加速度規原理、應用、校正及發展趨勢

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Outline

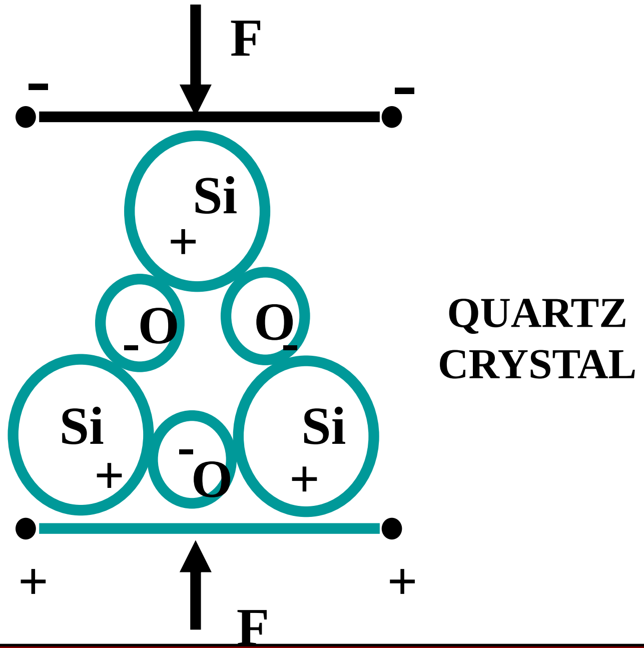
- Material of Sensor
- Piezoelectric Accelerometer Element Design
- DC Accelerometer
- MEMS Accelerometer
- Applications
- Sensor Calibration
- Futures

What is a Sensor?

- A sensor is a device that is used to measure a physical (mechanical) parameter and transform it into a representative electrical signal.
- Piezoelectric sensors can be used to measure: Force, Acceleration, Pressure Strain, Temperature, and Acoustics.

The Piezoelectric Effect

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



The Piezoelectric Effect

- Resulting charge is proportional the physical input.
- The charge is can be converted internally (IEPE) or externally (charge) to a low impedance voltage signal.
- Signal is routed to data acquisition equipment.

IEPE: Integrated Electronics Piezo Electric

ICP: Integrated Circuit Piezoelectric, PCB's registered trademark

Qualities of Crystals that are Important for Sensors

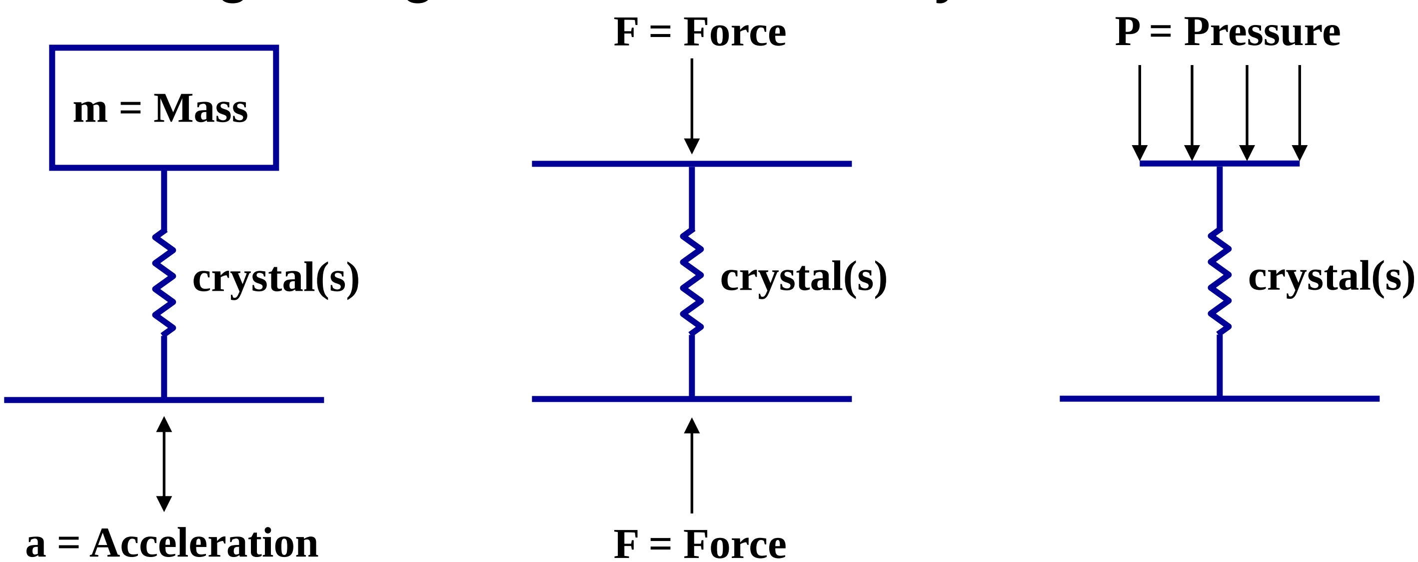
- High stiffness -- imparts high frequency response and long life
- High strength -- ruggedness, long life, high range capability in small size
- High output -- clean signal, good resolution
- Stability -- negligible aging effect
- Wide temperature range
- Temperature insensitivity

Qualities of Crystals that are Important for Sensors

- No capacitance change with temperature (especially for voltage mode sensors with built-in electronics)
- Economical
- Negligible pyro-electric output

Piezoelectric Sensor Structures

- Structure
  - Basic Single Degree of Freedom Systems



F = ma | | F = P * (area)

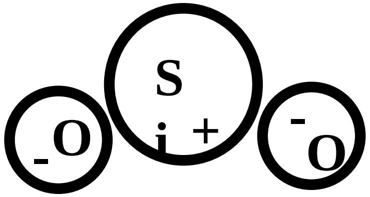
Accelerometer | **Force Sensor** | **Pressure Sensor**

Materials

- Two main types of piezoelectric materials are used today:
  - *Quartz* Crystals
  - Polycrystalline *Ceramic* Crystals

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
- Sensor Quartz is artificially grown under high pressure and temperature in large autoclaves
  - Very high quality
  - Takes approximately 1 month

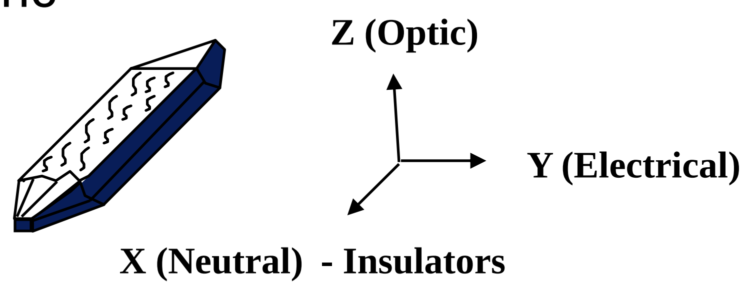


Quartz Crystals

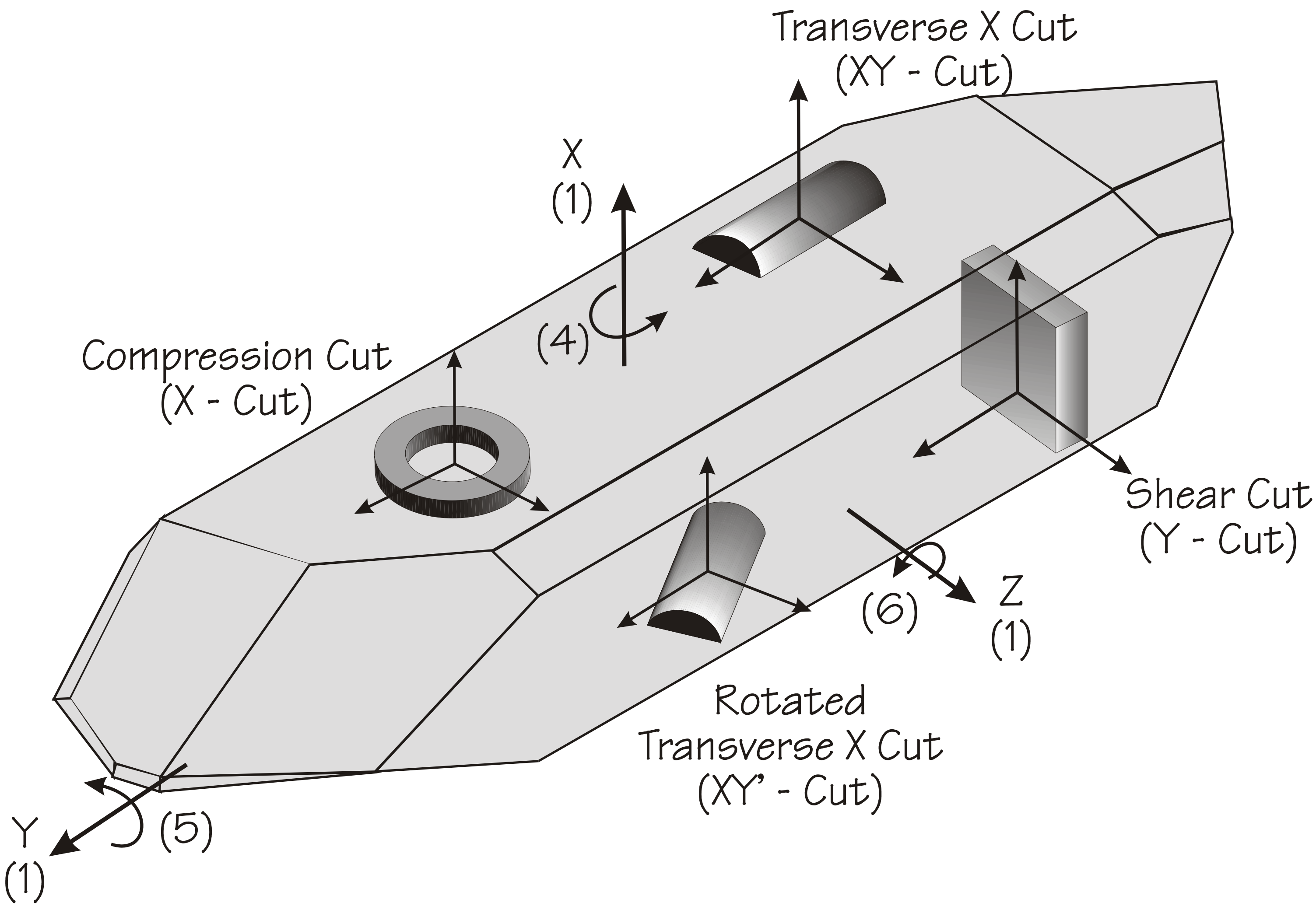
- Advantages
  - Naturally Piezoelectric
    - Excellent long term repeatability
  - Non-pyroelectric
    - Works well in thermally active environments
  - Low Capacitance
    - High Voltage Sensitivity (V=Q/C)
  - Low Temperature Coefficient
    - Little deviation over wide temperature range
  - High Stiffness
    - Extremely linear

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



Quartz Crystals



Quartz Accelerometers- Advantages

- Longer term stability - No change in sensitivity over time
- Lower thermal transient sensitivity - Better for thermally active Environments
- Lower temperature coefficient - Less change in sensitivity over temperature
- Uses voltage Amplifier- Better for Extreme IEPE temperatures -320 ^{o}F to 325 ^{o}F (-196 ^{o}C to 163 ^{o}C)

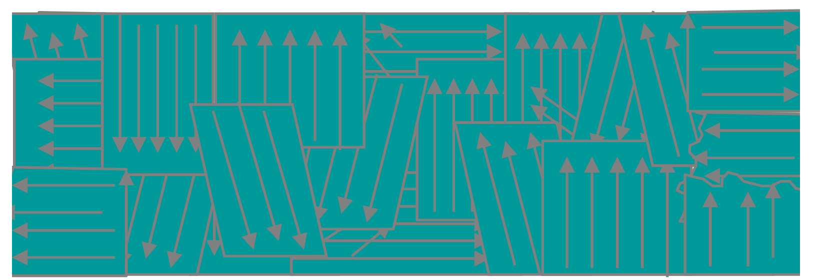
Ceramic Crystals

- 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”

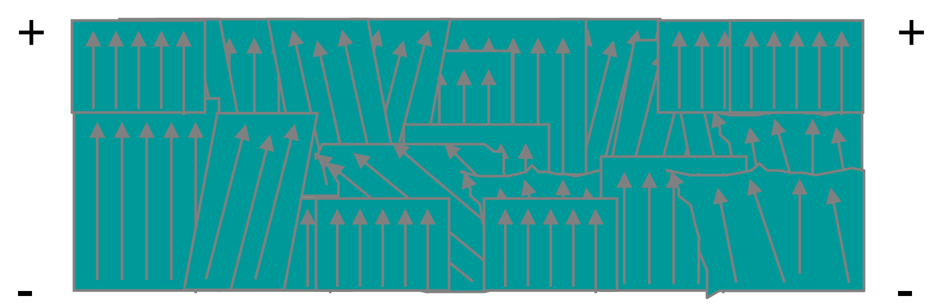
Ceramic Crystals

- Polarization Process (Poling)
  - An extremely high voltage placed on the polycrystalline ceramic causes the dipoles to align themselves.

BEFORE POLING



AFTER POLING



Ceramic Crystals

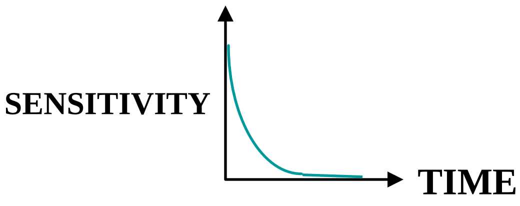
- Advantages
  - High Charge Output (pC)
    - Excellent for use with tests requiring high sensitivity and/or low-noise, charge-amplified systems
  - Unlimited Geometry
    - “Poling” occurs after shaping
    - Versatility for different sensor designs: plates, annular tubes, cones, etc...
  - High Temperature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

Ceramic Accelerometers

- Advantages
  - Better resolution and frequency response than comparable size quartz accelerometers
  - Lower noise than quartz
  - Easier to make smaller higher resolution accelerometers
  - Can use different crystal geometries for different shear designs
  - Higher charge output for use in Charge Mode Systems

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



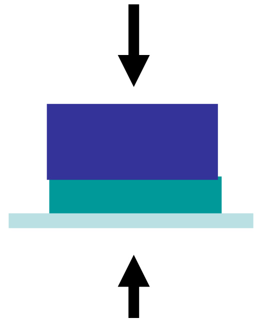
Ceramic Accelerometers

- Disadvantages
  - Higher Temp Coefficient-
    - Change in sensitivity over temperature
  - Higher thermal transient sensitvity
  - Possible Temperature Limitations when matched with internal electronics

Piezoelectric Accelerometer Element Design

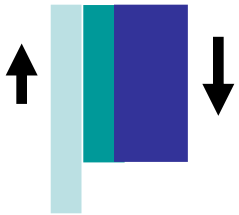
Crystal Structures

- These piezoelectric crystals can be cut and stressed in different ways:
  - Compression

