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Bridge-Type Sensor Measurements Are Enhanced by Autozeroed Instrumentation Amplifiers with Digitally Programmable Gain and Output Offset

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Resistance-based bridge circuits are widely used to provide electrical outputs from sensors measuring physical variables, such as pressure and force. These outputs are usually small—and thus require amplification to bring them up to levels required by A/D converters in measurement-and-control systems. This article describes a versatile new IC instrumentation amplifier that has very low drift and many useful features, and discusses its role in solving problems of bridge instrumentation, using pressure measurement as an example.

Pressure Sensing

Figure 1 illustrates the functionality of a typical electrical output pressure instrument. Pressure is sensed by the motion of mechanical elements, such as diaphragms, Bourdon tubes, bellows, and capsules, all of which deflect when pressure is applied. This deflection causes a change in the resistances of a strain gage.
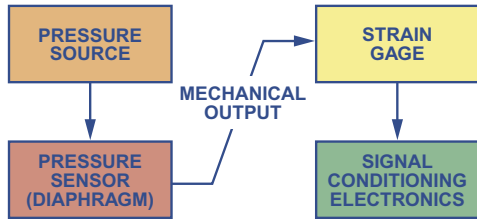
Figure 1. Converting pressure to an electrical signal.

The most popular pressure sensors use strain gages in a Wheatstone resistance-bridge configuration in which all four elements are variable—as shown in Figure 2D—thus providing optimal linearity and sensitivity. When pressure is applied to the diaphragm, two gage elements of the bridge are subjected to tension; the other two elements are subjected to compression. The corresponding changes in resistance are a measure of the incident pressure. The bridge is excited by a constant voltage or current, producing an electrical signal.

In one form of *gauge-pressure sensor* technology, the strain-gage elements are bonded to a metal diaphragm and produce a full-scale resistance variation, typically of the order of 0.1% of the base resistance. When a constant voltage or current is applied to the bridge, the change in the resistance over that range produces a linear unbalance, which is measured as a differential voltage (or current). In another technology, *semiconductor strain gages* are bonded into a silicon diaphragm, and can generate a much larger response—in many cases about 1% of the base resistance.

A good detailed explanation of strain gages and various bridge configurations can be found in the Analog Devices *Sensor Signal Conditioning* manual.[1]

Signal Conditioning

The signal produced by the bridge is generally small and is subject to noise, offset, and gain errors. Before the bridge output can be digitized, it must be amplified, with offset adjusted to match the span of the A/D converter, and filtered, to remove noise. Although the signal conditioning block shown in Figure 3 could be built with operational amplifiers and discrete circuit elements, instrumentation amplifiers have proved to save on parts cost, circuit-board area, and engineering design time.
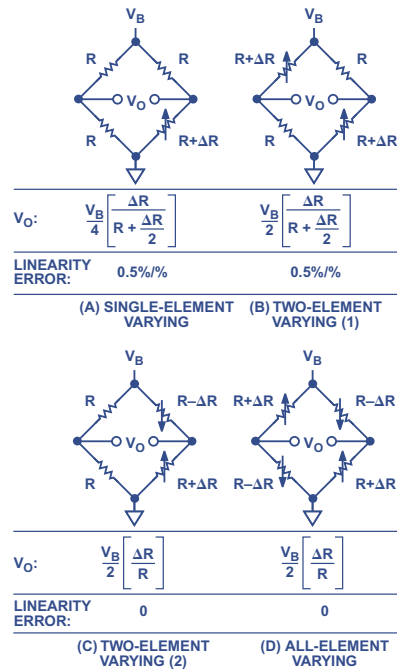
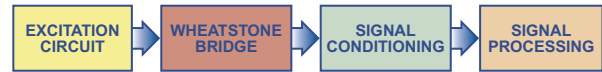Figure 2. Bridge with four resistive elements.

Figure 3. Pressure measuring instrumentation.

In typical pressure sensor applications, a resistive bridge outputs a differential signal—with a span of tens or hundreds of millivolts—that is proportional to the applied pressure and the excitation voltage applied to the bridge. The Honeywell 26PC01SMT series microstructure pressure sensor, for example, has a ±1.0-psi full-scale span. With 5 V applied, it would have a zero-pressure null offset of ±2 mV, a full-scale output span anywhere in the range of ±14.7 mV to ±18.7 mV, and a 2.5-V common-mode level. In order to accurately resolve this small differential output voltage in the presence of the high common-mode voltage, an instrumentation amplifier's ability to reject common-mode signal is essential. For example, 12-bit readout resolution calls for an LSB of less than 10 μV (35 mV/4096), or about 101 dB below the common-mode level.

