STRESS OUT; STRAIN GAUGES IN

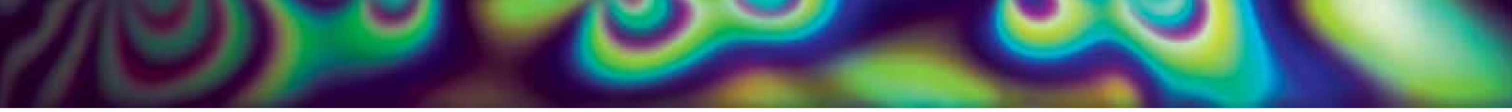
BY PAUL RAKO • TECHNICAL EDITOR

THE CAREFUL SELECTION AND APPLICATION OF STRAIN GAUGES CAN ENSURE GOOD RESULTS FROM THIS DIFFICULT MEASUREMENT.

Strain gauges are the fundamental sensing elements for many types of sensors, including pressure sensors, load cells, torque sensors, and position sensors. Most strain gauges are foil types, available in a wide choice of shapes and sizes to suit a variety of applications (**Figure 1**). They consist of a pattern of resistive foil, which is mounted on a backing material. They operate on the principle that, as you subject the foil to stress, the resistance of the foil changes in a defined way. Foil gauges provide the ultimate in precision, but they also are expensive and provide small signals that are difficult to amplify. Strain gauges can also be silicon, in which metal is deposited in a thin-film semiconductor process on the silicon die. That die, often a MEMS (microelectromechanical system), forms the bendable diaphragm that responds to pressure changes. The same silicon die that carries the diaphragm structure can also have circuitry to amplify and linearize the output and compensate for any temperature effects.

By measuring strain, engineers can infer the stress of a material—an important factor because stress defines whether a part will bend or break. The stress may also represent a fluid pressure behind a diaphragm that is bending under a load. One interesting application for strain gauges involves bending: You measure the flexibility of a PCB (printed-circuit board) as a vacuum holds it in position on a test fixture. If you flex the board too far, the solder joints will break. By building a sample board with strain gauges, you can ensure that your electrical testing won't reduce the circuit's reliability, according to Swapnil Padhye, data-acquisition-product manager at National Instruments (**references 1** and **2**).

Strain gauges operate inside load cells to precisely measure force, monitor torque, or monitor pressure (**Figure 2**). They excel in measuring weight in scales, tanks, and vessels and for measuring the tension in films and strips in industrial processes. The gauges can infer the pressure in a pipe from the amount it swells, ensuring that the inside of the pipe is clean for applications such as food processes. Strain gauges in the load-bearing mounts of hoppers and bins find use in industrial processes. If you need to measure mass rather than weight, however, you must know your application's local gravity to make a precise conversion, according to Dave Cornwell, chief technology officer for Har-



dy Instruments. Strain gauges also find use in industrial, medical, and scientific equipment. The changes in measured strain may be slow or rapid, such as those of cyclical forces on an engine's connecting rod, which operates at tens of thousands of rotations per minute.

Mechanical engineers need strain gauges in the same way that electrical engineers need oscilloscope probes. Both groups must verify simulations, whether they are verifying finite-element mechanical models or Spice electrical models. Mechanical engineers can use strain gauges to collect real-world data on parts and structures they are designing. In addition, strain gauges are often permanent parts of designs, such as those monitoring the strain in a trestle bridge spanning a river.

