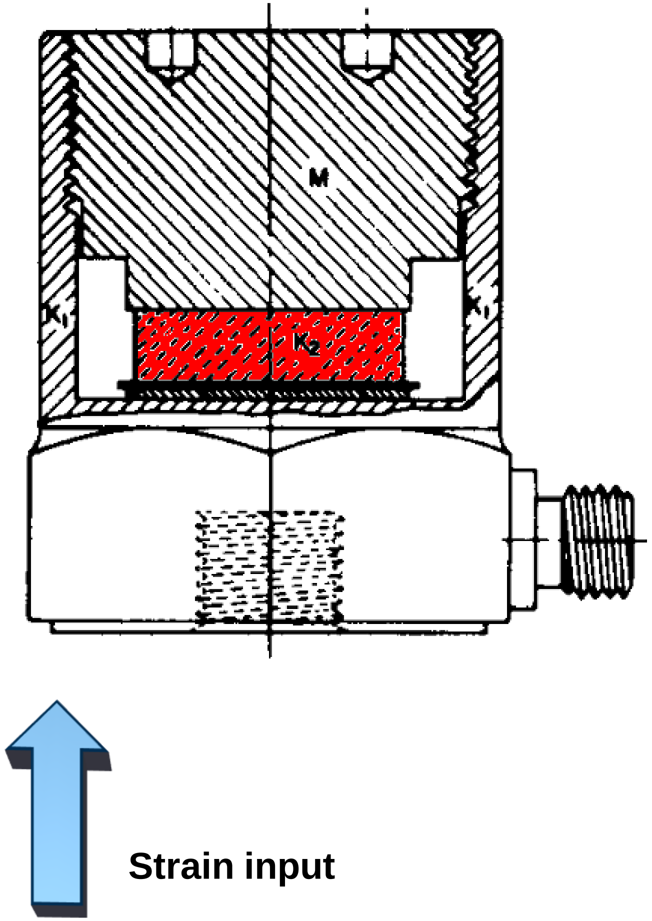
- What are the environmental conditions to which the unit will be exposed? If the environment is humid or wet seal the accelerometer / cable interface with a suitable compound.
- Configuration / Mounting
  - Where do you want to mount the accelerometer and how?
- Physical size and mass
  - Will the unit fit where you want to mount it?
  - Will the accelerometer mass load the structure?
- How long a cable assembly do you require?
  - This could reduce the HF response of the unit (capacitive filtering effect)
- What signal conditioning equipment do you have already?

Error Sources

- Base strain / bending
- Mass loading
- Pyroelectric effect
- Zero shift
- Transverse sensitivity
- Electromagnetic sensitivity
- Acoustic sensitivity
- Radiation sensitivity
- Triboelectric effect
- Saturation and Clipping

Base Strain – what is it?

Deformation of the accelerometer case leading to the generation of a non linear and erroneous acceleration output. It is probably easier to understand "base strain" as "base bending"

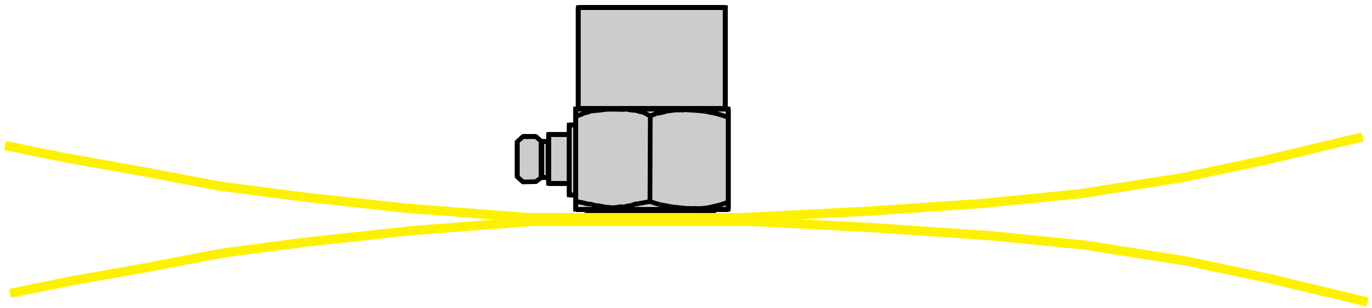


Strain input

Error Sources

Base Strain / Bending Sensitivity

"equivalent g per microstrain"



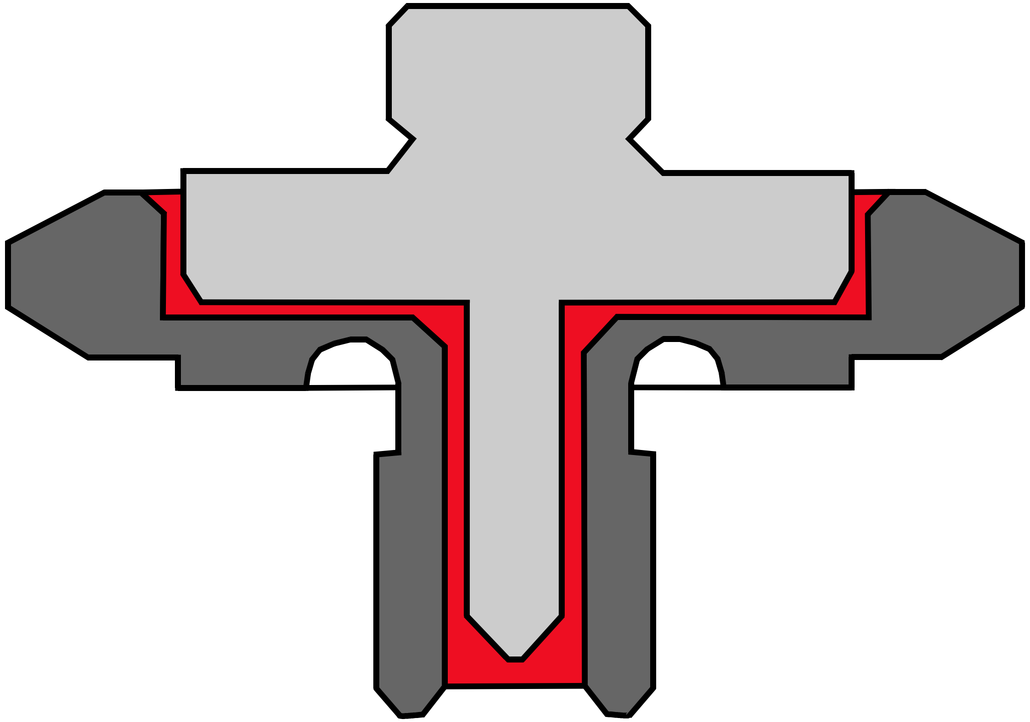
Low Frequency Effect

SEC	0.1 equivalent g per microstrain
ISOBASE	0.002
Annular Shear	0.05 to 0.001
ISOSHEAR	0.002 to 0.00008

Error Sources

Base Strain - How can we avoid it???

Use an isolated mounting stud



Error Sources

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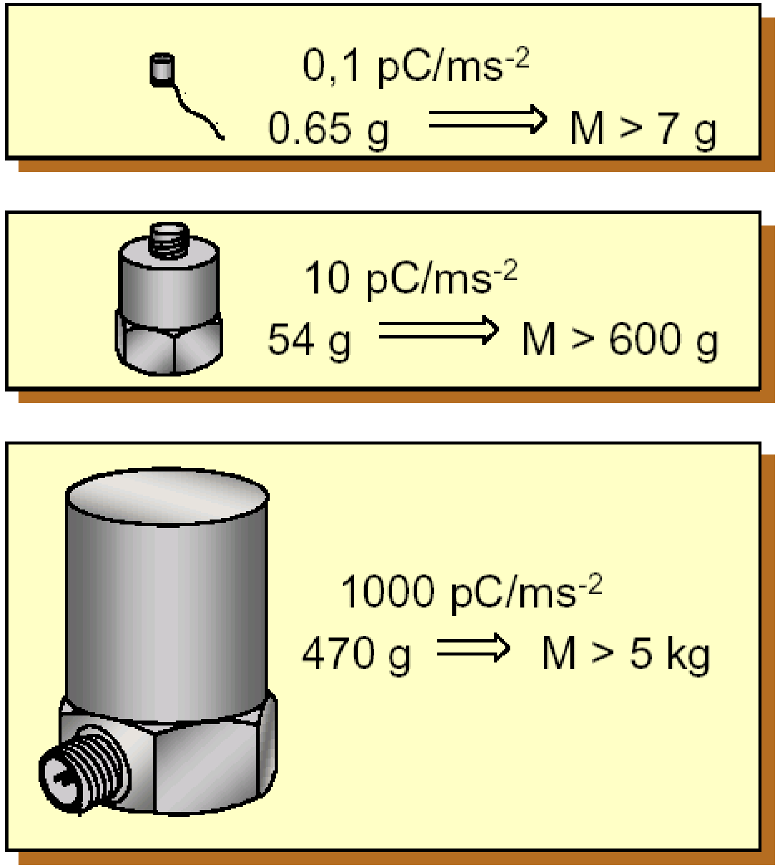
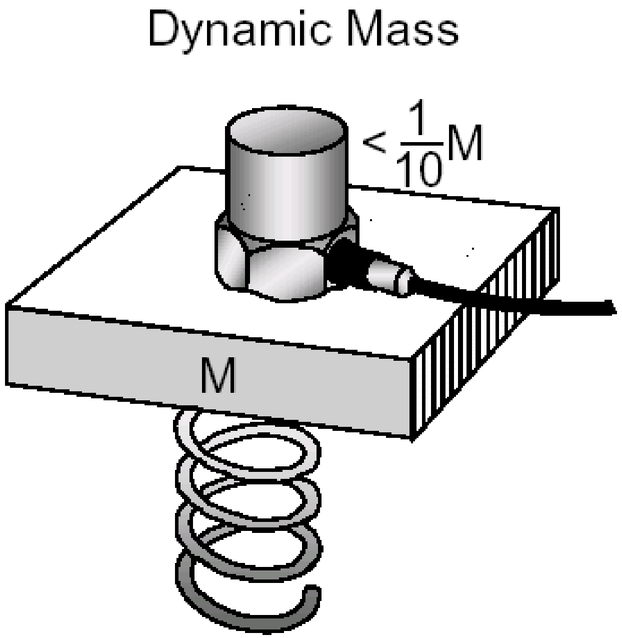
Mass Loading – what is it???

