Chapter - 6

Physical Variables and Transducers

Transducers :

Basically transducer is defined as a device which converts energy or information from one form to another. A device which converts physical quantities into equivalent electrical quantities is known as electrical transducer. An electrical transducer transfers or converts a physical, mechanical or optical quantity to be measured directly or with a suitable mechanism into an electrical signal current, voltage or frequency.

* Classification of Transducers :

1) Primary and secondary Transducers :

A transducer in which physical quantities (input signal) is converted into the electrical form directly is known as primary transducer.

Eg :- Thermistor used in temperature measurement

A transducer in which input is sensed first by some detector or sensor and then the output of sensor or detector being in the form other than input is converted into electrical form is known as secondary transducer eg: LVDT

2) Active and Passive transducers :-

A self generating type transducer which do not requires external power is known as active transducer eg : Thermo Couple

A transducer which requires an external power source for energy conversion is known as passive transducer

Eg : strain gauge

3) Analog and Digital transducers :

A transducer which converts input signal into output signal which is a continuous function of time is known as analog transducer

eg : Strain gauge, LVDT, thermocouple etc

A transducer which converts input signal into output signal in the form of pulses is known as digital transducer

* Selection of Transducers :

The points to be considered in determining a tranducer suitability for a specific measurement are:

1 Range :

The range of the transducer should be large enough to encompass all the expected magnitudes of the measurand.

2 Sensitivity :

The transducer should give a sufficient output signal per unit of measured input inorder to yield meaningful data.

3 Electrical Output characteristics:-

The electrical characteristics such as the output impedance frequency response, and the response time of the transducer output signal should be compatible with the recording device and the rest of the measuring system equipment.

4 Physical Environment:-

The selected transducer must be compatible to withstand the environmental conditions in which measurement performed.

5 Errors :-

The errors due to operation of transducer itself or due to environmental condition must be controllable ~~compatible to~~ enough to take meaningful data under measurement.

* Requirement of good transducer:

1) Ruggedness :-

It should be capable of withstanding overload and some safety arrangement should be provided for overload protection.

2 Linearity:

Its input-output characteristics should be linear and it should produce these characteristics in symmetrical way.

3 Repeatability :-

It should produce same output signal when the same input signal is applied again and again under fixed environmental conditions eg:- temperature, pressure, humidity etc.

4 High output signal quality:-

The quality of output signal should be good i.e the ratio of the signal to noise should be high and the amplitude of the output signal should be enough.

5 High Reliability and Stability:-

It should give minimum error in measurement for temperature variations and vibrations, other various change in surrounding.

6 Good dynamic response :-

It's output should be faithful to input when taken as a function of time. The effect is analysed as the frequency response.

7 No hysteresis:-

It should not give any hysteresis during measurement while input signal is varied from it's low value to high value and vice versa.

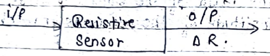
8 Residual Deformation:

There should be no deformation on removal of input signal after long period of application.

* Types of Transducers:

1. Resistive transducers:

In such transducer, resistance between the output terminals of a transducer get varied according to the measurand. Resistive transducers are preferred over other transducers because dc and ac both are suitable resistance measurement.



Potentiometric Transducers

It is an electromechanical device containing a resistance element that is contacted by a movable slider. The motion of slider result in a resistance change which may be linear, logarithmic, exponential and so depending on the manner of resistance wire winding. This transducer converts linear or rotational displacement into a voltage.

The figure below shows the basic diagram of a potentiometric transducer.

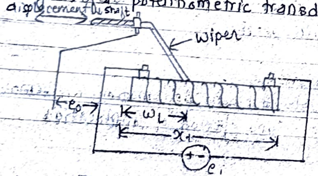


Fig:1 Linear POT

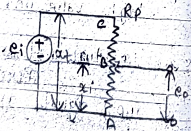


Fig:2 Equivalent circuit of Fig (1)

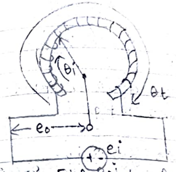


Fig3: Rotatory POT.

