SANTA CLARA UNIVERSITY

Strain Gauge

Synopsis on Sensor Presentation

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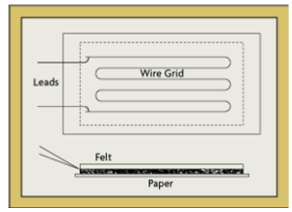
Presentation Slides

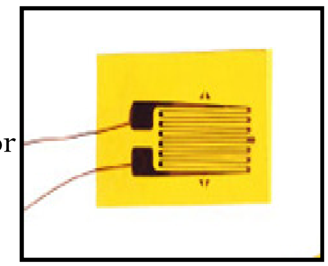
Introduction

- Strain Gauges are designed to convert mechanical motion into an electronic signal.
- They are used to measure displacement, force, load, pressure, torque or weight.
- The basic concept is if a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. This changes its resistance (R).
- Resistance is proportion to the Gauge factor (GF) of the wire's resistance.

$$GF = (\Delta R/R)/(\Delta L/L) = (\Delta R/R)/\text{ Strain}$$

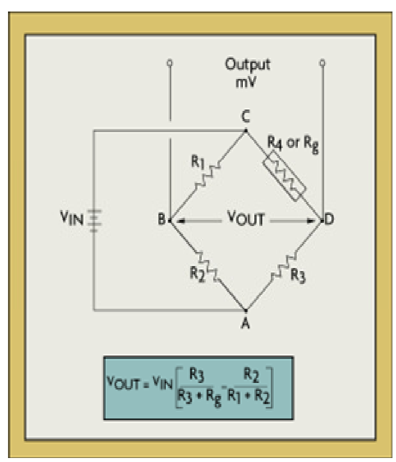


Bonded Resistance S.G.

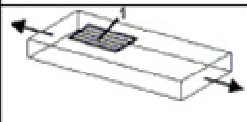
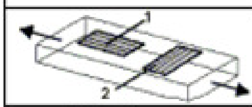
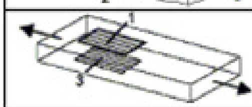
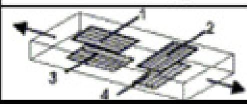

Metal Foil S.G.

Principle: Wheatstone Bridge

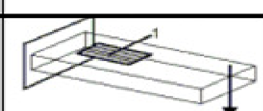
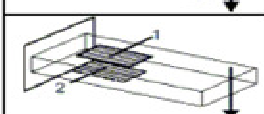
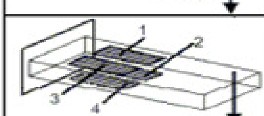
- Strain gauge transducers usually employ four strain gauge elements electrically connected to form a Wheatstone bridge circuit
- The sensor can occupy 1/2/3/4 arms of the bridge, depending on the application.
- So when R1, R2, R3 & R4 are balanced there in no Vout.
- If R4 acts as element and is strained we get Vout which is in mV



Implementation

Strain	Gauge Setup	Bridge Type	Sensitivity MV/V @ 1000 uE	Details
Axial		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Also responds to Bending Strain.
		½	0.65	Better: Temperature compensated, but it is sensitive to bending strain.
		½	1.0	Better: Rejects Bending Strain, but not temperature. Must use dummy gauges if compensating for temperature.
		Full	1.3	Best: More sensitive and compensates for both temperature and bending strain.

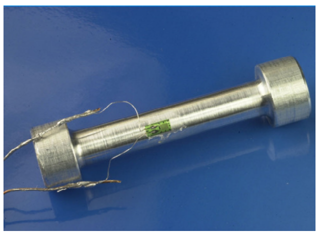
Implementation

Strain	Gauge Setup	Bridge Type	Sensitivity MV/V @ 1000 uE	Details
Bending		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Responds equally to Axial Strain.
		½	1.0	Better: Rejects axial strain and is temperature compensated
		Full	2.0	Best: Rejects axial strain and is temperature compensated. Most sensitive to bending strain.
Torsional and Shear		½	1.0	Good: Gauges must be mounted at 45 degrees from centerline. Axial and Bending forces produce equal strain and are hence rejected.
		Full	2.0	Best: More sensitive full-bridge version of previous setup. Rejects both axial and bending strains.

