MECH 420
Sensors and Actuators

Presentation Part 7

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Part 7: Analog Sensors and Transducers, Part b (Force and Other Sensors)

- Effort Sensors
- Strain Gauges
- Tactile Sensors
- Gyroscopic Sensors
- Optical Sensors
- Ultrasound Sensors
- Thermo-fluid Sensors (Pressure, Flow, Humidity, Temperature)

Plan

***Note*: Only illustrative examples are elaborated. You should self-learn others through that knowledge.**

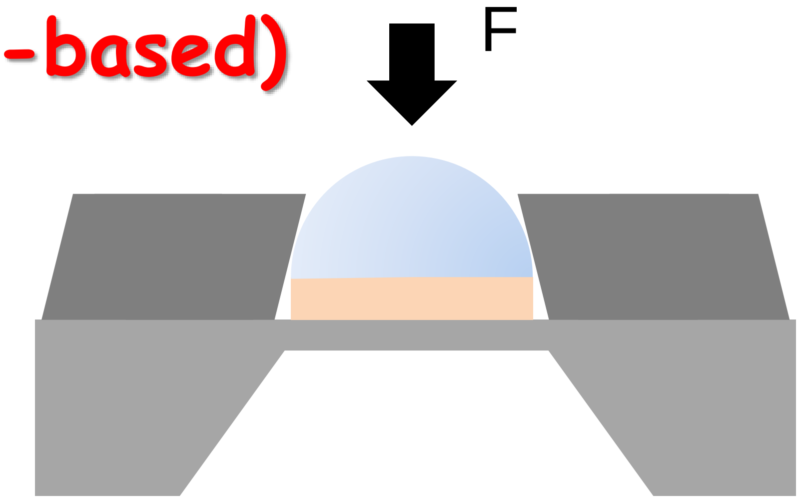
- **Strain Gauge Sensors**
- **Tactile Sensors**
- **Gyroscopic Sensors**
- **Other Sensors and Transducers (Optical, Lasers, Ultrasonic, Thermo-fluid, etc.)**

Effort Sensors

Effort Sensors

- Response of a mechanical system depends on excitation inputs (Effort: forces and torques)
- In many applications, process performance is specified in terms of forces and torques
  - Machine-tool operations - grinding, cutting, forging, extrusion, and rolling
  - Manipulator tasks - parts handling, assembly, engraving, and robotic fine manipulation
  - Actuation tasks – locomotion
- Accurate measurement of forces and torques are needed for:
  - Performance monitoring and evaluation
  - Failure detection and diagnosis
  - Dynamic testing
  - Control of dynamic systems

Piezoresistive Force Sensor
(Load Cell; Strain Gauge-based)



- Sensitivity: 12.2 mV/N
- Operating Force (O.F.): 0 to 14.7 N
- Supply Voltage: 5.0 Vdc typ.
- Null Offset: ± 15 mV
- Linearity: ± 0.7%
- Input Resistance: 5.0 kOhms
- Output Resistance: 5.0 kOhms
- Overforce: 44 N

force sensor FSS-SMD Series by Honeywell

Example: Data Sheet of a Load Cell (Saw Before)

Specific

Note: All specifications are a maximum, as a %

% of full load

Nominal Capacity	3kg ~ 250kg
Signal Output at Capacity	2mV/V ± 10%
Linearity Error	< 0.020% FSO
Non-Repeatability	< 0.010% FSO
Combined Error	< 0.025% FSO
Hysteresis	< 0.015% FSO
Creep/Zero Return (30 mins)	< 0.030% / 0.020% FSO
Zero Balanc	< 3.000% Capacity
Temperature Effect on Span/10°C	< 0.010% FSO
Temperature Effect on Zero/10°C	< 0.015% Capacity

Model PT1000

LOW COST SINGLE POINT LOAD CELL

A direct bolt replacement for most industry standard single point cells.

The PT1000 is a dual designed model providing for increased capacities.

The smaller cell is from 3kg to 35kg and at only 22mm high and 130mm long it's perfect for small low cost retail scales, medical and check weighing applications with platforms up to 350mm x 350mm.

The larger size cell measures from 50kg to 250kg capacity and is ideal for platform sizes 400mm x 500mm.

This is a very compact cell for its capacity range.

Direct bolt industry standard makes both large and small PT1000's ready replacements for other less well-protected models. The PT1000 comes as standard with SURESEAL sealing and is protected to IP66.

APPLICATIONS

- Low cost retail scales
- Low cost bench and person weighers
- Hopper scales & net weighing scales

FEATURES

- Marine grade anodised finish
- Protected with SURESEAL™
- Dual design, increased capacities
- Generous platform sizes 350mm x 350mm up to 35kg
- Generous platform sizes 400mm x 500mm 50kg up to 250kg

Specifications

Note: All specifications are a maximum, as a % (±) of full load, unless otherwise stated.

Nominal Capacity	3kg ~ 250kg	Input Impedance	425Ω ± 15Ω
Signal Output at Capacity	2mV/V ± 10%	Output Impedance	350Ω ± 3Ω
Linearity Error	< 0.020% FSO	Insulation Impedance	> 5000 MΩ at 100V DC
Non-Repeatability	< 0.010% FSO	Excitation Voltage (Recommended)	5 ~ 12V AC/DC
Combined Error	< 0.025% FSO	Excitation Voltage (Maximum)	15V AC/DC
Hysteresis	< 0.015% FSO	Eccentric Loading (effect/cm)	< 0.0085% FSO (3 ~ 35kg)
Creep/Zero Return (30 mins)	< 0.030% / 0.020% FSO		< 0.0074% FSO (50 ~ 250kg)
Zero Balanc	< 3.000% Capacity	Deflection at Rated Capacity	< 0.4mm
Temperature Effect on Span/10°C	< 0.010% FSO	Storage Temperature Range	-50 ~ 70°C
Temperature Effect on Zero/10°C	< 0.015% Capacity	Cable Type	4mm, Screened, PVC Sheath
Compensated Temperature Range	-10 ~ [illegible]		4 Core x 0.09mm² (28 AWG)
Operating Temperature Range	-30 ~ 70°C	Cable Length	0.5 Metre (3kg ~ 35kg)
Service Load	100% of Rated Capacity		1 Metre (50kg ~ 250kg)
Safe Load	150% of Rated Capacity	Material	Aluminium
Ultimate Load	300% of Rated Capacity	Finish	Marine Anodised

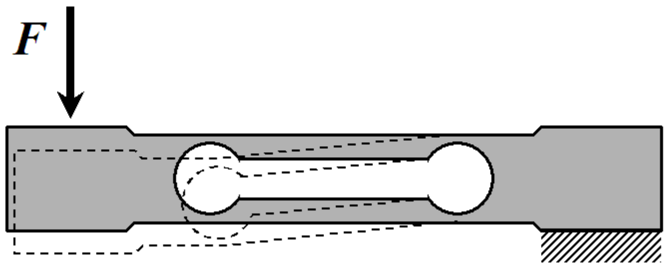
IP 66

Manufactured in New Zealand

PT Limited©

http://www.pt-global.com

FSO: Full scale operation or Full spectrum output or Full scale output or Full spectrum operation

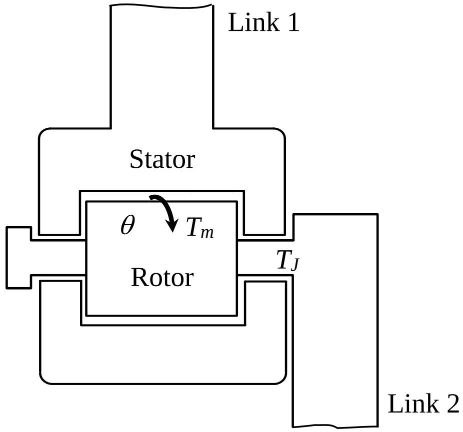


Torque Sensors

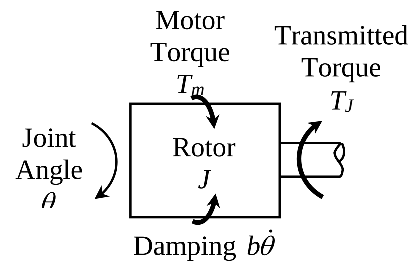
Common Sensing Methods:

- Measure strain in a sensing member between drive element and the driven load, using a strain gage bridge
- Measure displacement in a sensing member: (a) directly, using a displacement sensor; (b) indirectly, by measuring a variable that varies with displacement (e.g., magnetic inductance or capacitance)
- Measure reaction in support structure or housing (by measuring a force) and associated lever arm length
- In electric motors, measure field or armature current that produces motor torque; in hydraulic or pneumatic actuators, measure actuator pressure
- Measuring torque directly (e.g., piezoelectric sensors)
- Measure angular acceleration caused by unknown torque in known inertia element
- Servo method: Balance unknown torque with a feedback torque generated by an active device (e.g., servomotor) whose torque characteristics are known

Torque Sensing in Robotic Joints



(a)



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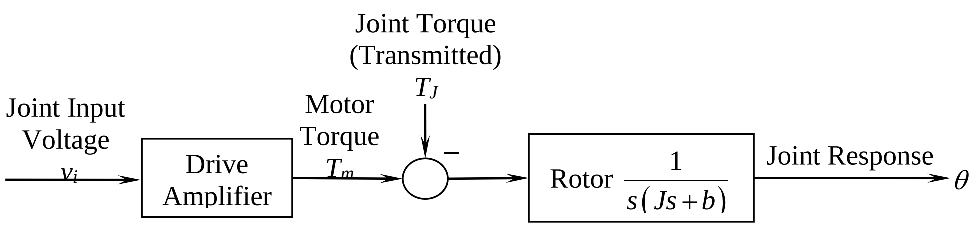

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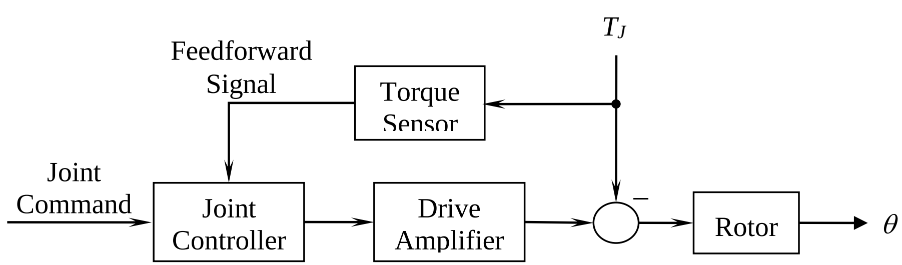


(d)

Example 1: Proper Location of Torque Sensor

Joint of a Direct-drive Robotic Arm: Motor **Rotor** is integral with driven link (no speed reducers); Motor **Stator** is integral with drive link

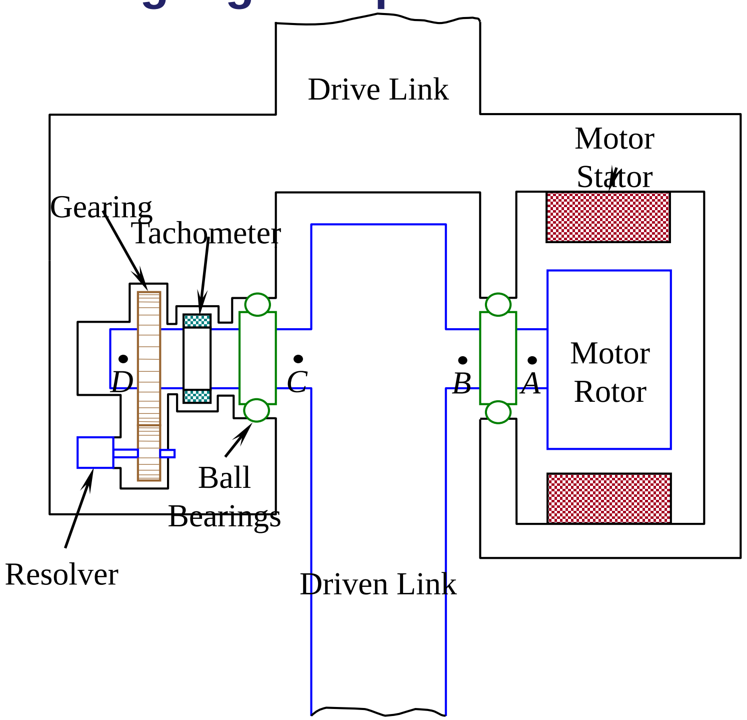
Tachometer: Measures joint speed; **Resolver:** Measures joint rotation

***Note*: Gearing is used to improve resolver resolution**

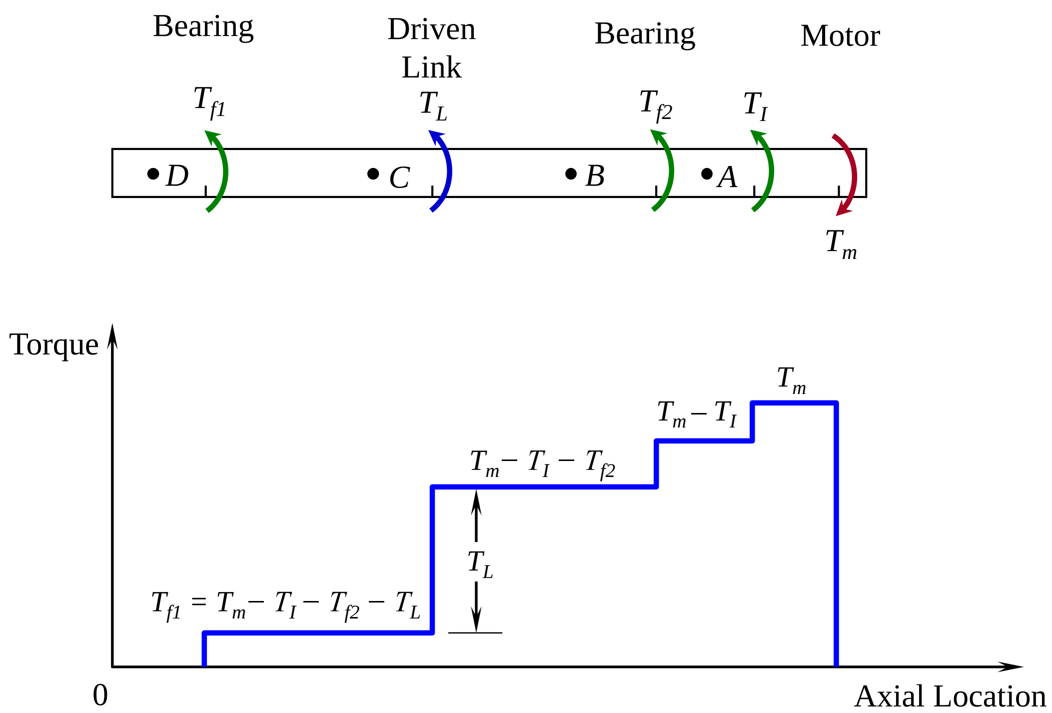
Neglect mechanical loading from sensors and gearing; including bearing friction

(a) Sketch torque distribution along the joint axis

(b) Suggest a proper location (or locations) to measure net torque transmitted to driven link using a strain-gauge torque sensor



Example 1: Solution



- **For accurate results two strain gages at locations, at B and C, should be installed**
- **A single sensor at B is also okay, since the bearing friction is small**
- **Motor torque T_m is approximately equal to the transmitted torque when inertia and friction are small**

Example 2: Sensing Bandwidth

Rigid load (inertia J_L) driven by motor with rigid rotor (inertia J_m)

Torque sensing member: Stiffness K_s between rotor and load

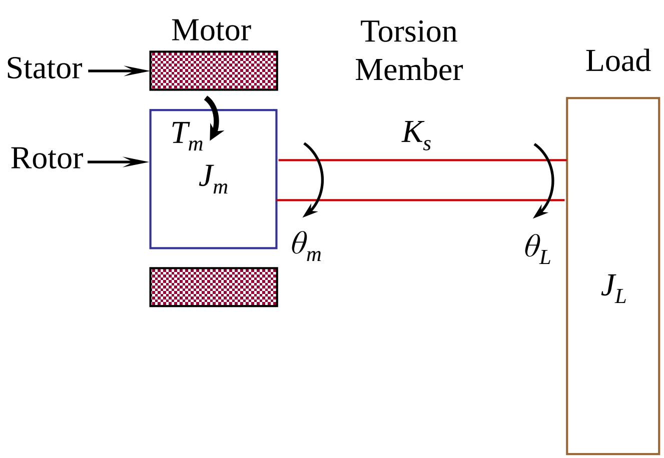
(a) Determine transfer function between motor torque T_m and twist angle of torsion member

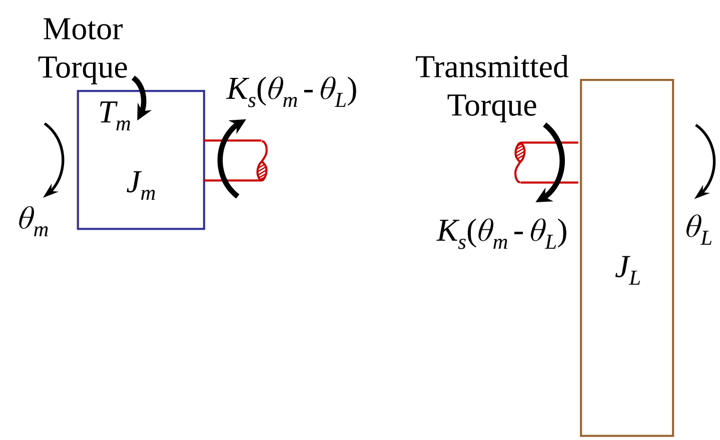
(b) What is the torsional natural frequency ω_n of the system?

