Lecture #2: Principles of Sensors

Mario Bergés

Professor

**Some slides obtained from 12-740 for Fall 2006*

12-778: Sensors, Circuits and Data Interpretation/Mgmt. for CEE

Civil & Environmental ENGINEERING

Carnegie Mellon

But first…

- Office Hours → Does this work?
  - Thursdays 10-11am
- Readings posted → Starting now, please read before class
- Equipment distribution -> Let’s do it.

Recap

- Sensors, Actuators, Transducers?
- What physical phenomena can we sense to estimate indoor occupancy?

Additional Info

- http://inferlab.github.io/12740/
- Past projects:
  - http://wiki.marioberges.com/courses/12-740/
    - User: inspiration
    - Password: expiration

Agenda for today

Chapters 1 and 2 from Fraden

PRINCIPLES OF SENSORS

Instruments

- Instruments are devices we create to measure/estimate physical quantities of interest.
  - Transducers are but a component inside instruments.
- What you typically work with in practice are not just sensors, but instruments.

Instruments: what to know

- Transform physical stimulus to electrical signal
  - Designed for this purpose by combining different components
  - Tested
  - Response and drift are considered
  - Accuracy and errors are considered
  - They are (re-)calibrated
  - Could be analog or digital
  - Moving towards micro-instruments or virtual

LET’S DRAW SOME DIAGRAMS OF INSTRUMENTS.

Definition of Sensor

Definition of Sensor:

- A device that receives and responds to a signal or stimulus.
- An electronic device that respond to some kind of an input physical property and convert it into an electrical signal which is compatible with electronic circuit.
- Sensor outputs can be in a form of voltage, current, or charge.

Sensor vs. Transducer:

- Transducer converts one type of energy into another form of energy. For example: a speaker that converts electrical signal into variable magnetic field, and into acoustic waves. Actuators are other examples.
- Sensor converts any type of energy into electrical signals.

Sensor Classifications

- Passive or Active
- Absolute or Relative
- By their characteristics:
  - Specifications
  - Materials
  - Detection Means
  - Conversion Phenomena
  - Application Area
  - Stimulus

Sensor Examples

- Accelerometer
- Fiber optic sensor
- Thermocouple
- Strain gauge
- Current Transformer

alog output CMOS integrated-cir-
t operates over a –55°C to +130°
power supply operating range is
sfer function of LM20 is predomi-
t predictable parabolic curvature.
) when specified to a parabolic
t an ambient temperature of +30°
ncreases linearly and reaches a
emperature range extremes. The
ed by the power supply voltage. At
2.7 V to 5.5 V the temperature
and –55°C. Decreasing the pow-
changes the negative extreme to
mains at +130°C.

ent is less than 10 µA. Therefore,
2°C in still air. Shutdown capability
cause its inherent low power con-
wered directly from the output of
ot necessitate shutdown at all.

- HVAC
- Disk Drives
- Appliances

Features

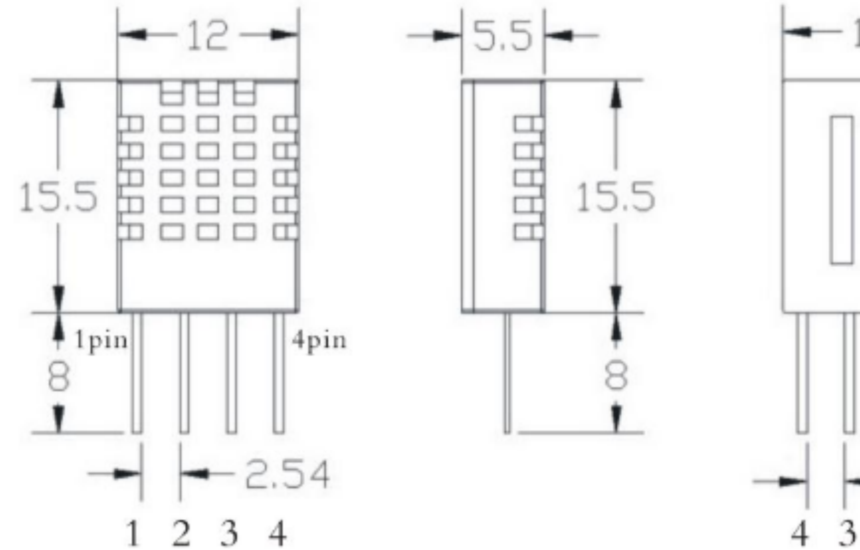
- Rated for full –55°C to +130°C range
- Available in an SC70 and micro SMD package
- Predictable curvature error
- Suitable for remote applications

Key Specifications

■ Accuracy at +30°C	±1.5 to ±4 °C (max)
■ Accuracy at +130°C & –55°C	±2.5 to ±5 °C (max)
■ Power Supply Voltage Range	+2.4V to +5.5V
■ Current Drain	10 µA (max)
■ Nonlinearity	±0.4 % (typ)
■ Output Impedance	160 Ω (max)
■ Load Regulation	
0 µA < I_L < +16 µA	–2.5 mV (max)

