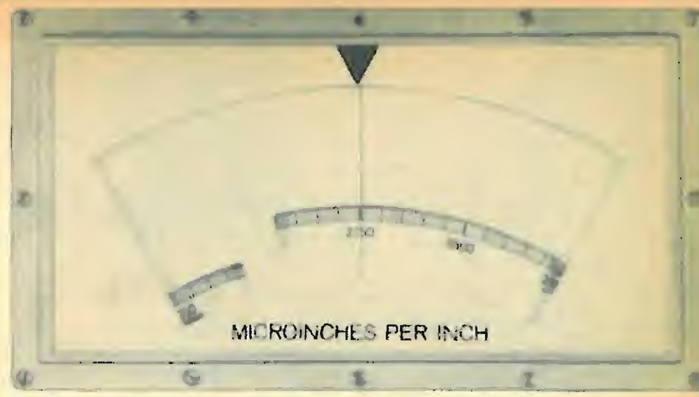
STRAIN GAGES COME OF AGE



By JOSEPH TUSINSKI/Chief Technical Instructor, Old Dominion College

It appears little is known about what constitutes a strain gage and how it works. This article discusses some heretofore hidden characteristics of the device and tells technical men how they can get the most out of it.

IF you should see a group of technicians hovering around a giant *Boeing* 707 cargo carrier checking instrument dials and flicking switches, chances are they're using strain gages to find the aircraft's center of gravity or to measure stress caused by cargo loading. The strain gage has been available for more than two decades, but only now are technical men beginning to use them effectively. The motivation?—technological advances in electronics.

What is a strain gage? An electrical strain gage is an instrument that measures the change in resistance of a conductor as it is stretched or compressed. This principle is utilized in a number of devices where displacement takes place as the result of force.

Linear Stress

Linear deformation or strain occurs when an external force (stress) is applied to the body of a material, that is, it changes its dimensions. Hooke's Law, which relates small deformations of elastic bodies to the applied stress, does not recognize limits or the point where elongation is not proportional to applied force. However, this important non-conformity, which is called the proportional limit, makes deformation or strain a dependent variable and related to the amount of force exerted. The force, which is normally referred to as stress, is measured in pounds per square inch. A typical stress-strain curve of a metal is shown in Fig. 1. Unfortunately, strain which is graphed as the independent variable, can lead to some misconceptions.

Note that a new term, Young's modulus, has been injected in Fig. 1. This is defined as the ratio of stress to strain. Strain is deformation and hence it has units of length. However, it can also be defined as the ratio of a change in length to the original length, that is, inches-per-inch (at times called a unit strain as opposed to total strain). Thus $\varepsilon = \Delta L/L$ (inches/inch). Since strain measuring instruments are calibrated in microinches/inch, it is becoming popular to use the term "microstrain" in lieu of microinches/inch. Thus, one microstrain equals one-millionth of an inch per inch of material. This, of course, shortens the description of the unit, but it loses meaning.

There is another important physical concept in strain measurement analysis. The resistance of a wire varies according to the type of material (specific resistivity) and its length, and is inversely proportional to the cross-sectional area. Thus, if a piece of wire is stretched, it will get longer and R will increase. However, its cross-sectional area also decreases, so R increases further. What is important is that R does not increase proportionally. A little known fact is responsible for this relationship, *i.e.*, the volume of an elastic body decreases as opposed to a plastic (putty-like material) body, whose volume remains the same when stretched. Wire is an elastic body when it is stretched below its proportional limit.

If the ratio of the change in diameter to the change in length is considered for metals, this ratio will vary between 0.25 to 0.35 but will be 0.5 for plastic materials. The ratio of a change in diameter to a change in length is called Poisson's ratio. What does all this mean? Well, the most significant fact is that the specific resistivity of the wire changes. Thus the change in resistance cannot be predicted simply by physical relationships alone.

The above relationship is accounted for by a unit called the gage-factor (*G.F.*), and is used in the equation: $\Delta R/R = G.F.\ (\Delta L/L)$.