These gauges are not the only way to measure strain. For example, you can instead make an epoxy-plastic model of a part, heat it, apply loads, let it cool, and then illuminate it with polarized light. The light produces colored fringes that correspond to the strain on the plastic. Princeton Professor Robert Mark used this method to model the flying buttresses of Gothic cathedrals. This work shows why they have survived for centuries: The buttresses are in a state of pure compression—that is, compression everywhere and for all wind and snow loads. If there were any tension on these buttresses, they would fall apart because they are just stacked stones (**Reference 3** and **Figure 3**). Another approach to measuring strain involves the use of StressCoat, a brittle lacquer, which engineer Greer Ellis invented in 1942 while at strain-gauge manufacturer Magnaflux Corp (**Reference 4**). In this approach, you paint the part with the lacquer, apply design loads to the part, and observe the cracking in the coating. StressKote markets a similar product. Some engineers may dismiss this method, instead relying on computer simulations and FEA (finite-element-analysis) approaches. Real-world loads on real-world parts are far more reassuring, however, than pretty pictures on a computer screen.

Figure 2 This Mettler Toledo scale has a precision load cell with a memory chip for linearization and calibration.

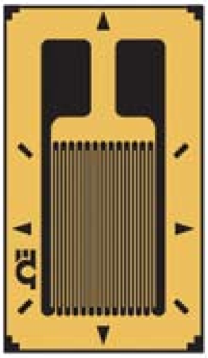


Figure 1 The most common type of strain gauge is made from a metal foil (courtesy Omega Engineering).

Vishay developed another novel method, PhotoStress, which combines the intuitive visualization of StressCoat and the flexibility of polarized-light viewing. The method uses polarized light to illuminate a proprietary optical film. You contour the film to your part, apply the design loads, and illuminate the part with polarized light, letting you see the strain patterns in the part. Optical transducers on a polariscope also give quantitative measurements of strain, and companies such as Vishay provide liquid-photosensitive coatings for casting contourable sheets.

One of the greatest problems engineers have in applying strain gauges is the existence of so many uncontrolled variables. With voltmeters and light sensors, the manufacturers control most of the precision; you need only to connect the voltage probes to the circuit or to shine light on the sensor. With strain-gauge measurements, however, you must first select a gauge from hundreds or thousands of types, select a location for the device, prepare the surface, and bond the gauge to the part you are measuring. You make connections between the strain gauge and the measuring amplifier. Figuring out these processes is not the end of your troubles, however. You also need to ensure that you stay within the temperature range of the gauge, that you linearize the gauge output, and that you fully understand the relationship between stress and strain in the part you are measuring—a fundamental requirement.

Another problem is the fact that some materials, such as fiberglass and carbon fiber, are anisotropic—having properties that differ according to the direction of the measurement. In these cases, the fibers are often oriented in a certain direction, and the relationship between stress and strain depends on the applied direction as well as the interaction of the directions inside the material. You can see that effect when you open or close window blinds. The blinds don't break during this process because there is little pressure on

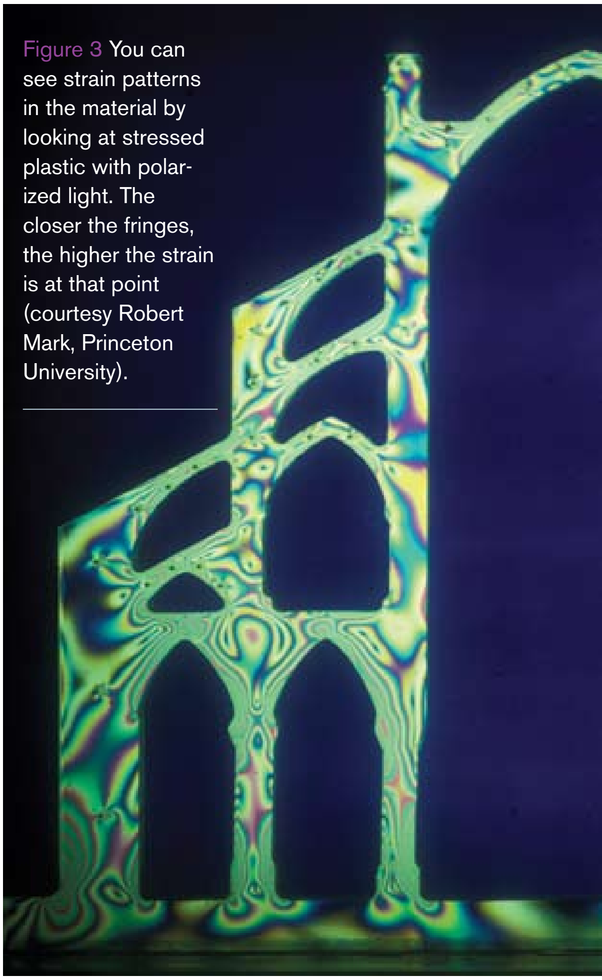
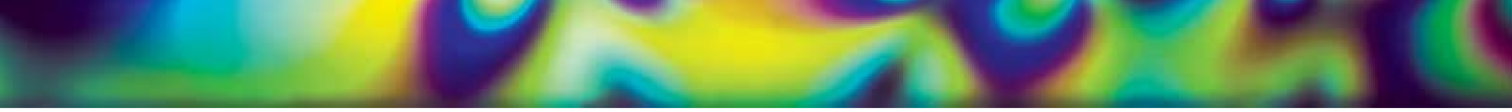