Your Temperature Sensor

Temperature and Humidity Module DHT11



5. Parameters

Relative Humidity

Resolution：16Bit

Repeatability：±1%RH

Accuracy：25℃ ±5%RH

Interchangeability：Fully interchangeable

Response time：1/e (63%)25℃ 6s

1m/s Air 6s

Typical Accelerometer Data Sheet

Model Number 320C02	ACCELEROMETER, ICP®

Performance	ENGLISH	SI	
Sensitivity (±10 %)	20 mV/g	2.04 mV/(m/s²)	
Measurement Range	±250 g pk	±2452 m/s² pk	
Frequency Range (±5 %)	1 to 6000 Hz	1 to 6000 Hz	
Frequency Range (±10 %)	0.7 to 9000 Hz	0.7 to 9000 Hz	
Frequency Range (±3 dB)	0.35 to 18000 Hz	0.35 to 18000 Hz	
Resonant Frequency	≥35 kHz	≥35 kHz	
Broadband Resolution (1 to 10000 Hz)	0.002 g rms	0.02 m/s² rms	[1]
Non-Linearity	≤1 %	≤1 %	[2]
Transverse Sensitivity	≤5 %	≤5 %	[3]
Environmental			
Overload Limit (Shock)	±7000 g pk	±68670 m/s² pk	
Temperature Range (Operating)	-100 to +325 °F	-73 to +163 °C	
Temperature Response	See Graph	See Graph	[1]
Base Strain Sensitivity	≤0.0005 g/με	≤0.005 (m/s²)/με	[1]
Electrical			
Excitation Voltage	18 to 30 VDC	18 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤100 ohm	≤100 ohm	
Output Bias Voltage	8 to 12 VDC	8 to 12 VDC	
Discharge Time Constant	0.5 to 2.0 sec	0.5 to 2.0 sec	
Spectral Noise (10 Hz)	150 μg/√Hz	1472 (μm/s²)/√Hz	[1]
Spectral Noise (100 Hz)	30 μg/√Hz	294 (μm/s²)/√Hz	[1]
Spectral Noise (1 kHz)	10 μg/√Hz	98 (μm/s²)/√Hz	[1]
Physical			
Sensing Element	Quartz	Quartz	
Sensing Geometry	Shear	Shear	
Housing Material	Titanium	Titanium	
Sealing	Welded Hermetic	(Welded Hermetic)	
Weight	0.38 oz	10.5 gm	[1]
Electrical Connector	10-32 Coaxial Jack	10-32 Coaxial Jack	
Electrical Connection Position	Top	Top	

Optional Versions (Optional
for standard model except wh

J - Ground Isolated
Frequency Range (5 %)
Frequency Range (10 %
Frequency Range (3 dB)
Resonant Frequency
Electrical Isolation (Base

W - Water Resistant Cable
Electrical Connector

Electrical Connection Posi

Notes
[1] Typical.
[2] Zero-based, least-s
[3] Transverse sensitiv
[4] See PCB Declaratio

Supplied Accessories
080A109 Petro Wax (1)
081B05 Mounting Stud (10-
ACS-1 NIST traceable frequ
M081B05 Mounting Stud 10

Accelerometer Applications

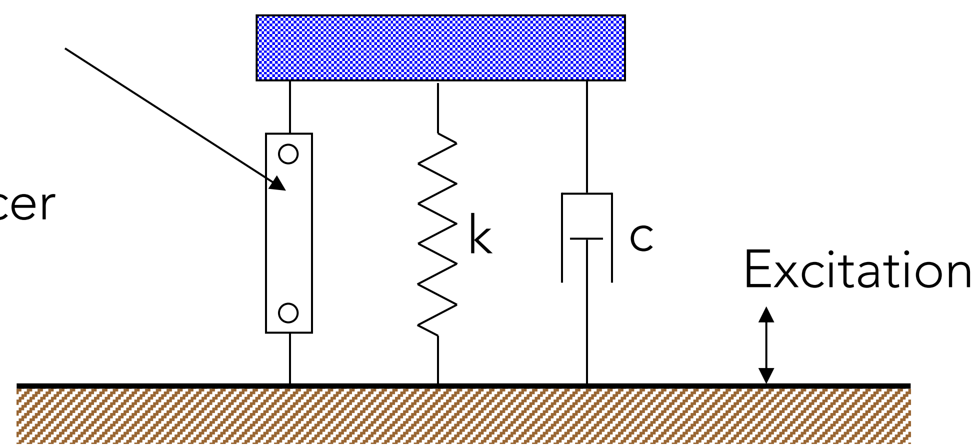
- Air Bag
- Navigation System
- Estimation of velocity and displacement
- Control systems
- And more…

Accelerometer Basics

- Definition: Accelerometers are electromechanical transducers used for measuring absolute acceleration.
- Purpose: Proper selection of accelerometers requires a fundamental understanding of an accelerometers' basic principles of operation.
- Types: two basic types of accelerometers are
  - Seismic accelerometers (a.k.a.: accelerometers)
  - Servo accelerometers (a.k.a.: force-balanced, inertial accelerometers)

Displacement Transducer

- Piezoelectric transducer
- Piezoresistance transducer
- Capacitance transducer



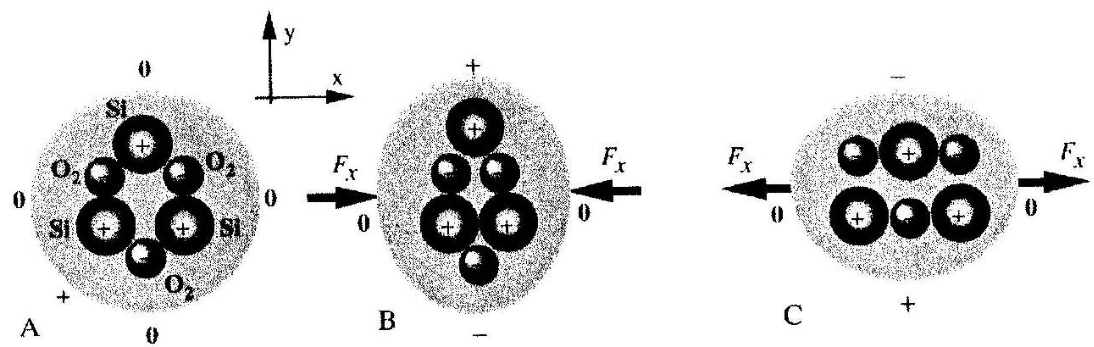
Piezoelectricity

- In piezoelectric materials such as quartz, the generated charge (Q) is proportional to the applied force (F):

