BITS Pilani
Pilani Campus

Mechatronics (Merged - DEZG516/DMZG511/ESZG511)

Lecture 3

Session 3

Type	Content Ref.	Topic Title	Study/HW Resource Reference
Pre CH			
During CH	T1, T2	Sensing physical quantities: Force, strain, velocity and motion Sensing physical quantities: Fluid flow rate, pressure and liquid level	T1: Chapter 2, T2: Chapter 9
Post CH			Chapter end problems

Force and Pressure measurement

Force and Pressure

- A **force (A push or pull)** can cause an object with mass to change its velocity (which includes to begin moving from a state of rest), i.e., to accelerate. F= M x A
- **Pressure** (symbol: p or P) is the force applied perpendicular to the surface of an object per unit area over which that force is distributed. P= F/A

Strain Gauge sensors

- Stress and Strain Measurement
- Load Measurement
- Pressure Measurement

Gauge Factor – Strain Gauge measurement

- The resistance change of the strain gauge is usually measured using a Wheatstone bridge, which is related to the strain by the quantity known as the *gage factor (GF)*.

$$GF = \frac{\Delta R / R}{\varepsilon}$$

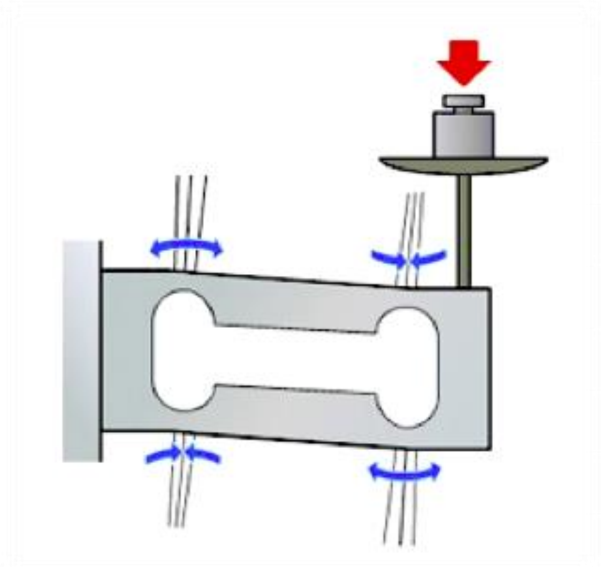
ΔR is the change in resistance caused by strain
R is the resistance of the undeformed gauge
$\epsilon = \Delta L/L$ is strain

Stress: $\sigma=\varepsilon\times E_m=F/A$ (N/m^2), where F is the force, A is the area, E_m is the modulus of elasticity

Strain Gauge

Resistance

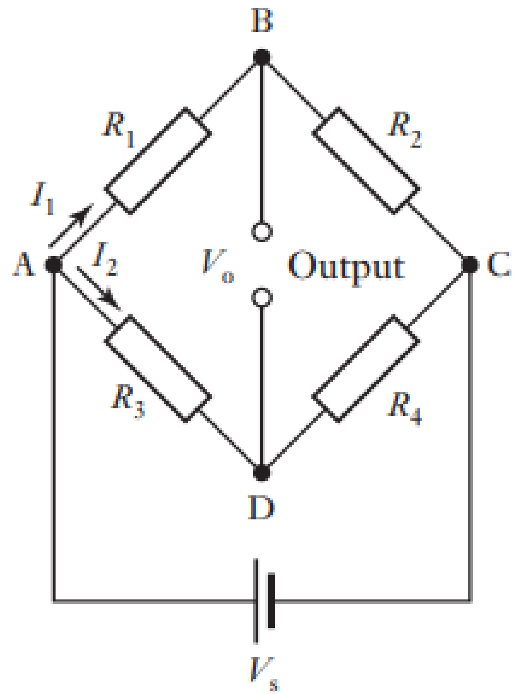
$$R = \rho \frac{\ell}{A}$$



- Strain Gauge under tension. Resistance goes up.
- Strain Gauge under compression. Resistance goes down.

Wheatstone Bridge

- The Wheatstone bridge can be used to convert a resistance change to a voltage change.
- When the output voltage Vo is zero, then the potential at B must equal that at D.
- The potential difference across R1, i.e. V_{AB}, must then equal that across R3 i.e. V_{AD}
- When the bridge is balance , $\frac{R1}{R2} = \frac{R3}{R4}$

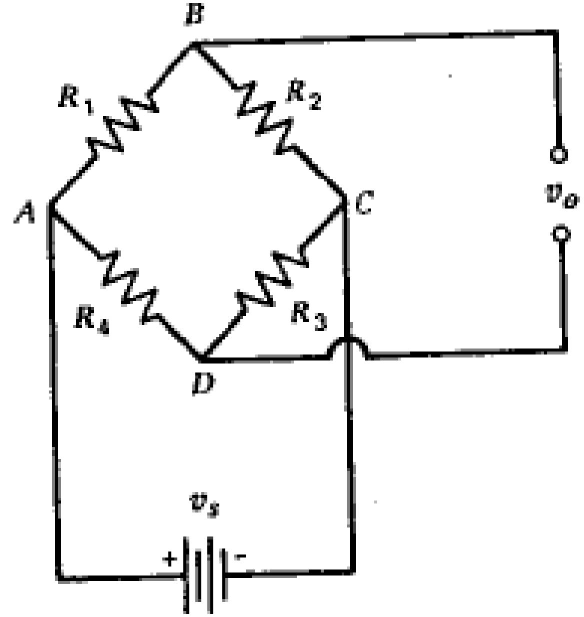


Wheatstone Bridge

$$V_{AB} = \frac{R_1}{R_1 + R_2} V_s$$

$$V_{AD} = \frac{R_4}{R_3 + R_4} V_s$$

$$V_o = \frac{R_2 R_4 - R_1 R_3}{(R_1 + R_2)(R_3 + R_4)} V_s$$



Wheatstone Bridge Sensitivity

$$\Delta V_o = \frac{(R_2 + \Delta R_2)(R_4 + \Delta R_4) - (R_1 + \Delta R_1)(R_3 + \Delta R_3)}{(R_1 + \Delta R_1 + R_2 + \Delta R_2)(R_3 + \Delta R_3 + R_4 + \Delta R_4)} V_s$$

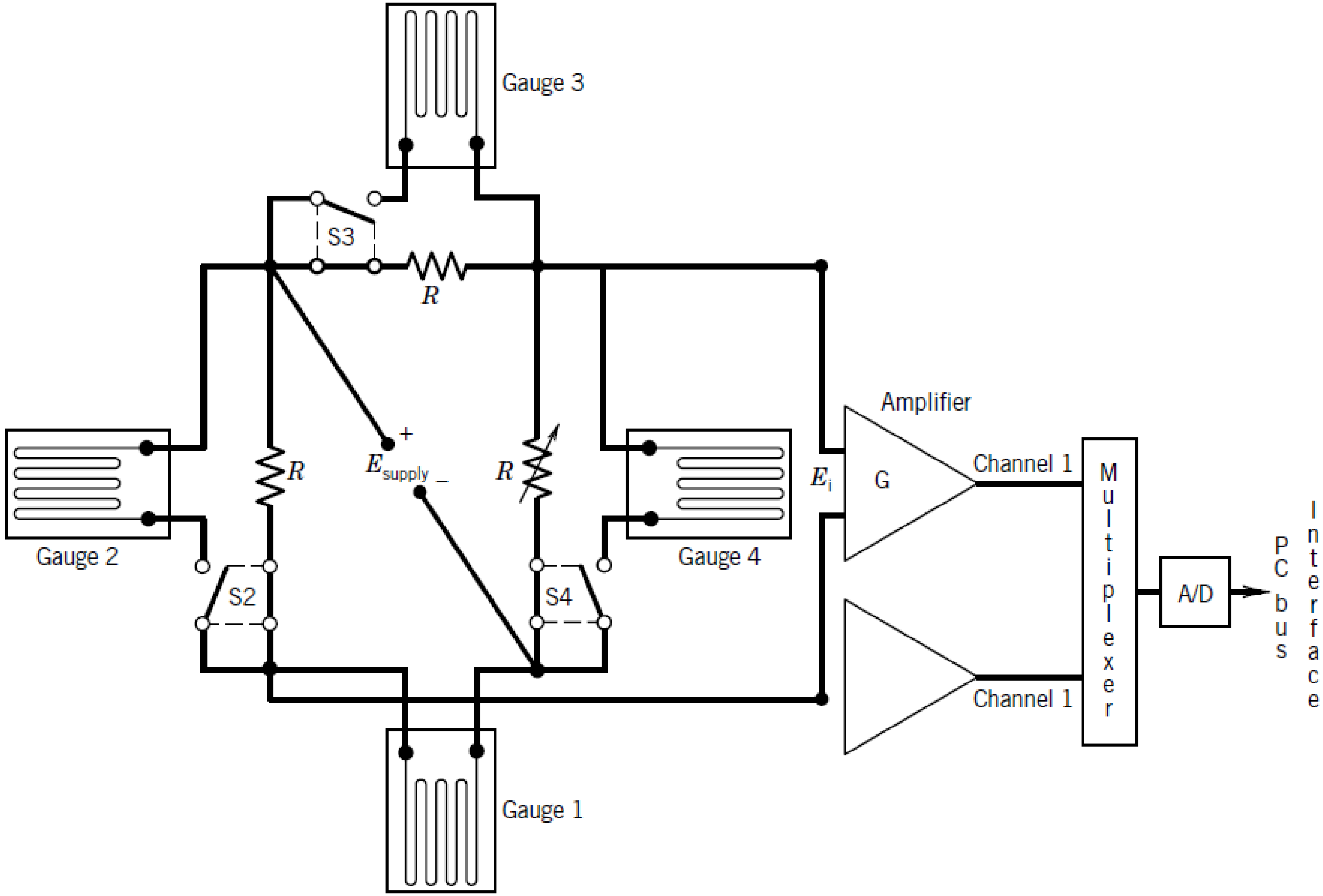
$$\Delta V_o = \frac{R_1 R_2}{(R_1 + R_2)^2} \left(\frac{\Delta R_2}{R_2} - \frac{\Delta R_1}{R_1} + \frac{\Delta R_4}{R_4} - \frac{\Delta R_3}{R_3}\right) V_s$$

$$r = \frac{R_1}{R_2} \Rightarrow \Delta V_o = \frac{r}{(1+r)^2} \left(\frac{\Delta R_2}{R_2} - \frac{\Delta R_1}{R_1} + \frac{\Delta R_4}{R_4} - \frac{\Delta R_3}{R_3}\right) V_s$$

