Ellathrai (1)

ROLL No.
NAME
STREAM
SUBJECT

Chapter:- 3 (12 hrs)

Physical Variables and Transducers:-

Physical variables and their types:-

Physical variables are the variables to be measured in an instrumentation system, which make its first contact with the primary sensing Elements. It is the information for the measurement system in the form of a physical phenomenon or an electrical signal.

Types of Physical variables:-

(i) Process variables:-

Temperature, pressure and flow rate are the process variables which are widely employed in process and production plants.

(ii) Electrical variables:-

Current, voltage, resistance, inductance, capacitance frequency, phase angle, power are the electrical variables.

(iii) Mechanical variables:-

Spring (Force to displacement), Manometer (pressure to displacement), Thermocouple (temperature to electric current), Hydrometer (specific gravity to displacement), Turbines (linear to angular velocity) etc. are the mechanical variables.

(iv) Bio-physical variables:-

Here, the information is taken from living beings. ECG (Electro Cardio Graph) for heart, EEG (Electro Encephilo Graph for Brain), EMG (Electro mio Graph for

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muscular), exitation potential, restoring potential are the bio-physical variables.

Transducer:-

It is a device which converts non-electrical quantity into an electrical form in order to use electrical methods and techniques for measurement, manipulation or control.

Basic Requirement of Transducer:-

The main function of the transducer is to respond only for the measurement under specified limit for which it is designed.

ⓐ Ruggedness:-

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

ⓑ Linearity:-

It's input-output characteristics should be linear.

ⓒ Repeatability:-

It should reproduce same output signals when the input signal is applied again and again under fixed environment condition.

ⓓ High quality output signals:-

The ratio of Signal to Noise (SNR) should be high and the amplitude of the output signal should be upto detectable level.

ⓔ High Reliability and Stability (minimum error):-

We should get minimum error in measurement for

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temperature variations, vibrations and other various changes in surroundings.

(f) Good Dynamic Response:-

It's output should be faithful to input when taken as a function of time.

Selection of Transducer:-

(a) Range:-

The range of the transducer should be large enough to cover up all the expected magnitude of quanity under measurement.

(b) Sensitivity:-

Transducer should give a sufficient output signal per unit of measured input in order to yield meaningful data.

(c) Electrical output characteristics:-

The electrical characteristics such as output impedance, frequency response should be compatible with the recording devices.

(d) Physical Environment:-

The transducer selected should be able to withstand the environmental conditions to which it is likely to be exposed.

(e) Error:-

The error inherent in the operation of the transducer itself or those errors caused by environmental condition of the measurement should be small enough or controlable enough that they allow meaningful data to be taken.

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Classification of Transducer:-

(i) On the basis of transduction form used:-

The transducers can be classified on the basis of principle of transduction as resistive, inductive, capacitive etc. depending upon how they convert the input quantity into resistance, inductance or capacitance respectively. They can be classified as piezoelectric, thermoelectric, magnetorestrictive, electrokinetic and optical.

(ii) as primary and secondary transducers:-

There are two stages of transduction, firstly, the pressure is converted into a displacement by Bourdon tube, then the displacement is converted into an analogous voltage by LVDT. The Bourdon tube is called a primary transducer while LVDT is called a secondary transducer.

(iii) as passive and active transducers:-

Passive transducers derive the power required for transduction from an auxiliary power source. They are also known as 'externally powered transducers'. Example: resistive (potentiometer, strain gauge), inductive (LVDT) and capacitive (variable capacitance pressure gauge, Dielectric gauge) transducers.

Active transducers are those which don't require an auxiliary power source to produce their output, so called as self generating type as they develop their own voltage or current output. Examples: Thermocouples, photovoltaic cells and piezoelectric crystals.

(iv) as analog and digital transducers:-

Analog transducers convert the input quantity into an analog output which is a continuous function of time. Example strain Gauge, LVDT, thermocouple, thermistor.

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Digital transducers convert the input quantity into an electrical output which is in the form of pulses (0 and 1).

and (v) as transducers and inverse transducers:-

Transducers is a device which converts a non-electrical quantity into an electrical quantity.

An inverse transducer is a device which converts an electrical quantity into a non-electrical quantity.

