Electronic Strain Gages

By Forrest M. Mims III

The strain gage is an electronic transducer that senses physical expansion, compression or bending of a surface. A strain gage is usually bonded directly to the surface it's designed to monitor. Additionally, some strain gages can monitor the displacement of a surface from a short distance away.

Many types of strain gages are used for dozens of different applications. Before we discuss several ways you can make strain gages of your own, let's find out how they're used and examine some typical kinds of commercial strain gages.

Applications

Among the most important applications for strain gages is continual monitoring of mechanical structures subject to compression, expansion, flexing and torsion. Shown in Fig. 1 is a pictorial representation of each of these kinds of strain. Depending on their location in the structure, steel girders in a highway bridge may be subject to either compression or expansion. Airplane wings are subjected to flexing. Shafts and axles are subjected to torsion. Many structures can experience more than one kind of strain, and the direction of maximum strain can vary over a period of time.

Strain gages permit the strain experienced by these structures to be continually monitored over their lifetime. Strain gages can also provide a warning when excessive strain occurs.

The ability of a strain gage to detect strain makes possible many kinds of sensors. For example, a strain gage can be attached to a pedestal that supports a weight to form an accelerometer. When the object to which the accelerometer is mounted moves, the weight tends to remain at rest. This causes the pedestal to bend, thereby distorting the strain gage.

A strain gage can be bonded to a flexible diaphragm and used to detect pressure changes in sealed vessels. When bonded to a shaft, a strain gage can detect torque when the shaft is rotated. A displacement sensor can be made by mounting a strain gage on a flexible arm that's moved by flowing gas or liquid or a mechanical force.

Commercial Strain Gages

Most commercial strain gages have a sensing element made from a thin metal wire or a foil pattern with an electrical resistance that changes when the element is compressed, expanded or bent. Some strain gages have a silicon sensing element. Figure 2 shows a simplified outline view of all three kinds.

Foil gages are by far the most common. They resemble tiny etched circuit boards. A film of copper-nickel alloy or similar metallic foil several micrometers thick is laminated onto a thin, flexible substrate. The foil is then etched to produce a grid or whatever pattern is desired. Overall resistance of a typical foil strain gage may range from around 30 to as much as 3,000 ohms. Gages with a resistance of a few hundred ohms are most commonly used. When the gage is distorted, the resistance of the foil changes.

An important feature of foil strain gages is that they can be made with very uniform characteristics. They're also durable and light in weight. Still another important advantage is that multiple strain gages can be easily made on the same substrate. This means a single very thin, compact sensor can detect the direction of expansion, compression and rotation of a substrate being monitored.

Wire strain gages are no longer as important as they once were. Their operation is dependent on the well-known fact that the resistance of a wire increases as the wire is stretched. The wires used to make strain gages vary in diameter from around 12 to 25 micrometers.

Silicon strain gages employ a bar of silicon with a thickness of around a 0.25 millimeter. Their resistance is considerably greater than that of foil and wire gages. While they produce a much greater resistance change for the same strain than do foil and wire gages, silicon strain gages can't be used to measure large strains since the silicon element is very brittle.

Other electronic sensors can measure strain, but for various reasons they aren't used nearly as much as resistive devices. They include inductors and capacitors whose electrical parameters are changed by movement of one part of the component with respect to another. They also include piezoelectric devices that generate a voltage when strained.

Configurations

Two basic kinds of strain gages are shown in Fig. 3. The single-element gage is designed to detect strain along a single axis. While strain often occurs only along a single axis, some structures are subjected to twisting (torsion) and bending, as well as stretching and compression. It's possi-