Do (b) and (c) sound familiar?

(c) Why does torque sensor operating range (or, bandwidth) can be improved by increasing K_s, decreasing J_m, or decreasing J_L

(d) Mention advantages and disadvantages of introducing a gearbox at motor output.





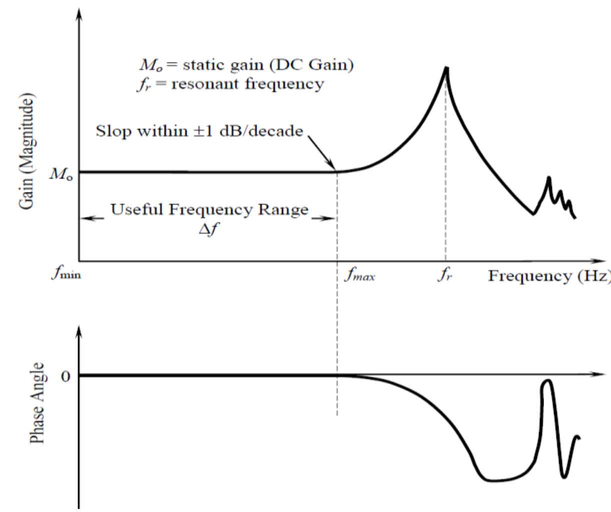
Example 2: Solution

Motor: $$T_m = J_m\ddot{\theta}_m + K_s(\theta_m - \theta_L)$$ **Load:** $$K_s(\theta_m - \theta_L) = J_L\ddot{\theta}_L$$

➔ $$\ddot{\theta}_m - \ddot{\theta}_L = -K_s\left(\frac{1}{J_m} + \frac{1}{J_L}\right)(\theta_m - \theta_L) + \frac{T_m}{J_m}$$

Let, Twist: $\theta = \theta_m - \theta_L$

➔ $$\ddot{\theta} + K_s\left(\frac{1}{J_m} + \frac{1}{J_L}\right)\theta = \frac{T_m}{J_m}$$; $$G(s) = \frac{\theta(s)}{T_m(s)}$$



➔ $$G(s) = \frac{1/J_m}{s^2 + K_s(1/J_m + 1/J_L)}$$ ➔ $$\omega_n = \sqrt{K_s\left(\frac{1}{J_m} + \frac{1}{J_L}\right)}$$

When gears are added, equivalent inertia increases and equivalent stiffness decreases ➔ Reduction in BW

BW can be increased by increasing K_s and by decreasing J_m and J_L

Example: Torque Sensor Selection

Three commercial torque sensors are shown below.

Which one do you prefer, and why?

(a)

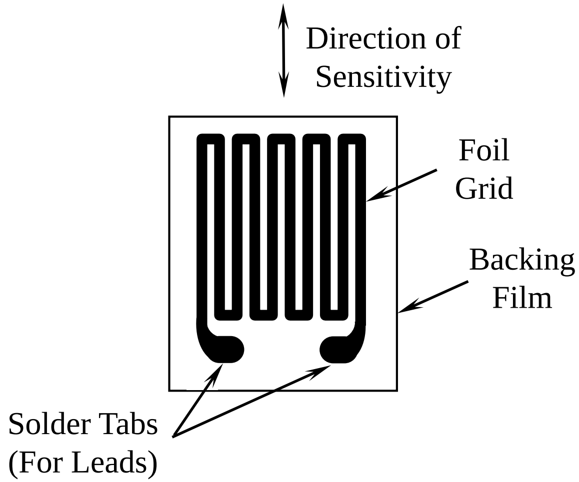
(b)

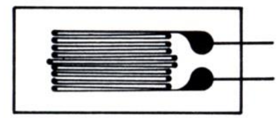
(c)

Strain Gauge (SG) Sensors

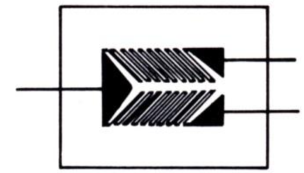
Strain Gauges

Metallic foil (copper-nickel alloy – constantan):

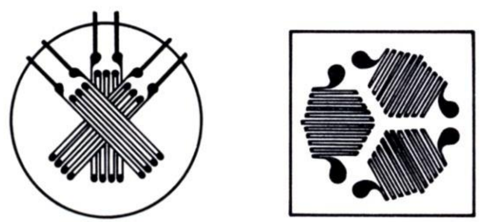




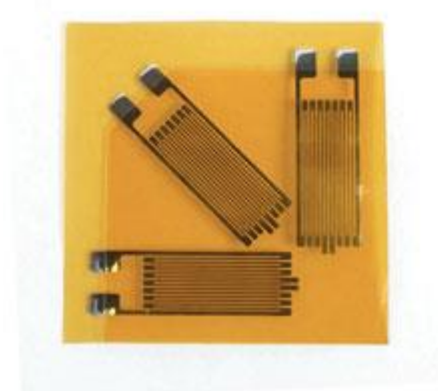
Single Element



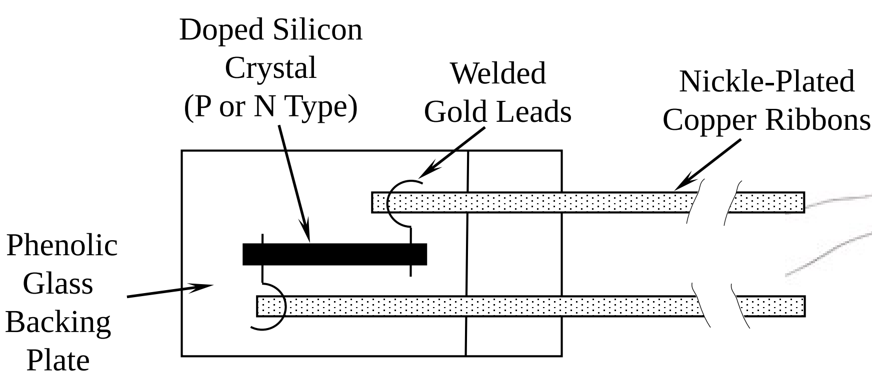
Two-Element Rosette

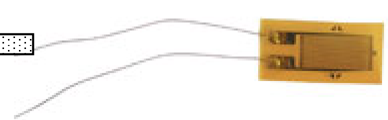


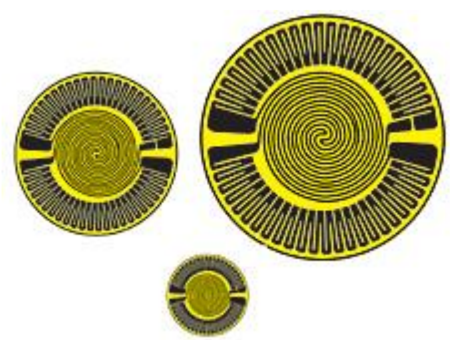
Three-Element Rosettes



Semiconductor (silicon with impurity):

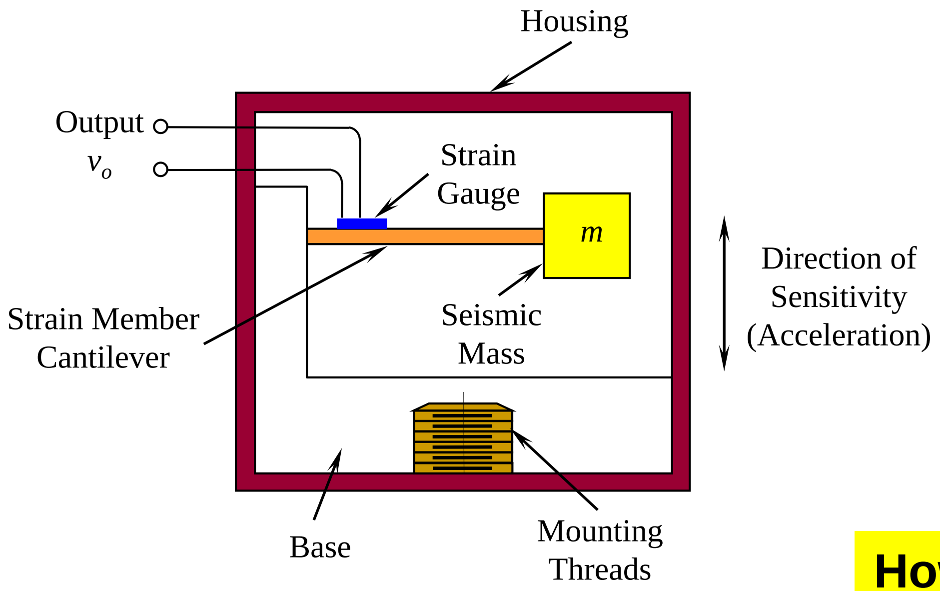






Application of Strain Gauges

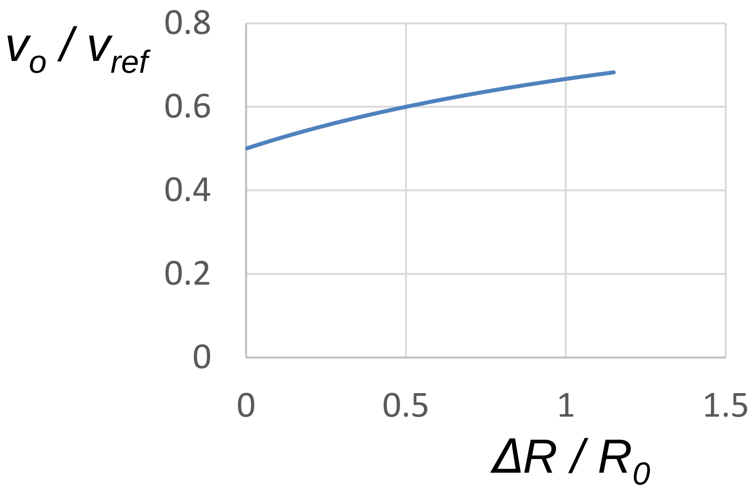
- **Change in resistance is measured (using an electrical circuit)**
- **Many variables can be measured (Displacement, acceleration, pressure, temperature, liquid level, strain, stress, force, torque, temperature, etc.)**
- **Some variables (e.g., stress, force, torque) can be determined by directly measuring strain**
- **Other variables can be measured by converting the measurand into stress (strain) using a front-end auxiliary device**

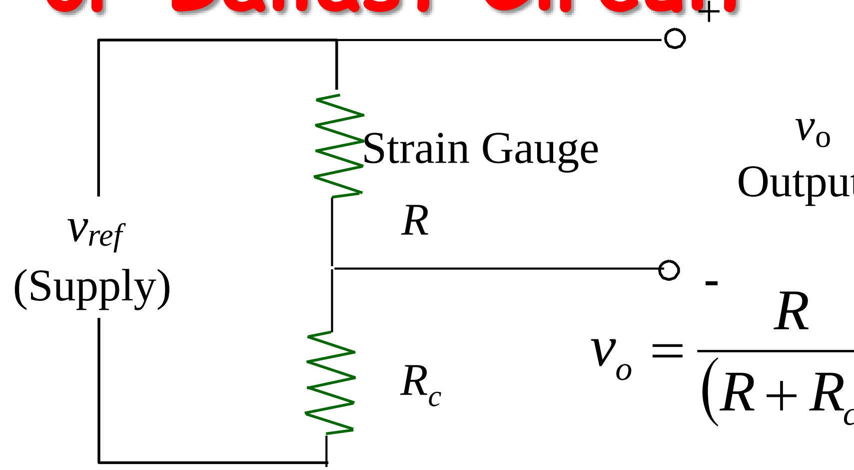


Example: Strain gauge accelerometer

How does this device work? Sensor stage? Transducer stage?

Potentiometer or Ballast Circuit





$$v_o = \frac{R}{(R + R_c)} v_{ref}$$

For this curve, assume $R_0 = R_{0c}$

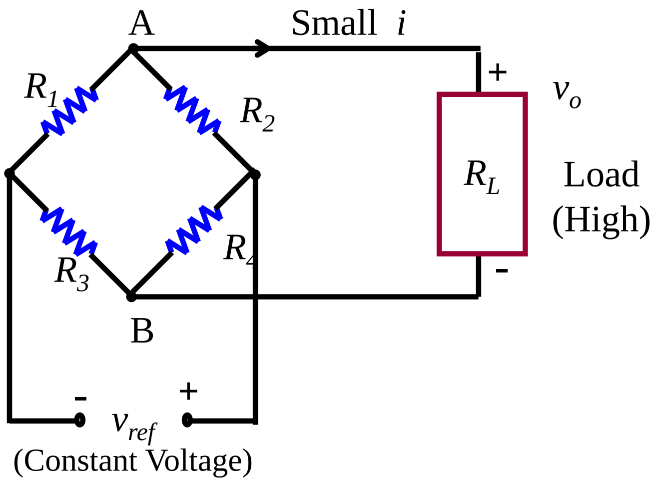
Initial values of R and R_c are R_0 and R_{0c}

- **Nonlinear?**
- **Ambient temperature changes will introduce error? Check this.**
- **Variations in supply voltage will affect the output**
- **Electrical loading effect will be significant**
- **Voltage change due to strain is a very small fraction output (problems?)**

Question: Show that effects of temperature is automatically compensated for.
Assume: R and R_c are made of the same material. Other assumptions?
See Example

Wheatstone Bridge Circuit

Much better than the pot! Why?



$$v_o = \frac{R_1 v_{ref}}{(R_1 + R_2)} - \frac{R_3 v_{ref}}{(R_3 + R_4)} = \frac{(R_1 R_4 - R_2 R_3)}{(R_1 + R_2)(R_3 + R_4)} v_{ref}$$

When the bridge is balanced (i.e., zero output):

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

True for any R_L

Signal Conditioning for a Wheatstone Bridge

Objective: Avoid loading

Solution: Use an instrumentation amplifier at the bridge output

Example: INA 118 (Burr-Brown / Texas Instruments; seen before)

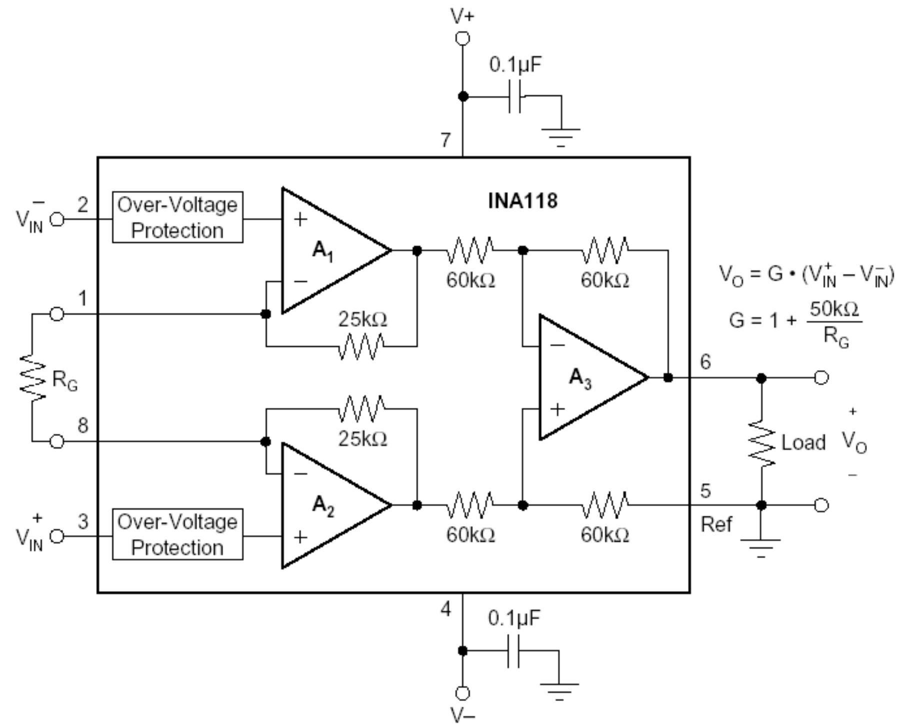
APPLICATIONS

- BRIDGE AMPLIFIER
- THERMOCOUPLE AMPLIFIER
- RTD SENSOR AMPLIFIER
- MEDICAL INSTRUMENTATION
- DATA ACQUISITION

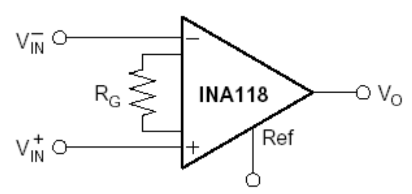
$R_{in} = 10^{10}\ \Omega$

DESIRED GAIN	R_G (Ω)	NEAREST 1% R_G (Ω)
1	NC	NC
2	50.00k	49.9k
5	12.50k	12.4k
10	5.556k	5.62k
20	2.632k	2.61k
50	1.02k	1.02k
100	505.1	511
200	251.3	249
500	100.2	100
1000	50.05	49.9
2000	25.01	24.9
5000	10.00	10
10000	5.001	4.99

NC: No Connection.