Figure 3 You can see strain patterns in the material by looking at stressed plastic with polarized light. The closer the fringes, the higher the strain is at that point (courtesy Robert Mark, Princeton University).

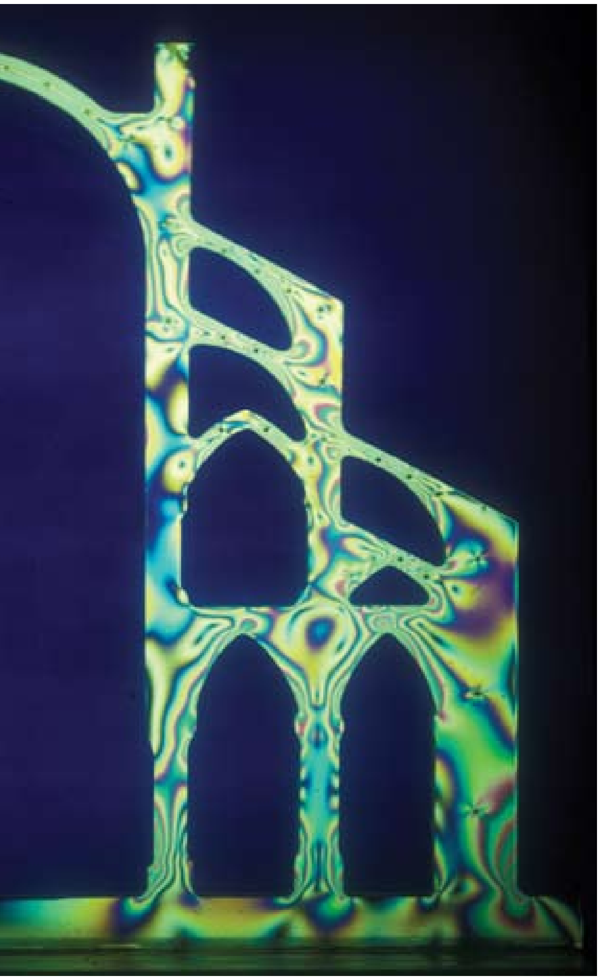


them. Bending those blinds over your knee presents a stiffer structure, which fails catastrophically if you subject it to any significant amount of strain. You can evaluate strain in anisotropic materials by using a "rosette" strain gauge, which allows you to simultaneously measure strain in two or three directions (**Figure 4**).

