Overall Considerations 2 Interface-Design Examples

Chapter 6

In the preceding chapters, we have considered separately the various elements of the transducer interfacing problem. In the chapters that follow, in Section II, a variety of applications are described in differing levels of detail. The focus of the Applications section is on circuitry employing lower levels of system integration. It is principally intended for those readers who are interested in design and are not considering purchase of a packaged interface, replete with interface cards, data acquisition, digital processing capability, software, and system support.*

As a transition to the Applications section, this chapter treats some of the questions that must be considered to obtain a good trouble-free design; it also brings together in a pair of design examples some of the factors discussed in the earlier chapters.

INTERFACE DESIGN QUESTIONS

When an interface problem is considered, there are some basic questions that must be answered before a level is reached that is relevant to the readers of this book:

What kind of physical information is really needed in electrical form to accurately reflect the state of the environment?

What is the best way to obtain the needed information?

Once these questions have been resolved, and a set of measurements and the transducers to implement them have been chosen, then the technical and economic issues relating to the choice of interface circuit/system can be considered. Some of the seminal technical questions (they will lead to additional questions) are:

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*Such as MACSYM Measurement And Control (sub) SYsteMs.

What accuracy and stability are desired? Over what range of ambient (and measured) temperature?

What is the sensitivity of the transducer under consideration? As a matter of good design practice, it is desirable to have as high a sensitivity as the economics permit, and to give up as little as possible in attenuation. Obtaining high sensitivity may require sacrifices in linearity, dynamic range, and other characteristics, but it may be well worth it if resolution is to be preserved against noise and drift.

What are the energy (voltage or current) and impedance levels at the output of the transducer, and what are the implications for circuit wiring and performance? For example, low-level transducers, like thermocouples, require good low-noise, low-drift amplifiers to stably resolve small temperature changes; high-impedance devices, such as piezoelectric transducers, require attention to wiring capacitance and amplifier input characteristics (input impedance, leakage current, *mode*: charge or voltage).

What are the error sources in the transducer? Besides such obvious considerations as noise and linearity, what are the effects of temperature on a load cell or pressure transducer; what are the effects of physical forces on an RTD? Is electrical interference characterizable? What kinds of correction capability must the interface have?

Is the output signal single-ended or differential? Is there any choice? What is the common-mode level; what are the sources of common-mode error? Will an instrumentation amplifier or an isolator be necessary to remove ground noise and 60Hz artifacts?

What sources of noise and interference are likely to be encountered? How much? To what degree will judicious wiring and grounding practices help?

What is the fastest rate-of-change of transducer output signals? What are the tradeoffs affecting choice of filtering circuitry—amplitude and phase errors vs. noise and interference? Check for sufficient bandwidth—both for signal and for common-mode rejection—in the electronic circuitry.

For how long and over what range of temperature excursion must amplifiers and associated components function, and with what degree of repeatability and stability? This important consideration directly influences the certainty and credibility of the data at the output of the interface.

Is offsetting required? Linearizing? If they are, should they be implemented in the transducer, in the preamplifier or subsequent analog stages, or in digital form?

Does the transducer require some form of excitation? If so, what are the power, accuracy, and stability requirements of the excitation source? Must it have absolute stability, or is some form of ratiometric measurement more economically feasible.

Attention to these criteria, and to others which logically follow from them in any given situation, is the key to success in almost any interface job. The successful interface designer is typically an *optimistic skeptic*—confident of success and wary of the forces of nature. Even a seemingly mild requirement should call for careful thought to avoid surprises.

THERMOMETER EXAMPLE

In this application, there is a need to measure temperatures from 0°C to +100°C, to within 1.0°C, at low cost, at a remote location several hundred feet from the instrumentation. The ambient temperature in the vicinity of the instrumentation is expected to be 25°C ±15°. A number of possible transducers will operate over the specified range, but the requirement for a remote measurement suggests the use of the current-output two-wire AD590 semiconductor temperature sensor, because the current is unaffected by voltage drops and induced voltages.

Consulting the "Accuracies of the AD590" (see the Appendix), we find that the AD590J, with two external trims, would be suitable; its maximum error over the 0°C to 100°C range is 0.3°. This permits an allowance of 0.7° for all other errors. If a tighter tolerance were required, it would be worthwhile to consider using the AD590M with two trims, for an error *below 0.05°C.*

Since AD590 measures absolute temperature (its nominal output is 1μA/K), the output must be offset by 273.2μA in order to read out in degrees Celsius. The output of the AD590 flows through a 1kΩ resistance, developing a voltage of 1mV/K (Figure 6-1). The output of an AD580 2.5-volt reference is divided down by resistors to provide a 273.2mV offset, which is subtracted from the voltage across the 1kΩ resistor by an AD521 instrumentation amplifier. The AD521 provides a gain of 10.0, so that the output range, corresponding to 0° to 100°C, is 0 to 1.00V (10mV/°C).

