Getting the Most out of
Strain Gauge Load Cells

Optimized performance is the result of a blend of good manufacturing processes, smart system integration, high-dynamic range A/D converters, and software compensation.

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You've heard of strain gauge load cells. You may have even seen one or two. But do you know how they work? More to the point, do you know how to get one to deliver optimal performance? A number of factors combined determine how well a load cell works. Orchestrating the interaction of these factors is a must for the systems engineer. But the first step is to understand the basic device.

The Strain Gauge Load Cell

The load cell is a metal spring optimized for the measurement of strain (see Photo 1). Strain, which is induced by an applied force, is the ratio of the change in the length of the spring to its initial length.

$$\text{Strain } (\varepsilon) = \frac{\Delta L}{L} \tag{1}$$

The metal spring is designed to change in length by about 500 to 2000 ppm when subjected to the maximum force it is made to measure. A change of 1 ppm in spring length is called a *microstrain* (με).

Gauge Factor. The sensor's spring concentrates the strain on a specific point of the structure. Strain is measured by attaching metal foil resistors to the area of the spring where the strain is concentrated. In the presence of strain, the resistance of the strain gauge changes. The ratio of the change in the resistance of the gauge to the change in the strain that is induced is called the *gauge factor*. For metal foil gauges mounted on a metal spring, the gauge factor is typically near 2.0.

$$\text{Gauge Factor (K)} \quad \frac{\frac{\Delta R_G}{R_G}}{\frac{\Delta L}{L}} \tag{2}$$

Output Signal. The gauges mounted on the spring are connected in a Wheatstone bridge (see Figure 1). The bridge outputs a differential signal proportional to the applied force. For a load cell spring designed for a full scale of 500 με (gauge factor

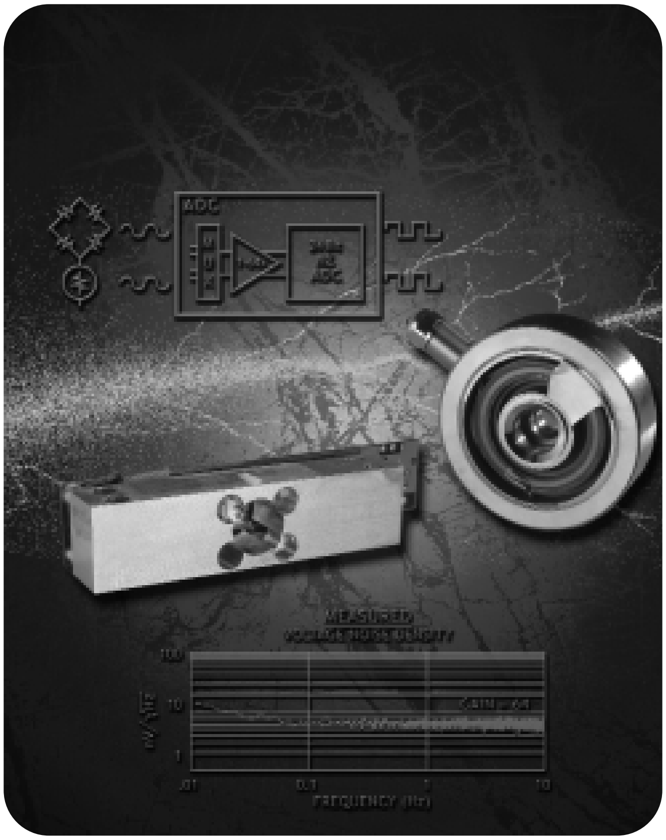

Photo 1. Load cells are mechanical devices that measure weight (force) and pressure. Unfortunately, they only output low-level analog signals. To digitize the signals and attain high accuracy, you need a low-noise amplifier, a high-dynamic range A/D converter, and software compensation.

= 2.0), the electrical sensitivity of the bridge is about 1 mV/V of excitation voltage. With a 5 V supply to the bridge, the full-scale differential signal output will be about 5 mV.

Many mechanical engineers design load cells to yield a slightly lower output (typically –5% to 10%) than the nominal 5 mV. They do this to avoid any possibility of having too much signal for electronics that might be designed for a 5 mV maximum signal.

Error Sources. The mechanically induced output caused by the applied force on the bridge may be 4.5—5 mV. But in addition to the mechanically induced output, there are numerous sources of error in the bridge. For example, the gauges themselves are not identical but have a resistance tolerance of 0.3%. A rule of thumb says this error may actually double when the gauges are mounted on the spring. When four gauges are used in the bridge, the error may introduce a worst-case error of 30 mV of differential offset in the bridge. This is more than six times greater than the signal generated when the mechanical force is applied to the spring.