Another tricky, uncontrolled variable is the captive stress that exists in the part you are measuring. You may remember from your statics and dynamics courses that bridges do not connect at both ends. The mathematical calculations cannot solve for an overconstrained system. You face the same problem in taking strain measurements. Bolting the part into place and pulling it into alignment with a wrench causes a significant amount of stress and strain on the part. If you then glue a strain gauge to that part, the output will display zero strain, even though the part may be on the verge of breaking or may have already bent when you muscled it into position. "For making accurate measurements, the gauge is important, but the steel or aluminum it sits on is more important," says Hardy's Cornwell. To avoid linearity and hysteresis problems, Cornwell suggests using special alloys and heat-treating the part after machining to relieve local stresses from the machining operations. A strain gauge also averages the strain over its area. A hole near the gauge causes a stress concentration with large strains, but the gauge averages that concentration with the strain along the rest of its length and indicates a lower strain. "You need to select a gauge that is the appropriate length for the strain field or stress concentration you are looking at," says Tom Rummage, a senior application engineer at Vishay.

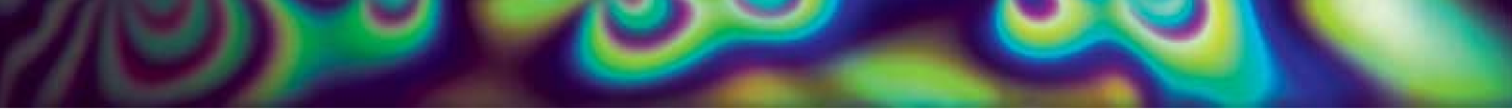
AT A GLANCE

- Strain gauges can be made of metal foil, silicon, or piezoresistive materials.
- Strain gauges provide a small change in resistance, so they find use in bridge configurations.
- The last step in manufacturing a gauge is when you glue it to your part.
- Watch out for residual stresses in parts. These stresses can cause catastrophic failure under light loads.
- Strain-gauge amplifiers are expensive because they are difficult to make. You should have a good reason for designing your own bridge-interface circuits.
- Taking good measurements may require weeks instead of hours.



More subtle problems can also occur. An outside layer of a casting, for example, may harden first. Then, as the inside of the part solidifies, the part's cooling generates residual stresses. You have to realize that any casting, weldment, or machined part with surface stresses has static internal stresses far beyond what you can trivialize as second- or third-order effects. As always, you should experiment and collect data. "Stress cannot exist at a free boundary," says Rummage. "Put a strain gauge down that has three elements a certain distance away from where you are going to drill a hole. As you drill the hole, you create that free boundary. If it collapses in, it was under compression. If it pulls away, it was under tension. By knowing those three gauges and their angular relationship to one another, you can calculate the residual stress the part was experiencing." By verifying internal residual stresses in a part, you can then design-in a way to accommodate them. That approach might be heat-treating, using a different casting alloy, or taking a set of measurements to prove that no strain that approaches the elastic-limit or fatigue-failure guidelines exists anywhere in the part. Make sure that there are not multiple molds, different processes, or new vendors that could create variances in the internal stress. Even with these variances, however, the design may be perfectly acceptable because prestressed concrete depends on pre-existing internal stresses to meet design loads.

You must know the static and dynamic loads of what you are measuring. Select a gauge that works with the expected strain, but also consider shock loads and the effects of momentum and point-loading on the material. You also must make sure that static discharges will not damage the sensor electronics. "Everything normally is designed for CE [Conformité Européenne], which is the human-body model," says Hardy's Cornwell. "In a factory, you have the fork-lift model. When someone runs around in a fork lift, he gets a lot more voltage than CE stipulates." Cornwell explains that, once the operator lowers a pallet onto a platform scale, a giant arc jumps from the forks on the fork lift. If the operator doesn't use a ground strap, the only ground-return path is through the load cells and the strain-gauge wires. In addition, the strain gauge may be subject to fatigue failure if you strain it too many times over too large a range. Also remember that the modulus of elasticity may differ under compression and tension in your material. It is not a com-



mon problem, but it highlights the fact that a good strain-gauge engineer must know mechanics, materials, electronics, physics, and the theory of experiments.