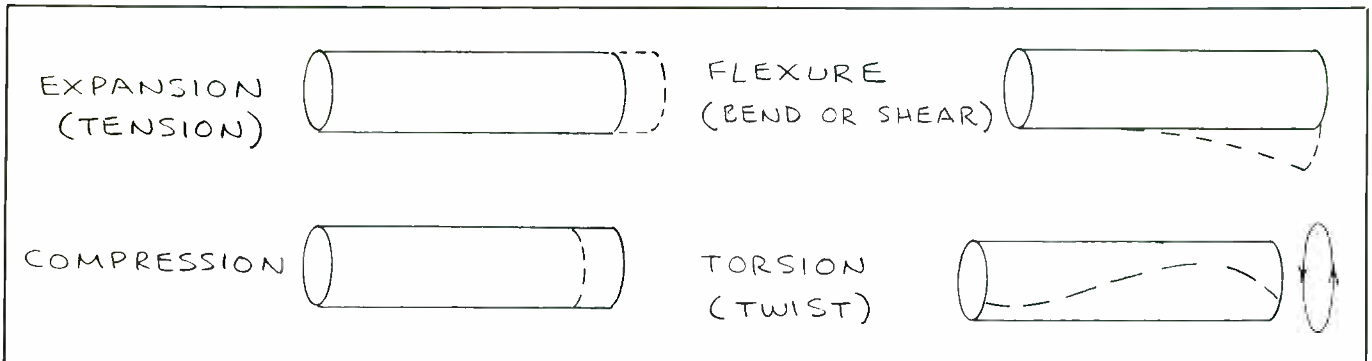

Fig. 1. Important types of mechanical strain.

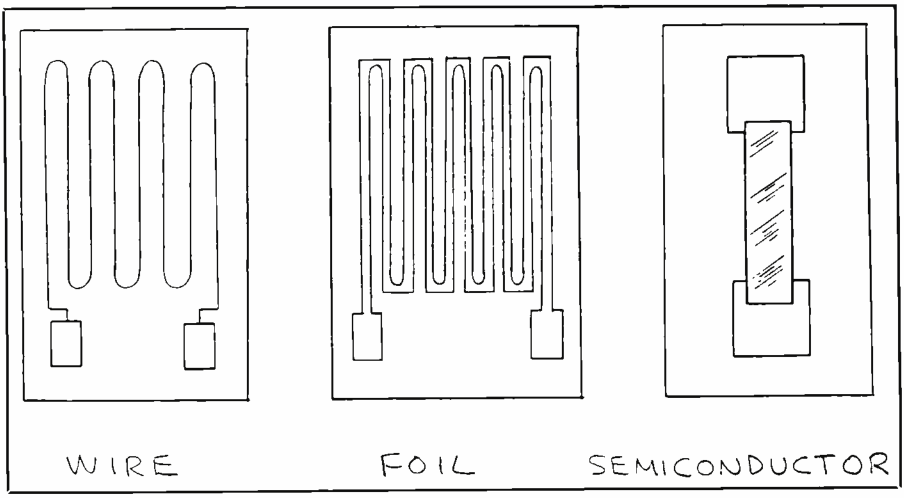

Fig. 2. The most-important types of strain gages.

ble to detect strains along more than one axis by using two or more gages that are aligned in different directions. One way this is accomplished is to stack two or more gages on top of each other, as shown in Fig. 3.

Another way to detect the direction of strain is to form several gages, each aligned in a different direction, on the same substrate. The result is known as a strain gage rosette. The principal direction of strain can then be calculated by in-