Application

Experimental stress analysis.

- multi axial stress fatigue testing, proof testi
- residual stress
- vibration measurement
- torque measurement
- bending and deflection measurement



- Compression measurement
- Tension measurement
- Strain measurement

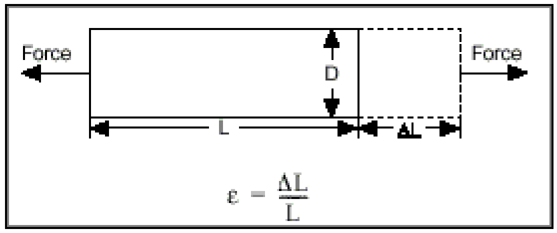
Failure analysis.

Challenges

- The output of a strain gage circuit is a **very low-level voltage signal** requiring a sensitivity of 100 microvolts or better.
- The low level of the signal makes it particularly susceptible to unwanted **noise from other electrical devices**.
- **Capacitive coupling** caused by the lead wires' running too close to AC power cables or ground currents are potential error sources in strain measurement.
- Other error sources may include **magnetically induced voltages** when the lead wires pass through variable magnetic fields, parasitic (unwanted) contact resistances of lead wires, insulation failure, and thermocouple effects at the junction of dissimilar metals.
- Differences in expansion coefficients between the gage and base materials, because of **temperature variation** may cause dimensional changes in the sensor element.

What is strain?

Strain is the amount of deformation of a body due to an applied force. More specifically, strain (e) is defined as the fractional change in length, as shown in the figure defining strain gauge below.



Definition of Strain

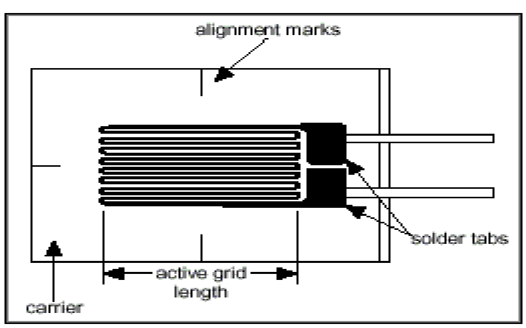
Strain can be positive (tensile) or negative (compressive). Although dimensionless, strain is sometimes expressed in units such as in/in or mm/mm. In practice, the magnitude of measured strain is very small. Therefore, strain is often expressed as microstrain ($\mu\varepsilon$), which is E x 10^{-6}.

When you strain a bar with a uniaxial force, as depicted in the figure defining strain gauge above, a phenomenon known as Poisson strain causes the girth of the bar, D, to contract in the transverse, or perpendicular, direction. The magnitude of this transverse contraction is a material property indicated by its Poisson's ratio. The Poisson's ratio (v) of a material is defined as the negative ratio of the strain in the transverse direction (perpendicular to the force) to the strain in the axial direction (parallel to the force), or $\nu = -\varepsilon_T/\varepsilon$. For example, Poisson's ratio for steel ranges from 0.25 to 0.3.

The Strain Gauge

While there are several methods of measuring strain, the most common is with a strain gauge. A strain gauge's electrical resistance varies in proportion to the amount of strain placed on it. The most widely used gauge is the bonded metallic strain gauge.

The metallic strain gauge consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction (shown as the "active grid length" in the Bonded Metallic Strain Gauge figure). The cross sectional area of the grid is minimized to reduce the effect of shear strain and Poisson strain.



Bonded Metallic Strain Guage

It is very important that you properly mount the strain gauge onto the test specimen. This ensures the strain accurately transfers from the test specimen through the adhesive and strain gauge backing to the foil.