$$Q = dF$$

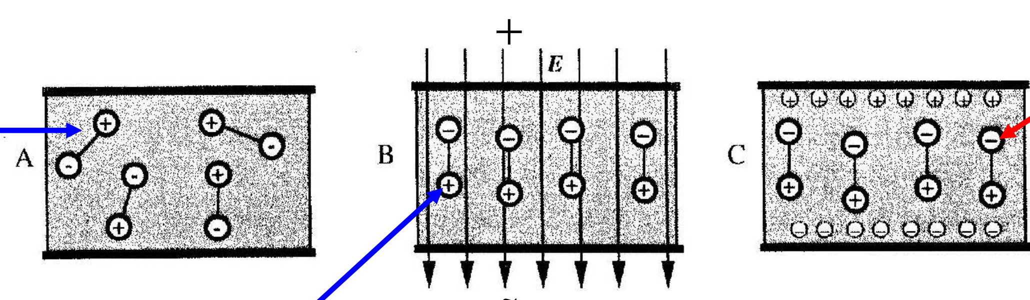
Piezoelectric coefficient

$$V = Q/C = \frac{dF}{C}$$



- Artificially polarized materials such as ceramics and some polymers can also be polarized to have the piezoelectric effect.

Crystalline materials have randomly oriented dipoles



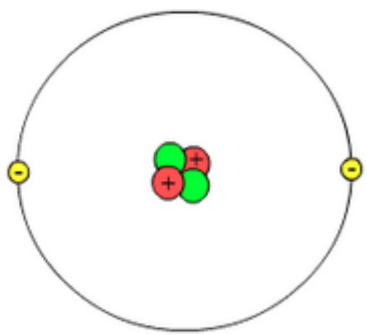
below the Curie temperature, their polarization remains permanent

High temperature produces stronger agitation of dipoles and when they are subjected to electric field, they are aligned along the field lines

Carnegie Mellon

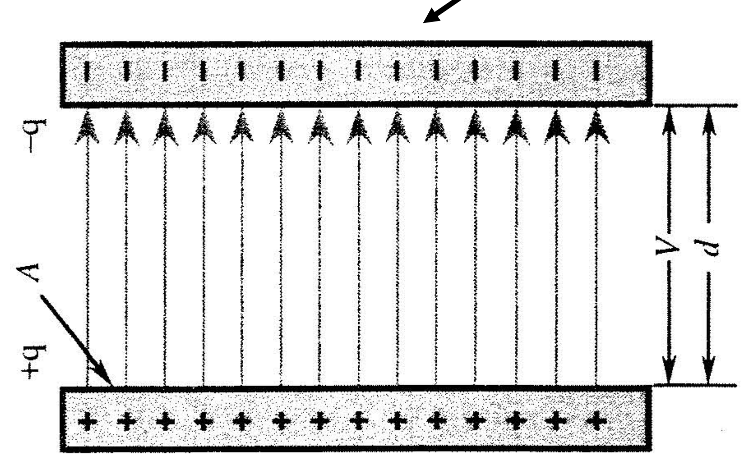
Capacitance

- C (i.e. Q/V) is a measure of the amount of electric charge stored for a given electric potential.
- Q=CV where Q is charge in Coulombs, V is voltage in Volts, and C is capacitance in Farads.
- Electrons have a charge of e=1.602x10^{-19} Coulombs.



Helium atom (schematic)
Showing two protons (red), two neutrons (green) and two electrons (yellow).

Electrodes (conductive plates)



$$C = \varepsilon_0 \frac{A}{d}$$

Permitivity constant=8.8542x10^{-12} C^2/Nm^2

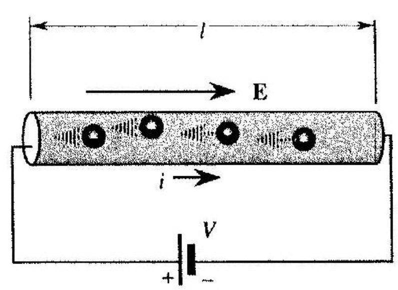
Resistance

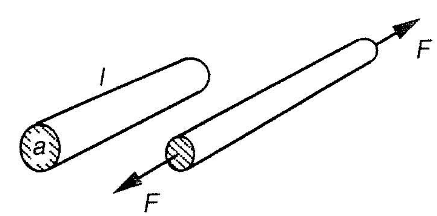
- Electrical resistance is a measure of the opposition that a material imposes to electric current passing through it. (R=V/i)
- The resistance of the material is related to the cross section (a), length of the conductor (l) and the resistivity (ρ) of the material
- Electrical resistance changes when the material is mechanically deformed.

$$R = \rho \frac{l}{a} = \rho \frac{l^2}{v} \Rightarrow dR = 2\rho \frac{l}{v} dl$$

- The resistance is also related to temperature.