In addition to gauge mismatch, there are other sources of error in the bridge. Temperature effects occur because of changes in the ambient environment or because of self-heating that occurs when the bridge resistors are excited. If the spring is subjected to any temperature change, it will expand and induce a strain in the bridge resistors, even when no force is applied.

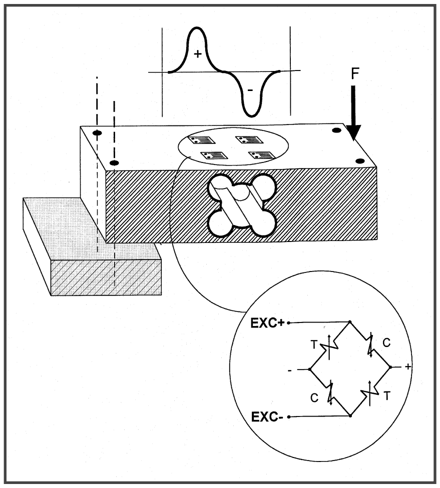

Figure 1. The strain gauge load cell is fundamentally a spring optimized for strain measurement. Gauges are mounted in areas that exhibit strain in compression or tension. The gauges are mounted in a differential bridge to enhance measurement accuracy.

Figure 2 illustrates a typical plot of the temperature effects on the bridge output. Manufacturers offer strain gauges with temperature compensation characteristics intended to match the temperature characteristics of the foil gauge to the particular metal used as the spring material. But the compensation for thermal output is beneficial only over a limited temperature range. Note that the plot of Figure 2 is for one particular temperature-compensating gauge on one type of spring element material (Aluminum 2024-T4). The characteristics of a production lot would exhibit a spread about the thermal output curve shown in the graph. A second curve on the graph indicates the change in the gauge factor over temperature.

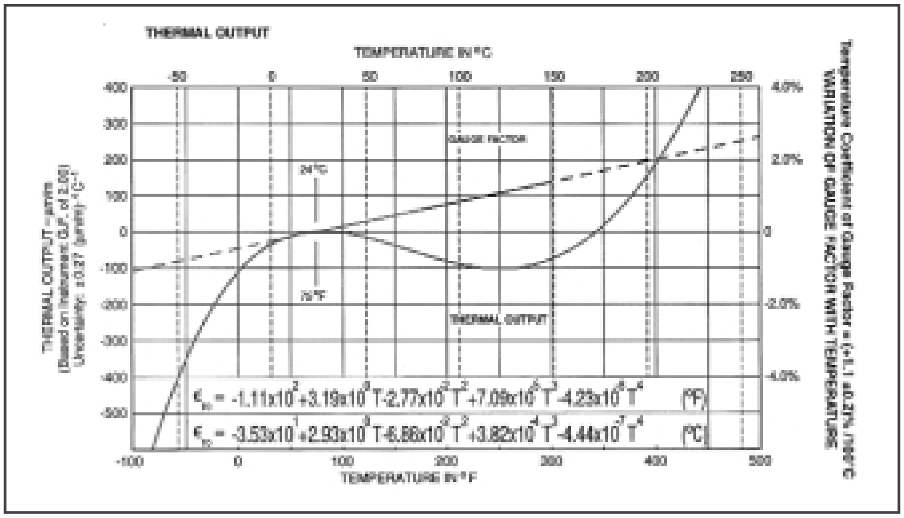

Figure 2. The spring material/gauge combination exhibits strain output over temperature that is not a function of the applied force. The gauge factor is also influenced by temperature changes, whether they are caused by ambient temperature changes or by self-heating. (Illustration courtesy of Vishay Measurements Group.)

If you have to use the load cell over a temperature range of –40°C to 85°C, you can obtain information about the magnitudes of errors caused by temperature. For example, from the curves, you can see that thermal output will cause an error of about –290 µε at –40°C, and gauge factor will contribute an error of about –72 µε at –40°C (see Table 1). Note that the output due to mechanical strain is <12% of the worst-case dynamic range requirement.

Manual Compensation

Most load cells are manually compensated to remove most of these errors. This requires the manufacturing process to include steps to trim the offset, offset temperature drift, span, and span temperature drift. Figure 3 illustrates a bridge with resistors added to compensate for these errors. The resistors may be a length of wire or a foil resistor with cuttable links that enable the resistance to be trimmed in known amounts.

Trimming out these errors is time consuming and expensive. The manufacturer adds a constantan zero balance resistor to achieve a balanced bridge output. Then it temperature-cycles the cell to assess the drift of the bridge offset over temperature. The manufacturer trims the copper resistor to the correct value to compensate for the offset temperature drift. Next, it adds a constantan span resistor to trim the initial span error. Finally, the manufacturer temperature-cycles the cell and places it under a load to assess the temperature drift of the span. After cycling to assess the span drift, it trims the Balco gauge factor compensation resistor.