Manual Bridge Compensation

Wheatstone bridges in pressure sensors are typically manually compensated to remove their offset and span errors. This requires the instrumentation manufacturing process to include steps to trim the offset, offset temperature drift, span, and span temperature drift. Figure 4 illustrates a bridge with resistors added to compensate for these errors. Trimming out these errors is time consuming and expensive. Alternatively, the offset can be adjusted by applying a programmable dc voltage from a D/A converter to the reference pin of an instrumentation amplifier. Offset correction is required since the offset would otherwise reduce the available dynamic range of the ADC.
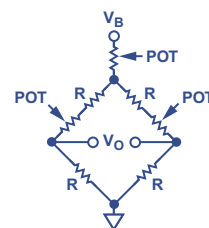
Figure 4. Manual bridge compensation.

Gain uncertainties in pressure sensors make gain adjustment a requirement in most instrumentation amplifier-based systems. This was traditionally done by adding a trim potentiometer in series with the external gain resistor of the instrumentation amplifier. To achieve higher levels of performance over a wider temperature range, system designers turned to software-controlled gain compensation.

Instrumentation Amplifier Errors

Figure 5 shows some typical error sources that occur when a sensor is interfaced to a signal conditioning circuit. The bridge amplifier bias current flows through the output resistance of the bridge. Any unbalance in the resistance or bias current produces an offset error. This error, multiplied by the gain, appears at the output. In addition, the offset voltage and bias current are functions of temperature. Other important errors to consider are the amplifier's gain accuracy, nonlinearity, and noise. A high-performance amplifier with low input offset voltage, bias current, offset-voltage TC, and bias-current TC is required for bridge-measurement applications.[2]
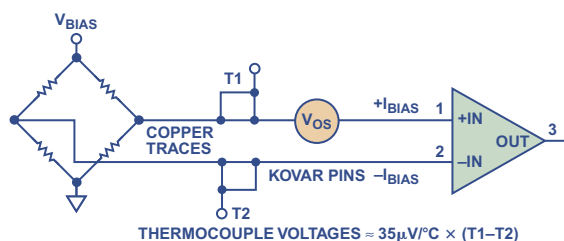

Figure 5. Amplifier error sources.

The AD8555 to the Rescue

Measurement system designs that use bridge circuits, such as pressure sensors, will benefit by the AD8555, a new *zero-drift* digitally programmable amplifier from Analog Devices.[3] Its instrumentation amplifier configuration employs three autozeroed amplifiers (A1, A2, A3), as shown in Figure 6.
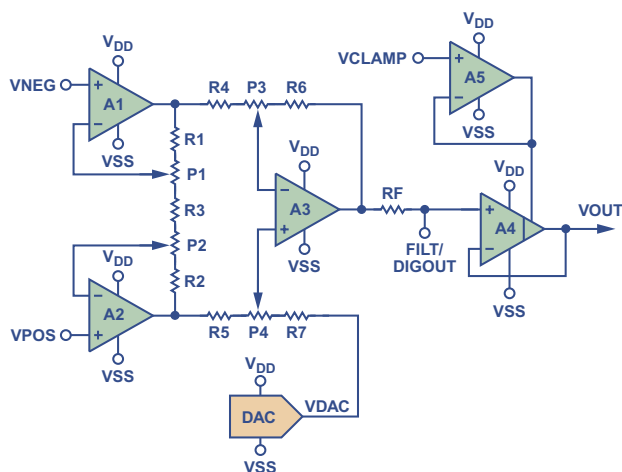

Figure 6. Functional block diagram of the AD8555 instrumentation amplifier.

To avoid loading the sensor's bridge, the differential inputs feature high impedance and low bias current at both terminals (V_{POS} and V_{NEG}). Autozero techniques minimize offset and offset drift by continuously correcting for amplifier-generated dc errors. This results in a 10-μV maximum input offset voltage over a temperature range of −40°C to +125°C, with maximum drift of just 65 nV/°C.

Gain, ranging from 70 to 1280, is programmed in steps of less than 1 (with better than 0.4% resolution)—via a single-wire serial interface—by adjusting the gains of the two stages individually. In the DigiTrim® process, the gain setting is locked in place by blowing polysilicon fuses.[4] The first-stage gain is trimmed from 4.00 to 6.40 in 128 steps by a 7-bit-code that adjusts both P1 and P2; and the second-stage gain is set from 17.5 to 200 by an 8-step, 3-bit-code that adjusts P3 and P4. The adjustment values can be temporarily programmed, evaluated, and readjusted for optimum calibration accuracy—before the settings are permanently fixed.