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor (GF). Gauge factor is the ratio of fractional change in electrical resistance to the fractional change in length (strain):

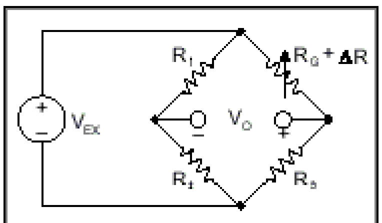
$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}$$

The gauge factor for metallic strain gauges is typically around two.

Ideally, the resistance of the strain gauge would change only in response to applied strain. However, strain gauge material, as well as the specimen material to which you apply the gage, will also respond to changes in temperature. Strain gauge manufacturers attempt to minimize sensitivity to temperature by processing the gauge material to compensate for the thermal expansion of the specimen material intended for the gauge. While compensated gauges reduce the thermal sensitivity, they do not remove it completely. For example, consider a gauge compensated for aluminum that has a temperature coefficient of 23 ppm/°C. With a nominal resistance of 1000 ΩGF = 2, the equivalent strain error is still 11.5 $\mu\varepsilon$/°C. Therefore, additional temperature compensation is important.

Measuring Strain

In practice, the strain measurements rarely involve quantities larger than a few millistrain (ε x 10-3). Therefore, measuring strain requires accurate measurement of very small changes in resistance. For example, suppose a test specimen undergoes a substantial strain of 500 $\mu\varepsilon$. A strain gauge with a gauge factor GF = 2 will exhibit a change in electrical resistance of only $2 \cdot (500 \times 10^{-6}) = 0.1\%$. For a 120 Ωgauge, this is a change of only 0.12 Ω.

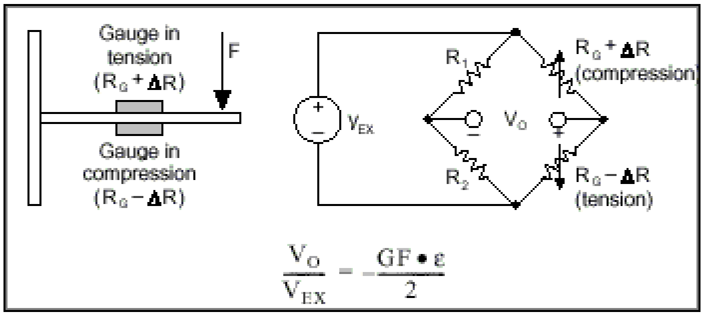


$$\frac{V_O}{V_{EX}} = -\frac{GF \bullet \varepsilon}{4}\left(\frac{1}{1 + GF \bullet \frac{\varepsilon}{2}}\right)$$

Quarter-Bridge Circuit

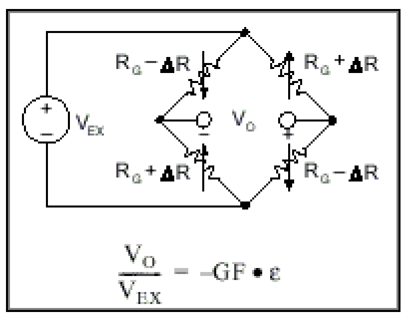
Alternatively, you can double the sensitivity of the bridge to strain by making both gauges active, although in different directions. For example, the Half-Bridge Circuit figure illustrates a bending beam application with one bridge mounted in tension (R_G + ΔR) and the other mounted in compression (R_G - ΔR). This half-bridge configurati

on, whose circuit diagram is also illustrated in the Half-Bridge Circuit figure, yields an output voltage that is linear and approximately double that of the quarter-bridge circuit.