In the end, the best manually trimmed loads cells are typically linear to 1 part in 5000 (1 part in 2000 is more common). And manually trimmed load cells are rated for accuracy over a limited temperature range (–10°C to 50°C being typical).

Software Compensation

To achieve higher levels of performance over a wider temperature range, system designers turn to software compensation.

An A/D converter with a high dynamic range greatly simplifies this approach.

Let's review the example we've discussed. The strain gauge load cell can output as little as 4.5 mV but requires a worst-case signal span of 38.1 mV. The portion of the sensor's output induced by the applied pressure or the applied force is actually a much smaller portion of the total sensor output when all the worst-case errors are considered.

To digitize the 4.5 mV signal, a system designer must choose an A/D converter with a large enough input range to accommodate the total output (including errors) from the sensor and still have adequate resolution for the portion of the span that represents the actual force-induced signal.

Figure 4 shows Cirrus Logic's 24-bit CS5532 A/D converter connected to a load cell bridge. The A/D converter has a high dynamic range and doesn't require a D/A converter. The software-compensated load cell shown in Figure 4 does not use all the trim resistors for compensation (as shown in Figure 3). Some designers do use a temperature-compensating resistor in series with the bridge (see Figure 4A). The resistor is mounted in a place on the spring that is not subject to strain. The resistor provides first-order compensation of the span of the bridge over temperature, and it acts as a temperature sensor for mapping the load cell temperature characteristics. Alternatively, a designer can choose to connect the bridge to the excitation supply directly—this yields higher differential output—and then use a separate temperature sensor for monitoring the spring temperature (see Figure 4B).

In either case, there are two signals to be measured. The A/D converter has two amplifiers to handle the signals. The low-level differential bridge signal requires a low-noise instrumentation amplifier, with the gain set at 64. This yields an input span of about 39 mV, which can accommodate the worst-case output from the load cell and still yield high resolution on the 4.5 mV signal. The instrumentation amplifier has a noise floor of 6 nV/√Hz (see the sidebar, for details) and is chopper stabilized. The offset drift of the amplifier is 20 nV/°C. When the converter is set for a conversion rate of 7.5 Hz, its peak-to-peak noise is only 51 nV. This yields 4.5 mV/51 nV = 88,000 noise-free counts on the 4.5 mV differential signal.

TABLE 1

Strain Gauge Bridge Outputs: Worst-Case Value (Sensitivity = 1 mV/V and Excitation = 5.0 V)

	Strain	Voltage at Input	Percent Output
Gauge Tolerance	3000 με	30.0 mV	78.6%
Thermal Output	300 με	3.0 mV	7.9%
Gauge Factor	65 με	0.65 mV	1.7%
Mechanical Output	450 με	4.5 mV	11.8%
Total	3815 με	38.15 mV	100.0 %

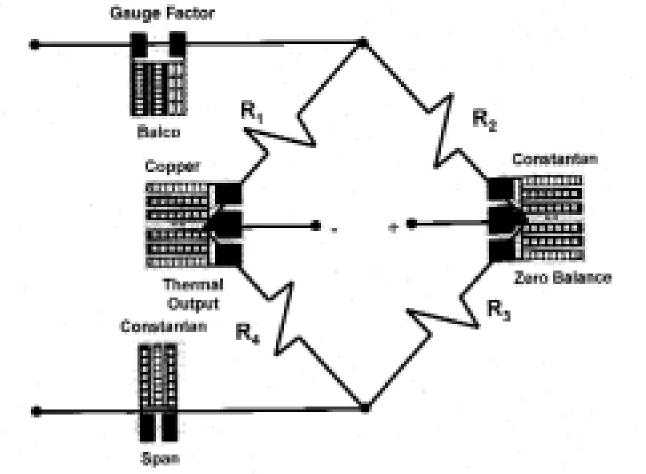

Figure 3. Many load cells are trimmed manually with additional resistor elements to remove bridge offset, offset temperature drift, span error, and span drift over temperature.

