The Strain Gage

When external forces are applied to a stationary object, stress and strain are the result. Stress is defined as the object's internal resisting forces, and strain is defined as the displacement and deformation that occur. For a uniform distribution of internal resisting forces, stress can be calculated (Figure 2-1) by dividing the force (F) applied by the unit area (A):

$$\text{Stress } (\sigma) = F/A$$

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain is calculated by dividing the total deformation of the original length by the original length (L):

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

Typical values for strain are less than 0.005 inch/inch and are often expressed in micro-strain units:

$$\text{Micro-strain} = \text{Strain} \times 10^{6}$$

Strain may be compressive or tensile and is typically measured by strain gages. It was Lord Kelvin who first reported in 1856 that metallic conductors subjected to mechanical strain exhibit a change in their electrical resistance. This phenomenon was first put to practical use in the 1930s.
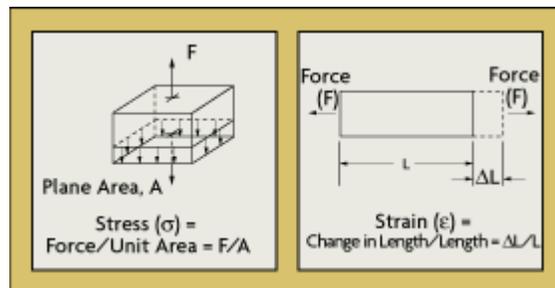

Figure 2-1: Definitions of Stress & Strain

Fundamentally, all strain gages are designed to convert mechanical motion into an electronic signal. A change in capacitance, inductance, or resistance is proportional to the strain experienced by the sensor. If a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. This changes its resistance (R) in proportion to the strain sensitivity (S) of the wire's resistance. When a strain is introduced, the strain sensitivity, which is also called the gage factor (GF), is given by:

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

The ideal strain gage would change resistance only due to the deformations of the surface to which the sensor is attached. However, in real applications,

temperature, material properties, the adhesive that bonds the gage to the surface, and the stability of the metal all affect the detected resistance. Because most materials do not have the same properties in all directions, a knowledge of the axial strain alone is insufficient for a complete analysis. Poisson, bending, and torsional strains also need to be measured. Each requires a different strain gage arrangement.

Shearing strain considers the angular distortion of an object under stress. Imagine that a horizontal force is acting on the top right corner of a thick book on a table, forcing the book to become somewhat trapezoidal (Figure 2-2). The shearing strain in this case can be expressed as the angular change in radians between the vertical y-axis and the new position. The shearing strain is the tangent of this angle.
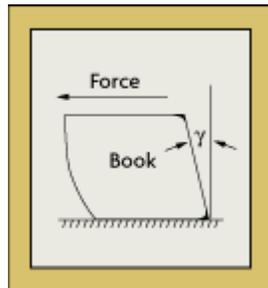

Figure 2-2: Shearing Strain

Poisson strain expresses both the thinning and elongation that occurs in a strained bar (Figure 2-3). Poisson strain is defined as the negative ratio of the strain in the traverse direction (caused by the contraction of the bar's diameter) to the strain in the longitudinal direction. As the length increases and the cross sectional area decreases, the electrical resistance of the wire also rises.

Traverse Strain $(\varepsilon_t) = \Delta D/D$
Longitudinal Strain $(\varepsilon_l) = \Delta L/L$
Poisson Ratio $(\upsilon) = -[(\Delta D/D)/(\Delta L/L)] = -(\varepsilon_t/\varepsilon_l)$
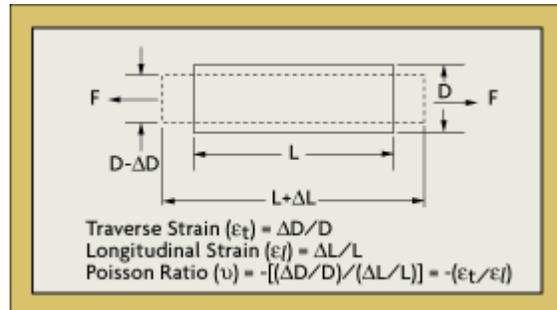
Figure 2-3: Poisson Strain

Bending strain, or moment strain, is calculated by determining the relationship between the force and the amount of bending which results from it. Although not as commonly detected as the other types of strain, torsional strain is measured when the strain produced by twisting is of interest. Torsional strain is calculated by dividing the torsional stress by the torsional modulus of elasticity.