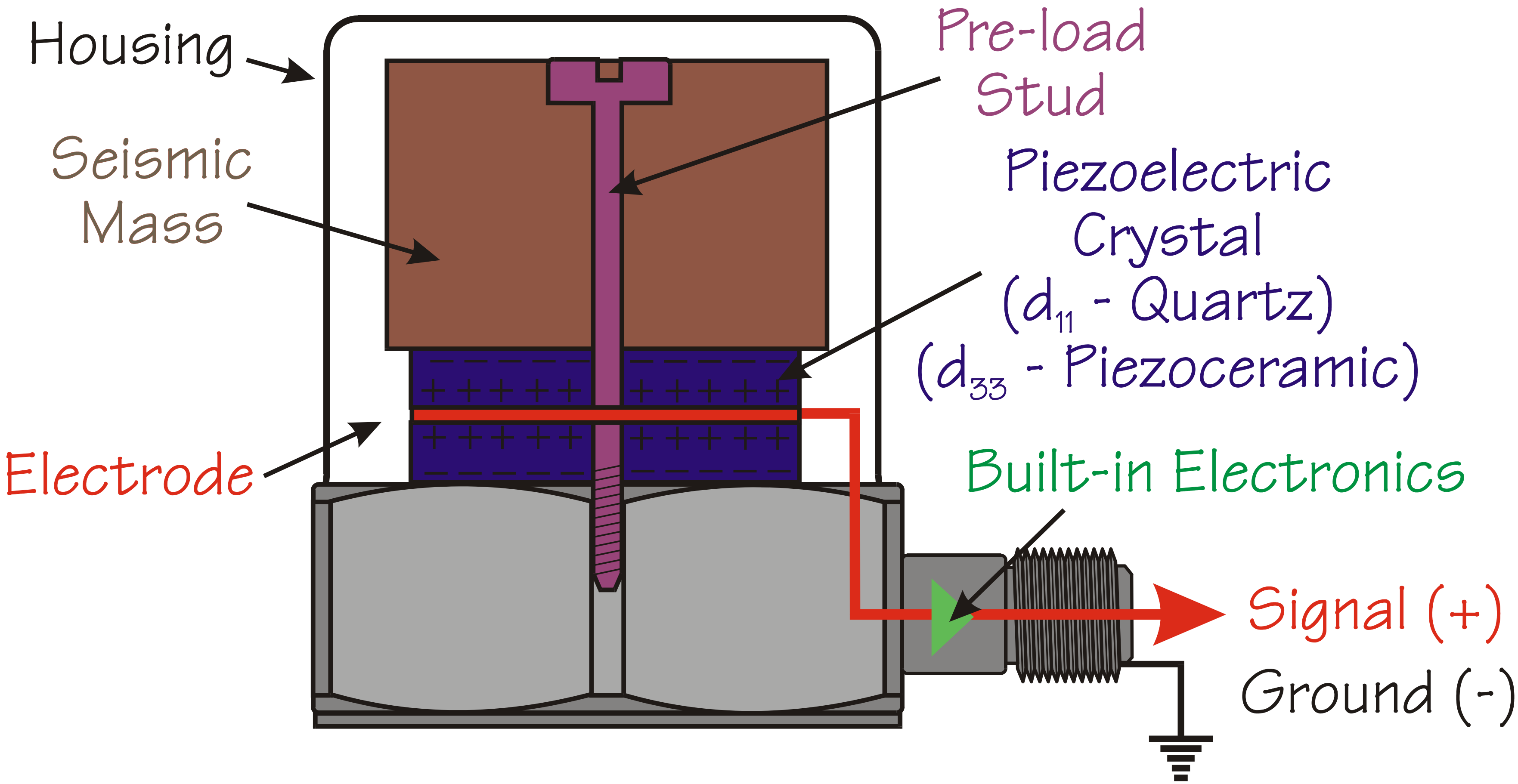


  - Flexural

  - Shear



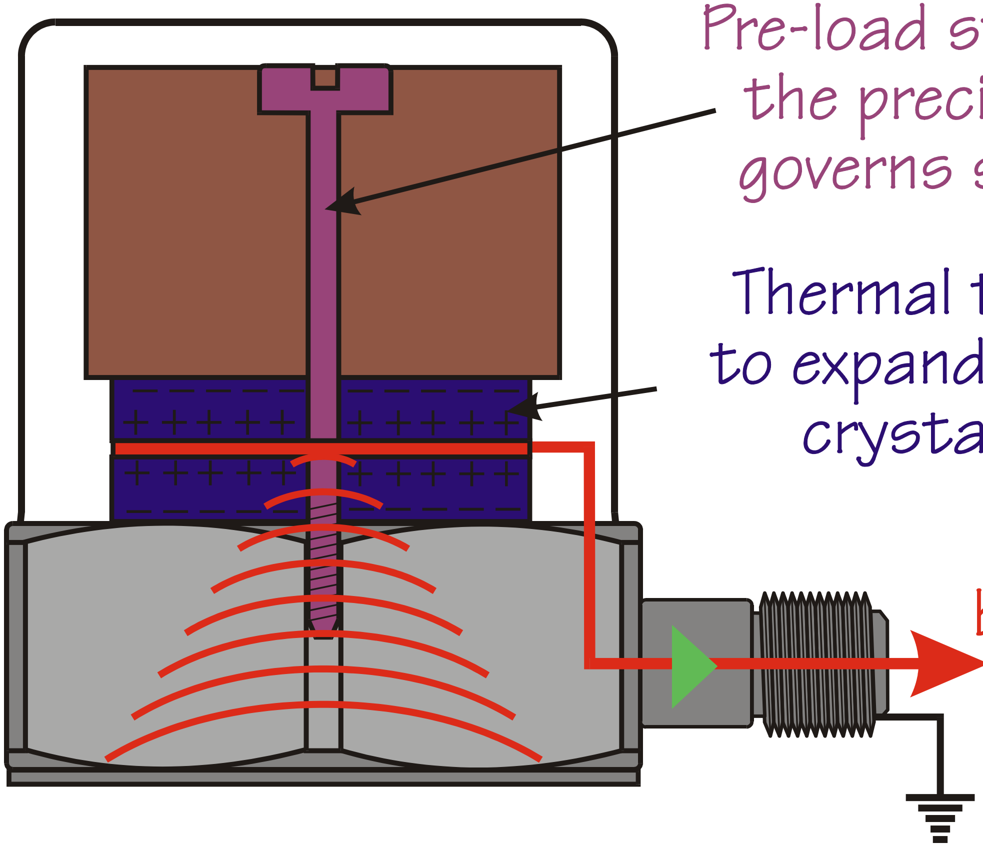
Compression Mode



Compression Mode

- Advantages
  - Few Parts / Easy to Fabricate
  - High Resonant Frequency
- Disadvantages
  - Very high thermal transient sensitivity
  - High base strain sensitivity

Compression Mode

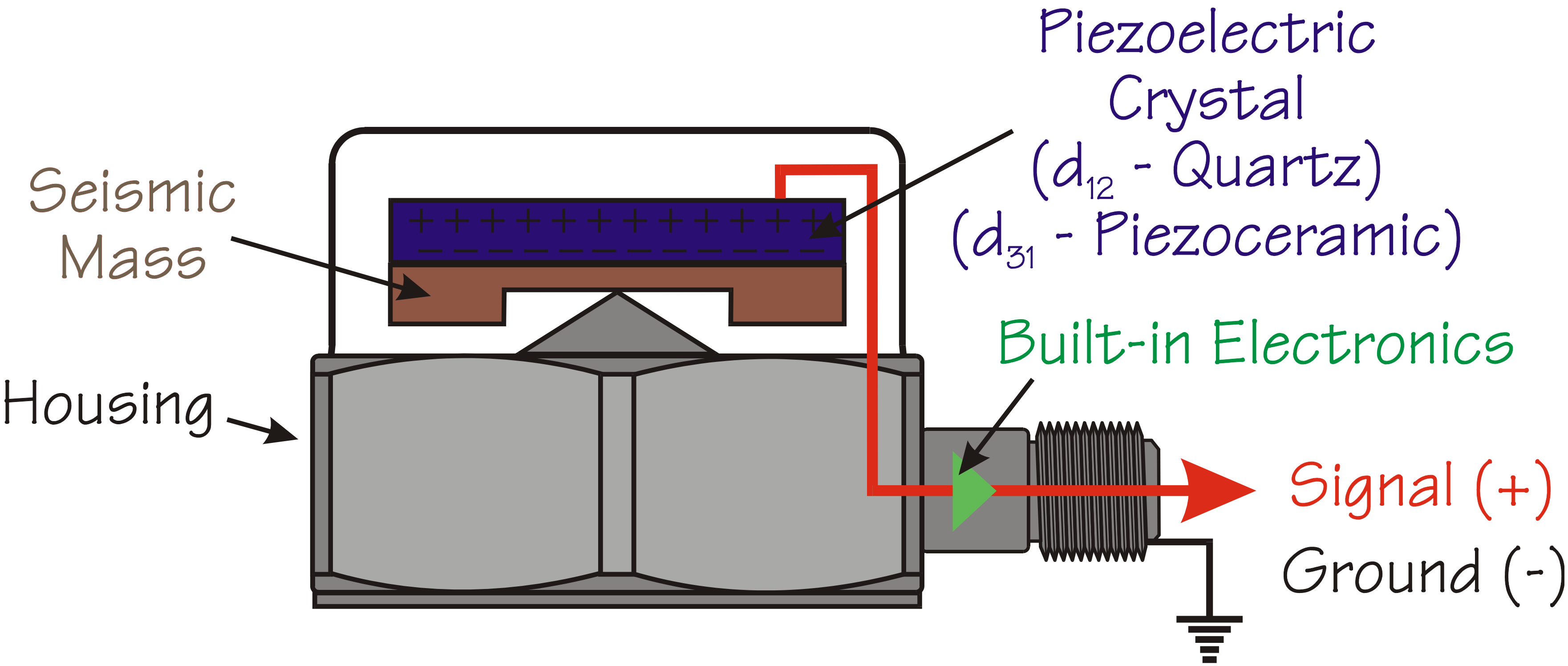


Pre-load stud and the quality of the precision parts interface governs stiffnes and linearity

Thermal transients cause metals to expand and contract...stressing crystals along sensitive axis

Strain waves due to bending of the test structure, travel unimpeded directtly into the crystal

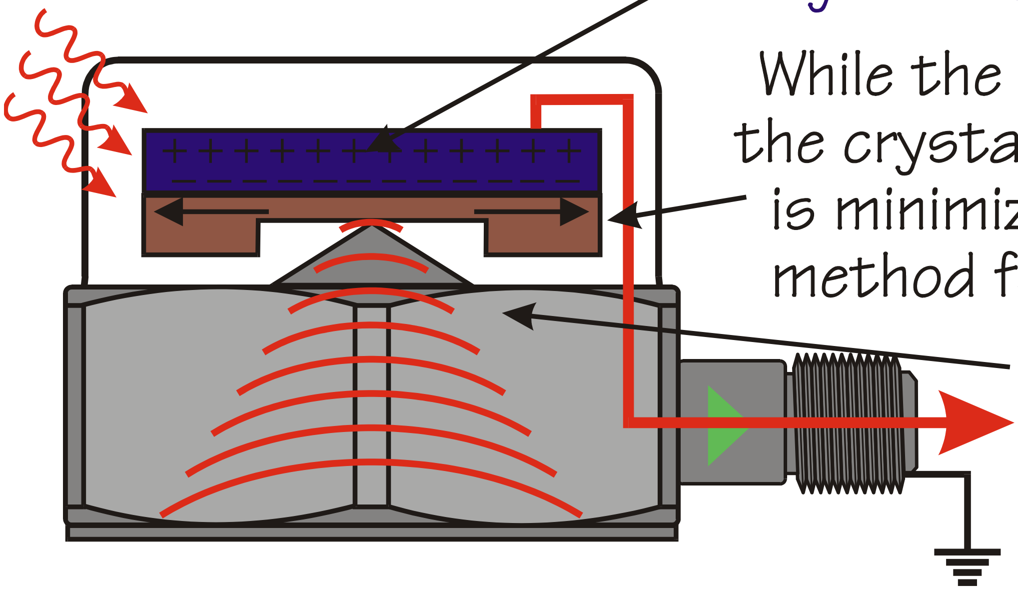
Flexural Mode



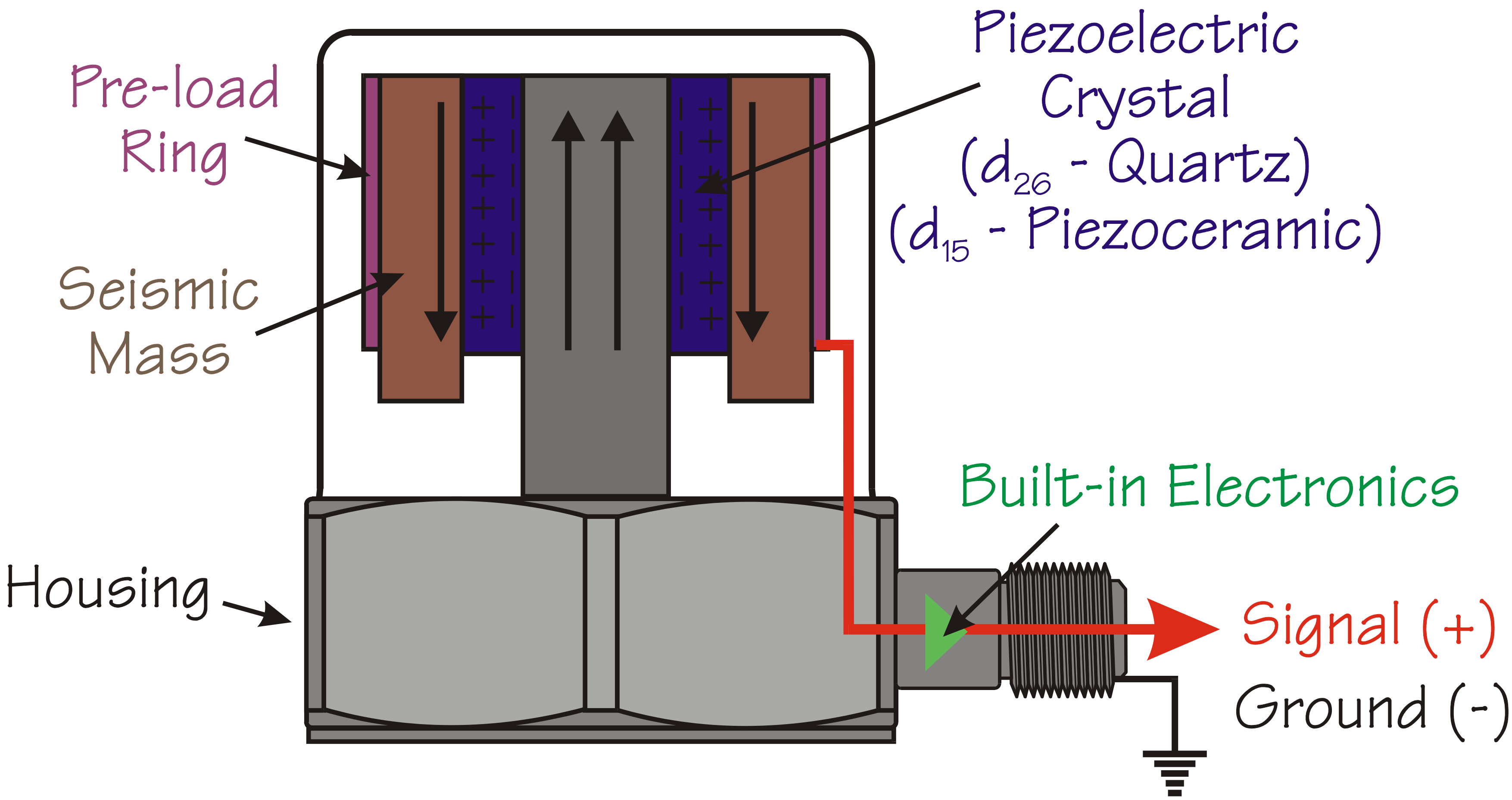
Flexural Mode

- Advantages
  - Few Parts
    - Low Cost
  - Small Size and Low Profile
  - Low Base Strain Sensitivity
  - Low Thermal Transient Sensitivity
- Disadvantages
  - Low Resonant Frequency
    - Limited High Frequency Range

Flexural Mode



Shear Mode

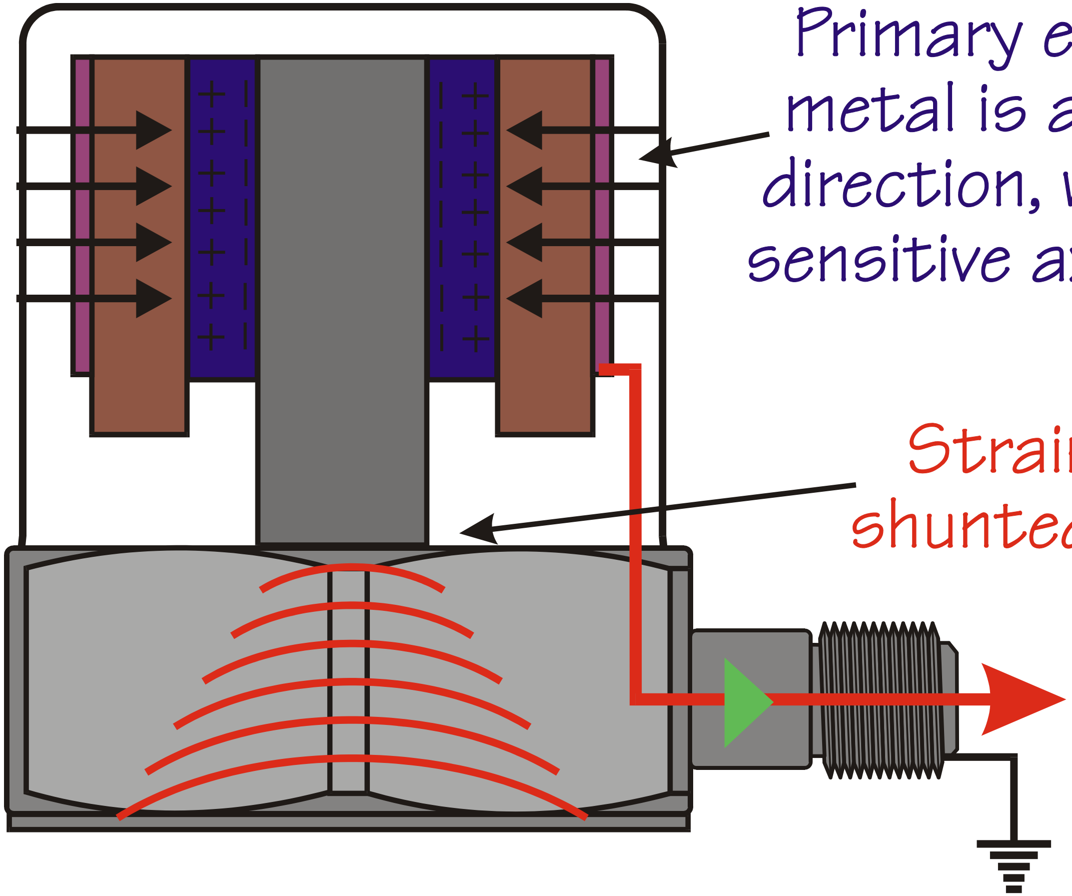


Pre-load Ring
Seismic Mass
Housing
Piezoelectric Crystal
(d_{26} - Quartz)
(d_{15} - Piezoceramic)
Built-in Electronics
Signal (+)
Ground (-)

Shear Mode

- Advantages
  - Low Thermal Transient Sensitivity
    - Allows for low frequency operation in thermally unstable environments
  - Very Low Base Strain Sensitivity
    - Excellent for use on flexible structures
  - Small Size
- Disadvantages
  - ???????