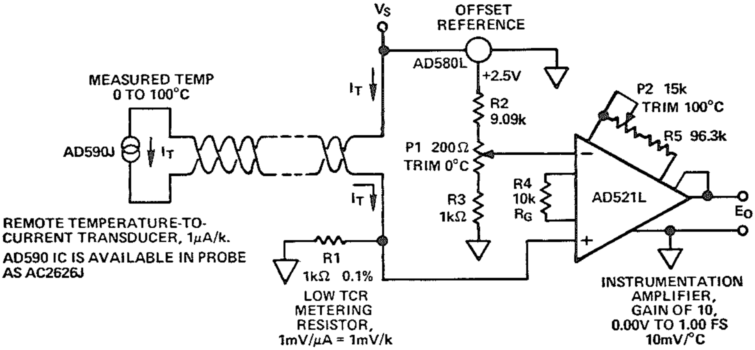

Figure 6-1. Thermometer circuit

The desired system accuracy is to within 1.0°C; as noted, all errors other than that of the AD590 must contribute the equivalent of less than 0.7°. It will be helpful to assemble an error budget for the circuit, assessing the contributions of each of the elements (Table 1). Errors will be expressed in degrees Celsius.

AD590 regulation. If the AD590 is excited by a voltage source of between 5 and 10V, the typical regulation is 0.2μA/V (0.2°C/V). With 1% source regulation, this contribution will be

0.01°C

AD590 linearity error. Total error for the AD590J, over the 0° to 100°C range, with two trims, is 0.3°C. Those trims will be the gain and offset trims for the whole circuit, accounting for resistor and ratio errors, AD521L gain, offset and bias-current errors, AD580L voltage error, and the AD590J's calibration error.

0.3°C

R1 temperature coefficient. Since R1 is responsible for the conversion of the AD590's current to voltage, high absolute accuracy is important. Consequently, we would expect to use a device having 10ppm/°C or less in this spot. For ±15°C, the maximum error is 373.2μA × 10^{-5}/°C × 15° = 0.06μA

0.06°C

AD580 temperature coefficient. The specified tempco for the AD580L is 25ppm/°C typical (61ppm/°C max over the range 0° to 70°C). Since operation is over a narrow range, the typical

TABLE 1. DEVICE SPECIFICATIONS PERTINENT TO THE ANALYSIS IN THE TEXT

(typical at 25°C and rated supply voltage unless noted otherwise)

Parameter	**Condition**	**Specification**
AD580L 2.5V VOLTAGE REFERENCE		
Output voltage	$V_S = +15V$	2.450V min, 2.550V max
Input voltage, operating		30V max, 7V min
Line regulation	$7V \leqslant V_{IN} \leqslant 30V$	2mV max
Temperature sensitivity	0 to 70°C	4.3mV max, 25ppm/°C, typ
Noise	0.1 to 10Hz	60μV, p-p
Stability (drift with time)	long term	250μV (0.01%)
	per month	25μV (10ppm)
AD590J 1μV/K TEMPERATURE TRANSDUCER		
Output current	Nominal at 25°C (298.2k)	298.2μA
Input voltage, operating		30V max, 4V min
Calibration error	25°C, $V_S = 5V$	±5°C max
Linearity error	Two trims, 0 to 100°C range	0.3°C max
Repeatability	per month	0.1°C max
Long-term drift		0.1°C max
Noise spectral density		$40pA/\sqrt{Hz}$
Power-supply rejection	$+5V \leqslant V_S \leqslant +15V$	0.2μA/V
Operating range		-55°C to +150°C
AD521L DIFFERENTIAL INSTRUMENTATION AMPLIFIER		
Gain equation (volts/volt)	Nominal	$G = R_S/R_G$
Error from equation	Untrimmed	(±0.25 - 0.004G)%
Nonlinearity	±9V output	0.1% max
Gain tempco	0 to 70°C	±(3 ± 0.05G)ppm/°C
Voltage offset	Input	1.0mV max
	Output	100mV max
Voltage offset tempco	Input, 0 to 70°C	2μV/°C max
	Output, 0 to 70°C	75μV/°C max
Voltage offset vs. supply	Input	3μV/%
	Output, untrimmed*	0.5mV/%
Bias current	25°C	40nA max
Bias current tempco	0 to 70°C	500pA/°C
Input impedance	Common-mode	$6 \times 10^{10}\Omega \| 3.0pF$
Common-mode rejection	G = 10, dc to 60Hz, 1kΩ source unbalance	94dB min
Voltage noise	G = 10, 0.1Hz to 10Hz, p-p, RTO	225μV