Half-Bridge Circuit

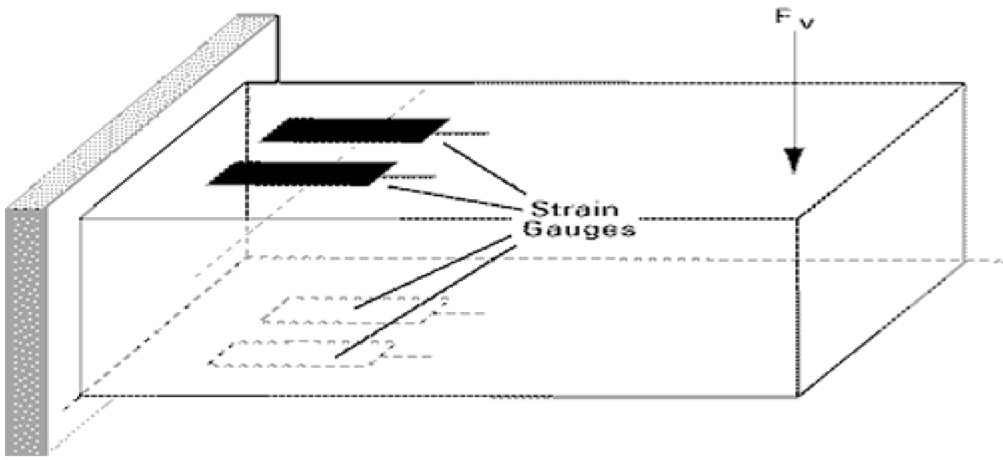
Finally, you can further increase the sensitivity of the circuit by making all four of the arms of the bridge active strain gauges and mounting two gauges in tension and two gauges in compression. The full-bridge circuit is shown in the Full-Bridge Circuit figure below.



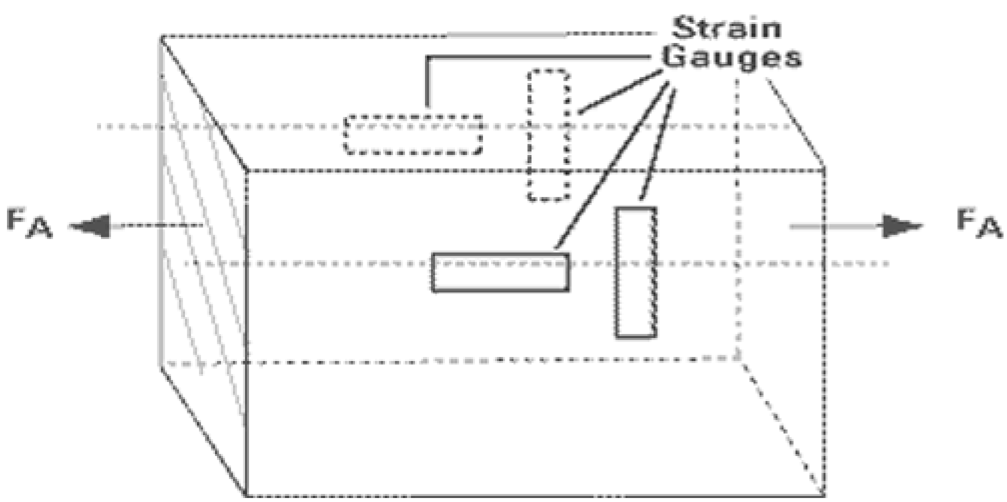
Full-Bridge Circuit

The equations given here for the Wheatstone bridge circuits assume an initially balanced bridge that generates zero output when you do not apply strain. In practice however, resistance tolerances and strain induced by gauge application will generate some initial offset voltage. This initial offset voltage is typically handled in two ways. First, you can use a special offset-nulling, or balancing, circuit to adjust the resistance in the bridge to rebalance the bridge to zero output. Alternatively, you can measure the initial unstrained output of the circuit and compensate in software.