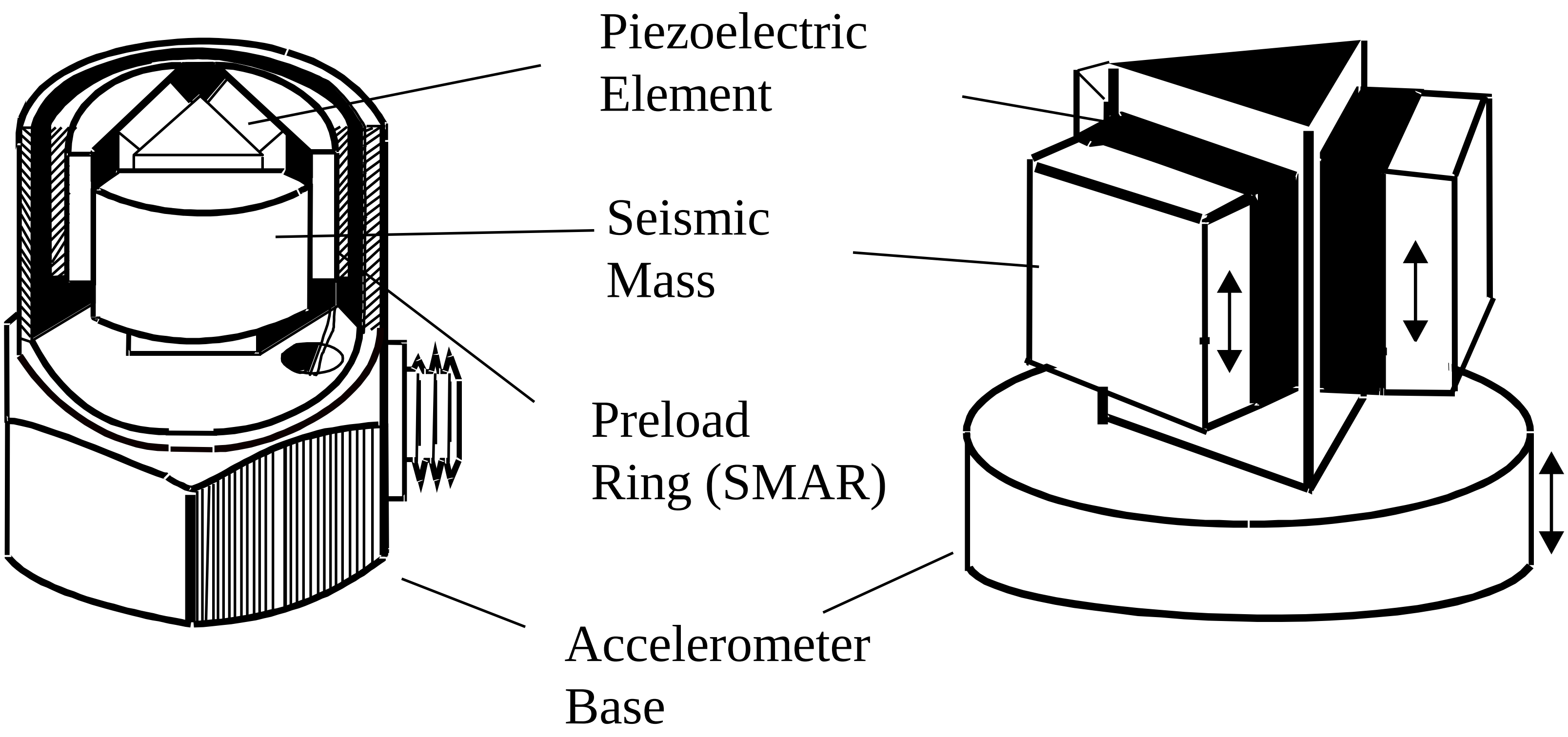
Shear Mode



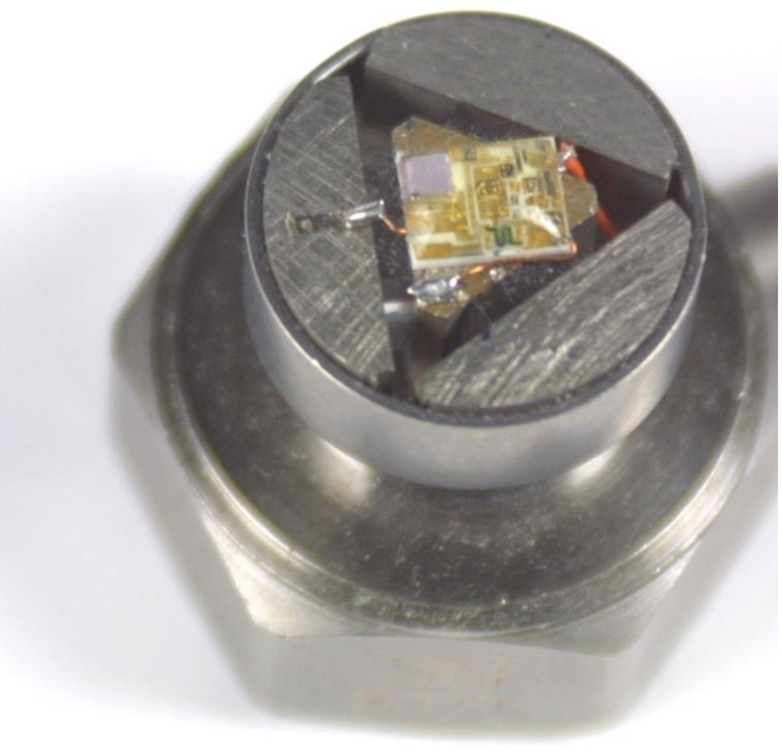
Primary expansion of the metal is along pre-loaded direction, which is the non-sensitive axis of the crystal

Strain waves are shunted at the post

Accelerometer Construction
PCB's "Tri-Shear" Design



Accelerometer Construction

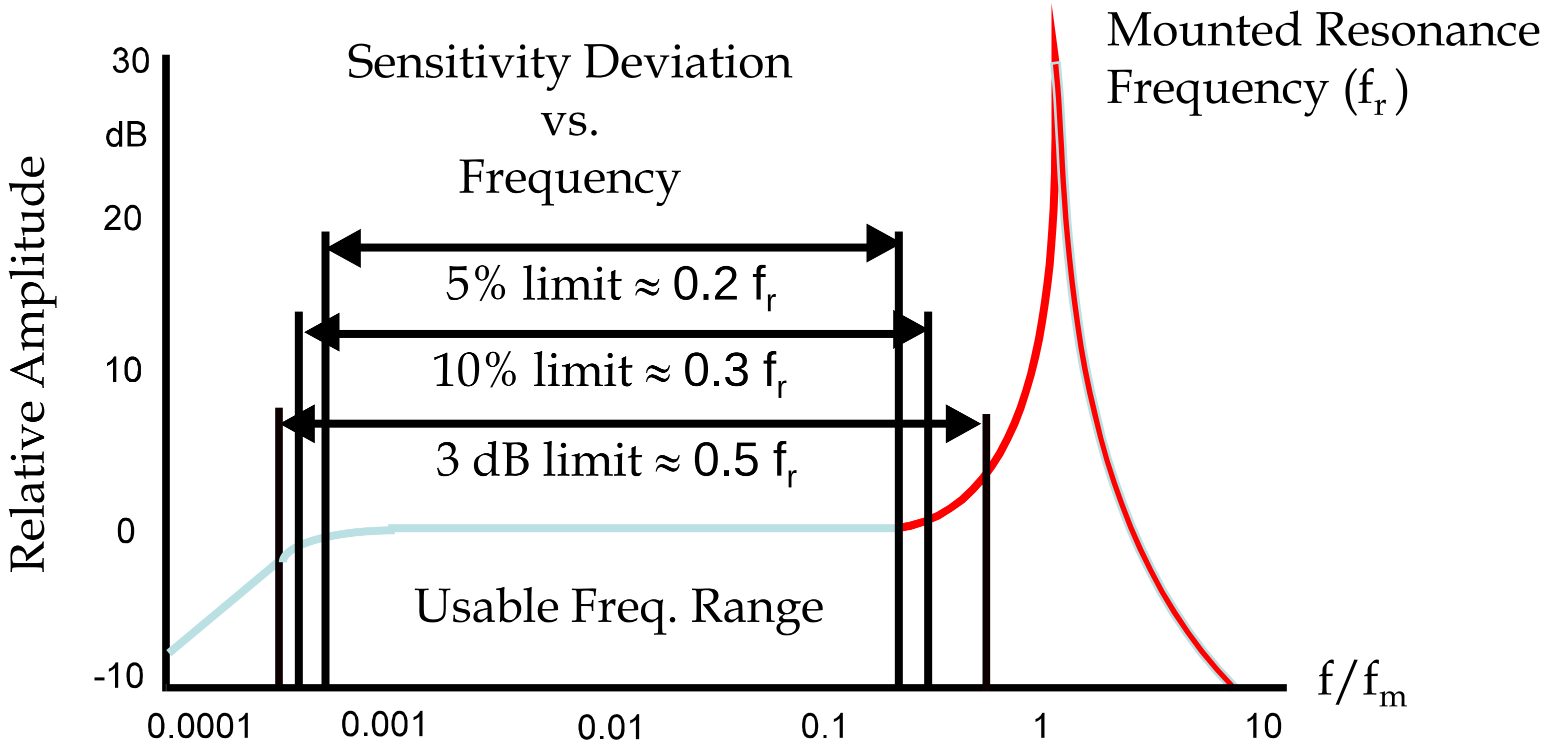


Structures

- Other environmental effects include:
  - Acoustic
    - Housing acts as shield
    - Smaller sensors are more affected
  - Magnetic Fields
    - Precludes the use of invar & other materials
  - Humidity
    - All welded, hermetic sensors vs. epoxy sealed
  - EMI / RFI
    - Internal shielding
    - Twisted, shielded cabling

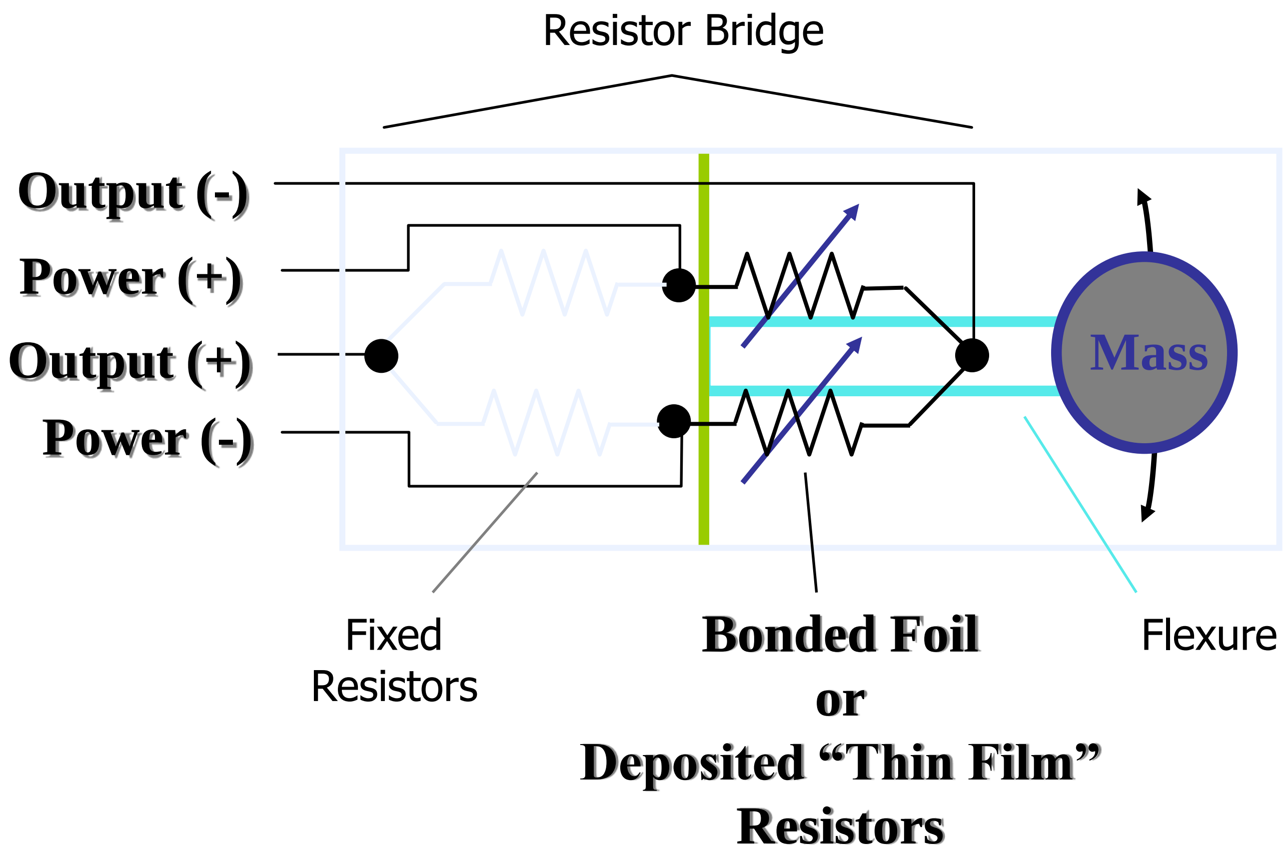
Frequency Response

- Ideal accelerometer treats frequencies of interest the same.