- The loading effect caused by the mass of an accelerometer resulting in a change in the dynamic response of the item under test

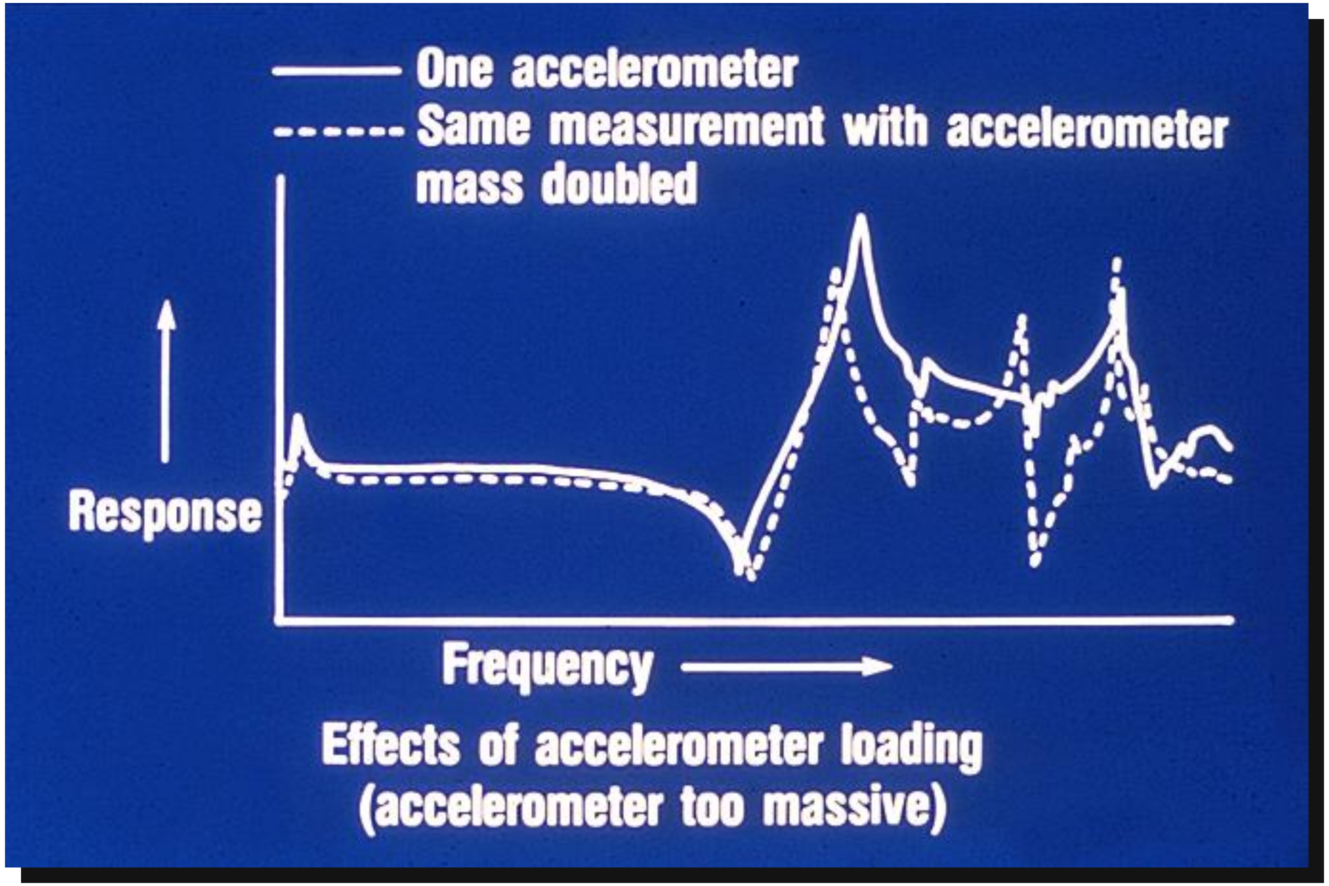
Error Sources

Mass Loading

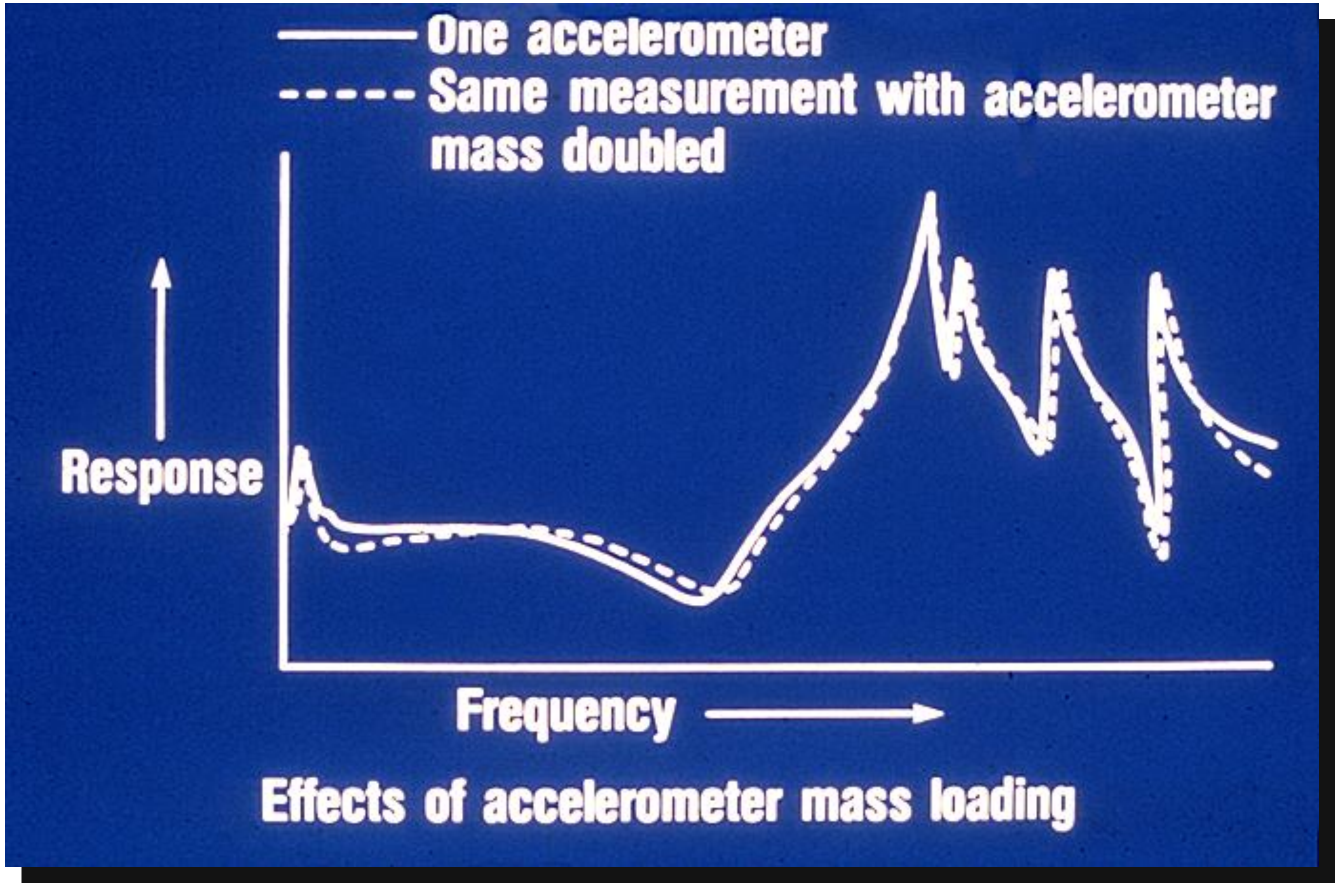




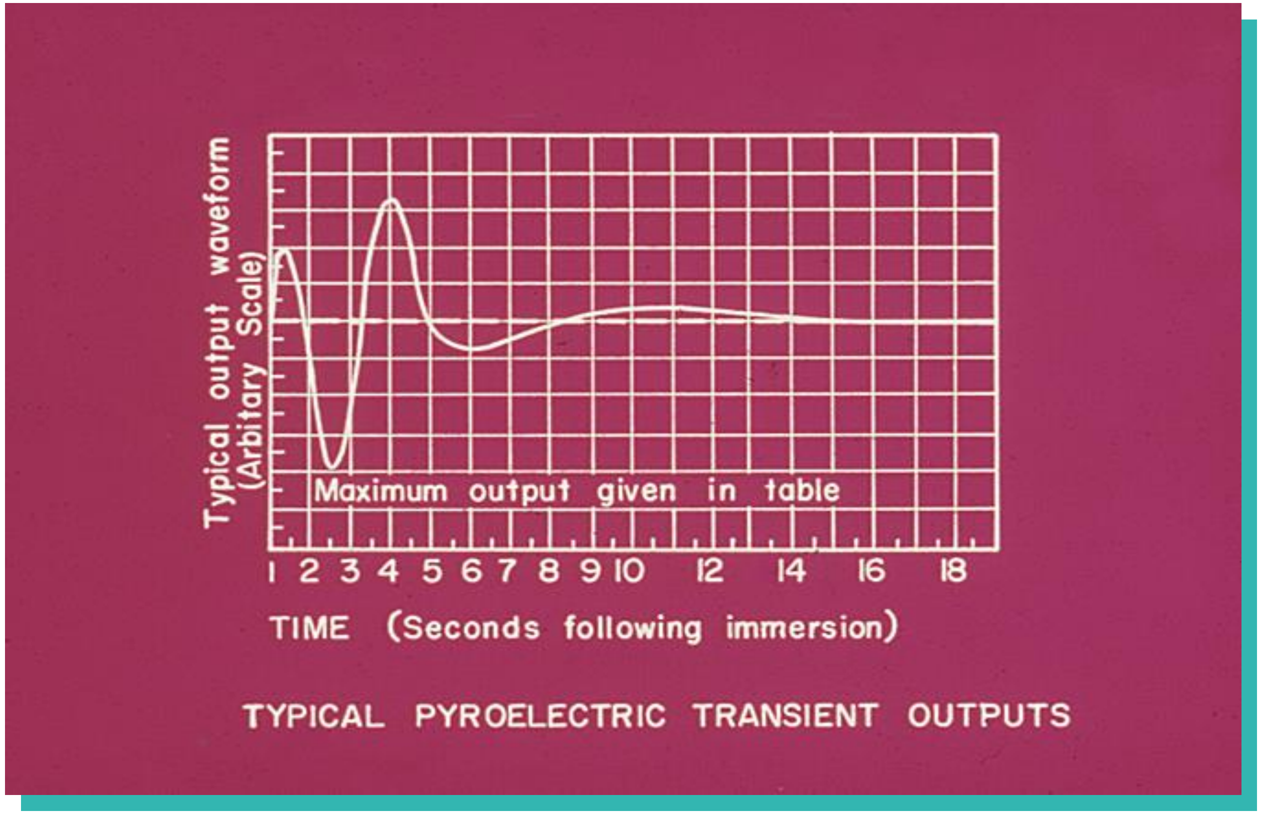