Sensor Designs
The deformation of an object can be measured by mechanical, optical, acoustical, pneumatic, and electrical means. The earliest strain gages were mechanical devices that measured strain by measuring the change in length and comparing it to the original length of the object. For example, the extension meter (extensiometer) uses a series of levers to amplify strain to a readable value. In general, however, mechanical devices tend to provide low

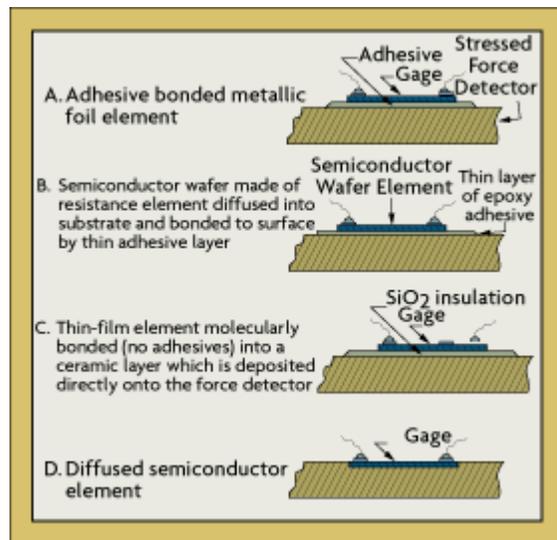resolutions, and are bulky and difficult to use.

Figure 2-4: Strain Gage Designs

Optical sensors are sensitive and accurate, but are delicate and not very popular in industrial applications. They use interference fringes produced by optical flats to measure strain. Optical sensors operate best under laboratory conditions.

The most widely used characteristic that varies in proportion to strain is electrical resistance. Although capacitance and inductance-based strain gages have been constructed, these devices' sensitivity to vibration, their mounting requirements, and circuit complexity have limited their application. The photoelectric gage uses a light beam, two fine gratings, and a photocell detector to generate an electrical current that is proportional to strain. The gage length of these devices can be as short as 1/16 inch, but they are costly and delicate.

The first bonded, metallic wire-type strain gage was developed in 1938. The metallic foil-type strain gage consists of a grid of wire filament (a resistor) of approximately 0.001 in. (0.025 mm) thickness, bonded directly to the strained surface by a thin layer of epoxy resin (Figure 2-4A). When a load is applied to the surface, the resulting change in surface length is communicated to the resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain. The foil diaphragm and the adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the foil grid and the surface.

When selecting a strain gage, one must consider not only the strain characteristics of the sensor, but also its stability and temperature sensitivity. Unfortunately, the most desirable strain gage materials are also sensitive to temperature variations and tend to change resistance as they age. For tests of short duration, this may not be a serious concern, but for continuous industrial measurement, one must include temperature and drift compensation.

Each strain gage wire material has its characteristic gage factor, resistance, temperature coefficient of gage factor, thermal coefficient of resistivity, and stability. Typical materials include Constantan (copper-nickel alloy), Nichrome V (nickel-chrome alloy), platinum alloys (usually tungsten), Isoelastic (nickel-iron alloy), or Karma-type alloy wires (nickel-chrome alloy), foils, or semiconductor materials. The most popular alloys used for strain gages are copper-nickel alloys and nickel-chromium alloys.

