Offsetting and Linearizing

Chapter 5

In the earlier chapters, we have discussed the basics of electrical-output transducers, signal-conditioning for bridges, interference problems, and the characteristics of amplifiers used in signal conditioning. This chapter deals with two processes that are often found useful in making sensitive and accurate measurements: *offsetting* and *linearizing*.

OFFSETTING

As used here, *offsetting* embraces the use of analog techniques to shift the level of a signal by a predictable amount. Typical applications include:

- Measurement of small changes about a large initial value
- Incremental measurements, employing a device that has an absolute scale (gauge vs. absolute pressure, °C vs. K)
- Reducing a common-mode level
- Restoring or introducing an offset (for example, in converting from a 0 to +10V range to a 4 to 20mA range for transmitting analog signals).

For some applications, an accurately developed constant is unnecessary. For example, an isolation amplifier can be used to measure small differential signals riding on large common-mode voltages. The isolator simply ignores the common-mode voltage. Or if the useful portion of the transducer output is an ac signal, capacitive or transformer coupling may be used to eliminate the dc level.

Figure 5-1 provides an illustration of offsetting with a *bridge* configuration. The transducer, in this case, is a linear voltage divider. The variable we are interested in is the fractional deviation from half-scale, $k\frac{E_b}{2}$.

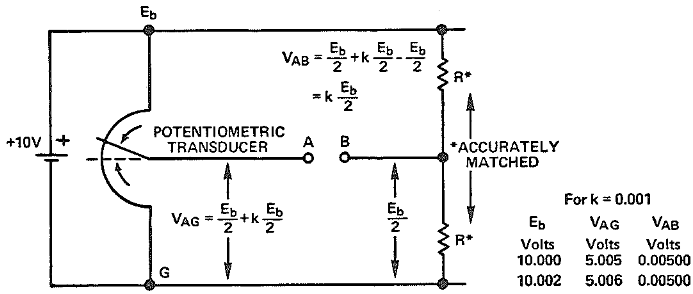


Figure 5-1. Use of bridge in offsetting. Note that, while the fractional part of V_{AG} changes by 20%, V_{AB} is essentially unchanged.

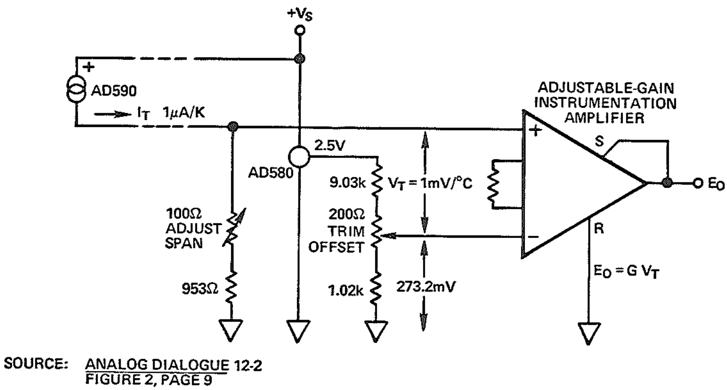
If E_b is 10V, then $E_b/2$ is 5V, and a 0.1% deviation, k, is represented by a 5-millivolt change. An accurate digital voltmeter at AG, between the wiper of the potentiometer and the low end of E_b, would read +5.005V, and the positive deviation, +0.005V, could be read by ignoring the initial digit. Unfortunately, the output is highly sensitive to error; a 0.02% error in either the power-supply voltage or the meter reading would cause a *20% error* in the measured value of $k\frac{E_b}{2}$.

If, on the other hand, a bridge were formed, using an accurately matched resistance pair to produce an offsetting voltage, V_{BG}, and the meter were to read the *difference*, $V_{AB} = 0.005V$, the effect of small changes of power-supply voltage would be cancelled, because both voltages would be changed by about the same amount (to within *microvolts*, in the example). Meter accuracy could be improved by the use of a low-full-scale voltage range (e.g., 0.1999 volts on a 3 1/2-digit meter) and/or preamplification of the difference voltage (which is much easier to handle than the sum of a large and a small voltage).

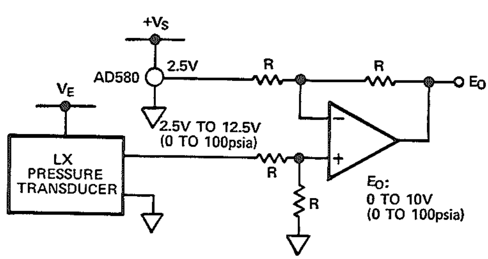
Users of resistive transducers that do not inherently involve bridges find this bridge-building technique quite useful. Examples of such transducers include thermistors, RTD's, and strain gages.

