Transducer/Sensor Excitation and Measurement Techniques

By Albert O'Grady

INTRODUCTION

Input transducers, or *sensors* are classified as either active or passive. *Passive* sensors, such as thermocouples or photodiodes (in the voltage-output mode) are two-port devices that directly transform physical energy to electrical energy, generating output signals without the need for an excitation source. *Active* sensors (like active circuits in general) require an external source of excitation. Examples can be found in the class of resistor-based sensors, such as thermistors, RTDs (resistance-temperature detectors), and strain gages; they require a current or voltage for excitation in order to produce an electrical output.

This article will consider a variety of excitation methods that can be used in active sensor/transducer applications and will show some typical circuits. The discussion includes the benefits and shortcomings of ac and dc excitation techniques using current and voltage. Accurate measurement of low-level analog signals with a data-acquisition system generally requires more than simply wiring the output of the transducer to the signal conditioning circuitry and then to the analog-to-digital converter. To maintain high-resolution and accuracy within the measurement system, the designer must exercise care in selecting the excitation source for the transducer—and in the field-wiring scheme used in conveying the low-level analog signal from the transducer to the A/D converter. Figure 1 shows a generalized block diagram of a transducer-based data acquisition system. The integrity of the data acquired in these systems depends on all parts of the analog signal path shown here.

For a given excitation source, the system designer is faced with the challenge of measuring the output signal and dealing with the issues that may arise. For example, wiring resistance and noise pickup are among the biggest problems associated with sensor-based applications. A variety of measurement techniques are available for employment in quest of optimum performance from the measurement system. Principal choices include ratiometric vs. non-ratiometric operation, and 2-wire vs. 3- and 4-wire Kelvin force/sense connections.

EXCITATION TECHNIQUES

Active transducers can be excited using a controlled current or voltage. The choice between voltage and current excitation is generally at the discretion of the designer. In data-acquisition systems, it is not uncommon to see constant-voltage excitation used for strain and pressure sensors, while constant current excitation is used to excite resistive sensors such as RTDs or thermistors. In noisy industrial environments, current excitation is generally preferable due to its better noise immunity.

AC or dc excitation sources can be used in transducer applications; each offers advantages and disadvantages. The advantages associated with dc excitation include simplicity of implementation and low cost. The downside of dc excitation includes the difficulty of separating the actual signal from unwanted dc errors due to offsets and parasitic-induced thermocouple effects. DC offsets are not fixed; they vary unpredictably due to temperature drift and both thermal and 1/f noise sources.

Although ac excitation techniques are more expensive to implement, they offer many performance benefits. AC excitation operates similarly to the chopping scheme used in precision amplifiers; it is used advantageously in transducer signal-conditioning circuits to remove offset errors, average out 1/f noise and eliminate effects due to parasitic thermocouples. With decreased sensitivity to 1/f-noise, a discernible output signal can be produced with much lower excitation currents or voltage. Decreased excitation means that the self-heating effects of current flow in resistive sensors can be greatly reduced. Since a relatively narrow bandwidth is involved, it is also likely that ac excitation also offers greater immunity to RF interference than dc excitation.

There are two major factors in selecting an excitation source that will enhance overall system performance. First, resolution: the magnitude of the excitation should be sufficient that the minimum change in the variable being measured produces an output from the transducer that is large enough to overcome the noise and offset in the system. Second, power level: if the sensor is resistive the designer must ensure that the self-heating effects of excitation current flowing through the transducer do not adversely affect the measured results.