In the mid-1950s, scientists at Bell Laboratories discovered the piezoresistive characteristics of germanium and silicon. Although the

materials exhibited substantial nonlinearity and temperature sensitivity, they had gage factors more than fifty times, and sensitivity more than a 100 times, that of metallic wire or foil strain gages. Silicon wafers are also more elastic than metallic ones. After being strained, they return more readily to their original shapes.

Around 1970, the first semiconductor (silicon) strain gages were developed for the automotive industry. As opposed to other types of strain gages, semiconductor strain gages depend on the piezoresistive effects of silicon or germanium and measure the change in resistance with stress as opposed to strain. The semiconductor bonded strain gage is a wafer with the resistance element diffused into a substrate of silicon. The wafer element usually is not provided with a backing, and bonding it to the strained surface requires great care as only a thin layer of epoxy is used to attach it (Figure 2-4B). The size is much smaller and the cost much lower than for a metallic foil sensor. The same epoxies that are used to attach foil gages also are used to bond semiconductor gages.

While the higher unit resistance and sensitivity of semiconductor wafer sensors are definite advantages, their greater sensitivity to temperature variations and tendency to drift are disadvantages in comparison to metallic foil sensors. Another disadvantage of semiconductor strain gages is that the resistance-to-strain relationship is nonlinear, varying 10-20% from a straight-line equation. With computer-controlled instrumentation, these limitations can be overcome through software compensation.

A further improvement is the thin-film strain gage that eliminates the need for adhesive bonding (Figure 2-4C). The gage is produced by first depositing an electrical insulation (typically a ceramic) onto the stressed metal surface, and then depositing the strain gage onto this insulation layer. Vacuum deposition or sputtering techniques are used to bond the materials molecularly.

Because the thin-film gage is molecularly bonded to the specimen, the installation is much more stable and the resistance values experience less drift. Another advantage is that the stressed force detector can be a metallic diaphragm or beam with a deposited layer of ceramic insulation.

Diffused semiconductor strain gages represent a further improvement in strain gage technology because they eliminate the need for bonding agents. By eliminating bonding agents, errors due to creep and hysteresis also are eliminated. The diffused semiconductor strain gage uses photolithography masking techniques and solid-state diffusion of boron to molecularly bond the resistance elements. Electrical leads are directly attached to the pattern (Figure 2-4D).

The diffused gage is limited to moderate-temperature applications and requires temperature compensation. Diffused semiconductors often are used as sensing elements in pressure transducers. They are small, inexpensive, accurate and repeatable, provide a wide pressure range, and generate a strong output signal. Their limitations include sensitivity to ambient temperature variations, which can be compensated for in intelligent transmitter designs.

In summary, the ideal strain gage is small in size and mass, low in cost, easily attached, and highly sensitive to strain but insensitive to ambient or process temperature variations.
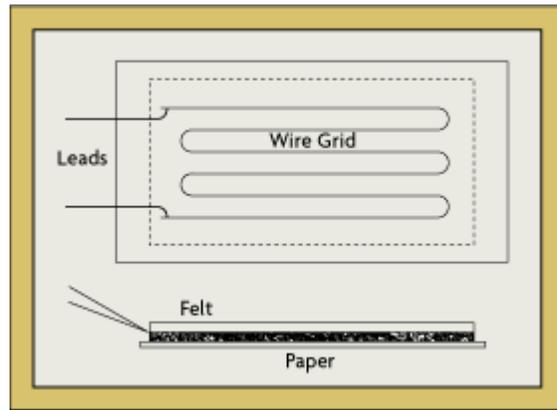
Figure 2-5: Bonded Resistance
Strain Gage Construction

Bonded Resistance Gages
The bonded semiconductor strain gage was schematically described in Figures 2-4A and 2-4B. These devices represent a popular method of measuring strain. The gage consists of a grid of very fine metallic wire, foil, or semiconductor material bonded to the strained surface or carrier matrix by a thin insulated layer of epoxy (Figure 2-5). When the carrier matrix is strained, the strain is transmitted to the grid material through the adhesive. The variations in the electrical resistance of the grid are measured as an indication of strain. The grid shape is designed to provide maximum gage resistance while keeping both the length and width of the gage to a minimum.