Example: piezoelectric crystal (voltage to displacement).

Input characteristics of the Transducer:-

(i) Type of Input and Operating Range:-

The type of input, which can be any physical quantity, is generally determined in advance. The useful operating range of the transducer may be a decisive factor in selection of a transducer for a particular application. The upper limit is decided by the transducer capabilities while the lower limit of range is normally determined by the transducer error or by the unavoidable noise originating in the transducer.

(ii) Loading Effects:-

Ideally a transducer should have no loading effect on the input quantity being measured. In practice, it is impossible and hence steps may be taken to reduce the loading effects to negligible proportions.

Output characteristics of Transducer:-

The three conditions in the output characteristics which should be considered are

(i) type of electrical output:-

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The output quantities (voltage, current, impedance or a time function of these amplitudes) may or may not be acceptable to the latter stages of the instrumentation system. They may have to be manipulated so as to make them drive the subsequent stages of instrumentation system.

(ii) Output Impedance:-

The output impedance of a transducer determines to the extent the subsequent stages of instrumentation is loaded. Ideally, the value of output impedance should be zero if no loading effects are there on the subsequent stage. It also determines the amount of power that can be transferred to the succeeding stages of the instrumentation system for a given output signal level.

and (iii) Useful output Range:-

The output range of a transducer is limited at the lower end by noise signals and the upper limit is set by the maximum useful input level.

Error of transducer:-

The errors in transducers occur because they do not follow the input-output relationship in many situations. The error can be split into three components which are (i) scale error, (ii) dynamic error and (iii) error on account of noise and drift.

(i) Scale Error:-

It is of four different types:

(a) Zero Error:-

Here, the output deviates from the correct value by a constant factor over the entire range of the transducer.

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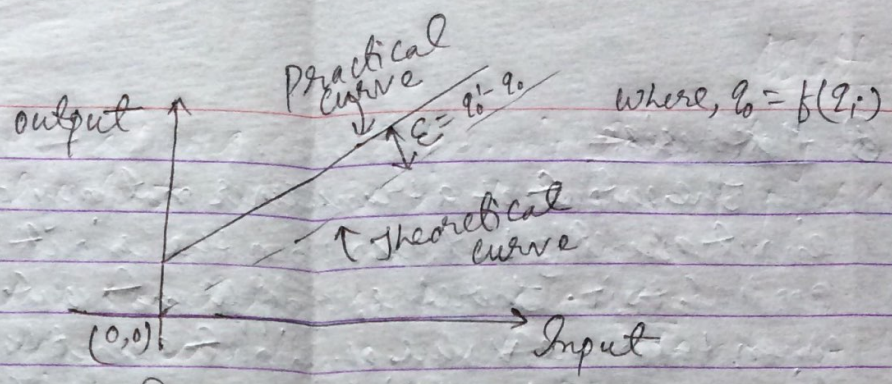

Fig. Transducer zero error.

ⓑ <u>Sensitivity Error:-</u>

It occurs when the observed output deviates from the correct value by a constant value. Suppose the correct output is q_o, the output would be Kq_o over the entire range of the transducer, where K is a constant.

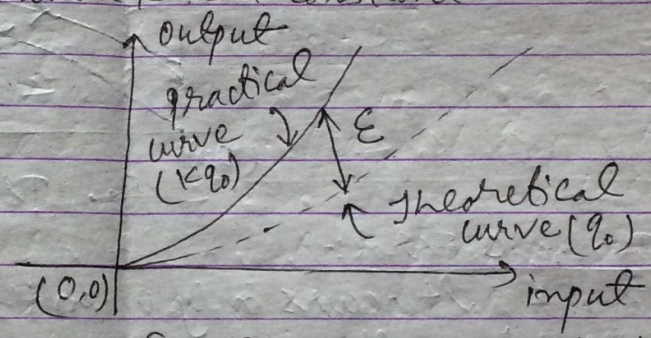

Fig. Transducer sensitivity Error.

ⓒ <u>Non-conformity:-</u>

Here, the experimentally obtained transfer function deviates from the theoretical transfer function for almost every input.

