Electronic Measurements (1)

Transducers - Part 3

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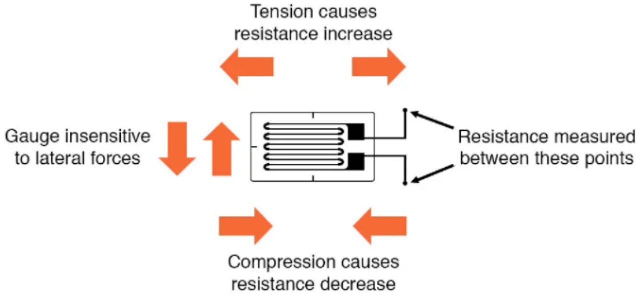
Lecture Contents

- Strain Gauges Transducers
- Thermistors
- Piezoelectric Transducers

Strain Gauges - Definition

strain gauge works on the principle of electrical conductance ($\sigma = 1/\rho$) and its dependence on the conductor's geometry. Whenever a conductor is stretched within the limits of its elasticity, it doesn't break but, gets narrower and longer.

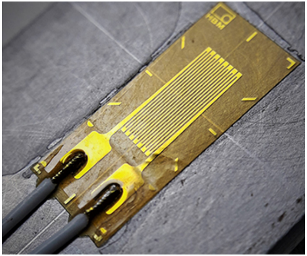


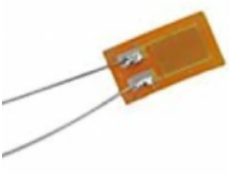
$$R = \frac{\rho L}{A}$$

Strain is a measure of the deformation of a material when subjected to an external force or load. It's a dimensionless quantity that describes the relative change in length or shape of a material

Strain Gauges - Definition

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

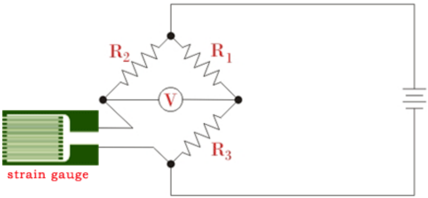




- The change in resistance of a strain gauge owing to external physical parameters such as force, pressure, stress, etc., is measured based on the Wheatstone bridge circuit.

Strain Gauges - Bridge Circuit

- R_1 and R_3 are the ratio arms equal to each other, and R_2 is the rheostat arm has a value equal to the strain gauge resistance.
- When the gauge is unstrained, the bridge is balanced, and voltmeter shows zero value.
- As there is a change in resistance of strain gauge, the bridge gets unbalanced and producing an indication at the voltmeter.
- The output voltage from the bridge can be amplified further by a differential amplifier.



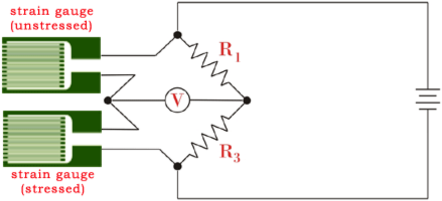
Quarter-bridge strain gauge circuit

Variation of Temperature of Strain Gauge

- An important factor that affects the resistance of the gauge is temperature.
- If the temperature is more resistance will be more and if the temperature is less the resistance will be less.
- This is a common property of all the conductors.
- We can overcome this problem by using (1) strain gauges that are self- temperature-compensated or by (2) a dummy strain gauge technique.
- (1) Most of the strain gauges are made of constantan alloy which cancel out the effect of temperature on the resistance.
- Constantan alloy: is a copper–nickel alloy. Its main feature is the low thermal variation of its resistivity, which is constant over a wide range of temperatures.

Variation of Temperature of Strain Gauge

- (2) some strain gauges are not of an isoelastic alloy. In such cases, dummy gauge is used in the place of R_2 in the quarter bridge strain gauge circuit which acts as a temperature compensation device.
- Whenever temperature changes, the resistance will change in the same proportion in the both arms of the rheostat, and the bridge remains in the state of balance. Effect of temperature get nullifies.

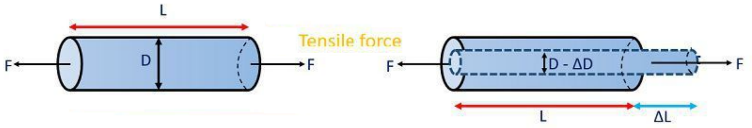


Quarter-bridge strain gauge circuit with temperature compensation

Strain Gauges - Theory

- **Strain gauge:** is a device which is when subjected to some force results change in resistance of the material.
- It is directly used for the measurement of load and indirectly it is used for the measurement of displacement
- **Operating principle** when a conductor is stretched or compressed within its elastic limit, its resistance changes due to changes in its length, diameter, and resistivity.
- The property of change in the conductor's resistivity due to mechanical strain is called "Piezoresistive effect"
- Therefore, resistance strain gauges are also known as piezoresistive gauges or piezoresistive transducers.