Bonded resistance strain gages have a good reputation. They are relatively inexpensive, can achieve overall accuracy of better than +/-0.10%, are available in a short gage length, are only moderately affected by temperature changes, have small physical size and low mass, and are highly sensitive. Bonded resistance strain gages can be used to measure both static and dynamic strain.
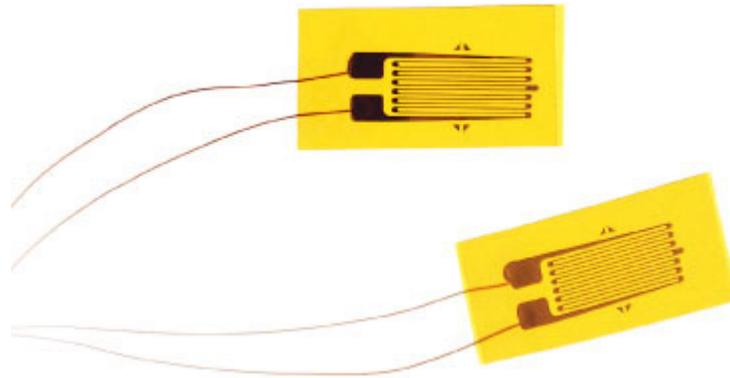
Typical metal-foil strain gages.

In bonding strain gage elements to a strained surface, it is important that the gage experience the same strain as the object. With an adhesive material inserted between the sensors and the strained surface, the installation is sensitive to creep due to degradation of the bond, temperature influences, and hysteresis caused by thermoelastic strain. Because many glues and epoxy resins are prone to creep, it is important to use resins designed specifically for strain gages.

The bonded resistance strain gage is suitable for a wide variety of environmental conditions. It can measure strain in jet engine turbines

operating at very high temperatures and in cryogenic fluid applications at temperatures as low as -452*F (-269*C). It has low mass and size, high sensitivity, and is suitable for static and dynamic applications. Foil elements are available with unit resistances from 120 to 5,000 ohms. Gage lengths from 0.008 in. to 4 in. are available commercially. The three primary considerations in gage selection are: operating temperature, the nature of the strain to be detected, and stability requirements. In addition, selecting the right carrier material, grid alloy, adhesive, and protective coating will guarantee the success of the application.

Measuring Circuits

In order to measure strain with a bonded resistance strain gage, it must be connected to an electric circuit that is capable of measuring the minute changes in resistance corresponding to strain. Strain gage transducers usually employ four strain gage elements electrically connected to form a Wheatstone bridge circuit (Figure 2-6).

A Wheatstone bridge is a divided bridge circuit used for the measurement of static or dynamic electrical resistance. The output voltage of the Wheatstone bridge is expressed in millivolts output per volt input. The Wheatstone circuit is also well suited for temperature compensation.
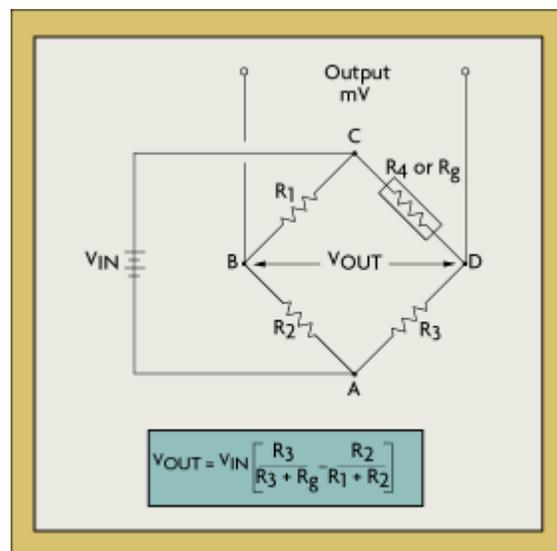

$$V_{OUT} = V_{IN} \left[\frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2} \right]$$