Mass Loading



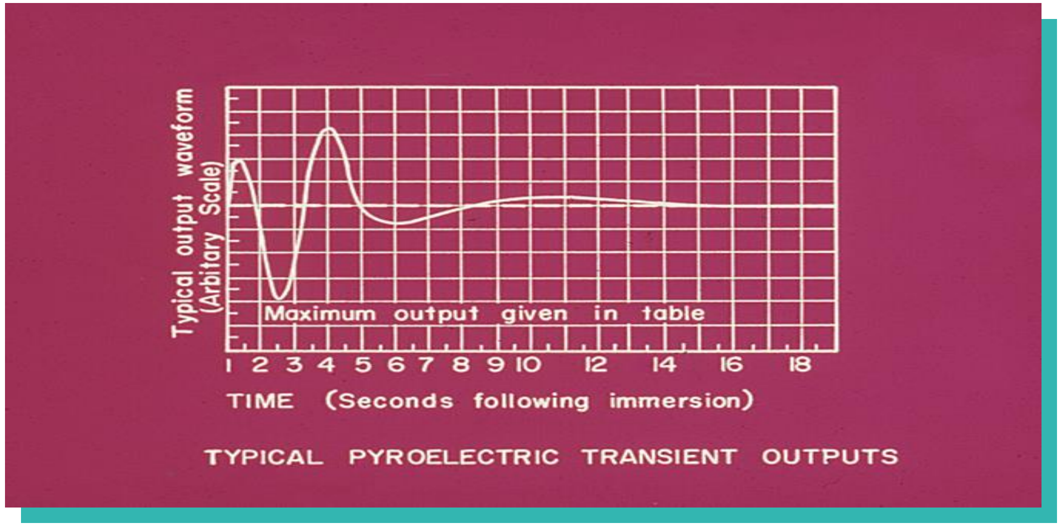
Mass Loading



Pyroelectric effect



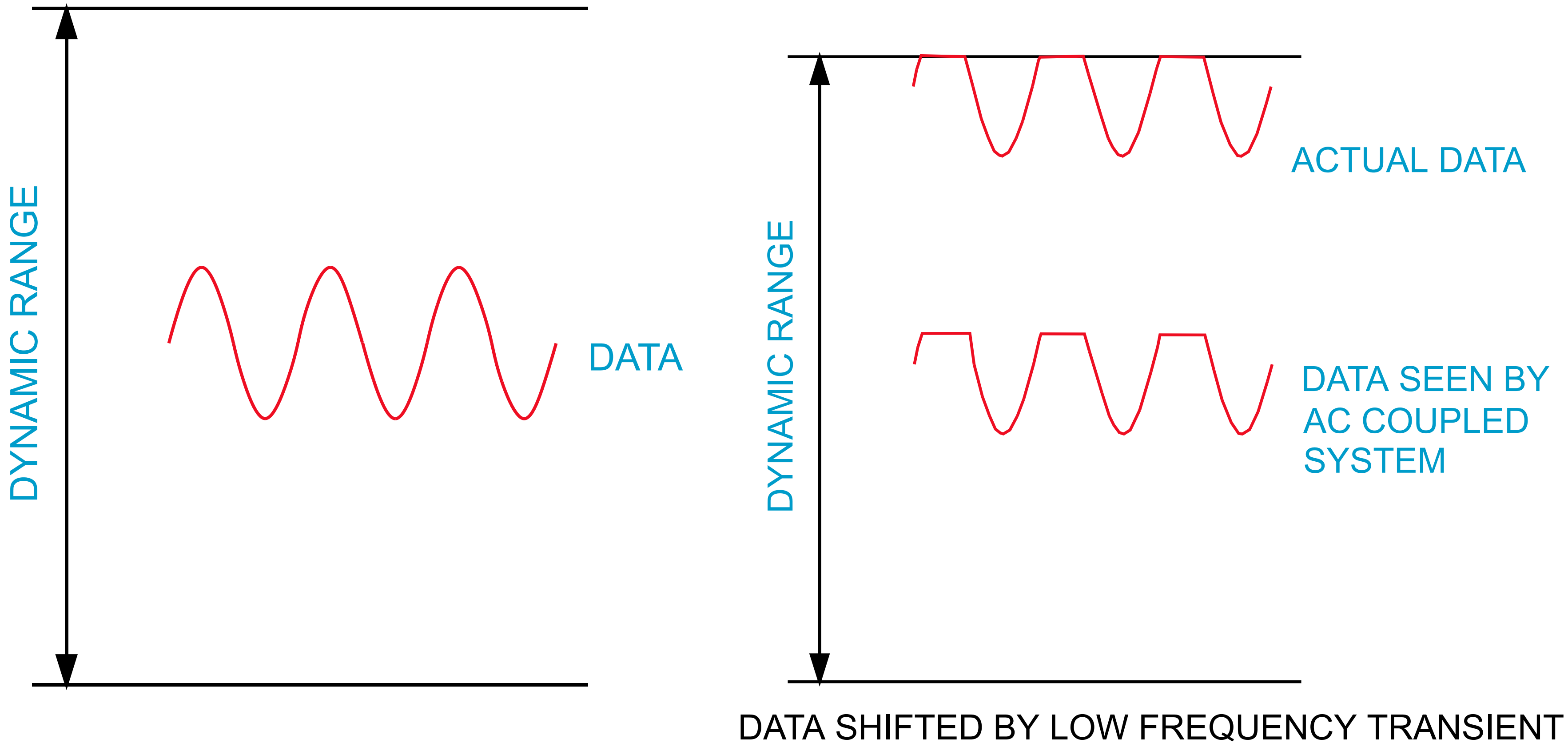
Pyroelectric effect



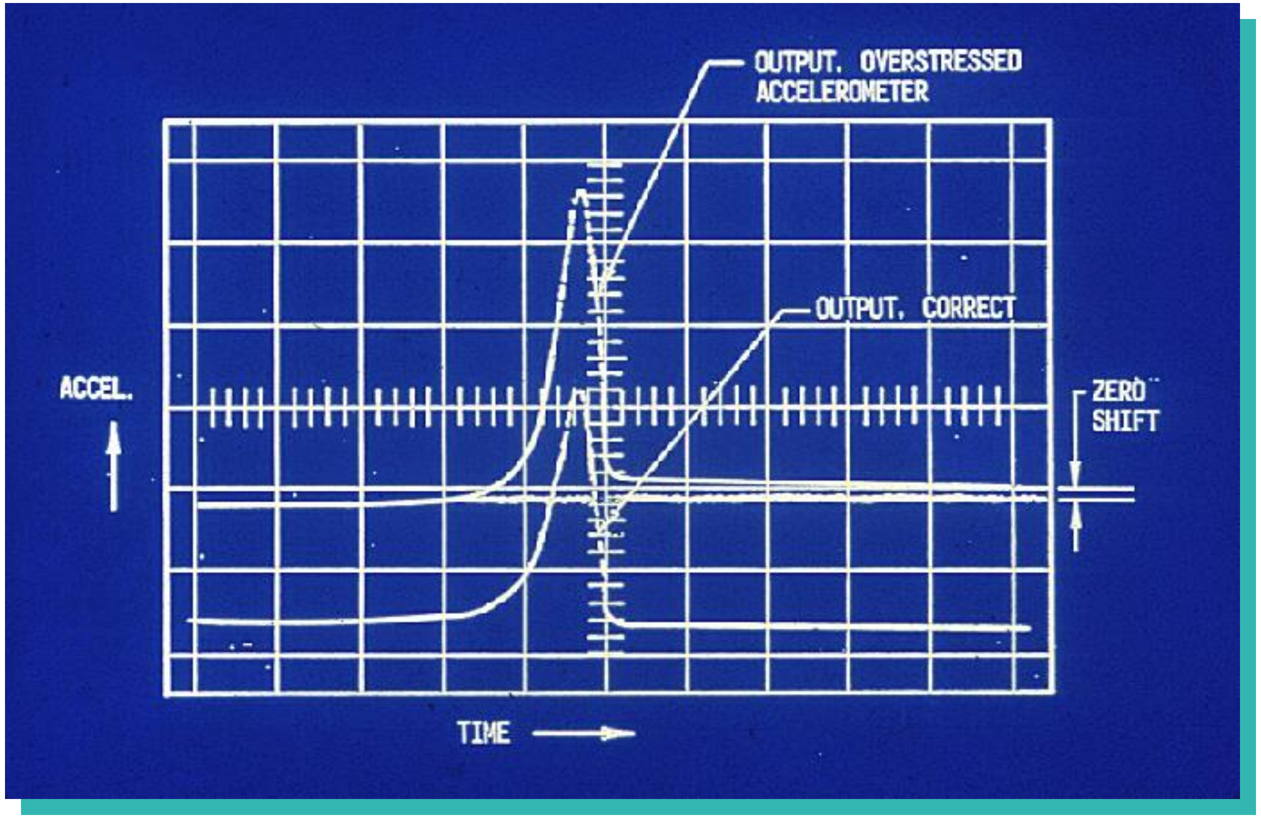
- **For sudden 10°C change in temperature - total immersion**