Strain Gauges - Theory



- Let a tensile force 'S' be applied to a wire of length 'L', diameter 'D', area 'A', and resistivity 'ρ'.
- This produces a positive strain causing the length to increase and the area to decrease as shown in Figure.
- Let $\Delta L =$ change in length, $\Delta A =$ change in area, $\Delta D =$ change in diameter, and $\Delta R =$ is the change in resistance.
- Resistance of unstrained gauge: $R = \frac{\rho \, L}{A}$

Strain Gauges - Theory

In order to find how ΔR depends upon the material physical quantities, the expression for R is differentiated with respect to stress S. Thus,

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

Dividing Eq. (1) throughout by resistance $R=\rho\frac{L}{A}$, it becomes

$$\frac{1}{R}\frac{dR}{dS}=\frac{1}{L}\frac{\partial L}{\partial S}-\frac{1}{A}\frac{\partial A}{\partial S}+\frac{1}{\rho}\frac{\partial \rho}{\partial S} \quad (2)$$

It is clear from Eq. (2), that the per unit change in resistance is due to the following:

Per unit change in length = $\frac{\Delta L}{L}$,

Per unit change in area = $\frac{\Delta A}{A}$ and

Per unit change in resistivity = $\frac{\Delta \rho}{\rho}$

- Piezoresistive effect $=\frac{\Delta\rho}{\rho}$, represents the changes in the lattice structure of the material.

Area $A = \frac{\pi}{4} D^2 \therefore \frac{\partial A}{\partial S} = 2 \cdot \frac{\pi}{4} \cdot D \cdot \frac{\partial D}{\partial S}$

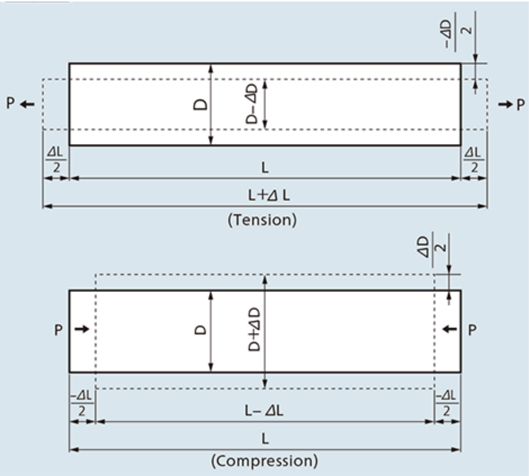
$$\frac{1}{A}\frac{\partial A}{\partial S} = \frac{(\pi/2)D}{(\pi/4)D^2} \cdot \frac{\partial D}{\partial S} = \frac{2}{D}\frac{\partial D}{\partial S}$$

or,

putting this value of $\frac{1}{A}\frac{\partial A}{\partial S}$ in Eq. (2), it becomes

$$\frac{1}{R}\frac{\partial R}{\partial S} = \frac{1}{L}\frac{\partial L}{\partial S} - \frac{2}{D}\frac{\partial D}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}$$

Strain Gauges - Theory



Longitudinal strain $\frac{\Delta L}{L}$ or $-\frac{\Delta L}{L}$

Lateral strain $-\frac{\Delta D}{D}$ or $\frac{\Delta D}{D}$

Strain Gauges - Theory

Poisson's ratio $\boxed{\nu = \frac{\text{Lateral strain}}{\text{Longitudinal strain}} = -\frac{\partial D / D}{\partial L / L}}$

$\therefore \quad \partial D / D = -\nu \times \partial L / L$

$\therefore \quad \frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} + \nu \frac{2}{L}\frac{\partial L}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}$ (4)

For most metallic strain gauges, the gauge factor can be expressed in terms of three components:
1. Geometric Effect: Change in length and cross-sectional area under strain.
2. Poisson Effect: Due to the material's Poisson's ratio, which affects lateral strain.
3. Piezoresistive Effect: Changes in the material's intrinsic resistivity with strain.