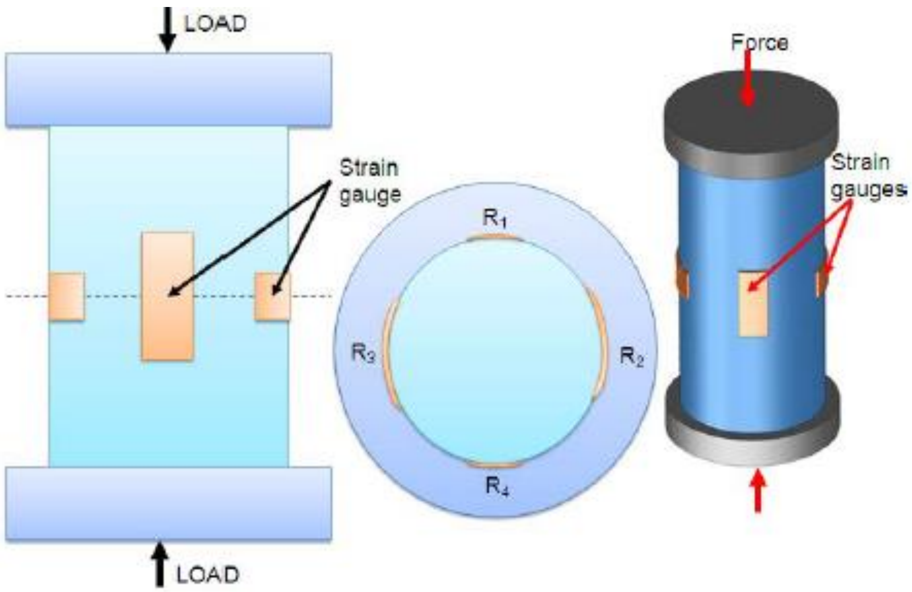
Simplifying

$$v_o = \frac{1}{4} \frac{\Delta R}{R} v_i$$

A Complete Strain Gage-based Measurement Device



Load cells



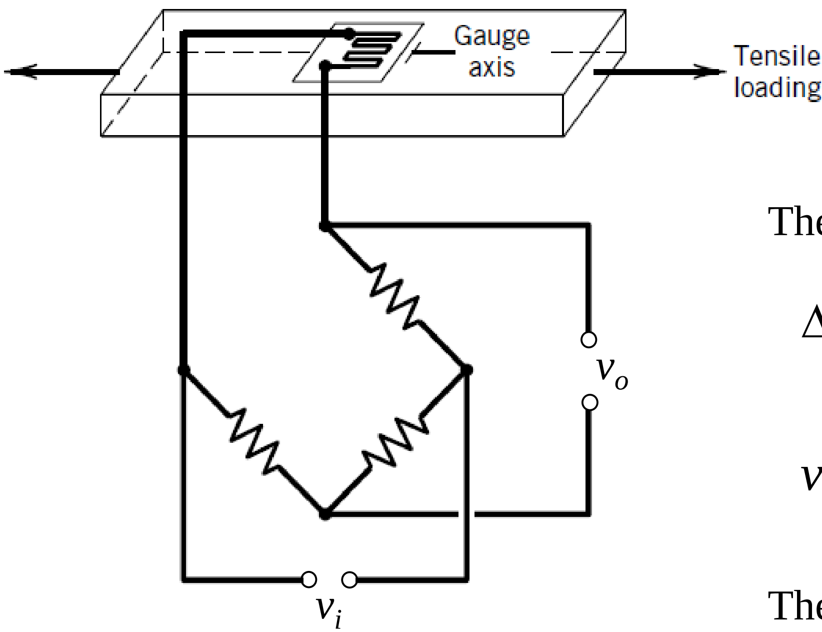
It comprises of cylindrical tube to which strain gauges are attached.

A load applied on the top collar of the cylinder compress the strain gauge element which changes its electrical resistance. Generally strain gauges are used to measure forces up to 10 MN.

The non-linearity and repeatability errors of this transducer are ±0.03% and ±0.02% respectively.

Example

A strain gauge, having a gauge factor of 2±0.01, is mounted on a rectangular steel bar (E_m =200×10^6 kN/m^2), as shown in Figure. The bar is 3 cm wide and 1 cm high, and is subjected to a tensile force of 30 kN. Determine the resistance change of the strain gauge if the resistance of the gauge was 120Ω in the absence of the axial load. In the Wheatstone bridge circuit, all the resistors are 120 Ω, v_i=10V and it is balanced without external forces. Please determine v_o. If the measurement device is required to have a resolution of 1N, please determine the gain needed for a 12-bit ±5V sampling device.



$$\varepsilon = \frac{F}{A \cdot E_m} = \frac{\Delta R / R}{GF} \Rightarrow \Delta R = \frac{F \cdot GF \cdot R}{A \cdot E_m} = 0.12\Omega$$

$$v_o = \frac{1}{4}\frac{\Delta R}{R} v_i = 0.0025V$$

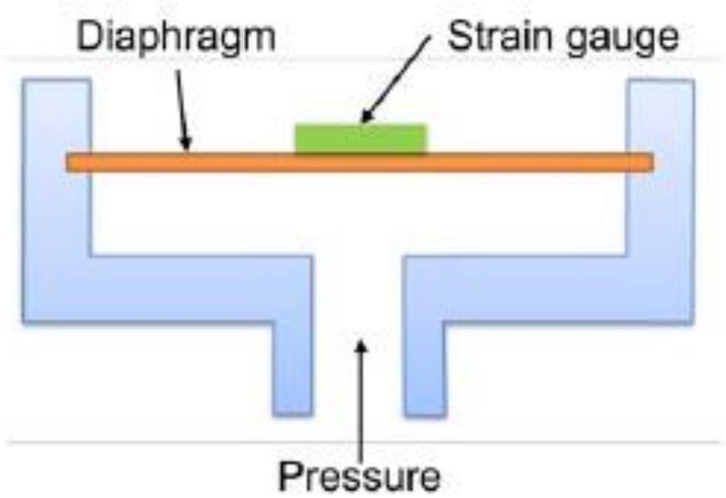
The resolution is 1N for the instrument. For 1N,

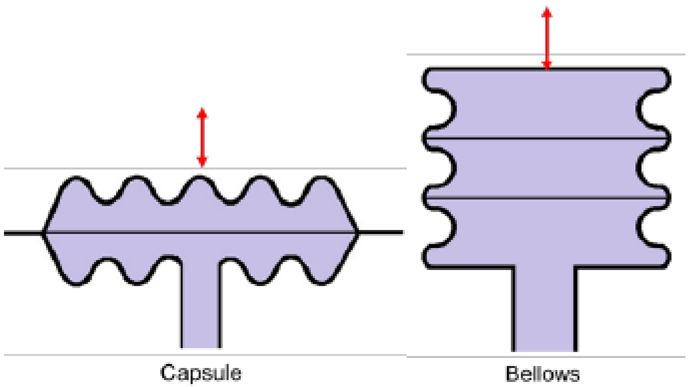
$$\Delta R = \frac{F \cdot GF \cdot R}{A \cdot E_m} = 4 \times 10^{-6}\Omega$$

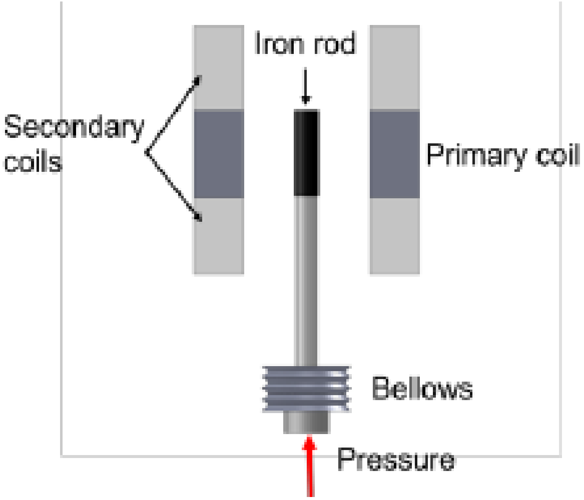
$$v_o = \frac{1}{4}\frac{\Delta R}{R} v_i = 8.33 \times 10^{-6} mV$$

The resolution for the A/D is 1/2^{12}*10=2.44mV. Hence the gain needed is 2.44/(8.33*10^{-6})=0.293*10^6

Pressure measurement Sensors

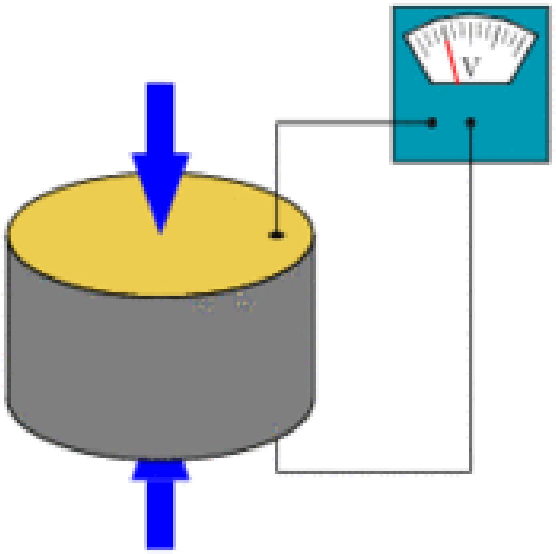






Diaphragms, capsules and bellows are made from such materials as stainless steel, phosphor bronze, and nickel, with rubber and nylon also being used for some diaphragms. Pressures in the range of about 10^3 to 10^8 Pa can be monitored with such sensors.