Because your procedures and design can have a large effect on the validity of strain-gauge measurements, it is always a good idea to include the strain-gauge vendor's applications engineers in your plans. You may have concerns about using the vendor's strain gauge in your application. Some vendors, such as Omegadyne, can address those concerns: They apply the gauge for you, using all the expertise their engineers have accumulated over the years. Omegadyne can custom-design a gauge for you in as little as two weeks, according to William Hamilton, a design-and-manufacturing engineer at the company.

Don't underestimate the importance of strain-gauge measurements: Although you can slap a gauge on a part and have an answer in an hour, the answer will be wrong. In your rush, you might glue down the gauge with an epoxy that hardens in five minutes. This fast-drying epoxy not only releases heat but also heats or shrinks as it hardens. This condition places strain in the gauge, which then yields erroneous readings. Similarly, you can't just slap a foil gauge on a thick blob of epoxy because the distance between the foil gauge and the part's surface provides a substantial error. You must measure the strain of the part, not the strain on ⅛ in. of epoxy between the part and your gauge.

Rather than rushing a measurement, conduct a series of experiments that prove the validity of strain-gauge selection and mounting. "The biggest problem our customers have is making the right choice of strain gauge," says Rob Carney, OEM-sales manager at Omegadyne. "Accuracy, stability, temperature range, elongation, and test duration are all important factors." Once you mount the gauges, make sure that they always return to zero when you remove the strain, that there is no hysteresis, and that they provide good repeatability. You should correlate those measurements to a NIST (National Institute of Standards and Technology) standard and then take the measurement. The gauges themselves are often the smallest cost you face. The larger costs are in the mounting and characterization of the gauges, as well as the circuitry and test equipment you need to record the results. For this reason, buying a strain-gauge-conditioning system may be better than designing your own circuitry.

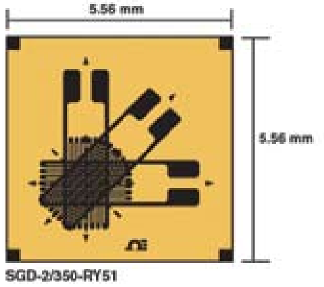


Figure 4 This rosette-type strain gauge has three gauges to measure strain in three directions at once (courtesy Omega Engineering).

Figure 5 This strain-gauge amplifier costs $1149 and provides 24-bit measurement accuracy, excitation, bridge completion, and a host of other features (courtesy National Instruments).

STRAIN FUNDAMENTALS

To understand why strain-gauge instruments are sophisticated and costly, you must understand their fundamentals. A microstrain is a change of one-millionth in the resistance of a strain gauge, meaning that a bridge factor of two and an excitation of 1V yield 0.5 µV per microstrain. "Take a rope that is 15.8 miles long," says Vishay's Rummage. "If you pull that rope to a uniform strain of one microstrain, [the result] is 1 in. If you are not careful with your surface preparation, that one part in 1 million may not be achievable." Some inexperienced engineers and academic researchers try to use an ohmmeter for this measurement, but they soon realize that the data it yields is unusable. To make the change in strain become a large percentage change in the sensed measurement, experienced engineers incorporate the strain gauge into a Wheatstone bridge, a four-resistor device that nulls out errors and makes the change in strain a large percentage change in sensor output. Better yet, if you use four strain gauges in proper orientation, you get four times the signal amplitude and sensitivity. To infer the resistance change, you provide the bridge with an ac or a dc excitation voltage. The ac approach has certain advantages, such as nulling out the thermocouple effects of the lead-wire material you are soldering to the gauge's foil material. These thermocouple potentials do not change potential when the bridge excitation changes, so you can null out the dc error when you use synchronous demodulation to extract a dc value from the ac signal.

Due to improvements in operational amplifiers, a four-gauge full bridge is not always necessary to get a measurement. You can instead use a quarter-bridge configuration in which only one active strain gauge and three passive resistors complete the bridge. Alternatively, you can use a half-bridge with two gauges in one leg. This approach cancels out the temperature coefficient of the strain gauges. You then complete the bridge with two passive resistors that also share the same temperature coefficient. The bridge configuration ensures that the temperature coefficients of the gauges and passive resistors are ratiometric and cancel out. With some amplifiers, you need not even mount the second gauge to measure strain. Instead, you can just use a "dummy" gauge as a passive resistor, as long as it is at the same temperature as the active strain gauge.