For small variations, the above relationship can be written as

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

The gauge factor is defined as the ratio of per unit change in resistance to per unit change in length.

$$\therefore \quad \boxed{\text{gauge factor } G_f = \frac{\Delta R / R}{\Delta L / L} = 1 + 2\nu + \frac{\Delta \rho / \rho}{\varepsilon}} \qquad (6)$$

where $\varepsilon = \Delta L / L$ = Strain

This approximation is often valid for metallic strain gauges, where the change in resistivity under strain is minimal compared to the effects of geometry and Poisson's ratio.

- If the third term is neglected, then the gauge factor becomes:

gauge factor $G_f = \frac{\Delta R / R}{\Delta L / L} = 1 + 2\nu$ · **ΔR/R=G.ε** Young's modulus, $Y = \frac{\text{stress}}{\text{strain}}$ (Where, stress = $\frac{\text{Force}}{\text{Area}}$)

Strain gauge - Gauge factor

- The gauge factor GF is a unit less number.
- The gauge factor provides sensitivity information on the expected change in resistance for a given change in the length of a strain gauge.
- The gauge factor varies with temperature and the type of material.
- It is important to select a material with a high gauge factor and small temperature coefficient.

Constantan is an alloy of 55% Copper and 45% Nickel. The main feature of this alloy is its low temperature coefficient of resistance due to which its resistivity remains constant over a wide range of temperatures.

- For a common metal wire strain gauge made of constantan, GF is approximately equal to 2.
- Semiconductor strain gauges made of silicon have a GF about 70 to 100 times higher and are therefore much more sensitive than metallic wire strain gauges.
- This because in semiconductors the contribution of the piezoresistive term ($\Delta\rho/\rho$) is much larger than the geometric terms compared with the conductors.

Strain Gauges - Applications

- **Civil engineering:** and geotechnical monitoring regularly use strain gauges to detect failures in structures like bridges, buildings, and much more. These structures require constant monitoring because any significant deformation could lead to injuries or death.
- **Aerospace:** use millions of strain gauges to verify results from CAD (Computer Aided Design) and FEA (Finite Element Analysis) simulations. These tests are often conducted in dynamic conditions to display an accurate representation of how different forces affect aircraft.
- Rail monitoring, vibration and torque measurement, bending and deflection measurement, tension, strain, and compression measurement


Strain Gauges - Advantages

- High precision, function well at long distances from the test object, and require minimal effort to set up and maintain over long periods of time.
- Testing in the field is frequently quite different from laboratory testing under ideal conditions. One of the reasons strain gauges are highly valued is the fact that they can be used in harsh environments, yielding repeatable results with high precision. When an engineer tests objects with irregular shapes in harsh environments with difficult-to-access configurations, a specialized device like a strain gauge is often needed.
- Small and inexpensive.
- No moving parts

Strain Gauges

Young's Modulus is a measure of a material's stiffness or rigidity.
Young's Modulus has units of pressure
A high Young's Modulus means the material is stiff or rigid and requires a large amount of stress to deform it. For example, steel has a high Young's Modulus.
A low Young's Modulus indicates a flexible material that deforms more easily under stress, like rubber.

- Only the surface strain of the component can be measured, but not the internal strain of the component.
- Needs regular calibration.

Why Piezoresistive Effect is Larger in Semiconductors

*Stronger Bonding and Lattice Sensitivity: Semiconductors, such as silicon, have a crystal lattice structure that is highly sensitive to deformation. When strain is applied, the atomic spacing changes, significantly impacting the energy band structure and carrier mobility. This results in a large change in resistivity.

*Carrier Mobility Impact: In semiconductors, strain can alter the mobility of charge carriers (electrons and holes), leading to a greater change in resistivity. In metals, this effect is minimal because the free electrons are less affected by lattice deformations.

Thermistors

- Thermistors are included in the class of solids known as semiconductors, having electronic conductivities between those of conductors and insulators.
- Thermistors, thermally sensitive resistors, (construction of thermal resistor) are semiconductors which behave as resistors with usually a high negative temperature coefficient of resistance. The resistance of a thermistor varies as a function of temperature.
- The resistance R_T (ohm) of a thermistor at temperature T (Kelvin):

$$R_T = R_0\, exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{1}$$

- where R_T and R_0 are the resistances in ohms of the thermistor at absolute temperatures T and T_0.
- β is a thermistor constant ranging from $3500^o K$ to $5000^o K$. The reference temperature T_0 is usually taken as $298^o K$ or $25^o C$.