–SEC	**12 pC/g**	**130 g**
–ISOBASE	**11 pC/g**	**12 g**
–Annular Shear	**17 pC/g**	**0.6 g**
–ISOSHEAR	**50 pC/g**	**0.07 g.**

Pyroelectric effect



Zero Shift

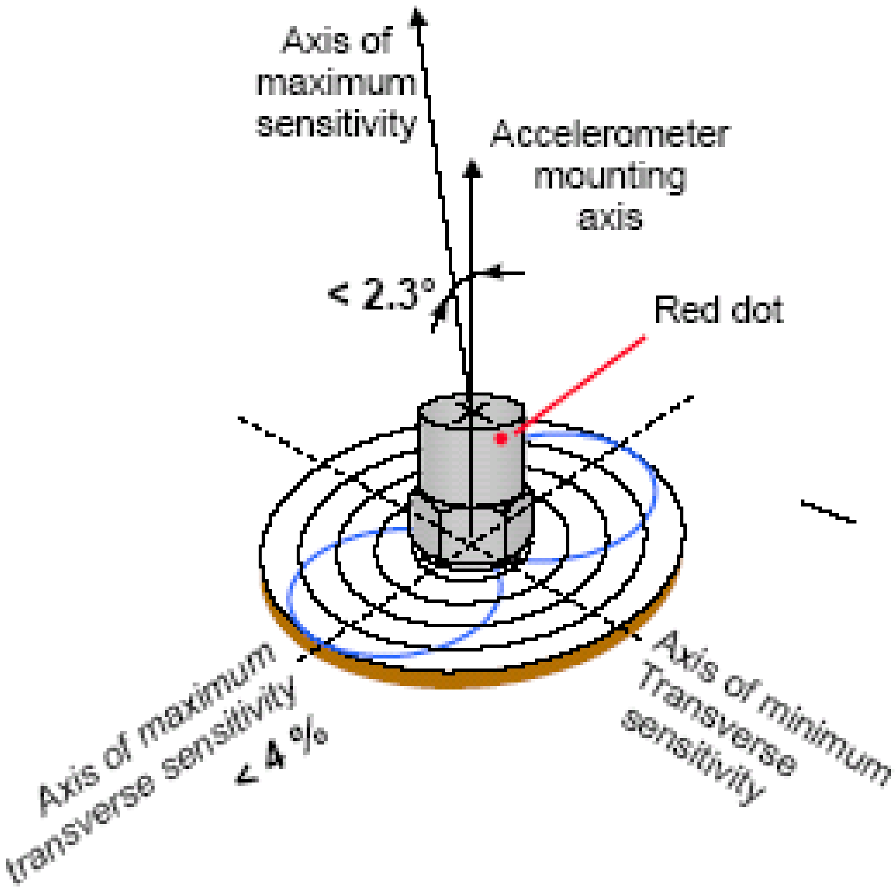

OUTPUT, OVERSTRESSED
ACCELEROMETER
OUTPUT, CORRECT
ACCEL.
ZERO
SHIFT
TIME

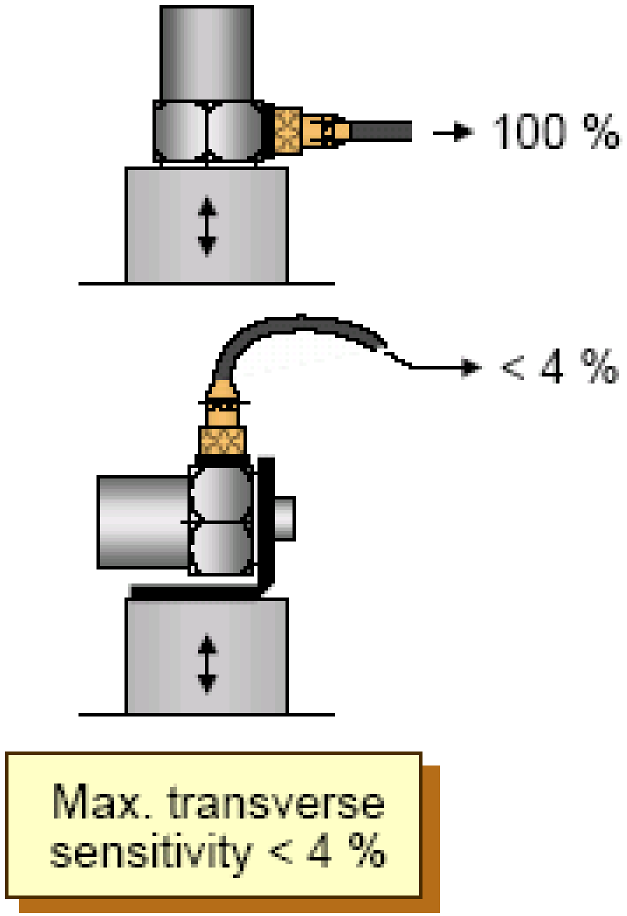
Error Sources

Zero Shift – the causes

- Overstressed piezoelectric element
- Damaged piezoresistive gauges
- Hysteresis in assembled parts
- Cable noise
- Strain induced errors
- Inadequate low-frequency response
- Signal conditioner overload.
- Amplifier slew limiting

Transverse Sensitivity





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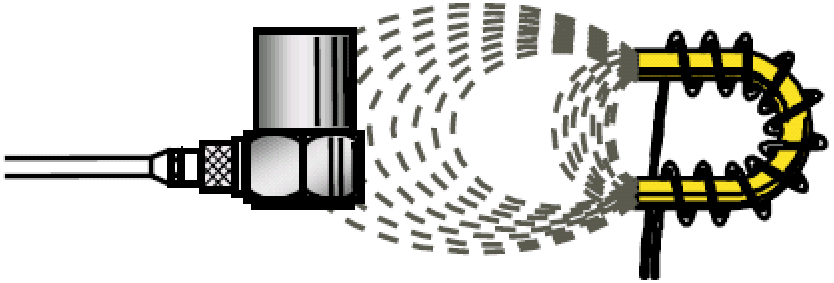
Electromagnetic Sensitivity

Bruel and Kjaer and Endevco accelerometers are typically insensitive to magnetic fields. Any sensitivity to electro-magnetic fields typically lies in the range 0.005 to 0.3g per k Gauss (worst case with the flux flowing in the direction of maximum sensitivity. There some exceptions to this statement however as some of the very early designs of Piezoelectric and Piezoresistive accelerometer which had masses made of ferromagnetic materials.

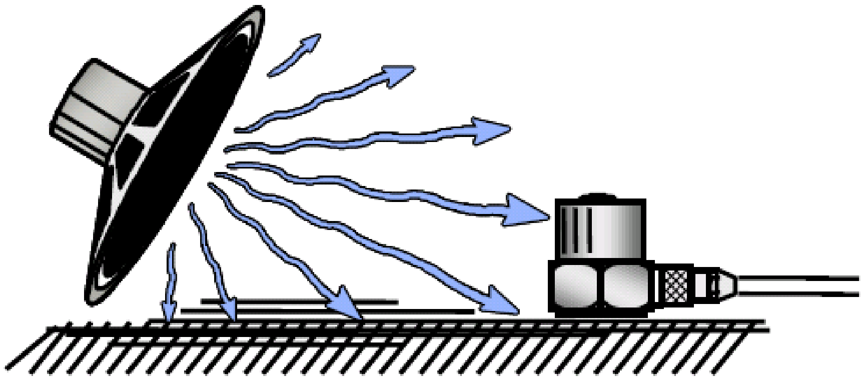
Variable Capacitance designs of accelerometer are more sensitive to electromagnetic inputs than Piezoelectric or Piezoresistive designs.



Acoustic Sensitivity

High level acoustic noise impinging on the case of an accelerometer can cause it to generate an output similar to that of a microphone. Acoustic sensitivity has been found to correlate closely with case strain sensitivity. Modern Delta Shear / Isoshear designs offer significant better immunity to acoustic inputs than older compression designs.

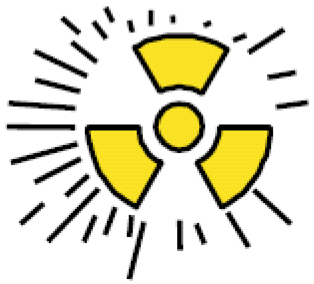
The typical acoustic sensitivity of a Delta Shear accelerometer is in the range 0.001 to 0.04g for a SPL of 154dB in the 2 to 100Hz range.



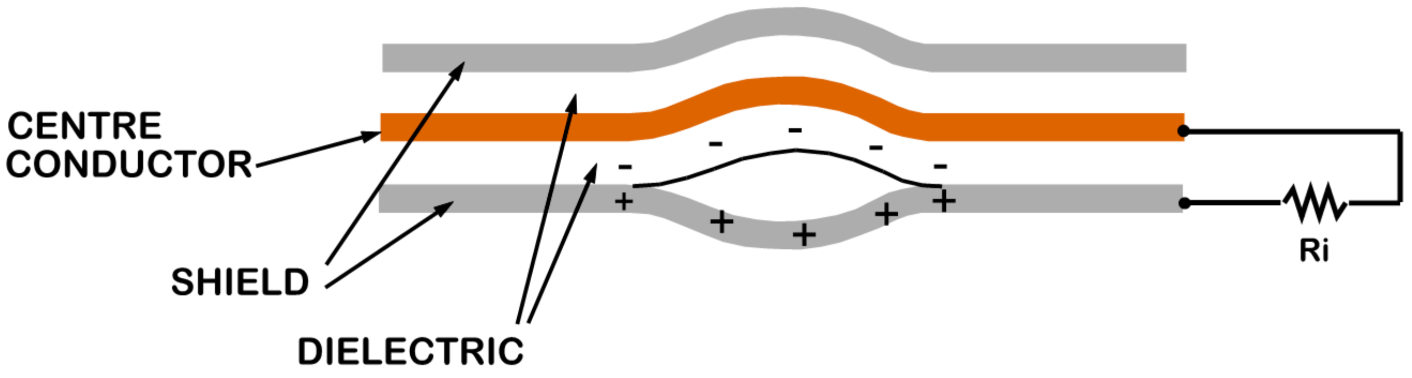
Radiation Sensitivity

Many types of Bruel & Kjaer Piezoelectric and Piezoresistive accelerometers can survive exposure to relatively large doses of Neutron radiation (10^{16} neutrons/cm^2) and Gamma radiation (10^{11} ergs/gram (c)) without any detrimental effect on the performance of the units. If however using a unit in such an environment on a long term basis we would recommend the purchase of a unit specifically designed to operate in such an environment to ensure good long term stability.