Piezo Electric Sensors



On application of force or pressure these materials get stretched or compressed. During this process, the charge over the material changes and redistributes.

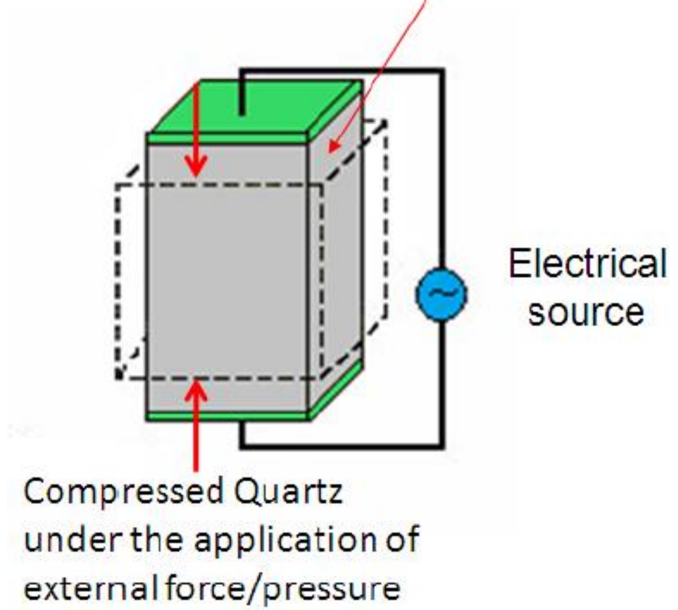
One face of the material (Quartz, PVDF, Barium titanate) becomes positively charged and the other negatively charged.

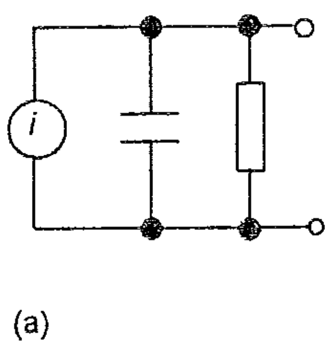
The net charge q on the surface is proportional to the amount x by which the charges have been displaced.

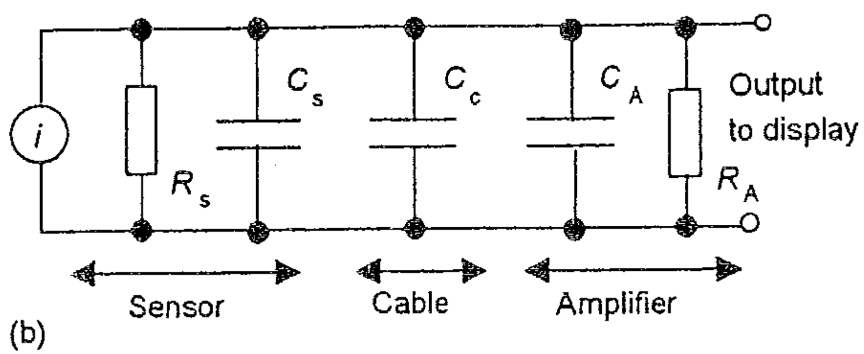
The displacement is proportion to force.

Piezo Electric Sensors

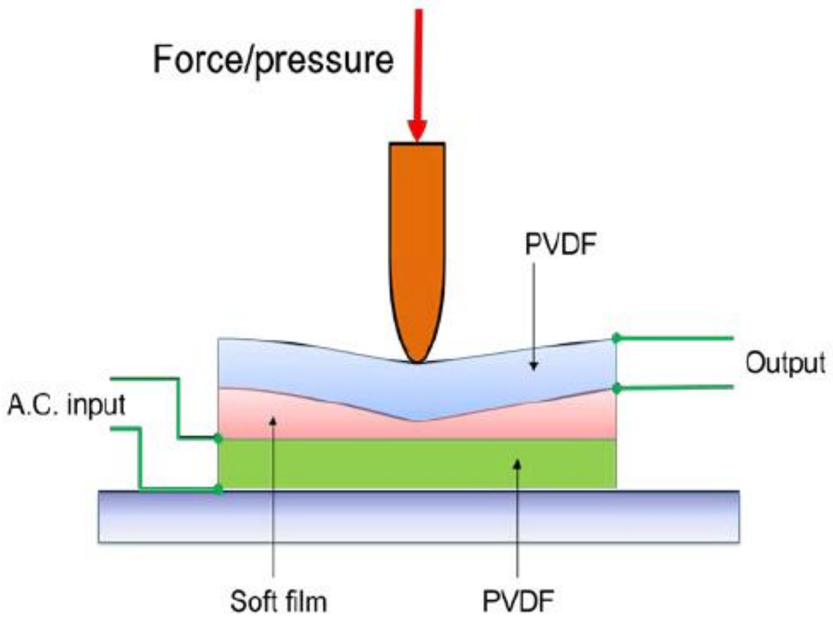
Piezoelectric Effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress.







Piezo Electric Sensors



PVDF – Polyvinylidene Flouride

It has two PVDF layers separated by a soft film which transmits the vibrations.

An alternating current is applied to lower PVDF layer which generates vibrations due to reverse piezoelectric effect.

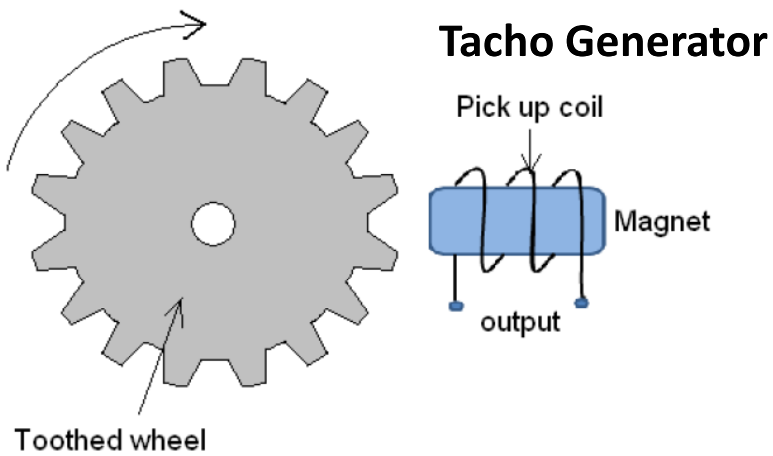
These vibrations are transmitted to the upper PVDF layer via soft film.

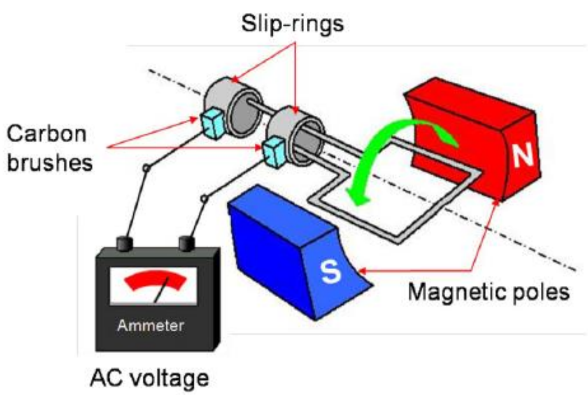
These vibrations cause alternating voltage across the upper PVDF layer.

When some pressure is applied on the upper PVDF layer the vibrations gets affected and the output voltage changes.
This triggers a switch or an action in robots or touch displays

