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What Do Aircraft "Growing Pains," Strain Gages, and Precision Resistors Have in Common?

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We've heard much recently about the "growing pains" of the latest generation of passenger jets. First, overheated lithium-ion batteries were discovered, prompting regulators to ground the worldwide fleet for several months. Second, cracks were found in the wings of new airplane designs. These two issues raised questions about how such problems could have been monitored, especially the wing cracks. Because of normal metal fatigue, it is difficult to eliminate these cracks, but monitoring can prevent catastrophic failures and also help reduce maintenance costs. In this article we will focus on the use of precision resistors and strain-gages as part of the monitoring system.

The role of strain gages

Strain gages are fundamental sensing devices that function as the building blocks for many other types of transducers — including pressure, load, and torque sensors — which are used extensively in structural testing and monitoring applications. Strain gage based transducers convert a mechanical input into an electrical output. In these designs, strain gages are connected as a Wheatstone bridge, providing a rugged and stable sensor capable of operating in extreme environments. To improve accuracy, the Wheatstone bridge is compensated for manufacturing tolerances and environmental and self-heating temperature effects. High-precision bridge-compensation resistors are added to correct for bridge unbalance, and to adjust output sensitivity (span set). Other compensation resistors correct for errors that result when the transducer is used over a widely changing temperature range.

Even though strain gages are very common, acquiring reliable data from them can be challenging. Several factors affect the measurement performance of a strain gage: the signal conditioning, the construction and location of the Wheatstone bridge (the most common bridge type used to measure resistance), inductance and capacitance, the precision resistors used in the circuit, and the excitation source.

Precision resistors in bridge completion and shunt calibration strain gage circuits

Precision resistors have two basic uses in standard strain gage circuits: (1) bridge completion and (2) shunt calibration of strain-measuring instruments.

Bridge Completion

For bridge completion when a single strain gage (R1 in Fig. 1) is connected in a quarter-bridge arrangement, a precision resistor (R2 in Fig. 1) of equal electrical resistance to the strain gage is used in the adjacent arm of the Wheatstone bridge, and two additional precision resistors (R3 and R4 in Fig. 1) make up the ratio arm to complete the circuit. Common values include 120 Ω, 350 Ω, 1 kΩ, and 5 kΩ. To maintain long-term precision of the measurements, the ratio arms of the bridge should also consist of high-precision foil resistors. The two ratio-arm resistors must be of equal resistance value, but not necessarily equal to the strain gage. The accuracy of the strain measurement is directly affected by the accuracy and stability of the precision resistors used to complete the bridge circuit. That's why only resistors of the highest precision and stability should be used; the choice is between Z or Z1 technology Bulk Metal® Foil resistors.

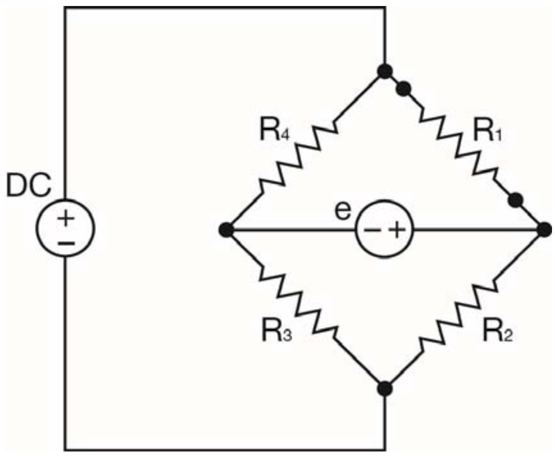


Figure 1: Basic Wheatstone bridge circuit diagram

Achieving accurate and repeatable data from strain gage based transducers under varying environmental conditions requires stable strain gages with low temperature sensitivity, good gage-to-gage matching, excellent linearity, and negligible hysteresis. Similar to Bulk Metal® Foil resistors, Micro-Measurements (MM) strain gages benefit from an in-house foil processing capability. The thin, rolled metal foil is engineered and manufactured to maximize transducer performance.

Using paired strain gages like the 125MG or S085X patterns can further improve gage-to-gage matching. The two gages, produced on a common backing, are separated using a razor blade or precision scissors and wired as adjacent arms of the Wheatstone bridge circuit with one gage bonded in a positive strain area (tension strain) and one bonded in a negative strain area (compression strain). Or, when the application allows, using a half-bridge pattern like the T028X or T015X offers the same improvement. In this case, the tension and compression strain areas must be positioned to coincide with spacing of the two grids on the pattern. Since both grids are bonded in one step, this method also simplifies gage installation and wiring. For best gage matching and simplest installation, use a full-bridge pattern like the S1449 or S055X. As with half-bridge gages, the tension and compression strains must be properly positioned to coincide with the location of the four grids in the full-bridge pattern.