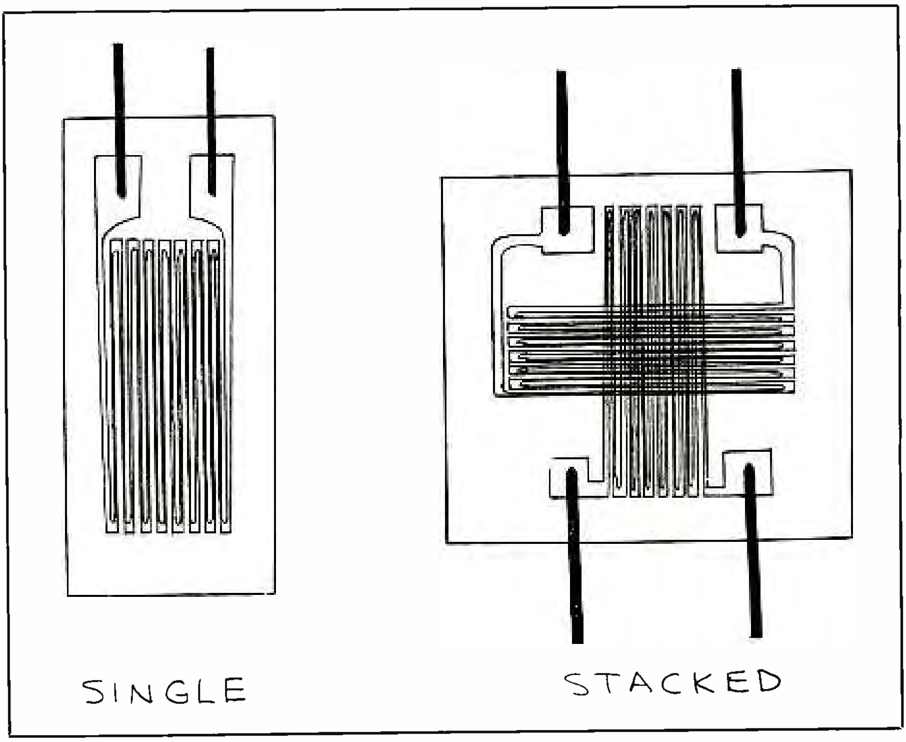

Fig. 3. Single-axis (left) and stacked (right) strain gages.

serting the resistance changes of each gage into an equation whose derivation is given in *Experimental Stress Analysis and Motion Measurement* by R.C. Dove and P.H. Adams (Charles E. Merrill Books, 1964). The same equation is given in *Experimental Methods for Engineers* by J.P. Holman (McGraw-Hill, 1984).

Figure 4 shows one kind of strain gage rosette. A more common kind incorporates a circular pattern of three strain gages arranged 120 degrees apart.

Bonding Strain Gages

Strain gages are usually cemented to surfaces to be monitored. If you don't properly bond a strain gage to the surface, it may not respond to the strain you want to monitor. Both the strain gage and the surface must be absolutely clean to insure a uniform, stable bond. It may be necessary to first buff the surface with emery paper and to then scrub with a cleaning solvent for best results.

Various kinds of cement can be used to bond strain gages. Duco cement can be used with paper-base gages. Cyanoacrylate adhesives are often used with foil gages on resin substrates. Whichever you use, it's important that the cement be completely dry or cured before readings from the strain gage can be considered reliable. Even though the cement around the edges of the gage might be cured, the cement under the central portion of the gage might still be wet. For detailed information about bonding commercial strain gages, see the literature supplied by the various manufacturers.

Temperature Problems

Foil and wire strain gage performance is affected by temperature in at least two ways. Since the resistance of the metal foil or wire that forms the element of the gage varies with temperature, changes in temperature can cause erroneous signals. Another temperature effect can result when the coefficient of expansion of the strain gage differs from that of the surface to which it is bonded. Changes in temperature can also cause uneven expansion of either the surface or the gage, thereby giving rise to an erroneous indication of strain.