Also drawn in simplified form:



Bridge Measurement

(a) Null Balance Method:

1. When stain gage (active element) in the bridge deforms, the balance is upset.

2. Balance is restored by changing a variable resistor

➔ Amount of change → change in stain

Note: Note real time; Time consuming – servo balancing can be used

(b) Direct Measurement of Output Voltage:

1. Measure the output voltage resulting from the imbalance

2. Use calibration constant (Bridge sensitivity) to determine the strain

$$\frac{\delta v_o}{v_{\text{ref}}} = \frac{\left(R_2 \delta R_1 - R_1 \delta R_2\right)}{\left(R_1 + R_2\right)^2} - \frac{\left(R_4 \delta R_3 - R_3 \delta R_4\right)}{\left(R_3 + R_4\right)^2}$$

When is this relation valid?

Note: To compensate for temperature changes, temperature coefficients of adjacent pairs should be the same

Bridge Sensitivity

Bridge Output (with equal arm resistors): $$\frac{\delta v_o}{v_{ref}} = k\frac{\delta R}{4R}$$

Bridge Constant: $$k = \frac{\text{bridge output in the general case}}{\text{bridge output if only one strain gage is active}}$$

Change in SG resistance: $$\frac{\delta R}{R} = S_s \varepsilon$$

S_s = Sensitivity or gauge factor → $$\frac{\delta v_o}{v_{ref}} = \frac{1}{4}kS_s\varepsilon = C\varepsilon$$

Calibration Constant: $$C = \frac{k}{4}S_s$$

- **More than one resistor in the bridge can be active**
- **If all four resistors are active → best sensitivity**
- **R_1 and R_4 in tension and R_2 and R_3 in compression → largest sensitivity**

Why?

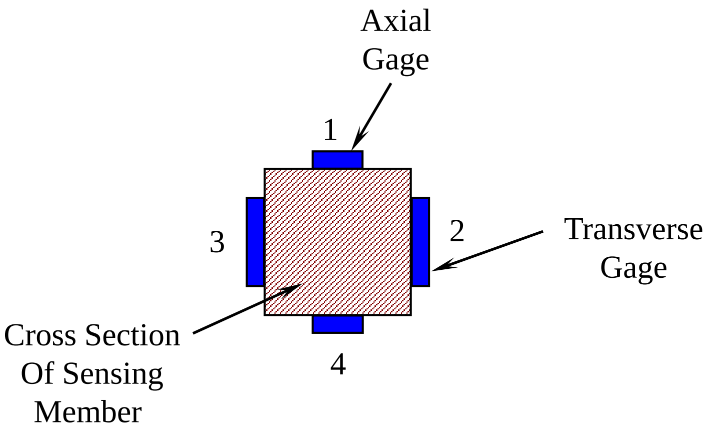
Example: Axial Load Cell

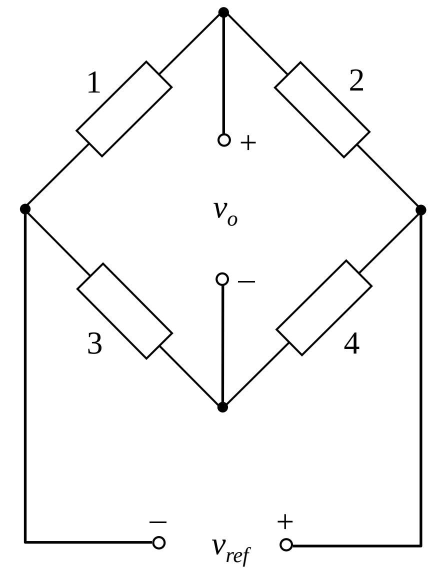
Strain Gauge Load Cell (Force Sensor): Four identical strain gauges in Wheatstone bridge; Mounted on a rod of square X-section

One opposite pair mounted axially; Other pair mounted transversey

To maximize bridge sensitivity, SGs are connected in bridge as shown.

Determine the bridge constant *k* in terms of *Poisson's ratio v* of the rod material.





Transverse strain = (-*v*) x longitudinal strain

Example: SG Accelerometer

Strain Gauge Accelerometer: Point mass of weight *W* (sensing element)

Light cantilever of rectangular X-section, mounted in housing

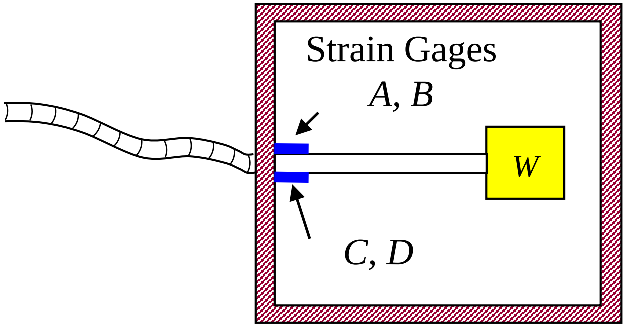
Front End Element (converts the inertia force of *W* into strain)

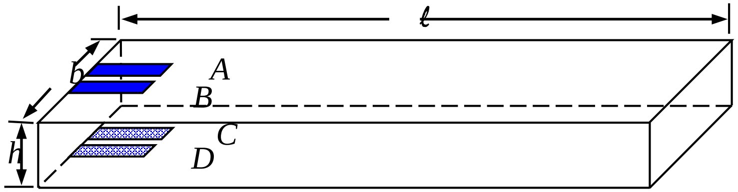
Max bending strain at cantilever root is measured using four identical active semiconductor SGs

Two SGs (*A* and *B*) are mounted axially on top surface of cantilever

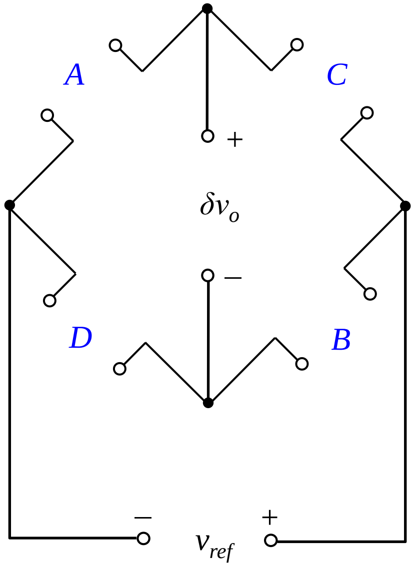
Remaining two (*C* and *D*) are mounted on bottom surface

(a) To maximize accelerometer sensitivity, indicate bridge connection.
(b) What is the bridge constant of the circuit?





(a)



(b) $k = 4$

Example: SG Accelerometer (cont'd)

(c) Obtain an expression relating acceleration *a* (in units of *g*) to bridge output (bridge balanced at zero acceleration) in terms of the following parameters:

> **$W = Mg$ = weight of seismic mass at free end of cantilever; E = Young's modulus of cantilever;**
> **ℓ = length of cantilever; b = X-section width of cantilever; h = X-section height of cantilever; S_s = gauge factor (sensitivity) of each strain gage; v_{ref} = supply voltage to the bridge.**

***Note*: This gives the sensitivity $\delta v_o / a$ of the overall device**

(d) For M = 5 gm, $E = 5 \times 10^{10}$ N/m^2, ℓ = 1 cm, b = 1 mm, h = 0.5 mm, S_s = 200, and v_{ref} = 20 V, determine sensitivity of accelerometer in mV/*g*.

(e) If yield strength of cantilever element is 5×10^7 N/m2, what is the max acceleration that could be measured?

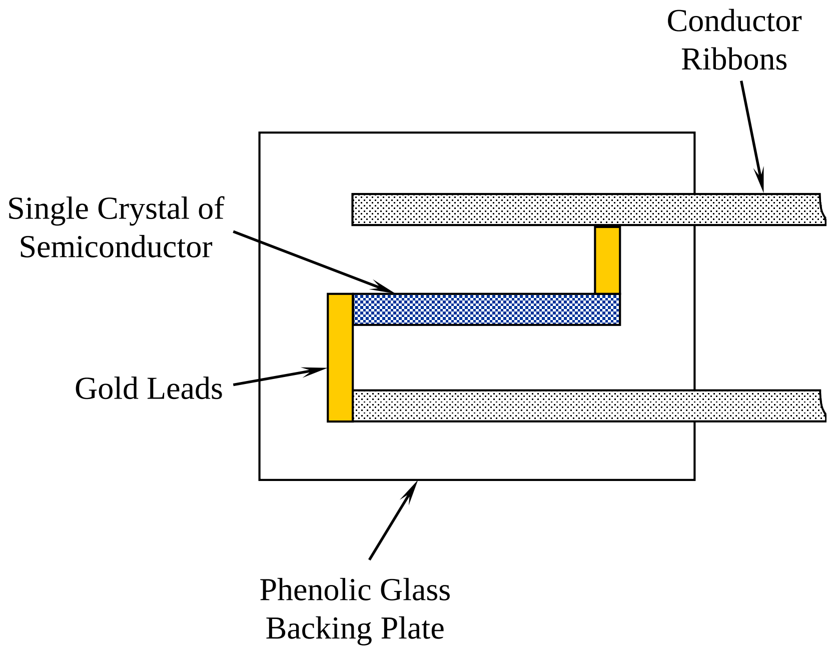
(f) If the ADC from bridge to computer has the range 0 to 10 V, how much amplification (bridge amplifier gain) would be needed so that this maximum acceleration corresponds to the upper limit of ADC (10 V)?

(g) Is the cross-sensitivity due to tension and other direction of bending small with this arrangement? Explain.

***Given*: For a cantilever subjected to force *F* at free end, max stress at root =**

$$\sigma = \frac{6F\ell}{bh^2}$$

Semiconductor Strain Gauges



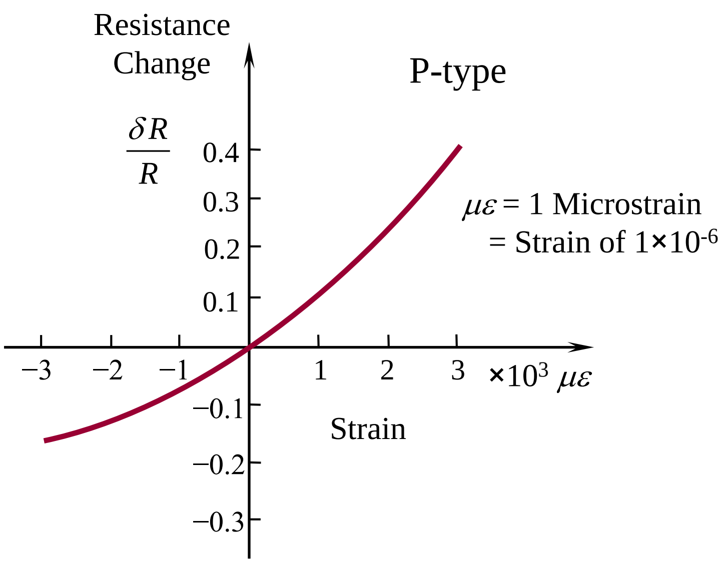
- Gage factor – 40 – 200
- Resitivity is higher – reduced power consumption
- Resistance – 5kΩ
- Smaller and lighter

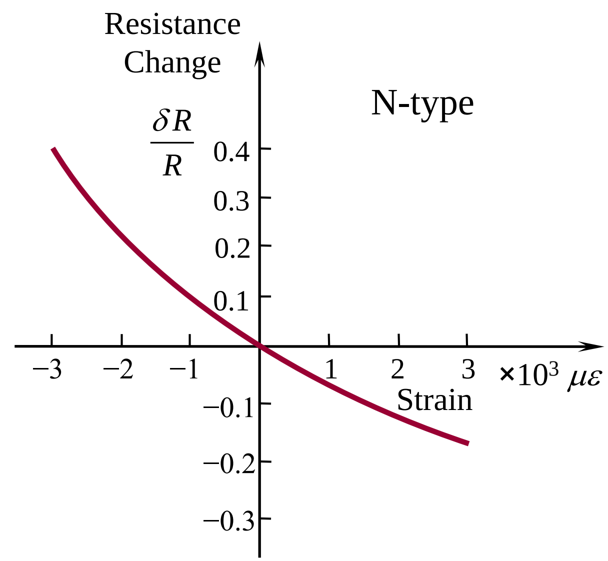
Properties of Common SG Material

Material	Composition	Gage Factor (Sensitivity)	Temperature Coefficient of Resistance (10^{-6}/°C)
Constantan	45% Ni, 55% Cu	2.0	15
Isoelastic	36% Ni, 52% Fe, 8% Cr, 4% (Mn, Si, Mo)	3.5	200
Karma	74% Ni, 20% Cr, 3% Fe, 3% Al	2.3	20
Monel	67% Ni, 33% Cu	1.9	2000
Silicon	p-type	100 to 170	70 to 700
Silicon	n-type	-140 to –100	70 to 700

Disadvantages of Semiconductor Strain Gages

- **Strain-resistance relationship is nonlinear**
- **Brittle and difficult to mount on curved surfaces**
- **Maximum strain that can be measured is an order of magnitude smaller (typically, less than 0.001 m/m)**
- **More costly**
- **Has a much larger temperature sensitivity**





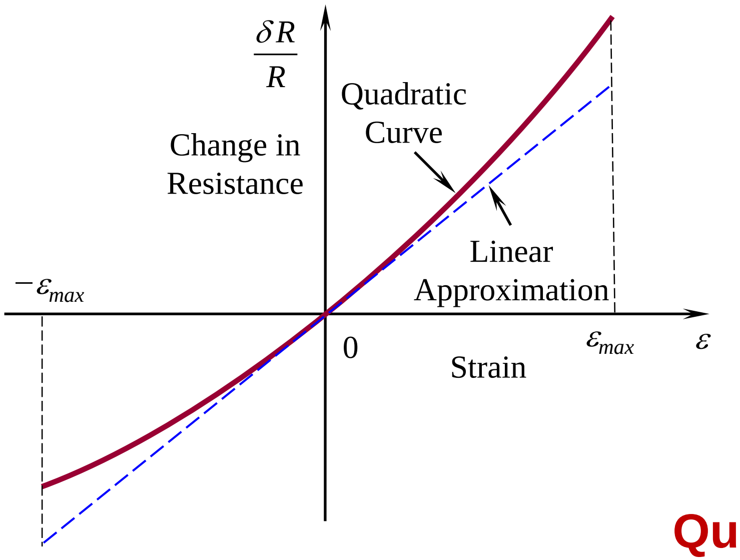
Nonlinearity of Semiconductor SGs

Strain-Resistance Relationship:

$$\frac{\delta R}{R} = S_1 \varepsilon + S_2 \varepsilon^2$$

- S_1 = linear sensitivity
  - Positive for p-type gages
  - Negative for n-type gages
  - Magnitude is larger for p-type
- S_2 = nonlinearity
  - Positive for both types
  - Magnitude is smaller for p-type

Linear Approximation



$$\left[\frac{\delta R}{R}\right]_L = S_s \varepsilon$$

Error $e = \frac{\delta R}{R} - \left[\frac{\delta R}{R}\right]_L = S_1 \varepsilon + S_2 \varepsilon^2 - S_s \varepsilon$

$$= (S_1 - S_s)\varepsilon + S_2 \varepsilon^2$$

Quadratic Error:

$$J = \int_{-\varepsilon_{\max}}^{\varepsilon_{\max}} e^2 d\varepsilon = \int_{-\varepsilon_{\max}}^{\varepsilon_{\max}} \left[(S_1 - S_s)\varepsilon + S_2 \varepsilon^2\right]^2 d\varepsilon$$

Minimize Error: $\frac{\partial J}{\partial S_s} = 0.$

➔ $$\int_{-\varepsilon_{\max}}^{\varepsilon_{\max}} (-2\varepsilon)\left[(S_1 - S_s)\varepsilon + S_2 \varepsilon^2\right] d\varepsilon = 0$$

➔ $S_1 = S_s$

➔ **Maximum Error:** $e_{\max} = S_2 \varepsilon_{\max}^2$

Linear Approximation (Cont'd)