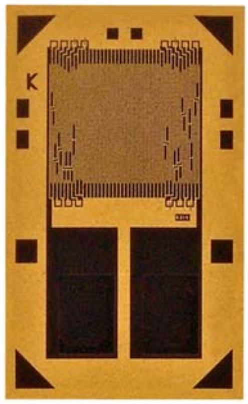


Figure 2: S5024 (top) and S5030K (bottom) pattern of Advanced Sensor Technology strain gages from Micro-Measurements

Strain gage final resistance, often called the "package resistance," is traditionally adjusted by a manufacturer using techniques like chemical or abrasion thinning of the sinuous foil grid. Minor gage-to-gage variations in temperature and strain responses can be caused by the amount of metal removed to achieve the desired final resistance value of each strain gage. To avoid these performance differences caused by resistance adjustment, the Advanced Sensor group of Micro-Measurements uses uniquely designed laser trimming features and automated laser trimming stations to make the final resistance adjustment. This method ensures precise and repeatable resistance adjustment of every strain gage, without thinning the metal foil. By combining gage matching techniques with this non-invasive, laser-trim electrical resistance adjustment process, Micro-Measurements Advanced Sensor Technology strain gages provide the ultimate gage property matching.

Shunt calibration

In shunt calibration, a fixed value high-precision resistor temporarily shunts across one of the bridge arms to produce a known and controlled resistance change in the bridge circuit. The resulting instrument indication is then compared to the calculated strain corresponding to the resistance change.

Shunt calibration of a Wheatstone bridge strain gage circuit is a common and convenient method of periodically monitoring the gain or span of a signal conditioner being used in conjunction with a strain-gage-based transducer. A fixed precision resistor, such as the leaded Z-Series or surface-mount VSMP/VFCP/FRSM Series (0603-2512), is connected to shunt across one leg of the Wheatstone bridge. This doesn't amount to a complete calibration, since no mechanical pressure is actually applied. Instead, the shunt calibration provides a simulation of the mechanical input to a transducer by unbalancing the bridge and providing a scenario that shows how to reduce the errors and shifts associated with the electrical characteristics of the strain gages and the connected electrical components. The shunt resistor that is added in parallel to the strain gages simulates what would happen if a real load were measured by the pressure transducer or any other load cell configuration.

This approach works best when done using a high-precision resistor with a tight tolerance such as the oil-filled, hermetically sealed 0.001% to 0.01% VHP101 secondary standard resistor, with a known resistance, low sensitivity to temperature (especially power TCR), and low thermal EMF. The output in millivolts (mV) can be compared to what would be expected should actual pressure be applied. Then the difference in output signal can be compensated within the monitoring instrumentation.

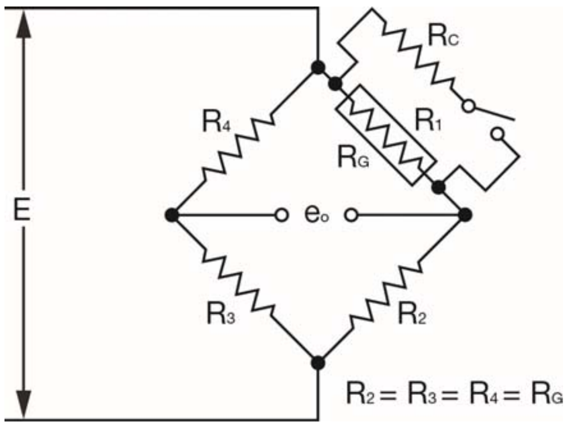


Figure 3: Shunt calibration resistors are chosen to accurately simulate resistance change in a strain gage subjected to specified levels of compressive strain. Strain indicators generally will produce a linear output with a fully active half-bridge or full-bridge input circuit, and will be slightly in error when a single active arm is used. The same nonlinearity occurs whether the gage is actually strained in compression or simulated by shunting the gage with the corresponding calibration resistor.

Shunt calibration is accepted throughout the industry as a means of constant calibration of a signal conditioner and transducer between calibrations of known, applied, traceable, mechanical input values. It's important to remember that the shunt resistor can simulate either a tension or compression input in the Wheatstone bridge. Thermal EMF and TCR errors can affect the process and should be minimized by choosing an appropriate resistor. The shunt calibration can be applied conveniently and at any moment, and most importantly, during the test programs.

For convenience to the user, manufacturers of strain-gage-based transducers supply shunt calibration data with a precision shunt calibration resistor as a standard feature. Of course, regular physical calibration is recommended as well to ensure the accuracy, stability, reliability, and linearity of the instrument itself.