Velocity and Motion

Tachogenerator / Alternator for angular motion





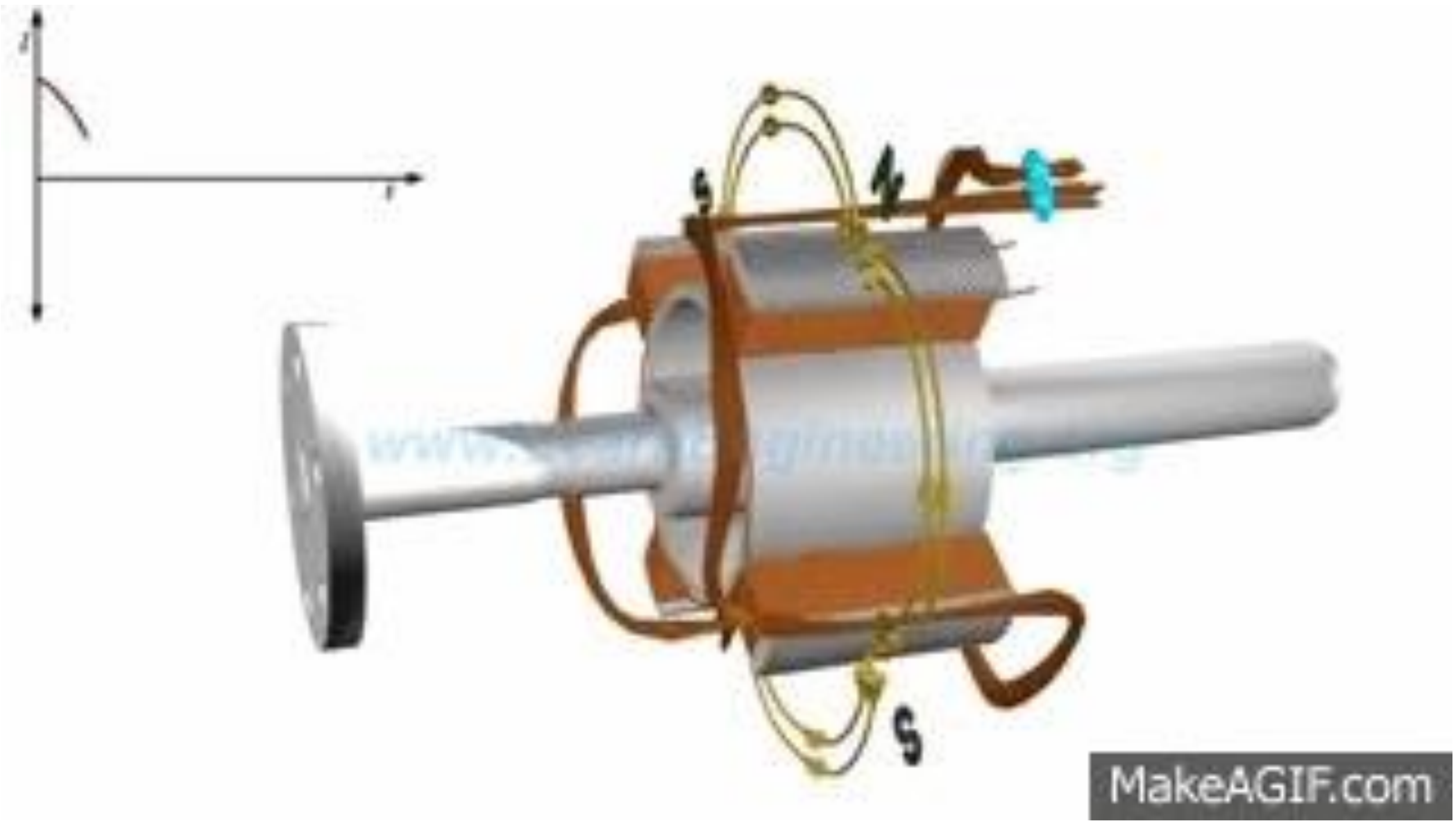
Toothed wheel is mounted on the shaft or the element of which angular motion is to be measured.

Magnetic circuit comprising of a coil wound on a ferromagnetic material core.

As the wheel rotates, the air gap between wheel tooth and magnetic core changes which results in cyclic change in flux linked with the coil.

The alternating emf generated is the measure of angular motion.

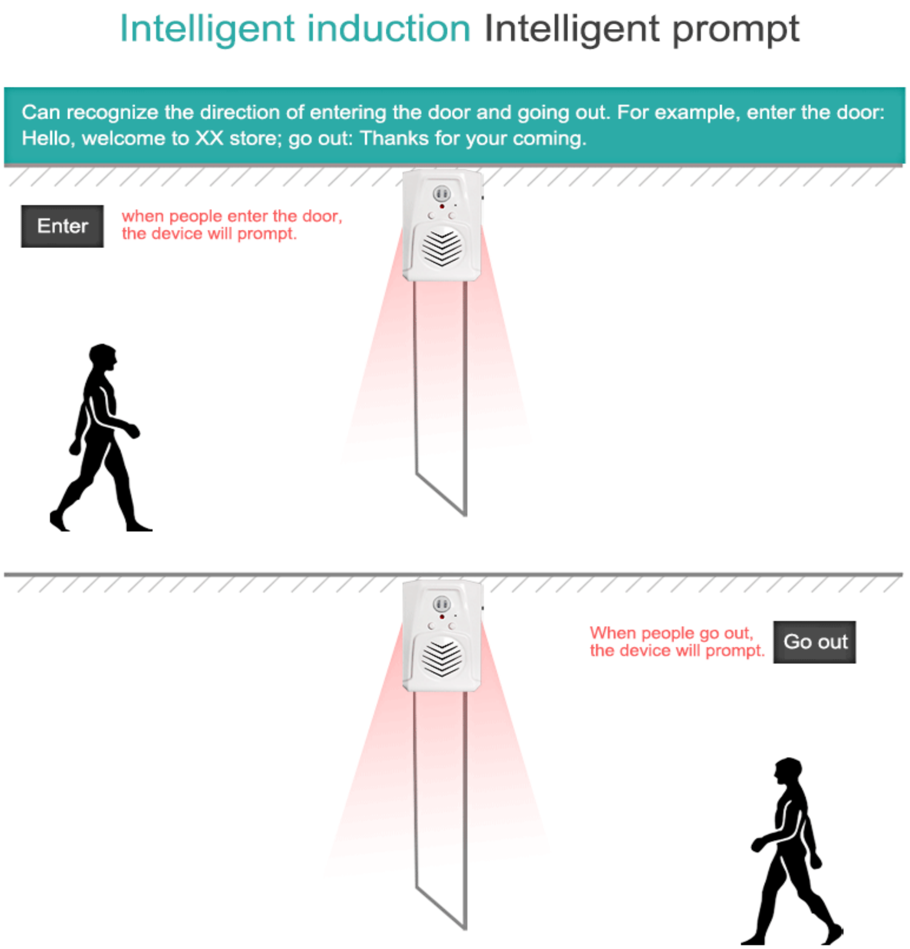
Tachogenerator / Alternator for angular motion



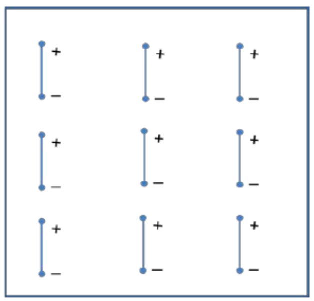
Pyroelectric Sensor (Lithium Tantalite)

- **Pyro electricity** can be described as the ability of certain **crystalline materials** to generate a temporary voltage when they are heated or cooled.
- The change in temperature modifies the positions of the atoms slightly within the crystal structure, such that the polarization of the **material** changes.

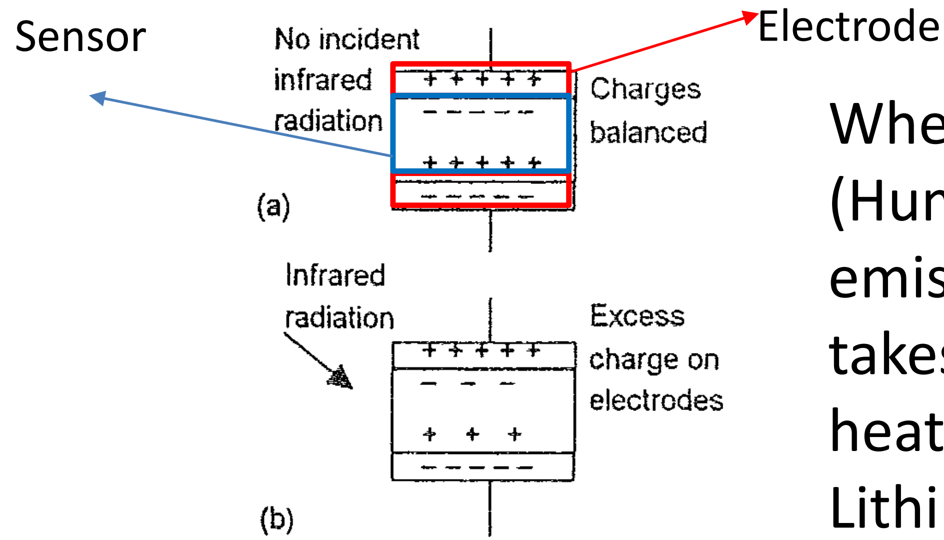
Pyroelectric Sensor (Lithium Tantalite)

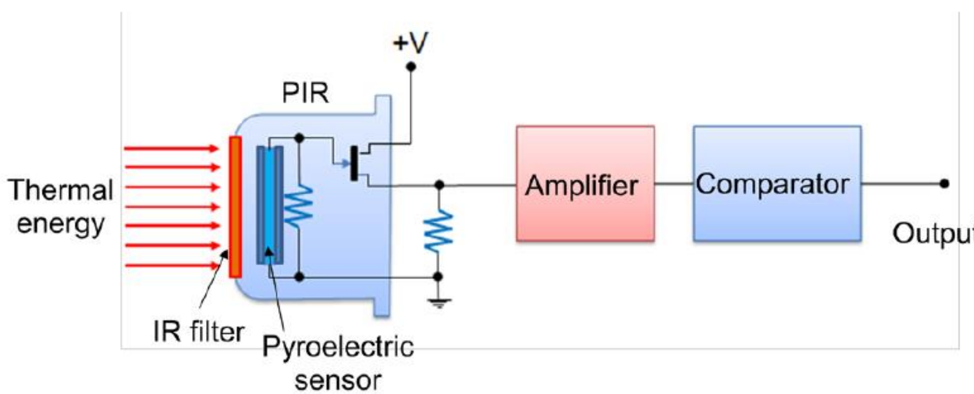


Pyroelectric Sensor (Lithium Tantalite)



Polarized Crystal





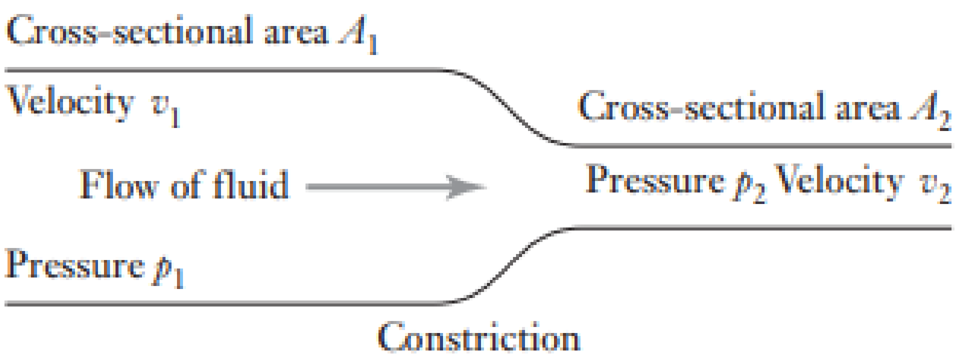
When an intruder (Human) walks emission of infrared takes place and this heats up the Lithium Tantalite crystal and it loses its polarization.