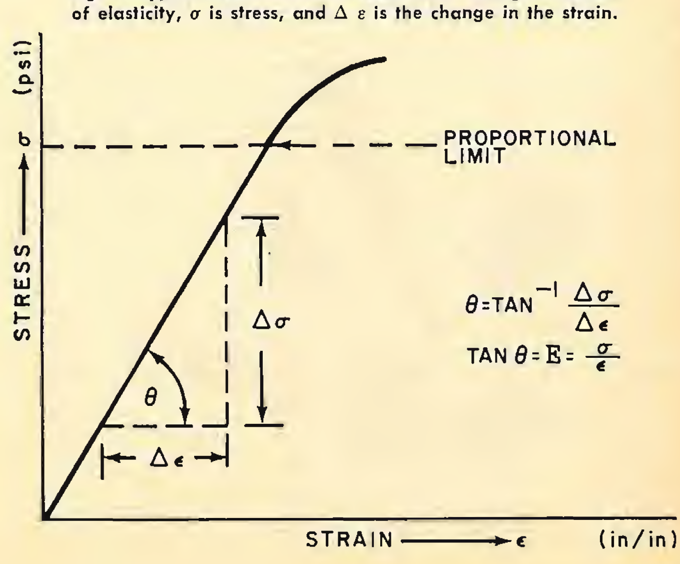
Thus the gage factor is defined as: $G.F. = (\Delta R/R)\ (\Delta L/L)$ or $\Delta R/R\varepsilon$, where $\varepsilon = \Delta L/L =$ strain.

Gage-factors vary considerably, depending on the type of material used for the gage. For example, nichrome has a factor of 2, platinum 4.8, and nickel −12.1, and some of the semiconductor gages have factors of several hundred. However, most wire and etched-foil gages have identical characteristics when compressed as compared to elongation (tension). The resistance of the gage decreases in most cases when under compression and increases under tension. Some gages, like nickel, work in reverse.

Suppose that we apply some of these mechanical concepts and then consider the electrical side of a problem.

Let us determine the strain exerted on a 10-inch piece of a *hypothetical* metal which has a cross-sectional area of two square inches. Under stress, the 10-in bar becomes

Fig. 1. Typical stress curve for metal. E is Young's modulus of elasticity, σ is stress, and $\Delta\ \varepsilon$ is the change in the strain.



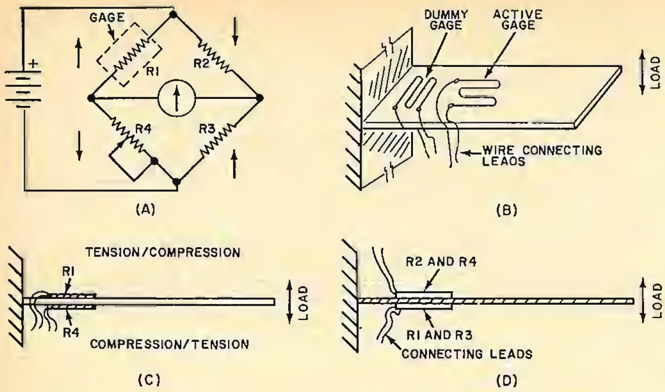


Fig. 2. (A) Wheatstone bridges are used to measure resistance changes. (B) Temperature compensation using dummy gage. (C) Temperature sensitivity is enhanced by using two active gages. (D) If a load on a cantilevered beam is down, then R2 and R4 (A) are under tension, and R1 and R3 are under compression.

10.01 inches long. $\Delta L = 10.1 - 10.0 = 0.1$ inch. That is, the bar changed 0.1 inch for the entire 10-inch length. The strain is then, $\varepsilon = \Delta L/L = 0.1''/10'' = 0.01$ in/in.

Suppose further, to achieve this strain, a total load of 10,000 pounds was used. The stress is then:

$$\sigma = \frac{\text{Force (lbs)}}{\text{Area (in}^2)} = \frac{10{,}000 \text{ lbs}}{2 \text{ in}^2} = 5000 \text{ lbs/in}^2$$

The modulus of elasticity can then be computed as:

$$\frac{\sigma}{\varepsilon} = \text{E} = \frac{5000 \text{ lbs/in}^2}{0.01 \text{ in/in}} = 500{,}000 \text{ (psi)}.$$

Analyzing this relationship another way, suppose what we want to know is how much a ½" rod will elongate if it has a total length of two feet and is subjected to a 10,000-lb load. From a table of physical constants of materials, this grade of metal has a modulus of elasticity of 30×10^6 lbs/in^2 (psi).

The stress in lbs/in^2 is computed first. Thus, $\sigma = F$, lbs/A in^2 = 10,000 lbs/0.1964 in^2 = 50,916 lbs/in^2; where area $= \pi r^2 = 3.1416\ (0.25)^2 = 0.1964$ in^2.

The amount of strain is then:

$$\varepsilon = \frac{\sigma}{\text{E}} = \frac{50{,}916 \text{ lbs/in}^2}{30 \text{ x } 10^6 \text{ psi}} = 1.697 \times 10^{-3} \text{ in/in}$$

or 1697 microstrains.

Then, from $\varepsilon = \Delta L/L$, $L\varepsilon = \Delta L$ and $\Delta L = 24'' \times 1.697 \times 10^{-3} = 0.04$ inch or 40 mils. From these equations we can see the measurement of strain can be incorporated into load-cells which are capable of measuring hundreds or even thousands of pounds of load.