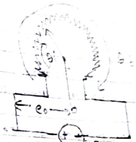


Fig: Equivalent ckt for Fig(3)

Let, total resistance of the potentiometer $= R_P$

total length of potentiometer $= x_t$.

So, resistance per unit length $= R_P/x_t$.

displacement $= x_i$

resistance of displacement $= R_{AB} = \frac{R_P}{x_t} \cdot x_i$

$$= \frac{x_i}{x_t} \cdot R_P.$$

$$\therefore R_{AB} = K R_P.$$

where,

$$K = \frac{x_i}{x_t} \quad \& \quad 0 \leq K \leq 1.$$

The ideal O/P voltage is given by:

$$e_0 = \frac{R_{AB}}{R_{AB} + R_{BC}} \, e_i$$

$$e_0 = \frac{K R_P}{R_P} \cdot e_i$$

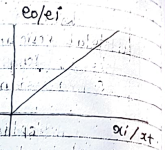
$$\therefore e_0 = K e_i = \frac{x_i}{x_t} e_i \quad \text{—— (I)}$$

$$\therefore \frac{e_0}{x_i} = \frac{e_i}{x_t} = \text{constant} \quad \text{—— (II)}$$

$$\therefore \frac{e_o}{e_i} = \frac{x_i}{x_t} \quad \text{—— (III)}$$

Thus, there exist a linear relation between output and input as shown in figure.

Sensitivity of the device is given by:



$$S = \frac{\text{mag. of O/P}}{\text{mag. of I/P}}$$

$$\text{or, } S = \frac{e_o}{e_i} = \frac{x_i}{x_t} = \text{constant} \quad \text{(IV)}$$

Thus, the sensitivity of the device is also constant. Also, the equation from (I) to (IV) is applicable for rotatory potentiometer if $x_i \to \theta_i$ and $x_t \to \theta_t$.

ie

$$e_o = ke_i = \frac{\theta_i}{\theta_t} e_i \quad \text{—— (Ia)}$$

$$\frac{e_o}{\theta_i} = \frac{e_i}{\theta_t} = \text{constant} \quad \text{—— (IIa)}$$

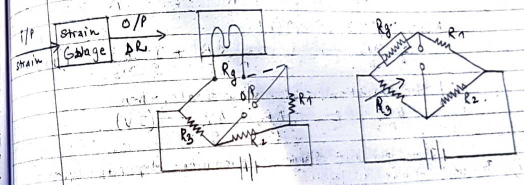
$$\frac{e_o}{e_i} = \frac{\theta_i}{\theta_t} \quad \text{—— (IIIa)}$$

$$S = \frac{e_o}{\theta_i} = \frac{e_i}{\theta_t} \quad \text{—— (IV)a}$$

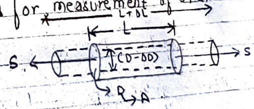
Strain Gauge:-

A strain is a thin, wafer like device that can be attached to a variety of materials to measure applied strain. It is a passive transducer that converts a mechanical displacement into a change of resistance.

Principle of operation



It is one of the example of resistive sensor and it is used for measurement of strain.



The unstrained resistance is given by

$$R = \frac{\rho L}{A} \quad \text{—— (I)}$$

When a tensile stress 'S' is applied, there will be change in resistance not only due to the change in physical dimension but also due to the change in resistivity. This effect is known as piezo-resistive effect. Thus, piezo-resistive effect is defined as change in resistance due to change in resistivity.

Differentiating eq^n (I) partially with respect to 's'

$$\frac{\partial R}{\partial s} = \frac{\partial}{\partial s}\left[\frac{\rho L}{A}\right]$$

or, $$\frac{\partial R}{\partial s} = \frac{\rho}{A}\frac{\partial L}{\partial s} - \frac{\rho L}{A^2}\frac{\partial A}{\partial s} + \frac{L}{A}\frac{\partial \rho}{\partial s} \quad \text{—(II)}$$

Now, eq^n (II) ÷ eq^n (I)

$$\frac{1}{R}\frac{\partial R}{\partial s} = \frac{1}{L}\frac{\partial L}{\partial s} - \frac{1}{A}\frac{\partial A}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s} \quad \text{—(III)}$$