It should be noted that even in low level radiation environments units containing electronic circuitry - Deltatron Isotron and Variable Capacitance type accelerometers for example, will deteriorate when exposed to radiation.

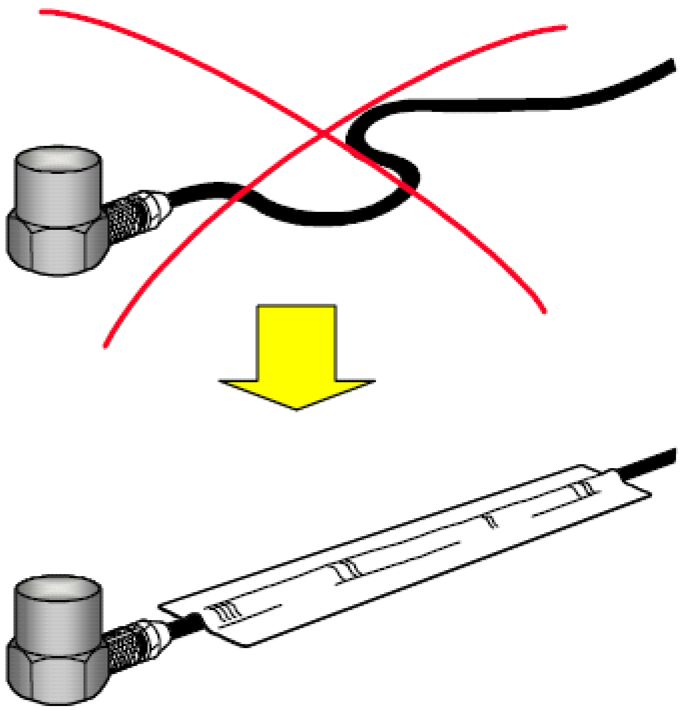


Triboelectric effect

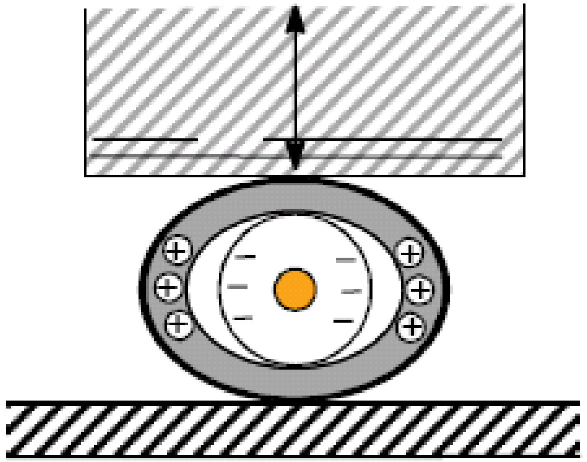


- Charge error signal caused by cable motion
- Tie down cable
- It is essential to use good quality low-noise cable with piezoelectric accelerometers
- Alternatively use IEPE, PR or VC accelerometers.

Triboelectric effect



Route cables away from where they can be crushed / trapped



Error Sources

Saturation and Clipping

Why do these conditions occur?

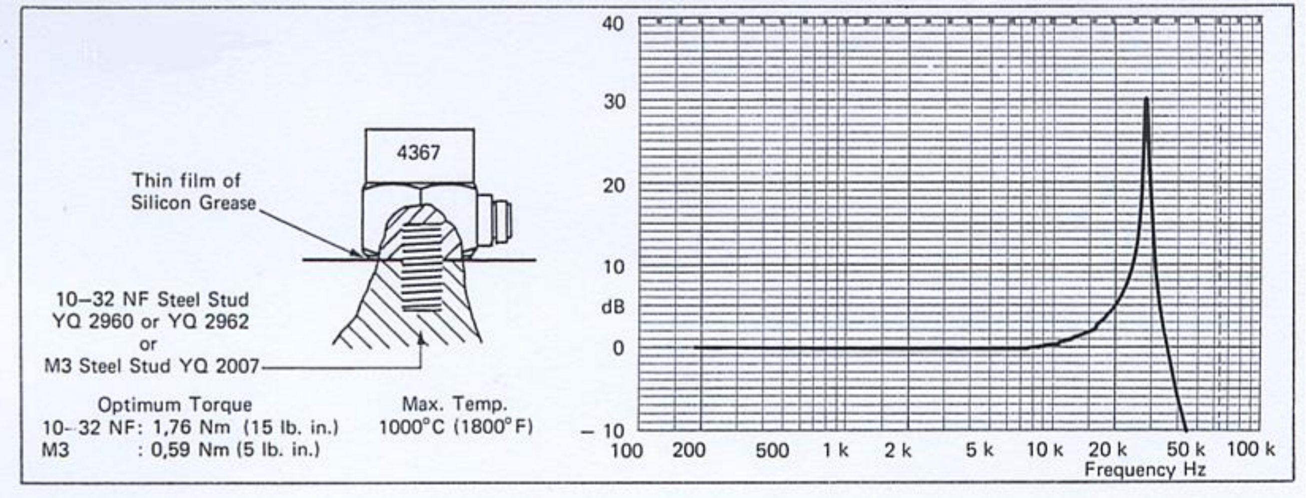
- Over-ranging / Saturation of the accelerometer
- Over-ranging / Saturation of the signal conditioner
- Excitation of the accelerometer resonance frequency

Different mounting techniques and their frequency response characteristics

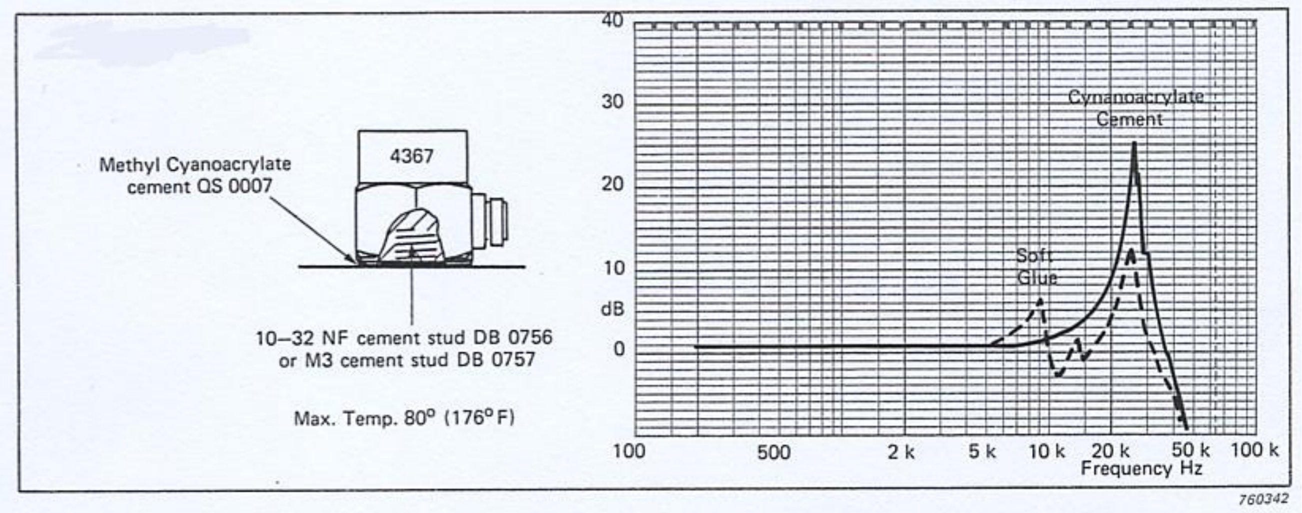
What are the options open to us??

- Plain steel or insulated mounting studs
- Cyanoacrylate adhesive
- Bees wax / Petro-wax
- Hot Glue
- Double sided tape
- Magnet
- Inverted / Hand held probes