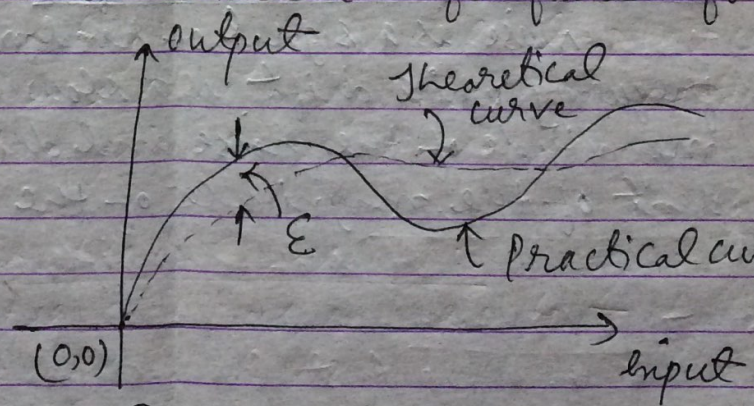

Fig. Transducer Non-conformity

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(d) Hysteresis:-

The output of a transducer not only depends upon the input quantity but also upon the input quantity previously applied to it. Therefore, a different output is obtained when the same value of input quantity is applied depending upon whether it is increasing or decreasing. For decreasing values, a greater output is obtained than with increasing values for the same value of the input quantity.

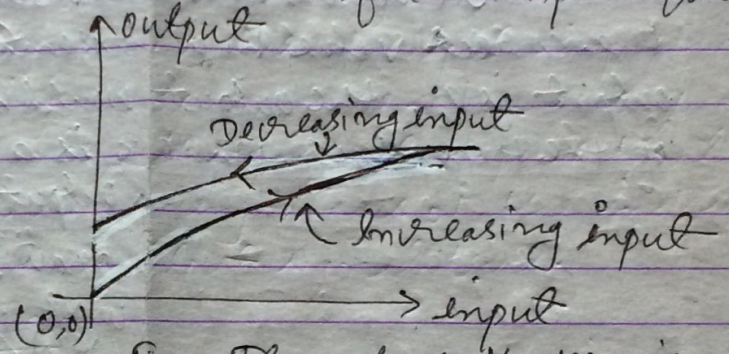

Fig. Transducer Hysteresis.

(ii) Dynamic Error:-

It occurs only when the input quantity is varying with time. It can be made small by having a small time constant. It reduces as the time after application of the input increases.

(iii) Error due to Noise and Drift:-

Noise is a signal of random amplitude and random frequency while drift is a slow change with time. The magnitude of the noise and drift is normally independent of the magnitude of the input signal.

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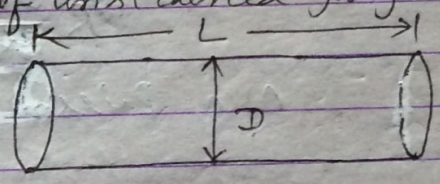
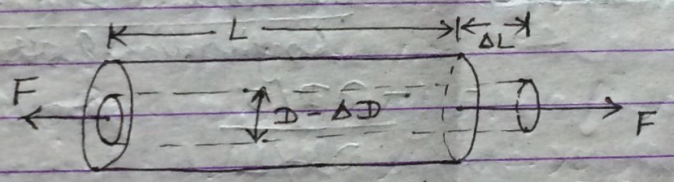
Strain Gauges:-

The strain gauges are used for measurement of strain and associated stress in experimental stress analysis. If a metal conductor is stretched or compressed, its resistance changes on account of the fact that both length and diameter of conductor change. Also, there is a change in the value of resistivity of the conductor when it is strained and this property is called piezoresistive effect. Therefore, resistance strain gauges are also known as piezoresistive gauges.

Let us consider a strain gauge made of circular wire. The wire has the dimensions: length = L, area = A, diameter = D before being strained. The material of the wire has a resistivity ρ. Therefore, Resistance of unstrained gauge is given by $R = \rho L/A$





Tensile Force

fig. change in diamensions of a strain gauge element when subjected to a tensile force.