If the variation is very very small, then

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \quad \text{—(IV)}$$

Thus per unit change in resistance depends upon:

i) Per unit change in length
ii) per unit change in area of cross-section
iii) Per unit change in resistivity

As we know $A = \frac{\pi D^2}{4}$ —(V)

$$\therefore \frac{\partial A}{\partial s} = \frac{\pi}{4} 2D \cdot \frac{dD}{\partial s} \quad \text{—(VI)}$$

Now, eq^n (VI) ÷ (V)

$$\frac{1}{A}\frac{\partial A}{\partial s} = \frac{2}{D}\frac{\partial D}{\partial s} \quad \text{—(VII)}$$

From eq^n (VII) and (III) we get,

$$\frac{1}{R}\frac{\partial R}{\partial s} = \frac{1}{L}\frac{\partial L}{\partial s} - \frac{2}{D}\frac{\partial D}{\partial s} + \frac{1}{\rho}\frac{d\rho}{ds} \quad \text{—(VIII)}$$

If the variation is very very small, then

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{2\Delta D}{D} + \frac{\Delta \rho}{\rho} \quad \text{—(IX)}$$

Poisson's ratio is denoted by,

$$\mu = \frac{\text{lateral strain}}{\text{longitudinal strain}}$$

$$\mu = -\frac{(\Delta D/D)}{(\Delta L/L)}$$

or, $$-\frac{\Delta D}{D} = \mu\frac{\Delta L}{L}$$

$$\therefore -\frac{\Delta D}{D} = \mu\epsilon \quad \text{—(X)}$$

where, $\epsilon = \frac{\Delta L}{L}$ = strain

From eq^n (IX) and (X)

$$\frac{\Delta R}{R} = \epsilon + 2\mu\epsilon + \frac{\Delta \rho}{\rho} \quad \text{—(XI)}$$

Gauge Factor (G):

It is defined as ratio of per unit change in resistance to per unit change in length.

$$\therefore G = \frac{(\Delta R/R)}{(\Delta L/L)}$$

or, $$\frac{\Delta R}{R} = G\frac{\Delta L}{L} = G\epsilon \quad \text{—(XII)}$$

From eq^n (XI) and (XII)

$$G\epsilon = \epsilon + 2\mu\epsilon + \frac{\Delta \rho}{\rho}$$

$$G = 1 + 2\mu + \frac{\Delta \rho/\rho}{\epsilon}$$

If the effect of resistivity is neglected, then.

$$G = 1 + 2\omega \quad \text{—(XIV)}$$

Though, strain is a unitless quantity, it is expressed in microstrain

$$E = \frac{\Delta L}{L}$$

$$1 \text{ micro-strain} = \frac{1\,\mu m}{1 m}$$

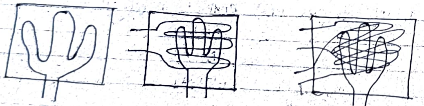
$$\therefore E = 8 \text{ micro-strain} = 8 \times 10^{-6}$$

→ Tensile strain is taken as positive where compressive strain is taken as negative.

1 A compressive strain of 5 micro-strain is applied,

$$E = -5 \text{ micro-strain}$$
$$= -5 \times 10^{-6}$$

Strain guage is available in varity of configuration. Such as vaiaxial, biaxial or multidirectional, based on strain to be measured.



a) Uniaxial strain guage.

b) Two element strain guage

c) Three different element resetter

Application of strain guage:-

1) It extensively used for analyzing the dynamic strains in complex structures, such as stress and strainbridges, automobiles, roads etc.

2) It is used for measuring tension, torque, force, stresses in structures.

3) It is used for measurement of force by strain produced in load rings.

Resistance Thermometers:-

Resistance thermometer, often referred as resistance-temperature detector (RTD) operates upon the fact that ~~elemen~~ almost all pure metals have the property of varying their resistance with temperature, and change in resistance is almost directly proportional to the change in temperature. Electrical resistance with temperature, for most metallic materials, can be represented by an equation of the form

$$R_t = R_0(1 + \alpha t + \beta t^2 + r t^3 + \cdots + w t^n) \quad \text{—(i)}$$

where, R_t = Resistance at temperature t

R_0 = Resistance at 0°c

$\alpha, \beta, r, \cdots w$ = temperature co-efficients.