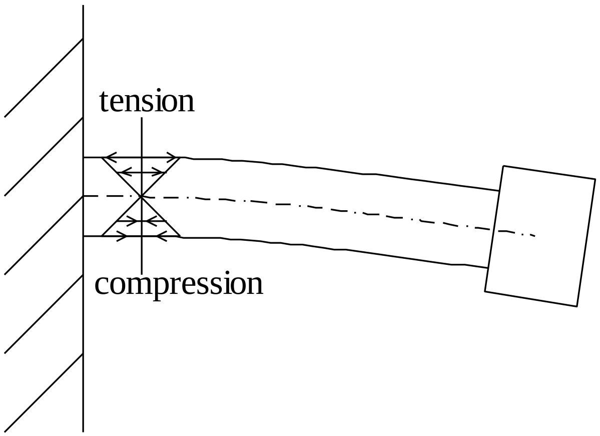


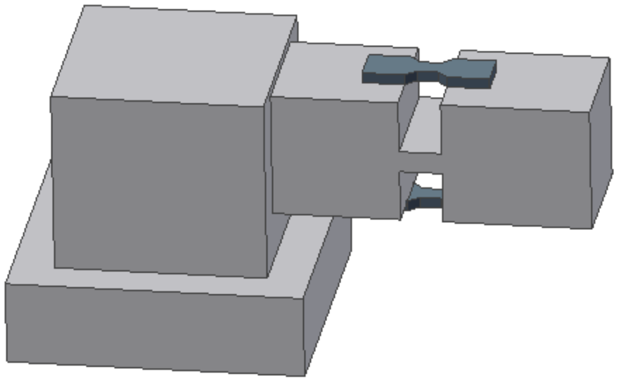
DC Accelerometer

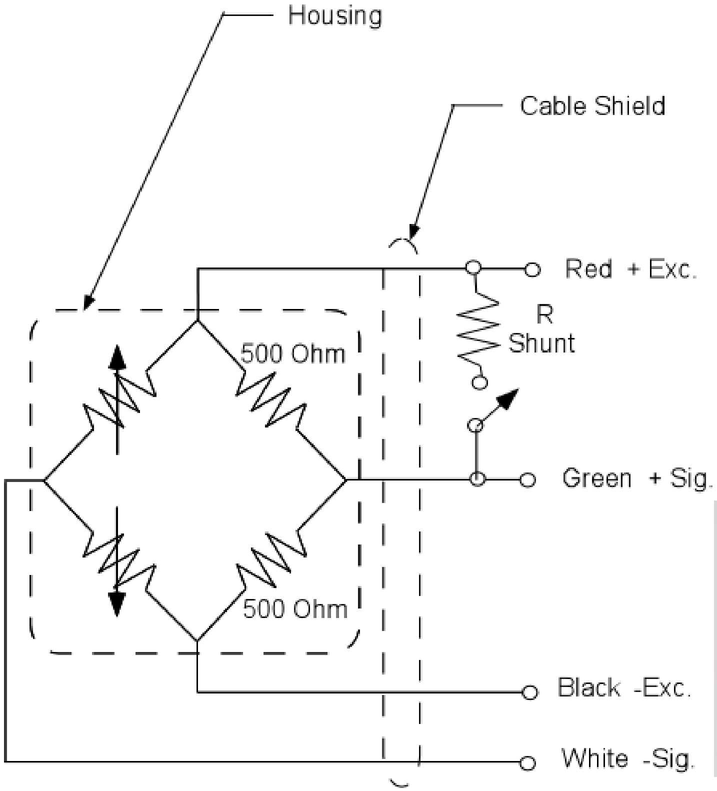
DC Accelerometer – Piezoresistive



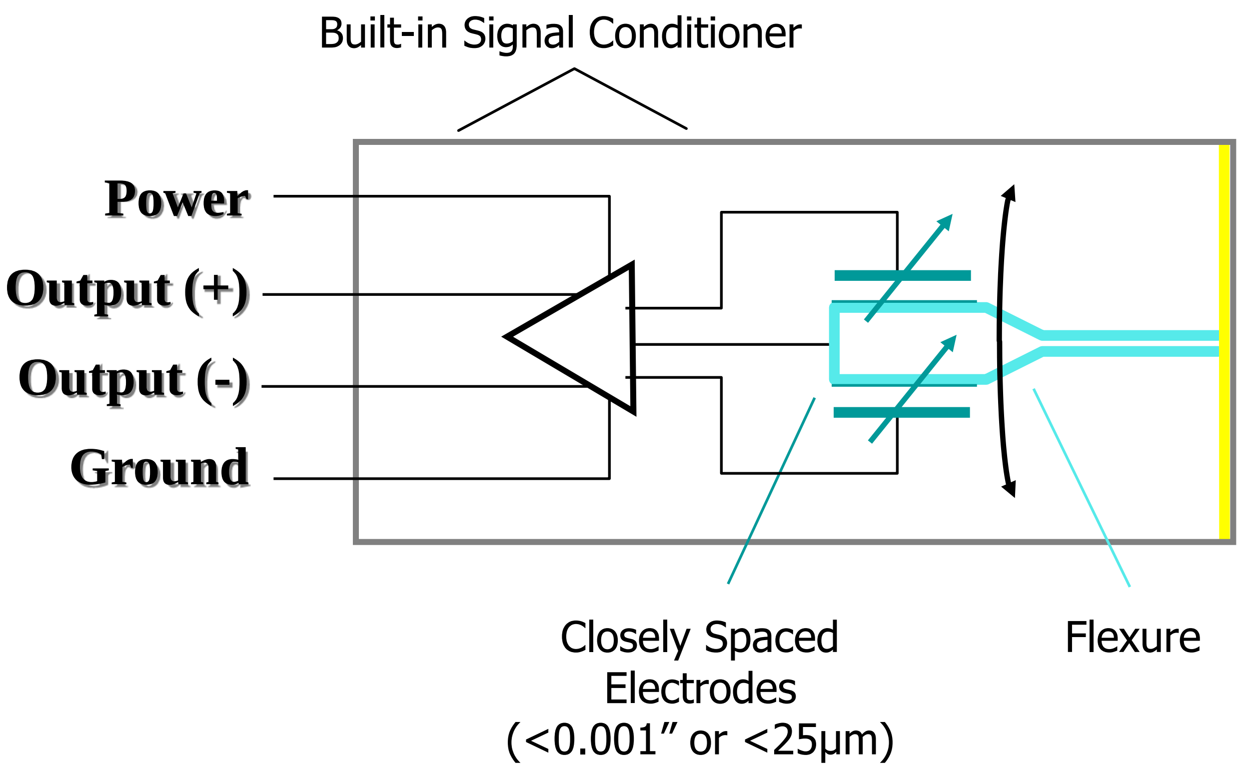
DC Accelerometer – Piezoresistive







DC Accelerometer – Variable Capacitance



DC Accelerometer – Variable Capacitance

A = Area of proof mass

ε = permittivity of air

t = displacement

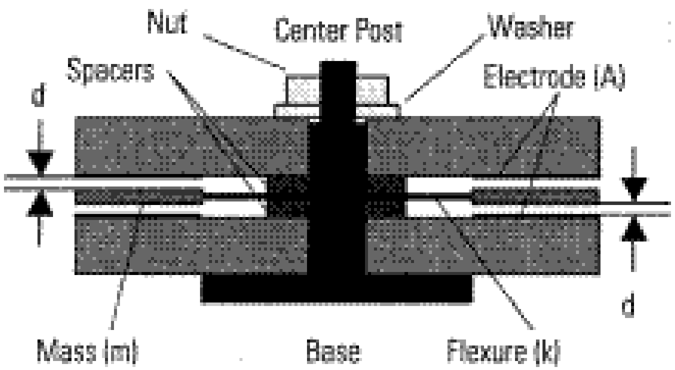
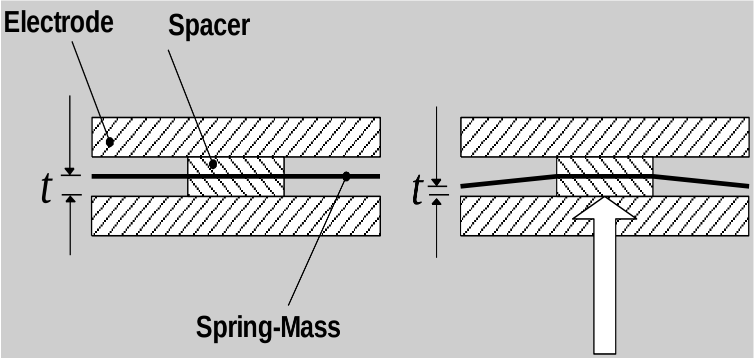
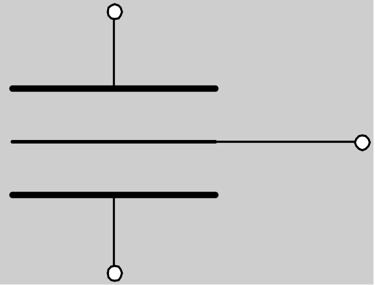


Figure 1a: Sensing Element in "0 g" Condition



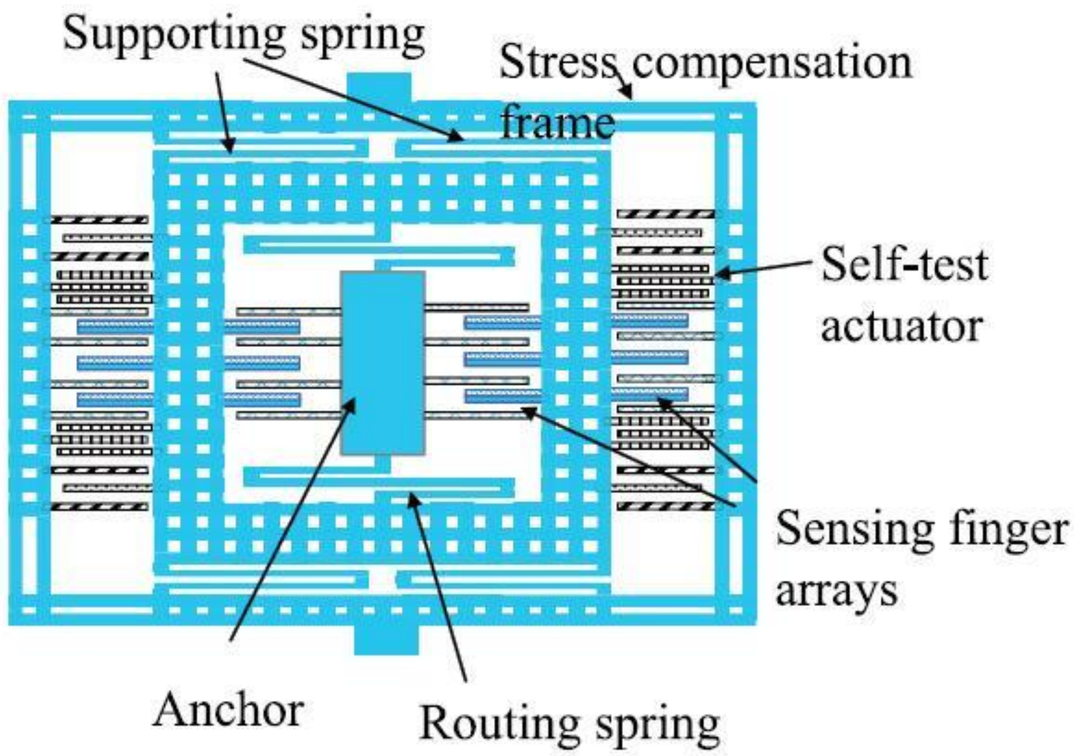
$$C = \frac{A\varepsilon}{t}$$



MEMS Accelerometer

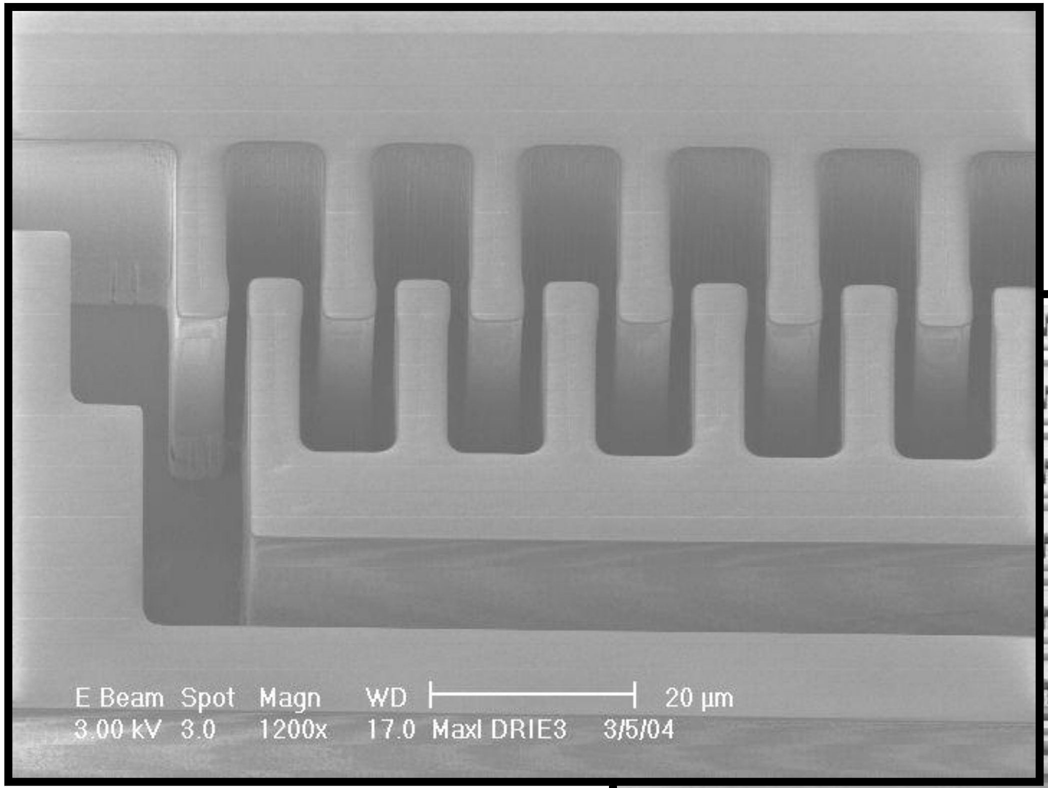
MEMS Accelerometer

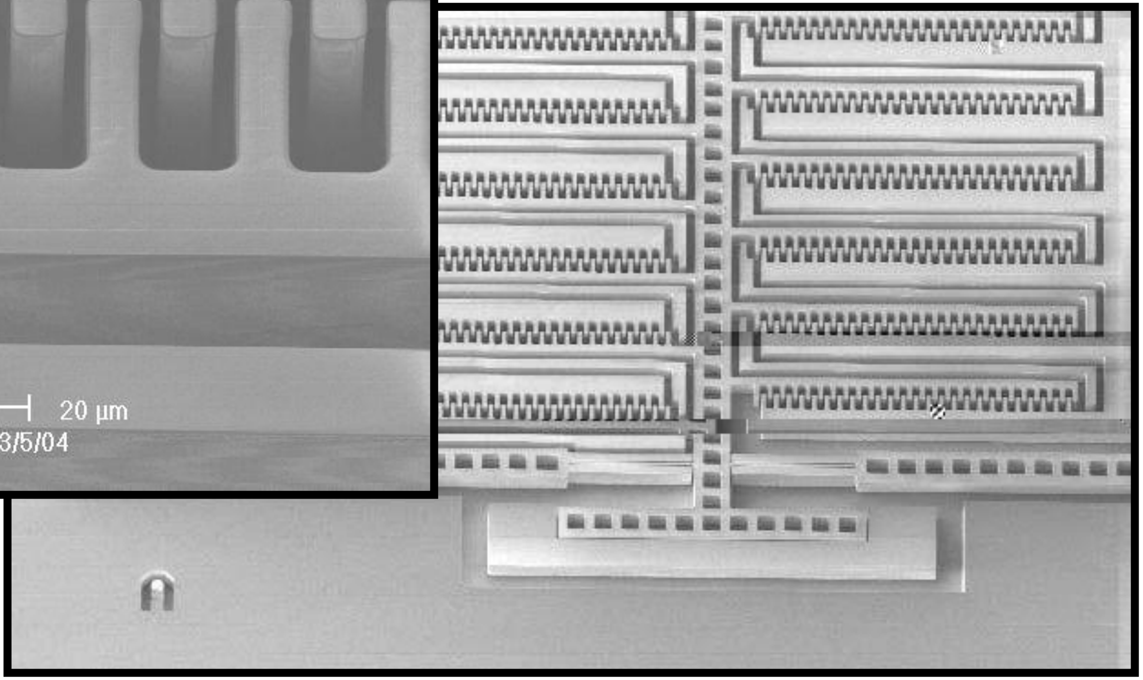
- Micro Electro Mechanical System



資料來源：清華大學動機系 方維倫教授/國科會產學合作暨成果發表專刊

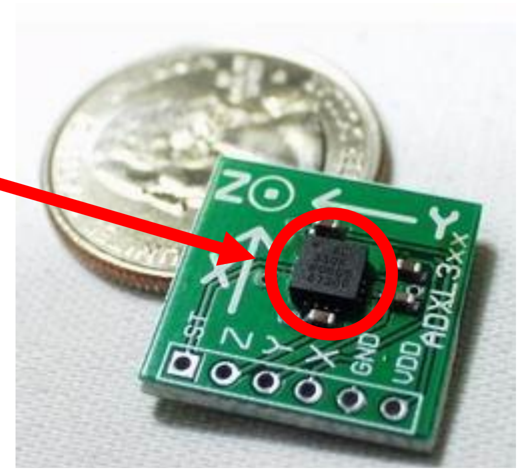
MEMS Accelerometer

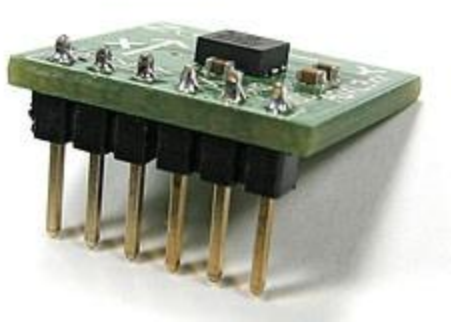


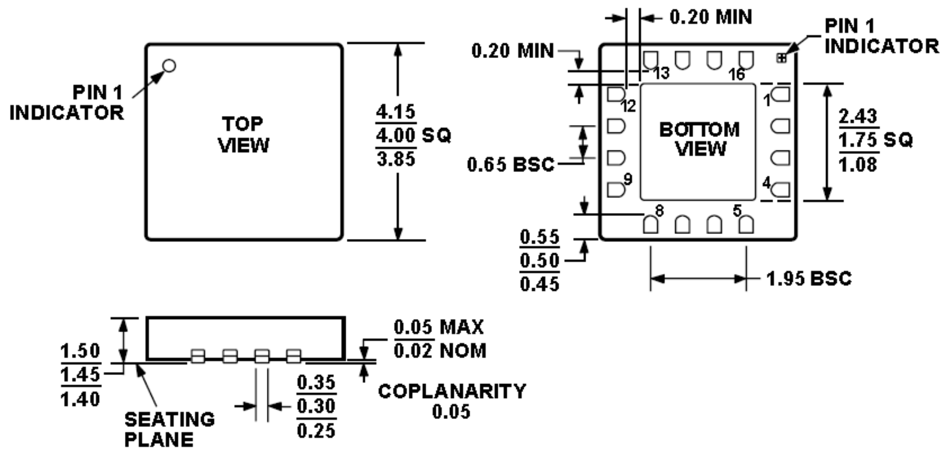


MEMS Triaxial Accelerometer

- ADXL3xx





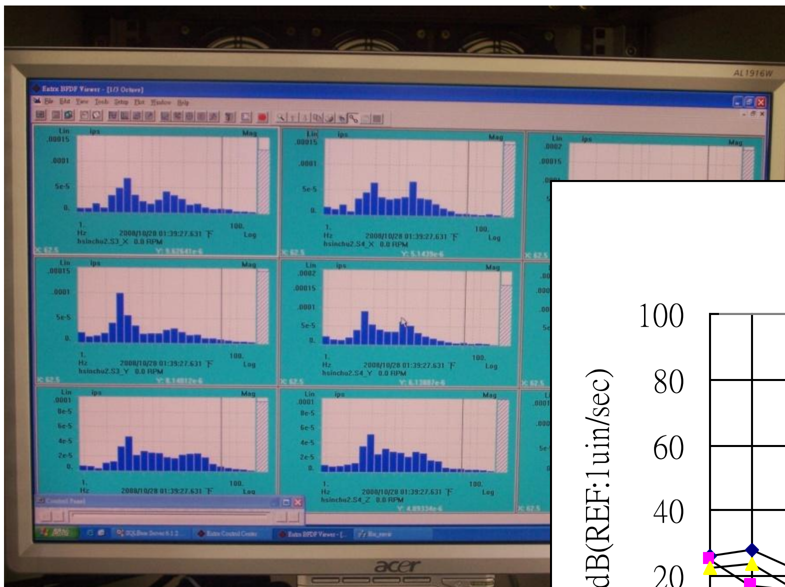


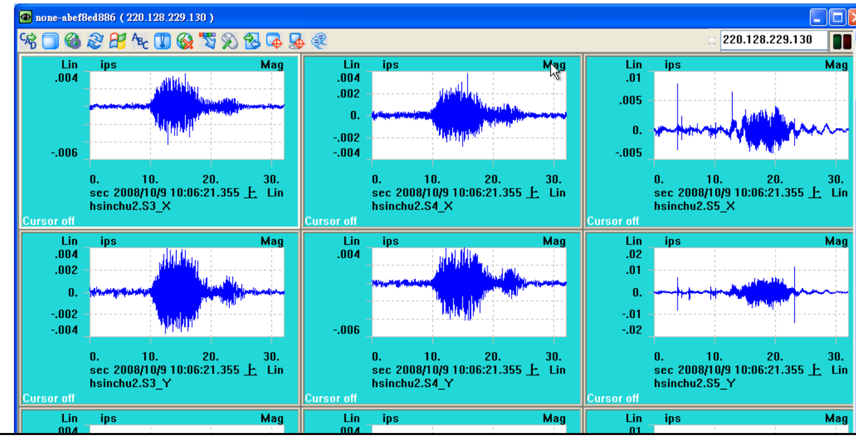
資料來源：Analog Device, Inc.

