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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

VII Semester

AU3008 Sensors and Actuators

UNIT – 2 - Variable Resistance and Inductance Sensors

2.2 Strain Gauges

Principle of operation- Construction details- Characteristics and applications of Strain Gauges

2.2.1 Piezoresistive Effect:

- 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. The strain gauges are used for measurement of strain and associated stress in experimental stress analysis. Secondly, many other detectors and transducers, notably the load cells, torque meters, diaphragm type pressure gauges, temperature sensors, accelerometers and flow meters, employ strain gauges as secondary transducers.

2.2.2 Gauge Factor:

- The change in the value of resistance by straining the gauge may be partly explained by the normal dimensional behaviour of elastic material. If a strip of elastic material is subjected to tension, as shown in **Fig. 2.1** or in other words positively strained, its longitudinal dimension will increase while there will be

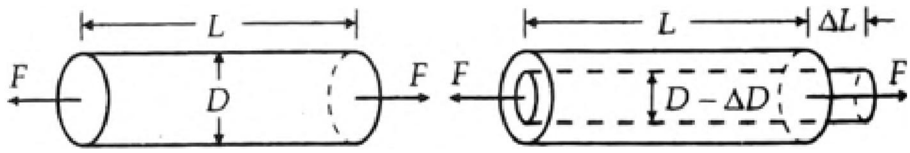


Fig. 2.1 Change in dimensions of a strain gauge element when subjected to a tensile force.

a reduction in the lateral dimension.

- So, when a gauge is subjected to a positive strain, its length increases while its area of cross-section decreases as shown in **Fig. 2.1**. Since the resistance of a conductor is proportional to its length and inversely proportional to its area of cross-section, the resistance of the gauge increases with positive strain.
- The change in the value resistance of strained conductor is more than what can be accounted for an increase in resistance due to dimensional changes. The extra change in the value of resistance is attributed to a change in the value of resistivity of a conductor when strained. This property, as described earlier, is known as **peizoresistive effect**.
- 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 p.
- Resistance of unstrained gauge $R = pL/A$.
- Let a tensile stress *s* be applied to the wire. This produces a positive strain causing the length to increase and area to decrease as shown in Fig. 2.1.
- Thus, when the wire is strained there are changes in its dimensions. Let **Δ**L = change in length, **Δ**A = change in area, **Δ**D = change in diameter and **Δ**R = change in resistance.

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

$$\text{Gauge factor} \qquad G_f = \frac{\Delta R / R}{\Delta L / L}$$

Gauge factor can also be written as,

$$= 1 \quad + \quad 2\nu \quad + \quad \frac{\Delta\rho/\rho}{\varepsilon}$$

Resistance change due to change of length	Resistance change due to change in area	Resistance change due to piezoresistive effect

$$G_f = \frac{\Delta R / R}{\Delta L / L} = 1 + 2\nu + \frac{\Delta\rho/\rho}{\Delta L / L}$$

The strain is usually expressed in terms of microstrain. 1 microstrain = 1 μm / m.
If the change in the value of resistivity of a material when strained is neglected, the gauge factor is :

$$G_f = 1 + 2\nu$$

Above equation valid only when Piezoresistive Effect *i.e.,* change in resistivity due to strain is almost negligible.

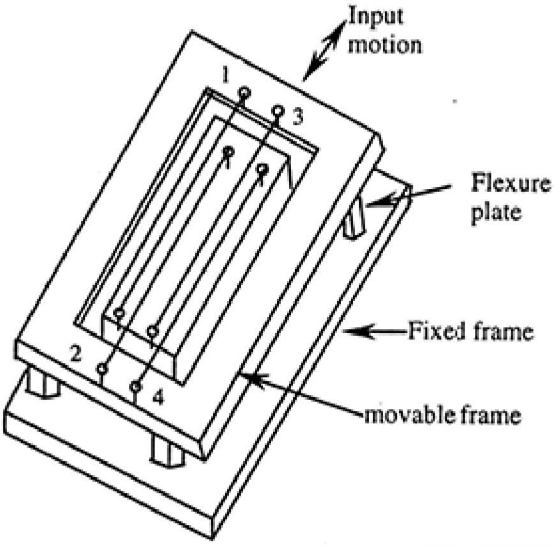
2.2.3 Types of Strain Gauges:

The following are the major types of strain gauges:

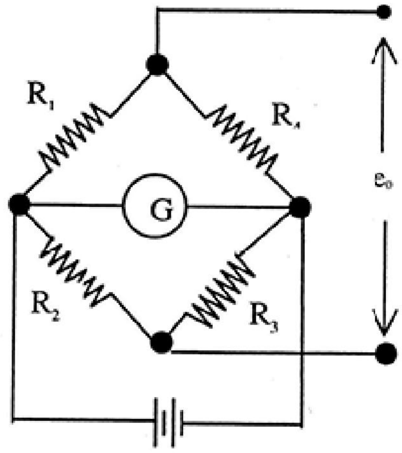
- Unbonded metal strain gauges
- Bonded metal wire strain gauges
- Bonded metal foil strain gauges
- Vacuum deposited thin metal film strain gauges
- Sputter deposited thin metal strain gauges
- Bonded semiconductor strain gauges
- Diffused metal strain gauges.

2.2.3.1 unbounded strain gage:

- In unbonded type, the resistance wires of about 0.025 mm diameter (0.001 inch) are fixed with some initial tension between two frames which can move relative to each other. This initial tension or preload is necessary to avoid buckling under compression or negative displacement and this preloading should be greater than any expected compression or negative displacement. A simplified figure is shown in Fig. 2.2.



2.2 a Unbonded strain gauge



2.2 (b) Circuit Connection

❖ Unbonded type strain gage for rotational motion is shown in fig. 2.3.

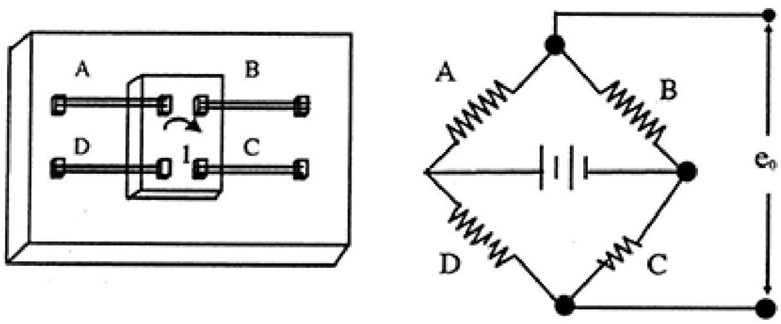


Fig. 2.3 Unbonded type strain gage for rotational stress

❖ The angular motion given to the inner member which is pivoted to the outer stationary member, increases the tension on the wires and reduces the preload on the other two wires.

❖ For example, clockwise twist given to the centre beam increases the tension on wires A and C and reduces the preloaded tension on wires B and D. If they are connected in a bridge as shown then the output voltage available is four times the voltage that would have been obtained due to a single wire.

- This arrangement is useful for measurement of tortional Strain and angular displacement. This type of gages can be used to measure only very small displacements of the order of .004 cm full scale. Normally these gages are used as sensors for force, pressure and acceleration.
- In these cases, the strain wires serve as the necessary spring elements to transduce force to displacement and this displacement is sensed as a resistance variation. The range of force and deflection values are decided by the size, length of wires and the number of wires used.
- The sensitivity for a bridge excitation of 5 volts is 40mv full scale output for .006 cm full scale displacement. The nominal value of resistance of the bridge arms is 350 ohms. The thermal sensitivity shift is 0.02 %/°C between -18°C and 120°C.

2.2.3.2 Bonded Type

In case of bonded-filament strain gages, the resistance wire is made into a form of a grid and cemented between two pieces of thin paper.

The factors to be considered to have a detailed description are

- ✓ Filament construction
- ✓ Material of the filament wire
- ✓ Base carrier material or backing material
- ✓ Cement used to bond the filament to the carrier
- ✓ Lead wire connections

(A) Filament construction:

The filament wire in bonded type is made in the form of a flat grid or flattened helix or a thin foil etched to give a flat grid pattern as shown in **Fig**. 2.2.4