The net charge change is detected by the signal circuit.

Fluid Flow / Level

Flow measurement - Bernoulli's equation

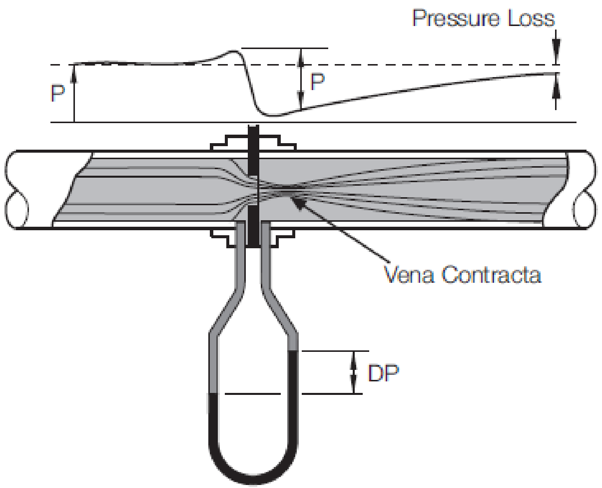
$$\frac{v_1^2}{2g} + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + \frac{p_2}{\rho g}$$



we have $A_1 v_1 \rho = A_2 v_2 \rho$. But the quantity Q of liquid passing through the tube per second is $A_1 v_1 = A_2 v_2$. Hence

$$Q = \frac{A}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

Orifice meters



$$p_1 + \frac{1}{2} \cdot \rho \cdot V_1^2 = p_2 + \frac{1}{2} \cdot \rho \cdot V_2^2$$

or:

$$p_1 - p_2 = \frac{1}{2} \cdot \rho \cdot V_2^2 - \frac{1}{2} \cdot \rho \cdot V_1^2$$

By continuity equation:

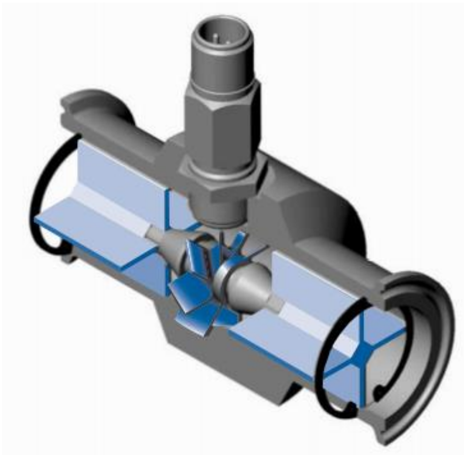
$$q_v = A_1 \cdot V_1 = A_2 \cdot V_2 \quad \text{or} \quad V_1 = q_v / A_1 \text{ and } V_2 = q_v / A_2 :$$

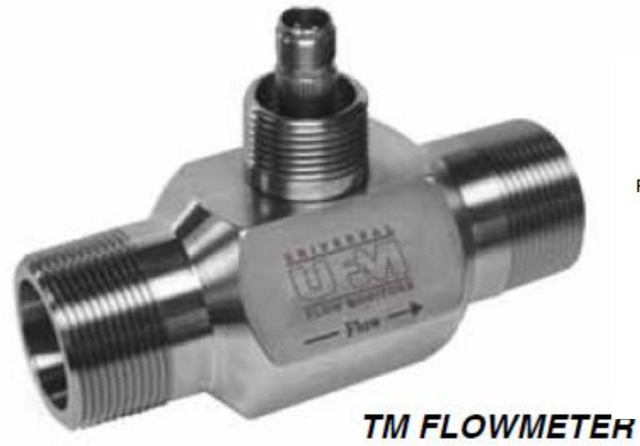
$$p_1 - p_2 = \frac{1}{2} \cdot \rho \cdot \left(\frac{q_v}{A_2}\right)^2 - \frac{1}{2} \cdot \rho \cdot \left(\frac{q_v}{A_1}\right)^2$$

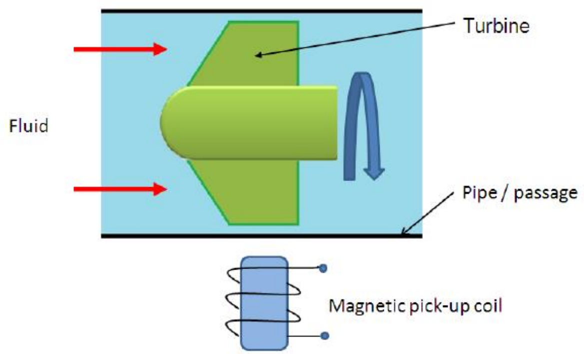
Solving for q_v:

$$q_v = A_2 \sqrt{\frac{2\,(p_1 - p_2)/\rho}{1 - (A_2/A_1)^2}}$$

Turbine flow meters





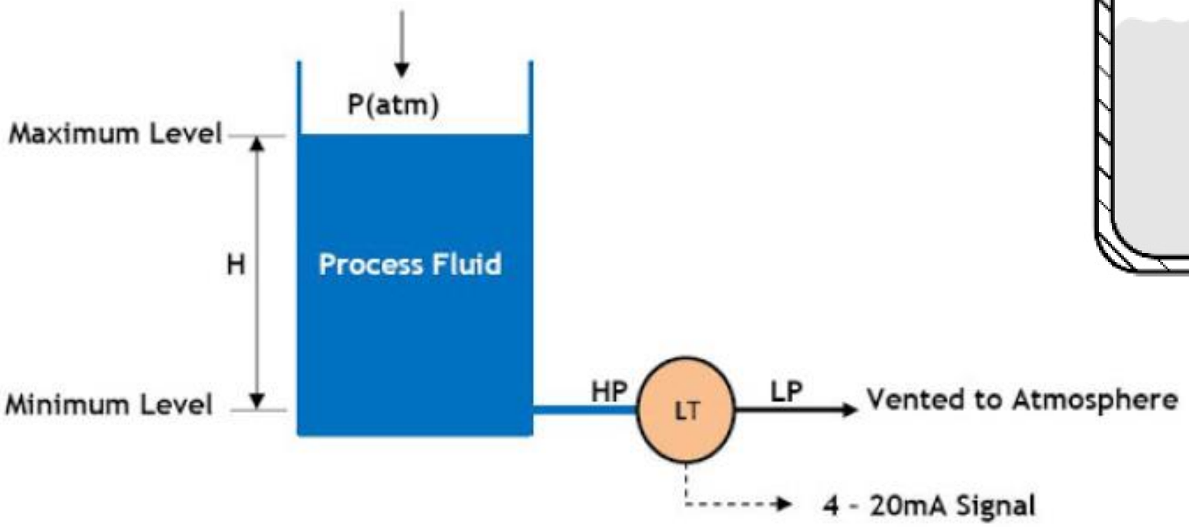


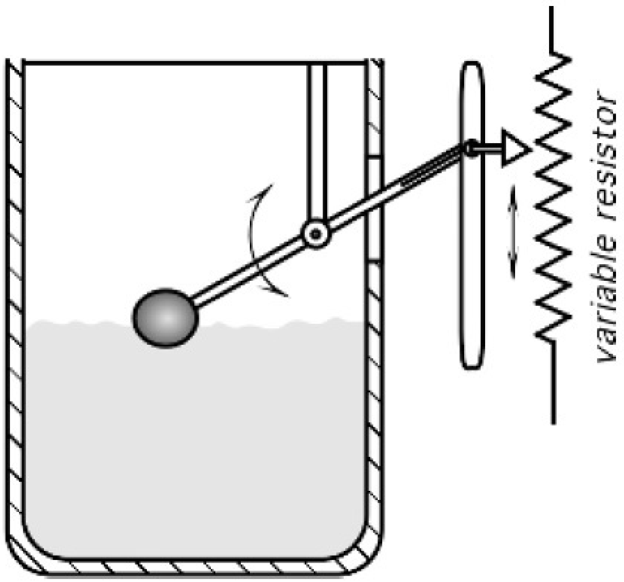
Revolution of rotor is picked by Magnetic pickup and pulses are counted.

Turbine flowmeters are less accurate at low flow rates due to rotor/bearing drag that slows the rotor.

Accuracy is 0.3% to 1.0% of flow.

Fluid level meters



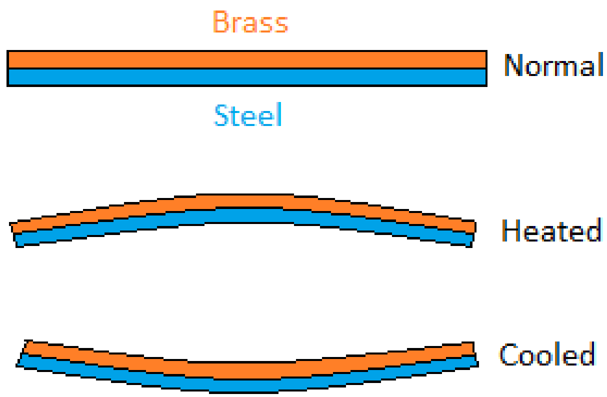


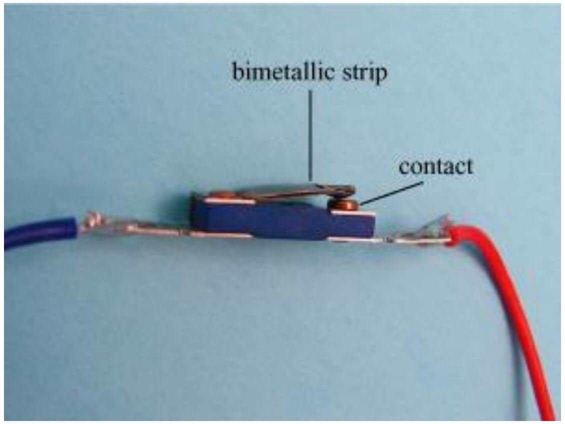
Temperature

Types of Temperature Measurement Sensor

- Bi metallic strip
- Thermo couple
- Thermistors
- RTD

Bimetal Strips





Bimetallic strips are used as thermal switch in controlling the temperature or heat in a manufacturing process or system.