Although canceling out the temperature coefficient of the strain-gauge material is important, you must also deal with a more basic temperature-compensation problem: The material that you are measuring has a thermal coefficient of expansion, meaning that, as you heat the material, it expands, and the strain gauge you glued to the specimen will expand along with the material, providing an erroneous output. Thus, your gauge produces an output even though no strain exists in the material. To avoid this problem, carefully select a gauge material that has the same temperature coefficient of expansion as the material that you are trying to measure. Gauge manufacturers make a large variety of both positive- and negative-expansion coefficients that allow you to null out this temperature problem. The thermal coefficient of expansion might differ in each direction in a carbon fiber or other nonisotropic material.

"A strain gauge gives a very small change in resistance, so the resulting voltages are very small," says David Potter, market-development manager at National Instruments. "Depending on where you are using them, the environment, and how long the wires are, the SNR [signal-to-noise ratio] can be pretty low." It might be a good idea to take data from the gauges without excitation. This approach gives you a measurement of the noise because the gauge has no valid output without excitation. You can now appreciate why a strain-gauge amplifier is an expensive and specialized instrument (**Figure 5**). It has to complete, excite, and offset-null the bridge; measure small signals; reject noise; provide antialiasing filters for the analog-to-digital conversion; and buffer the output to reduce noise entering the signal path. Top-grade instruments also provide shunt-range calibration and remote sensing, in which a separate pair of leads ensures the precise control of the voltage at the bridge. If the instrument can excite an ac bridge, the instrument must also demodulate the excitation to give you a dc signal. A lab technician using a cell phone nearby can cause some unexplained sensor signals. "You can ground the wiring shield at the amplifier and leave it open at the part," says Vishay's Rummage. "This scheme is the most prevalent."

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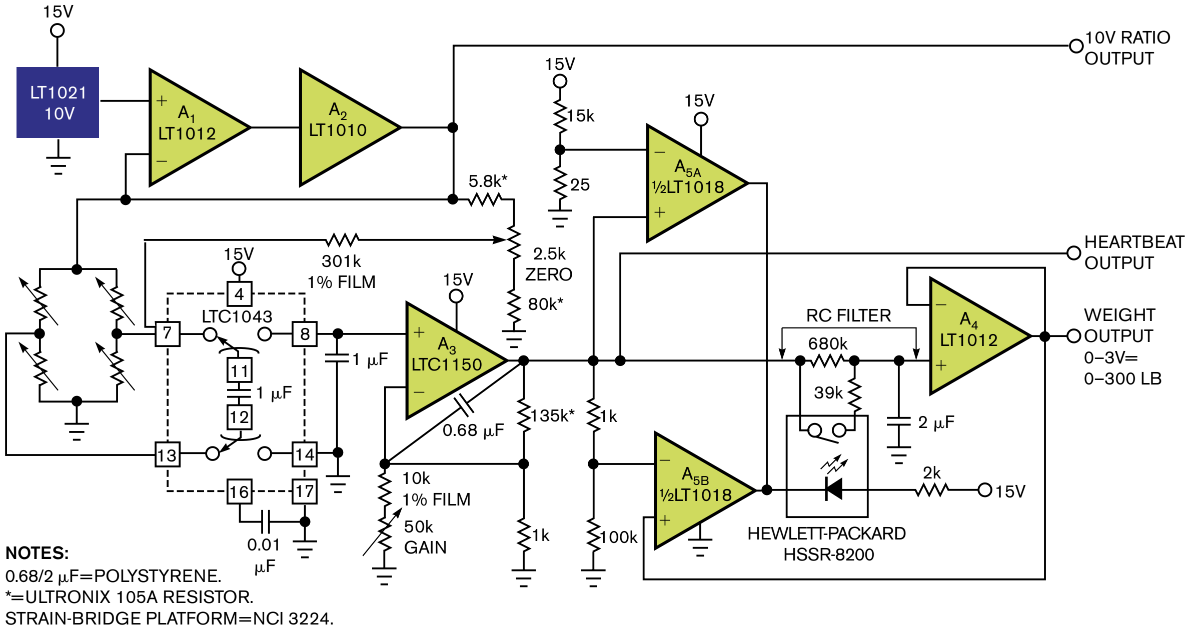
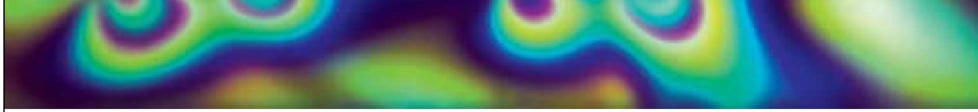
Rummage also advises providing grounding at the part and leaving the shield open at the instrument if your design has noise problems. You may also want to try grounding the cable shield at both ends. As with mounting and selecting the gauge, the measurement must also try to control all the variables. Once you select a gauge and connect it to the amplifier, you must control the measuring environment or at least conduct experiments that yield good data. Keep both the strain gauges and the amplifier within their specified temperature ranges.