Let a tensile stress S be applied to the wire. This produces a positive strain causing the length to increase and area to decrease. Thus when the wire is strained, there are changes in its dimensions. Let ΔL = change in length, ΔA = change in area, ΔD = change in diameter and ΔR = change in resistance. In order to find how ΔR depends upon the material physical quantities, the expression for R is differentiated w.r.to stress S i.e.

$$\frac{dR}{dS} = \frac{\rho}{A}\frac{\partial L}{\partial S} - \frac{\rho L}{A^2}\frac{\partial A}{\partial S} + \frac{L}{A}\frac{\partial \rho}{\partial S} \quad \text{—} ①$$

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Dividing eqⁿ (1) throughout by resistance $R = \rho L/A$, we get

$$\frac{1}{R}\frac{dR}{ds} = \frac{1}{L}\frac{\partial L}{\partial s} - \frac{1}{A}\frac{\partial A}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s} \quad \text{--- (2)}$$

It is evident from eqⁿ (2) that the per unit change in resistance is due to (i) per unit change in length $= \Delta L/L$, (ii) per unit change in area $= \Delta A/A$ and (iii) per unit change in resistivity $= \Delta\rho/\rho$.

Now, Area $(A) = \pi/4\, D^2$ $\therefore \dfrac{\partial A}{\partial s} = 2\cdot\pi/4\, D \dfrac{\partial D}{\partial s}$

$$\text{so, } \frac{1}{A}\frac{\partial A}{\partial s} = \frac{1}{(\pi/4\, D^2)} \times 2\cdot\pi/4\, D \cdot \frac{\partial D}{\partial s} = \frac{2}{D}\frac{\partial D}{\partial s}$$

and eqⁿ (2) becomes

$$\frac{1}{R}\frac{dR}{ds} = \frac{1}{L}\frac{\partial L}{\partial s} - \frac{2}{D}\frac{\partial D}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s} \quad \text{--- (3)}$$

Also, Poisson's ratio $(\nu) = \dfrac{\text{lateral strain}}{\text{longitudinal strain}}$

$$= \frac{-\partial D/D}{\partial L/L}$$

$$\Rightarrow \frac{\partial D}{D} = -\nu \times \partial L/L \quad \text{so eqⁿ (3) becomes}$$

$$\frac{1}{R}\frac{dR}{ds} = \frac{1}{L}\frac{\partial L}{\partial s} + \nu\frac{2}{L}\frac{\partial L}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s} \quad \text{--- (4)}$$

For small variations, the eqⁿ (4) can be written as

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} + 2\nu\frac{\Delta L}{L} + \frac{\Delta \rho}{\rho} \quad \text{--- (5)}$$

The Gauge Factor is defined as the ratio of per unit change in resistance to per unit change in length i.e.

$$\text{Gauge Factor } (G_f) = \frac{\Delta R/R}{\Delta L/L}$$

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as, $\frac{\Delta R}{R} = G_f \frac{\Delta L}{L} = G_f \times \epsilon$ — (6)

Where, ϵ = strain = $\frac{\Delta L}{L}$

Solving eqn (5) and (6), we get,

$$G_f \times \epsilon = \frac{\Delta R}{R} = \epsilon + 2\nu\epsilon + \Delta\rho/\rho$$

as, $G_f = 1 + 2\nu + \frac{\Delta\rho/\rho}{\epsilon}$ — (7)

ϵ ← Resistance change due to change in resistivity.

Resistance change due to change in area

Resistance change due to change of length

If the change in the value of resistivity of a material when strained is neglected i.e. piezoresistive effect is negligible, the gauge factor is

$$G_f = 1 + 2\nu \quad \text{— (8)}$$

Poisson's ratio for most metals lies in the range of 0.25 to 0.35, and the gauge factor would then be on the order of 1.5 to 1.7.

Hooke's law gives the relationship between stress and strain for a linear stress-strain curve in terms of the modulus if elasticity of the material under tension. Hooke's law is written as

$$\text{Strain, } \epsilon = \frac{S}{E}$$

where, $\epsilon = \frac{\Delta L}{L}$ = strain (no units),

S = stress (kg/cm^2) and

E = Young's modulus / modulus of elasticity of material (kg/cm^2)

<u>Applications of strain Gauges:-</u>

(i) Experimental stress analysis of machines and structures and (ii) construction of force, torque, pressure, flow and acceleration transducers.