Range of resistance change:

$$\frac{\Delta R}{R} = \left(S_1 \varepsilon_{\max} + S_2 \varepsilon_{\max}^2\right) - \left(-S_1 \varepsilon_{\max} + S_2 \varepsilon_{\max}^2\right)$$

$$= 2S_1 \varepsilon_{\max}$$

Percentage nonlinearity error:

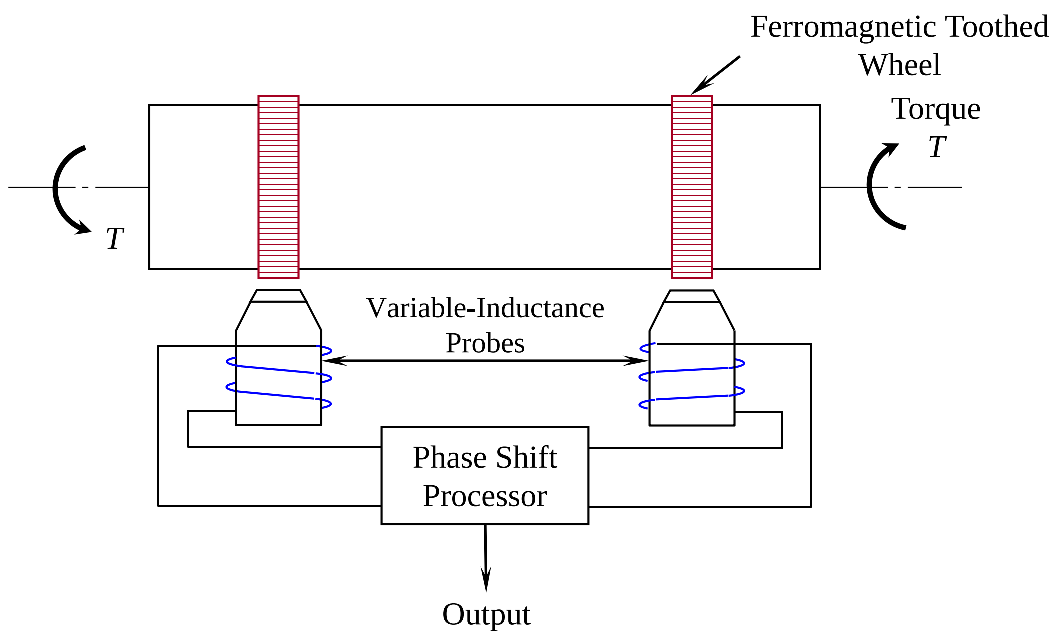
$$N_p = \frac{\text{max error}}{\text{range}} \times 100\% = \frac{S_2 \varepsilon_{\max}^2}{2S_1 \varepsilon_{\max}} \times 100\%$$

$$N_p = 50 S_2 \varepsilon_{\max} / S_1 \%$$

Other
Torque/Force Sensors

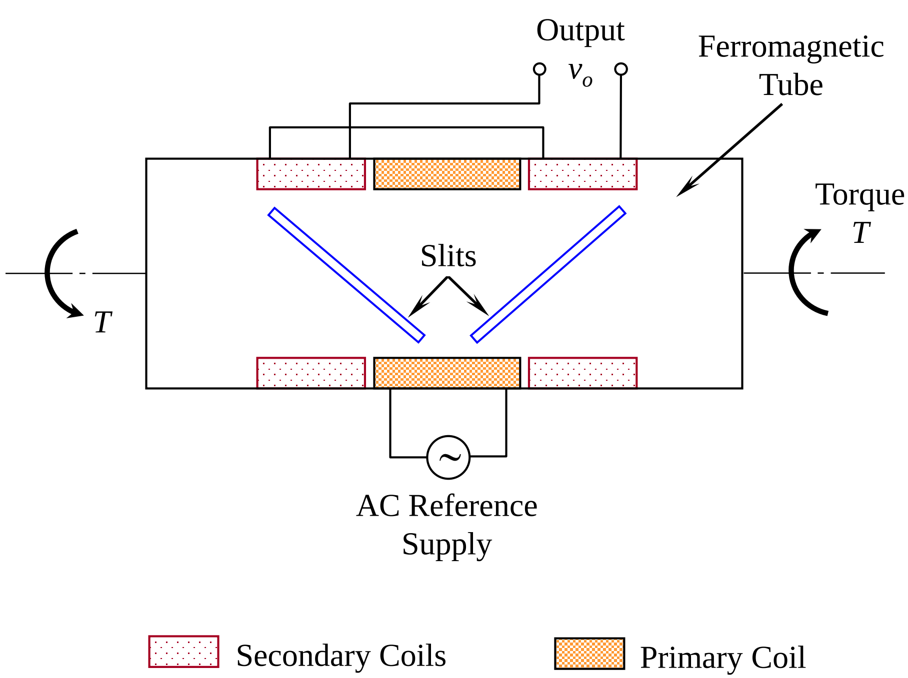
Deflection-based Torque Sensor

- **Measurement of “twist angle” is used to measure torque**
- **Proximity probes produce pulse sequences as the shaft rotates**
- **Phase shift of the two signals → angle of twist → transmitted torque**
- **Both magnitude and direction of torque can be measured**



Variable Reluctance Torque Sensor

- Operates like a differential transformer
- Torque sensing element: ferromagnetic tube with two slits placed in principal stress directions
- Torque → one slit opens and other closes → reluctance changes
- Output voltage → transmitted torque



Reaction Torque Sensors

Reaction torque sensor

Method: 1. Cradle the housing; 2. Measure force needed to hold the structure. *Note*: Force is measured at a "fixed" location (good)

Eliminates many problems of other methods:

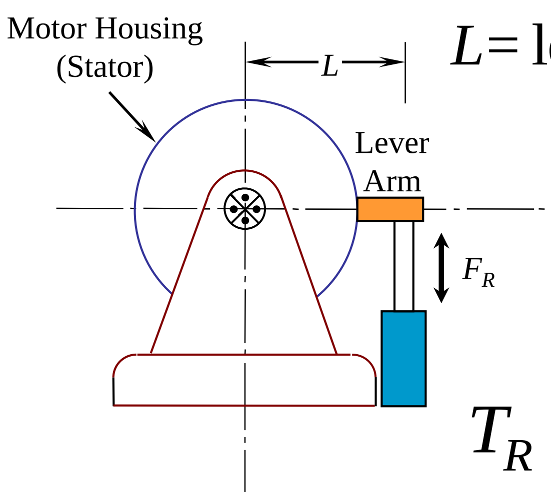
- **Measurement of torque at a moving location**
- **Torque sensing element modifies the original system dynamics:**

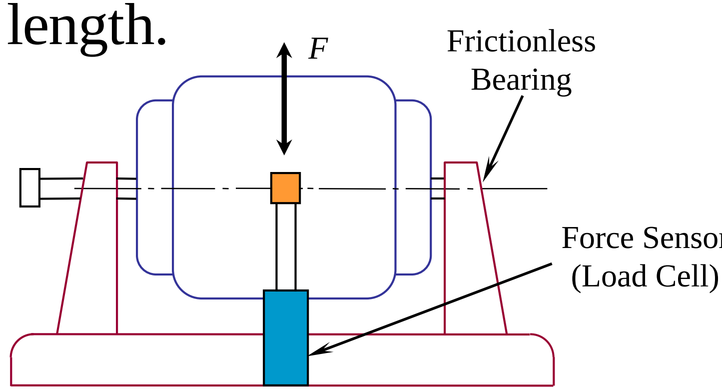
1. Reducing the system stiffness (decrease of system bandwidth);

2. Extra loading (mechanical) of the system

F_R = reaction force measured using load cell

L = lever arm length.





$$T_R = F_R \cdot L$$

A Drawback Reaction Torque Sensors

- **Inertia torque (due to acceleration/deceleration) affects the measured torque**

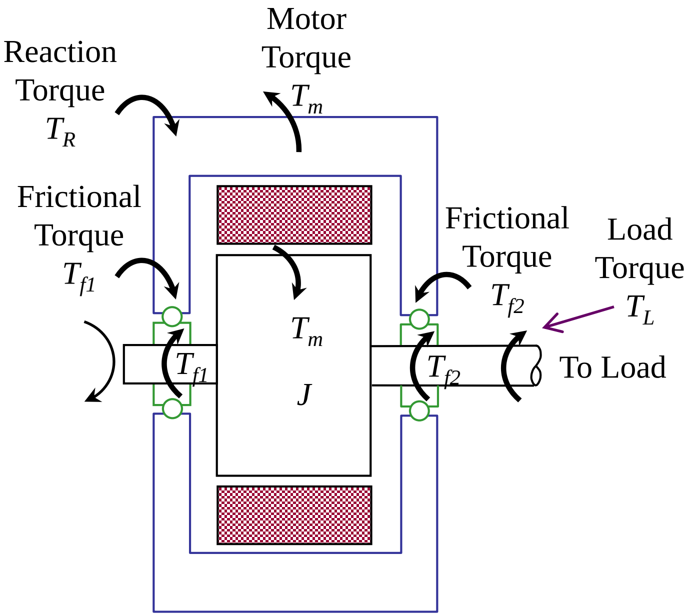
Proof: Apply Newton's second law to the entire system:

$$J\ddot{\theta} = T_R - T_L$$

Note: Bearing torques and motor torque do not enter into equation

$$\rightarrow \quad T_L = T_R - J\ddot{\theta}$$

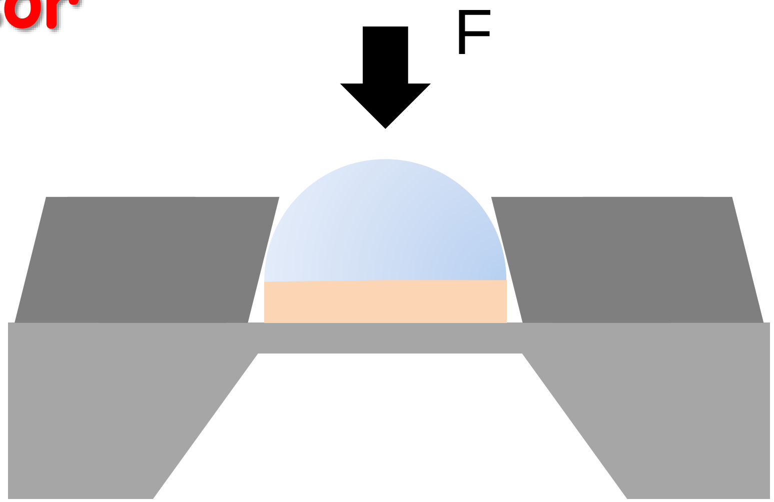
***Note*: Inertia torque can be compensated for by measuring shaft acceleration**



Torque sensing of

Fixed housing

Piezoresistive Force Sensor



- Sensitivity: 12.2 mV/N
- Operating Force (O.F.): 0 to 14.7 N
- Supply Voltage: 5.0 Vdc typ.
- Null Offset: ± 15 mV
- Linearity: ± 0.7%
- Input Resistance: 5.0 kOhms
- Output Resistance: 5.0 kOhms
- Force Limit: 44 N

Seen before

force sensor FSS-SMD Series by Honeywell

Data Sheet for PT1000-7kg Load Cell

Seen before

Specifications

Note: All specifications are a maximum, as a % (±) of full load, unless otherwise stated.

Nominal Capacity	3kg ~ 250kg
Signal Output at Capacity	2mV/V ± 10%
Linearity Error	< 0.020% FSO
Non-Repeatability	< 0.010% FSO
Combined Error	< 0.025% FSO
Hysteresis	< 0.015% FSO
Creep/Zero Return (30 mins)	< 0.030% / 0.020% FSO
Zero Balanc	< 3.000% Capacity
Temperature Effect on Span/10°C	< 0.010% FSO
Temperature Effect on Zero/10°C	< 0.015% Capacity
Compensated Temperature Range	-10 ~ 40°C
Operating Temperature Range	-30 ~ 70°C
Service Load	100% of Rated Capacity
Safe Load	150% of Rated Capacity
Ultimate Load	300% of Rated Capacity

Input Impedance	425Ω ± 15Ω
Output Impedance	350Ω ± 3Ω
Insulation Impedance	> 5000 MΩ at 100V DC
Excitation Voltage (Recommended)	5 ~ 12V AC/DC
Excitation Voltage (Maximum)	15V AC/DC
Eccentric Loading (effect/cm)	< 0.0085% FSO (3 ~ 35kg) < 0.0074% FSO (50 ~ 250kg)
Deflection at Rated Capacity	< 0.4mm
Storage Temperature Range	-50 ~ 70°C
Cable Type	4mm, Screened, PVC Sheath 4 Core x 0.09mm^2 (28 AWG)
Cable Length	0.5 Metre (3kg ~ 35kg) 1 Metre (50kg ~ 250kg)
Material	Aluminium
Finish	Marine Anodised

Motor Current Torque Sensors

For a DC Motor with armature windings on rotor and field windings on stator:

$$T_m = k i_f i_a$$

$$i_f = \text{field current}$$

$$i_a = \text{armature current}$$

$$k = \text{torque constant.}$$

- **Motor torque can be determined by measuring i_f or i_a**

***Note*: Magnetic torque is only an approximation of the transmitted torque (It includes inertial torque and frictional torque)**

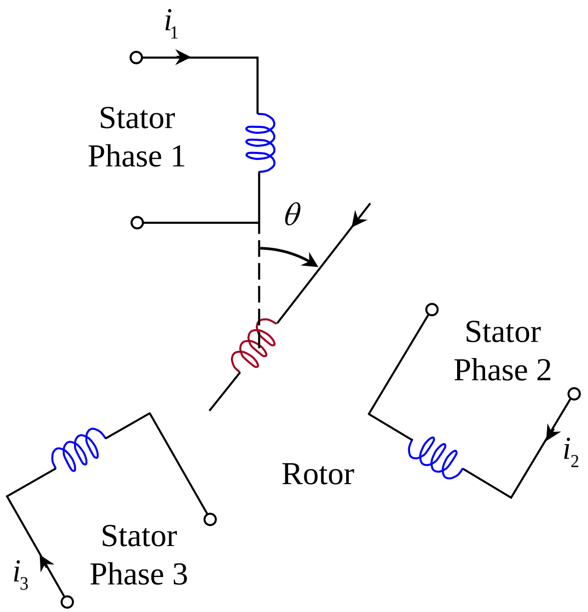
AC Motor Current Torque Sensor

For a 3-phase AC synchronous motor:

Torque: $$T_m = k i_f \left[i_1 \sin\theta + i_2 \sin\left(\theta - \frac{2\pi}{3}\right) + i_3 \sin\left(\theta - \frac{4\pi}{3}\right) \right]$$

With phase currents:

$$i_1 = i_a \sin \omega t \;;\quad i_2 = i_a \sin\left(\omega t - \frac{2\pi}{3}\right) \;;\quad i_3 = i_a \sin\left(\omega t - \frac{4\pi}{3}\right)$$



$$\Rightarrow \quad T_m = 1.5 k i_f i_a \cos(\theta - \omega t)$$

θ = angle of rotation

ω = line frequency

Question: Torque Sensor Location

In each example, indicate (with reasons) what torque it measures and whether it is a good location for torque sensing.

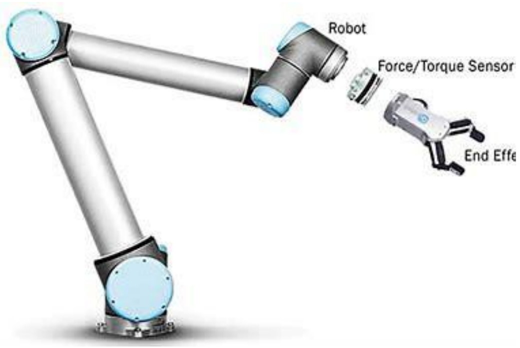
(a)

(b)

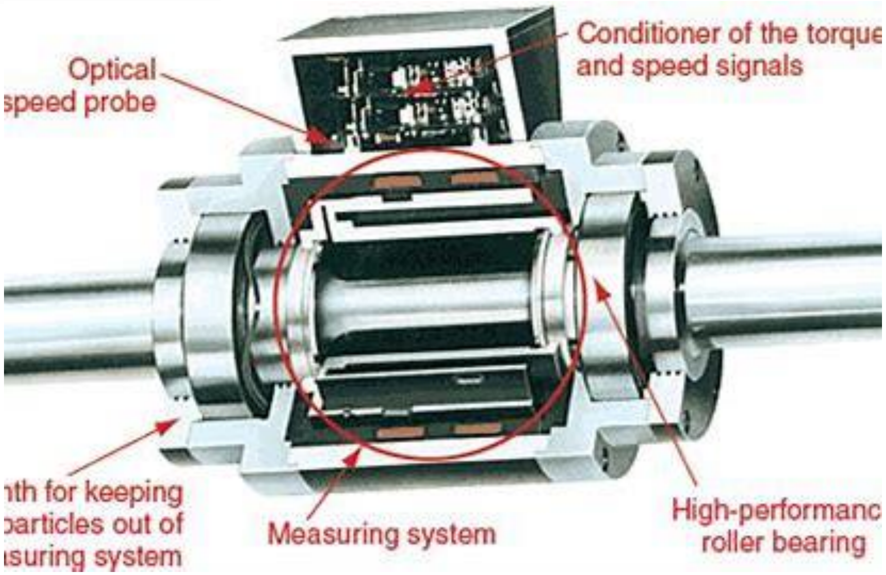
(c)

(d)

(e)



(f)



Tactile Sensors

Tactile Sensors

Force "distribution" is measured

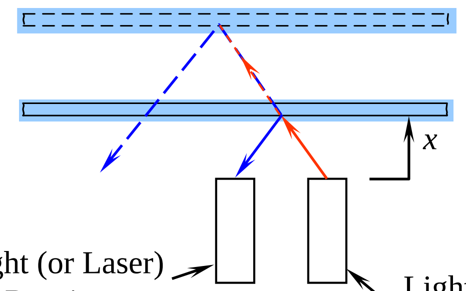
Closely spaced array of force sensors is used → exploits skin-like properties of human hand

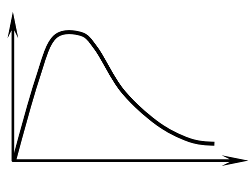
In Robotics: 1. Grasping; 2. Object identification.

