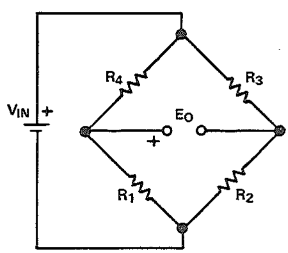
Interfacing Considerations
Bridges

Chapter 2

Figure 2-1 shows the common Wheatstone bridge (actually developed by S. H. Christie in 1833). In its simplest form, a bridge consists of four two-terminal elements connected to form a quadrilateral, a source of excitation (voltage or current)—connected along one of the diagonals, and a detector of voltage or current—comprising the other diagonal. The detector, in effect, measures the difference between the outputs of two potentiometric dividers connected across the excitation supply.



$$E_O = \frac{R_1}{R_1 + R_4} V_{IN} - \frac{R_2}{R_2 + R_3} V_{IN}$$

$$= \frac{\frac{R_1}{R_4} - \frac{R_2}{R_3}}{\left(1+\frac{R_1}{R_4}\right)\left(1+\frac{R_2}{R_3}\right)} V_{IN}$$

AT BALANCE, $E_O = 0$ IF $\frac{R_1}{R_4} = \frac{R_2}{R_3}$

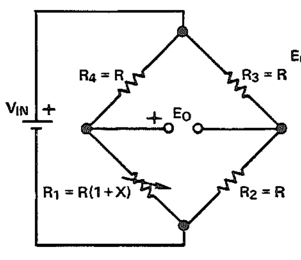
Figure 2-1. Basic bridge circuit — voltage excitation and voltage readout

A bridge measures an electrical property of a circuit element indirectly, i.e., by comparison against a similar element. The two principal ways of operating a bridge are as a null detector and as a device that reads a difference directly in voltage or current.

When $R_1/R_4 = R_2/R_3$, the resistance bridge shown in Figure 1 is at a *null*, irrespective of the mode of excitation (current or voltage, ac or dc), the magnitude of excitation, the mode of readout (current or voltage), or the impedance of the detector. Therefore, if the ratio R_2/R_3 is fixed at K, a null is achieved when $R_1 = K R_4$. If R_1 is unknown and R_4 is an accurately determined variable resistance, the magnitude of R_1 can be found by adjusting R_4 until null is achieved. Conversely, in transducer-type measurements, R_4 may be a fixed reference and a null occurs when the magnitude of the measurand is such that R_1 is equal to $K R_4$.

Null-type measurements are principally used in feedback systems, involving electromechanical and/or human elements. Such systems, as noted in the previous chapter, seek to force the active element (strain gage, RTD, thermistor, mechanically coupled potentiometer) to balance the bridge by influencing the parameter being measured. Because the null is independent of the excitation, the null mode may also be used to discriminate between the two polarities of output, i.e., as a *comparator.* In such applications, the *polarity* of the off-null signal might be of greater significance than its *magnitude* (for example, if the level of a tank is below a preset value, a valve is caused to open to fill the tank.

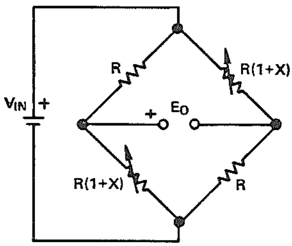
For the majority of transducer applications employing bridges, the *deviation* of one or more resistors in a bridge from an initial value must be measured as an indication of the magnitude (or a change) of the measurand. Figure 2-2 shows a bridge with all resistances nominally equal; but one of them (R_1) is variable by a factor, $(1 + X)$, where X is a fractional deviation around zero, as a function of (say) strain. As the equation indicates, the relationship between the bridge output and X is not linear, but for small ranges of X it is sufficiently linear for many purposes. For example, if $V_{IN} = 10V$, and the maximum value of X is ± 0.002, the output of the bridge will be linear to within 0.1% for a range of outputs



$$E_O = \frac{R(1+X)}{R+R(1+X)} V_{IN} - \frac{1}{2} V_{IN}$$
$$= \frac{2+2X-2-X}{2(2+X)} V_{IN}$$
$$= \frac{V_{IN}}{4} \cdot \frac{X}{1+\frac{X}{2}}$$
$$\cong \frac{V_{IN}}{4} X \text{ FOR } X<<1$$

Figure 2-2. Bridge used to read deviation of a single variable element from 0 to ±5mV, and to 1% for the range 0 to ±50mV (±0.02 range for X).