Thermistors - Temperature coefficient

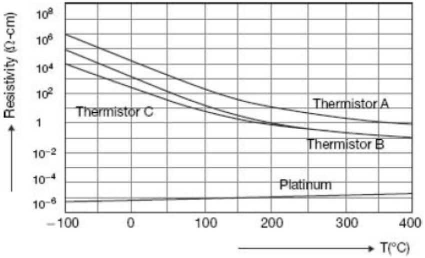
- The temperature coefficient (α) of a thermistor is usually expressed as a percent change in resistance per degree of temperature change , is deduced from (1) as:

$$\frac{dR}{dT}\left(\frac{1}{R}\right) = -\frac{\beta}{T^2} \tag{2}$$

- Assume $\beta = 4000^o k$, at $T = 298$, then: $\alpha = -0.045\ \Omega/^o C$.
- This is evidently a rather high temperature coefficient because for a platinum the corresponding figure is $0.0035/^o C$.

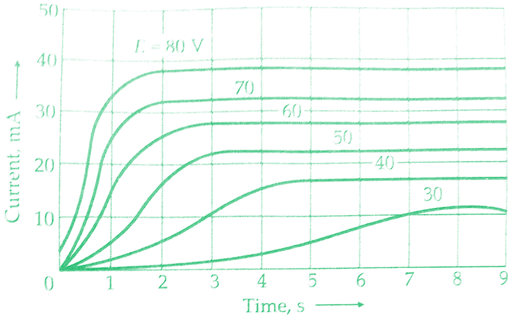
Thermistors - Resistance temperature characteristics

- Figure below demonstrates the logarithm of the specific resistance versus temperature relationship for three typical thermistor materials as compared to platinum metal.
- The specific resistance of the thermistor represented by the curve decreases by a factor of 50 as the temperature is increased from 0 to 100°C.
- Over thee same temperature range, the resistivity of platinum will increase by an approximate factor of 1.39.

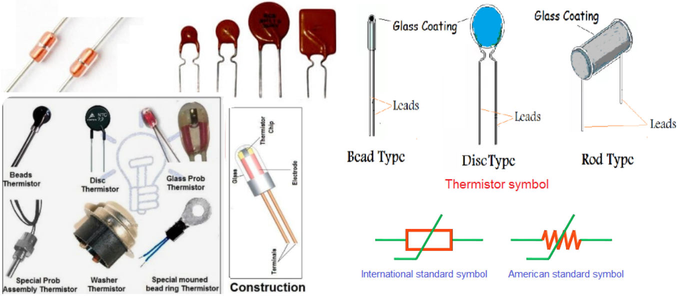


Thermistors

- The current-time characteristics of thermistor shown in the below figure indicate the time delay in reaching maximum current as a function of the applied voltage.
- When the heating effect just described occurs in a thermistor network, a certain finite time is required for the thermistor to heat and the current to build up to a maximum steady-state value.



Thermistors - Types, construction, and symbol



Thermistors - Notes

- **NTC:** Negative temperature coefficient thermistors used in automobiles.
- **PTC:** Positive temperature coefficient thermistors used for measurement and control of temperature.
- $R_T = R_0 \; exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$ for $T > 75$
- $R_T = R_0(1 + \alpha \, \Delta T)$ for $T < 75$

Thermistors - Advantages and disadvantages

Advantages

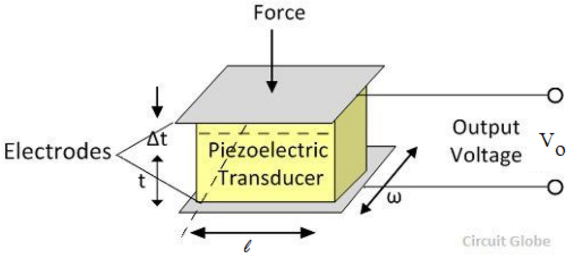
- They are compact, rugged, inexpensive.
- Their calibration is stable.
- They have a small response time,
- Their accuracy is high.

Disadvantages

- Thermistors exhibit a highly **non-linear characteristics** of resistance vs. temperature.
- **Time delays** from milliseconds to several minutes are possible with thermistor circuit.

Piezoelectric Transducers

- **Piezoelectric Effect:** When piezoelectric crystals are under the influence of some external force or pressure, This causes a deformation which produces an emf (as electric charge is generated within the crystal) that is a function of the deformation. This effect is reversible, i.e. if the varying potential applies to a piezoelectric transducer, it will change the dimension of the material or deform it. This effect is known as the piezoelectric effect (piezo means force). Electromotive force
- No external supply is required and hence it is an active transducer.