RATIOMETRIC VS. NON-RATIOMETRIC OPERATION

Figure 2 shows a ratiometric configuration in a bridge transducer application. The same reference source is used for both the transducer excitation and the A/D converter. A given percentage change in excitation is countered by the same percent change in the conversion process (or vice versa). The ADC output code, D_{OUT}, is a digital representation of the ratio of the converter's input, AIN, to its reference, VREF. Since the input to the converter and
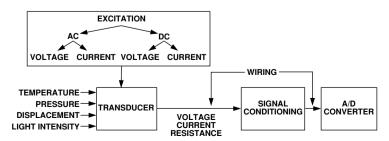

Figure 1. Typical transducer-based data acquisition system.

its reference are derived from the same excitation source, changes in the excitation do not introduce measurement errors. Thus, in ratiometric configurations, if the variable being measured by the transducer is unchanged, the digital output code from the ADC is immune to variations in the bridge excitation

For this reason, an accurate stable reference is not necessary to achieve accurate measurements. Ratiometric operation is very powerful; it permits measurement and control, using the system analog supply, to obtain accuracy independent of the stability of voltage references or excitation supplies. Because the power supply rejection of most ADCs is fairly high, drifts in the power supply voltage do not adversely affect the measurement.
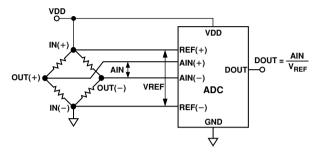

Figure 2. Ratiometric operation in a bridge transducer application.

Figure 3 demonstrates the disadvantage of dc non-ratiometric operation. It shows a typical non-ratiometric configuration in a bridge transducer application. As in the previous application, the ADC outputs a digital code, D_{OUT}, the ratio of AIN to VREF. In this example, the output code is sensitive to relative changes between the bridge excitation and reference voltage. Any change in the excitation voltage results is a change in the analog input voltage seen by the ADC. Since the reference is independent of the excitation, the digital output code will reflect the changed excitation. Non-ratiometric circuits are principally suitable for applications requiring measurements against an absolute reference—or where a single converter serves a variety of unrelated analog inputs. Since changes in reference, excitation, etc., will not be removed but will be reflected in the measurement, highly accurate, precise, and stable references and excitation sources are required for most applications.
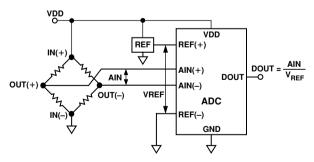

Figure 3. Non-ratiometric operation in a bridge-transducer application.

In the design of high-resolution data-acquisition systems, designers should always keep in mind the cost-effectiveness of ratiometric operation wherever its use is feasible.

WIRING CONFIGURATIONS

There are a variety of wiring configurations that can be employed when connecting to resistive sensors such as RTDs and thermistors in temperature-measurement applications. The basic 2-, 3- and 4-wire connections are shown in Figure 4. Why are these formats available, with their various complexities and costs? Lead-wire resistance can introduce significant measurement errors if adequate precautions are not taken to eliminate them, particularly in low-resistance 100-Ω RTD applications. In RTD circuits a controlled (usually constant) current is passed through the sensor, a resistor whose resistance increases gradually, repeatably, and approximately linearly with temperature. As its resistance increases, its voltage drop increases and, though small, can be measured without difficulty.

In an ideal application the voltage measured should only include the increase in resistance of the sensor itself. In practice, though, especially in 2-wire configurations, the actual resistance between the sensor terminals at the point of measurement includes the resistances of both the sensor and the lead wires. If the lead-wire resistance were to remain constant, it would not affect the temperature measurement. However, the wire resistance does change with temperature; and as the ambient conditions change, the wire resistance will also change, introducing errors. If the sensor is remote and the wire is very long, this source of error will be significant in RTD applications, where the nominal sensor value will be 100 Ω or 1 kΩ, and incremental changes are typically of the order of 0.4%/°C. Thermistor applications, where nominal sensor resistance values are higher than for RTDs, tend to be less sensitive to lead-resistance, since the leads contribute less error.
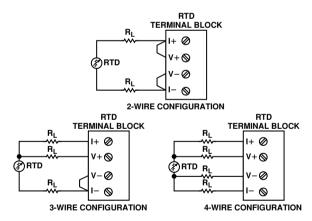

Figure 4. Typical wiring configurations for resistance based sensors.