$$R = R_0[1 + \alpha(T - T_0)]$$



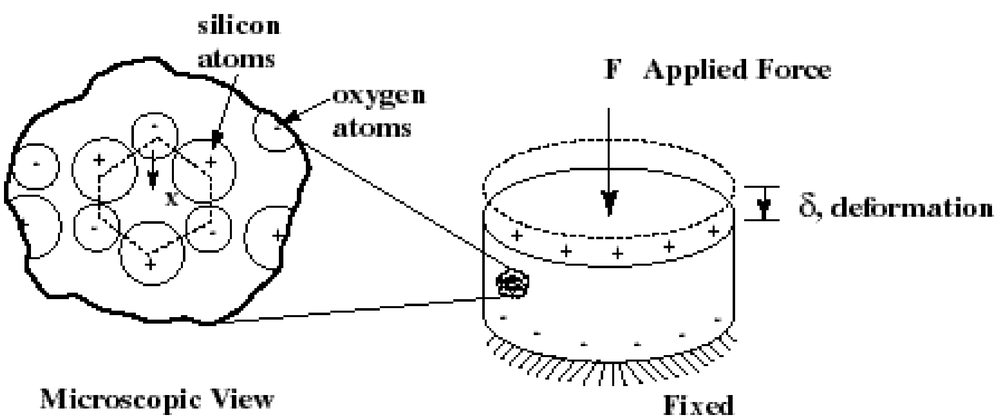


Different Displacement Transducers

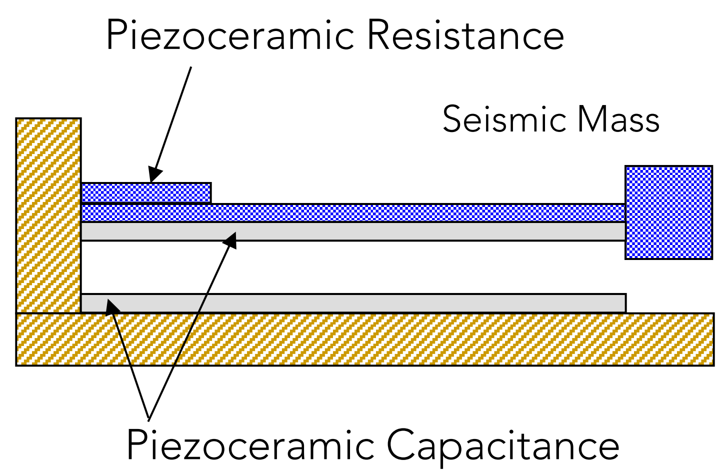
- Piezoelectric Transducer: Charge is proportional to applied force and deformation. Good for a high frequency range. Most commonly used for experimental modal analysis.

- Piezoresistance Transducer: A change in resistance is proportional to imposed deformation. This type of accelerometer has excellent low frequency response down to DC level.

- Capacitance Transducer: The motion of the mass changes the capacitance of the capacitor.