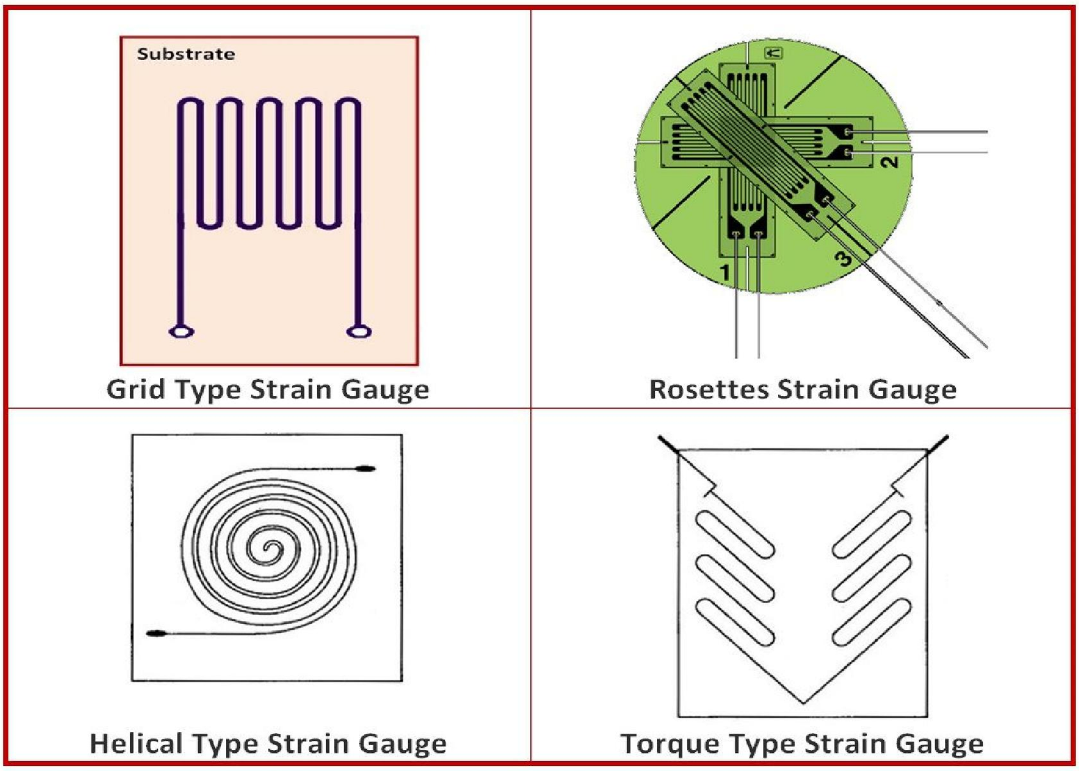


Figure- Different type of bonded strain gauge

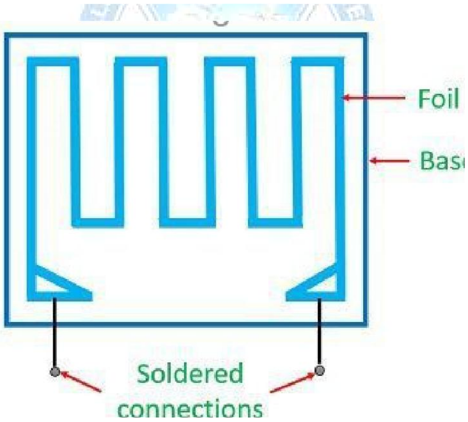


Fig. 2.2.4 Bonded metal Foil strain gauge.

- In the flat grid type the gage lengths were around 2.5 cm and wire size 0.025 mm.
- for shorter gage lengths up to .15 cm helical grid type is suitable. In this type the resistive wire is wound round a thin walled cylinder in the form of a helix. This cylinder is then flattened and bonded between two sheets of insulating material.
- For still shorter gages up to 1mm, foil type is suitable. In this type a metal foil of about 0.0004 mm thickness is formed on plastic film of 0.025 mm giving a total

thickness of 0.025 mm. This foil is etched by suitable process so that a metallic grid is formed.

- These strain gages are mainly sensitive to the component of strain along their longitudinal axis. However, they are also sensitive to a small extend to strain in the transverse direction. The nominal value of resistance for these gages range from 40 to 2000 ohms, but 120, 350 and 1000 being the common values.