Another–less-critical–form of offsetting is used in reducing measurements from absolute to gage, from kelvin to degrees

Celsius, or in translating the outputs of high-level transducers that have offset ranges. The technique is simple input summation in operational or instrumentation amplifiers, or using the *reference* input of an instrumentation amplifier. Figure 5-2a shows how the 1μA/K absolute-reading AD590 output may be scaled to 1mV/K by resistance and offset by a fixed 273.2mV to provide a voltage output representing °C. Figure 5-2b shows how the output of a high-level semiconductor pressure transducer, with an output range of 2.5 to 12.5V, representing a 0 to 100psi a range of pressure, might be offset to provide zero volts out for zero psi.



a. Offsetting the AD590 1μA/K temperature transducer for Celsius measurements



b. Offsetting semiconductor pressure-transducer output

Figure 5-2. Range offsetting

Cold-junction compensation is a special form of offsetting used with thermocouples in applications where it is inconvenient to provide an ice bath for the reference ("cold") junction (the vast majority of applications fall within this category). The offsetting circuit measures the ambient temperature at the cold junction and adds a voltage approximately equal to the voltage expected to be developed by the cold junction but of opposite polarity. The net output of the circuit is equal to the Seebeck voltage of the measuring junction.

The circuit of Figure 5-3 provides cold-junction compensation (CJC) for a type J thermocouple (iron-constantan). The reference junction is established in intimate thermal contact with an AD590 temperature-to-current integrated circuit (current in microamperes is equal to absolute temperature, kelvin). The resistance network adds a constant term and a term proportional to temperature; when adjusted to read the correct value of voltage output at a nominal reference temperature (say 25°C), the circuit provides accuracy to within about 0.5°C for ambient temperatures between 15° and 35°C.

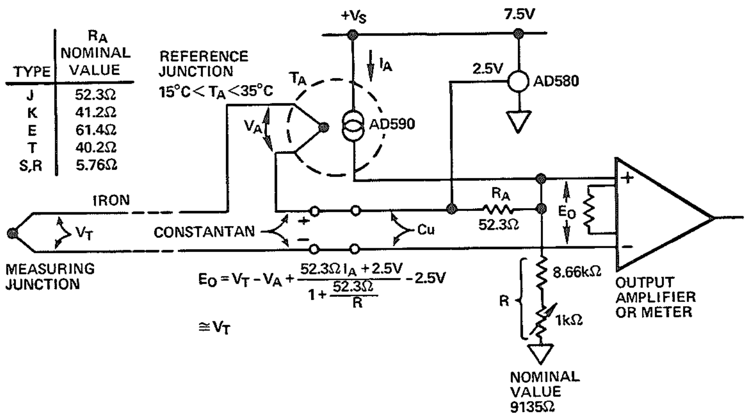


Figure 5-3. Cold-junction compensation circuit for type J thermocouple, employing AD590 to sense cold-junction ambient temperature and provide compensation over the ambient range 15°C to 35°C. Voltage across R_A compensates for V_A, and the 2.5V reference offsets the voltage across R, due to AD590's 273.2μA (absolute temperature) measured at 0°C.

The principal contributions to error come from the temperature coefficients of the voltage reference and resistances. While this example is for J thermocouples, the circuit will serve for other thermocouple types, if different resistance values are calculated and substituted for R_A.

Nominal values of R_A for some common thermocouple types are tabulated in Figure 5-3.

As noted in an earlier chapter, cold-junction compensation is not necessary if the ambient temperature variation is small compared to the temperatures being measured. Cold-junction compensation is provided in a variety of system-solution products.*

4-TO-20mA CURRENT TRANSMISSION

In many process-control applications, information is transmitted in the form of current, with a span of 16mA full scale, and an offset range of 4 to 20mA. The transmission of current provides a degree of noise immunity, since the received information is unaffected by voltage drops in the line, stray thermocouples, contact voltage or resistance, and induced voltage noise. At the same time, the offset provides a distinction between *zero* (represented by 4mA) and *no information*, due to an open circuit (zero current flow).

An additional benefit of this form of transmission is that, for some applications, power can be furnished remotely, via the 4mA of current that is not needed for information transfer. Thus, power is transmitted in one direction—signal in the return direction. No local source of power is needed at such a transducer, and only two wires are needed for transmission.

Finally, information in the form of current permits several loads at differing locations to be connected in series—up to a specified maximum voltage. For example, the output of a transducer could drive a chart recorder and a meter, and provide an input to a controller. Figure 5-4a shows a typical 4-to-20mA process-control loop using a modular voltage-to-loop-current converter. Figure 5-4b shows an isolated voltage-to-4-to-20mA converter; excitation for the output current is furnished (in this instance) by an external loop supply (but is also available within the unit).†

*Examples of products available from Analog Devices include the 2B50 and 2B51 thermocouple signal conditioners (2B50 has ±1500V dc isolation); the 2B56 cold-junction compensator, as a companion to the 2B54 low-level four-channel isolated multiplexer; the AD2036 6-channel scanning digital thermometer; and the thermocouple input cards provided with MACSYM intelligent Measurement And Control SYsteMs. An IC thermocouple preamplifier with cold-junction compensation will become available during 1980.