It contains two different metal strips bonded together. The metals have different coefficients of expansion.

On heating the strips bend into curved strips with the metal with higher coefficient of expansion on the outside of the curve

Resistance Temperature Detectors

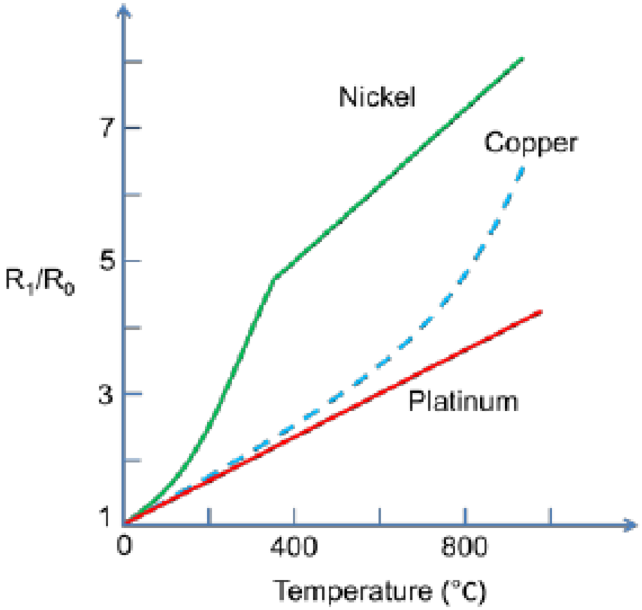
2. Resistance temperature detectors (RTDs)

RTDs work on the principle that the electric resistance of a metal changes due to change in its temperature. On heating up metals, their resistance increases and follows a linear relationship as shown in Figure 2.5.2. The correlation is

$$R_t = R_0(1 + \alpha T) \qquad (2.5.1)$$

Where R_t is the resistance at temperature T (ºC) and R_0 is the temperature at 0ºC and α is the constant for the metal termed as temperature coefficient of resistance. The sensor is usually made to have a resistance of 100 Ω at 0ºC

Resistance Temperature Detectors (RTD)



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where R_t is the resistance at temperature T (^{0}C) and R_0 is the temperature at 0^0C and α is the constant for the metal termed as temperature coefficient of resistance. The sensor is usually made to have a resistance of 100 Ω at 0 °C

Thermistors

Thermistors follow the principle of decrease in resistance with increasing temperature. The material used in thermistor is generally a semiconductor material such as a sintered metal oxide (mixtures of metal oxides, chromium, cobalt, iron, manganese and nickel) ordoped polycrystalline ceramic containing barium titanate ($BaTiO_3$) and other compounds. As the temperature of semiconductor material increases the number of electrons able to move about increases which results in more current in the material and reduced resistance.Thermistors are rugged and small in dimensions. They exhibit nonlinear response characteristics.

Thermistors are available in the form of a bead (pressed disc), probe or chip. Figure 2.5.4 shows the construction of a bead type thermistor. It has a small bead of dimension from 0.5 mm to 5 mm coated with ceramic or glass material. The bead is connected to an electric circuit through two leads. To protect from the environment, the leads are contained in a stainless steel tube.

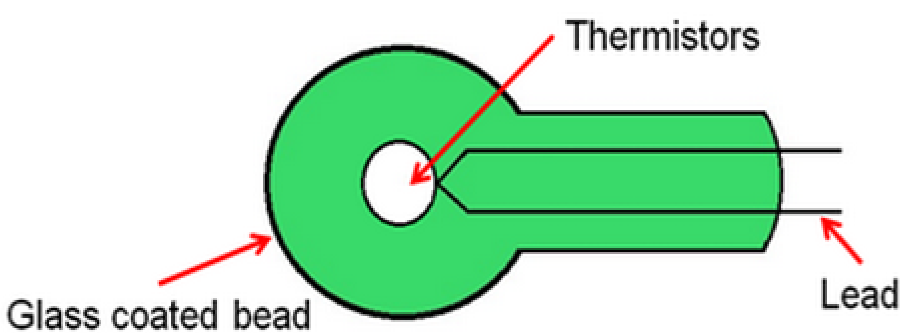
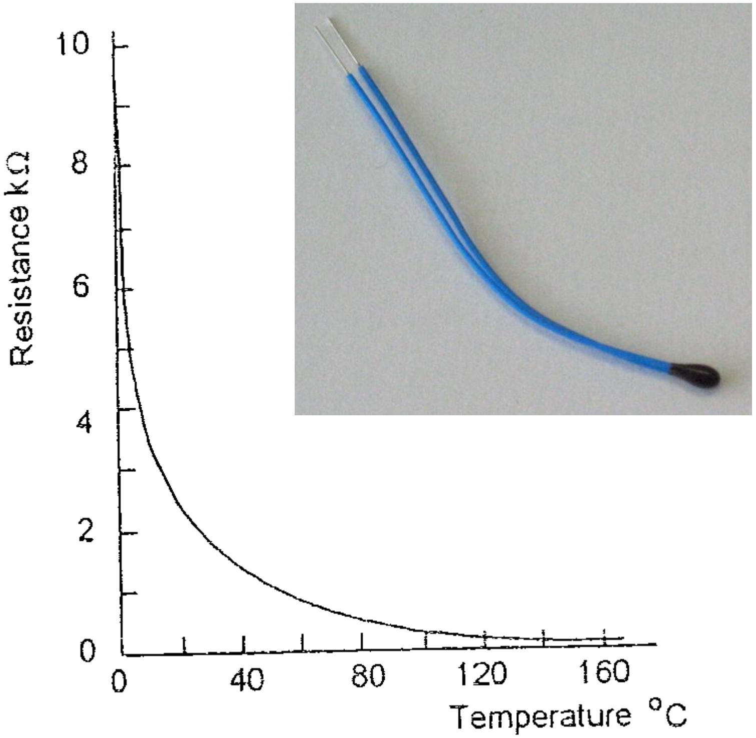


Figure 2.5.4 Schematic of a thermistor

Thermistors



Thermistors follow the principle of decrease in resistance with increasing temperature.

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Thermistors

Thermistor Resistance vs. Temperature

Model No.	44004 44033	44005 44030	44007 44034	44006 44031	44008 44032	Model No.	44004 44033	44005 44030	44007 44034	44006 44031	44008 44032
Ω 25°C	2252	3000	5000	10,000	30,000	Ω 25°C	2252	3000	5000	10,000	30,000
BODY	BLACK ORANGE	BLACK ORANGE	BLACK ORANGE	BLACK ORANGE	BLACK ORANGE	BODY	BLACK ORANGE	BLACK ORANGE	BLACK ORANGE	BLACK ORANGE	BLACK ORANGE
END	YELLOW ORANGE	GREEN BLACK	VIOLET YELLOW	BLUE BROWN	GREY RED	END	YELLOW ORANGE	GREEN BLACK	VIOLET YELLOW	BLUE BROWN	GREY RED
TEMP. °C	RESISTANCE Ω					TEMP. °C	RESISTANCE Ω				
+40	1200	1598	2663	5592	16.15K	+100	152.8	203.8	339.6	816.8	2069
41	1152	1535	2559	5389	15.52K	101	148.4	197.9	329.8	794.6	2009
42	1107	1475	2459	5193	14.92K	102	144.2	192.2	320.4	773.1	1950
43	1064	1418	2363	5006	14.35K	103	140.1	186.8	311.3	752.3	1894
44	1023	1363	2272	4827	13.80K	104	136.1	181.5	302.5	732.1	1840
45	983.8	1310	2184	4655	13.28K	105	132.3	176.4	294.0	712.6	1788
46	946.2	1260	2101	4489	12.77K	106	128.6	171.4	285.7	693.6	1737
47	910.2	1212	2021	4331	12.29K	107	125.0	166.7	277.8	675.3	1688
48	875.8	1167	1944	4179	11.83K	108	121.6	162.0	270.1	657.5	1640
49	842.8	1123	1871	4033	11.39K	109	118.2	157.6	262.6	640.3	1594
+50	811.3	1081	1801	3893	10.97K	+110	115.0	153.2	255.4	623.5	1550

$$R_t = K e^{\beta/t}$$

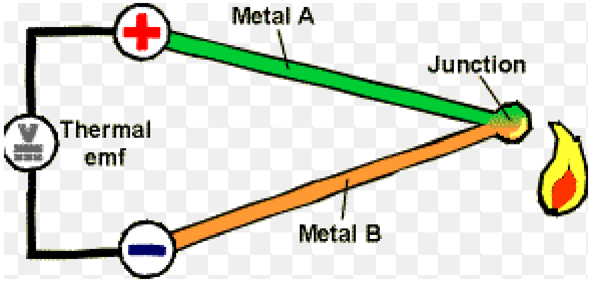
where R_t is the resistance at temperature t, with K and β being