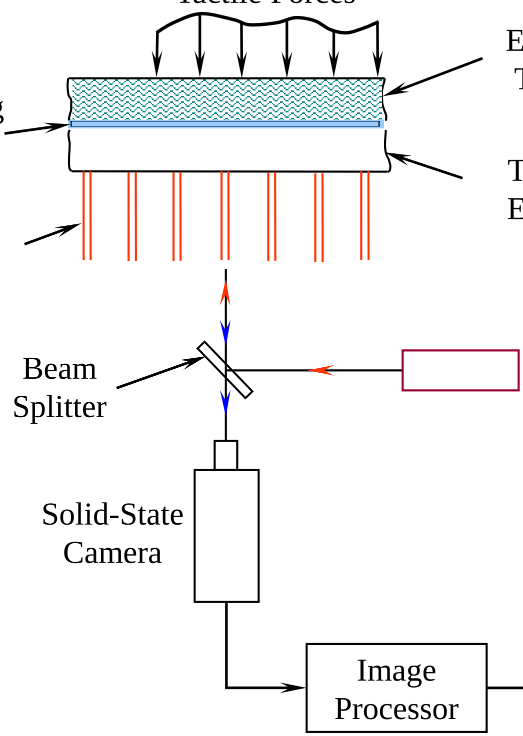
Considerations (Mimic human hand):

1. **Spatial resolution of about 2 mm**
2. **Force resolution (sensitivity) of about 2 gm**
3. **Force capacity (maximum touch force) of about 1 kg**
4. **Response time of 5 ms or less**
5. **Low hysteresis (low energy dissipation)**
6. **Durability under harsh working conditions**
7. **Robustness and insensitivity to change in environmental conditions (temperature, dust, humidity, vibration, etc.)**
8. **Capability to detect and even predict slip.**

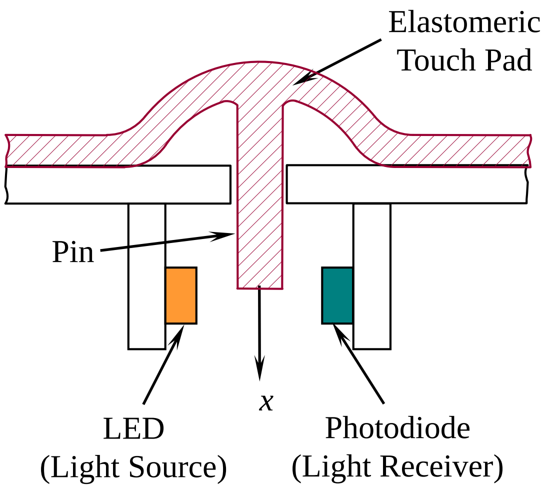
Construction and Operation of Tactile Sensors







Optical Tactile Sensor with Local Light Sources and Photosensors



Can Use:

1. **An array of semiconductor strain gages (photo resistive) mounted on touch pad (measures force distribution)**

2. **An error of photosensors mounted under touch pad (measures deflection profile)**

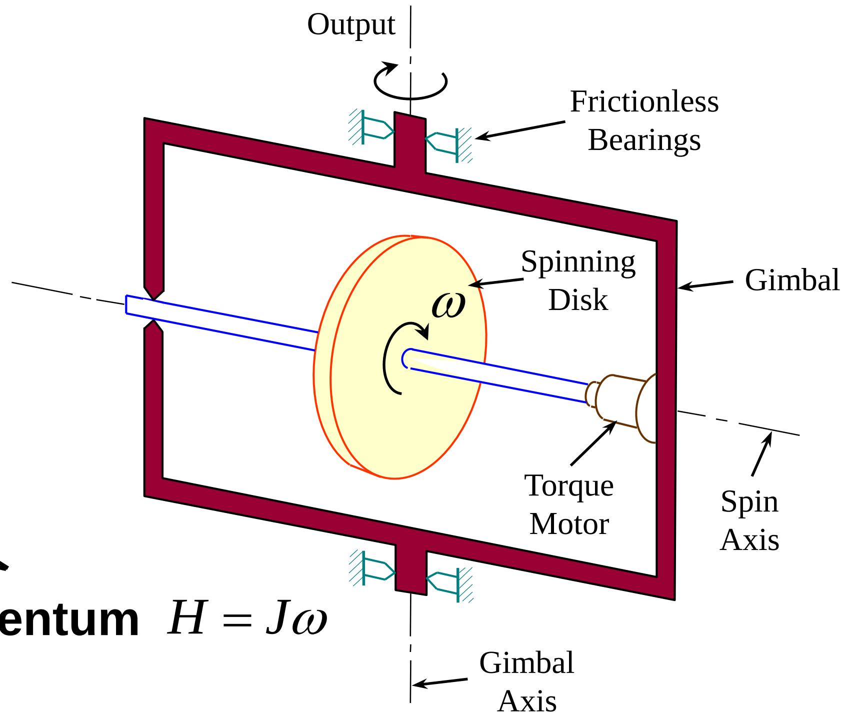
3. **A tactile surface with two membranes separated by an air gap, with ultrasound sensors—pulse echo ranging (measures deflection profile)**

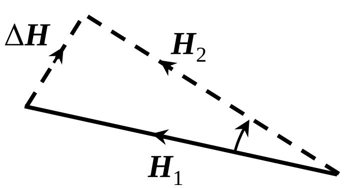
Other Sensors

Gyroscopic Sensors

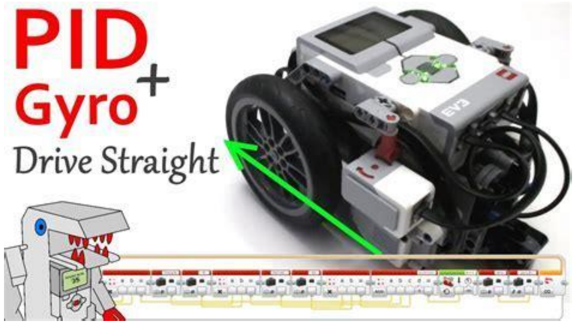
Uses Gyroscope Principle: Angular momentum and associated angle are measured (e.g., Inertial Measurement Unit (IMU))

Measures: Angular orientation and rotating speed





Angular Momentum $H = J\omega$



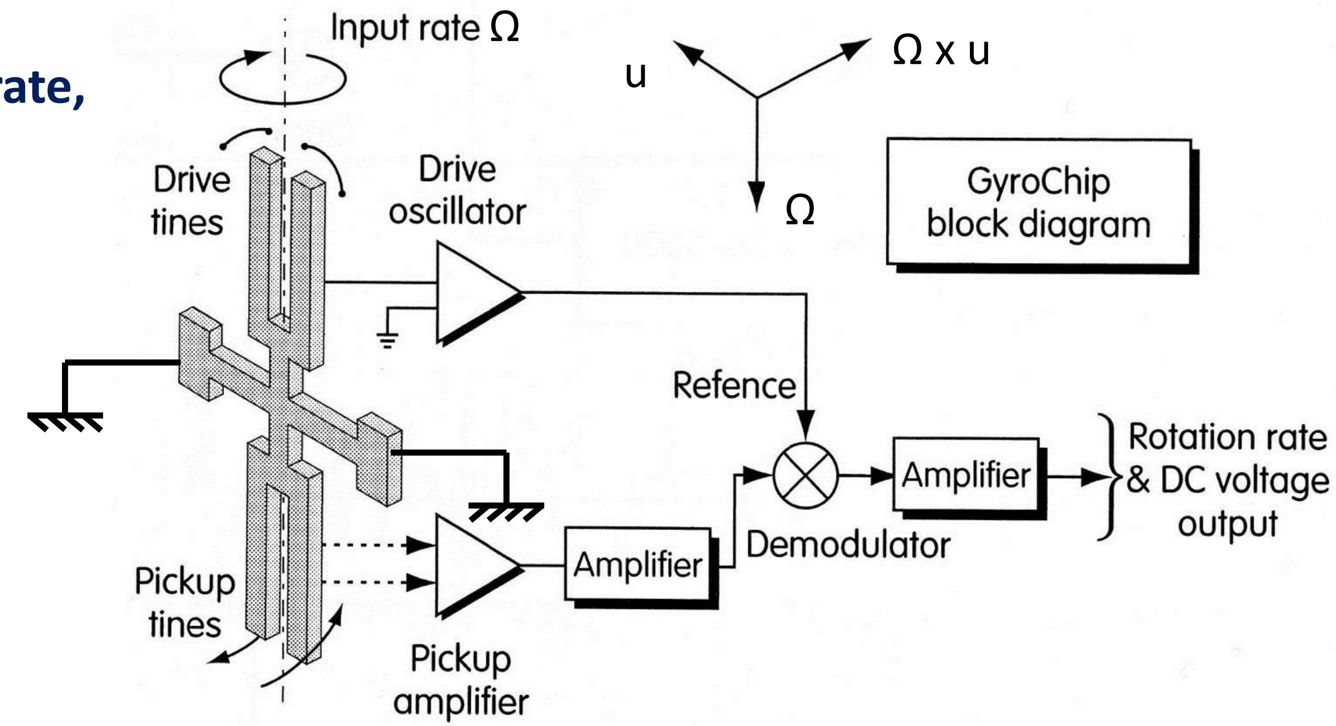
Applications: Ships, vehicles, hand-held and assistive devices, various mechanical instruments

Tuning Fork Gyroscope

- Drive tines move at a precise amplitude and frequency (~ 10 kHz) toward and away from each other
- Coriolis force causes a torque in the structure (at same frequency)
- Torque causes the pickup tines to vibrate, which is measured

$$\vec{F}_C = -2m\vec{\Omega}\times\vec{u}$$

(along 3rd axis)



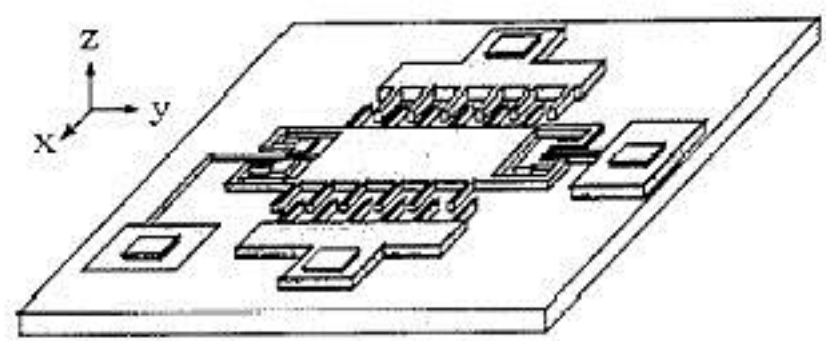
GyroChip by Systron Donner Inertial (SDI)

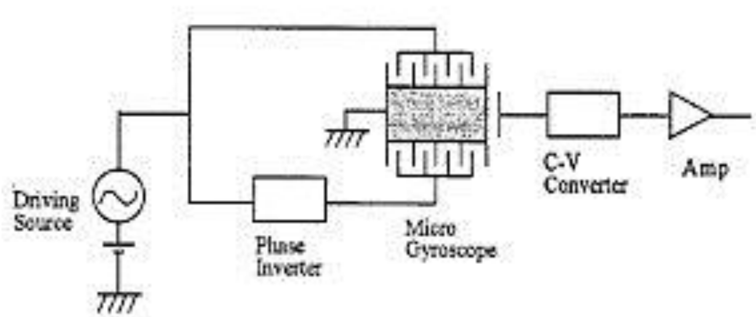
Standard ranges: +/- 50 to +/- 1000 °/s

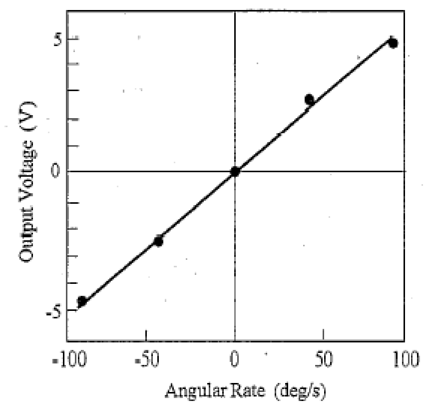
Bandwidth: ~ 60 Hz

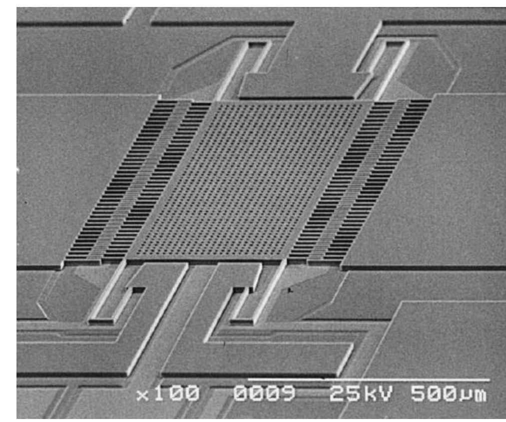
Vibrating Micro-gyroscope

- **Driven in *x*-direction**
- **Angular rate about *y*-axis to be measured**
- **$F_C \rightarrow$ vibrate in the *z*-direction**
- **Measure this force: resulting deflection (change in capacitance of the gap)**







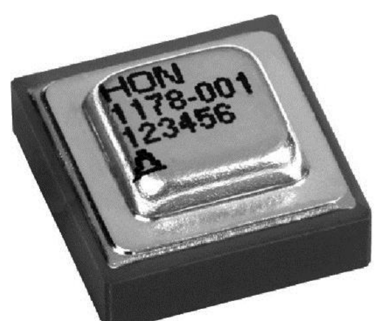


K. Tanaka, Y. Mochida, M. Sugimoto, K. Moriya, T. Hasegawa, K. Atuchi, K. Ohwada, "A micromachined vibrating gyroscope", Sensors and Actuators A, vol. 50, pp. 111-115, 1995.

Commercial product:

MEMS Rotational Rate Sensor

GG1178 by Honeywell



Operating range: +/- 75-300 °/s
Bandwidth: 31, 62 or 125 Hz
Sensitivity: 6.7 – 26.7 mV/ °/s

Magnetometer

Measures direction (pose) wrt Direction of Earth's Magnetic Field (*Note*: May measure magnetic flux density as well, not relevant here)

Principle of Operation:

Method 1, Compass (Simple, Not Robust): A compass needle orients along earth's magnetic field. Measure its angle wrt a reference axis of the sensor

Method 2, Electro-magnetic Induction (More Complex): An ac induces an oscillating voltage in a coil. The induced voltage is "modulated" by earth's magnetic field. Modulation strength depends on the coil orientation wrt earth's magnetic field. Demodulate → strength of the modulating field → angle

Method 3, Hall Effect (Somewhat Complex, Accurate): Semiconductor element. 1. Apply voltage in one direction; 2. Measure output Voltage in an Orthogonal direction (depends on the magnetic field along the other (3rd) orthogonal direction, which depends on the Semiconductor orientation wrt earth's magnetic field).

Magnetometer and gyro are typically integral in an IMU

Inertial Motion Unit (IMU)

IMU is a combination (integrated unit) of:

accelerometer, gyroscope, and magnetometer.