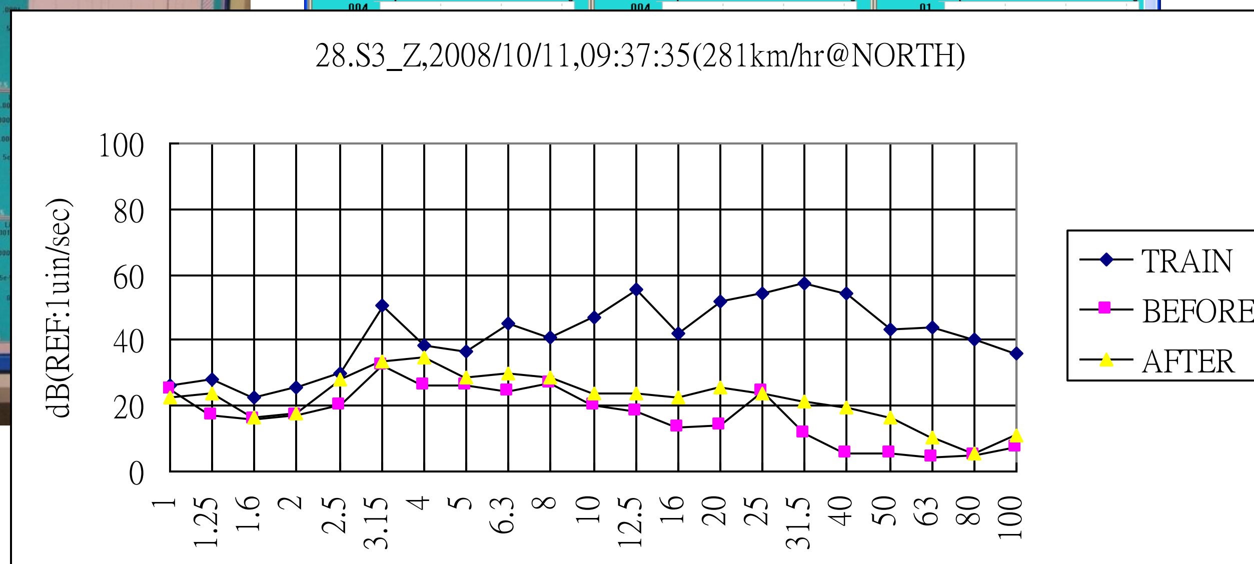
Applications

Environmental Monitoring

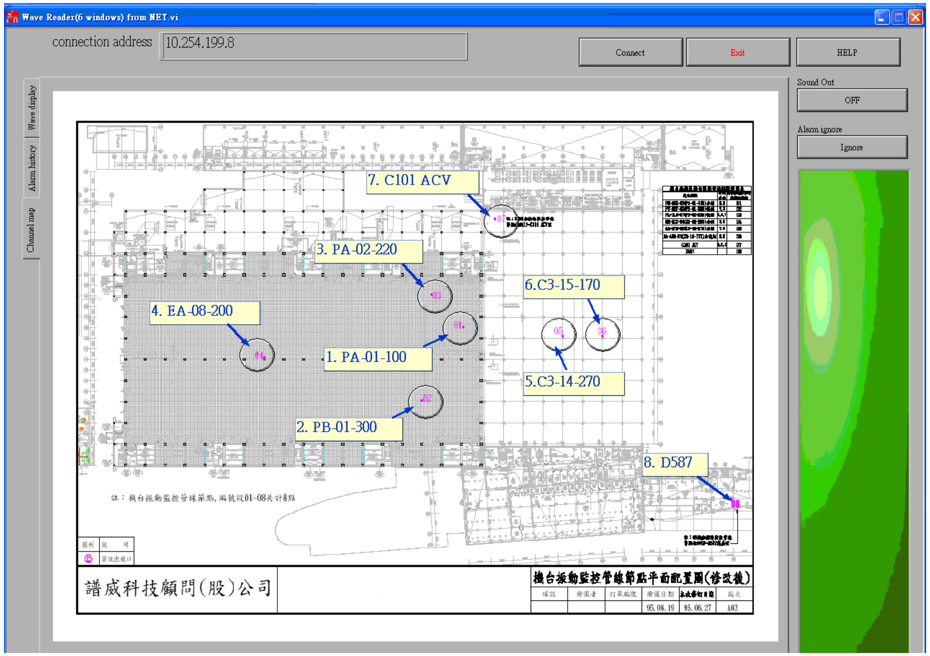
Environmental Monitoring

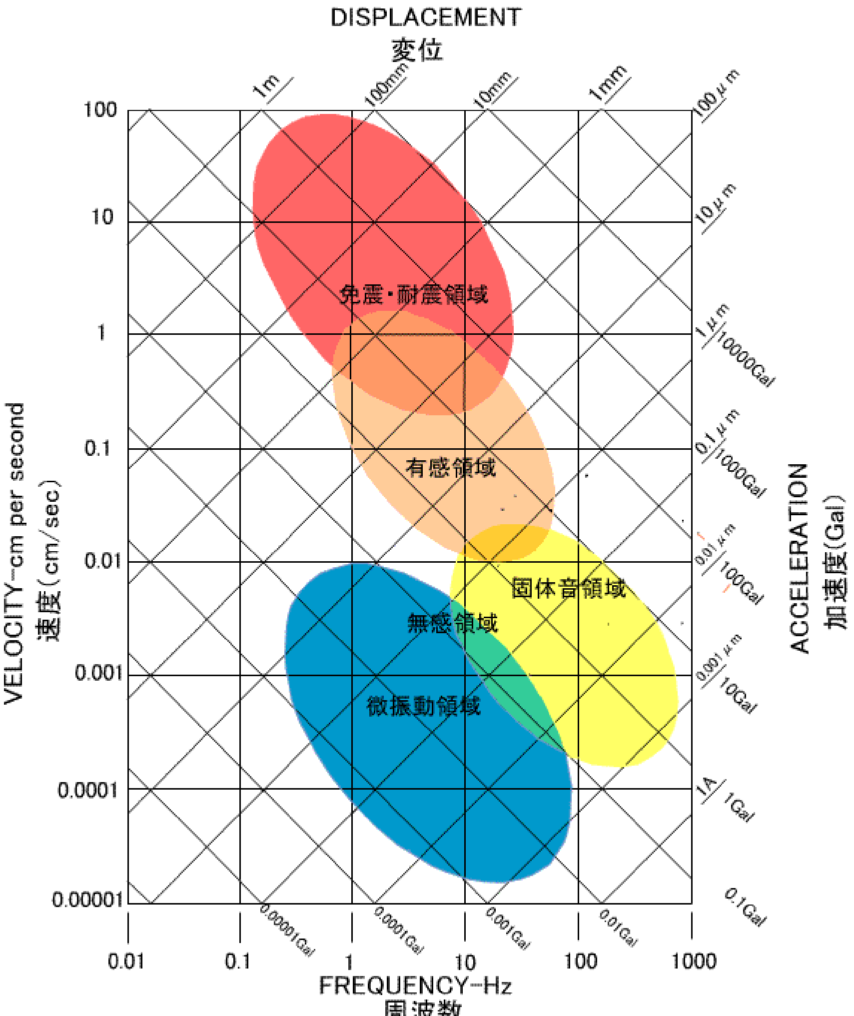






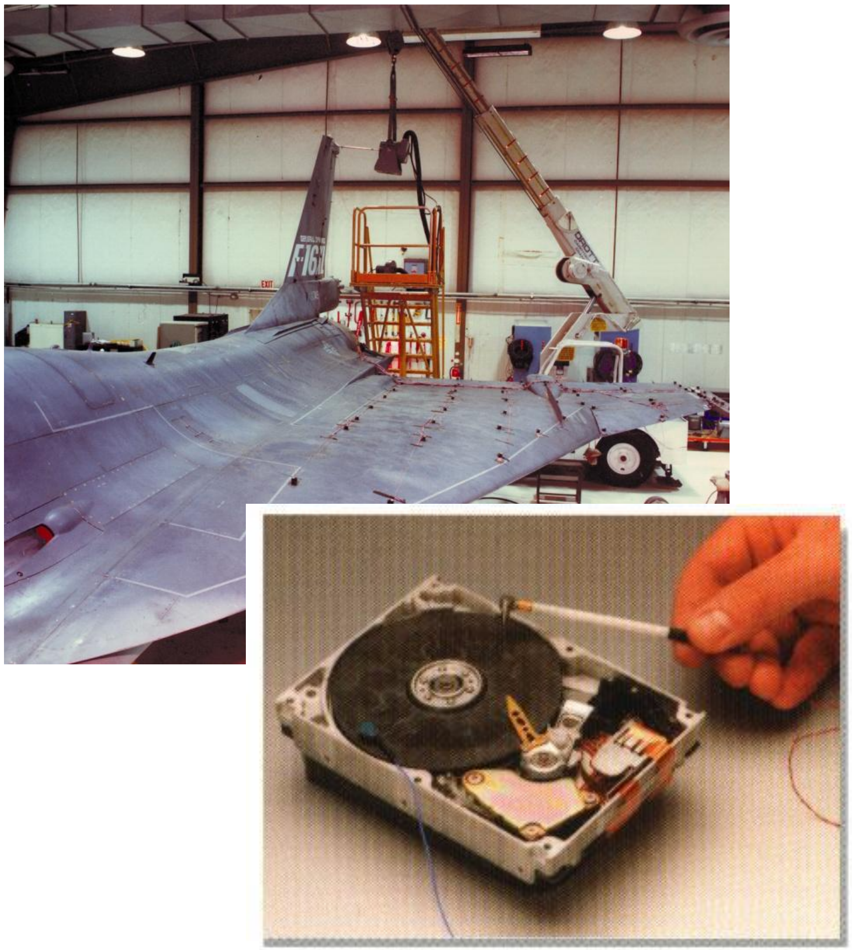
Micro-Vibration

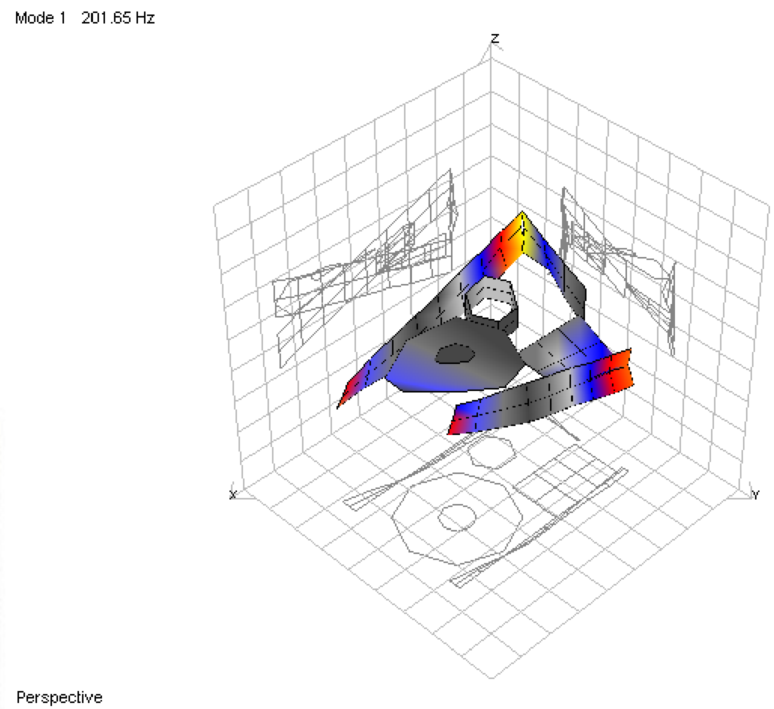




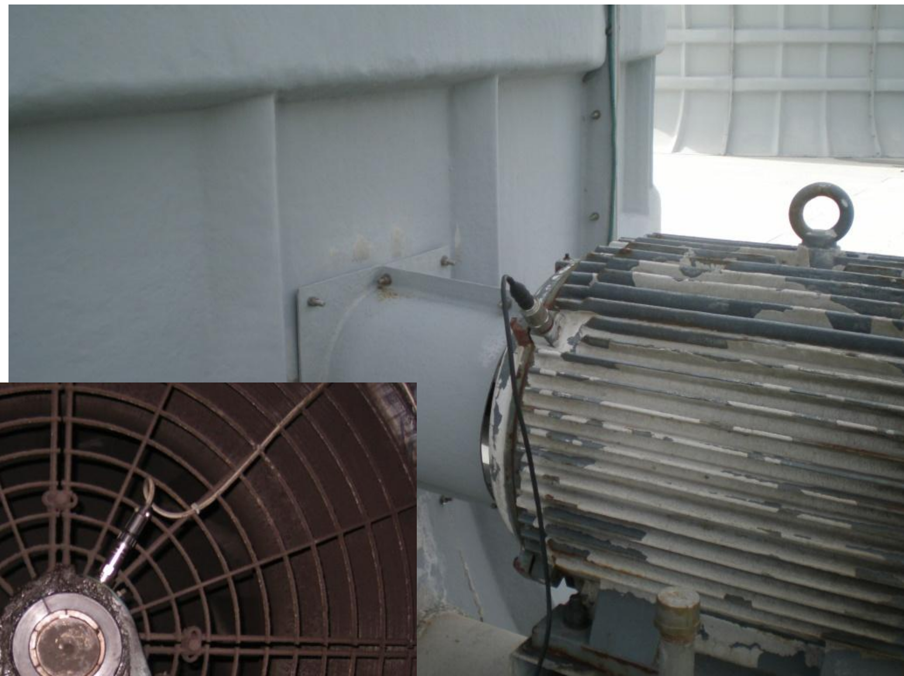
資料來源: TOKKYOKIKI Corp

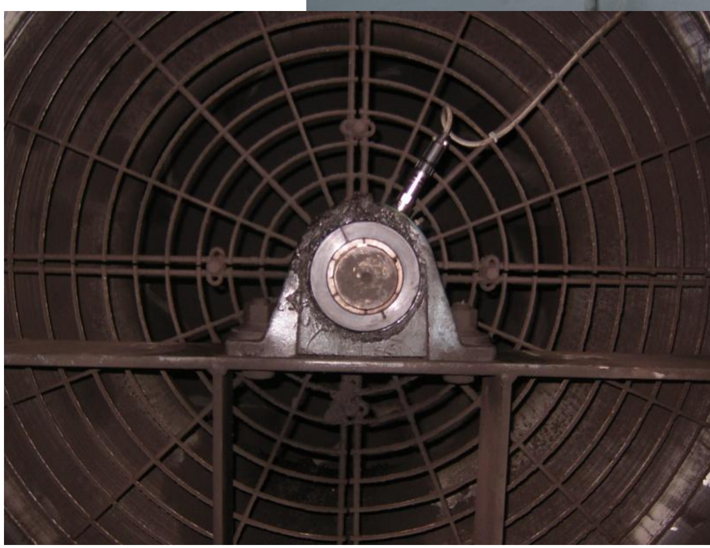
Modal Testing



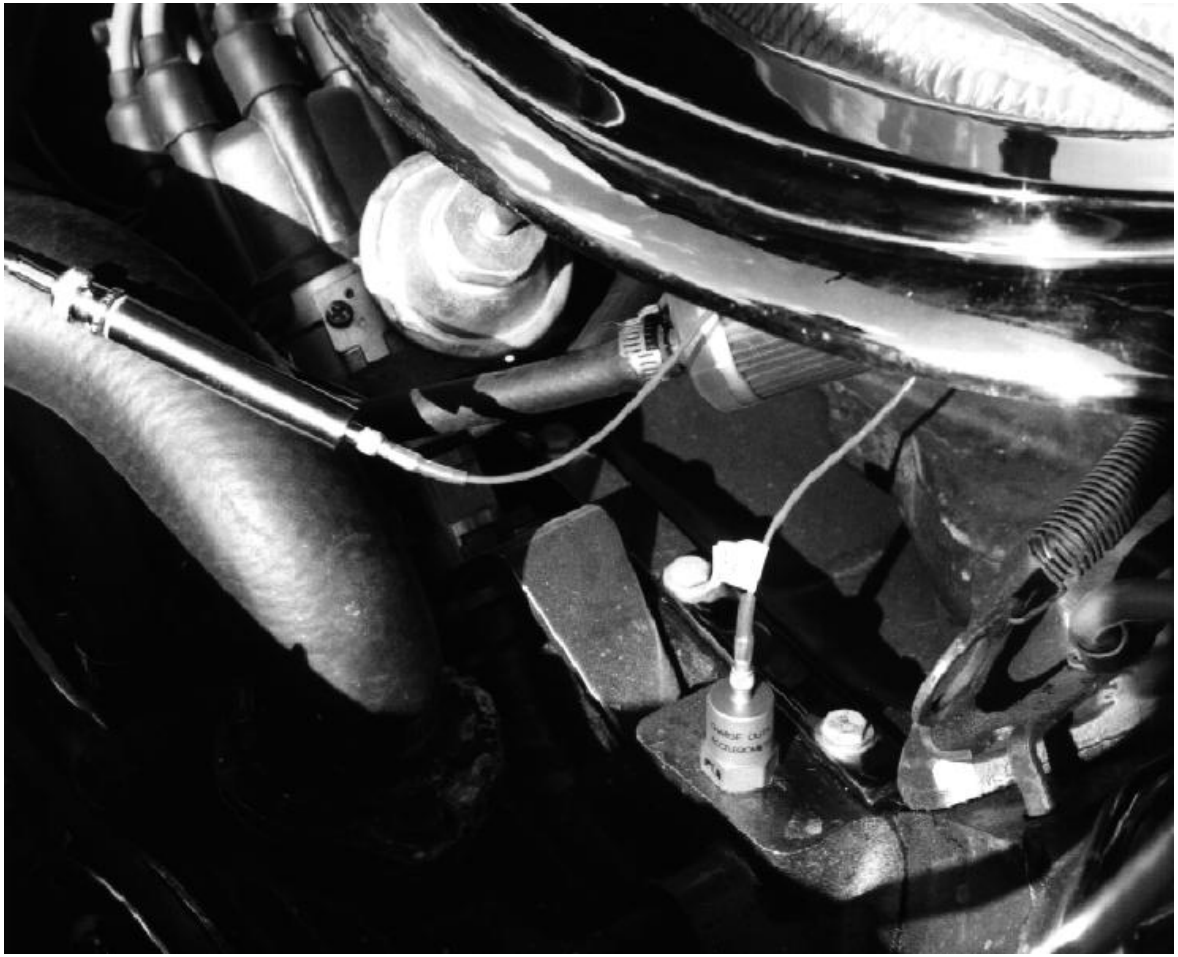


Motor, Fan and Pump

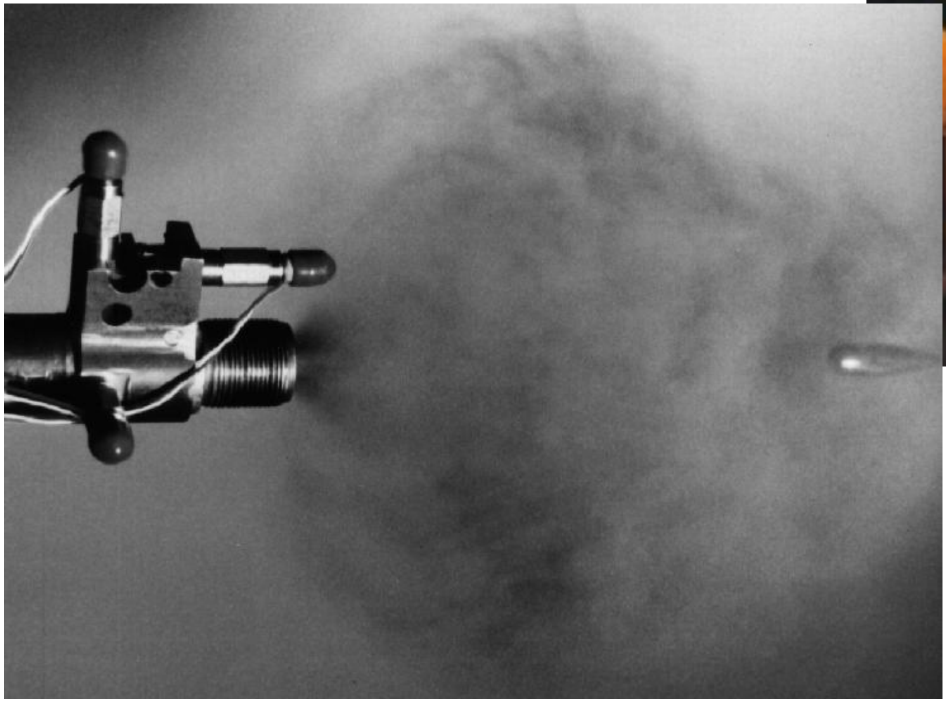




Automobile Engine Test



Shock Test



Crash Test

Tool Machine

Consumer Product

資料來源：Apple, Nintendo, HTC

Sensor Calibration

Accelerometer

Standard for Accelerometer Calibration

- ISO 16063 Methods for the Calibration of Vibration and Shock Transducers
  - 16063 Part 11. Primary vibration calibration by laser interferometry
  - 16063 Part 13. Primary shock calibration by laser interferometry
  - 16063 Part 21. Vibration calibration by comparison method
  - 16063 Part 22. Shock calibration by comparison method

Accelerometer Calibration

Gravimetric

Single Accel

Back to Back

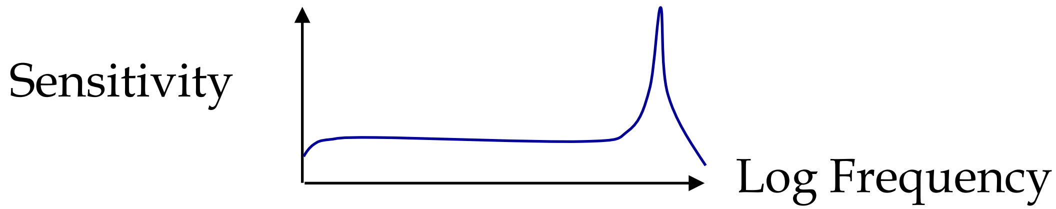
Primary

Accelerometer Calibration

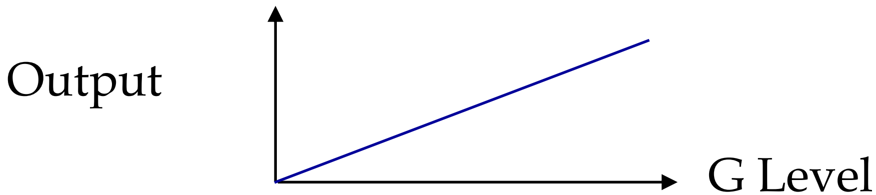
- Sensitivity
  - Rated output of the sensor per unit of acceleration