Thermocouples

Thermocouple works on the fact that when a junction of dissimilar metals heated, it produces an electric potential related to temperature. As per Thomas Seebeck (1821), when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, then there is a continuous current which flows in the thermoelectric circuit. Figure 2.5.5 shows the schematic of thermocouple circuit. The net open circuit voltage (the Seebeck voltage) is a function of junction temperature and composition of two metals. It is given by,

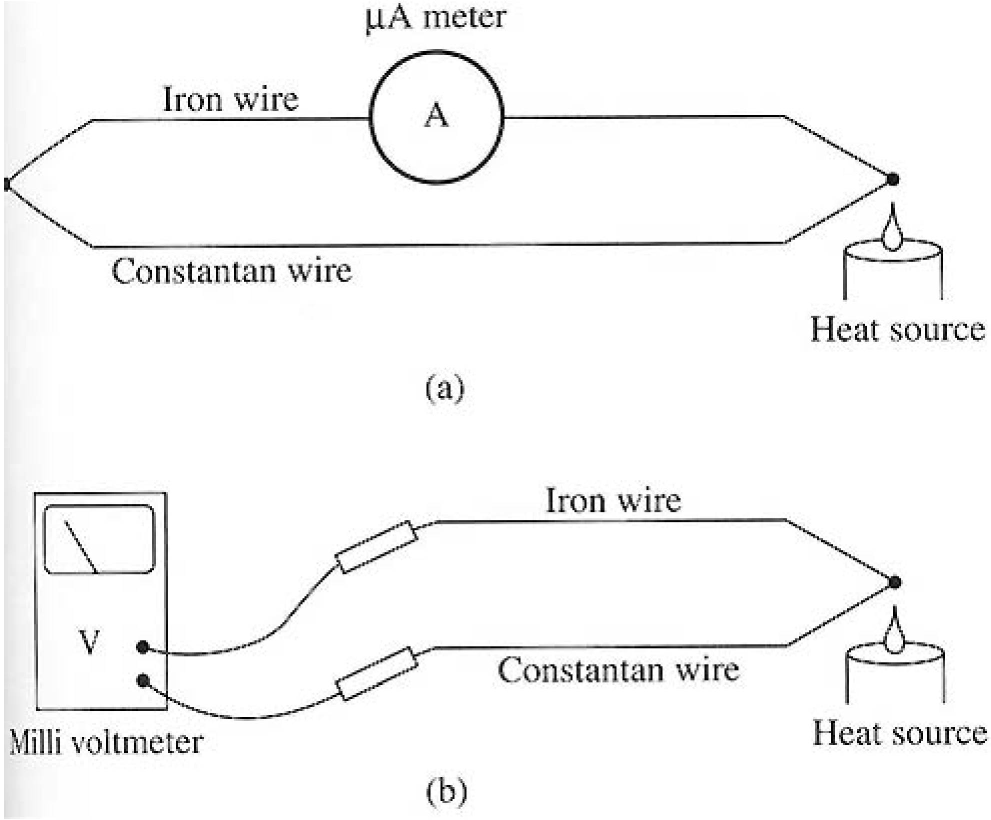
$$\Delta V_{AB} = \alpha \Delta T$$

Where α, the Seebeck coefficient, is the constant ofproportionality.

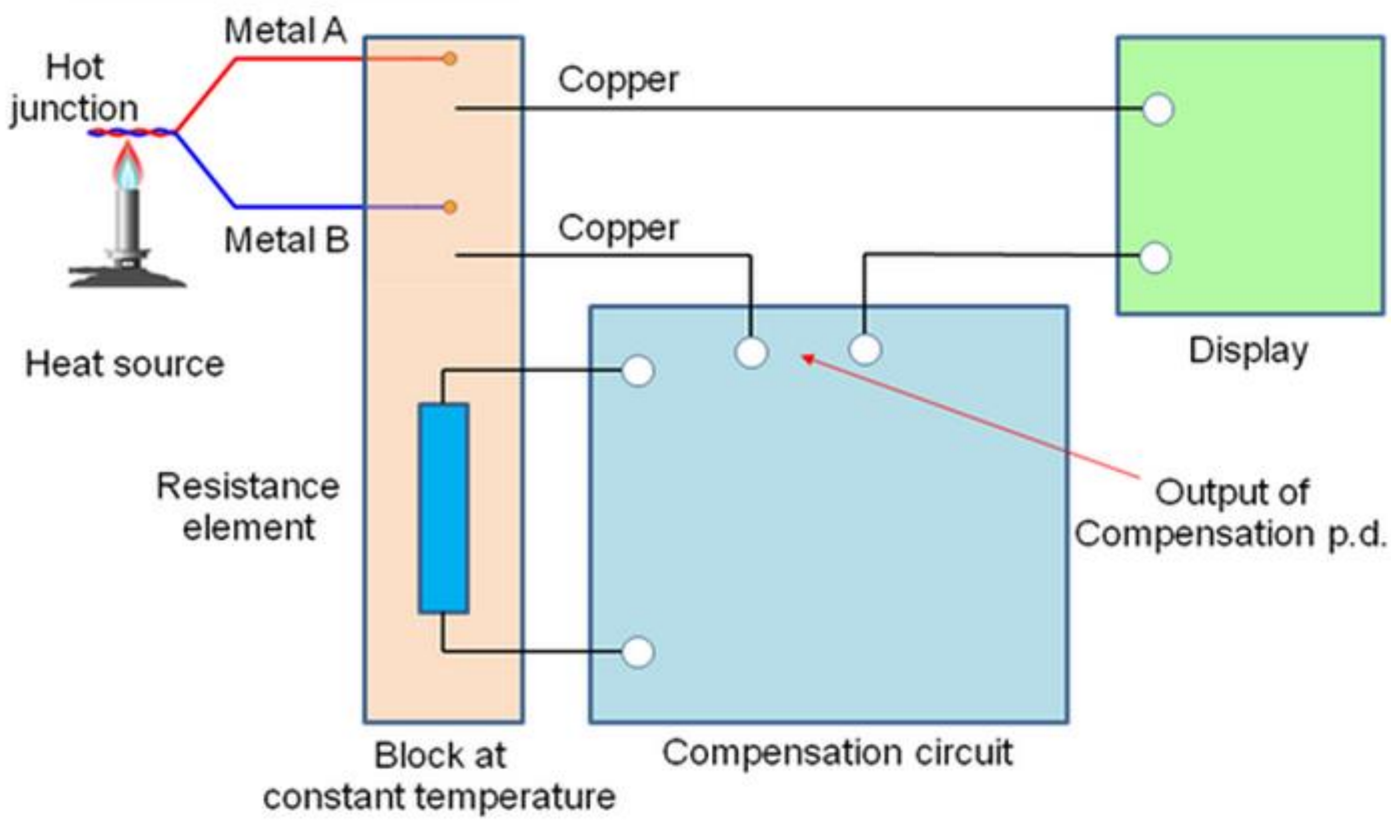


Generally, Chromel(90% nickel and 10% chromium)–Alumel(95% nickel, 2% manganese, 2% aluminium and 1% silicon) are used in the manufacture of a thermocouple. Table 2.5.1 shows the various other materials, their combinations and application temperature ranges.

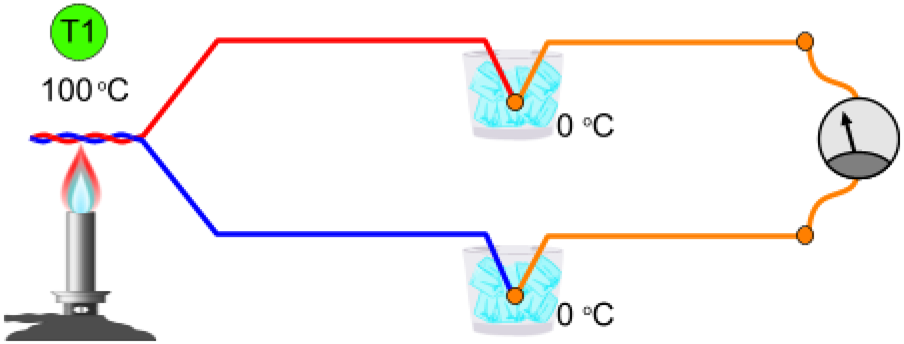
Thermocouples

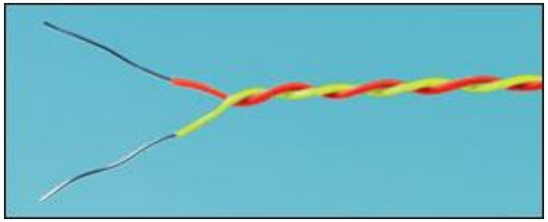


Thermocouples



Thermocouples





Hot Junction (Or the junction to be measured)

Cold junction (Reference Junction)

Thermocouple works on the fact that when a junction of dissimilar metals heated, it produces an electric potential related to temperature

. As per Thomas Seebeck (1821), when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, then there is a continuous current which flows in the thermoelectric circuit.