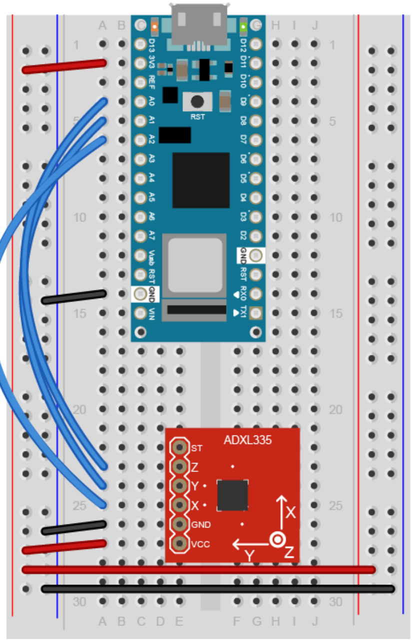
Characteristics (Top Photo):

1. IMU measures motion in multiple axes

2. Accelerometer: measures acceleration on the sensor

3. Gyroscope: measures angular rotation and angular speed.

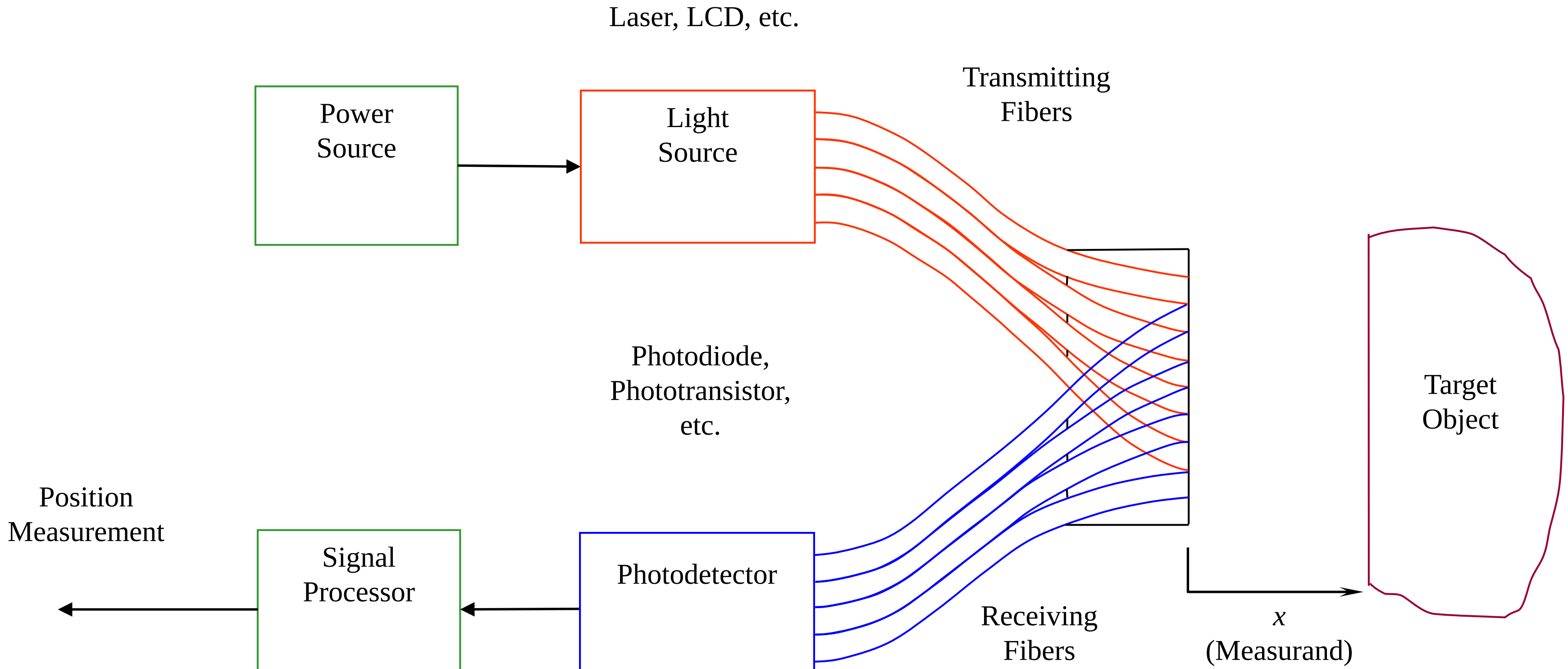
4. Magnetometer: measures heading (pose). It measure the sensor tilt wrt Earth's magnetic field



Connection to a Microcontroller (Bottom Photo):

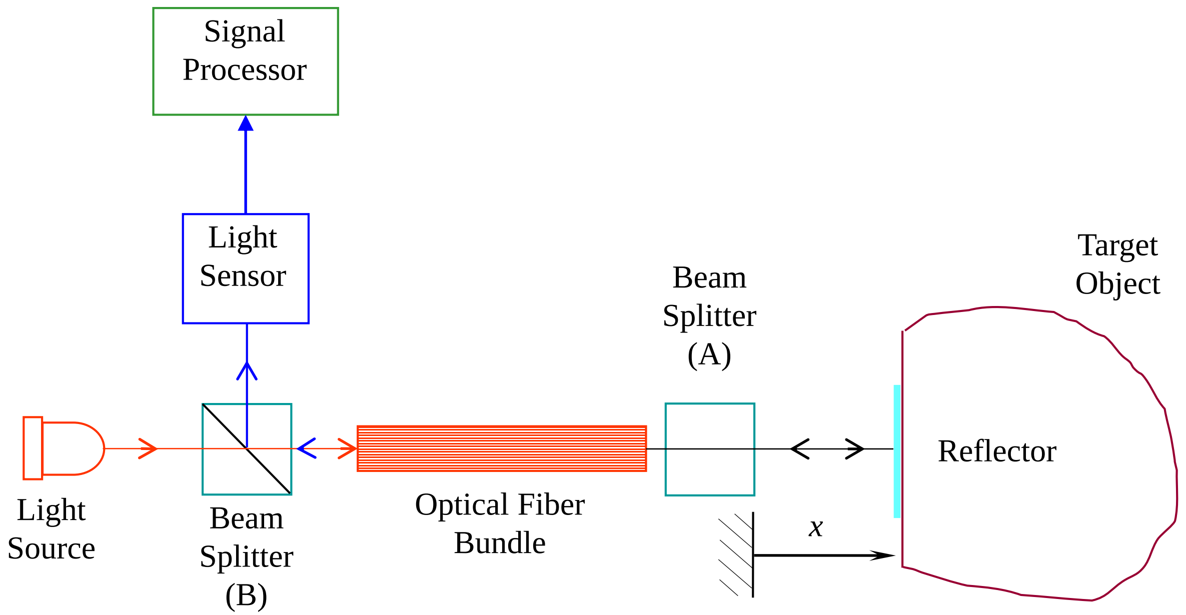
- **A microcontroller (e.g., Arduino) and a sensor (e.g., IMU or Accelerometer) on a breadboard.**
- **USB connector is provided for programming the microcontroller**
- **Voltage (dc) pin of the microcontroller is connected to the Voltage Bus of the breadboard (to supply power to devices on the Breadboard)**
- **External dc power source (of compatible voltage) may be needed**

Optical Sensors



Optical fiber diameter ~μm – 0.01mm

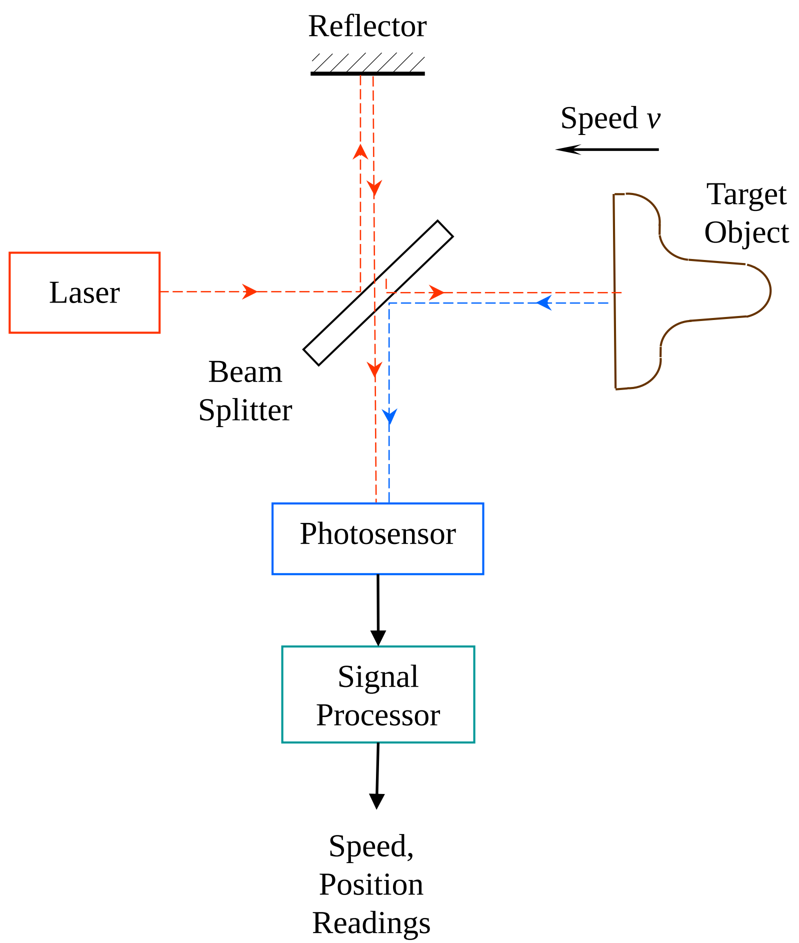
Laser Interferometer



- **Part of the beam is reflected back to the sensor from Beam splitter (A)**
- **The other part travels an extra distance ($2x$)**
- **Phase shift between the two components gives *x*:**

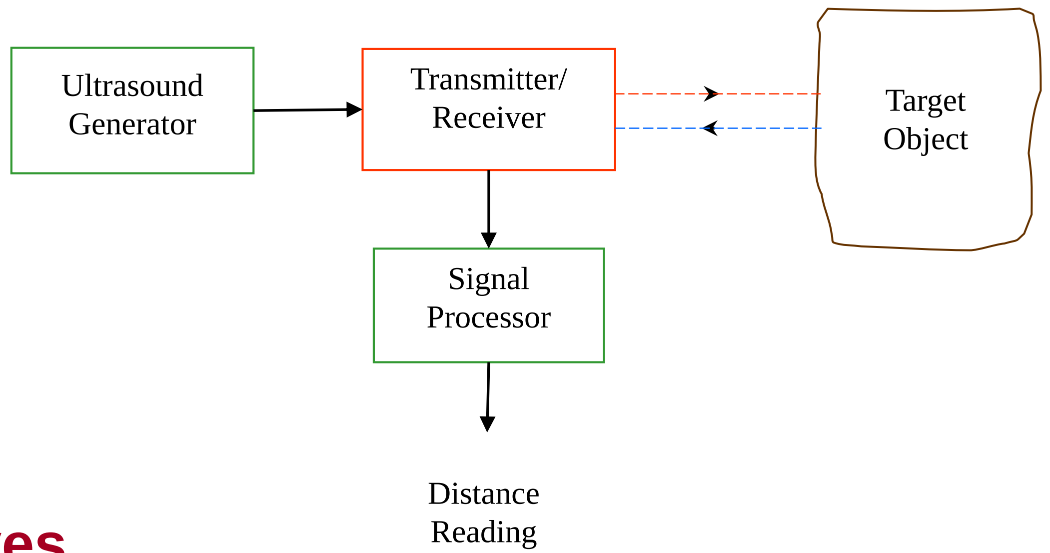
$$\phi = \frac{2x}{\lambda} 2\pi$$

Laser Doppler Interferometer



Frequency of received signal is changed due to speed of reflecting object (Doppler effect). Measure this change using: 1. Spacing of fringe patterns; or 2. Timing of “beats”

Ultrasound Sensors



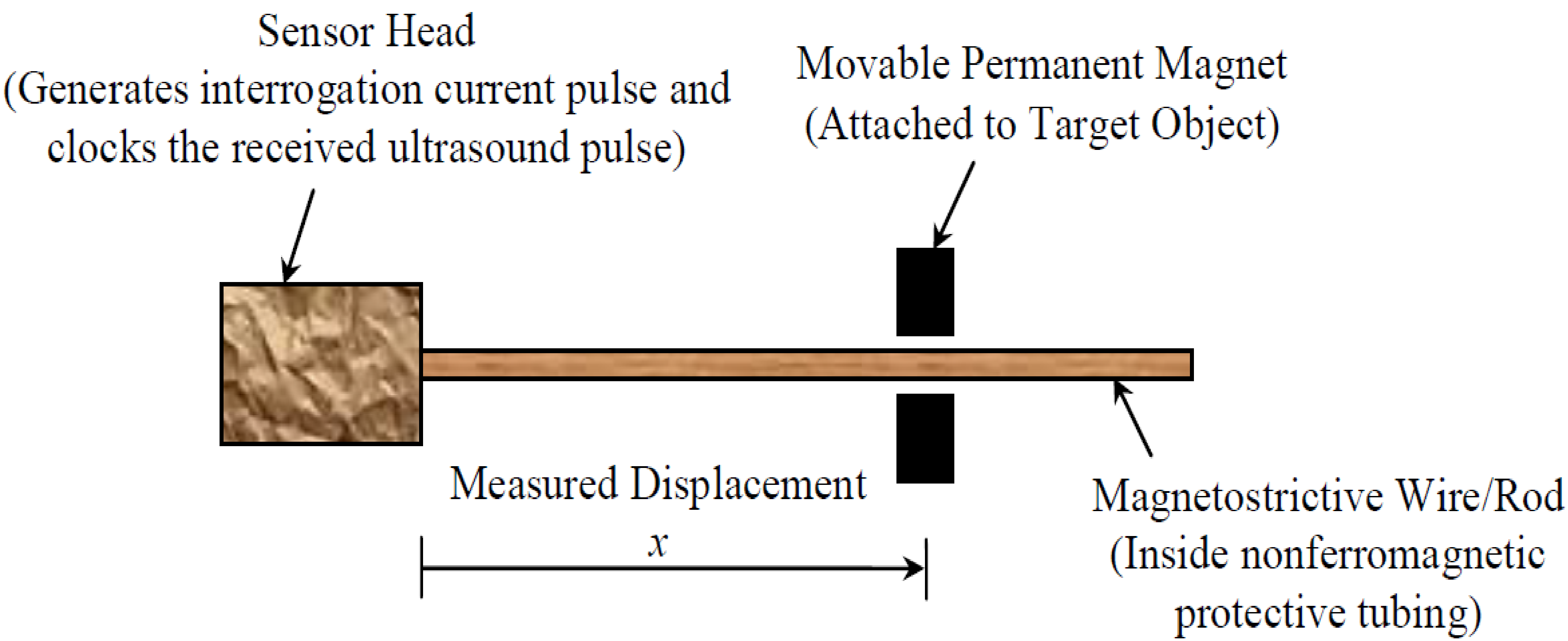
Ultrasound Waves

- **Are pressure waves like sound waves, but frequency is higher (40kHz, 75kHz, ~ 10MHz) than in audible waves**
- **Can be generated by piezoelectric or magnetostrictive devices (ferromagnetic material deform when subject to a magnetic field)**

Method: Time the signal reflected by object: $x = \frac{vt}{2}$

Magnetostrictive Position Sensor

Ultrasound-based time of flight method. Interrogation current pulse travels along magnetostrictive wire (*waveguide*). It interacts with magnet (at sensed object) and generates an ultrasound (strain) pulse (magnetostrictive action). Return pulse is timed



Alternative to LVDT.
Used in applications like hydraulic motion systems

Thermo-fluid Sensors

Sensors Used in a Hydraulic System

Flow Sensor: Turbine-type

Flow velocity is obtained using miniature turbine and tachometer → proportional to volume flow rate (flow X-section is constant)

Pressure Sensors: Diaphragm-type

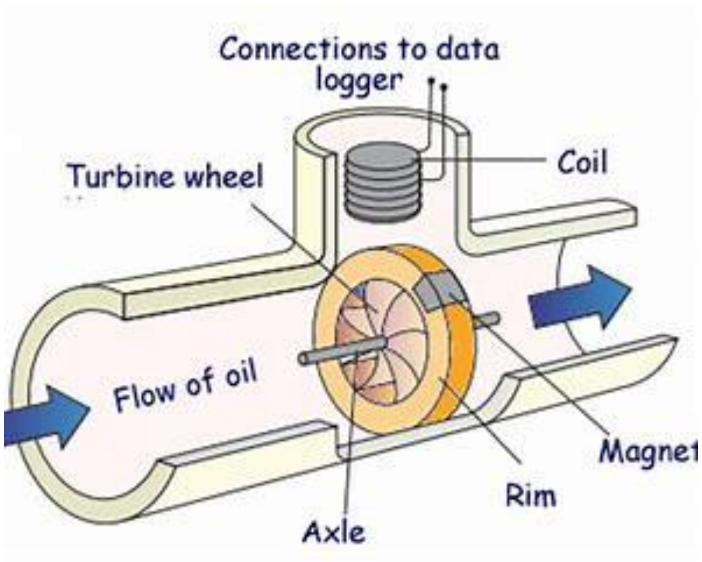
Metal diaphragm deflects with pressure → measured by strain gauges. Integrated with Wheatstone bridge and signal conditioning