The 2-wire configuration is the least accurate of the three systems shown above, because the lead wire resistance, $2R_L$, and its variation with temperature contribute significant measurement errors. For example, if the lead resistance of each wire is 0.5 Ω in each wire, R_L adds a 1-Ω error to the resistance measurement. Using a 100-Ω RTD with α = 0.00385/°C, the resistance represents an initial error of 1 Ω/(0.385 Ω/°C) or 2.6°C, and variation of the lead resistance with ambient temperature contributes further errors.

The 3-wire configuration in Figure 4 offers significant improvements over the 2-wire configuration due to the elimination of one current-carrying lead wire. If the measurement wire

returning to V(+) feeds into a high impedance node, no current flows in this wire and no wiring error is introduced. However, the lead resistance and thermal characteristics of the RTD return wire to V(–) and I(–) still introduces errors, so the errors have been reduced to one-half the error in a 2-wire system.

The 4-wire configuration in Figure 4 offers the best performance, in terms of accuracy and simplicity, compared to the 2- and 3-wire configurations. In this application, the errors due to the lead-wire resistance and thermal heating effects are removed by measuring the temperature right at the RTD. The return wires from the RTD are generally buffered by a high-impedance circuit (amplifier/analog to digital converter), and thus no current flows in the return wires and no error is introduced.

If two matched current sources are available, it is possible to design 3-wire systems that essentially eliminate any wiring resistance or thermal effects. An example, using the AD7711 converter, is shown in Figure 5. The excitation is furnished by current from the upper 200-μA current source, flowing through the resistance of the connecting wire, R_{L1}. The lower current source provides a current flowing through the other measurement wire, with resistance R_{L2}, creating a voltage drop essentially equal and opposite to the drop across R_{L1}, cancelling it when measured differentially. The sum of the two currents flows harmlessly through the return wire (R_{L3}) to ground (the differential measurement ignores the common-mode voltage). The 200-μA current, flowing through the series 12.5-kΩ resistor, develops a voltage that is used as a reference for the converter, providing a ratiometric measurement.
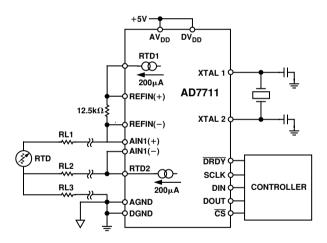

Figure 5. Eliminating errors due to field-wiring resistance in 3-wire RTD applications.

The AD7711, a high-resolution sigma-delta ADC, converts the voltage from the RTD to digital. The AD7711 is an ideal choice of converter for this application; it offers 24-bit resolution, an on-chip programmable gain amplifier and a pair of matched RTD excitation current sources. As is evident from the example, a complete solution can be built without the need for extra signal conditioning components.

AC EXCITATION

Figure 6 shows some of the system error sources associated with dc-excitation and measurement in a bridge sensor application. In this bridge circuit, it is not possible to distinguish how much of the amplifier's dc (and low-frequency) output is actually from the bridge and how much is due to error signals. Errors introduced by 1/f noise, parasitic thermocouples, and amplifier offsets cannot be

dealt with unless some method is used to differentiate the actual signal from these error sources. AC excitation is a good solution to this problem.
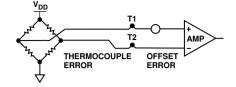

Figure 6. Error sources associated with dc-excitation in a bridge transducer measurement system.

The signals from a bridge transducer, which depend on the excitation, are typically small. If the excitation is 5 V and the bridge sensitivity is 3 mV/V, the maximum output signal is 15 mV. Sources of degradation for the information provided by these low-level signals include noise (both thermal and 1/f), voltage from parasitic thermocouples and amplifier offset errors. For example, parasitic thermocouples exist in normal circuit wiring. Junctions between tin-lead solder and copper PC board traces can introduce thermocouple effects of 3 to 4 μV/°C, if thermal gradients exist across the circuit. Thermocouple junctions will also exist between the copper traces of the circuit board and the Kovar pins of the amplifier, creating voltage errors as large as 35 μV/°C. In a high-resolution data-acquisition system, these thermocouple errors, along with the amplifier offset errors and the noise in the system, will all add up to significant dc and low-frequency error.