    - ICP - Voltage Sensitivity: mV/g
    - Charge - Charge Sensitivity: pC/g

Accelerometer Calibration

- Accelerometer sensitivity
  - Frequency dependent

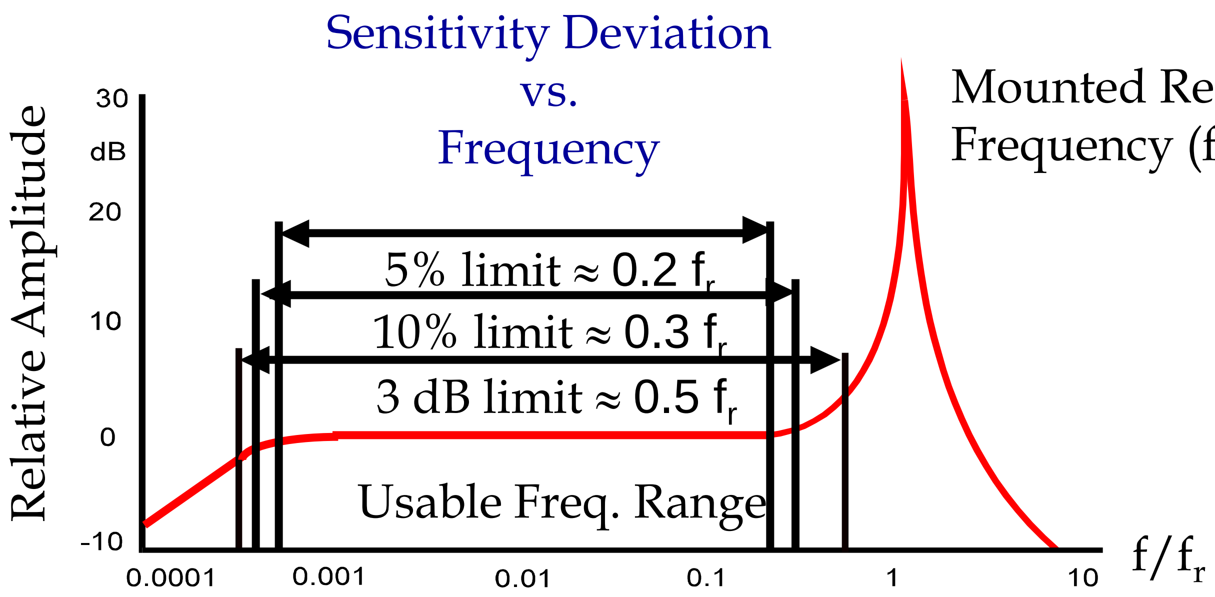


  - Amplitude dependent



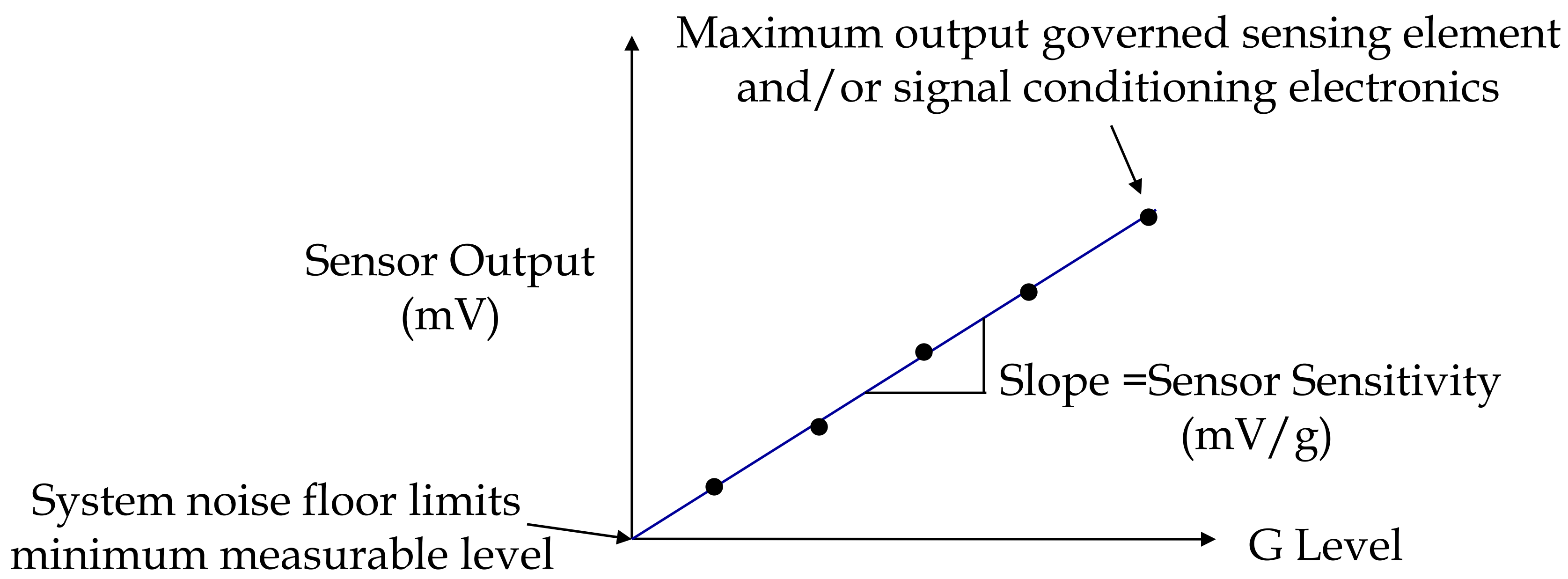
Accelerometer Calibration

- Sensitivity
  - Frequency Dependent
    - An ideal accelerometer treats frequencies of interest the same



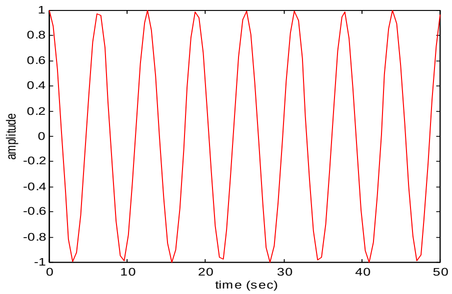
Accelerometer Calibration

- Sensitivity
  - Amplitude Dependent
    - An ideal accelerometer treats amplitudes proportionally



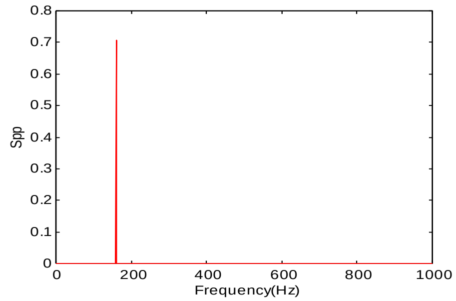
Accelerometer Calibration

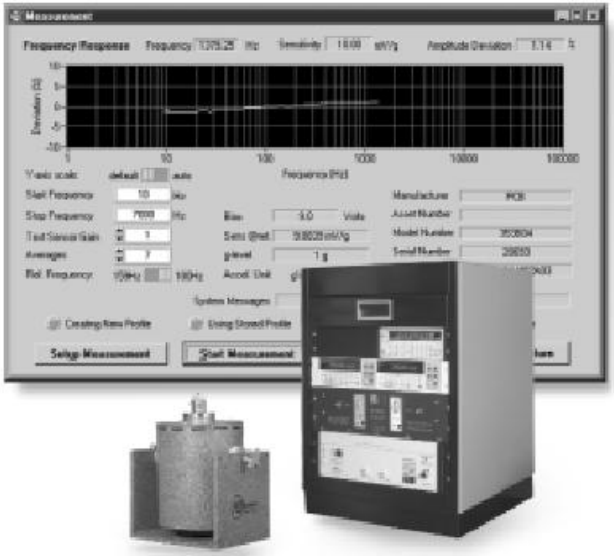
- Back-to-Back Calibration
  - Uses a sinusoidal excitation of a known frequency swept through the frequency range at fixed amplitude



Time Domain

Frequency Spectrum





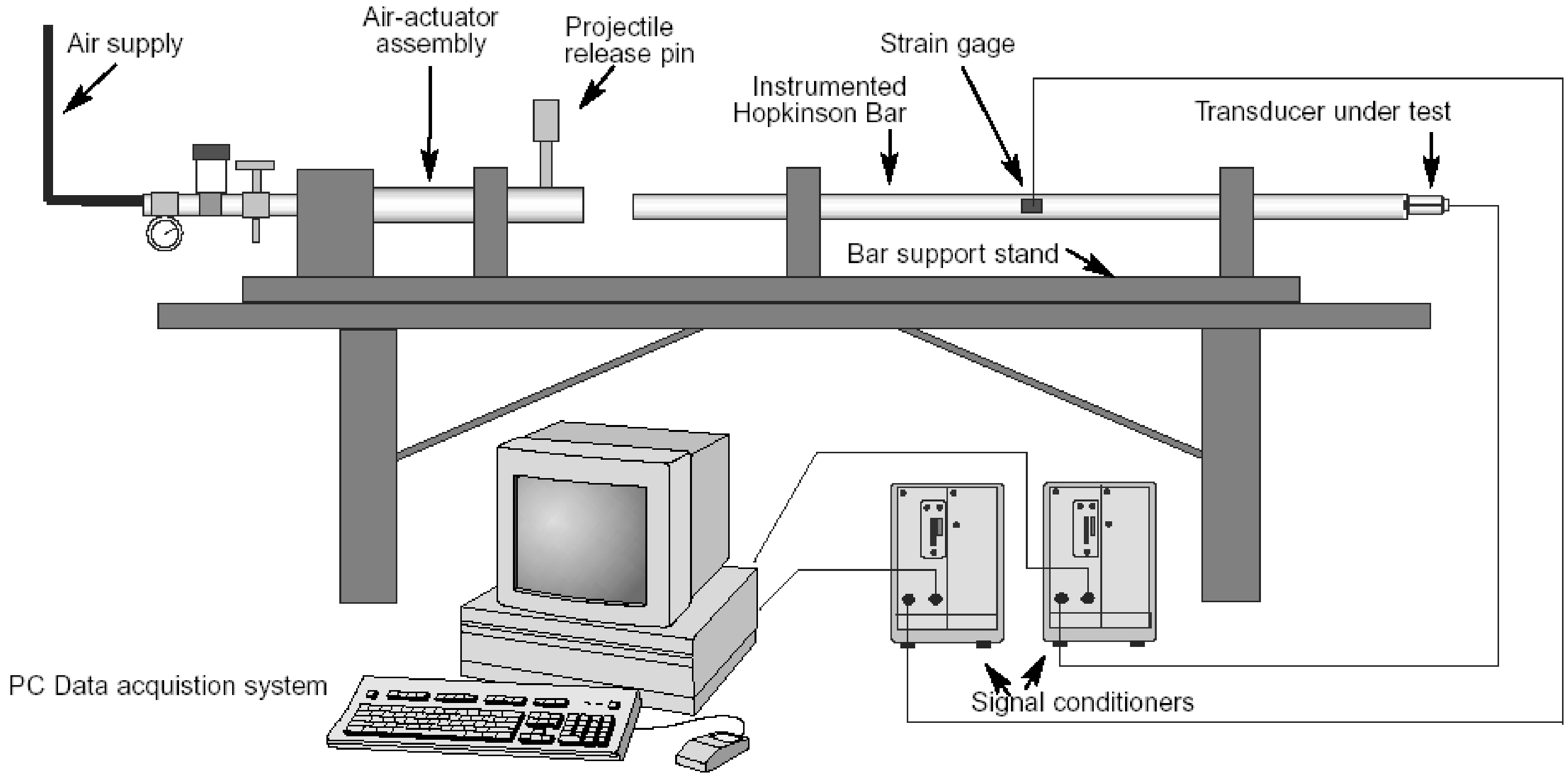
Calibration System in ARTC

Accelerometer Calibration

- High ‘G’ Shock Calibration
  - Laboratory test which generates fast rise time and high peak acceleration found in severe shock environment.
    - Test sensor survivability to over 100,000g.
    - Test cables connectors.
    - Evaluate accelerometer zero-shift.
    - Evaluate sensor linearity to 100,000g.
    - Determine frequency response at high g levels.