The easiest way to solve both these pro-

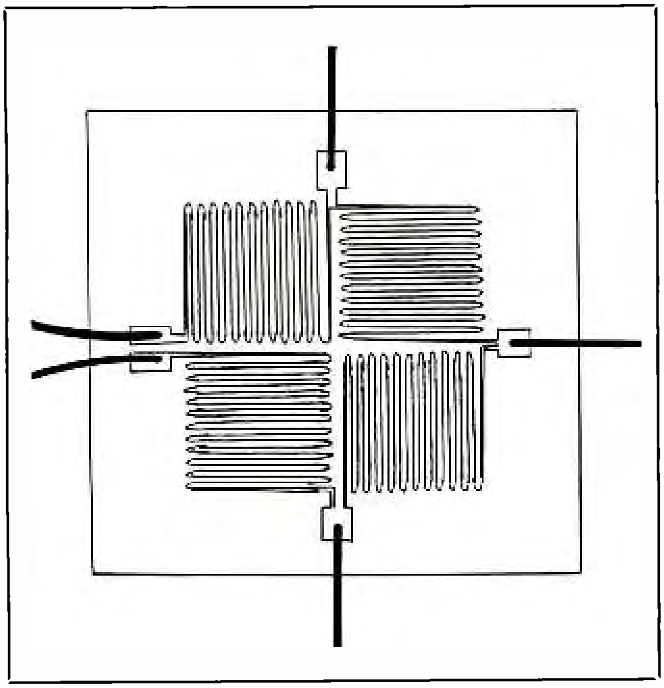

Fig. 4. Full bridge rosette strain-gage configuration.

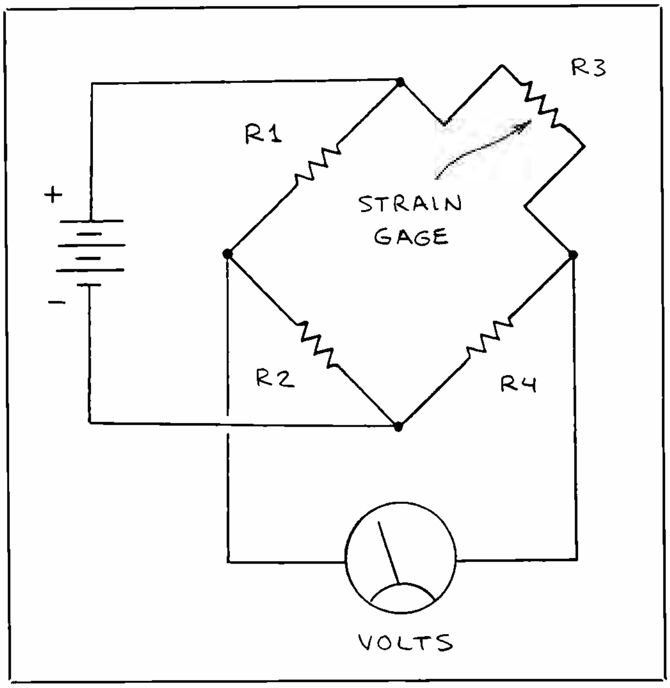

Fig. 5. How to connect a strain gage to a Wheatstone bridge.

blems is to connect two identical gages in a Wheatstone bridge, as shown in Fig. 5. One gage, the sensor (*R3*), is bonded to the surface to be monitored. The second gage, the reference or compensation gage (*R1*), is installed on a nearby surface that's identical to the first but not subject to strain. As long as both gages are installed in the same way, both will remain at the same temperature. The bridge remains balanced, and no current flows. Only when the sensor gage is strained will the bridge become unbalanced.

Noise Problems

Strain gages exhibit such tiny changes in resistance that it's usually important to guard against electrical noise that might interfere with the measurement of the resistance change. Noise can enter the strain gage directly if its exposed wire leads touch the metal structure to which the gage is bonded. Noise can also be induced into the strain gage's wire leads, particularly if they're long. These problems can be prevented by using shielded cable and by carefully insulating any exposed wire leads and connections.

Amplifiers

You can use a digital multimeter to measure the very small changes in a strain gage's resistance. In most applications, however, an amplifier is used to beef up the very tiny voltage or current changes caused by strain.

Figure 6 shows how to connect an operational amplifier to a strain gage that forms part of a Wheatstone bridge. The bridge circuit permits the output to be set to any desired level simply by adjusting *R4*. The resistance of *R4* should be somewhat greater than the maximum expected resistance of the strain gage.

Automatic temperature compensation can be provided by using identical strain gages for *R1* and *R3*. Increasing *R5* increases the circuit's gain and, hence, its sensitivity to strain.

The output voltage of the circuit in Fig. 6 decreases as the resistance of *R3* increases. In other words, an increase in strain causes the output voltage to decrease. This operating mode can be reversed by transposing the positions of *R3* and *R4*.