AC excitation is a powerful approach to separating these errors from the signal. By using a square wave for ac-excitation, with the polarity of the excitation signal reversed between measurements, the induced dc errors can be effectively cancelled. This chopping scheme also has the effect of removing 1/f noise, which is dominant at low frequencies (dc to a few Hz) in these applications.
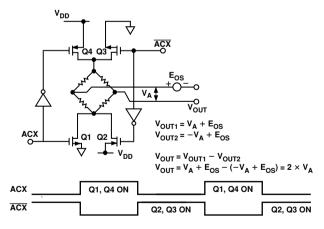

Figure 7. Typical bridge configuration employing ac excitation.

Figure 7 shows how a bridge can be configured for ac-excitation. The polarity of the excitation voltage to the bridge is reversed on alternate cycles, using transistors Q1 to Q4 to perform the switching. All the induced dc and low-frequency errors have been lumped together as E_{OS}. During phase 1, Q1 and Q4 are *on* while Q2 and Q3 are *off*; the output, V_{OUT}, is given by ($V_A + E_{OS}$). During phase 2, Q2 and Q3 are on while Q1 and Q4 are off, with the output, V_{OUT}, represented by ($-V_A + E_{OS}$). The actual output is the sum of the two phases, giving $V_{OUT} = 2 \times V_A$. The control signals for the ac-excitation must be non-overlapping clock signals. This

scheme removes the errors associated with dc excitation at the expense of a more complex design.

Figure 8 shows a bridge-transducer application using the AD7730 bridge-transducer ADC, which includes on-chip all the necessary circuitry to implement ac excitation and produce the computed output result following the switching of the excitation.

The AD7730 sigma-delta ADC is a complete analog front-end for weigh-scale and pressure-measurement applications. Operating from a single +5-V supply, it accepts low-level signals directly from a transducer and outputs a serial digital word. The input signal is applied to a proprietary programmable gain front end, based on an analog modulator. A low-pass programmable digital filter with adjustable filter cutoff, output rate, and settling time processes the modulator output. There are two buffered differential programmable-gain analog inputs, as well as a differential reference input. It accepts four unipolar and bipolar analog input ranges from 10 mV to 80 mV full-scale.

The peak-to-peak resolution achievable directly is 1-in-230,000 counts. An on-chip 6-bit DAC allows compensation for tare voltage in weigh-scale applications. The device's serial interface can be configured for 3-wire operation and is compatible with microcontrollers and digital signal-processors. The AD7730 contains self-calibration and system calibration options, and features an offset drift of less than 5 nV/°C and a gain drift of less than 2 ppm/°C. With this level of drift performance, calibration in the field is usually unnecessary.

In Figure 8, transistors Q1 to Q4 perform the switching of the excitation voltage. These transistors can be discrete matched bipolar or MOS transistors—or a dedicated bridge-driver chip such as the 4427 from Micrel can be used to perform the task.

Since the analog input voltage and the reference voltage are reversed on alternate cycles, the AD7730 must be synchronized with these reversals of the excitation voltage. For synchronous switching, it provides the logic control signals for switching the excitation voltage. These signals are the non-overlapping CMOS outputs, ACX and $\overline{ACX}$. One of the problems encountered with ac-excitation is the settling time of the analog input signals after switching, especially in applications where there are long leads from the bridge to the AD7730. The converter could produce erroneous data because it is processing signals that are not fully settled. Accordingly, the user is allowed to *program* a delay of up to 48.75 μs between the switching of the ACX signals and the processing of data at the analog inputs. The AD7730 also scales the ACX switching frequency in accordance with the output update rate. This avoids switching the bridge at an unnecessarily faster rate than the system requires.