Mounting Techniques

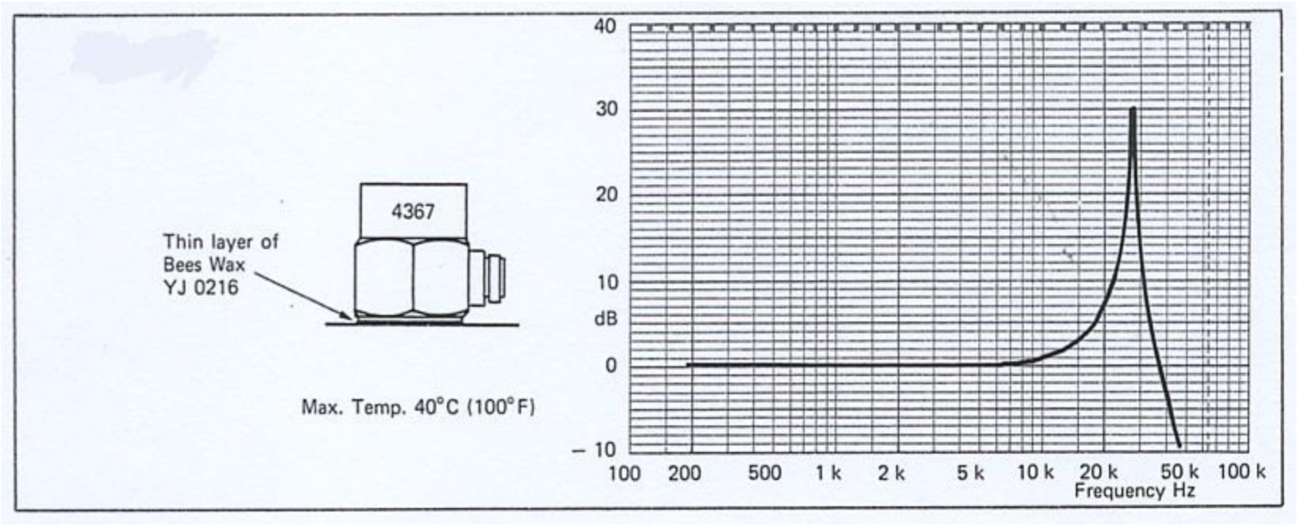


Stud Mounting

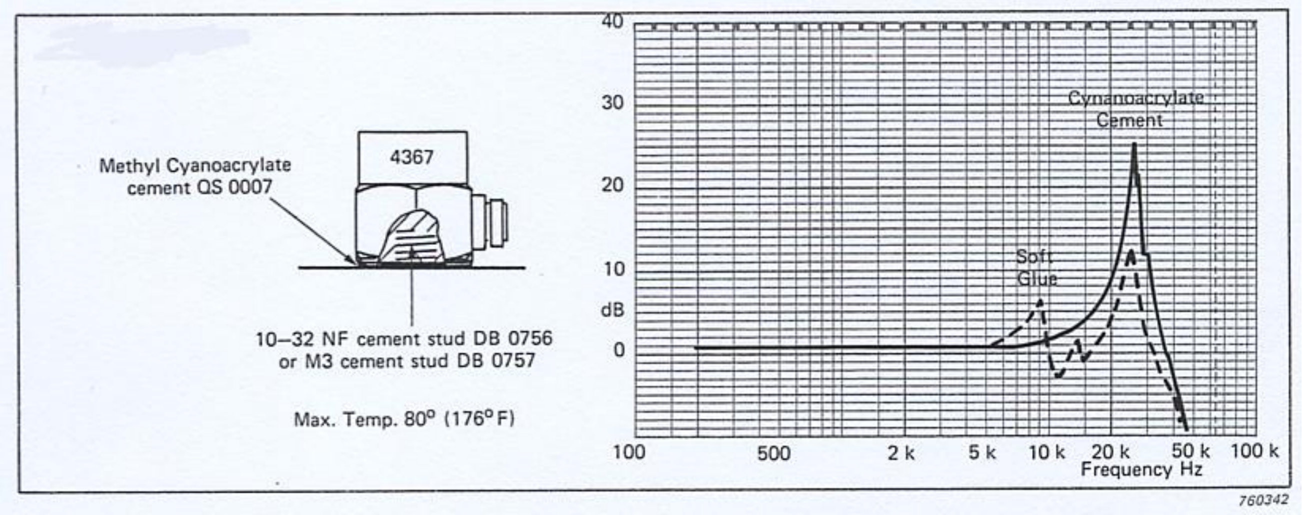


Cyanoacrylate Adhesive

Mounting Techniques

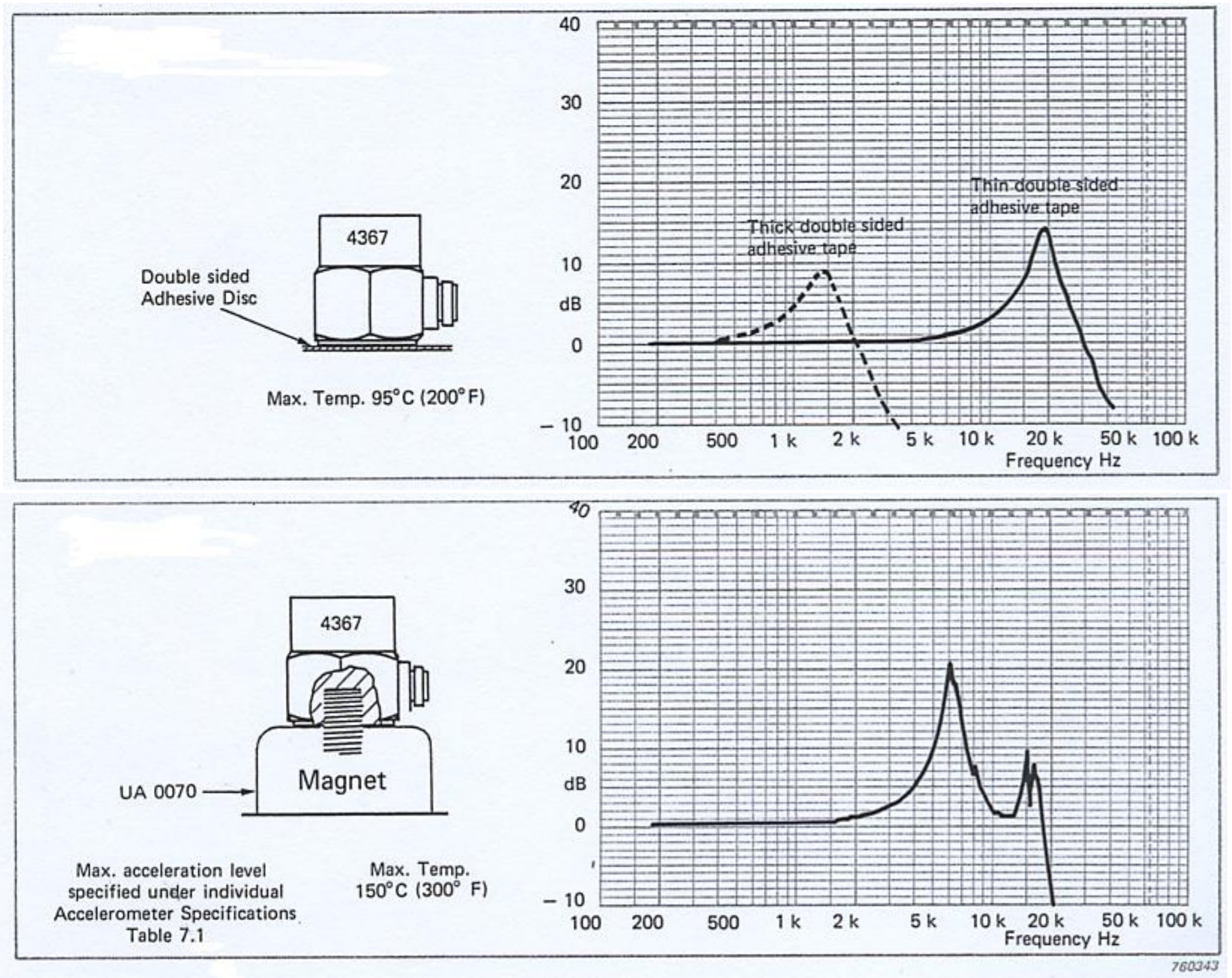


Bees wax



Hot / Soft Glue

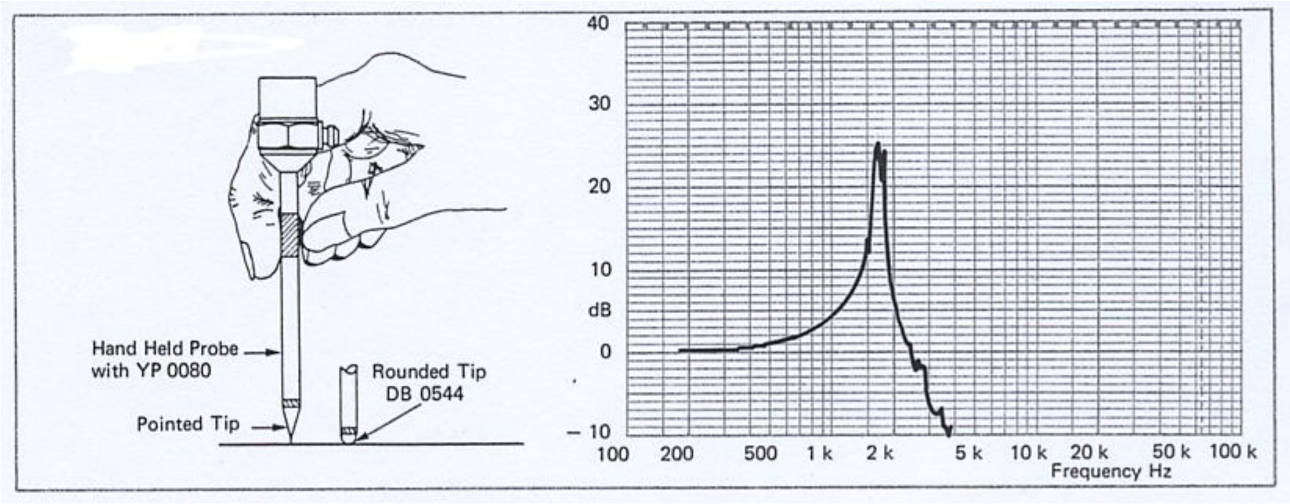
Mounting Techniques



Double Sided Tape

Magnet

Mounting Techniques



Inverted / Hand Held Probes

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Attachment Methods – The Pro's and Con's

Stud Mounting

- Advantages
  - Will provide optimum accelerometer performance
  - Will not limit the accelerometers rated temperature range
  - Offers a high degree of integrity under severe test conditions
- Disadvantages
  - Test item has to be drilled and tapped to accept the stud which is not always acceptable on high value items
  - Surface must be finished to a relatively high standard for the best results (high frequency response)

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Attachment Methods – The Pro's and Con's

Cyanoacrylate Adhesive

- Advantages
  - Broad frequency response
  - Wide temperature range (typically –18ºC to + 121ºC)
  - Quick and easy to use
  - Fast (near instant) room temperature cure
  - Can be applied directly or using a cementing stud
- Disadvantages
  - Solvent required for removal
  - Cleaning of mounting surfaces can be time consuming (mounting and removal)
  - Adhesive has a limited shelf life
  - Potential for damage on removal (miniature types)

Attachment Methods – The Pro’s and Con’s

Bees Wax

- Advantages
  - Quick and easy to apply, no cure time
  - Convenient storage – no mess or potential for spillage
  - Easily removed from mounting surfaces, no solvents required
- Disadvantages
  - Limited upper temperature range (+ 54°C maximum)
  - Limited amplitude range (accelerometer mass limitation)

Attachment Methods – The Pro’s and Con’s

Hot Glue

- Advantages
  - Quick and convenient
  - Fast cure time and easy removal
  - Ready supply of adhesive (glue sticks)
- Disadvantages
  - The glues relative lack of stiffness can severely limit the accelerometers dynamic range, hence is it only really suitable for use in modal applications
  - Very rapid cure time can lead to situations where the glue can partially set before the accelerometer can be attached to the test item resulting in poor adhesion and hence a reduction in frequency response.