†The 2B20 meets the requirements for Type 3, Classes L and U (non-isolated), and the 2B22 meets the requirements for Type 4, Class U (isolated), of ISA Standard S50.1, "Compatibility of Analog Signals for Electronic Industrial Process Instruments."

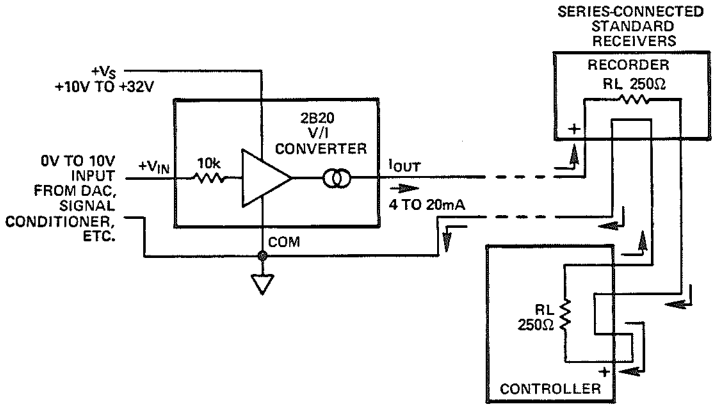


Figure 5-4a. Typical 4-to-20mA process-control loop using the 2B20 as a transmitter.

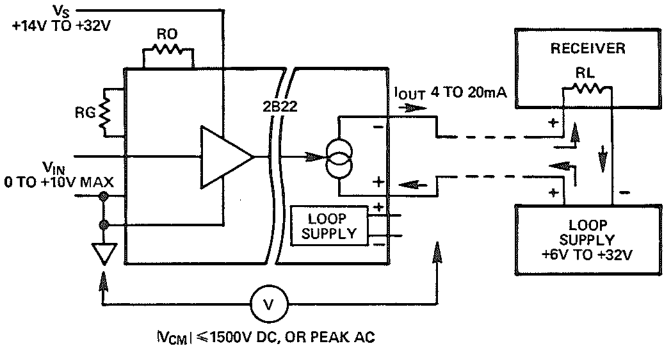


Figure 5-4b. Typical isolated 4-to-20mA process-control loop using the 2B22 as a modulator.

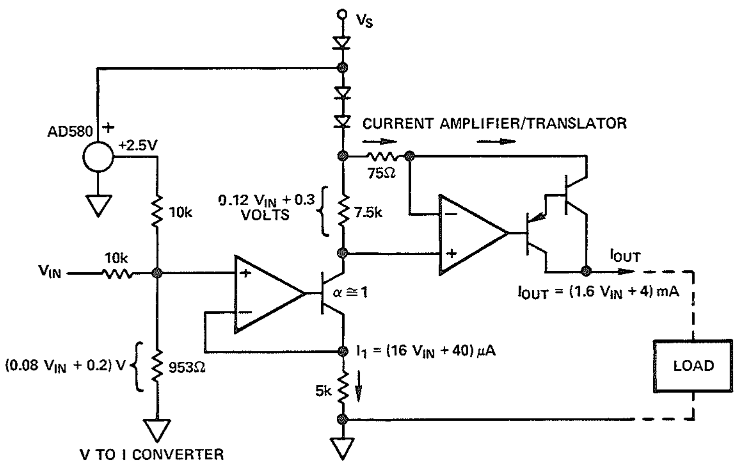


Figure 5-5. Basic 0 to 10V to 4 to 20mA translation circuit

The devices shown in Figure 5-4 represent low-cost system solutions, embodying specified guaranteed performance. However, there are a number of ways for a determined designer, familiar with op-amp circuitry, to build a successful voltage-to-current converter, using published op-amp circuits. Attention must be paid to the requirements for accuracy, grounding, input voltage range, output current and compliance voltage, power-supply requirements, reference, and dc stability. The rudiments of such a circuit are shown in Figure 5-5.

NONLINEARITY AND LINEARIZING – BASIC IDEAS

A linear system or element is one for which cause and effect are proportional; if there are several inputs, the output is proportional to their (weighted) sum*. Nonlinearity is a measure of the departure from proportionality. Figure 5-6 shows an input-output plot of an ideal linear relationship, a nonlinear relationship, and the difference between the two (*nonlinearity*).