Figure 2-6: Wheatstone Bridge Circuit Schematic

In Figure 2-6, if R1, R2, R3, and R4 are equal, and a voltage, VIN, is applied between points A and C, then the output between points B and D will show no potential difference. However, if R4 is changed to some value which does not equal R1, R2, and R3, the bridge will become unbalanced and a voltage will exist at the output terminals. In a so-called G-bridge configuration, the variable strain sensor has resistance Rg, while the other arms are fixed value resistors.

The sensor, however, can occupy one, two, or four arms of the bridge, depending on the application. The total strain, or output voltage of the circuit (VOUT) is equivalent to the difference between the voltage drop across R1 and R4, or Rg. This can also be written as:

$$V_{OUT} = V_{CD} - V_{CB}$$

For more detail, see Figure 2-6. The bridge is considered balanced when R1/R2 = Rg/R3 and, therefore, VOUT equals zero.

Any small change in the resistance of the sensing grid will throw the bridge out of balance, making it suitable for the detection of strain. When the bridge is set up so that Rg is the only active strain gage, a small change in Rg will result in an output voltage from the bridge. If the gage factor is GF, the strain measurement is related to the change in Rg as follows:

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

   The number of active strain gages that should be connected to the bridge depends on the application. For example, it may be useful to connect gages that are on opposite sides of a beam, one in compression and the other in tension. In this arrangement, one can effectively double the bridge output for the same strain. In installations where all of the arms are connected to strain gages, temperature compensation is automatic, as resistance change due to temperature variations will be the same for all arms of the bridge.
   In a four-element Wheatstone bridge, usually two gages are wired in compression and two in tension. For example, if R1 and R3 are in tension (positive) and R2 and R4 are in compression (negative), then the output will be proportional to the sum of all the strains measured separately. For gages located on adjacent legs, the bridge becomes unbalanced in proportion to the difference in strain. For gages on opposite legs, the bridge balances in proportion to the sum of the strains. Whether bending strain, axial strain, shear strain, or torsional strain is being measured, the strain gage arrangement will determine the relationship between the output and the type of strain being measured. As shown in Figure 2-6, if a positive tensile strain occurs on gages R2 and R3, and a negative strain is experienced by gages R1 and R4, the total output, VOUT, would be four times the resistance of a single gage.
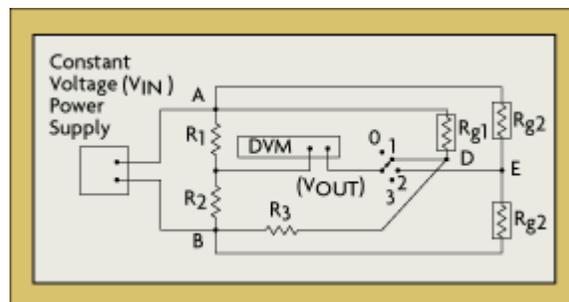

Figure 2-7: Chevron Bridge Circuit Schematic

The Chevron Bridge
The Chevron bridge is illustrated in Figure 2-7. It is a multiple channel arrangement that serves to compensate for the changes in bridge-arm resistances by periodically switching them. Here, the four channel positions are used to switch the digital voltmeter (DVM) between G-bridge (one active gage) and H-bridge (two active gages) configurations. The DVM measurement device always shares the power supply and an internal H-bridge. This arrangement is most popular for strain measurements on rotating machines, where it can reduce the number of slip rings required.
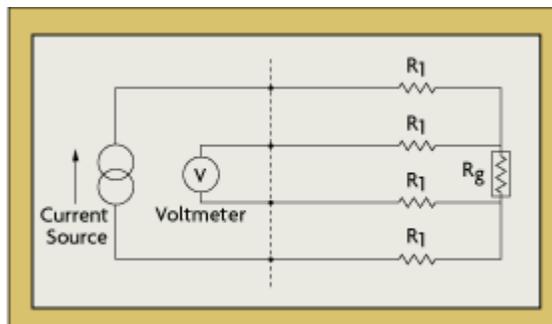