The 741 op amp is readily available and inexpensive. Much better op amps are available, and these should be used for precision applications. Many other strain gage amplifier circuits are available as well. You can find them in application notes published by strain gage makers and manufacturers of op amps.

Do-It-Yourself Strain Gages

It's possible to make strain gages using commonly available materials and supplies. Years ago, I was studying the movements of a small guided rocket in a homemade wind tunnel that was strapped to the side of my car. I needed a way to measure the displacement of the rocket in response to guidance commands. The rocket was mounted on a stiff length of piano wire that flexed when the rocket moved. The obvious solution was to attach a strain gage to the piano wire. But I didn't have a strain gage!

The solution to this measurement problem was deceptively easy. First, I coated all but the ends of the wire with a layer of insulating paint. After this layer of paint dried, I applied a coat of conductive paint over the insulating paint and the exposed end of the wire to which the rocket was attached. I then attached wires to the unpainted end of the piano wire and to the conductive paint. The completed strain gage is illustrated in Fig. 7.

When the wire was flexed, the electrical resistance between the particles of copper in the paint changed. It was, therefore, possible to monitor the movements of the rocket simply by connecting an ohmmeter to the piano wire-conductive paint strain gage.

Conductive paints and inks can be used to make many kinds of strain gages. The paint can be applied as a thin zig-zag, curved or straight line. It might even be possible to make a template so that strain gages with similar dimensions can be made. Whether or not two such strain gages with the same appearance also have the same resistance is another matter, though. Variations in the thickness of the conductive paint can make significant differences in the resulting resistance.

In any case, of course, the paint must be applied over an insulating surface. And there must be a means for attaching leads to opposite ends of the painted region. Often, leads can be bonded directly to conductive paint. It's also possible to solder leads to some conductive paints. A better approach is to apply the paint to a very thin, flexible etched circuit substrate on which a pair of electrodes have been formed. You can then solder leads to the copper foil electrode. Flexible copper-clad substrate is available from some electronics parts suppliers and surplus dealers among others.

A very simple strain gage can be made by cementing a length of conductive foam plastic to an object that is subject to bending, compression or expansion. The resistance of the conductive foam will increase when the foam is stretched and decrease when it's compressed. For repeatable results, it's essential that connections to the foam be stable.

Optical Strain Gages

Many types of strain gages can be made with the help of optoelectronic components and optical fibers. For example, simple displacement sensors can be made by placing between the arms of a slot-type optoisolator a vane attached to the object in which strain is to be detected. If the vane has an angular profile and if it's carefully positioned, the slightest move-

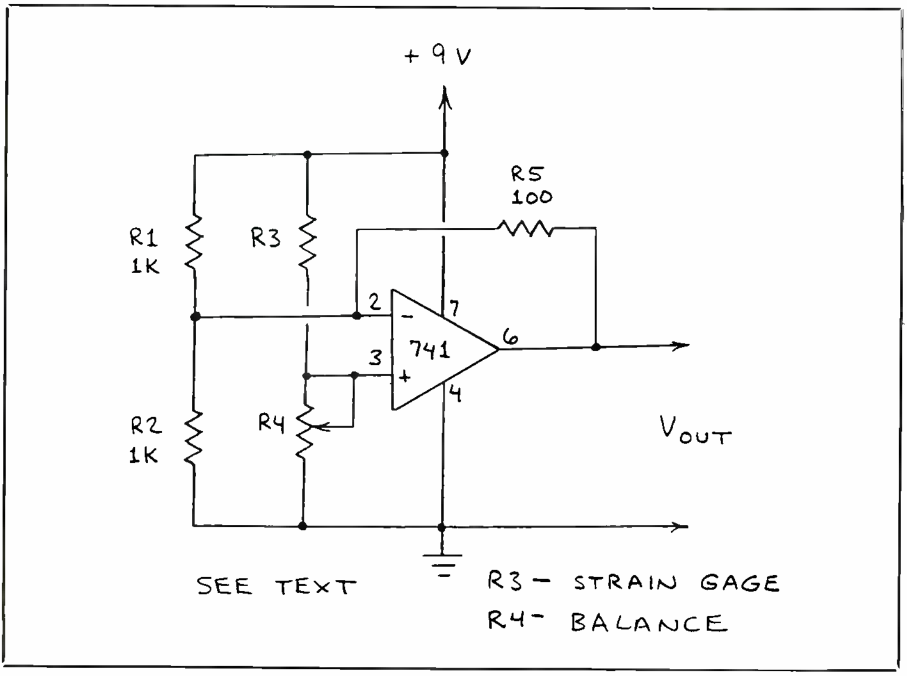

Fig. 6. Schematic details of a strain-gage amplifier circuit.