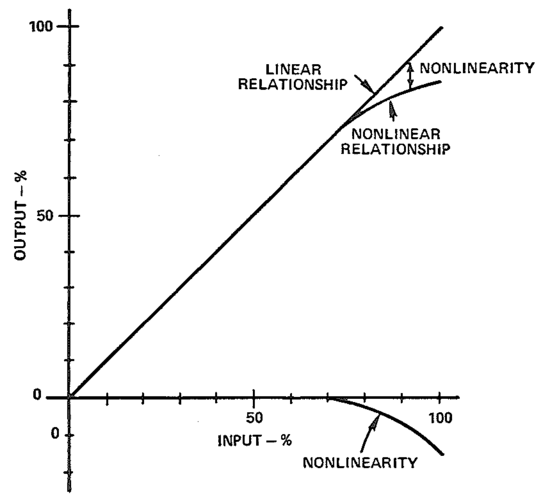


Figure 5-6. Typical nonlinear relationship

All devices are characterized by nonlinearity. For some, it is a desired characteristic (for example, the logarithmic characteristic of a log-antilog amplifier); for some others, it is a performance limit that is predictable by the nature of the device characteristics (thermocouple, off-null bridge). for the rest, it is a performance

*Graffito in an MIT facility: "Happiness is when it's linear."

limit that differs from device to device and must simply be accepted as a worst-case specification (usually in some such terms as the *maximum deviation from a "best straight line" over a given range of input*).

In this section, we are concerned with the second class, *undesired but predictable nonlinearities.* We shall discuss several means of dealing with them to obtain useful data.

Digital Linearizing

If the data are to be digitized and processed digitally, as soon as possible, it probably makes sense to perform any needed linearization in the digital domain. The principal techniques involve read-only-memory (ROM) and computational algorithms.

ROM has the fastest access and is used where processing capability and time are limited, and where the nonlinearity is well-defined and fixed. A ROM may be hard-wired to the converter output, and gated by the end-of-conversion flag, so that the signal presented for further processing has already been linearized. Each output level from the converter corresponds to an address in ROM, and the word stored at that address is either the correctly linearized value of the variable or an additive correction term.

If the nonlinear input source is to be looked at infrequently and memory is limited, but rapid mathematics is available, a mathematical function that approximates the inverse of the nonlinear relationship—or the difference between the ideal signal and the actual signal—can be derived and stored in program memory. Then, whenever the input from the nonlinear source is needed, the processor computes the correct value, based on its mathematical relationship to the measured input variable.

Analog Linearizing

For many applications, it is best to linearize the output of the transducer at some point in the analog process. This is obviously true for the case where no digital processing is used, but it is also true where limited processing capability and/or memory are available, and where the analog processing can be done simply and at low cost.

To linearize the signal from a transducer, one can—in some cases—modify the transducer circuitry; more often, some form of analog processing of the transducer output signal is used. An example of modifying the transducer circuitry can be seen in Figure 2-4, where an amplifier provides a feedback signal that balances the bridge to obtain an output that is proportional to the resistance change of the active element. In another example, the active leg of a bridge may be driven by a current derived from the voltage applied to the reference leg. And yet another example of modifying the transducer circuitry is the use of networks involving thermistors and resistors to obtain an electrical output that is linear over limited ranges. Manufacturers use a technique involving resistors and combinations of differing thermistor elements to provide linearized devices having linearities to within 0.2°C over ranges such as 0° to 100°C.

If resistance is connected in series or in parallel with a simple thermistor, the output of the circuit can be linearized in a rudimentary way over limited ranges of temperature. Figures 5-7 and 5-8 illustrate the technique.

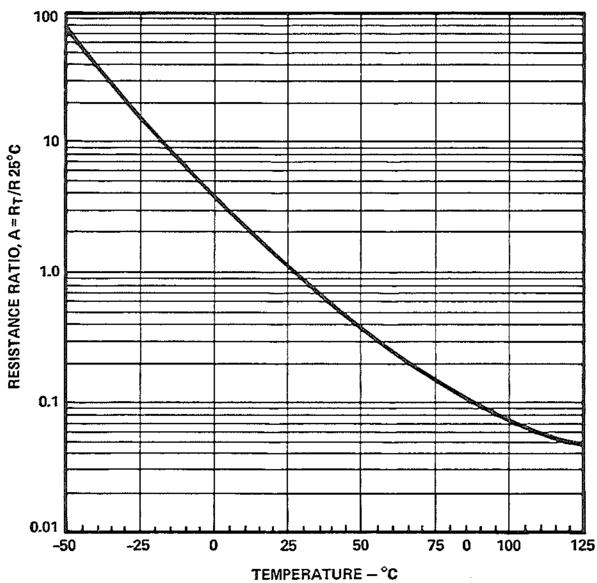


Figure 5-7. Typical thermistor characteristic. Note its essentially logarithmic character.