Figure 2-8: Four-Wire Ohm Circuit Schematic

Four-Wire Ohm Circuit
Although the Wheatstone bridge is one of the most popular methods of measuring electrical resistance, other methods can also be used. The main advantage of a four-wire ohm circuit is that the lead wires do not affect the measurement because the voltage is detected directly across the strain gage element.

A four-wire ohm circuit installation might consist of a voltmeter, a current source, and four lead resistors, R1, in series with a gage resistor, Rg (Figure 2-8). The voltmeter is connected to the ohms sense terminals of the DVM, and the current source is connected to the ohms source terminals of the DVM. To measure the value of strain, a low current flow (typically one milliampere) is supplied to the circuit. While the voltmeter measures the voltage drop across Rg, the absolute resistance value is computed by the multimeter from the values of current and voltage.

The measurement is usually done by first measuring the value of gage resistance in an unstrained condition and then making a second measurement with strain applied. The difference in the measured gage resistances divided by the unstrained resistance gives a fractional value of the strain. This value is used with the gage factor (GF) to calculate strain.

The four-wire circuit is also suitable for automatic voltage offset compensation. The voltage is first measured when there is no current flow. This measured value is then subtracted from the voltage reading when current is flowing. The resulting voltage difference is then used to compute the gage resistance. Because of their sensitivity, four-wire strain gages are typically used to measure low frequency dynamic strains. When measuring higher frequency strains, the bridge output needs to be amplified. The same circuit also can be used with a semiconductor strain-gage sensor and high speed digital voltmeter. If the DVM sensitivity is 100 microvolts, the current source is 0.44 milliamperes, the strain-gage element resistance is 350 ohms and its gage factor is 100, the resolution of the measurement will be 6 microstrains.
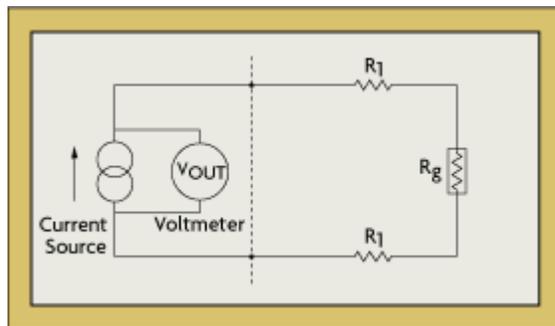

Figure 2-9: Constant Current Circuit Schematic

Constant Current Circuit
Resistance can be measured by exciting the bridge with either a constant voltage or a constant current source. Because R = V/I, if either V or I is held constant, the other will vary with the resistance. Both methods can be used.

While there is no theoretical advantage to using a constant current source (Figure 2-9) as compared to a constant voltage, in some cases the bridge output will be more linear in a constant current system. Also, if a constant current source is used, it eliminates the need to sense the voltage at the bridge; therefore, only two wires need to be connected to the strain gage element.

The constant current circuit is most effective when dynamic strain is being measured. This is because, if a dynamic force is causing a change in the resistance of the strain gage (Rg), one would measure the time varying

component of the output (VOUT), whereas slowly changing effects such as changes in lead resistance due to temperature variations would be rejected. Using this configuration, temperature drifts become nearly negligible.