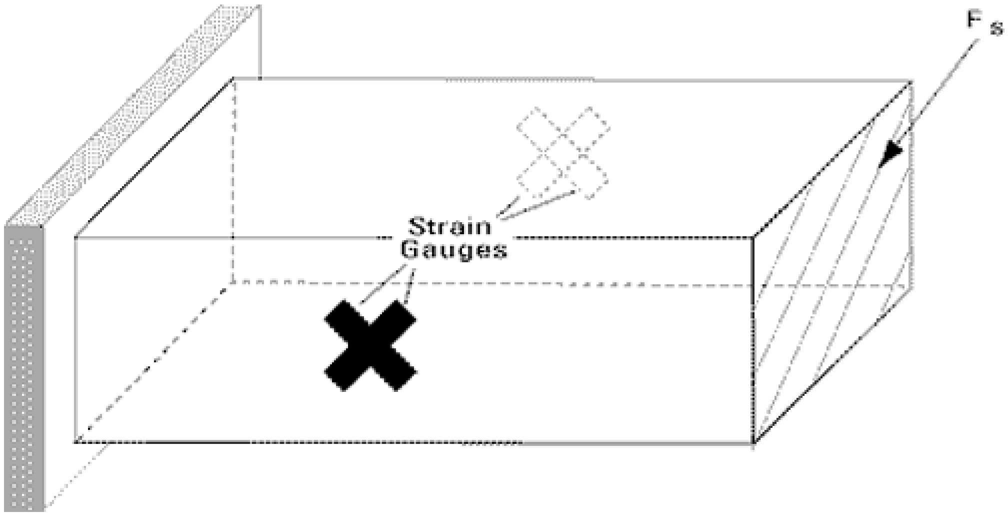
With this in mind, there are several types of commonly measured strain (in order of relative popularity):



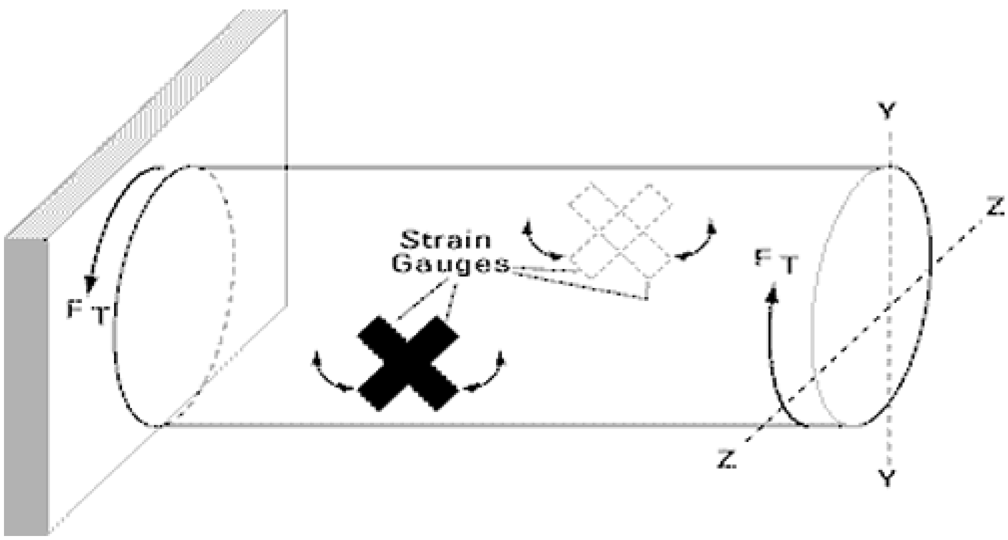
Bending Strain -- resulting from a linear force (F_V) exerted in the vertical direction.



Axial Strain -- resulting from a linear force (Fa) exerted in the horizontal direction.