Position Sensor: Magnetostrictive

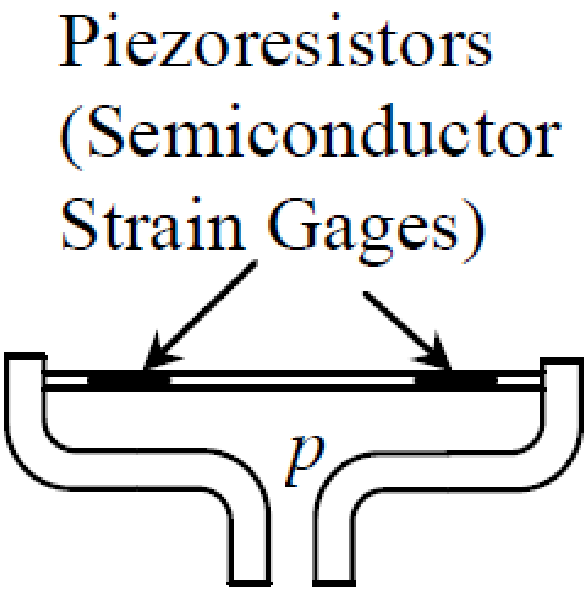
See what was presented before on this sensor

Fluid Sensor Examples

Flow Sensor: Turbine-type



Pressure Sensors: Diaphragm-type

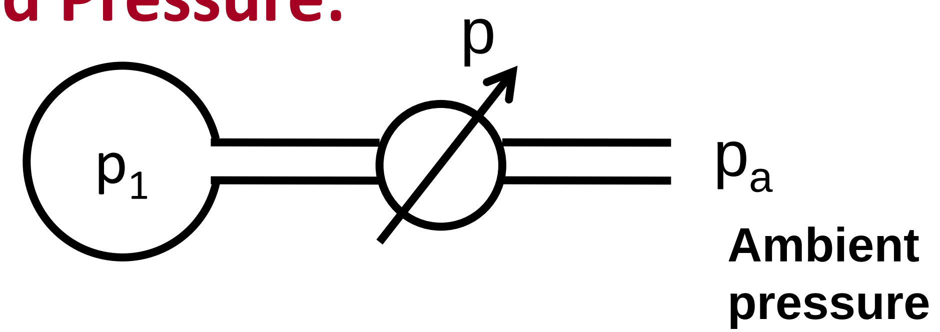


Pressure Measurement

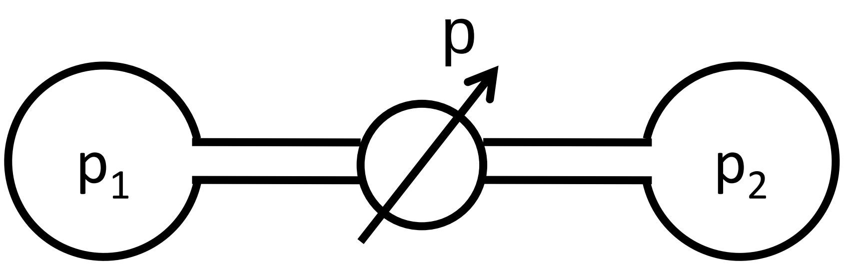
Pressure: $p = F / A$ [Pa]

3 General Types of Measured Pressure:

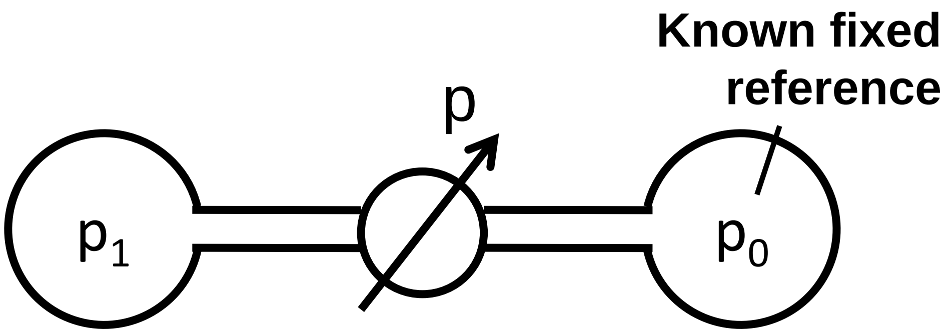
- **Gauge pressure**



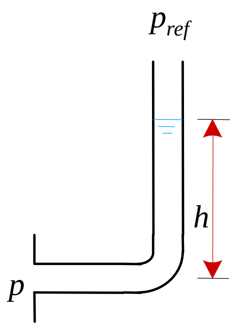
- **Differential pressure**

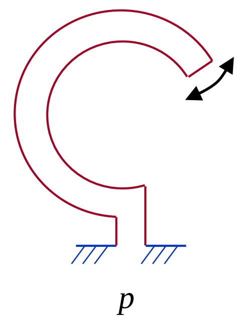


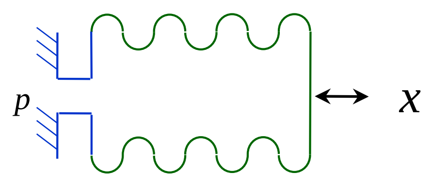
- **Absolute pressure**



Pressure Sensors



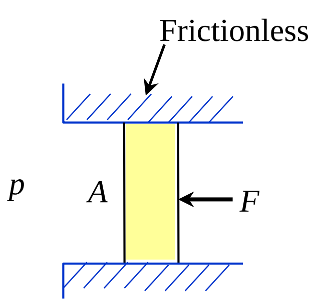


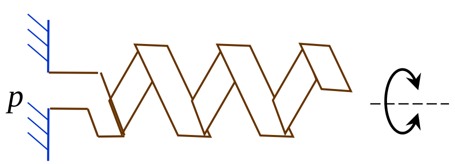


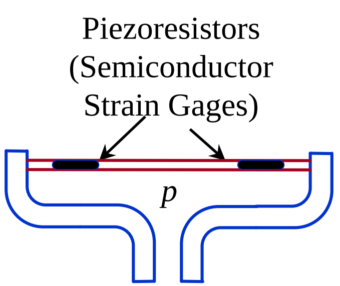
$$p \propto x$$

$$p - p_{ref} = \rho g h$$

Measure deflection/displacement using a displacement sensor (LVDT or capacitive)





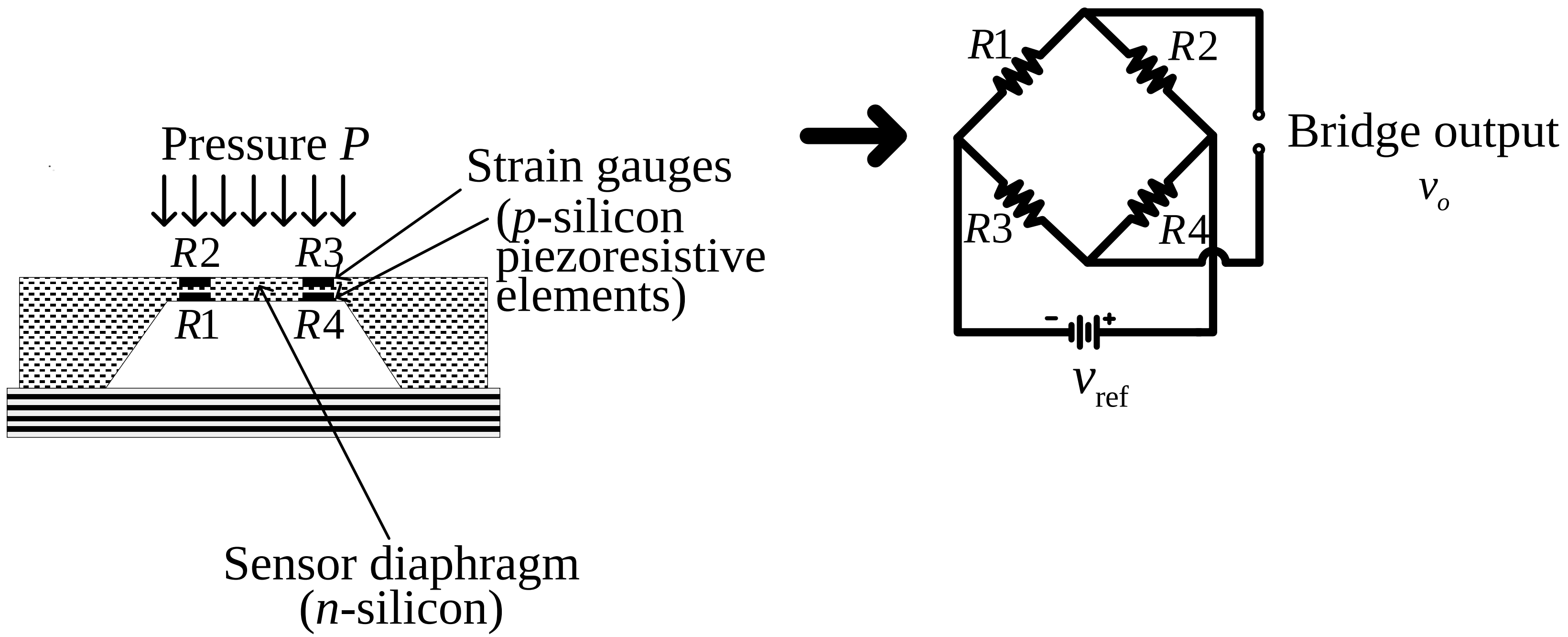


$$p \propto \theta$$

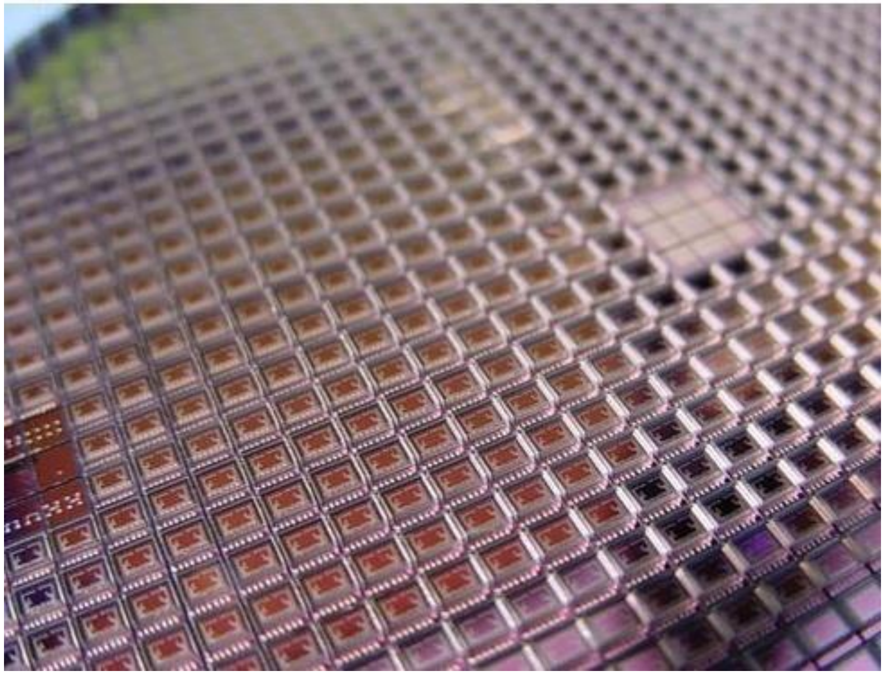
$$p = \frac{F}{A}$$

Measure angular displacement using an RVDT, resolver, or potentiometer

MEMS-based Piezo-resistive Pressure Sensor

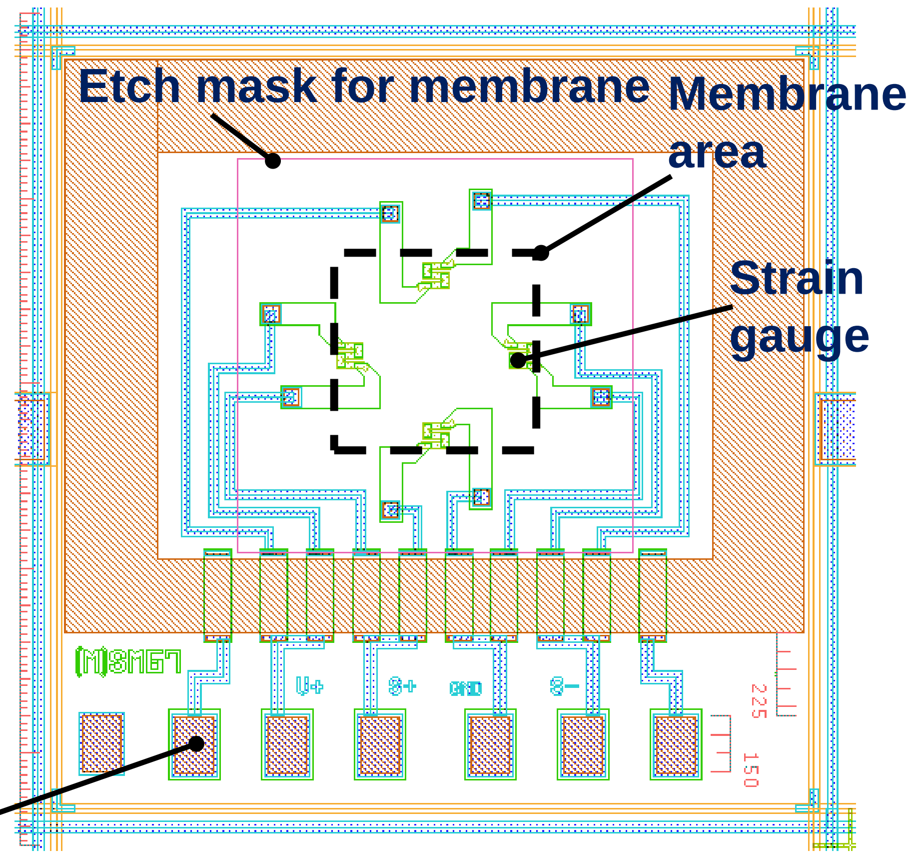


Silicon Pressure Sensor



Silicon sensor dies (1 mm x 1 mm) by Silicon Microstructures

Cross-section of a pressure sensor

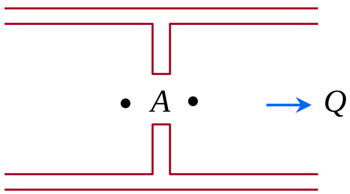


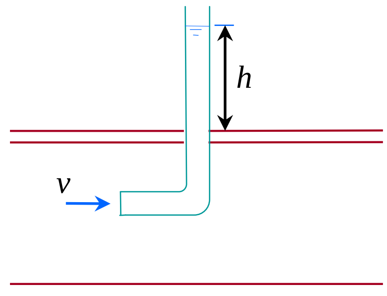
Layout of a pressure sensor die (masks)