In the narrow range of operation, β and higher order co-efficients are negligibly small and, therefore the expression for electrical resistance with temperature becomes:

$$R_t = R_0(1+\alpha t) \quad \text{—— (ii)}$$

The RTD doesnot generate it's own voltage, so a voltage source is required to be incorporated into the measuring circuit.

RTD is applicable for measurements of small temperature differences as well as for wide ranges of temperature. The main drawback of an RTD lies in it's large size and sophisticated instrumentation.

Thermistors :-

Thermistor or thermal resistors are semiconductor device having negative temperature co-efficient of resistance. It's resistance changes with temperature i.e. their resistance decreases with the increase in temperature. It is very small sensitive to temperature and will suited to precision measurement, control and compensation. Thermistor has non-linear characteristics. The resistance of thermistor at any temperature can be expressed as:

$$R_T = R_0 e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)} \quad \text{------ (i)}$$

where,

R_T = Resistance at temperature T.

R_0 = Resistance at temperature T_0.

β = experimentally determined constant or curve fitting constant for given thermistor material.

Thermistors are composed of a sintered mixture of metallic oxides. Their resistances ranges from 0.5Ω to 75 MΩ and they are available in varity of shape and sizes.

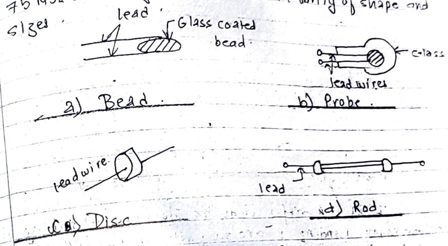


Fig: Commercial form of thermistor

2) Inductive Transducers:

These are analog passive transducers. These transducers operates generally upon one the following three principles.

i) Variation of self inductance of the coil.

ii) Variation of mutual inductance of coil.

iii) Production of eddy current

2.1) Linear variable Differential Transformer (LVDT):-

This is the most widely used inductive transducer for translating the linear motion into an electrical signal. The basic construction of an LVDT is shown in figure below.

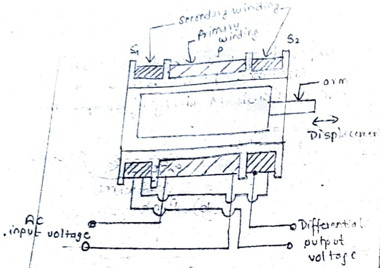
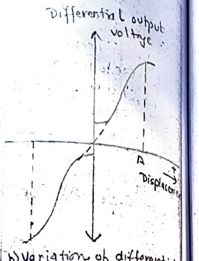


Fig: LVDT



b) Variation of differential output voltage with displacement

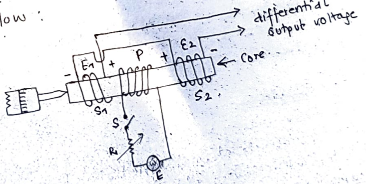
LVDT is a differential transformer consisting of one primary winding 'P' and two identical secondary windings S_1 and S_2, wound over a hollow bobbin of non-magnetic and insulating material. The secondary windings S_1 and S_2 having equal number of turns are arranged concentrically and placed either side of the primary winding P. A soft iron core in the shape of rod or cylinder which is attached to the sensing element slides freely in the hollow portion of the bobbins. Primary winding is connected to an a/c source.

When the core is moved inside the bobbin, it varies coupling of primary winding to secondary windings S_1 and S_2. In position of the core is in central position, coupling of primary winding to both of the secondary windings are equal and so output voltage induced in secondary

~~windings are equal and~~

windings S_1 and S_2 are equal. As the core moves towards right from it's null position, the magnetic linkage to secondary winding S_2 increase and the secondary winding S_1 decreases because the portion of the core inside secondary winding S_2 increases and that inside secondary winding S_1 decreases. Therefore, output voltage induced in secondary winding S_2 increased whereas the output voltage induced in the secondary winding S_1 decreases. The movement of the core to the left will have opposite effect. As secondary windings S_1 and S_2 are connected in series opposition, the difference of output voltages of secondary windings gives the measurement of displacement.