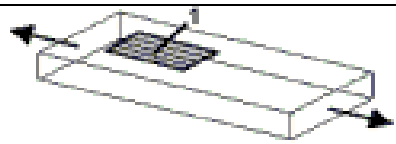
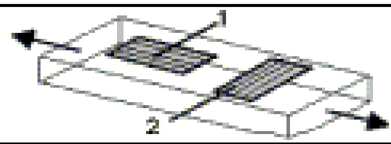
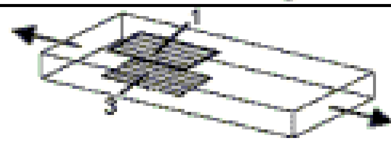
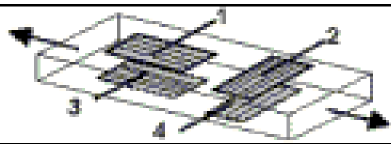
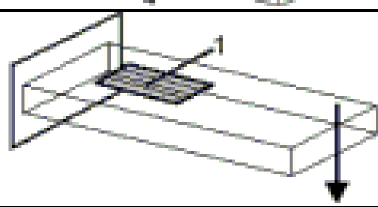
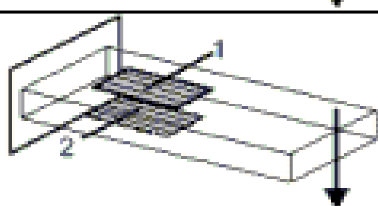
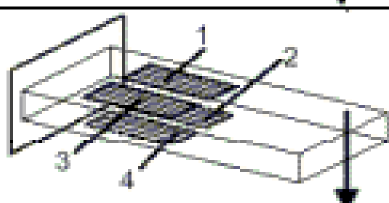
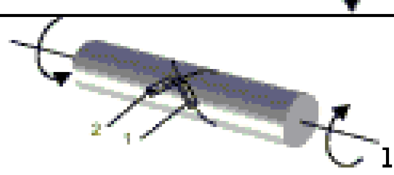
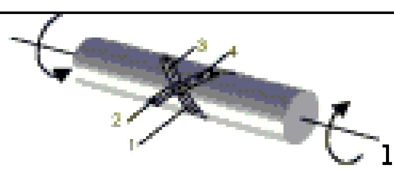
Shear Strain -- resulting from a linear force (F_S) with components in both the vertical and horizontal direction.



Torsional Strain -- resulting from a circular force (F_T) with components in both the vertical and horizontal direction.

Choosing the Right Type of Strain Gauge

The two primary criteria for selecting the right type of strain gauge are sensitivity and precision. In general, if you use more strain gauges, (a full-bridge circuit rather than a quarter-bridge) your measurement will respond more quickly and be more precise. On the other hand, cost will also play a large part in determining the type of strain gauge you select. Typically, full-bridge strain gauges are significantly more expensive than half-bridge and quarter-bridge gauges. For a summary of the various types of strain and strain gauges, please refer to the Strain Gauge Summary table below.

Strain	Gauge Setup	Bridge Type	Sensitivity MV/V @ 1000 uE	Details
Axial		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Also responds to Bending Strain.
		½	0.65	Better: Temperature compensated, but it is sensitive to bending strain.
		½	1.0	Better: Rejects Bending Strain, but not temperature. Must use dummy gauges if compensating for temperature.
		Full	1.3	Best: More sensitive and compensates for both temperature and bending strain.
Bending		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Responds equally to Axial Strain.
		½	1.0	Better: Rejects axial strain and is temperature compensated
		Full	2.0	Best: Rejects axial strain and is temperature compensated. Most sensitive to bending strain.
Torsional and Shear		½	1.0	Good: Gauges must be mounted at 45 degrees from centerline. Axial and Bending forces produce equal strain and are hence rejected.
		Full	2.0	Best: More sensitive full-bridge version of previous setup. Rejects both axial and bending strains.

Application & Installation

The output of a strain gage circuit is a very low-level voltage signal requiring a sensitivity of 100 microvolts or better. The low level of the signal makes it particularly susceptible to unwanted noise from other electrical devices. Capacitive coupling caused by the lead wires' running too close to AC power cables or ground currents are potential error sources in strain measurement. Other error sources may include magnetically induced voltages when the lead wires pass through variable magnetic fields, parasitic (unwanted) contact resistances of lead wires, insulation failure, and thermocouple effects at the junction of dissimilar metals. The sum of such interferences can result in significant signal degradation.