Fig. 3. These are examples of etched-foil and wire strain gages.

Now let us attach a wire strain gage to a ½" rod. Let us further use a gage that has a length of one inch and a resistance of 120 ohms (120 ohms is a popular value for a strain gage). The gage manufacturer has specified a *G.F.* of 2. Calculate the change of resistance that would take place when the 10,000-pound load is impressed. Since $\varepsilon = (\Delta R/R)/G.F. = (G.F.)\ \varepsilon R = \Delta R$, where $\varepsilon = 1.697 \times 10^{-3}$ (from the previous example), R = 120 ohms, and $G.F.$ = 2, then, $\Delta R = 2 \times 1.697 \times 10^{-3} \times 120 = 0.4073$ ohm.

To measure a change of 0.4073 ohm in a total resistance of 120.4073 ohms, an instrument such as a Wheatstone bridge must be used.

One of the advantages of a resistance gage is that it is a bilateral device, hence a bridge may be excited with a.c. or d.c. As shown in Fig. 2A, the gage is represented by *R*1, thus *R*4 may be made variable to restore balance to the bridge. This method has advantages for measuring certain static types of loading. It is also possible to calibrate *R*4 directly in microinches/in (or units of strain).

Temperature Effects

Temperature affects the resistance of a gage; and temperature changes (ambient or self-heating) cause false indications of strain. Thus, most strain gage applications employ a minimum of two gages. For example, if *R*4 is made a compensating gage and is positioned so that a 90° angle is formed with respect to the axis of stress, then the bridge will be self-compensating (Fig. 2B). Then sensitivity may be enhanced by making both gages active, as shown in Fig. 2C. Note that even though both gages are active, temperature effects will still cancel. This same procedure may be extended to make all of the bridge arms active, increasing sensitivity and improving temperature compensation. An arrangement showing all gages in an active mode is shown in Fig. 2D.

Bonded versus Unbonded Gages

The bonded gage was developed simultaneously on both coasts of the United States. Simmons of California Institute of Technology and Ruge of MIT developed the principles in 1938. These gages were given the designation of SR-4 (using the initials of the co-inventors), a trademark of the *Baldwin-Lima-Hamilton Corp.*

Extremely fine wires, supported by various materials, were used to fabricate the gages. The materials dictate where and how the gage is used. Paper is used extensively and Bakelite is also used to a large degree.

Etched-foil gages further improved gage instrumentation. For it was this development that resulted in an almost ideal gage. That is, they could be made so that the effective gage length was infinitesimal (individual conductors could not be seen with the unaided eye). Another characteristic was that the conductors could be made large at the loop ends so that transverse response was reduced to a minimum. Still another ideal characteristic was that the gage wire was flat, hence it had a more intimate physical contact than round wire and could conduct self-generated (I^2Rt) heat away more efficiently. Finally, the gage could attain virtually any configuration, and was only limited by the capabilities of the draftsman. Some of the configurations are shown in Fig. 3.

Plastic, thermosetting plastic, epoxies for high-temperature work, and special ceramic cements are used to bond the gage to a test member. Again, the type of adhesive is determined by the type of measurement, environment (temperature, humidity, etc.), and the type of stressed member.

Unbonded gages, as the name implies, are not supported by an adhesive, but the wire is self-supported by insulated posts or other structure. One type of patented fixture uses ruby support posts, as shown in Fig. 4.

Note that a force moving support #1 to the right causes

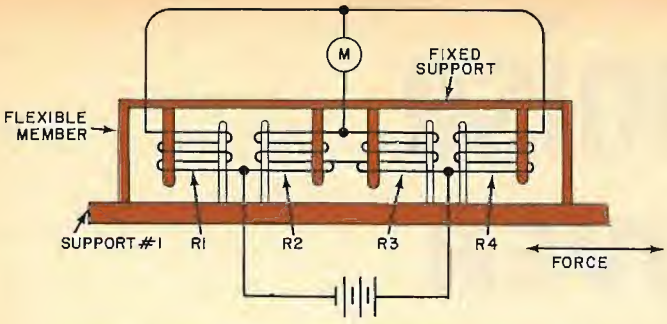


Fig. 4. Unbonded gages are supported by insulated posts.

$R1$ and $R3$ to increase, whereas $R2$ and $R4$ decrease. As can be seen in the diagram, this will cause four times the unbalance of a single gage (refer to Fig. 1). Secondly, any change in temperature-influenced resistance will affect all gages equally, thus the bridge will be temperature-compensated. Initially the wire is placed on the posts in a stressed condition, so stress may be increased further or decreased to measure plus or minus forces.