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Example:- ① A resistance strain gauge with a gauge factor (sensitivity of a strain gauge) of 2 is fastened to a steel member subjected to a stress of 1,050 kg/cm². The modulus of elasticity of a steel is approximately 2.1×10^6 kg/cm². Calculate the change in resistance, ΔR, of the strain gauge element due to the applied stress. Comment upon the result.

Soln:

Hooke's law yields

$$\epsilon = \frac{S}{E} = \frac{\Delta L}{L} = \frac{1,050}{2.1 \times 10^6} = 5 \times 10^{-4}$$

Again, The sensitivity of the strain gauge (Gauge factor) is

$$G_f = \frac{\Delta R / R}{\Delta L / L}$$

$$\Rightarrow \frac{\Delta R}{R} = G_f \times \epsilon = 2 \times 5 \times 10^{-4} = 10^{-3} = 0.1\%$$

∴ The change in resistance is only 0.1%.

The result shows that the relatively high stress results in a resistance change of only 0.1%, a very small change indeed. Lower stress produces still lower changes in resistance which may not be perceptible at all. To overcome this difficulty, the gauge factor of strain gauge should be high which produce large changes in resistance when strained.

Example ②:- A compressive force is applied to a structural member. The strain is 5 micro-strain. Two separate strain gauge are attached to the structural member, one is nickel wire strain gauge having a gauge factor of −12.1 and other is nichrome wire strain gauge having a gauge factor of 2. Calculate the value of resistance of the gauges after they are strained. The resistance of strain gauges before being strained is 120Ω.

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Soln:

According to our convention, the tensile strain is taken as positive while the compressive strain is taken as negative. Therefore, strain

$$\epsilon = -5\times10^{-6} \quad (1 \text{ micro-strain} = 1\ \mu m/m)$$

Now, $G_f = \dfrac{\Delta R/R}{\epsilon} \Rightarrow \dfrac{\Delta R}{R} = G_f \times \epsilon$

∴ change in value of resistance of nickel wire strain gauge is

$$\Delta R = G_f \epsilon \times R$$
$$= -1.2 \times (-5\times10^{-6}) \times 120$$
$$= 7.26\times10^{-3}\ \Omega = 7.26\ m\Omega$$

i.e. there is an increase of $7.26\ m\Omega$ in the value of resistance.

For nichrome,

the change in the value of resistance is

$$\Delta R = G_f \epsilon \times R$$
$$= 2\times(-5\times10^{-6}) \times 120$$
$$= -1.2\times10^{-3} = -1.2\ m\Omega$$

Thus, with compressive strain, the value of resistance gauge shows a decrease of $1.2\ m\Omega$ in the value of resistance.

Example (3):-

A strain gauge is bonded to a beam 0.1 m long and has a cross-sectional area $4\ cm^2$. Young's modulus for steel is $207\ GN/m^2$. The strain gauge has an unstrained resistance of 240Ω and a gauge factor of 2.2. When a load is applied, the resistance of gauge changed by 0.013Ω. Calculate the change in length of the steel beam and the amount of force applied to the beam.

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Soln:

We have, the gauge factor, $G_f = \frac{\Delta R/R}{\Delta L/L}$

$\therefore \Delta L = \frac{\Delta R/R}{G_f} \times L = \frac{(0.013/240)}{2.2} \times 0.1 = 2.46 \times 10^{-6} m$

$\Rightarrow$ Change in length of the steel beam is 2.46×10^{-6} m

Now, Hooke's law yields

$$e = S/E$$

$$\Rightarrow S = e \times E = \frac{\Delta L}{L} \times E = \left(\frac{2.46 \times 10^{-6}}{0.1}\right) \times 207 \times 10^{9}$$

$$= 5.092 \times 10^{6} \ N/m^2$$

So, the amount of force applied to the beam is

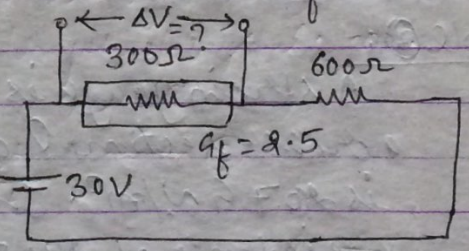
$$F = SA \quad \text{as } S = F/A$$

$$= (5.092 \times 10^{6}) \times 4 \times 10^{-4}$$

$$= 2.037 \times 10^{3} N.$$

Example ④:-

A strain gauge having a resistance of 300Ω and gauge factor 2.5 is connected in series with a blast resistance of 600 Ω across 30V. Determine the change in output voltage when a stress of 140 MN/m² is applied. The modulus of elasticity is 200 GN/m².