(B) Material of the filament wire:

- The material chosen should have high gage factor. Common materials are Advance, Isoelastic and Nichrome - V (Nickel-chrome alloy with a G.F of 2.2). the choice of material depends not only upon gage factor but also its temperature sensitivity.
- The metal alloys used for strain gages are temp, sensitive. For example, if strains are to be measured over long period and the temperature is likely to change widely between each test then low temperature sensitive materials like copper nickel alloy is to be used inspite of the fact it has low gage factor.
- For measurement of strain above 250°C Nichrome V is suitable. For strain measurements at still higher temperature platinum alloys are used.
- As a matter of fact, many more points are to be considered when the grid material is selected. Selection is actually a compromise between the following factors.
  - ✓ High gage factor
  - ✓ High resistivity
  - ✓ Low temperature sensitivity
  - ✓ High electrical stability
  - ✓ High yield point
  - ✓ High endurance limit
  - ✓ Good workability
  - ✓ Good solderability
  - ✓ Low hysteresis
  - ✓ Low thermal emf.
  - ✓ Good corrosion resistance.

(C) Base carrier material

- The carrier material or the support material should have the following properties.
  - ✓ Good adherence to cements used
  - ✓ High dielectric strength
  - ✓ High mechanical strength
  - ✓ Minimum thickness consistent with other factors
  - ✓ Minimum temperature restrictions.
- For room temperature applications, the carrier material for the filament wire is a nitrocellulose - impregnated paper. For higher temperatures, phenolic plastic impregnated cellulose or glass fibres are used. For cryo-genic applications, Nichrome foil gages are available in the phenolic-glass carrier construction with integral welded leads.

(D) Strain gage cements:

- The cement to be used for fixing the strain gage to the straining member should have the following properties.
  - ✓ High mechanical strength
  - ✓ High creep resistance
  - ✓ High dielectric constant
  - ✓ Good adherence
  - ✓ Minimum moisture attraction
  - ✓ Minimum temperature restriction
  - ✓ Ease of application
  - ✓ The capacity to dry fast

(E) Lead wire connections:

- The vulnerable point for failure in the ordinary wire strain gage is at the discontinuity formed by the junction between the grid and the lead. A soldered junction between the fine filament and heavier
- lead wire or ribbon may be alright for static or slowly varying loads.
- But for dynamic strain measurements, resistance welding is necessary to provide a fatigue free resistant joint. Lead wire materials should have low,

stable resistivity, minimum temperature coefficient of resistance. This lead wires are to be insulated properly with materials of the same thermal classification as the gage carrier and bonding cements. The recommended lead wire insulation material for the temperature range is given below.

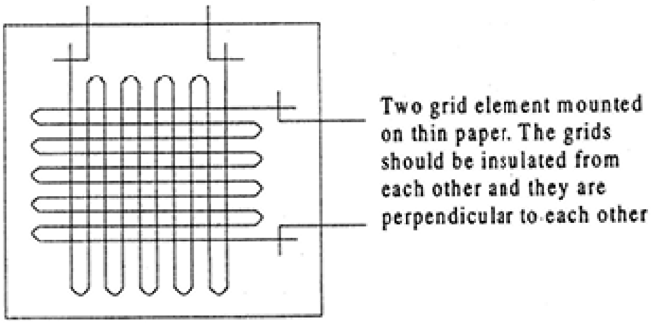
- ✓ Below 75°C - nylon
- ✓ Between 75°C and 65°C -vinyl
- ✓ Between - 75°C and 95°C -polyethylene
- ✓ Between 75°C and 260°C -teflon
- ✓ Above 260°C glass sleeving or glass impregnated silicone.

(F) Temperature Effect on Strain Gages:

- ❖ Temperature effect is one of the most troublesome factors in the use of resistance strain gages. The strain gage changes its resistance due to temperature variation in two ways besides the actual strain of our interest.
  - ✓ The strain produced by differential thermal expansion existing between the grid support and the gage.
  - ✓ The change in resistance due to temperature variations.
- ❖ Unless proper correction or compensation is done, the indicated strain will be very much different from the actual strain.
- ❖ This temperature effect can be cancelled in various ways. One way is to use a ***dummy gage*** identical to the active gage. This dummy gage is cemented to a piece of the ***same material*** which is unstrained and kept in the vicinity of the active gage so that the same temperature variation is experienced by the dummy. This dummy and the active are placed in the ***adjacent arms*** of a wheatstone bridge, so that resistance change due to differential thermal expansion and due to the temperature variation will have no effect on the bridge output voltage. Another way is to construct a special inherently temperature compensated gages.
- ❖ The temperature may change the ***gage factor*** also. This effect is negligible in metallic gages but affects seriously in case of semiconductor gages. This temperature problem has been successfully solved in the past for the temperature range from liquid Helium temperature **-70°Cto 1100°C**.