Shielding

Most electric interference and noise problems can be solved by shielding and guarding. A shield around the measurement lead wires will intercept interferences and may also reduce any errors caused by insulation degradation. Shielding also will guard the measurement from capacitive coupling. If the measurement leads are routed near electromagnetic interference sources such as transformers, twisting the leads will minimize signal degradation due to magnetic induction. By twisting the wire, the flux-induced current is inverted and the areas that the flux crosses cancel out. For industrial process applications, twisted and shielded lead wires are used almost without exception.

Guarding

Guarding the instrumentation itself is just as important as shielding the wires. A guard is a sheet-metal box surrounding the analog circuitry and is connected to the shield. If ground currents flow through the strain-gage element or its lead wires, a Wheatstone bridge circuit cannot distinguish them from the flow generated by the current source. Guarding guarantees that terminals of electrical components are at the same potential, which thereby prevents extraneous current flows.

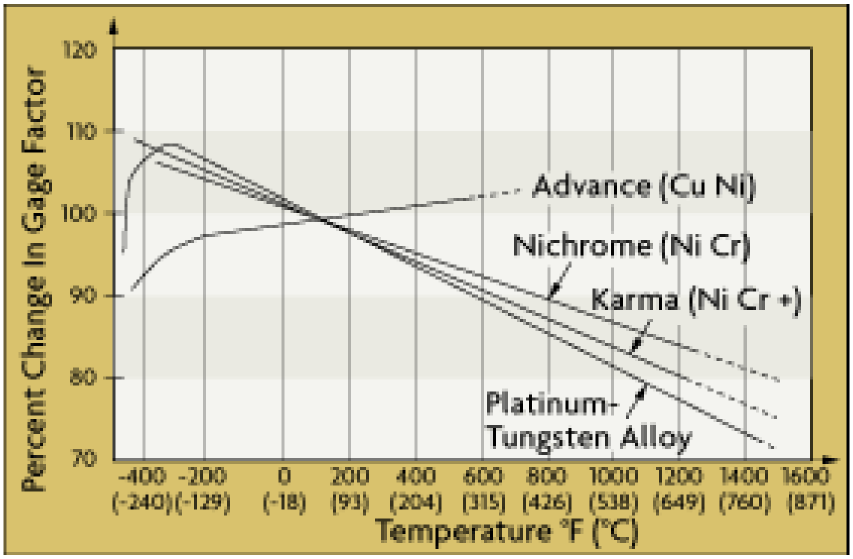
Connecting a guard lead between the test specimen and the negative terminal of the power supply provides an additional current path around the measuring circuit. By placing a guard lead path in the path of an error-producing current, all of the elements involved (i.e., floating power supply, strain gage, all other measuring equipment) will be at the same potential as the test specimen. By using twisted and shielded lead wires and integrating DVMs with guarding, common mode noise error can virtually be eliminated.

Temperature and the Gage Factor

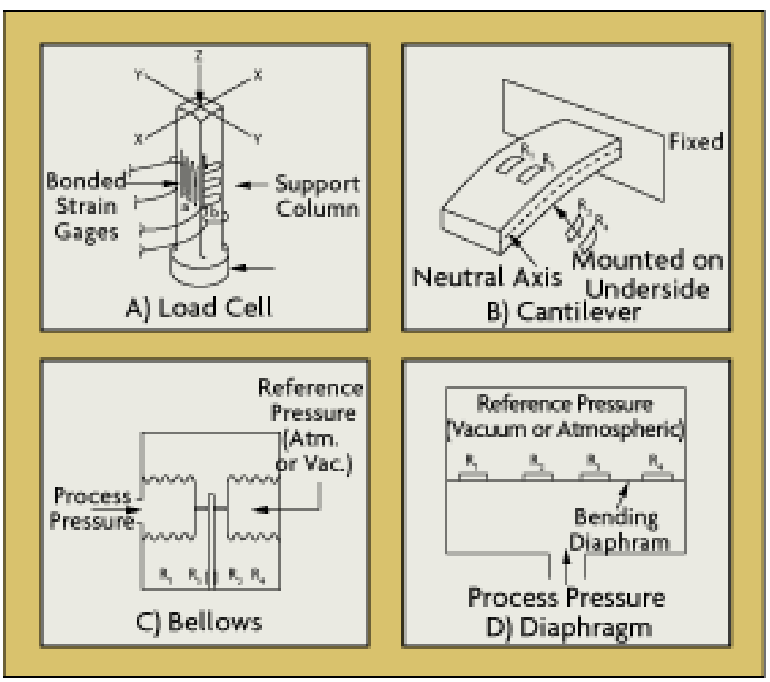
Strain-sensing materials, such as copper, change their internal structure at high temperatures. Temperature can alter not only the properties of a strain gage element, but also can alter the properties of the base material to which the strain gage is attached. Differences in expansion coefficients between the gage and base materials may cause dimensional changes in the sensor element.