*Can be reduced by trimming the output offset.

value is most useful, unless the AD580 has a critical effect on the overall error. 25 X 10^{-6}/°C X 273mV X 15° = 0.1mV.
0.10°C

Resistive divider tempco. The absolute values of R2 and R3 are of considerably less importance than their ability to track. 10ppm/°C is a reasonable value for tracking tempco. 10^{-5}/°C X 273mV X 15° = 0.04mV
0.04°C

Common-mode error. At a gain of 10, the minimum common-mode error of the AD521L amplifier is 94dB, one part in 50,000 of the common-mode voltage (273mV), or 5μV (negligible)	0.0°C
AD521 temperature coefficient. The specified input offset tempco for the AD521L is 2μV/°C max, and the output offset tempco is 75μV/°C max (7.5μV/°C, referred to the input), for a total of 9.5μV/°C R.T.I. 9.5μV/°C × 15° = 143μV.	0.14°C
AD521 bias-current tempco. The maximum bias-current change is 500pA/°C × 30° (range) = 15nA. The equivalent offset-voltage change is 15nA × 1kΩ = 15μV.	0.02°C
AD521 gain tempco. The circuit will be calibrated for correct output at 100°C by trimming of the gain of the AD521 at a 25°C ambient temperature. Variation of gain will cause output errors. The specified gain tempco at a gain of 10 for the AD521L is 3.5ppm/°C typical. If max is arbitrarily assumed to be ten times worse, and the resistors contribute 15ppm/°C additional, the maximum error will be 50 × 10^{-6}/°C × 100° × 15° = 0.075°	0.075°C
AD521 nonlinearity. The 0.1% nonlinearity specification applies for a ±9V output swing; for a 1V full-scale swing, it may be reasonable to expect a tenfold improvement, or a 1mV linearity error, equivalent to 0.1°C	0.1°C
Total error (worst case)	0.84°C

This means that, once the circuit has been calibrated at 0°C and 100°C (25°C ambient), the maximum error at any combination of measured and ambient temperatures can reasonably be expected to be less than 1°C.

If the summation were root-sum-of-squares, instead of worst-case, the error would come to less than 0.4°. This suggests that the design is quite conservative, since the probability of worst-case error is low; also (with some risk), it suggests that if an AD590M were used in the same design, temperature could be measured to within 0.25°C over the range. Naturally, every precaution should be taken to avoid additional errors attributable to either Murphy's or Natural Law. Aside from errors attributable to ambient temperature variations, this simple interface will require some form of protection from extraneous signals. Shielding and grounding should follow the practice suggested earlier in this book. In addition, capacitance across R1 will help reduce the effects of any ac currents induced in the twisted pair. Power supplies must be chosen to minimize error due to sensitivity of any of the elements to power-supply voltage changes, and bypassed to minimize coupling of interference through the power-supply leads.

Although this is one of the simplest forms of interface, it is impressive to consider the preparation required to ensure performance to within the desired specs. As the level of accuracy increases, additional parameters and issues could be mentioned, but the point that is made would begin to suffer from overkill. As the statement of a measurement problem becomes more complex and demanding, the increased scope demands more experience and subtlety of thought on the part of the designer.

EXAMPLE: HIGH-RESOLUTION SCALE

A high-sensitivity nutritional experiment at the Massachusetts Institute of Technology required an instrument that would repeatably resolve 0.01 pound, out of 300 pounds full-scale, about 33 parts per million.* In addition, the instrument was required to be hand-carryable, be free from adjustments ("forever"), and have an absolute accuracy to within 0.05lb.

Such instruments are based on the availability of pre-trimmed fully calibrated load-cell platforms having low temperature drift, excellent linearity, and compensation for off-center loading. In this case, a BLH Electronics PL-250 platform was chosen (Figure 6-2). Because the PL-250 has an output of 1.5 millivolts per volt of excitation at 250 pounds, the output produced by a 300-lb load, with 10 volts of excitation, is 18 millivolts (full scale!)

The resolution corresponding to 18mV full-scale is 1/30,000 of 18 millivolts, or 600 *nanovolts*! While the specified clinical temperature range of ±5° is usually benign in terms of error production, it is definitely a factor in this application, since the bridge readout

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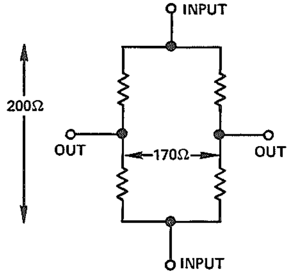
*One small doughnut bite for a 300-lb subject, or a shot-glass of whiskey in a full-size 1977 Cadillac.



a. Simplified schemetic

	GUARANTEED	AS MEASURED OR USED
ABSOLUTE MAXIMUM EXCITATION	15V	10V
CALIBRATION ACCURACY	0.25%	0.11%
NON-LINEARITY	0.05%	0.015%
REPEATIBILITY	0.02%	0.01%
TEMPERATURE COEFFICIENT	25ppm/°C	1.1ppm/°C
RANGE	0–300 Lbs.	20–30°C

b. Pertinent specs

Figure 6-2. Data on the BLH–PL250 platform used in this application

system must have less than 120nV/°C drift, and in fact, all drifts (including drift with time) must amount to less than 600nV.