2.2.4. Measurement of Strain:

- The strain measured with the help of the strain gage is going to be some sort of average strain as strain gage spreads over an area.
- But normally strain is defined with respect to a point. Our measurement will be correct only if the strain gradient is constant and the strain is uniaxial. The strain gage is to be fixed so that its axis is aligned with the strain axis and its mid -oint (which is marked by the manufacturer oh the gage) coincides with the point of interest.
- If the strain gradient is not constant over the area of gage and its form is not known then the strain read by the gage cannot be associated with a point. In such a situation, the smallest practical gage is very useful. There are situations where the direction and magnitude are both unknowns. In such a case, the strain measurement in three different directions at a point is necessary to determine the maximum strain and its direction. If three different gages are to be fixed at a point, then one oyer the other arrangement is to be done which may not be very satisfactory for obvious reasons.
- Fixing them side by side will cover more area and hence the uncertainty of the measurement will increase.



- To overcome all these difficulties to certain extent, strain gage ‘rosettes’ have been developed. They are available, both in wire type and also in foil type. Fig. 2.2.6 shows a two- element rosette.
- Often two strain measurements at right angle suffice to determine a stress both direction and magnitude in one quadrant of a plane.
- This rosette can also be used for measurement of strain in a known direction with temperature compensation. The grid perpendicular to the strain axis will

compensate the resistance variation due to temperature change and resistance variation due to strain is negligible.

- Fig. 2.2.7a is delta rosette and fig. 2.2.7 b rectangle rosette. These rosettes can be used for any strain measurements whose direction and magnitude is completely unknown and it can be in any quadrant of a plane.

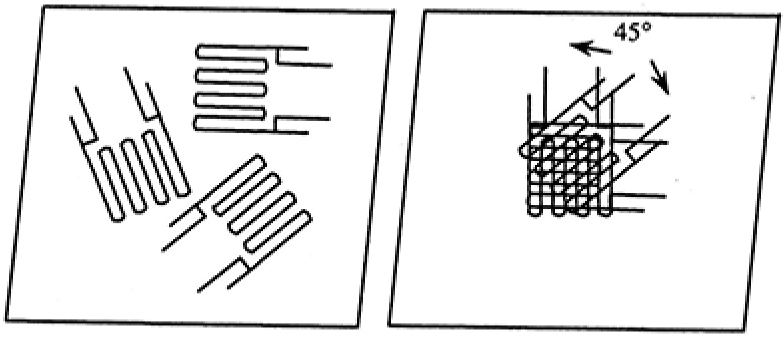


Fig. 2.2.7 (a) Delta rosette **(b)** Rectangle rosette

2.2.5 Strain Gage Circuitry:

- The strain gage can transduce a strain into a resistance change only. If a voltage change corresponding to the strain is needed, then a potentiometer circuit or a bridge circuit with an excitation should be thought of. One may think that an ohmmeter can be used to find out the change in resistance which can be properly calibrated to give the corresponding strain. This is not possible because the sensitivity of the ohmmeter is far less than the sensitivity required for strain measurement. As a matter of fact strains of the order of one micro m/m are detectable with commercial equipment.

- For a typical gage constants of gage factor F = 2.0 and R_g = 120 ohms, the change in resistance that is to be measured for a microstrain, is

$$\Delta R = F\epsilon R_g \quad \text{where } \epsilon \text{ is strain}$$

$$= 2 \times 1 \times 10^{-6} \times 120$$

$$= 0.00024 \text{ ohms.}$$

- No ohmmeter will be able to measure this small resistance change reasonably accurately. Therefore, bridge and potentiometric methods are used.

The Wheatstone Bridge Circuits:

- The simplest form of wheatstone bridge for the measurement of strain is shown in Fig. 2.4.8.
- The bridge is balanced initially when there is no strain. When the gage is strained, the resistance changes and thereby causing an unbalance in the bridge. The voltage output is given by the following expression.
- Considering the upper half of the bridge, potential of the centre point is

$$E_g = \frac{R_g}{R_g + R_1} E_i$$

- The change in this voltage for a change in R_g is the output voltage as the potential of the reference point is E_c, as R_2 and R_3 do not change.