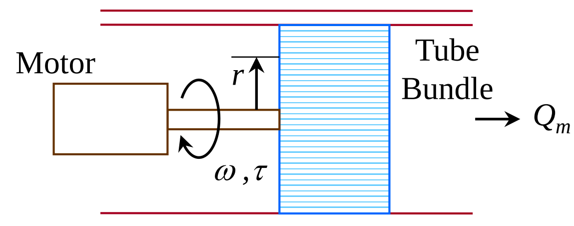
Flow Sensors

$$Q_m = \rho Q \qquad Q = Av$$

$$p + \frac{1}{2}\rho v^2 = \text{constant}$$



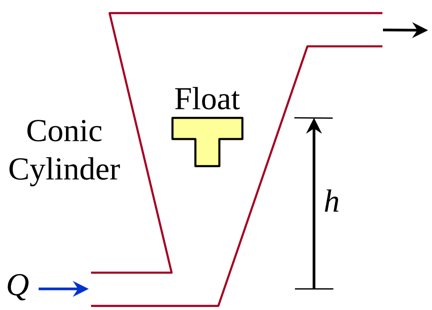


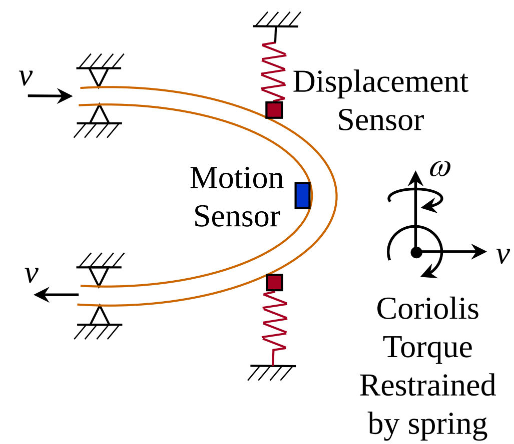


$$Q = c_d A\sqrt{\frac{2\Delta p}{\rho}}$$

$$v = \sqrt{2gh}$$

$$\tau = \omega r^2 Q_m$$



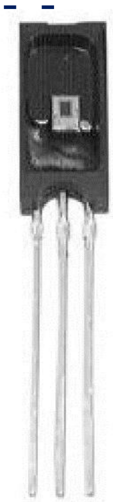


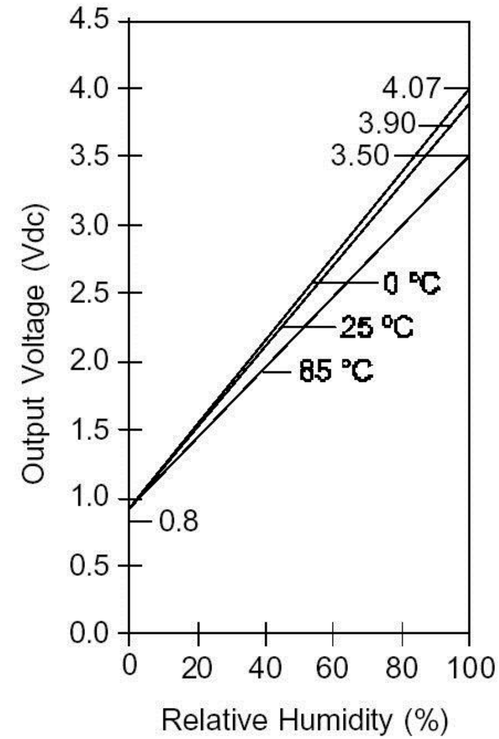
$$Q \propto h$$

$$\text{Coriolis Acceleration} = 2\omega v$$

Capacitive Humidity Sensor

Example: Honeywell HIH – 36100 Humidity/Moisture Sensor





Characteristics:

On-chip integrated signal processing

RH linearity: ± 0.5% RH typical

RH hysteresis: ± 1.2% RH span maximum

RH repeatability: ± 0.5% RH

RH response time: 15 sec

RH stability: ± 1% RH typical at 50% RH in 5 years

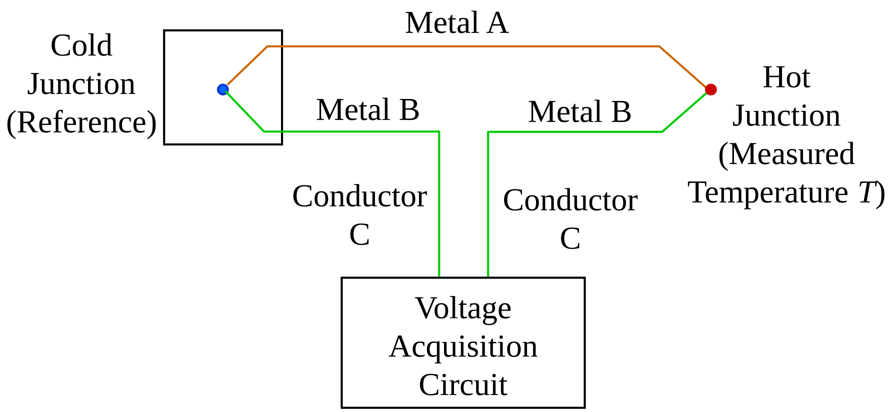
Low temperature effect (compared with other humidity sensors technologies)

Thermoset humidity sensors operate reliably in oil (or other chemically resistant liquids) to within 0.3 %

Temperature Sensors

Thermocouple:

Is this an active device or a passive device?



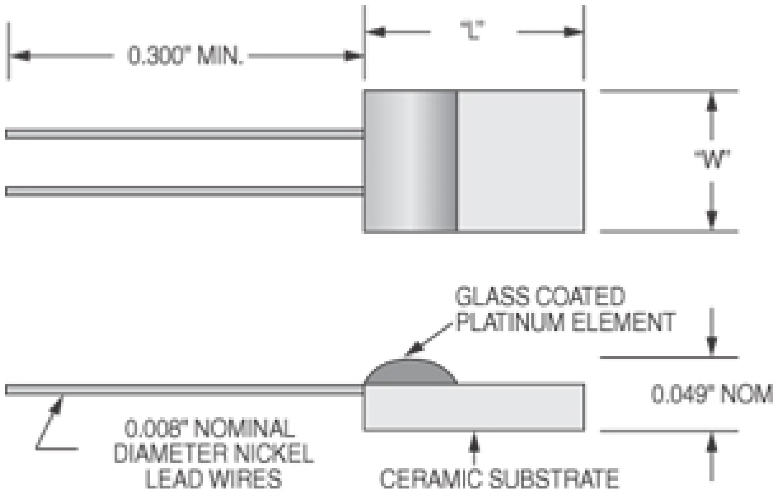
- **Electron configuration due to heat transfer produces a voltage – Seebeck Effect**
- **Two metals – Fe and Constantan, Cu and Constantan, Chrome and Alumel**
- **Sensitivity 10mV/^{o}C**

Resistance Temperature Detector (RTD): $R = R_0(1 + \alpha T)$

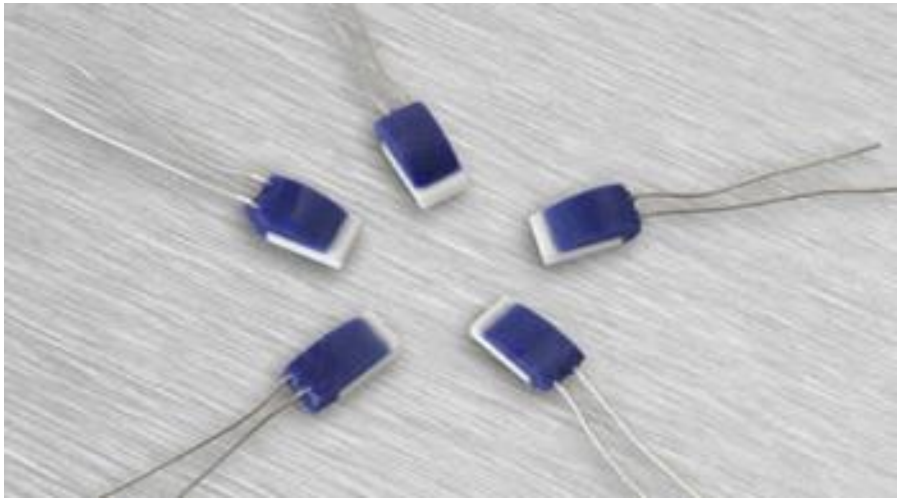
- **Metal element in a ceramic tube – resistance changes with temperature**
- **Metals used – Platinum, Nickel, Cu**
- **Nonlinear**

Resistance Temperature Detector (RTD)

A Common RTD Design: MEMS Metal thin film on ceramic substrate



W = 1.7-2.0 mm
L = 2.8-3.0 mm
Cost: $20 / piece



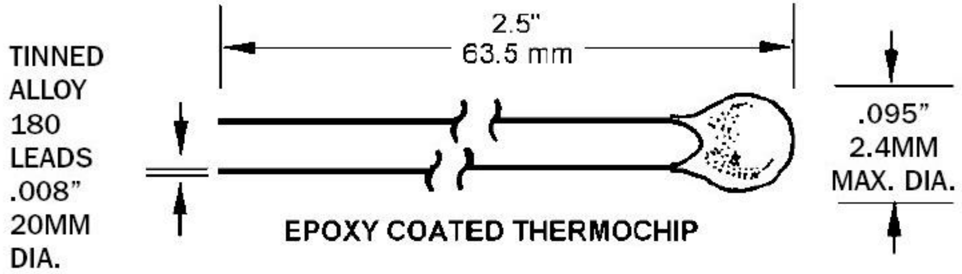
$$R(T) = R_0(1 + \alpha_1(T - T_0) + \alpha_2(T - T_0)^2 + \cdots),$$

Sensitivity coefficients: $\alpha_1 = 3.95 \cdot 10^{-3}/\mathrm{K}$; $\alpha_2 = -1.92 \cdot 10^{-7}/\mathrm{K}^2$

Only the linear term may be used

Thermistor

- Name came from thermally sensitive resistor
- Bulk semiconductor devices: doped polysilicon, metal oxides
  - Cr, Co, Ni, Mn, Fe-metal oxides
- Resistance decreases with temperature – unlike RTD
- High R_0
  - → Eliminates the problem of wire resistance compensation
- Fast response time and high sensitivity
- Temperature range: - 200°C to + 1000°C
- Often encapsulated in glass (protected)



type EC95 by Thermometrics (GE)

Thermistor Characteristic

Common thermistor model:

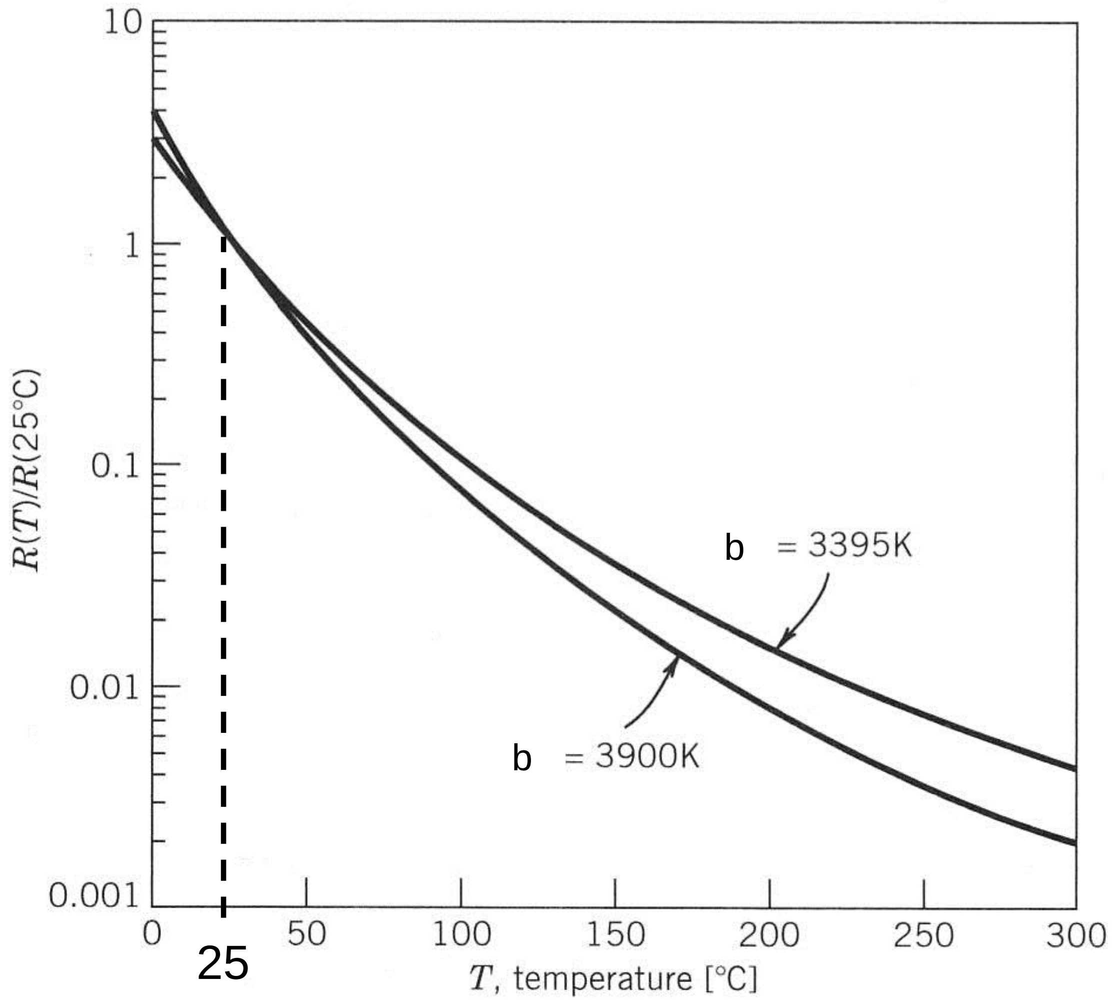
$$R(T) = R_0 \, e^{b\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

T_0 **= 298 K (25°C)**

"Characteristic temperature":
$b \approx$ **2000 – 4000 K**

$R_0 \approx$ **50 kOhm**

Use log scale to linearize



Rating Parameters of Some Sensors/Transducers

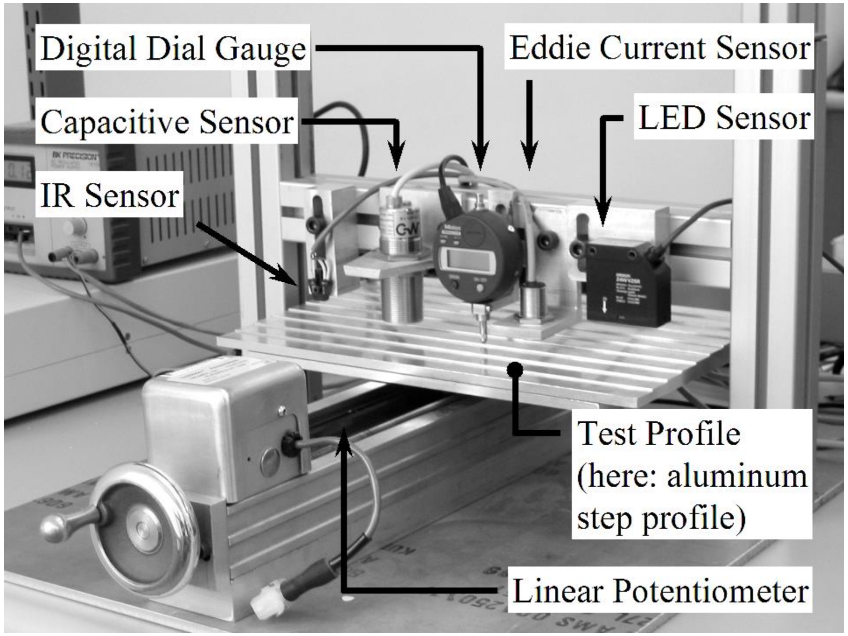
Transducer	Measurand	Measurand Frequency Max Min	Output Impedance	Typical Resolution	Accuracy	Sensitivity
Potentiometer	Displacement	10 Hz/ DC	Low	0.1 mm	0.1%	200 mV/mm
LVDT	Displacement	2,500 Hz/ DC	Moderate	0.001 mm or less	0.1%	50 mV/mm
Resolver	Angular displacement	500 Hz/ DC (limited by excitation freq.)	Low	2 min.	0.2%	10 mV/deg
Tachometer	Velocity	500 Hz/ DC	Moderate (50Ω)	0.2 mm/s	0.5%	5 mV/mm/s 75 mV/rad/s
Eddy current proximity sensor	Displacement	100 kHz/ DC	Moderate	0.001 mm 0.05% full scale	0.5%	5 V/mm
Piezoelectric accelerometer	Acceleration (and velocity, etc.)	25 kHz/ 1Hz	High	1 mm/s^2	0.1%	0.5 mV/m/s^2
Semiconductor strain gage	Strain (displacement, acceleration, etc.)	1 kHz/ DC (limited by fatigue)	200Ω	1-10µ€ (1µ€=10^{-6} unity strain)	0.1%	1 V/€ max 2000µ€
Loadcell	Force (10 - 1000 *N*)	500 Hz/ DC	Moderate	0.01 N	0.05%	1 mV/N
Laser	Displacement/ Shape	1 kHz/ DC	100Ω	1.0 *µm*	0.5%	1 V/mm
Optical encoder	Motion	100 kHz/ DC	500Ω	10 bit	±½ bit	10^4 Pulses/rev.

Lab 1: Data Acquisition and Proximity Sensors for Object Detection

Objectives

- **To understand how to acquire sensor signals with a PC-based data acquisition (DAQ) system**
- **To become familiar with the principles of potentiometric displacement sensor, LED proximity sensor, eddy current inductive proximity sensor, capacitive proximity sensor, and infrared reflective object detector**
- **To learn to calibrate sensors and determine their static transfer characteristics**
- **To recognize the limitations and possible areas of application for these sensor types**
- **Some results from lab exercises will be used again in later labs**

  Example: You will need calibration results from Lab 1 in Lab 4



Laboratory Report

- Carefully follow the Lab Manual
- On the first page indicate
  - Your name and student ID#
  - Lab date
  - Names of the TAs
- The report can be typed or handwritten
- Document the experimental setup and conditions such as sampling rates for data acquisition
- Document mathematical operations you have performed on the data by providing the corresponding equations as well as the results. Any person reading your report should understand what you have done
- Follow the manual questions instructions; answer questions
  - Always report the correct units
  - Make sure all graphs (including axes) are properly labelled
  - Data analysis and report preparation are individual work