Useful to measure very high temperatures and quiet inexpensive

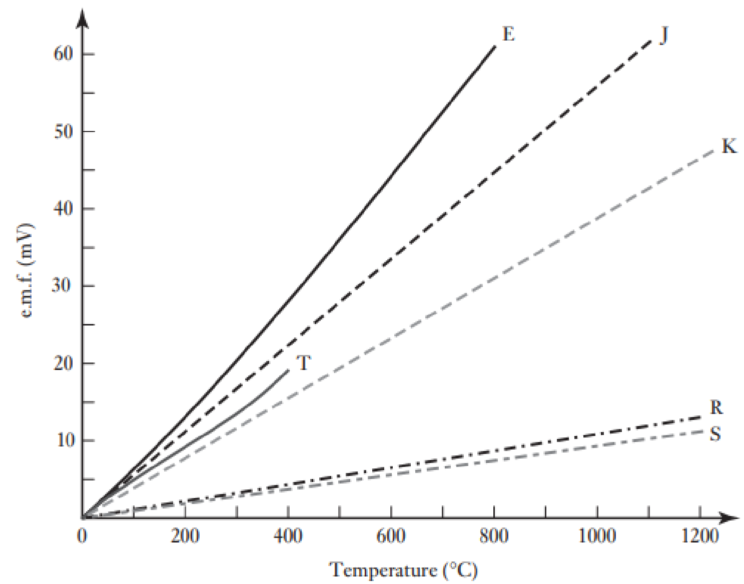
Thermocouples

$$E = at + bt^2$$

a, b are constants for the metal combinations

E- EMF
T- Temperature

Ref.	Materials	Range °C	μV/°C
B	Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
E	Chromel/constantan	−200 to 1000	63
J	Iron/constantan	−200 to 900	53
K	Chromel/alumel	−200 to 1300	41
N	Nirosil/nisil	−200 to 1300	28
R	Platinum/platinum 13% rhodium	0 to 1400	6
S	Platinum/platinum 10% rhodium	0 to 1400	6
T	Copper/constantan	−200 to 400	43

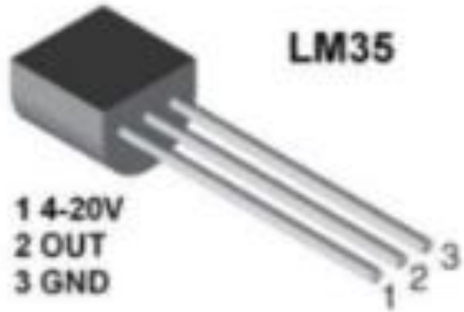


(b)

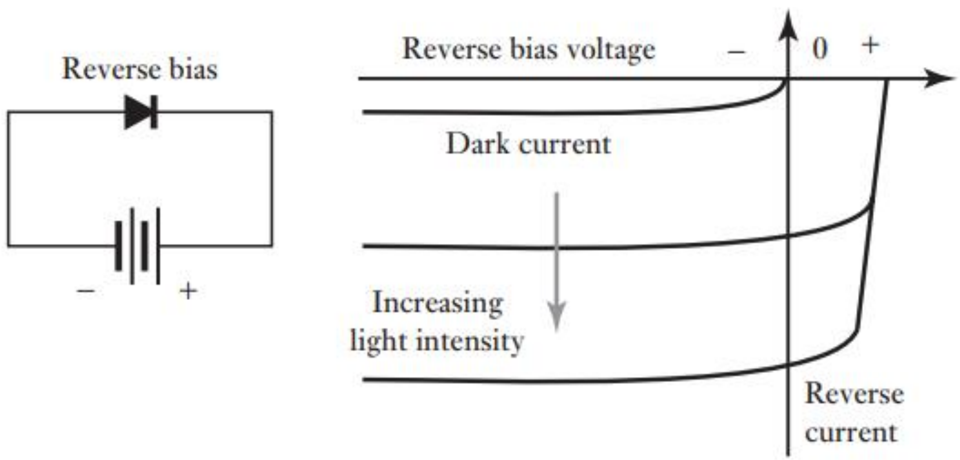
LM35 Temperature Sensor

- LM35-2The temperature sensors have well known applications in environmental and process control and also in test, measurement and communications.

- A digital temperature is a sensor, which provides 9-bit temperature readings. Digital temperature sensors offer excellent precise accuracy, these are designed to read from 0°C to 70°C and it is possible to achieve ±0.5°C accuracy.



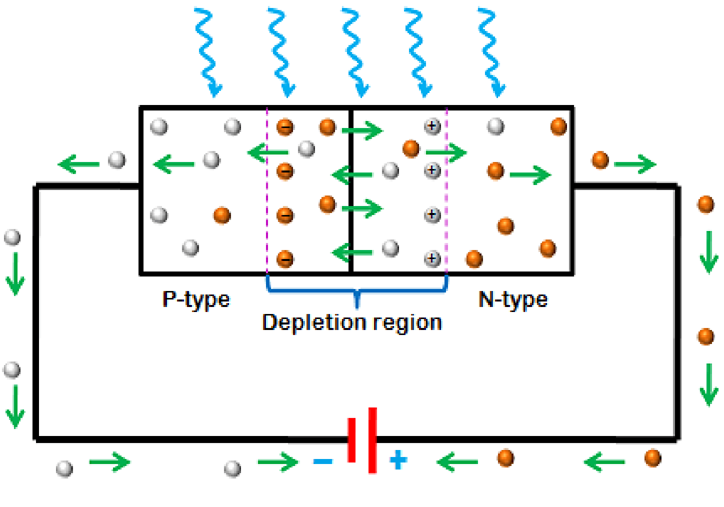
Light Sensors



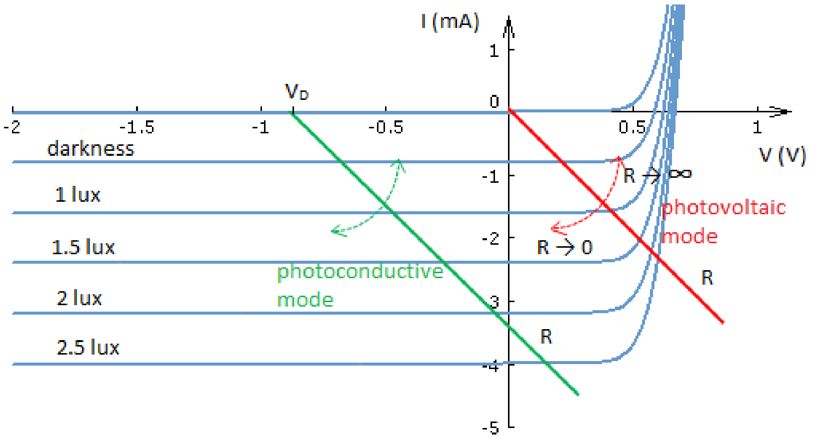
(a) (b)

- Photodiodes are semiconductor junction diodes -connected into a circuit in reverse bias giving a very high resistance.
- With no incident light, the reverse current is almost negligible and is termed the dark current.
- When light falls on the junction, extra hole–electron pairs are produced and there is an increase in the reverse current and the diode resistance drops.
- The reverse current is very nearly proportional to the intensity of the light.

Photodiodes



PN Junction photodiode



Without light, @ reverse bias of 3V, current could be 25µA, Resistance is 120KΩ,

With light of 25K Lumes/Sqm , the current raises to 375µA, Resistance is 8KΩ

Selection of Sensors

Variable to be measured
Nominal value
Range of values
Accuracy required
Required speed of measurement
Reliability of device
Environmental conditions
Nature of output of sensor

Solved Numerical

- Sensitivity of thermocouple is 0.01V/°C. Find the output voltage if input temp. is 200 °C Also find temp. at 3.5 V output

Ans

Sensitivity = change in output / change in input

S = 0.01V/°C

For input = 200 °C,

S = 0.01V/°C = Δo / 200 hence find Δo

For output = 3.5 V

S = 0.01V/°C= 3.5V / Δi hence find Δi

- What will be the change in resistance of an electrical resistance strain gauge with a gauge factor of 2.1 and resistance 50 ohm if it is subject to a strain of 0.001?

Ans

$$GF = \frac{\Delta R / R}{\varepsilon}$$

- A potentiometer is used as a position sensor. The voltage applied is 20V DC. If the maximum angle turned is 300° for potentiometer. Calculate the output voltage at 120°

Ans –

Min voltage = 0 V – Min displacement = 0°

Max voltage = 20V – Max. displacement = 300 °

Sensitivity = change in output / change in input = 20 / 300

Calculate output voltage = Sensitivity x i/p

- A shaft encoder is to be used with a 50 mm radius tracking wheel to monitor linear displacement. If the encoder produces 256 pulses per revolution, what will be the number of pulses produced by a linear displacement of 200 mm?
- R=50mm
- Circumference = 2πR = 2 x 3.14 x 50 =
- Revolution = 360° = 256 PPR
- Resolution = 256 / 2πR
- 200mm displacement pulses generated = 200 x 256 / 2πR = Ans

- A strain gauge and bridge circuit is used to measure tensile force in a bar, which has a c/s area 50mm^2. The SG has a GF of 2 and nominal resistance of 120Ω. The bridge is supplied with 10V. When the bar is unloaded, output is 0V. Then the force is applied to the bar, bridge voltage is 0.0005V. Find the force applied on the bar if E = 2.1 x 10^5 MPa.

Ans

$$GF = \frac{\Delta R / R}{\varepsilon}$$

$$v_o = \frac{1}{4}\frac{\Delta R}{R} v_i =$$

A pressure sensor consisting of a diaphragm with strain gauges bonded to its surface has the following information in its specification:

Ranges: 0 to 1400 kPa, 0 to 35 000 kPa
Non-linearity error: ±0.15% of full range
Hysteresis error: ±0.05% of full range

What is the total error due to non-linearity and hysteresis for a reading of 1000 kPa on the 0 to 1400 kPa range?

$$\%\text{non linearity error} = \frac{\textit{Max.deviation in input}}{\textit{Full scale}} \times 100$$

± 0.15 = MV-SP / 1400 = (MV – 1000)/1400

Hence find ±MV for non linearity error

$$\%\text{Hysteresis error} = \frac{\textit{Max.deviation in input}}{\textit{Full scale}} \times 100$$

± 0.05 = MV-SP / 1400 = (MV – 1000)/1400

Hence find ±MV for hysteresis error

Total error = non linearity error + hysteresis error

- You are offered a choice of an incremental shaft encoder or an absolute shaft encoder for the measurement of an angular displacement. What is the principal difference between the results that can be obtained by these methods?

Home work Time!

Mechatronics by W. Bolton, 4th Edition, Pearson

2.14, 2.15,2.16,2.17,2.18

Thank you