Figure 5-7 is the logarithmic plot of resistance ratio* vs. temperature for one type of thermistor. Although quite sensitive to tem-

*Like resistors, thermistors are available in a range of specified values of resistance (at 25°C), having similar normalized characteristics.

perature (resistance increases by 350% as temperature decreases from 25°C to 0°C), it is also highly nonlinear (approximately logarithmic). Yet it can be used in a simple circuit that has a sensitivity of about 1%/°C of the applied voltage over a range of about 50°C, with linearity to well within 5% of the range. Figure 5-8 shows the circuit and a plot of normalized output voltage vs. temperature.

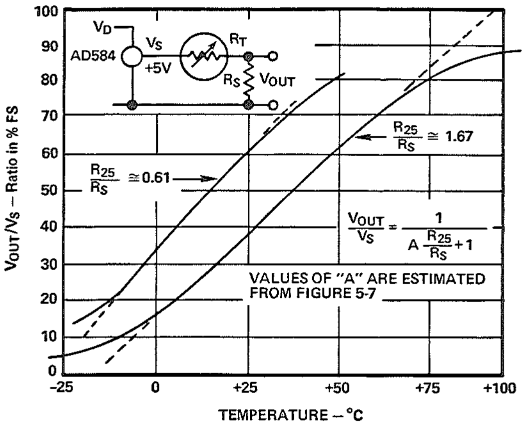


Figure 5-8. Calculated examples of linearized thermistor output, for device with the response of Figure 5-7, over limited ranges.

The approach used here starts with the relationship:

$$\frac{V_{OUT}}{R_S} = \frac{V_S - V_{OUT}}{A \cdot R_{25}}, \tag{5.1}$$

whence

$$\frac{V_{OUT}}{V_S} = \frac{1}{A\,\frac{R_{25}}{R_S} + 1} \tag{5.2}$$

where

V_{OUT} is the output voltage of the resistive divider into a high-impedance load

V_S is the constant input voltage

A is the ratio of thermistor resistance at any temperature (R_T) to its resistance at 25°C (R_{25})

R_{25} is the specified resistance of the thermistor at 25°C, when operated at a sufficiently low power to avoid significant dissipation.

R_S is the value of series compensating resistance.

With the reasonable assumption that, over a limited range of temperature (T the absolute temperature, kelvin),

$$A \cong \alpha \epsilon^{\beta/T} \qquad (5.3)$$

and with values of A picked off the curve at two temperatures, (0° and 50°C), the values of α and β for that region were calculated to be about 1.44×10^{-6} and 4016K.

If (5.3) is plugged into (5.2) and differentiated with respect to temperature*, and if different values of the ratio, R_{25}/R_S, are tried at various temperatures in the range, 0°C to 25°C, calculations show that at a ratio of about 0.61, the derivative will exhibit little change, implying that the function is nearly linear.

Two curves are plotted in Figure 5-8. One is based on the value of $R_S = 0.61\ R_{25}$, calculated for the 0° to 25°C range; the other is based on $R_S = 1.67\ R_{25}$, calculated for the 0° to 70°C range. If V_S is 5V and R_{25} is 10kΩ, the respective nominal values of R_S would be 16.4kΩ and 6.0kΩ. The useful ranges would be -10° to +30°C and -5° to +70°C, with respective temperature sensitivities of 55mV/°C and 45mV/°C.

A final example of modifying the transducer circuitry is the pair of circuits in Figure 5-9, where the output of a bridge preamplifier modulates the bridge's excitation. The simplified circuit of Figure 5-9a is shown in a practical embodiment, using the 2B31 bridge-signal conditioner, in Figure 5-9b. The adjustment permits a degree of over- or under-correction to partially compensate for the nonlinearity of the device (e.g., an RTD) as well as that of the bridge.

In Figure 5-9a, the output of the amplifier, E_O, is related to the fractional resistance deviation, X, and the excitation voltage, V_{IN}, by an expression of the form,

$$E_O = K\ V_{IN}\ f(X) \qquad (5.5)$$

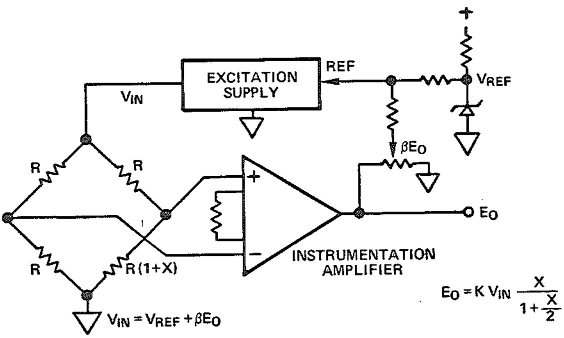
$$* \quad \frac{d\left[\frac{V_{OUT}}{V_S}\right]}{dT} = \frac{-1.443 \times 10^{-6}\ \frac{R_{25}}{R_S}\ \frac{4016}{T}\ \epsilon^{4016/T}}{\left[1.443 \times 10^{-6}\ \frac{R_{25}}{R_S}\ \epsilon^{4016/T} + 1\right]^2} \qquad (5.4)$$