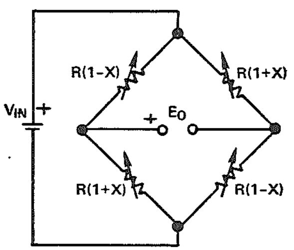
The *sensitivity* of a bridge is the ratio-to-the-excitation-voltage of the maximum expected change in the value of the output; in the examples given in the last paragraph, the sensitivities are ±500μV/V and ±5mV/V. The sensitivity can be doubled if two identical variable elements can be used, e.g., at positions R3 and R1, as shown in Figure 2-3a. An example of such a pair is two identically oriented strain-gage resistances aligned in a single pattern. Note that the output is doubled, but the same degree of nonlinearity exists.



$$E_O = \left[\frac{R(1+X)}{R+R(1+X)} - \frac{R}{R+R(1+X)}\right] V_{IN}$$
$$= \frac{X}{2+X} V_{IN}$$
$$= \frac{V_{IN}}{2} \frac{X}{1+\frac{X}{2}}$$
$$\cong \frac{V_{IN}}{2} X \text{ FOR } X \ll 1$$

Figure 2-3a. Bridge with two variable elements

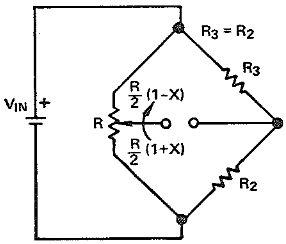
In special cases, another doubling of the output can be achieved. Figure 2-3b shows a bridge consisting of four resistors, two of which increases and two of which decrease in the same ratio. Two identical two-element strain gages, attched to opposite faces of a thin carrier to measure its bending, could be electrically configured in this way. The output of such a bridge would be four times the output for a single-element bridge; furthermore, the complementary nature of the resistance changes would result in a *linear* output.



$$E_O = \left[\frac{R(1+X)}{2R} - \frac{R(1-X)}{2R}\right] V_{IN}$$
$$= \left[\frac{1+X-1+X}{2}\right] V_{IN}$$
$$= X V_{IN}$$

Figure 2-3b. All elements variable

Figure 2-3c shows a bridge employing a zero-centred potentiometer to constitute two adjacent arms; the position of the potentiometer is a measure of the physical phenomenon. Since it is a 2-variable-element version of 2-3b, the output is twice that of the single-element bridge, and it is linear.



$$E_O = \left[\frac{\frac{R}{2}(1-X)}{R} - \frac{1}{2}\right] V_{IN}$$
$$= \frac{R - XR - R}{2R} V_{IN}$$
$$= \frac{V_{IN}}{2} X$$

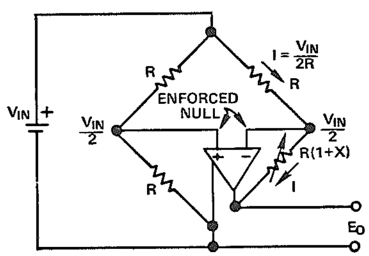
c. Linear potentiometer as variable arm

Figure 2-3. Useful bridge configurations

A distinction should be recognized between the linearity of the bridge equation and linearity of the transducer response to the phenomenon being sensed. For example, if the active element is a potentiometer, a bridge used to implement the measurement would be adequately linear; yet the output could still be nonlinear due to the pot's nonlinearity.

Manufacturers of transducers employing bridges address the nonlinearity issue in a variety of ways, including keeping the resistive swings in the bridge small, shaping complementary nonlinear response into the active elements of the bridge, using resistive trims for first-order corrections, and a variety of proprietary magical techniques. A bridge can, of course, be linearized by making it less sensitive (e.g., by making the initial ratios, R_4/R_1 and R_3/R_2, large), but the tradeoff of sensitivity for linearity is painful.

Figure 2-4 shows an active bridge in which an op amp produces



$$\frac{V_{IN}}{2} = E_O + IR(1+X)$$
$$\frac{V_{IN}}{2} = E_O + \frac{V_{IN}}{2}(1+X)$$
$$E_O = -\frac{V_{IN}}{2} X$$

Figure 2-4. Active bridge

a null by adding a voltage in series with the variable arm. That voltage is equal in magnitude and opposite in polarity to the incremental voltage across R_X, and it is inherently linear with X. Since it is an op-amp output, it can be used as a low-impedance output point for the bridge measurement. This active bridge has a gain of two over the standard one-active-element bridge, and the output is linear, even for very large values of X.