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.
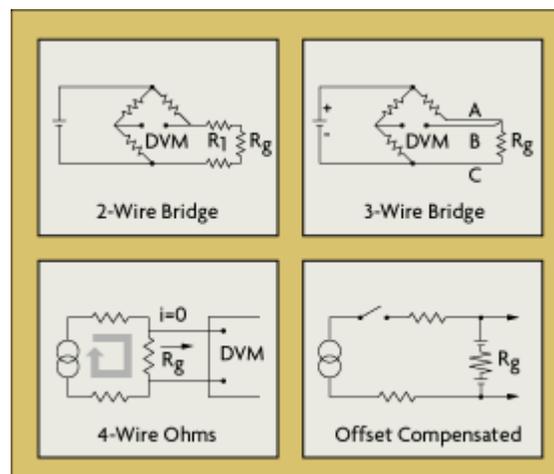

Figure 2-10: Alternative Lead-Wire Configurations

Lead-Wire Effects
Strain gages are sometimes mounted at a distance from the measuring equipment. This increases the possibility of errors due to temperature variations, lead desensitization, and lead-wire resistance changes. In a two-wire installation (Figure 2-10A), the two leads are in series with the strain-gage element, and any change in the lead-wire resistance (R1) will be indistinguishable from changes in the resistance of the strain gage (Rg).

To correct for lead-wire effects, an additional, third lead can be introduced to the top arm of the bridge, as shown in Figure 2-10B. In this configuration, wire C acts as a sense lead with no current flowing in it, and wires A and B are in opposite legs of the bridge. This is the minimum acceptable method of wiring strain gages to a bridge to cancel at least part of the effect of extension wire errors. Theoretically, if the lead wires to the sensor have the same nominal resistance, the same temperature coefficient, and are maintained at the same temperature, full compensation is obtained. In reality, wires are manufactured to a tolerance of about 10%, and three-wire installation does not completely eliminate two-wire errors, but it does reduce them by an order of magnitude. If further improvement is desired, four-wire and offset-compensated installations (Figures 2-10C and 2-10D) should be considered.

In two-wire installations, the error introduced by lead-wire resistance is a function of the resistance ratio R1/Rg. The lead error is usually not significant if the lead-wire resistance (R1) is small in comparison to the gage resistance (Rg), but if the lead-wire resistance exceeds 0.1% of the nominal gage resistance, this source of error becomes significant. Therefore, in industrial applications, lead-wire lengths should be minimized or eliminated by locating the transmitter directly at the sensor.
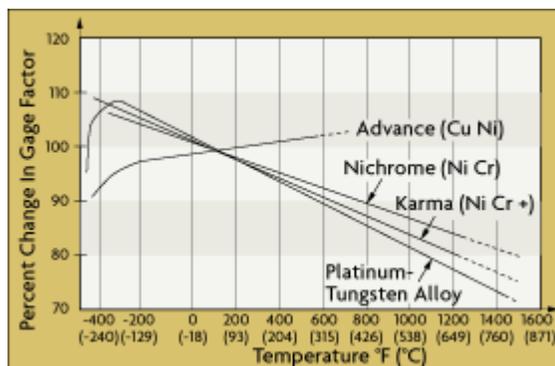

Figure 2-11: Gage-Factor Temperature Dependence

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.
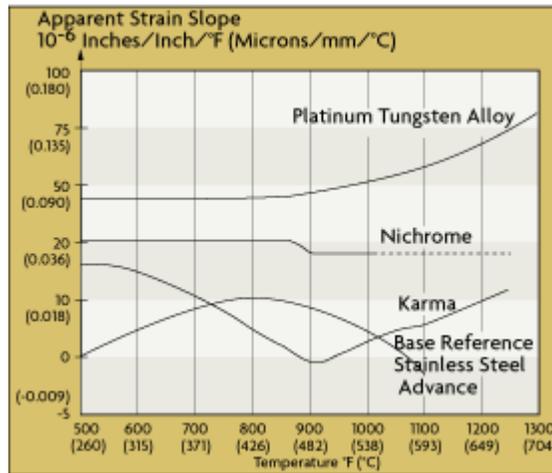
Figure 2-12: Apparent Strain Variation
with Temperature

Apparent Strain

Apparent strain is any change in gage resistance that is not caused by the strain on the force element. Apparent strain is the result of the interaction of the thermal coefficient of the strain gage and the difference in expansion between the gage and the test specimen. The variation in the apparent strain of various strain-gage materials as a function of operating temperature is shown in Figure 2-12. In addition to the temperature effects, apparent strain also can change because of aging and instability of the metal and the bonding agent.