We feed back a fraction of E_O, βE_O, to make V_{IN} a function of E_O,

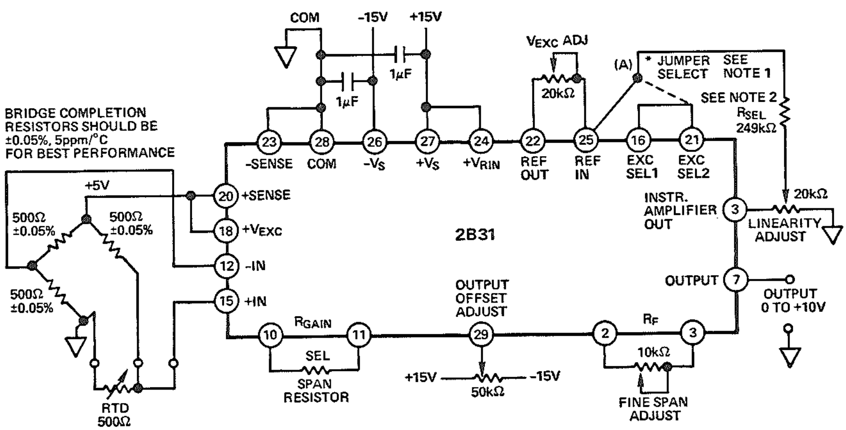
$$V_{IN} = V_{REF} + \beta E_O \tag{5.6}$$

Plugging 5.6 into 5.5, we find that

$$E_O = \frac{K V_{REF} f(X)}{1 - K \beta f(X)} \tag{5.7}$$



a. A small fraction, β, of the amplified bridge output is fed back to modulate the excitation voltage. β is adjusted to linearize the bridge output as a function of the deviation, X.



NOTES
1. SELECT JUMPER TO PIN 25 OR PIN 21 DEPENDING ON NONLINEARITY DIRECTION. JUMPER POINT "A" TO PIN 25 FOR ⌒ TRANSDUCER NONLINEARITY OR POINT "A" TO PIN 21 FOR ⌣ NONLINEARITY.
2. RESISTOR R_{SEL} DETERMINES MAGNITUDE OF CORRECTION.
3. THE SAME CIRCUIT MAY BE USED FOR STRAIN GAGE-TYPE TRANSDUCERS.

b. Practical linearizing circuit, employing the 2B31 signal conditioner

Figure 5-9. Transducer nonlinearity correction using feedback to affect bridge excitation.

If the bridge response is of the form, $f(X) = X/(1+X/2)$,

$$E_O = \frac{K V_{REF} X}{(1+\frac{X}{2})(1-K\beta \frac{X}{1+X/2})}$$

$$= K V_{REF} X \frac{1}{1+X(1/2-K\beta)} \tag{5.8}$$

In order to cancel the nonlinearity, by making the denominator = 1.

$$K\beta = 1/2 \tag{5.9}$$

In Figure 5-9b, this principle is applied to a bridge circuit, in which a 2B31 signal conditioner provides excitation and amplification for an RTD measurement. The sense of the feedback is determined by whether the nonlinearity is concave upward or concave downward (jumper A to pin 21, or to pin 25). The magnitude of the correction is determined by the resistor, R_{SEL}, and the *linearity adjust* pot provides a fine trim.

If an RTD is to be used, the adjustment can be made efficiently, without actually changing the temperature, by simulating the RTD with a precision resistance decade. The offset is adjusted at the low end of the resistance range, the fine span is adjusted at about one third of the range, and the linearity is adjusted at a resistance corresponding to full-scale temperature. One or two iterations of the adjustments will probably be found necessary because of the interaction of linearity error and scale-factor error. This circuit's applications are not restricted to RTD's; it will work in most cases where bridges are used—e.g., load cells and pressure transducers.