Soln:

Hooke's law yields

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

$$= \frac{140 \times 10^{6}}{200 \times 10^{9}} = 7 \times 10^{-4}$$

Again, Gauge factor is

$$G_f = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = \frac{\frac{\Delta R}{R}}{\epsilon} \quad \text{or, } \Delta R = G_f \epsilon \times R$$

$\therefore \Delta R = 2.5 \times 7 \times 10^{-4} \times 300 = 0.525\,\Omega$

i.e. there is an increase of $0.525\,\Omega$ in the value of resistance.

When unstrained, the voltage across strain gauge is

$$V_1 = \left(\frac{300}{300+600}\right) \times 30 = 10 \text{ Volts}$$

When strained, the voltage across strain gauge is

$$V_2 = \left[\frac{(300+\Delta R)}{(300+\Delta R)+600}\right] \times 30 = \left(\frac{300.525}{300.525+600}\right) \times 30$$

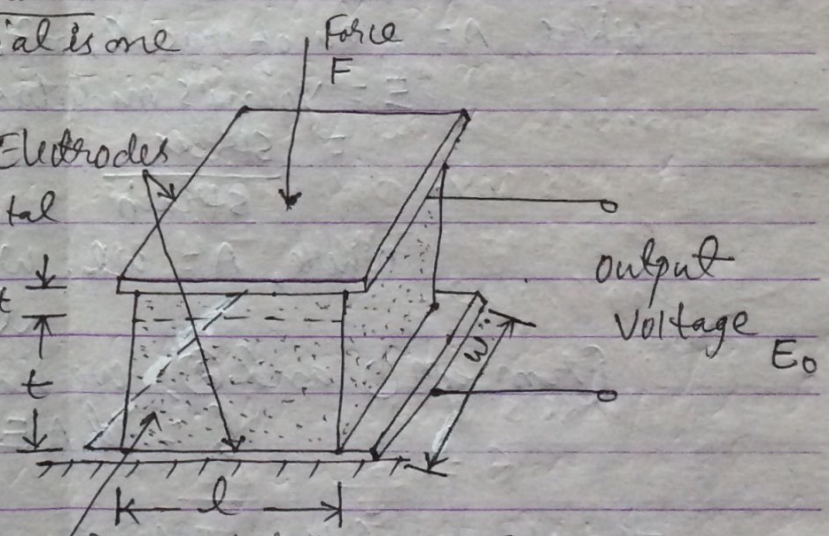
$$= 10.012 \text{ volts}$$

Hence, the change in output voltage (ΔV) is

$$\Delta V = V_2 - V_1 = 10.012 - 10 = 0.012 \text{ volts.}$$

Piezo-electric Transducers:-

A piezo-electric material is one in which an electric potential appears across certain surfaces of a crystal if the dimensions of the crystal are changed by the application of a mechanical force. The potential is produced by the displacement of charges and the effect is reversible.



Piezo-electric crystal

Fig. Piezo-electric crystal used for measurement of force.

Common piezo-electric materials include Rochelle salts, quartz, lithium sulphate and so on.

A piezo-electric element used for converting mechanical motion to electrical signals may be thought as charge generator and a capacitor. Mechanical deformation generates a charge and this charge appears as a voltage (Q/C) across the electrodes. The magnitude and polarity of the induced surface charges are proportional to the magnitude and direction of the applied force F, given by the expression

$$\text{charge, } Q = d \times F \text{ coulomb} \quad \text{——— (1)}$$

where, d = charge sensitivity of the crystal. it is constant for a given crystal; C/N

and F = applied force; N

The Force F causes a change in thickness of the crystal. so,

$$F = \frac{AE}{t} \times \Delta t \text{ Newton} \quad \text{——— (2)}$$

where, A = area of crystal; m^2, t = thickness of crystal; m and

E = young's modulus; N/m^2

$$= \frac{\text{stress}}{\text{strain}} = \frac{F/A}{\Delta t/t} = \frac{F \cdot t}{\Delta t \cdot A} \; N/m^2$$

where, $A = wl$, w = width of crystal; m and l = length of crystal; m.