Compensation for apparent strain is necessary if the temperature varies while the strain is being measured. In most applications, the amount of error depends on the alloy used, the accuracy required, and the amount of the temperature variation. If the operating temperature of the gage and the apparent strain characteristics are known, compensation is possible.

Stability Considerations

It is desirable that the strain-gage measurement system be stable and not drift with time. In calibrated instruments, the passage of time always causes some drift and loss of calibration. The stability of bonded strain-gage transducers is inferior to that of diffused strain-gage elements. Hysteresis and creeping caused by imperfect bonding is one of the fundamental causes of instability, particularly in high operating temperature environments.

Before mounting strain-gage elements, it should be established that the stressed force detector itself is uniform and homogeneous, because any surface deformities will result in instability errors. In order to remove any residual stresses in the force detectors, they should be carefully annealed, hardened, and stress-relieved using temperature aging. A transducer that uses force-detector springs, diaphragms, or bellows should also be provided with mechanical isolation. This will protect the sensor element from external stresses caused either by the strain of mounting or by the attaching of electric conduits to the transducer.

If stable sensors are used, such as deposited thin-film element types, and if the force-detector structure is well designed, balancing and compensation resistors will be sufficient for periodic recalibration of the unit. The most stable sensors are made from platinum or other low-temperature coefficient materials. It is also important that the transducer be operated within its design limits. Otherwise, permanent calibration shifts can result. Exposing the transducer to temperatures outside its operating limits can also degrade

performance. Similarly, the transducer should be protected from vibration, acceleration, and shock.
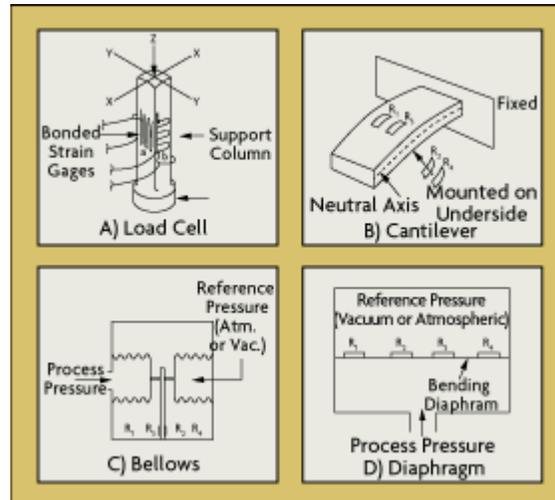

Figure 2-13: Strain Gage Installation Alternatives

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 2-13A, 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 (Figure 2-13B). 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. Figure 2-13C 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 (Figure 2-13D). 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 & Further Reading

Omegadyne Pressure, Force, Load, Torque Databook, OMEGADYNE, Inc., 1996

The Pressure, Strain, and Force Handbook, Omega Press LLC, 1996.

Instrument Engineers' Handbook, Bela Liptak, CRC Press LLC, 1995.

Marks' Standard Handbook for Mechanical Engineers, 10th Edition, Eugene A. Avallone, and Theodore Baumeister, McGraw-Hill, 1996.

McGraw-Hill Concise Encyclopedia of Science and Technology, McGraw-Hill, 1998.

Process/Industrial Instruments and Controls Handbook, 4th Edition, Douglas M. Considine, McGraw-Hill, 1993.

Van Nostrand's Scientific Encyclopedia, Douglas M. Considine and Glenn D. Considine, Van Nostrand, 1997.