Let us consider the different cases in the figure given below:



Case 1: When core is at centre
Differential output $(E_1 - E_2) = 0$. $[\because E_1 = E_2]$

Case II: When Core is towards left [$\because E_1 > E_2$]
Differential output $[E_1 - E_2] = +ve$

Case III: When core is towards right [$\because E_2 > E_1$]
Differential output $(E_1 - E_2) = -ve$

Hence, the output voltage shows both magnitude and direction of displacement.

Advantages:

1) It has linear characteristics.
2) It has high sensitivity
3) It consumes very less power (less than 1 watt)
4) It can be used on high frequency upto 20KHz.
5) It has low hysteresis, hence good repeatability can achieve.
6) It is rugged in construction thus can tolerate shocks and vibration.
7) Small in size, less in weight and more reliable device.
8) It has high output which eliminates the need of amplification.

Disadvantages:

1) It is sensitive to stray magnetic field.
2) It's performance get effected by vibrations and temperature.
3) It's dynamic response get limited mechanically by the mass of core and electrically by frequency of applied voltage.
4) It requires large displacement for differential output.

3) Capacitive Transducer:-

The variable capacitance transducer consists of a capacitor whose capacitance is varied by the non-electrical quantity being measured.

The capacitance of a parallel plate capacitor is given by

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \text{ farads}$$

where,

ε_0 = permittivity of free space = 8.85×10^{-12} F/m
ε_r = relative permittivity of dielectric.
A = area of plates.
d = distance between two plates.

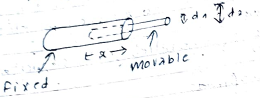
As the capacitance of a capacitor depends upon the area of it's electrodes, the distance between them and the relative permittivity of the dielectric material, such transducers can be used for measurement of non-electrical quantities by affecting any one of the above mentioned parameters.

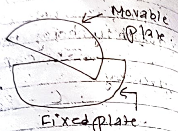
Capacitive transducers are analog passive transducer in which capacitance is varies by any one of the following three methods.

i) By varying overlapping area of plates, A
ii) By varying distance between plates, d
iii) By varying relative permittivity of dielectric material between two plates.

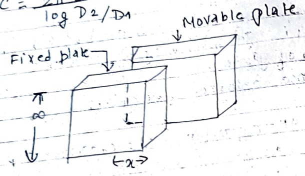
i) By varying overlapping area of plates, A :-

Such transducer operates on the fact that capacitance of any capacitor is proportional to the overlapping area of plates.



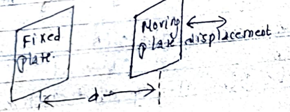


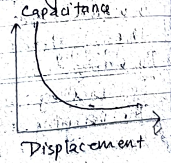
$$C = \frac{2\pi \varepsilon x}{\log D_2/D_1}$$



(ii) By varying distance between the plates:

Such transducer operates upon the facts that the capacitance of any capacitor is inversely proportional to the distance between the plates.

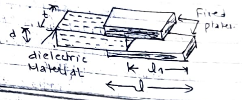




(iii) By varying relative permittivity of dielectric material between two plates.

In this arrangement, a dielectric material of relative permittivity ε_r moves between the two fixed parallel plates according to the displacement under measurement.

$$C = \frac{\varepsilon_0 b l_1}{d} + \frac{\varepsilon_0 \varepsilon_r b(l - l_1)}{d}$$



Advantages:-

1) It has high impedance, thus loading effect becomes minimum.
2) It is extremely sensitive.
3) It has excellent frequency response (up to 50 kHz). Thus used for measurement of both static & dynamic phenomenon.
4) It is not effected by stray magnetic field.
5) It can achieve a resolution of about 2.5 micron.
6) It requires small force and power to operate.

Disadvantages:-

1. Measuring circuit becomes complicated due to high output impedance.
2. Error introduces in measurement due to insulation resistance get effected by physical condition such as temperature, humidity.
3. It needs electrostatic screening.