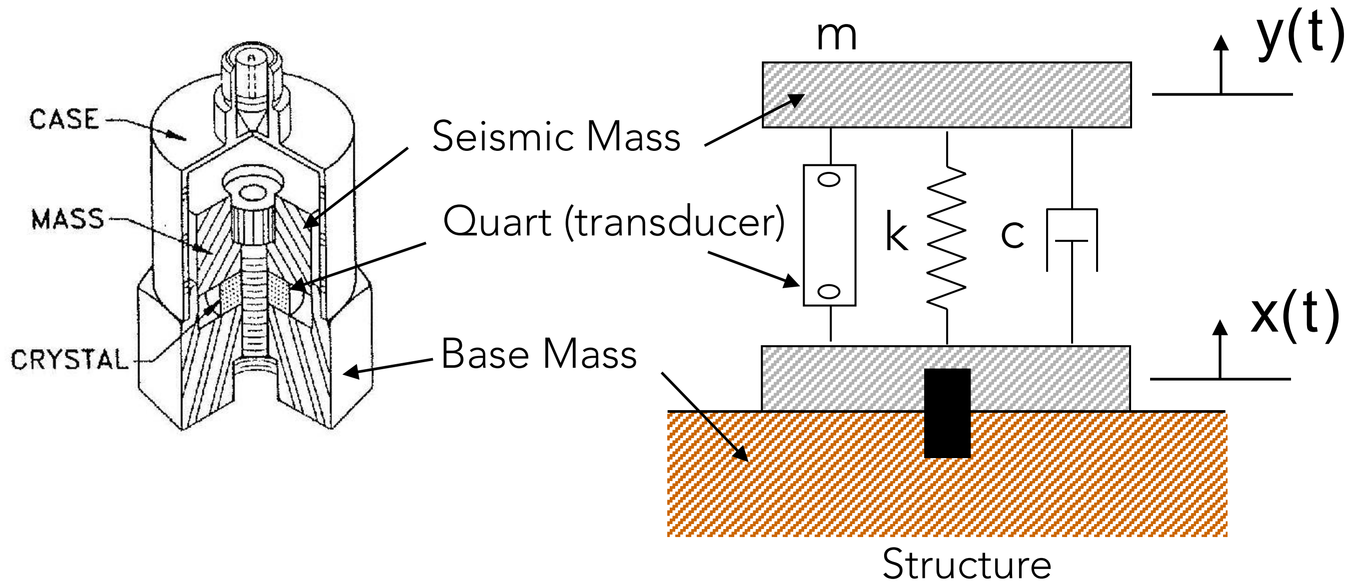


Piezoelectric Transducer



Piezoresistance or Capacitance Transducer

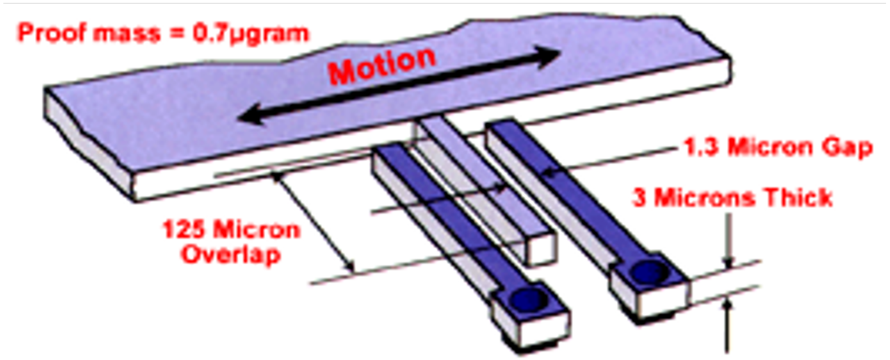
Piezoelectric Sensor



$$Define\ z(t) = y(t) - x(t)$$

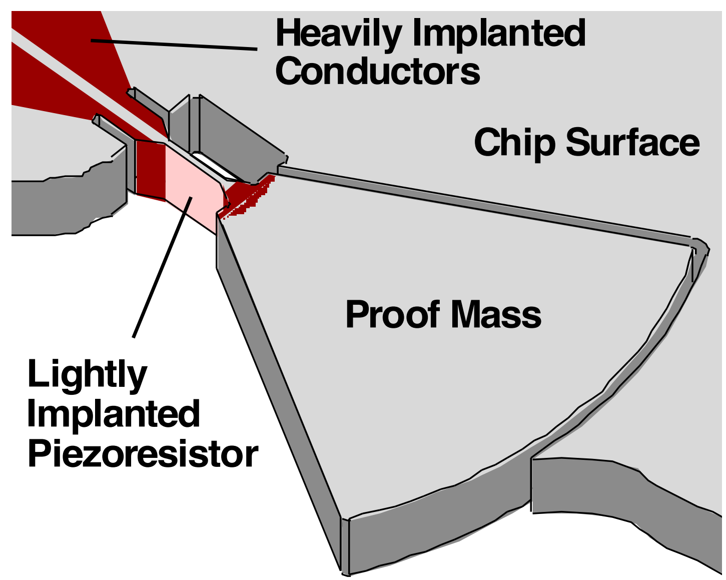
$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) = -m\ddot{x}(t)$$

Piezocapacitive and Piezoresisitve Accelerometers



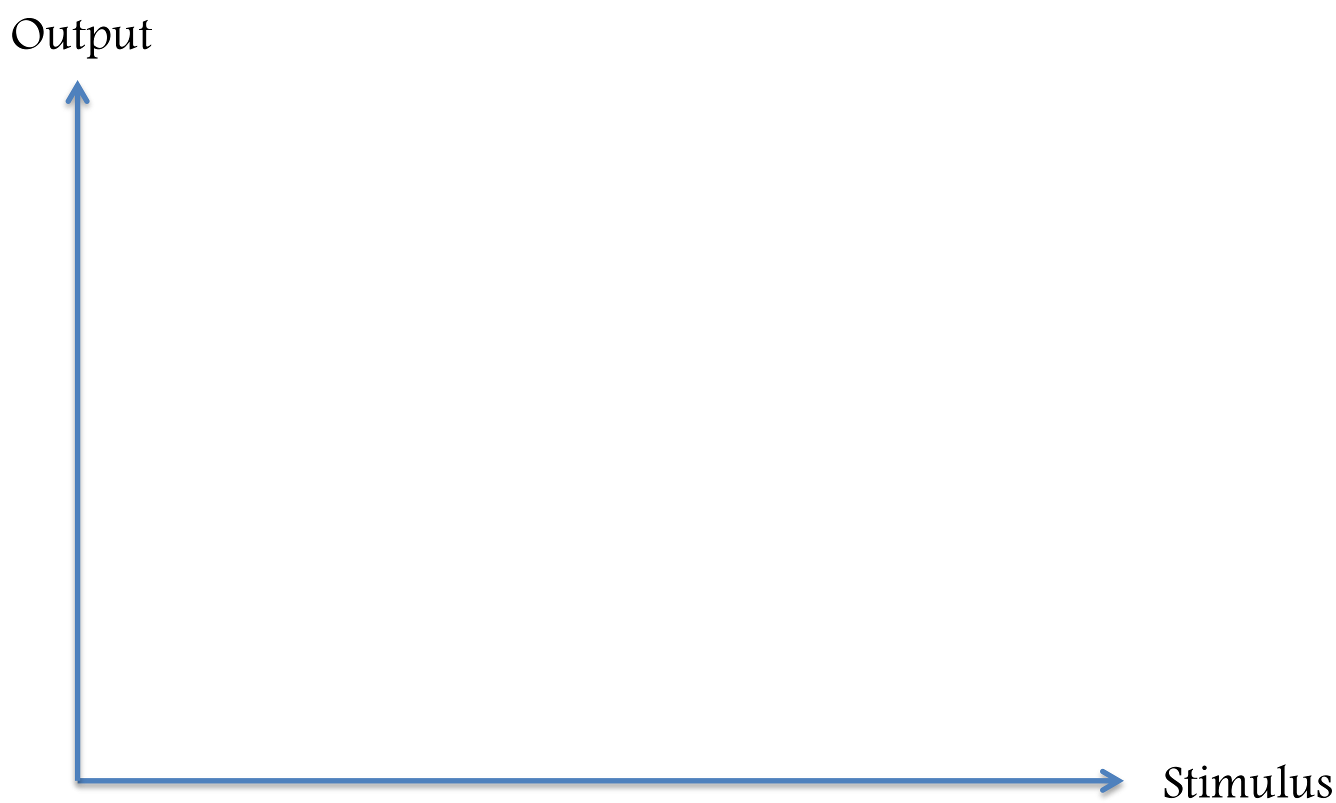
- Capacitive Accelerometer
  - Analog Devices ADXL210
  - Bosch SMB110
  - Crossbow CXL01LF1 (low "g" accelerometer)

- Piezoresistive Accelerometer
  - High Performance Planar Accelerometer
  - (Patridge et al. 2000)



TIME FOR A BREAK!