The ability of the AD7730 to handle reference voltages which are the same as the excitation voltages is particularly useful in ac-excitation, where resistor divider arrangements on the reference input add to the settling time associated with the switching.

AC-excitation can be effectively used to eliminate the effects of self-heating in temperature-measurement applications using resistive sensors. When measuring temperature using an RTD, the excitation current itself (however small) produces I^2R, or Joule heating, producing an indicated temperature somewhat higher than the temperature being measured. The degree of self-heating greatly depends on the medium in which the RTD is immersed. An RTD will self-heat to a much higher temperature in still air than in moving water.

With commonly used dc excitation, the excitation current through the sensor must be large enough so that the smallest temperature change to be measured results in a voltage change that exceeds the system noise, offset, and drift of the system. The excitation currents required to overcome these errors are typically 1 mA or greater. The power dissipated in the RTD causes its temperature to rise, introducing drift errors in the measurement, which reduces system accuracy. For example, using a 1-mA dc excitation source with a 1-kΩ RTD having a self-heating effect of 0.05°C/mW results in a drift error of 0.5°C.
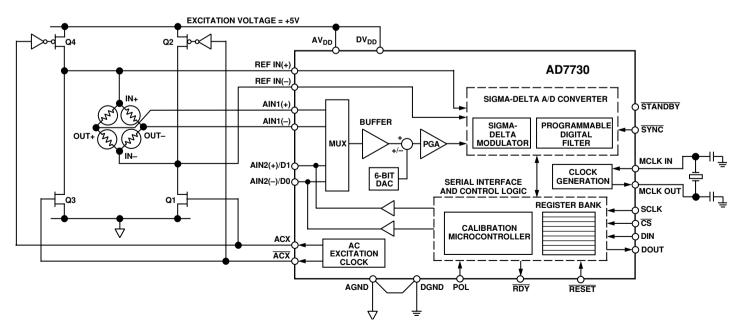

Figure 8. AC-excited bridge application using AD7730 sigma-delta converter.

Since an ac-excitation source will reduce offset and drift effects, much smaller excitation currents can be used in many applications. Thus, decreased excitation current not only reduces the self-heating effects in the RTD (by the square of the current reduction!); it also reduces the associated dc and low-frequency output errors as noted above.

Figure 9 shows the AD7730 high-resolution sigma-delta converter used for ac-excited RTD measurement. In this application, the AD7730 is operated with split supplies, i.e., AV_{DD} and DV_{DD} are at separate potentials, and AGND and DGND are at separate potentials. With this arrangement, it is necessary that AV_{DD} or DV_{DD} not exceed AGND by 5.5 V. Therefore, when operating with ±2.5-V analog supplies the DV_{DD} must be restricted to +3 V with respect to digital ground, which is the system ground.

The AD7730's ACX output, which controls the reversing of the current in this application, is established with respect to the AV_{DD} and AGND supplies. When ACX is high, a current of 100 μA flows through the RTD in one direction; when ACX is low the, 100-μA current flows in the opposite direction through the RTD. The switched-polarity current source is developed using op-amps U1 and U2 in a standard voltage-to-current conversion configuration. The AD7730, configured for its ac-excitation mode, produces a square wave at its ACX output. During the conversion process the ADC takes two conversion results—one on each phase of the ACX signal—and combines them within the ADC to produce one data output word representing the measured temperature.

For example, if the RTD output during phase one of the ACX signal is 10 mV, and a 1-mV circuit induced dc-error exists due to parasitic thermocouples, the ADC measures 11 mV. During the second phase the excitation current is reversed and the ADC measures –10 mV from the RTD, and again sees +1-mV dc-error, giving an ADC output of –9 mV during this phase. These measurements are processed within the ADC (11 mV-(–9 mV)/2 = 10 mV), thus removing the dc-induced errors within the system. AC-excitation allows currents in the vicinity of 100 μA to be effectively used in RTD applications, as shown in Figure 9, reducing self-heating effects substantially.