The AD8555 also has an 8-bit DAC-*programmable offset*, which can be used to compensate for offset errors in the input signal and/or add a fixed bias to the output signal. This bias is used, for example, to handle bipolar differential signals in a single-supply environment. The output offset voltage may be set with a resolution of 0.39% of the voltage difference between the supply rails, (V_{DD}–V_{SS}).

$$V_{out} = (Gain) \times (V_{diff}) + V_{offset}$$

and

$$V_{offset} \approx \left(\frac{N_{DAC-code} + 0.5}{256} \right) \times (V_{DD} - V_{SS}) + V_{SS}$$

where

  Gain = (1st-stage gain) × (2nd-stage gain)
  V_{diff} is the differential input voltage to be measured
  $N_{DAC-code}$ is the numerical value of the DAC's input code.

Like the gain, the output offset can be temporarily programmed, evaluated, and readjusted; and then can be permanently set by blowing the fuse links.

Single-supply operation has become an increasingly desirable characteristic of modern sensor amplifiers. Many of today's data acquisition systems are powered from a single low voltage supply. The AD8555 operates from single-supply voltages from 2.7 V to 5.5 V. The output of amplifier A4 swings to within 7 mV of either supply rail.

Fault detection in the AD8555 amplifier protects against open, shorted, and floating inputs. Any of these conditions triggers a circuit that causes the output voltage to be clamped to the negative supply rail (V_{SS}). Shorts and floating conditions are also detected on the V_{CLAMP} input. Using an external capacitor, the AD8555 can implement a low-pass filter to limit its dc-to-400-kHz output frequency range.

The AD8555's Role in Sensor Bridge Signal Conditioning

Systems engineers would prefer that all pressure sensors with the same part number exhibit nearly identical performance. Typically, off-the-shelf sensors do not meet such requirements with adequate accuracy. One way to achieve consistency from sensor to sensor is extensive trimming during the manufacturing process. If the behavior of these sensors is repeatable over temperature, a better way may be to use this new generation of programmable amplifiers to provide compensation.

The AD8555, with its zero-drift instrumentation amplifier, can provide amplification, gain setting and trim, offset setting and trim, and clamping—all established digitally. It can be used to compensate for offset and gain errors in bridge-type sensors, as well as providing an indication of sensor malfunction. It enables

adjustments using software, making compensation using trim potentiometers an outdated art in a manufacturing environment. In the many cases where sensors are used in harsh and crowded environments, measurements benefit from the wide temperature range and space-saving package size of the AD8555, which is housed in a 4-mm-by-4-mm lead-frame chip-scale package (LFCSP). Because the AD8555 is capable of driving very large capacitive loads, it can be placed close to the sensor and at a distance from the signal processing circuitry. Its high levels of programming flexibility and dc accuracy distinguish it from all other solutions.

Application Example

In a given batch of pressure sensors, sensor-to-sensor variations cause offset voltages of 20% of the sensor's full-scale output. Sensor-to-sensor gain can vary by almost 2 to 1. The following example shows how we can use the AD8555 to compensate for the offset and gain variations, while maximizing the dynamic range of the signal provided to the A/D converter. Figure 7 shows the application circuit, including the bridge, AD8555, and AD7476 A/D converter.
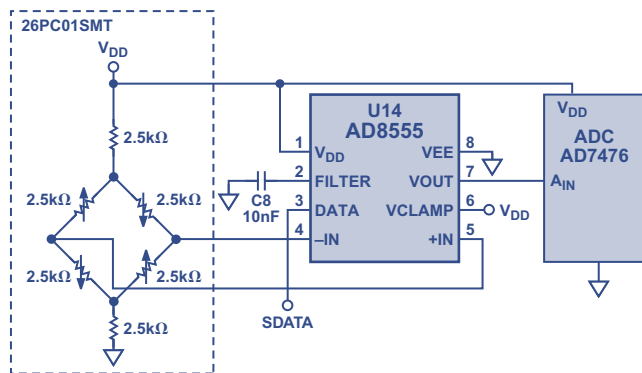

Figure 7. Pressure-sensing application example.