Sensor Characteristics



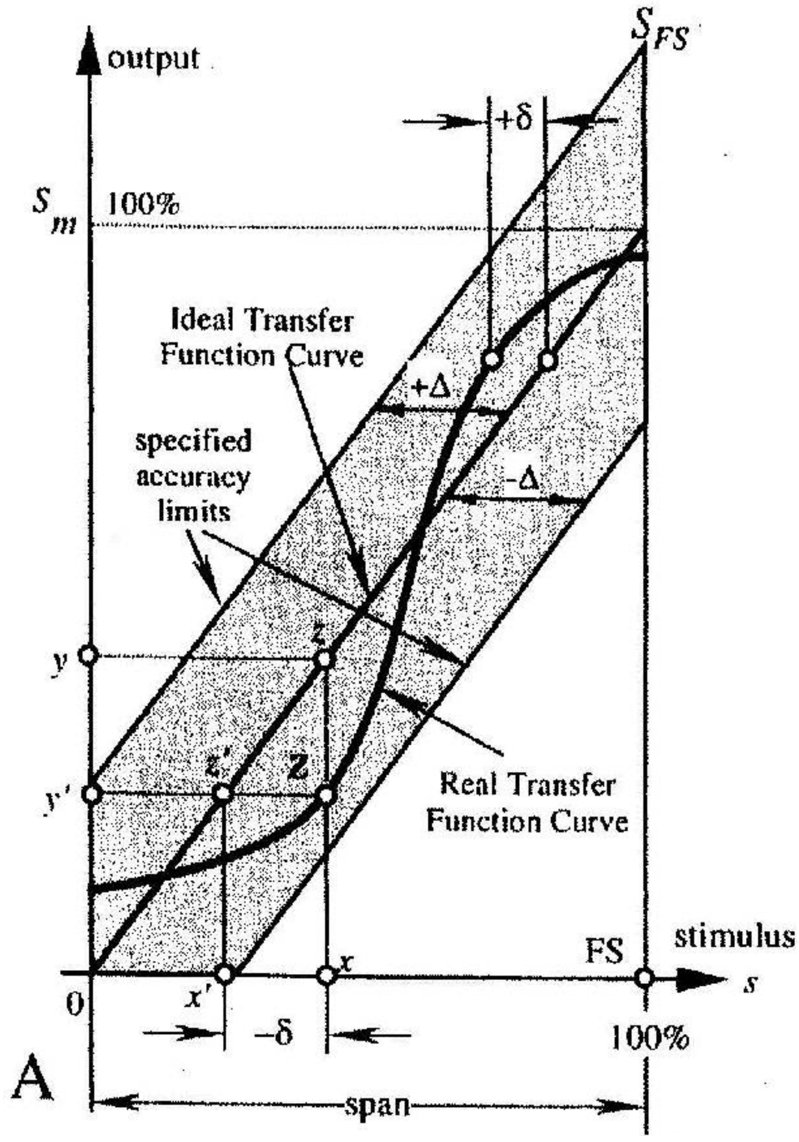
Sensor Characteristics

- Sensitivity

Sensor Characteristics I

- Here, a sensor is regarded as a black box where we are only concerned with the input and output relationship.
- Transfer function: An ideal or theoretical input-output relationship for each sensor. It can be a linear or nonlinear function.
- Input and output full scales: A dynamic range of a stimulus or output that is covered by a sensor
- Error: The difference between the ideal value and the measurement.
- Accuracy: The maximum error between the ideal value and the measured one. They are often represented in terms of (1) measured input value, (2) percent of input span, and (3) output voltage (current) value.