Because the converter's reference voltage is developed using the excitation current, the RTD's resistance is measured ratiometrically. Thus, the external resistance values in the voltage-to-current converter do not affect system accuracy, as the exact value of the drive current is not critical, about 1%. Therefore, 100-ppm/°C resistors will suffice. However, the resistance of R_{REF}, which uses the current to develop the ADC reference voltage, must be stable over temperature to avoid reference-induced errors in the measurement output. With the circuit shown, measured temperature ranges from –200°C to +200°C can be easily accommodated.

Since line-frequency pickup can produce offsets if chopping is at line frequency (50 or 60 Hz), chopper operation is suggested at an asynchronous 57 Hz (where a filter null occurs). Resolutions of 16-bit peak-to-peak are achievable when using the AD7730 in its unipolar 0–20-mV range with an update rate of 57 Hz. Another important benefit of using the AD7730 in RTD applications is its immunity to both radiated electric fields and fast transient bursts (EFT). When operating in a noisy environment it is recommended using the AD7730 in its chop mode. The chopper stabilization techniques used within the AD7730 eliminate offset and minimize offset drift. When the AD7730 is operated in CHOP mode the signal chain, including the first stage filter, is chopped. This reduces the overall drift performance to less the 5 nV/°C. The AD7730 can be operated in the presence of electric fields (1 V/m to 3 V/m) from 30 MHz to 1 GHz with flat offset across the frequency range. Without chopping, the offset performance degrades in the presence of an electric field and drifts with frequency.
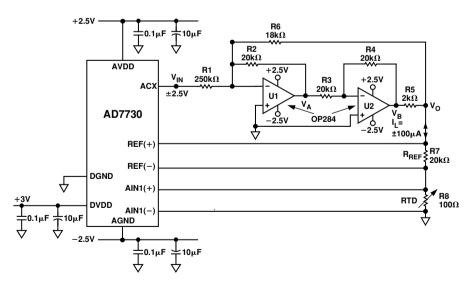

Figure 9. Eliminating self-heating effects in RTD temperature measurement applications using ac excitation and the AD7730 ADC.

SUMMARY

In designing high-resolution data acquisition systems care must be exercised in selecting the method of excitation, the excitation source for the transducer, and the field wiring scheme used in conveying the low-level analog signal from the transducer to the A/D converter.

Transducers can be excited with either ac or dc current or voltage. DC is more widely used than ac for excitation, because systems using dc excitation are easier to implement and troubleshoot; but they have a number of drawbacks. The excitation magnitude at the sensor must be enough so that the smallest change to be measured results in a voltage change that exceeds the noise, offset and drift of the system.

If large dc errors and low-frequency noise are expected, ac excitation is useful. The excitation source is switched on alternate cycles, and the resulting amplitudes are measured and averaged to provide a conversion result. AC excitation thus removes the effects of 1/f noise and dc induced parasitic thermocouple effects in a signal chain. This allows the excitation to be greatly reduced, in turn reducing the errors introduced from self-heating in resistance-based sensors. These benefits usually exceed the disadvantages of somewhat higher implementation cost and the care that must be taken to ensure adequate settling before a measurement is made.

Choices of sensor wiring configurations are available, involving from two to four wires, depending on the required accuracy. Four-wire configurations offer the best accuracy by eliminating the errors due to the lead wire resistance and thermal effects in the wiring. Systems can be configured with common excitation and references (ratiometric), or with independent references (non-ratiometric). Ratiometric is preferred because it permits measurement and control with accuracy greater than the stability of voltage references or excitation supplies. Measurements are insensitive to excitation variations.

Conclusion: Where possible, the best designs of high-resolution data-acquisition systems should use 4-wire configurations and exploit the benefits of ratiometric operation and ac excitation.