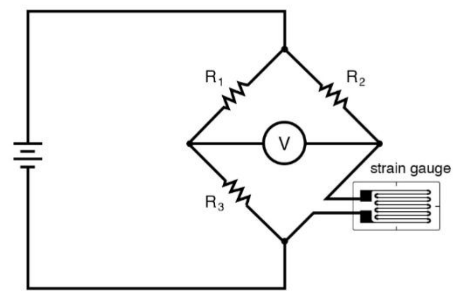


Fig 2.2.8 Strain gage bridge circuits

Wire Resistance:

- The strain gauge's resistance (Rgauge) is not the only resistance being measured: the wire resistances Rwire1 and Rwire2, being in series with Rgauge, also contribute to the resistance of the lower half of the rheostat arm of the bridge, and consequently contribute to the voltmeter's indication. This, of course, will be falsely interpreted by the meter as physical strain on the gauge.
- While this effect cannot be completely eliminated in this configuration, it can be

minimized with the addition of a third wire, connecting the right side of the voltmeter directly to the upper wire of the strain gauge:

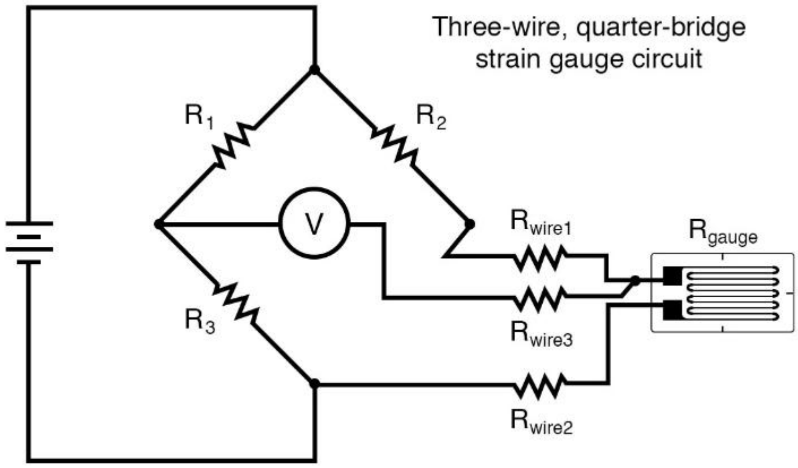


Fig. 2.2.9 Three-wire quarter bridge strain gauge circuit

- Because the third wire carries practically no current (due to the voltmeter's extremely high internal resistance), its resistance will not drop any substantial amount of voltage. Notice how the resistance of the top wire (Rwire1) has been "bypassed" now that the voltmeter connects directly to the top terminal of the strain gauge, leaving only the lower wire's resistance (Rwire2) to contribute any stray resistance in series with the gauge. Not a perfect solution, of course, but twice as good as the last circuit!
- There is a way, however, to reduce wire resistance error far beyond the method just described, and also help mitigate another kind of measurement error due to temperature.

Resistance Change in Temperature:

- An unfortunate characteristic of strain gauges is that of resistance change with changes in temperature. This is a property common to all conductors, some more than others.
- Thus, our quarter-bridge circuit as shown (either with two or with three wires connecting the gauge to the bridge) works as a thermometer just as well as it does a strain indicator. If all we want to do is measure strain, this is not good. We can transcend this problem, however, by using a "dummy" strain gauge in place of R2, so that both elements of the rheostat arm will change resistance in

the same proportion when temperature changes, thus canceling the effects of temperature change:

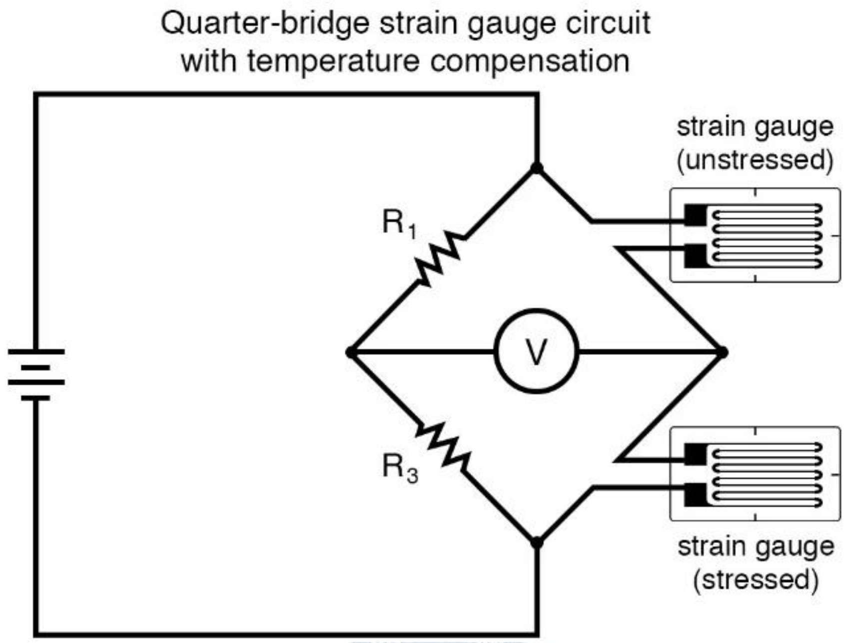


Fig 2.2.10 Strain gauge bridge circuit with temperature compensation

- Resistors R1 and R3 are of the equal resistance value, and the strain gauges are identical to one another. With no applied force, the bridge should be in a perfectly balanced condition and the voltmeter should register 0 volts. Both gauges are bonded to the same test specimen, but only one is placed in a position and orientation so as to be exposed to physical strain (the active gauge).
- The other gauge is isolated from all mechanical stress and acts merely as a temperature compensation device (the “dummy” gauge). If the temperature changes, both gauge resistances will change by the same percentage, and the bridge’s state of balance will remain unaffected. Only a differential resistance (difference of resistance between the two strain gauges) produced by physical force on the test specimen can alter the balance of the bridge.

2.2.6. Characteristics of Strain Gauges:

- The core element of a piezoresistive sensor is the strain gauge. The characteristics of a strain gauge are mainly defined by the gauge dimensions, resistance, gauge factor, temperature coefficient, resistivity, and thermal stability.
- **Gauge dimensions** and shape are very important in choosing a right type of strain gauge for a given application.
- **Gauge resistance** is defined as the electrical resistance measured between two metal tabs or leads. Gauge resistance is an important design and application parameter since it determines both the output signal amplitude of the gauge ($\Delta V/V = \Delta R/R$) and the dissipation power (V^2/R).
- **Gauge factor or strain sensitivity** is defined as the ratio of ($\Delta R/R$) and the strain ε. The real GF plots of common gauge materials are shown in Figure 1, where the GF is the slope of the curve.

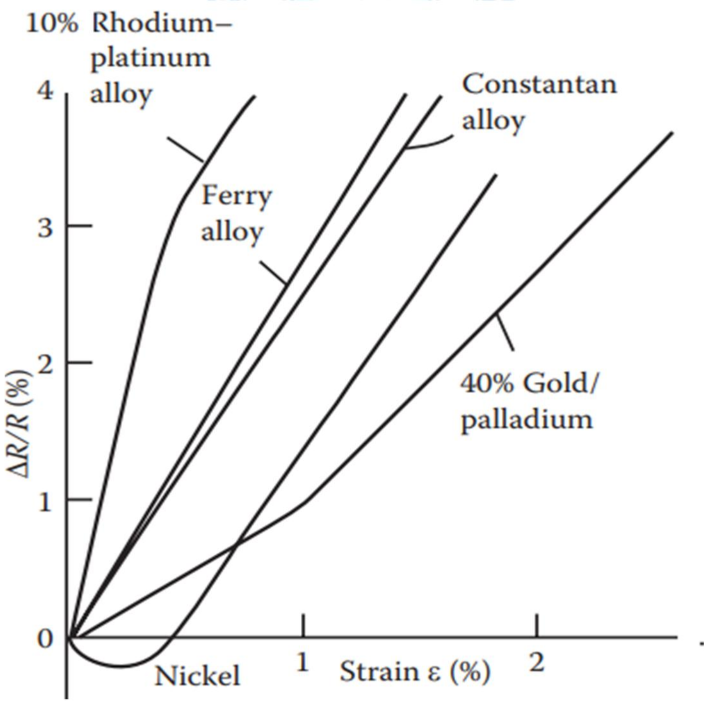


Fig. 2.2.11 GF plots for various strain gauge element materials.