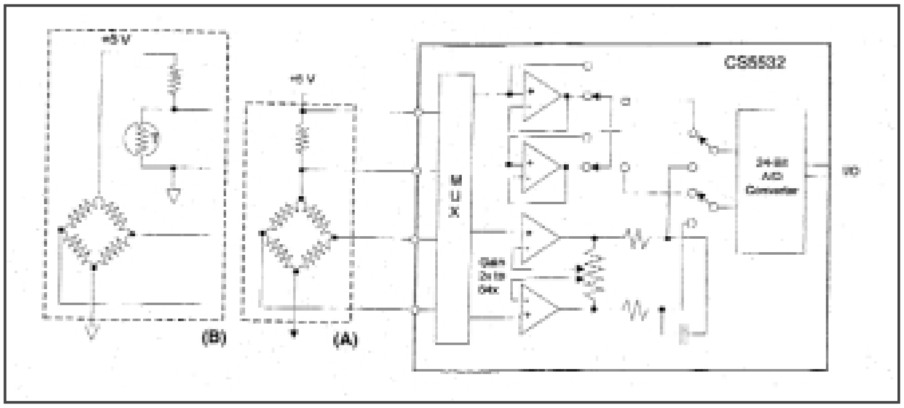

Figure 4. Software compensation of sensors requires the measurement of two different signals—the sensor output and the sensor's temperature. Temperature can be monitored by a temperature-sensitive resistor in series with the bridge (A), or with a separate temperature sensor (B). The two amplifiers in the A/D converter are optimized for measuring the bridge output and the temperature signal.

The amplifier for the temperature sensor signal doesn't require as low of a noise but must usually measure signals that are referenced to ground or to the positive excitation supply. The second amplifier in the converter is designed for this purpose. This amplifier is engaged whenever the gain is set for 1×. The combination of the two-amplifier architecture makes the converter ideal for low-level, software-compensated sensor applications.

Conclusion

Systems engineers would prefer that all strain gauge load cells with the same part number exhibit nearly identical performance. One way to achieve consistency from sensor to sensor is extensive trimming during the manufacturing process. But if the behavior of these sensors is repeatable over temperature, they can benefit from software compensation, which improves the accuracy of sensors that normally would vary greatly in offset, gain, and temperature coefficient.

In any of the configurations, the high dynamic range A/D converter allows the characteristics of the sensor to be mapped over the entire industrial temperature range or even over greater temperatures. Once this is done, compensation can be implemented in software. The entire process—including applying the pressure or force to the sensor over temperature—can be automated. This yields a sensor with higher accuracy.

For Further Reading

Paillard, Bruno. Jan. 1998. "Temperature-Compensating an Integrated Pressure Sensor," *Sensors*.

Thomsen, Axel. June 1998. "A Five-Stage Chopper-Stabilized Instrumentation Amplifier Using Feedforward Compensation," *Proc* The Symposium on VLSI Circuits. ■

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The MultiPath Amplifier—18 Bits of True Measurements

System amplifier requirements are driven by sensor output characteristics (signal levels typically <200 mV). For example, the optimal excitation voltage for a 1 mV/V load cell is 5 V. This excitation voltage is necessary because of the load cell's self-heating with higher excitation voltages. Unfortunately, with 5 V excitation, the full-scale output is only 5 mV. Because noise places a limit on how accurately a sensor's signal can be amplified, high-resolution measurement of low-level signals requires a low-noise, low-drift amplifier.

Until now, the best performance on a 5 mV signal with an amplifier/A/D converter was around 13 bits. The new amplifier/A/D converter technology in the Cirrus Logic's CS5532 provides 18 bits of true measurement performance (see Table 2). The converter is a two-channel, 24-bit device that incorporates a low-noise, low-drift, monolithic instrumentation amplifier. The instrumentation amplifier, which has programmable gain, is called the MultiPath amplifier.

The amplifier uses multipath feed-forward compensation and chopper stabilization to achieve low noise and low drift, as well as high open-loop gain. The amplifier technology, which is based on the work of Nyquist in the 1930s, provides >180 dB of open-loop gain. This guarantees 20-bit amplifier linearity even when the amplifier is in a closed-loop gain configuration of 64 (36 dB).

In the past, if system designers wanted a low-noise amplifier, they would use a bipolar amplifier and accept its 1/f and high drift (typical drift is 250 nV/°C or higher). If low drift were the concern, a CMOS chopper amplifier would be necessary. However, noise performance was the tradeoff. The MultiPath provides both low noise and low drift.

Measured Performance

The CDB5532 customer demo board was used to collect 3,276,800 samples. To keep the digital filter from affecting measurement results from 0.1 Hz to 10 Hz, the 120 Hz throughput was used. The CS5532's performance represents a ten-fold improvement at 0.1 Hz when compared with any other monolithic instrumentation amplifier (whether bipolar or CMOS-based). ■

TABLE 2

Key Specifications of the CS5532's Instrumentation Amplifier

Noise at 0.1 Hz*	Integrated Noise* 0.1–10 Hz	Maximum Drift*	Linearity (Gain = 36 dB)	Input Current
6 nV/√Hz	125 nV p-p	20 nV/°C	20 Bits	100 pA

* 64 × gain range

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