From eqn (1) and (2), we have, charge

$$Q = dAE\left(\frac{\Delta t}{t}\right) \quad \text{——— (3)}$$

The charge at the electrodes give rise to an output voltage E_0 as

$$E_0 = Q/C_p \quad \text{——— (4)}$$

where, $C_p = \epsilon_r \epsilon_0 A/t$ = capacitance between electrodes; F ——— (5) A = area of crystal; m^2.

$\epsilon = \epsilon_r \epsilon_0$ = permitivity of medium; F/m

ϵ_r = relative permitivity

ϵ_0 = permitivity of free space; 8.85×10^{-12} F/m.

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solving eqn (1), (4) and (5), we get

$$E_0 = \frac{d\,F}{\epsilon_r \epsilon_0 A/t} = \frac{dt}{\epsilon_r \epsilon_0}(F/A)$$

But, $F/A = p$ = pressure or stress in N/m^2

$$\therefore E_0 = \frac{d}{\epsilon_r \epsilon_0} t p = g t p$$

where, $g = d/\epsilon_r \epsilon_0$ is the voltage sensitivity of crystal which is constant for a given crystal; Vm/N

Now, $g = \frac{E_0}{tp} = \frac{E_0/t}{p}$

But, E_0/t = electric field strength; V/m

Hence, crystal voltage sensitivity, g is defined as the ratio of electric field intensity to pressure or stress.

Uses of Piezo-electric Transducers:-

(1) The use of piezo-electric transducer elements is confined primarily to dynamic measurements. The voltage developed by application of strain is not held under static conditions. Hence, the elements are primarily used in the measurement of such quantities as surface roughness and in accelerometers and vibration pickups.

Example:- A Barium Titanate pickup (piezo-electric crystal) has the dimensions of 5mm x 5mm x 1.25mm. The force acting on it is 5N. The charge sensitivity of Barium titanate is 150pC/N and its permitivity is 12.5×10^{-9} F/m. If the modulus of elasticity of Barium Titanate is 12×10^6 N/m², calculate the strain, the charge and the capacitance.

Soln:

Area of plates $(A) = 5\times10^{-3} \times 5\times10^{-3} = 25\times10^{-6}\ m^2$

pressure $(P) = F/A = \frac{5}{25\times10^{-6}} = 0.2\times10^{6}\ N/m^2$

Now, voltage sensitivity $(g) = \frac{d}{\epsilon_r \epsilon_0} = \frac{150\times10^{-12}}{12.5\times10^{-9}} = 0.012\ Vm/N$

Voltage generated $(E_0) = gtp = 0.012\times1.25\times10^{-3}\times0.2\times10^{6}$
$= 3$ Volts.

Strain $(\epsilon) = \frac{\text{Stress } (S)}{\text{Young's modulus } (E)} = \frac{F/A}{E} = \Delta t/t$

$= \frac{0.2\times10^{6}}{12\times10^{6}} = 0.0167$

Charge $(Q) = dF = 150\times10^{-12}\times5 = 750\times10^{-12}\ C$

and capacitance $(C_p) = \frac{Q}{E_0} = \frac{750\times10^{-12}}{3} = 250\times10^{-12}\ F$

<u>Merits and Demerits of Piezo-electric transducers:-</u>

<u>Merits:-</u>

(i) They are generally small in size, light weight and very rugged in construction.

(ii) They are active transducers as they don't need external supply.

(iii) They have very good frequency response and output is quite large.

(iv) They can be operated over a wide range of temperature without appreciable temperature induced.

<u>Demerits:-</u>

(i) The output of piezo-electric transducer is affected by temperature variations of the crystal.

(ii) There is a problems of leakage of charges through the surface of crystal.

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