In order to perform the differential measurement, the first kind of amplifier considered is the differential instrumentation amplifier. However, none is known to be available commercially with adequate drift performance. An additional problem is the need for high common-mode rejection: in order for common-mode error to be negligible, the CMR must be upwards toward 140dB, if a one-sided 10V excitation supply is used. A split supply (±5V) will ease this aspect of the problem, but the problem of drift remains.

The most economical solution calls for a chopper amplifier, because chopper amplifiers can be obtained with drifts less than 100nV/°C. Although single-ended chopper amplifiers, such as Model 261K, cannot normally take a differential measurement, the output of a bridge can be amplified as a single-ended signal if the *excitation supply* can float. This also eliminates the common-mode problem, since a truly floating source has no common-mode potential. So this approach yields the desired low drift and solves the common-mode problem (Figure 6-3).

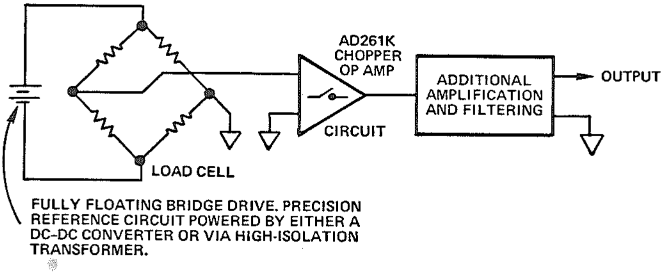


Figure 6-3. Block diagram of high-precision scale

However, there are still some difficulties. Besides the possibility that a floating supply may invite line-frequency pickup, there is the important consideration that the floating supply must furnish a regulated voltage *at least as stable as the 33ppm instrument specification*. This degree of stability is necessary because, with the bridge floating, a ratiometric measurement is no longer practical. If the bridge were a null type (forced to null by a servo loop), the precision of the excitation source would not cause difficulty; however, with the bridge operating off null, the output voltage depends directly on the excitation voltage.

The first difficulty, line-frequency pickup, can be of minor importance, because the impedance of the excitation source to ground is only about 100Ω. This means that, with good shielding, the combination of low coupling capacitance and low shunt resistance to ground will result in negligible pickup. Also, the isolation characteristics of the floating source at dc need not be outstanding (30,000 X 100Ω = 3MΩ).

The only important difficulty with this approach, then, is the requirement for a separate high-stability voltage drive for the bridge. While not trivial, a stable, floating bridge drive can be implemented with a power amplifier, driven by a high-stability reference, such as the AD581L or AD2700, powered by an isolated dc-to-dc converter, such as those in the 940 series (or via a high-isolation line transformer). The block diagram of Figure 6-3 illustrates this concept. Design details appear in the Applications section (Figure 12-5).

CONCLUSION

In this chapter, we have discussed the basic ingredients of successful application; and we have considered two examples that illustrate approaches to transducer interfacing applications. The first example shows an approach to error analysis of a simple and straightforward interfacing problem. The second example considers approaches to solving the key problems of a difficult interfacing assignment.

This chapter concludes what might be called the tutorial section of this book. The following chapters discuss some fifty real-world interfacing configurations. They begin immediately.

Applications

APPLICATIONS

The applications described in the following pages vary in degree of detail, from circuits that demonstrate techniques to detailed descriptions of measurement and control circuitry employing transducers. Many of the circuits are simple and straightforward and require little comment; others merit detailed discussion and explanation. Most (if not all) have been used in real-world applications.

The organization of Part Two is roughly parallel to that of the descriptions of transducers in Chapter 1; transducer applications are arrayed by phenomenon, by measurement technique, and by level of detail and manner of readout.

In general, to avoid excessive redundancy, we have not repeated circuits in one medium where they apply to commonly employed transducers in other media; for example, the discussion of thermal measurements to measure other quantities is limited in scope, as is the use of force and pressure to measure level and flow.

The final chapter of this section is a collection of miscellaneous circuits, most of them pertaining to analog signal processing. Though they could have been incorporated in specific applications, they are of sufficiently general applicability to warrant separate treatment.

Whether you are looking for a specific circuit or browsing for ideas, you should find the circuits in this section interesting.