Attachment Methods – The Pro’s and Con’s

Double Sided Tape

- Advantages
  - Ease of application and removal
  - Broad temperature range (-18°C to +93°C)
- Disadvantages
  - Limited amplitude range
  - Some limitations with top connector types or high profile style accelerometers due to cable motion

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Attachment Methods – The Pro’s and Con’s

Magnets

- Advantages
  - Ease of application and removal
  - Broad temperature range (0°C to +250°C in some cases)
- Disadvantages
  - Significantly reduced high frequency response
  - The surface of the test object must be ferro-magnetic. Alternatively you would have to screw or bond a ferro-magnetic disc to it which adds additional mass
  - Caution is required when fitting to the test item so as to avoid applying a high amplitude, high frequency shock pulse to the accelerometer

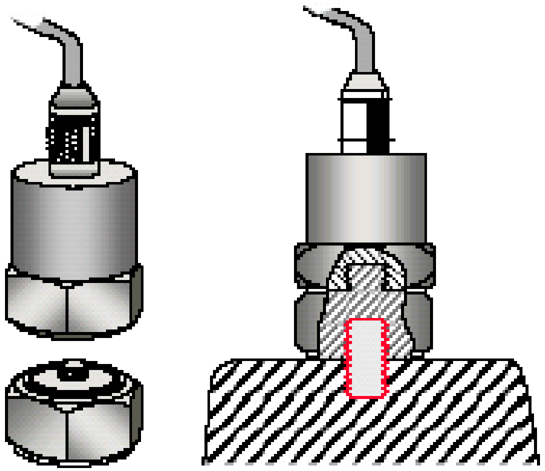
Attachment Methods – The Pro’s and Con’s

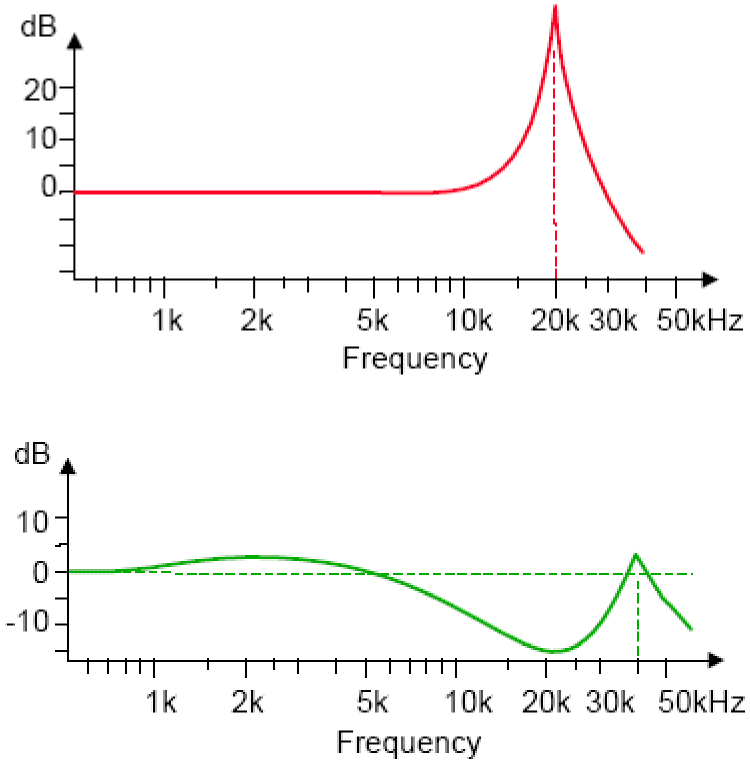
Inverted probe / Hand held probe

- Advantages
  - Fastest mounting method available
  - Can be moved to multiple positions with ease
- Disadvantages
  - The resonance frequency when mounted is brought down so low that it typically lies within the frequency range of most vibration measurements and renders the results invalid
  - Offers very poor repeatability

Mechanical Filters

What do they do? They provide an interface between the accelerometer and the test item which filters potentially damaging high frequency content





Mechanical Filters

HBK HOTTINGER BRÜEL & KJÆR

Mounting Surface Finish

- Surface flatness 10 µm (0.0003" TIR)
- Surface Roughness 1.6 µm √0.25 (√32)
- Perpendicularity ± 6 minutes
- Tap class 2A

Mounting Arrangements

Accelerometer Calibration

HOTTINGER BRÜEL & KJÆR

Why calibrate

- To find the sensitivity

Why recalibrate

- Legal obligation - QA requirement
- Good instrument practice
- Test for damage

Calibration using the “back to back” method

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How often should you have a unit calibrated?

We suggest yearly as a bare minimum but consider:

- What the unit is being used for and how frequently it is being used
- If the unit is being used at the extremes of its range
- If the unit is being used unskilled operators – is it being handled roughly / mistreated

If a unit is dropped on the floor should I have it recalibrated?
We would recommend it!!

Accelerometer Calibration Data

HBK
HOTTINGER BRÜEL & KJÆR

Calibration Chart for DeltaTron® Accelerometer Type 4507

Brüel & Kjær

Serial No.: 2195562

Reference Sensitivity [1] at 159.2 Hz (ω = 1000 s^{-1}), 20 ms^{-2} RMS, 4 mA supply current and 23 °C: 9.79 mV/ms^{-2} (96.0 mV/g)

Frequency Range: Amplitude (±10%): 0.3 Hz to 6 kHz; Phase (± 5°): 2 Hz to 5 kHz

Mounted Resonance Frequency: 18 kHz

Transverse Sensitivity [2]: Maximum (at 30 Hz, 100 ms^{-2}): < 5% re Reference Sensitivity

Transverse Resonance Frequency: > 18 kHz

Calculated values for TEDS [3]:

- Resonance frequency: 19.1 kHz
- Quality factor @ f_{res}: 283.2
- Amplitude slope: -2.3 %/decade
- High pass cut-off frequency: 0.143 Hz
- Low pass cut-off frequency: 91.1 kHz

Measuring Range: ± 700 ms^{-2} peak (± 71 g peak)

Polarity of the electrical signal is positive for an acceleration in the direction of the arrow on the drawing.

Electrical:

Bias Voltage: at full temperature and current range: + 12 V ± 1 V

Power Supply requirements: Constant Current: + 2 to + 20 mA; Unloaded Supply Voltage: + 24 V to + 30 V

Output Impedance: < 2 Ω

Start-up time (to final bias ± 10%): 5 s

Inherent Noise (RMS):
Broadband (1 Hz to 6 kHz): < 35 µV corresponding to < 0.0035 ms^{-2} (< 350 µg)

Spectral:

10 Hz:	1.5x10^{-4} $ms^{-2}/\sqrt{Hz}$	(15 µg/$\sqrt{Hz}$)
100 Hz:	3.5x10^{-5} $ms^{-2}/\sqrt{Hz}$	(3.5 µg/$\sqrt{Hz}$)
1000 Hz:	2x10^{-5} $ms^{-2}/\sqrt{Hz}$	(2 µg/$\sqrt{Hz}$)

Ground Loops can introduce error signals. These can be avoided by insulating the accelerometer from the mounting surface (see Mounting Technique).

Recommended cables: AO 1382, AO 0531, AO 0463 and other cables see Product Data Sheet

Environmental:

Temperature Range: - 54 to + 121°C (- 65 to + 250°F)

Temperature Coefficient of Sensitivity: + 0.09%/°C

Temp. Transient Sensitivity (3 Hz Low. Lim. Frq. (-3 dB, 6 dB/oct)): 0.2 ms^{-2}/°C

Magnetic Sensitivity (50 Hz, 0.038 T): 3 ms^{-2}/T

Base Strain Sensitivity (at 250 µε in base plane): Mounted on adhesive tape 0.09 mm thick: 0.005 ms^{-2}/µε

Max. Non-destructive Shock: 50 kms^{-2} peak (5000 g peak)

Humidity: 90 % RH non-condensing

Mechanical:

Case Material: Titanium ASTM Grade 2

Sensing Element: Piezoelectric, Type PZ 23

Construction: Theta Shear®

Sealing: Welded

Weight: 4.8 gram (0.17 oz)

Electrical Connector: 10 - 32 UNF-2A

Mounting Surface Flatness: < 3 µm

[1] This calibration is obtained on a modified Brüel & Kjær Calibration System Type [illegible]10 System No.: 150117.1 and is traceable to the National Institute of Standards and Technology. USA and Physikalisch-Technische Bundesanstalt, Germany.
The expanded uncertainty is 1.0% determined in accordance with EAL-R2. A coverage factor k=2 is used. This corresponds to a coverage probability of 95% for a normal distribution.

[2] The uncertainty is 0.3% of Reference Sensitivity.

[3] Transducer Electronic Data Sheet according to IEEE P1451.4. Built-in ID-information not included.

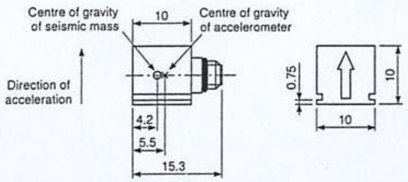
[4] Deviation from Reference Sensitivity.

Patents involved: US 08387851, JP 50952694 and DK 169653.

For further information, please see http://www.bk.dk and Product Data Sheet BP 1841.