4) Capacitance get effected by moisture, dust, temperature stray magnetic field etc.

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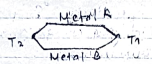
4 Thermocouples:

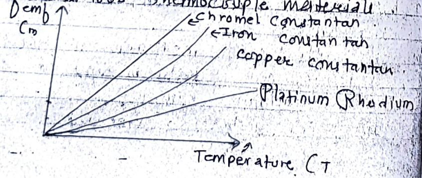


It consists of two dissimilar metal wire A & B insulated from each other but welded or brazed together at their ends forming two junctions as shown in figure.

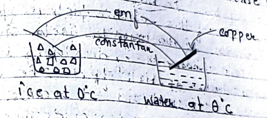
The operation of a thermocouple is based on seeback effect, i.e if two wires of different metals are joined together at each end and form a complete electric circuit then current flows in the circuit when the two junctions are kept at different temperatures. This current is caused by an emf called the thermo-electric emf. This thermoelectric emf is a function of temperature difference of two junctions. The relation between the thermo emf set up and temperature difference of hot and cold junction is given by

$$E = \alpha(T - T_0) + \beta(T^2 - T_0^2) \quad \text{----(1)}$$

The figure given below represents the relationship between seeback voltage and temperature for various thermocouple meterials.



There are several methods of joining the two dissimilar metals, For example joining of copper and constantan produces a voltage on the order of a few tens of millivolts with positive potential at copper side. An increase in temperature causes increase in voltage.



Laws governing thermocouples:

1 Law of intermediate temperatures.
2 Law of intermediate metals.

Advantages:

1 Lesser accuracy than RTD or thermistor.
2 It needs periodical checking when employed at elevated temperature.
3 Reference junction compensation is required.
4 It needs compensating leads.
5 It must protected in open or close metal protecting tubes to ensure long life.

Hall effect Transducers :-

When a conductor is kept perpendicular to the magnetic field and a direct current is passed via it, it results in an electric field perpendicular to the direction of both the magnetic field and current. The magnitude of this electric field is proportional to the product of the magnetic field strength and current. This phenomenon of developing voltage across a conductor is known as Hall effect. The voltage so developed is very small and it becomes difficult to detect it, but in some semiconductors such as germanium, this voltage becomes sufficient enough for measurement with a sensitive moving coil instrument.

The elements of hall effect transducer is illustrated in figure below. Here a ~~st~~ slab of conducting material is connected to a battery so that current (I) flows ~~on~~ via slab and potential difference created between top and bottom of the slab.

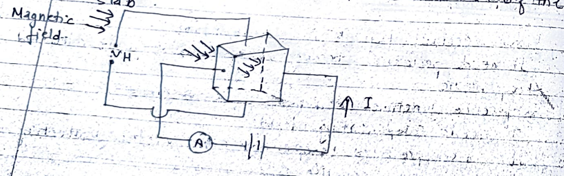


Fig: Hall effect

The magnitude of this induced voltage is proportional to the product of magnetic field strength and current via slab and is given by the expression

$$V_H = \frac{K_H I B}{t} \quad \text{---(ii)}$$

where,

K_H = Hall effect co-efficient

I = Current flowing through slab

B = Flux density of magnetic field

t = thickness of slab

6 Piezo electric Transducer:-

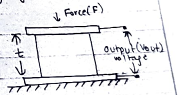
In some crystalline or ceramic materials, a potential difference appears across the opposite faces of the material as a result of dimensional changes when a mechanical force is applied to it. This is called piezoelectric effect and such material is called piezoelectric material. An emf produced across crystal, mainly depends upon three parameters: magnitude of applied pressure, voltage sensitivity and thickness of crystal.

$$V_{out} = gtp$$

where g = Voltage sensitivity

t = thickness of crystal

p = pressure applied



These transducers are widely employed for measurement of dynamic pressure, force and shock or vibratory motion.

* A resistance strain gauge with a guage factor of 2 is fastened to a steel member subjected to a stress of 1250 kg/cm². The modulus of elasticity of steel is approximately 2.1×10^6 kg/cm². Calculate the change in resistance of strain guage element due to applied stress and also compute poisson's ratio.