Analog processing of the transducer's output signal is used (where necessary) to compensate for nonlinearity in the transducer, the associated circuitry (such as bridges), or both. Depending on the nature of the nonlinearity, circuits used for linearizing may include:

Devices having inherently complementary nonlinearity (for example, circuits having logarithmic response to compensate for exponential functions of the measurand—Figure 5-10)

Simple analog computing circuits that provide functions complementary to the known functional relationships of the transducer circuitry (for example, circuits involving analog multi-

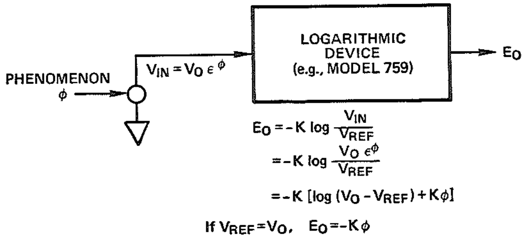


Figure 5-10. Logarithmic device performs exponential and log operations. If V_{IN} is a log function of the phenomenon, the log device is connected for exponential operation. As shown here, for an exponential voltage (or current) input, the device—connected for log operation—will provide a linear output.

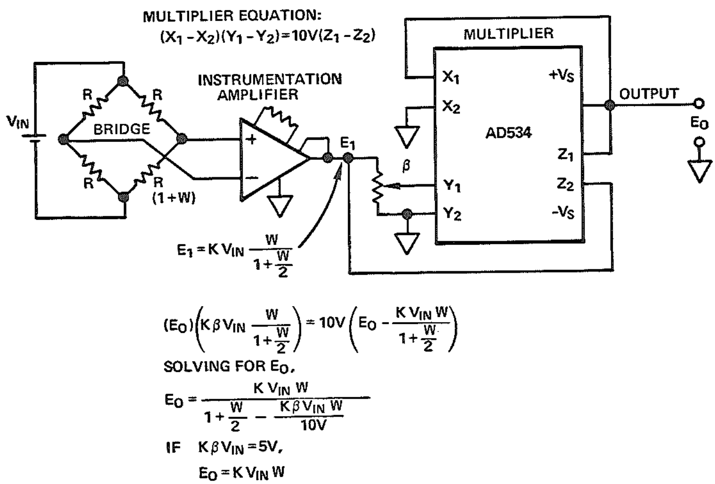


Figure 5-11. Nonlinearity correction for large-deviation off-null bridge using a single AD534 analog multiplier. Adjust β to trim overall linearity.

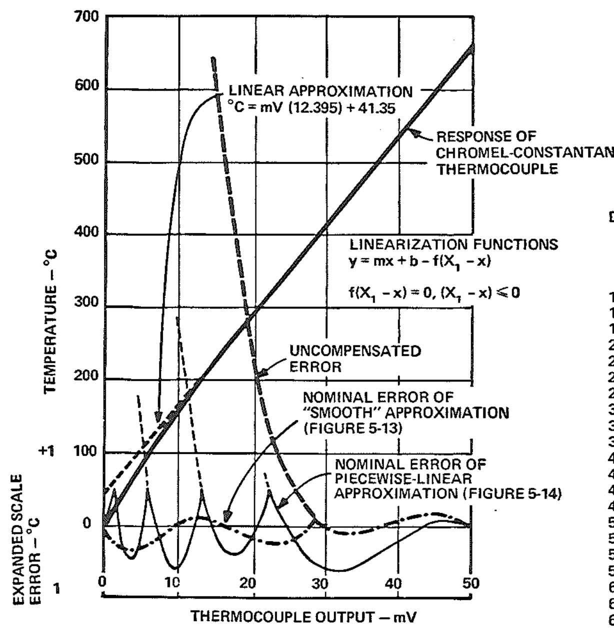
pliers* to compensate for off-null bridge nonlinearity—Figure 5-11)

Analog circuitry using analytic or piecewise-linear approximations to compensate for nonlinearities having an arbitrary form (for example, thermocouples and RTD's); both approaches are described comprehensively in the *Nonlinear Circuits Handbook.*[1]

*An analog multiplier, as shown, provides an output voltage that is equal to the true product of two input voltages, multiplied by a scale constant. A good introduction to analog multipliers may be obtained via a copy of the Analog Devices *Multiplier Application Guide* (1978), available upon request.

[1] Sheingold, D.H., Ed., *Nonlinear Circuits Handbook—Designing with analog function modules and IC's,* Analog Devices, Inc., 1974, pages 43-57 and 92-97