Sensor characteristics

The 26PC01SMT (surface-mount technology) pressure sensor is a Wheatstone bridge-based, printed circuit board-mountable device, which together with the AD8555, would appear to provide complete programmable pressure measurement and conditioning in a small footprint. Based on data sheet specifications at 10 V and 25°C, these are the expected sensor characteristics with a 5-V source:

Measurement Type	Gage, Vacuum Gage, Differential
Pressure Range, psi	±1.0
Input Resistance Range, kilohms	5.5 to 11.5
Output Resistance Range, kilohms	1.5 to 3.0
Output Voltage Span, mV, ±1 psi	±14.7 min, ±16.7 typ, ±18.7 max
Span Shift Over Temperature, %	±1.5 typ, ±4.5 max
Null Offset, mV	−2 to +2
Null Shift, mV, 25°C to 0°C; 25°C to 50°C	±1.0 max
Linearity Error, % of Span	±0.50 typ, ±1.75 max
Repeatability and Hysteresis Errors, %	0.20 typ
Overpressure, lb/in^2	20 max

Amplifier characteristics

The signal conditioning circuitry also introduces errors which appear as an offset. The error contributions of the AD8555 are listed in the following table.

Parameter	Error	PPM
Input Offset Voltage	$(2 \ \mu V + 2 \ mV/150) \times 150$	458
Input Offset Current	$2500 \ ohm \times 200 \ pA \times 150$	15
Gain Error	0.5%	5000
CMRR	100 dB	750
Gain Nonlinearity (1)	50 ppm	50
0.1–10 Hz 1/f Noise (2)	0.7 μV p-p × 150	21
Total Unadjusted Error	~7 bits	6294
Total Adjusted Error (1+2)	~14 bits	71

Conditions: R_{bridge} = 2500 ohm, Full scale = ±16.7 mV, A_V = 150, V_{OFF} = 2.5 V, V_{OUT} = 0 V to 5 V

The table shows that the dominant error sources are static errors appearing at the input of the AD8555. These will be trimmed out along with the corresponding variations in the sensor. Errors caused by current noise, gain drift, and offset drift are minimal, and can be ignored. The remaining errors, which cannot be trimmed out, are noise and gain nonlinearity.

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. The AD8555 has a voltage noise density floor of 32 nV/$\sqrt{Hz}$ at 1 kHz. The noise from dc to 10 Hz is 0.7 μV peak-peak.

The bridge, AD8555, and A/D converter are all excited by a +5-V supply. The full-scale output span of the bridge will be anywhere in the range of ±14.7 mV to ±18.7 mV. Its offset will be between −2 mV and +2 mV. Matching the 5-V full-scale input span of the A/D converter requires gain settings from 134 to 170. With the offset set to 2.5 V, the amplifier output will range from 0 V to 5 V as the pressure varies between −1 psi and +1 psi.

First set the gain to 134—the minimum required by this sensor. With a 0-psi input, adjust the offset until the amplifier output is at 2.5 V. This compensates for the null offset of the sensor and the amplifier error terms. Apply a 1-psi input, and adjust the gain so that the amplifier output voltage is 5 V – 1 LSB. The output offset is a function of the gain, so the offset and gain adjustments must be done iteratively. As an alternative, the required gain can be calculated after the output span is measured. The offset is adjusted after the gain has been set, and thus only needs to be adjusted once.

CONCLUSION

The AD8555 simplifies the design of bridge measurement systems by integrating a zero-drift instrumentation amplifier with programmable gain, programmable output offset, fault detection, output clamping, and low-pass filtering, thus providing the complete signal conditioning path between a sensor and an A/D converter. An evaluation kit containing sample pieces and evaluation software and hardware, is available from Analog Devices. ▶

REFERENCES
[1]"Bridge Circuits": from *Practical Design Techniques for Sensor Signal Conditioning*, edited by Walt Kester, Norwood, MA: Analog Devices, Inc., 1999, Section 2. http://www.analog.com/Analog_Root/static/pdf/amplifiersLinear/training/Sensor_sect2.pdf

[2]Analog Bridge Wizard™: *A Tool for Design and Product Selection* http://www.analog.com/Wizard/bridge/bridgeUserEntry/

[3]AD8555 Description and Data sheet: http://www.analog.com. Enter <AD8555> in SEARCH box.

[4]*Polysilicon fuses*. One advantage of using polysilicon fuses is their reliable performance over temperature—a requirement in automotive applications, for example. Once the user is satisfied with the offset and gain settings, the trim circuit is locked out by blowing the *master fuse* to prevent any accidental re-trimming.

This article can be found at http://www.analog.com/library/analogDialogue/archives/38-05/AD8555.html