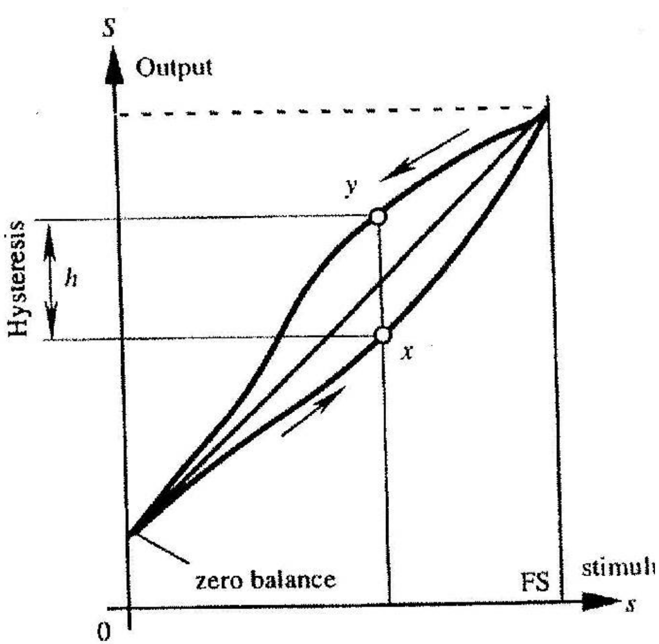
Sensor Characteristics II

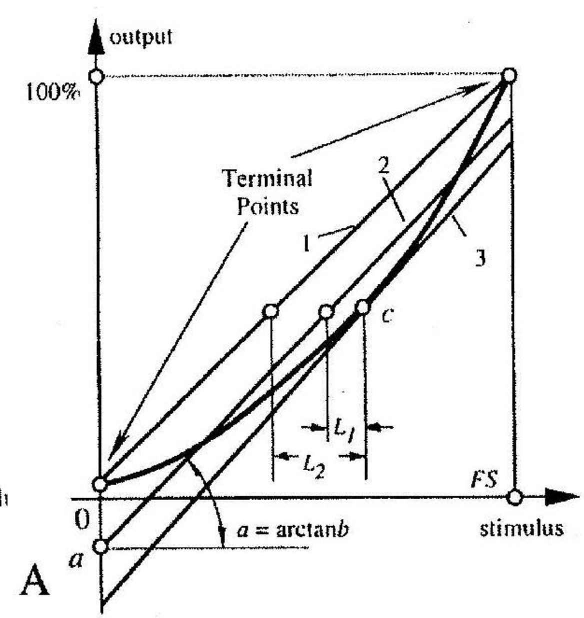


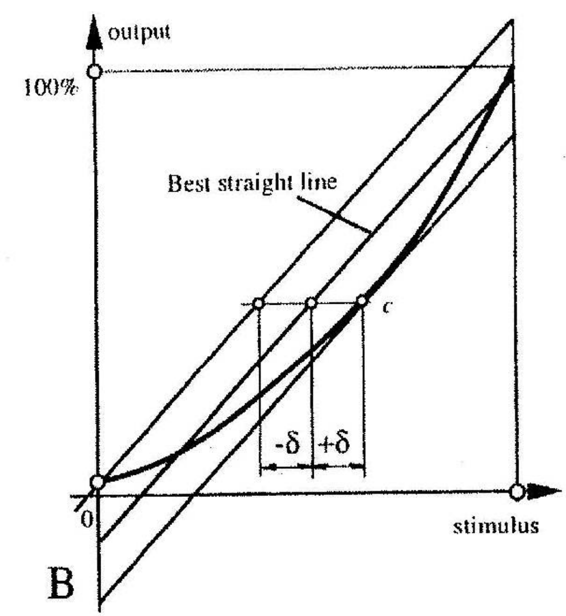
Carnegie Mellon

Sensor Characteristics III

- Hysteresis: A sensor displays a hysteresis behavior when the sensor response has a directionality. (Primary due to friction and structural change of the sensor materials).
- Nonlinearity: A nonlinearity is the maximum deviation of the real transfer function from the approximated straight line.

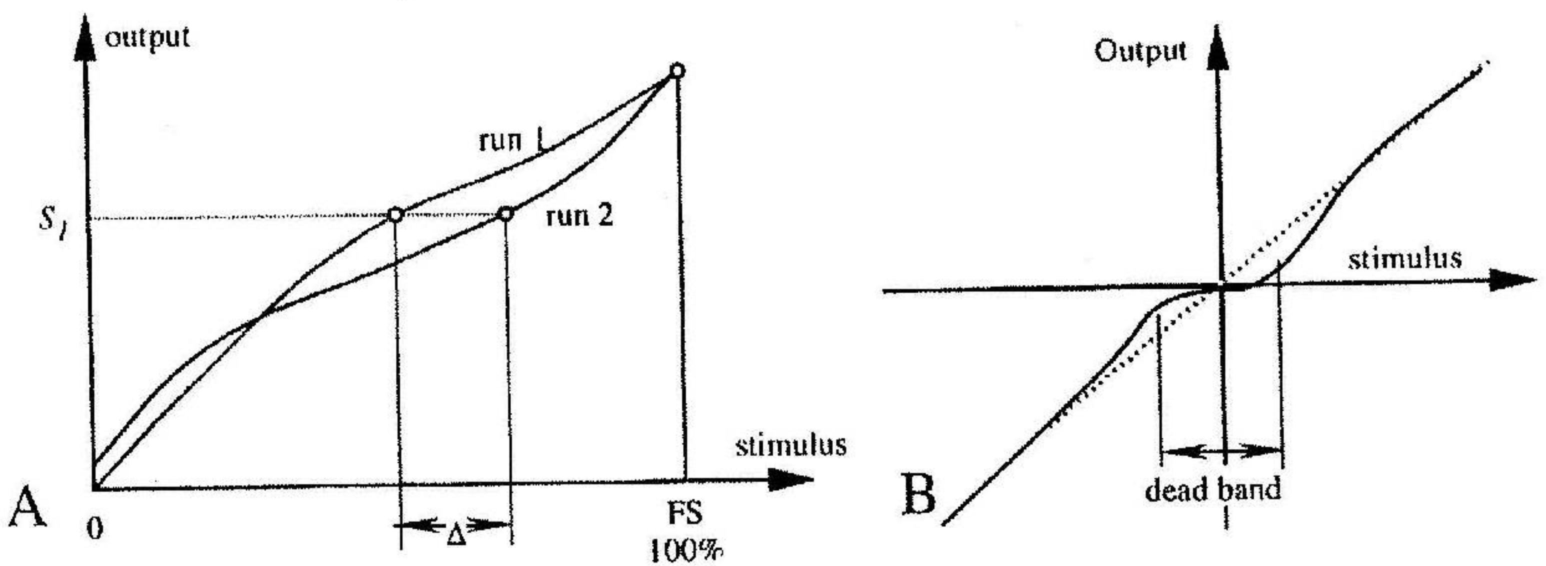






Sensor Characteristics IV

- Saturation: At a certain level of the input stimulus, the output signal become no longer responsive.
- Repeatability: The maximum difference between two consecutive readings.
- Resolution: the smallest variation of the stimulus that can be sensed at the output level. (There are several different definitions of resolutions, which will be described later on.)



Carnegie Mellon

What happens when the stimulus varies over time?