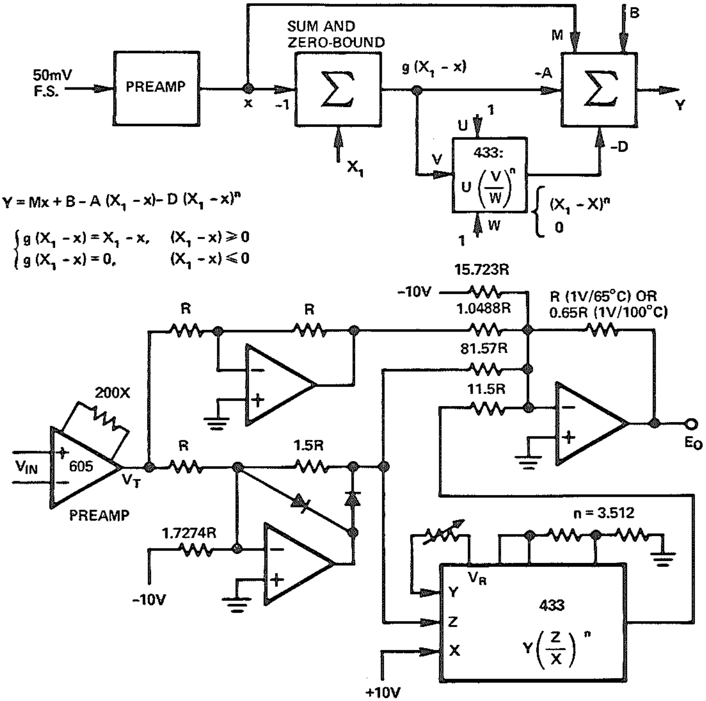
An example is worked through involving the linearization of a chromel-constantan thermocouple, for the range of temperature 0° to 650°C, to within ±1°C, with both smooth and piecewise-linear approximations. Though the argument is beyond the scope of this book, Figure 5-12 shows the nonlinear thermocouple response and the theoretical errors, Figure 5-13 shows the analytic approximation, using a Model 433 multifunction component to generate a $Y(Z/X)^{3.512}$ approximation; and Figure 5-14 shows a piecewise-linear (segmented) approximation using op amps as *ideal diodes*. Both circuits have been built, and they work.



Degrees C	Millivolts
0	0
50	3.047
80.26	5.000
100	6.317
150	9.787
153	10.
200	13.419
221.21	15
250	17.178
286.71	20
300	21.033
350	24.961
350.49	25
400	28.943
413.2	30
450	32.96
475.27	35
500	36.999
537.09	40
550	41.045
598.95	45
600	45.085
650	49.109
661.1	50

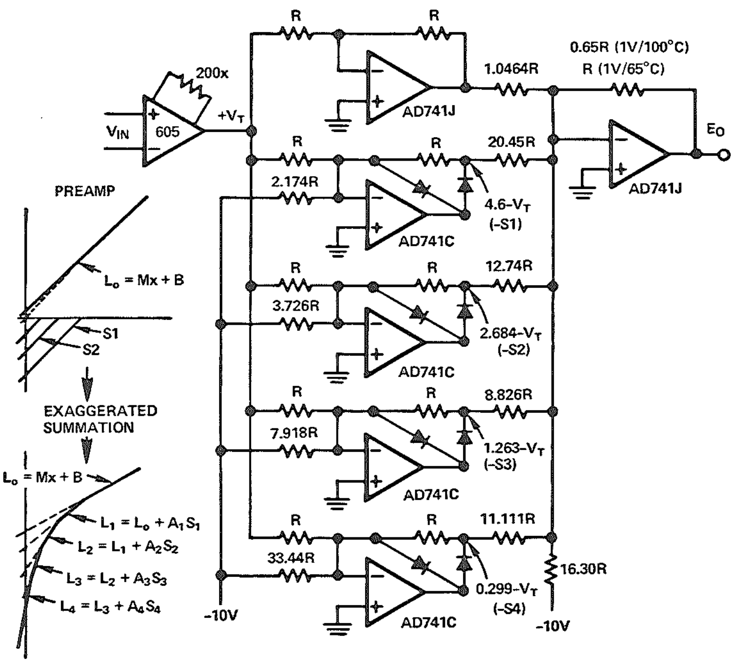
Figure 5-12. Nonlinear thermocouple response and theoretical residual errors, using two different linearizing functions. Read errors on expanded scale.

In this chapter, we have discussed the principles and a variety of techniques for offsetting and linearizing the outputs of transducers. In the next chapter, before proceeding to the Applications section, we will consider approaches to overall solutions to interfacing problems, expressed in terms of a couple of actual examples and discussed by a designer.



$$E_O = 0.9535V_{IN} + 0.6362 - 0.01226\,(8.6835 - 1.5V_{IN}) - (0.087)(10)\left[\frac{8.6835 - 1.5V_{IN}}{10}\right]^{3.512}$$

Figure 5-13. Block diagram and circuit for linearizing, using smooth approximation. Theoretical error is shown in Figure 5-12.



$$E_O = 0.9557V_{IN} + 0.6135 - 0.0489(4.6 - V_{IN}) - 0.0785(2.684 - V_{IN}) - 0.1133(1.263 - V_{IN}) - 0.09(0.299 - V_{IN})$$

Figure 5-14. Circuit for linearizing using piecewise-linear approximation