Piezoelectric Transducers

Classification of piezo-electric materials:

(i) **Natural Group:** Natural group include quartz and rochelle salt

(ii) **Synthetic Group:** Synthetic group include materials like Lithium sulphate, ethylene diamine tartarate, potassium dihydrogen phosphate, Barium titanate etc.

All piezo-electric materials are electrical insulators.

1. Piezo-electric effect is direction sensitive. A tensile force produces a voltage of one polarity while a compressive force produces a voltage of opposite polarity.
2. Two metal electrodes are placed on each side of the material to bring out the charge. Hence, a piezo-electric material is equivalent to a charge generator and a capacitor.
3. Piezoelectric transducers are suitable for dynamic pressure or force measurement.
4. For static inputs, the internal charges fastly discharges and hence the output becomes zero.

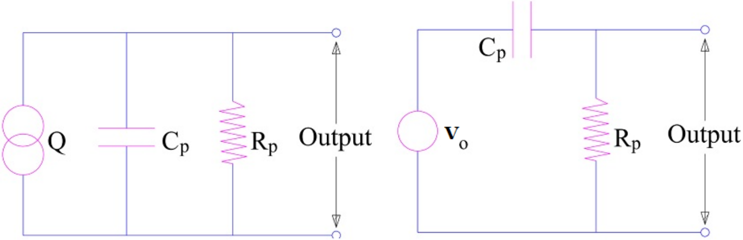
Piezoelectric Transducers

Let the applied force on the piezo-electric crystal be F.

Q = charge **C**
t = thickness of the crystal **mm**
E = electric field intensity **V/mm**
P = pressure applied **N/mm2**
g = voltage sensitivity of the crystal **V.mm/N**

- The charge sensitivity: $d = \frac{Q}{F}$ (C/N)
- Also, Charge sensitivity, $d = \epsilon_o \epsilon_r g$
  where, free space permittivity $\epsilon_o = 8.85 \times 10^{-12}$ (F/mm)
- Voltage sensitivity: $g = \frac{E}{P}$ (V.mm/N) where, $E = \frac{V_o}{t}$
- The output voltage $V_o = gPt$ (volt)

- **The equivalent circuit of the piezoelectric transducer:**

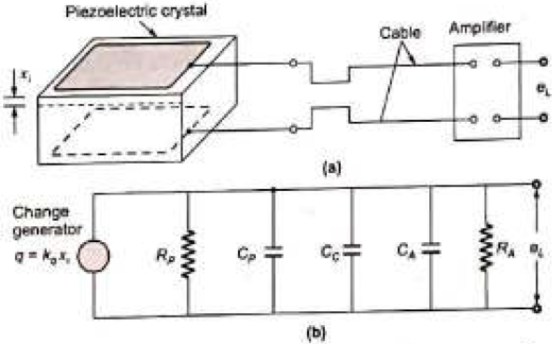


- Source is a charge generator (Q) whose value is equal to dF.
- The charge generated is across the capacitance C_p of the crystal and leakage resistance R_p
  where, $C_p = \frac{\epsilon \omega l}{t}$, and $R_p \approx 10^{12}\Omega$
- The charge generator can be replaced by an equivalent voltage source having a voltage of:

$$V_o = \frac{Q}{C_p} = \frac{dF}{C_p}$$

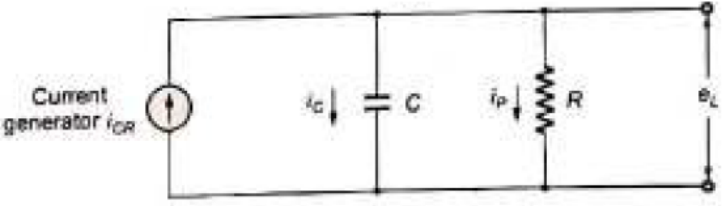
Piezoelectric Transducers

- **Cable Connection Model (Measuring Circuit)**



- R_P: Transducer (crystal) Leakage resistance.
- C_P: Transducer Capacitance.
- C_c: Cable capacitance.
- C_A: Amplifier Capacitance.
- R_A: Amplifier Resistance.

Piezoelectric Transducers



(c)

- The charge generator is converted into a constant current generator.
- The total capacitance is : $C = C_p + C_c + C_A$
- The total resistance is: $R = \frac{R_A\, R_p}{R_A + R_p}$
- **Note:** The impedance of the transducer is very high, so an amplifier with a high input impedance is necessary to avoid loading effect.