Semiconductor Gages

Semiconductor strain gages are characterized by extremely high gage factors, which can be positive or negative. Early gages were plagued by high temperature coefficients. Thus, users were wary of their measurements.

A significant achievement was attained when it was discovered that high radiation fields could reduce the temperature coefficient to almost zero. This hardening process opened up new vistas for the high-sensitivity semiconductor gage. The author experimented with some of the radiated gages and found that resistance would not change even when the gage was subjected to a match flame.

Recently, a new type of semiconductor strain gage, manufactured by the *Kulite Semiconductor Products Corporation,* has made inroads in the field of miniature instrumentation. The manufacturer is using integrated-circuit techniques to some extent. One of these gages is shown in Fig. 5A. These gages have nominal gage factors of about 50. This is considerably greater than the wire or foil gage; however, it does not surpass the bulk semiconductor gage. These devices may be used in temperatures ranging from −400°F to +1200°F. Gage lengths are measured in thousandths of an inch, hence they are approaching the ideal gage.

Recently, another type of transistor gage, manufactured by *Stow Laboratories,* has been marketed. This gage has been designated "Pitran" and is an *n-p-n* planar transistor with provisions for a mechanical pressure coupling. Therefore, it can be operated as a standard transistor, with the mechanical coupling modulating the collector current. The device is capable of measuring displacement; however the author feels that it is difficult to use to measure strain. The point is that a strain gage must be capable of measuring a change in length in the given length of the material. Thus all displacement gages cannot truly be classed as strain gages. This gage, however, is capable of measuring extremely low pressures and, if coupled to a stiff diaphragm, may be calibrated to measure high pressures.

Thin-film technology cannot be left out of the strain-gage picture. *Statham Instruments, Inc.* of Los Angeles has produced a thin-film gage having factors comparable to conventional gages. The advantages of attaching a deposited gage to a diaphragm is that no organic material is used as the adhesive, that is, adhesion is the result of semi-molecular adhesion. Thus creep and long-time stability are enhanced.

Some Applications

A typical commercial arrangement may utilize an amplifier to enhance the sensitivity of the system, as shown in Fig. 5B. Other arrangements use self-balancing bridges. For example, a four-arm bridge gage can be used to measure the force exerted on a ⅛-inch test beam when a coin is placed on one end and the other end is fixed.

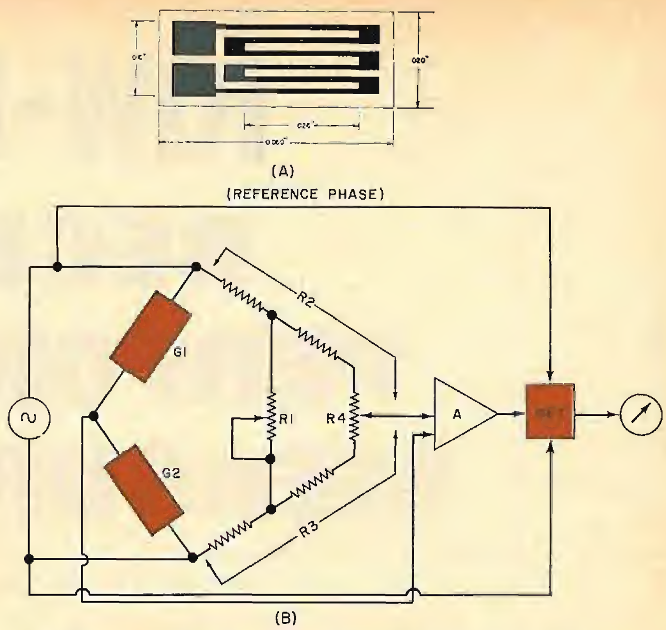


Fig. 5. Miniature diffused semiconductor gages have gage factors of 50. Commercial gage (B) uses amplifier to raise sensitivity of system. A is the amplifier; DET, the phase-sensitive detector; R1, gage-factor correction; R4, slide-wire balancer; and G1 and G2, active gages. The bridge network is a.c.-excited.

Care must be exercised in analyzing the effects of gage placement. For example, if tension is to be measured on a round rod, then some unpredictable results may be obtained Suppose that bending or twisting takes place when it was assumed only tension existed. Fig. 6 demonstrates the problem.

This problem is rectified by placing gages in series. Thus the average change in R will indicate true tension and the bending result is cancelled.

It is possible to dwell on a great number of problems and applications. However, it is the intent of this article only to acquaint the reader with an important innovation in the field of instrumentation. This is, of course, the strain gage and the vast number of jobs it is being called upon to perform. Secondly, more needs to be known about the device because only then can the technician and engineer start to use the strain gage knowledgeably in existing or future techniques. ▲

Fig. 6. If the test member is not loaded correctly (through its geometrical center), a bending moment can cause errors.