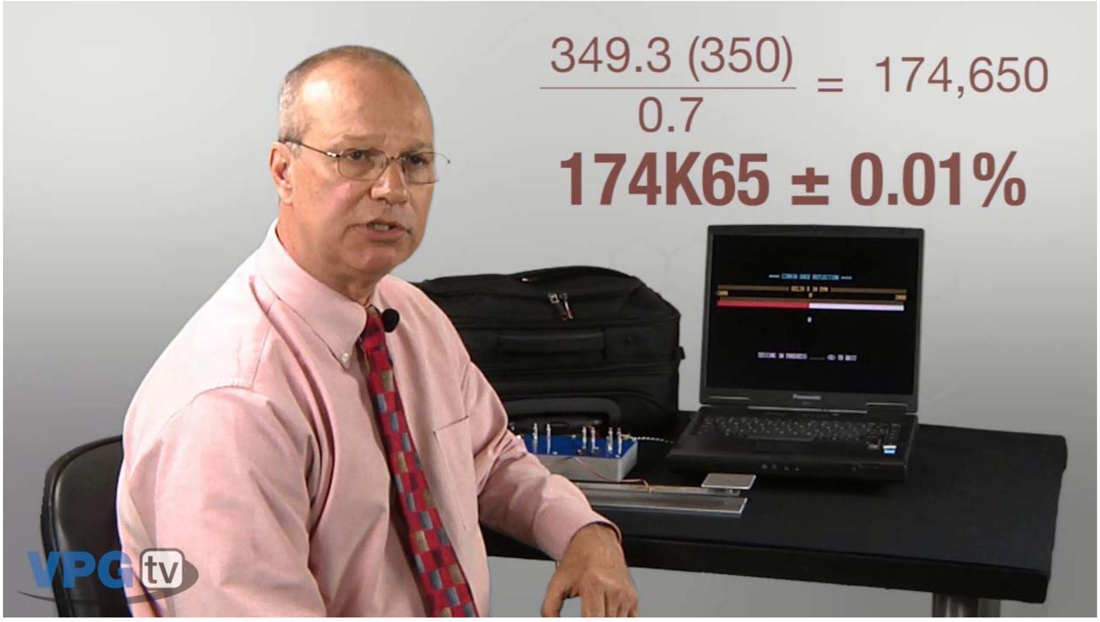
The aircraft application

For crack monitoring in particular, use of crack propagation and crack detection sensors is highly beneficial. Various sizes are available, ranging from small, single strand detectors like the CD-02-10A with a sensing span of 15 mm, to large multi-strand propagation detectors like the CPC03 pattern with a sensing span of 40 mm. Custom patterns are also readily available for use in special applications like sensing cracks originating from rivet holes.

Strain gage installations in a jumbo jet might require a long cable length between the strain gage location and the strain control and measuring instrumentation. The signal cable resistance is additive in the Wheatstone bridge circuit, but the cable itself isn't part of the change in resistance presented to the bridge circuit when the specimen is placed under load. Therefore, the signal cable resistance effectively reduces strain sensitivity. This error can be compensated by performing a shunt calibration directly on each active strain gage. Since strain gages are often unreachable after installation, shunt calibration may be performed at another part of the Wheatstone bridge or at the instrumentation. If not performed across the gage, then the long cable resistance is not compensated during shunt calibration.

A high-value Bulk Metal Foil resistor (typically 50 kΩ to 200 kΩ) may be placed in parallel across a strain gage or one leg of the Wheatstone bridge to produce a predictable mV offset shift, which can be measured and used to calibrate a load cell instead of a more inconvenient weighing standard. This resistor should be stable over a wide variety of temperatures, a long period of time, and various humidity conditions.

To illustrate how strain gage measurement systems can be calibrated electronically using precision Bulk Metal Foil resistors, Vishay Precision Group offers a video that employs a demonstration set-up utilizing a half-bridge connected to a Micro-Measurements 350 Ω / 350 Ω strain gage beam. To detect any change in resistance when under load, the bridge is deflected by a precisely known amount using a VFR Foil resistor in parallel with one side of the strain gage. The amount to be deflected is calculated using the parallel resistance formula "product over the difference." (see below). With any conceivable ohmic value to six digits available, a foil resistor of the exact calculated deflection amount can be utilized to accurately detect any change in resistance. This helpful video can be seen at: http://www.vishayfoilresistors.com/videos/?video=51



Shunt Calibration Calculation Example

If $\frac{1}{R_{gsh}} = \frac{1}{R_g} + \frac{1}{R_{sh}}$ Then $R_{sh} = \frac{R_g \times R_{gsh}}{R_g - R_{gsh}}$

where:

R_g = 350 = Resistance of the strain gage, ohms
2000 ppm = 0.002 = Full scale deviation of the meter
D = 350 x 0.002 = 0.7 = Corresponding resistance change, ohms
R_{gsh} = 350 – 0.7 = 349.3 = Corresponding resistance of the shunted gage
R_{sh} = Resistance of a shunt R_{sh} causing the change D

$$R_{sh} = \frac{(350 \times 349.3)}{(350 - 349.3)} = 174{,}650 \text{ ohms}$$

Additional shunt calibration calculation examples:
http://www.vishayfoilresistors.com/applications/shunt-calibration/

Further information about Vishay Foil Resistors products is available at: **www.vishayfoilresistors.com**

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