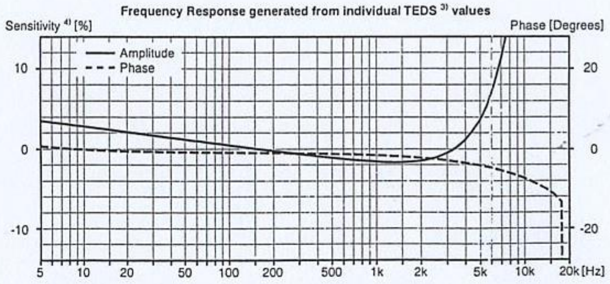
CE

Mounting Technique:
The accelerometer can be fastened directly to the measuring object by glue e.g., hot glue. However, if a reduced frequency range can be accepted, it is recommended to use one of the special mounting clips (see below) which is glued to the measuring object. In any case the mounting surface must be clean and smooth.
Three types of mounting clips are available: UA 1407 (set of 100) is a low profile clip recommended for mounting on plane surfaces. UA 1475 (set of 100) is a clip with a thick base which can be filed to fit a curved mounting surface. UA 1478 (set of 100) is a swivel base clip for use where the accelerometer is to be aligned according to a given co-ordinate system (see Product Data Sheet BP 1841).
Applying a little grease to the mounting surface of the accelerometer as well as the clip will improve the frequency response.
See also ISO 5348.

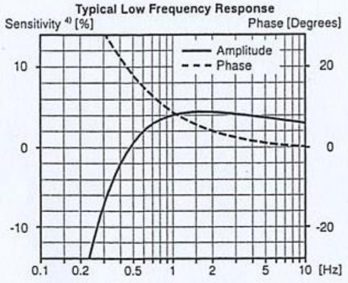


All dimensions in millimetres

Frequency Response generated from individual TEDS [3] values



Typical Low Frequency Response



Date 27 Oct 1999 Operator AH

Specifications obtained in accordance with ANSI S2.11-1969 and parts of ISO 5347.

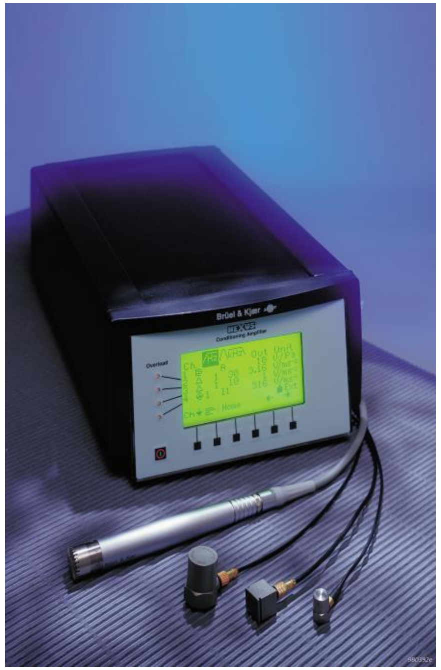
All values are typical at 25°C (77°F) unless measurement uncertainty is specified.

BC 0285-12

Serial No.: 2195562

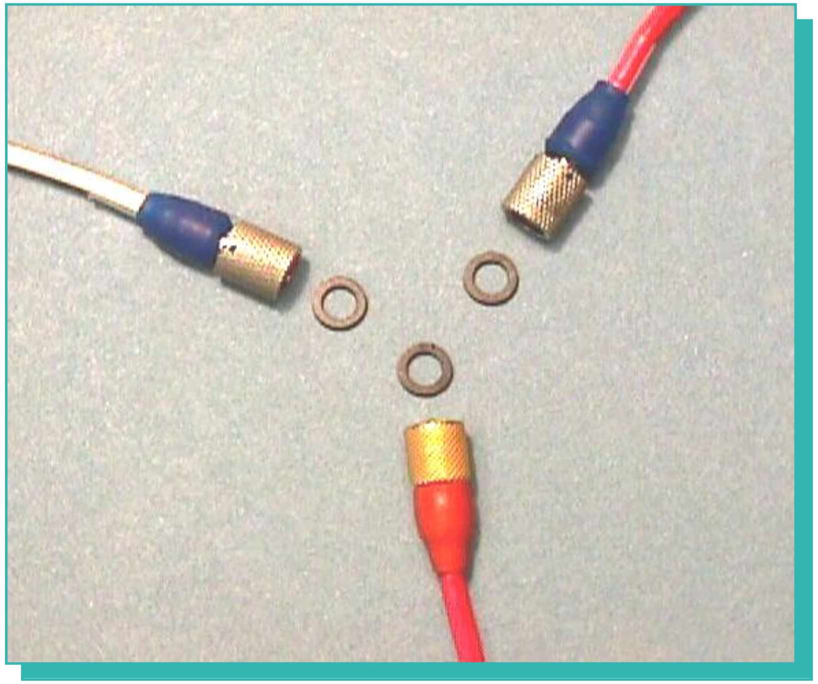
Signal Conditioning Equipment

- Charge Amplifiers
- Remote Charge Converters
- IEPE / ICP Power Supplies
- DC Differential Voltage Amplifiers



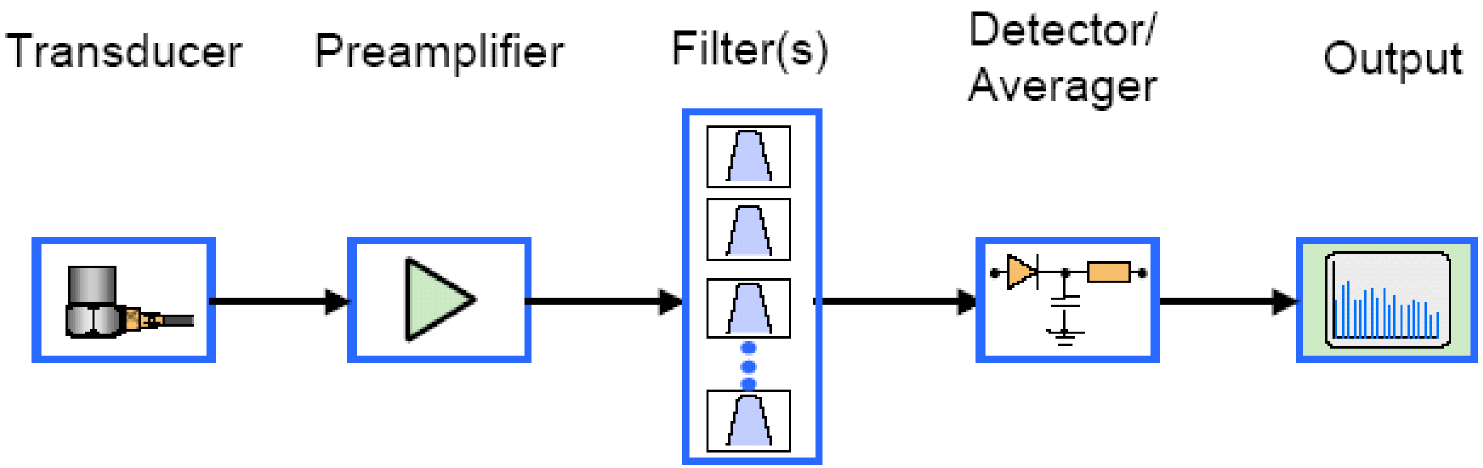
Cabling and Connectors

- “O” Rings – remove them if using other manufacturers cables with B&K accelerometers!



Checking the Measurement Chain

How can I do this?

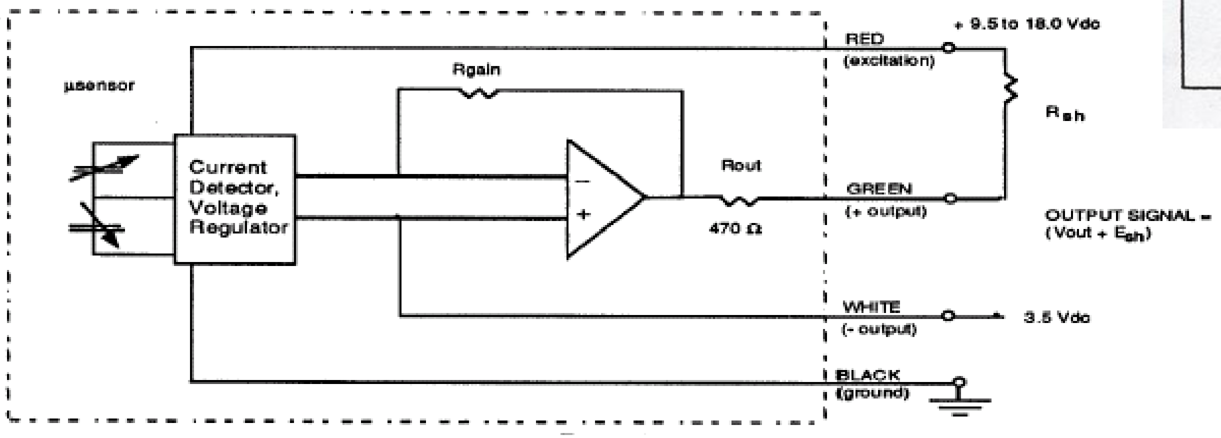


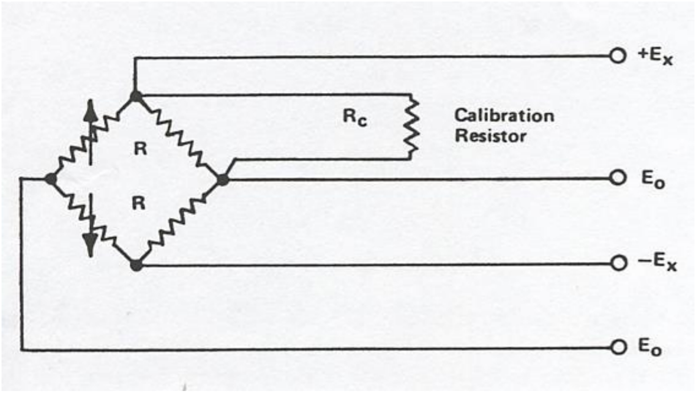
Checking the Measurement Chain

- Excite the accelerometer

- Using the shunt calibration method offset the transducers resistance bridge (PR accelerometers) or internal amplifier (VC accelerometers) to give a known output signal.

Model 7290A Circuit Block Diagram





Checking the Measurement Chain

HBK HOTTINGER BRÜEL & KJÆR

- Inject a known signal into the signal conditioner input

How not to treat your accelerometer!!

Any Questions???

Thank you!

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