- Both Ferry alloys and Constantan alloys have relatively high and constant GF values, indicating a well-behaved and consistent pattern.

- The 10% rhodium–platinum alloy exhibits a desirable and high GF feature between 0% and 0.4% range of strain ε, but its performance degrades above 0.4% strain ε point.

- Pure nickel even demonstrates a negative GF for small strain (ε < 0.5%).

- The GF values of semiconductor materials are much larger than the GF values of metals. Therefore, the majority of piezoresistive strain gauges used today are made of semiconductor materials.

- **Hysteresis** of a strain gauge is defined as the ratio (in percent) of the difference between the output signals of the gauge divided by the maximum output signal. The output signals of the gauge are obtained with increasing and decreasing strain loading at identical strain values.

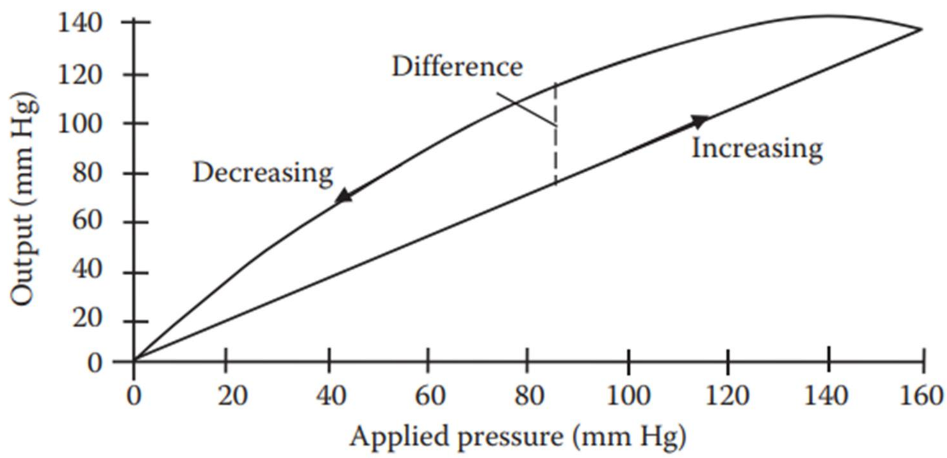


Fig. 2.2.12 shows the hysteresis of a strain-gauge-type pressure sensor.

2.2.7 Applications of Strain Gauges:

Strain gauges are highly sensitive devices used to measure the mechanical strain of an object. They are widely used in various industries due to their ability to accurately measure deformations, stresses, and forces. Here are some of the most common applications of strain gauges:

- **Automotive Industry**
  - ✓ **Tire pressure monitoring systems (TPMS):** To measure the strain in the tire sidewall to indirectly determine tire pressure.
  - ✓ **Suspension system testing:** To evaluate the performance and durability of suspension components.
  - ✓ **Crash testing:** To measure the deformation of vehicle components during impact.
- **Aerospace and Aviation**
  - ✓ **Aircraft wing stress analysis:** To evaluate the stress distribution in aircraft wings during flight.
  - ✓ **Rocket engine testing:** To measure the strain in rocket engine components during operation.
  - ✓ **Spacecraft structural health monitoring:** To monitor the structural integrity of spacecraft during missions.
- **Medical Devices**
  - ✓ **Prosthetic limbs:** To measure the forces exerted by patients on prosthetic limbs.
  - ✓ **Orthopedic implants:** To monitor the stress and strain in implants such as hip and knee replacements.
  - ✓ **Medical devices testing:** To evaluate the mechanical performance of medical devices.

- **Industrial Applications**

  - ✓ **Pressure measurement:** To measure pressure indirectly by measuring the strain in a pressure-sensitive element.
  - ✓ **Force measurement:** To measure forces applied to objects by measuring the strain in a load cell.
  - ✓ **Torque measurement:** To measure the torque applied to shafts by measuring the strain in the shaft.

- **Research and Development**

  - ✓ **Material testing:** To study the mechanical properties of materials under various loading conditions.
  - ✓ **Product development:** To optimize the design and performance of products.
  - ✓ **Scientific research:** To conduct experiments and investigations in various fields.

These are just a few examples of the many applications of strain gauges. Their versatility and accuracy make them an invaluable tool in a wide range of industries.

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