Here,

Gauge factor (K) = 2

Stress (P) = 1250 kg/cm²

Modulus of elasticity (E) = 2.1×10^6 kg/cm²

Now,

As we know,

$$\frac{\text{Stress}}{\text{stain}} = E$$

$$\text{Strain} = \frac{\text{Stress}(P)}{E} = \frac{1250}{2.1 \times 10^6} = 595.238 \times 10^{-6}$$

$$\text{Strain} = \left(\frac{\Delta L}{L}\right) = 595.238 \times 10^{-6}$$

Now,

$$\text{Gauge factor }(K) = \frac{(\Delta R/R)}{(\Delta l/l)}$$

$$\frac{\Delta R}{R} = K * \frac{\Delta l}{l}$$

$$= 2 \times 595.238 \times 10^{-6}$$

$$= 1.190 \times 10^{-3}$$

$$\% \frac{\Delta R}{R} = 0.119\ \%$$

Also we have,

$$K = (1 + 2\mu)$$

$$2 = 1 + 2\mu$$

$$\mu = 1/2 = 0.5 \text{ Ans}$$

Physical variables :-

The variables that exists in physical environments are physical variables. The physical variables to be measured (either pressure, displacement, temperature, light intensity force etc) are applied to input device or transducer. Suitable transducers are used for measurement of these physical quantities.

Measurement of various physical variables are presented below.

1 Pressure Measurement
i Variable Capacitance pressure guage
ii Piezo electric pickup

2 Displacement Measurement
i) Potentiometric device
ii) Linear variable differential transformer (LVDT)

3 Temperature Measurement
i) Thermocouple
ii) Resistance Thermometer
iii) Thermister

4 Light intensity measurement
i) Photo - voltaic cell
ii Photo - emissive cell

5 Magnetic flux / magnetic field :
i) Hall effect transducer

6 Force, Torque :

i) Strain guage

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* An LVDT is used for measuring the deflection of a bellows. The sensitivity of LVDT is 50 V/mm. The belows is deflected by 0.145 mm by a pressure of 10×10^5 N/m². Determine the sensitivity of LVDT in V/N/m² and pressure when voltage output for LVDT becomes 4.5 V

Here,

$V_{out} = 50 \times 0.145 = 7.25$ V

Hence sensitivity of LVDT $= \frac{V_{out}}{P}$

$= \frac{7.25}{10 \times 10^5} = 7.25 \times 10^{-6}$

$= 7.25 \times 10^{-6}$ V per N/m²

Again,

Pressure for output voltage of 4.5 V

$(F) = \frac{4.5}{7.25 \times 10^{-6}}$

$= 6.20 \times 10^{+5}$ N/m² Ans //

* A strain guage is bonded to a beam 0.1 m long and has a cross-sectional area 4 cm². Young modulus for steel is 207 GN/m². The strain guage has unstrained resistance of 240 Ω and a guage factor of 2.2. When a load is applied, the resistance of guage changes by 0.013 Ω. Calculate the change in length of the steel beam and the amount of force applied to the beam.

Here,

Unstrained resistance $(R_s) = 240\,\Omega$

Change in resistance $(\Delta R) = 0.013\,\Omega$

Gauge factor $(K) = 2.2$

Initial length of wire $(l) = 0.1$ m

Young Modulus of steel $(E) = 20.7$ GN/m²

Cross sectional area of wire $(a) = 4$ cm²

$= 4 \times 10^{-4}$ m²

Strain $(\epsilon) = \frac{\Delta l}{l} = \frac{\Delta R / R_s}{K}$

$= \frac{0.013/240}{2.2} = 0.0000246$

$\Delta L = 0.1 * 0.0000246$

$= 2.46 \times 10^{-6}$ m //

Stress $(p) = E *$ strain

$= 207 \times 10^9 * 0.0000246$

$= 5.0922 \times 10^6$ N/m²

Force applied $(F) = P * a$

$= 5.0922 \times 10^6 \times 4 \times 10^{-4}$

$= 2,036.88$ Ans //