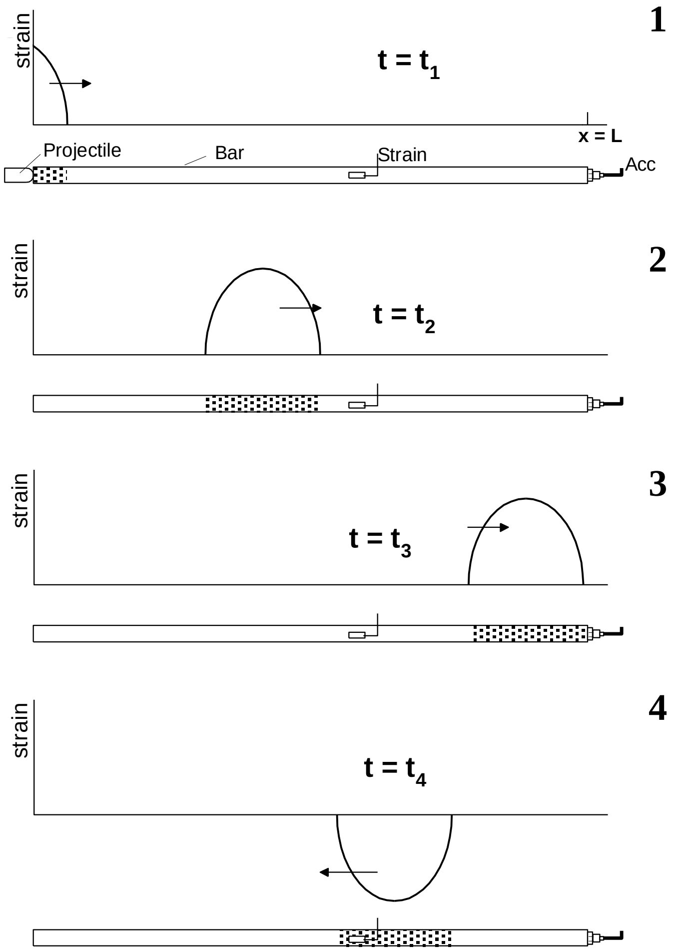
Accelerometer Calibration

- Hopkinson Bar Test System



Accelerometer Calibration

- Ideally, a one dimensional stress wave propagates down the long thin bar and reflects at the free end

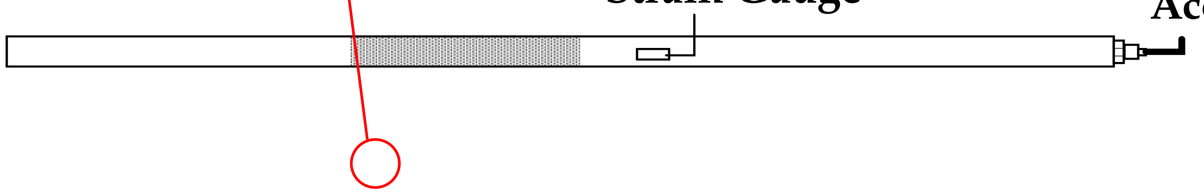


Accelerometer Calibration

- This wave can be converted to velocity experienced at end of bar using

$$v_r = 2c_o\varepsilon_r$$

where, c_o = speed of sound in bar material
ε = strain measured by gauge
2 = velocity doubles due to signal inversion



Accelerometer Calibration

- Once the strain sensor signal is scaled to velocity, it can be differentiated to obtain an equivalent acceleration signal

$$a_r = \frac{d}{dt} v_r$$

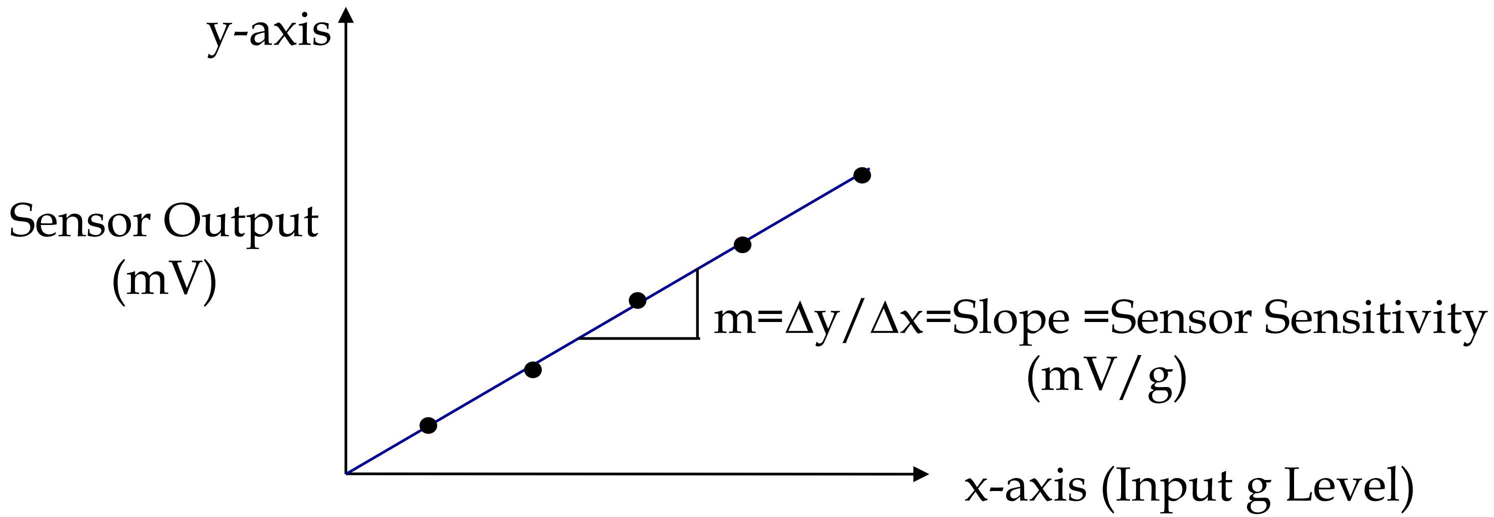
- Then, it can be compared to the test sensor signal to obtain sensitivity
  - Derivative Peak Picking Method
  - FFT Method

Accelerometer Calibration

Linearity

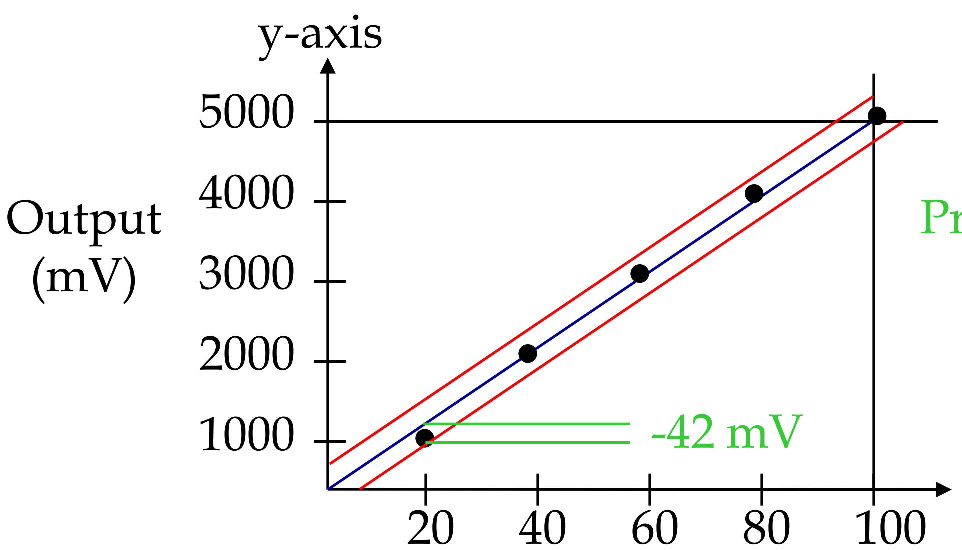
Accelerometer Calibration

- Linearity
  - Zero-Based, Best-Fit, Straight Line
    - Equation of line: y=mx
    - line is forced thru (0,0) as the sensor cannot have any output signal with no input



Accelerometer Calibration

- Acceptable Range
  - +/-1% of calculated full scale value
    - Printed linearity value is calculated by taking the maximum deviation of the points and dividing by the full scale value



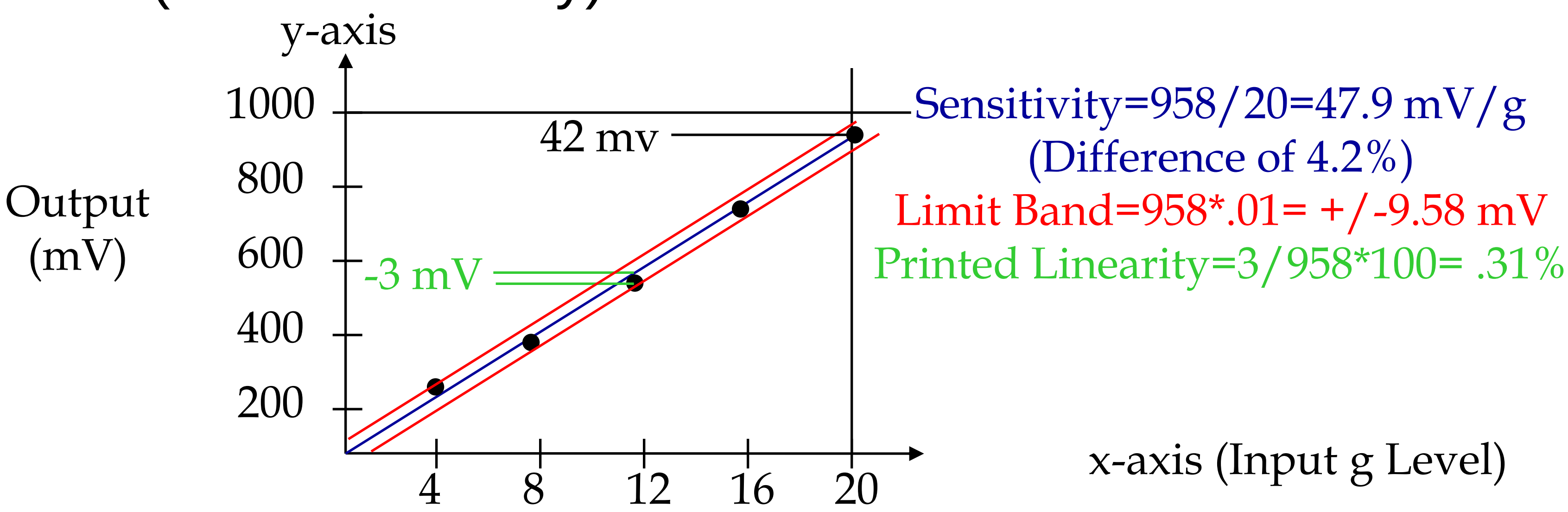
Sensitivity=5000/100=50.0 mV/g
Limit Band=5000*.01=+/- 50 mV
Printed Linearity=38/5000*100= .84%

How good is this sensor?

x-axis (Input g Level)

Accelerometer Calibration

- Zooming in on low accelerations tells tale
  - While the first chart appears to show the sensor operates well. It is a bit misleading as calibrating to a lower range clearly indicates a different behavior (lower sensitivity).

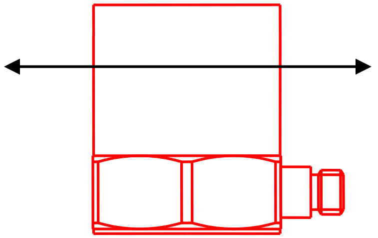


Accelerometer Calibration

Transverse

Accelerometer Calibration

- Transverse Sensitivity
  - Sensitivity of accelerometer to motion perpendicular to the sensitivity axis.



  - Expressed as percentage of axial sensitivity

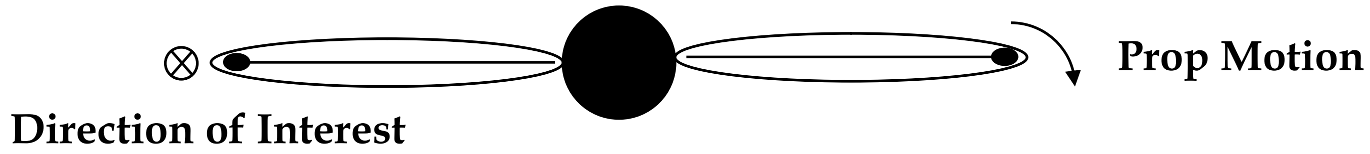
$$\% = \frac{\text{Transverse Sensitivity (mV/g)}}{\text{Axial Sensitivity (mV/g)}} \times 100$$

Accelerometer Calibration

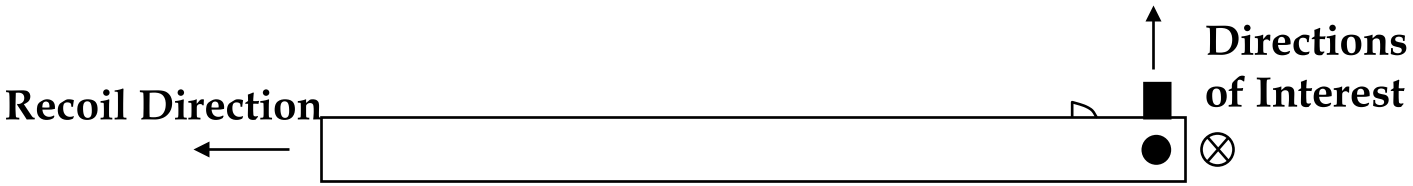
- Potential causes of transverse sensitivity
  - Raw Parts
    - Crystal cut or poling axis
    - Non-perpendicular parts
    - Poor surface finishes causing uneven loading
  - Design
    - Mechanical configuration / resonance
  - Process Control
    - Alignment of parts after assembly

Accelerometer Calibration

- Importance of low transverse sensitivity
  - Propeller Vibration
    - 352B22 used to measure motion at tip of blade

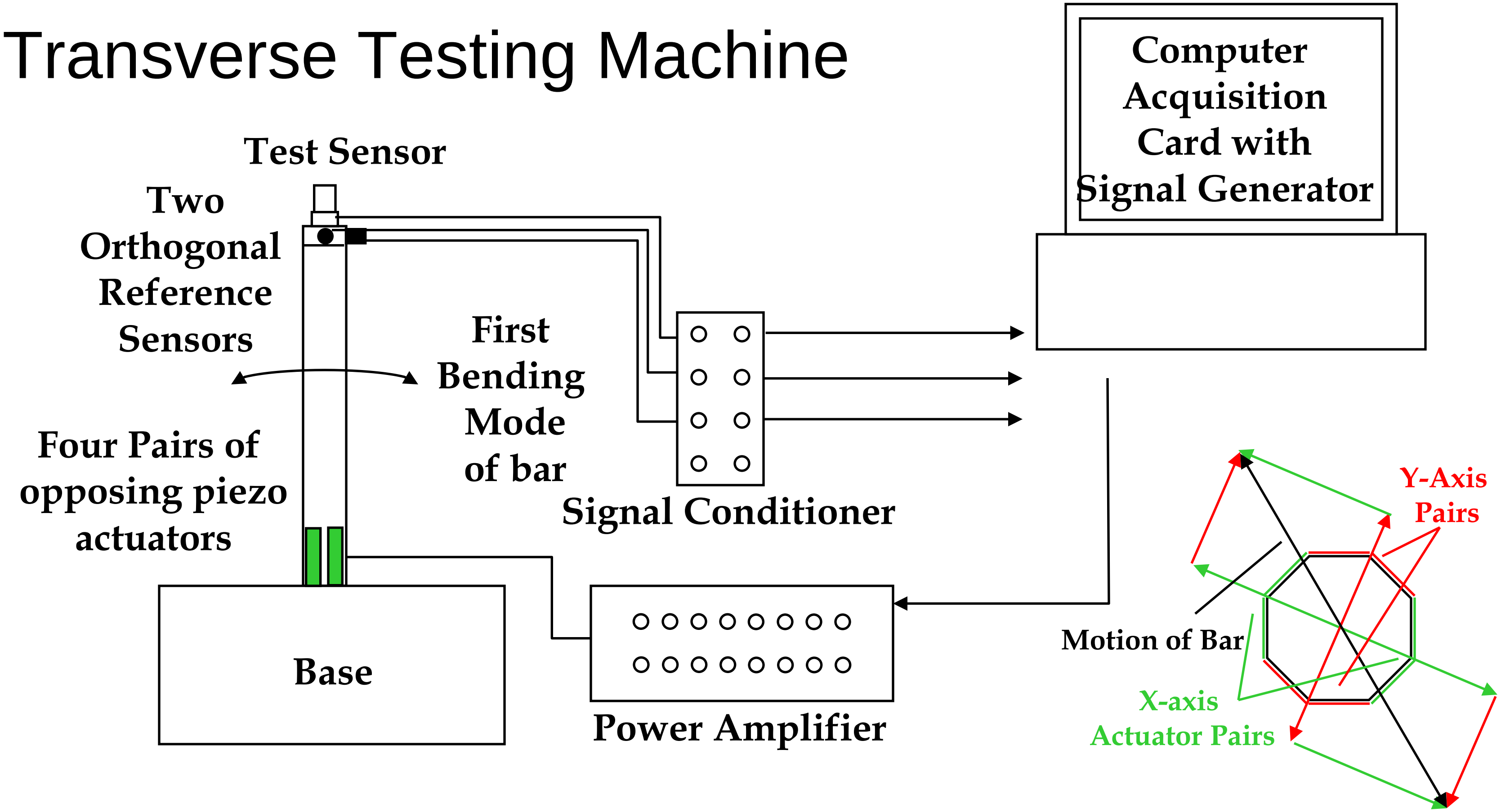


  - Gun Barrel Shock
    - 350B02 shock accelerometers monitor motion at the end of a gun barrel during firing