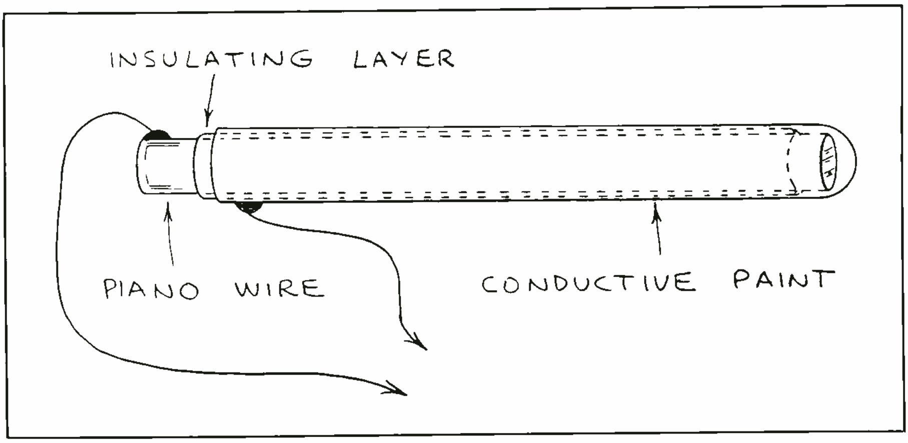

Fig. 7. Details for fabricating a piano-wire strain gage.

ment of the object to which it's attached will change the photocurrent through the phototransistor of the optoisolator.

Another very sensitive approach is to point the beam from a small laser at a tiny mirror cemented to the surface of the object being monitored. The reflected beam should form a spot of light on a fixed white surface some distance away. The slightest movement of the object will cause the reflected beam to move noticeably. This method is particularly good for detecting torsional strain.

Optical fibers can be used to make very sensitive strain gages. You can quickly demonstrate the sensitivity of an optical fiber as a strain gage simply by injecting the light from a helium-neon or diode laser into one end of the fiber. The light emerging from the opposite end of the fiber should strike a photodetector connected to an audio amplifier. When the fiber is still, the only sound from the amplifier will be a gentle rushing noise, which is always present. Depending on the kind of fiber and the coherence of the laser, when the fiber is slightly disturbed, the amplifier will emit sounds ranging from thumps and clicks to musical chirps.

You can use an optical-fiber strain detector to trigger an alarm or counter when the strain exceeds a certain threshold. For this purpose, a level detector should be connected to the detector amplifier's output. The level detector switches a logic circuit when the amplitude of the signal changes sufficiently. The simplest way to accomplish this is to couple the signal from the amplifier into one input of a comparator. A voltage divider connected to the comparator's second input can be used to set the trigger level. The output of the comparator can go to a one-shot if it's necessary to stretch the pulse long enough to trigger an alarm.

Additional Information

A brief but good introduction to strain gage principles is given in *Experimental Methods for Engineers* by J.P. Holman (McGraw-Hill, 1984). Manufacturers of strain gages publish applications information that provides valuable information on how to select, install and use various kinds of strain gages. You can find the names and addresses of strain gage manufacturers in various trade directories available at libraries and engineering companies.

One of the best sources of applications information is *Pressure, Strain and Force*, an annual publication available to serious inquirers from Omega Engineering, Inc. (Box 4047, Stamford, CT 06907). Omega also sells a wide variety of metal-foil strain gages, adhesives and strain-gage amplifiers and other instruments. ME