DYNAMIC CHARACTERISTICS

General Classification of Instruments based on Dynamic Characteristics

- Zero order instrument

$$a_0 y(t) = b_0 x(t)$$

- First order instrument

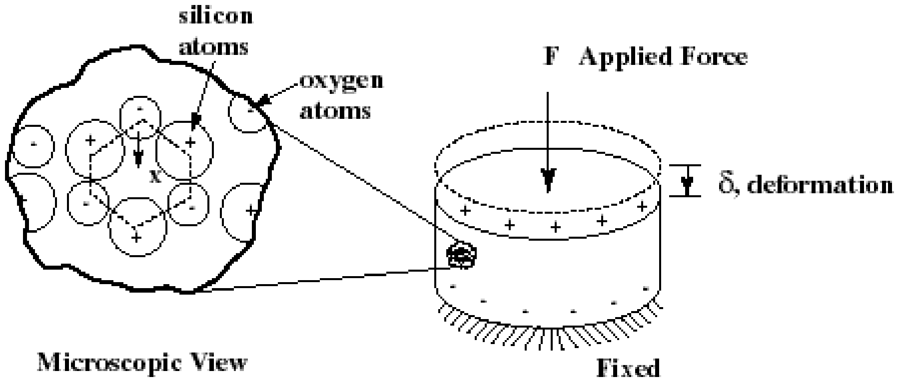
$$a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t)$$

- Second order instrument

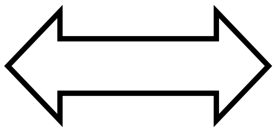
$$a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t)$$

Dynamic Characteristics of Sensor

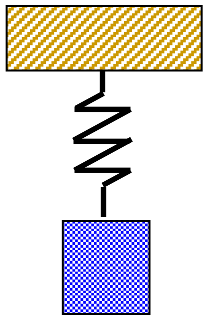
- Dynamic Characteristics: When an input stimulus varies, a sensor response generally does not follow exactly. This is because both the sensor and the interface circuit have a dynamic characteristic.
- Many sensors can be often modeled as a single degree-of-freedom system.
- To understand the dynamic characteristics of a sensor, let's review structural dynamics briefly.



Piezoelectric Transducer



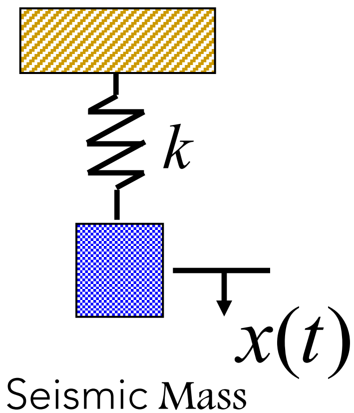
Equivalent



Seismic Mass

Review of Structural Dynamics I

(1) Free vibration of an undamped system



$$\text{Equation of motion:}\quad m\ddot{x}(t)+kx(t)=0$$

$$\text{Solution}: x(t)=A\cos\omega t+B\sin\omega t$$

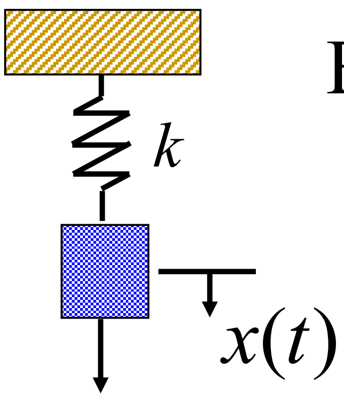
$$\text{where } \omega=\sqrt{\frac{k}{m}}: \text{resonance frequency}$$

(2) Free vibration of a damped system

Do it yourself (Refer to any structural dynamics or vibration books)

Review of Structural Dynamics II

(3) Response of an undamped system to harmonic loading



$$f(t) = F_o \sin \bar{\omega} t$$

$$\text{Equation of motion}: \; m\ddot{x}(t) + kx(t) = F_o \sin \bar{\omega} t$$

$$\text{Solution}: x(t) = \frac{F_o}{k}\left[\frac{1}{1-(\bar{\omega}/\omega)^2}\right]\sin \bar{\omega} t$$

(4) Response of a damped system to harmonic loading

Do it yourself (Refer to any structural dynamics or vibration books)

Review of Structural Dynamics III

$$M\ddot{y} + C\dot{y} + Ky = f(t)$$

$$F_o \sin \overline{\omega} t$$

$$x(t) = A \sin(\overline{\omega} t + \theta)$$

$$\text{where } A = \frac{F_o}{k}\left[\frac{1}{\sqrt{(1-r^2)^2 + (2\xi r)^2}}\right] \quad \text{and} \quad \tan\theta = \frac{2\xi r}{1-r^2}$$

$$r = \frac{\overline{\omega}}{\omega} \quad \text{and} \quad \xi = \frac{c}{c_{cr}} = \frac{c}{2\sqrt{km}}$$

Back to Dynamic Characteristics of Sensor

- Frequency band of operation: describes the frequency range that a sensor operates. Frequency limits are described by lower and higher cut-off frequency.
- **Frequency response** describes how fast and how slowly a sensor can respond to a change in the input stimulus.
- Time constant: For you to investigate.
- Cut-off frequency: For you to investigate.
- Resonant frequency: For you to investigate.

Selection of Accelerometer for Your Application

- What is the frequency range of your application?
- What is the anticipated magnitude of acceleration?
- What is the operating temperature range?
- What level of resolution is required?
- What is the maximum tolerable size?
- Is there intense acoustic electromagnetic or electrostatic field present?
- What kind of power supply is available?
- What is an anticipated overshock?
- What kind of data acquisition system will be used with your accelerometer?
- Is it compatible with your data acquisition system?
- Is it cost effective?

Summary

- We used an accelerometer as an example to study the following
  - Physical principles of sensors
  - How they are operated, fabricated?
  - How to choose the best sensor for your applications?
- Review of structural dynamics
- You should be able to follow similar logical steps to find appropriate sensors for your applications.

The End

QUESTIONS?

@bergesmario

marioberges.com

INFERLab

Intelligent Infrastructure Research Laboratory

Carnegie Mellon