Expansion or contraction of the strain-gage element and/or the base material introduces errors that are difficult to correct. For example, a change in the resistivity or in the temperature coefficient of resistance of the strain gage element changes the zero reference used to calibrate the unit.

The gage factor is the strain sensitivity of the sensor. The manufacturer should always supply data on the temperature sensitivity of the gage factor. Figure 2-11 shows the variation in gage factors of the various strain gage materials as a function of operating temperature. Copper-nickel alloys such as Advance have gage factors that are relatively sensitive to operating temperature variations, making them the most popular choice for strain gage materials.



Transducer Designs



Strain gages are used to measure displacement, force, load, pressure, torque or weight. Modern strain-gage transducers usually employ a grid of four strain elements electrically connected to form a Wheatstone bridge measuring circuit.

The strain-gage sensor is one of the most widely used means of load, weight, and force detection. In Figure A, a vertical beam is subjected to a force acting on the vertical axis. As the force is applied, the support column experiences elastic deformation and changes the electrical resistance of each strain gage. By the use of a Wheatstone bridge, the value of the load can be measured. Load cells are popular weighing elements for tanks and silos and have proven accurate in many other weighing applications.

Strain gages may be bonded to cantilever springs to measure the force of bending (B). The strain gages mounted on the top of the beam experience tension, while the strain gages on the bottom experience compression. The transducers are wired in a Wheatstone circuit and are used to determine the amount of force applied to the beam.

Strain-gage elements also are used widely in the design of industrial pressure transmitters. C shows a bellows type pressure sensor in which the reference pressure is sealed inside the bellows on the right, while the other bellows is exposed to the process pressure. When there is a difference between the two pressures, the strain detector elements bonded to the cantilever beam measure the resulting compressive or tensile forces.

A diaphragm-type pressure transducer is created when four strain gages are attached to a diaphragm (D). When the process pressure is applied to the diaphragm, the two central gage elements are subjected to tension, while the two gages at the edges are subjected to compression. The corresponding changes in resistance are a measure of the process pressure. When all of the strain gages are subjected to the same temperature, such as in this design, errors due to operating temperature variations are reduced.

Installation Diagnostics

All strain gage installations should be checked using the following steps:

1. Measure the base resistance of the unstrained strain gage after it is mounted, but before wiring is connected.

2. Check for surface contamination by measuring the isolation resistance between the gage grid and the stressed force detector specimen using an ohmmeter, if the specimen is conductive. This should be done before connecting the lead wires to the instrumentation. If the isolation resistance is under 500 megaohms, contamination is likely.

3. Check for extraneous induced voltages in the circuit by reading the voltage when the power supply to the bridge is disconnected. Bridge output voltage readings for each strain-gage channel should be nearly zero.

4. Connect the excitation power supply to the bridge and ensure both the correct voltage level and its stability.

5. Check the strain gage bond by applying pressure to the gage. The reading should be unaffected.

References:

- http://www.omega.com/Literature/Transactions/volume3/strain.html#sendes
- http://www.eidactics.com/Downloads/Refs-Methods/NI_Strain_Gauge_tutorial.pdf
- *Instrument Engineers' Handbook,* Bela Liptak, CRC Press LLC, 1995.