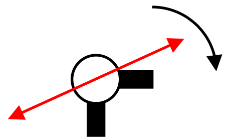
Accelerometer Calibration

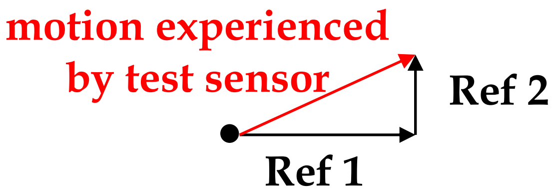
- Transverse Testing Machine



Accelerometer Calibration

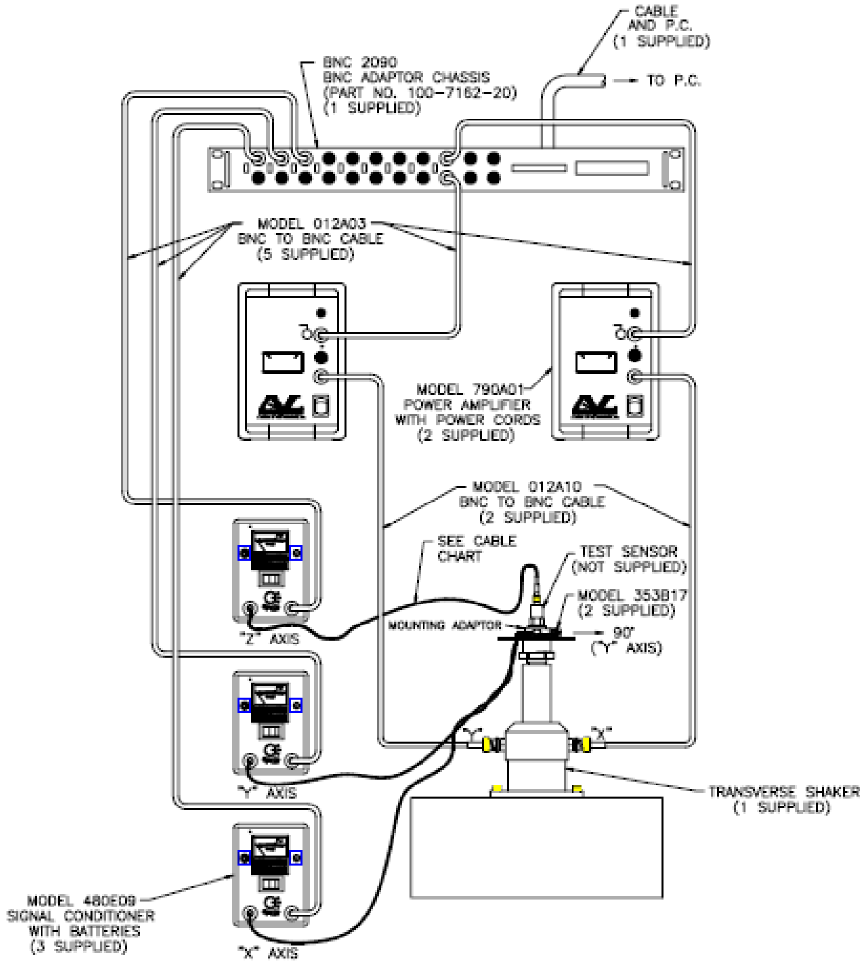
- Transverse Testing Machine
  - As motion of bar is rotated by actuators, reference sensors determine magnitude and direction of vibration

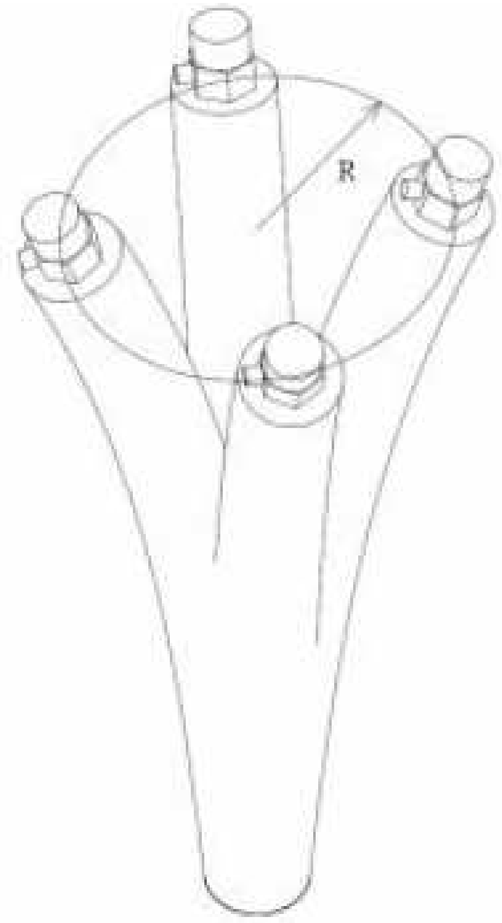




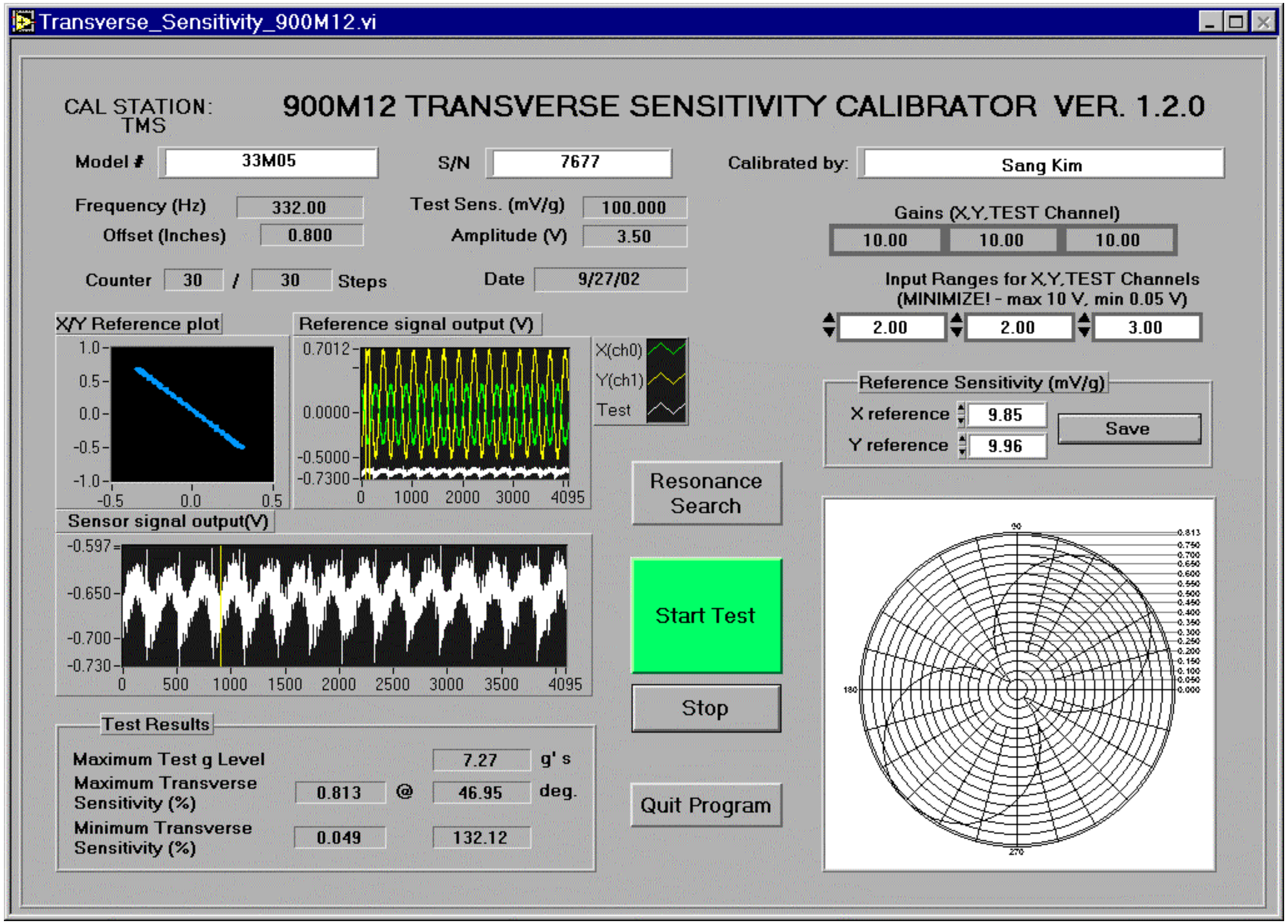
  - Then, the output of the test sensor (due to this off axis motion) divided by the vibration level provides the sensitivity in mV/g

Accelerometer Calibration





Accelerometer Calibration



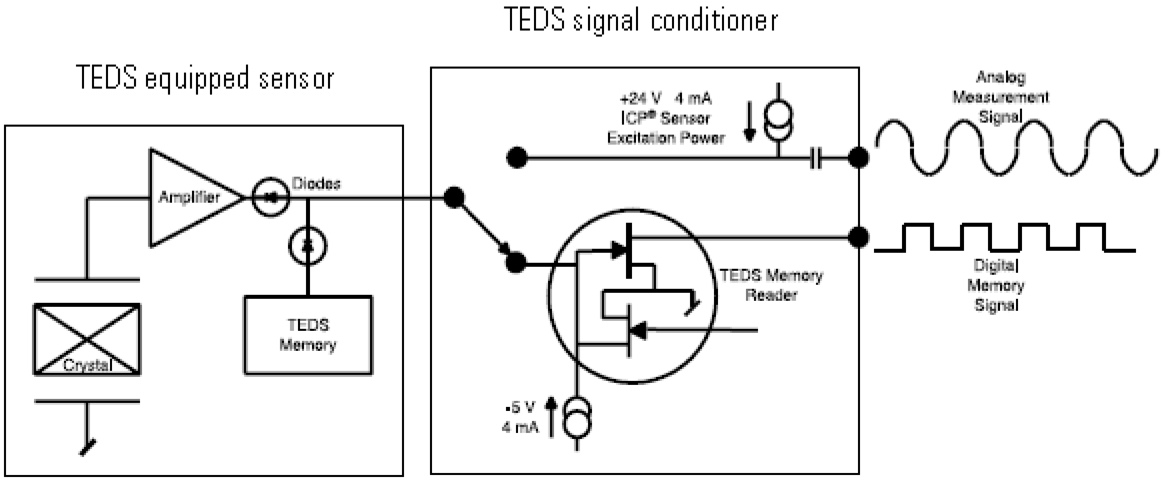
Futures

Futures

- TEDS
- MEMS with Higher Resolution
- Digital Sensors
- Wireless

TEDS

- "Smart" Sensor
- Transducer with Electronic Data Sheet
- IEEE 1451.4
- non-volatile memory within sensor

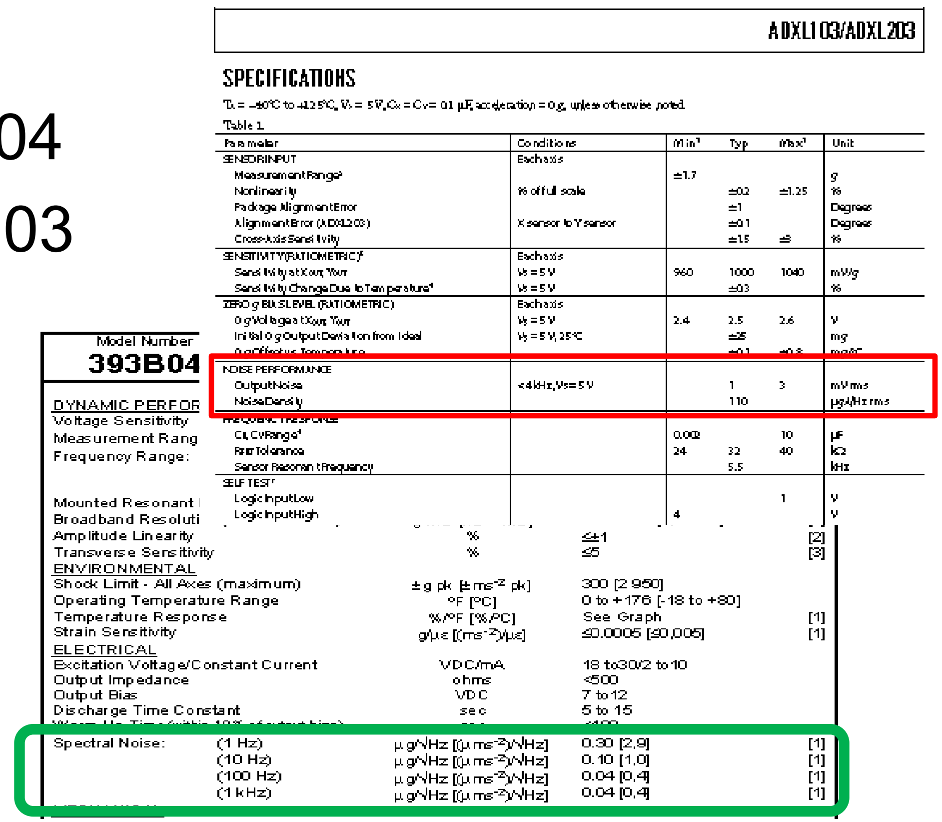


TEDS

Function	Property	Description	Access	Bits	Data Type (and Range)	Units
ID	TEMPLATE	Template ID	–	8	Integer (value = 25)	–
Sensor Characteristics	%Sens@Ref	Sensitivity @ reference condition	CAL	16	ConRelRes (5E-7 to 172, ±0.015%)	$V/(m/s^2)$
	%TF_HP_S	High pass cut-off frequency (F hp)	CAL	12	ConRelRes (0.01 to 2k, ±0.15%)	Hz
	%PhaseCorrection	Phase Correction @ reference	CAL	6	ConRes (-3.2 to 3.1, step 0.1)	°
	%Reffreq	Reference frequency	CAL	8	ConRelRes (8 to 13k, ±1.5%)	Hz
	%RefTemp	Reference temperature (T ref)	CAL	5	ConRes (15 to 30, step 0,5)	°C
	%Direction	Sensitivity direction (x, y, z)	CAL	2	Enumeration: x | y | z	–
	%Sign	Polarity (sign)	CAL	1	Enumeration: positive | negative	–
	%TF_SP (optional)	Low pass cut-off frequency	CAL	12	ConRelRes (20 to 4.2E+6, ±0.15%)	Hz
	%TF_KPr (optional)	Resonance frequency (f res)	CAL	9	ConRelRes (100 to 2.5E+6, ±1%)	Hz
	%TF_KPq (optional)	Quality factor at f res	CAL	7	ConRelRes (0.3 to 490, ±3%)	–
	%TF_SL (optional)	Amplitude slope (a)	CAL	7	ConRes (-6.3 to 6.4, step 0.1)	%/decade
	%TempCoef (optional)	Temperature Coefficient (b)	CAL	9	ConRes (-0.5 to 0.5, step 0.002)	%/°C
Calibration Information	%CalDate	Calibration date	CAL	16	DATE	–
	%CalInitials	Calibration initials	CAL	15	CHR5	–
	%CalPeriod	Calibration period	CAL	12	UNINT	days
User Information	%MeasID	Measurement location ID	USR	11	UNINT	–

MEMS with Higher Resolution

- Traditional Accelerometer v.s. MEMS
- Noise
  - 0.04μg/√Hz, PCB 393B04
  - 110μg/√Hz, ADXL103/203
- Quantity???



Digital Sensors

- IEEE 1451.3
- Intellibus

Wireless

- Standard
  - IEEE 802.11 / Wi-Fi
  - IEEE 802.15.4 / ZigBee
  - IEEE 802.15.1 / Bluetooth
- Bandwidth
- Power
- Distance

謝謝 敬請指教

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