Errors and nonlinearities can arise in myriad places and can degrade the accuracy of your measurement. Take frequent, controlled calibration runs. If you can verify the strain-gauge readings with an expensive load cell and a NIST-certified amplifier, you can take measurements over temperature, humidity, and any other conditions that might affect the material you are measuring. Once you have this data, you can correct the raw strain-gauge readings in software such as The MathWorks' Matlab or National Instruments' LabView. Do a calibration run both before and after you take the measurement to confirm that you have not damaged the gauge, glue, or part you are measuring. A calibration run cancels out most second- and third-order effects, such as the transverse sensitivity of the foil gauge. Transverse sensitivity arises because a foil gauge does



NOTES:
0.68/2 µF=POLYSTYRENE.
*=ULTRONIX 105A RESISTOR.
STRAIN-BRIDGE PLATFORM=NCI 3224.

Figure 6 This strain-gauge circuit can sense the flow of blood in your body and weigh you to within 0.01-lb accuracy (courtesy Linear Technology).



not reject all strain in the orthogonal direction.

Both Linear Technology and Analog Devices have contributed literature for those engineers brave enough to design their own bridge-excitation and amplification circuits (**references 5** and **6** and **Figure 6**). If you are designing a low-cost product that requires a strain gauge, you may have to design your own circuitry. Engineers who must measure strain as part of a product-development cycle should rely on measuring experts, such as Omega, Vishay, and National Instruments. Remember: Test equipment and circuitry cannot make up for a botched gauge selection or installation. Select the proper gauge material and type. Then, decide whether to use a full-, half-, or quarter-bridge configuration. Select the right mounting place and epoxy. Watch out for those captive stresses that render your measurements meaningless. Then, make sure you get the strain-gauge signal to your amplifier. If possible, solder the instrument's lead wires to the gauge. Any connectors that are not gold-plated cause gross errors in the measurement. Use first-class test equipment and understand the design of a bridge-measurement circuit. Frequently calibrate your system and make sure that FEA matches your real-world-strain measurements.

Both electrical and mechanic engineers put an absurd amount of faith into computer simulations because they believe a computer cannot make mistakes. FEA engineers often adamantly believe that simulations are accurate—only to find that captive stress in the part or a mesh-selection error in simulation gives erroneous results. "A lot of people completely and abjectly trust a finite-element model to tell them where the direction and magnitudes of the strains are," states Vishay's Rummage. "Those are assumptions they have made, and they have to be validated." If you carefully take your measurements and understand all the aspects of strain measurement, you should stand your ground against simulations.**EDN**

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