More information about linearization techniques can be found in Chapter 5.

EXCITATION

The choice of circuitry to produce the excitation voltage (or current) will depend on the system designer's background and inclinations and will depend on the degree of precision and any special requirements for the specific system. Details of a variety of approaches are shown in the Applications section. Choices range from assemblages of components to "system solutions."*

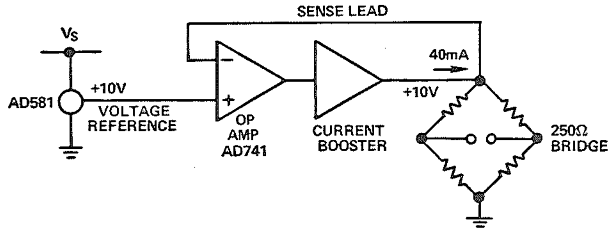
A stable bridge-driving potential may be obtained through the use of reference IC's and op-amp circuitry (Figure 2-5a). The particularities of op-amp circuitry can be avoided by the use of a fully engineered and specified signal-conditioning power supply, which provides resistor-programmable current or voltage and has sensing leads that permit precise voltage to be maintained at the bridge terminals in spite of voltage drops in the leads (Figure 2-5b). For minimum component count, complete signal conditioners provide programmable excitation, in addition to amplification and filtering.*

For high-precision measurements, the requirement for a highly stable and accurate supply may be less pressing if the same reference can be used for both the bridge and the readout device (e.g., a digital panel meter). Such measurements, in which the *ratio to full scale* for both devices is accurately maintained, are independent of the actual level of the excitation; not surprisingly, this technique is known as *ratiometric* measurement (Figure 2-5c).

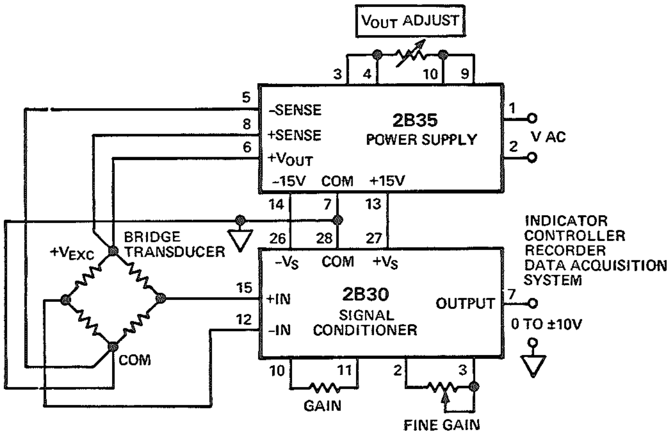
READOUT

The hardware to detect and measure the output from a bridge can

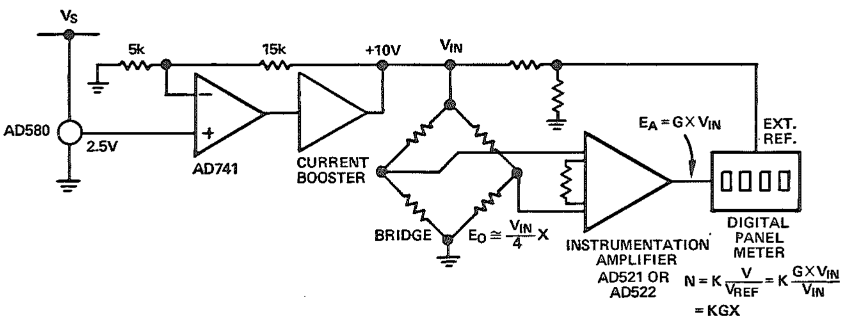
*It will be difficult to maintain the appearance of objectivity in the discussion of hardware, since it is available in many guises from Analog Devices. We will seek to avoid references to Model numbers in the text, unless absolutely necessary. However, since they constitute useful real-world information, they will be used liberally in circuit diagrams and, where appropriate, in footnotes, throughout the book.



a. Basic bridge-drive circuitry



b. Use of transducer power supply for bridge drive



c. Basic ratiometric system using a low-cost 2.5V reference

Figure 2-5. Bridge excitation schemes

take many forms. While the early and elegant forms of analog microammeters and mirror galvanometers could easily resolve sub-microvolt variations, they are hardly applicable to today's industrial environment, which calls for considerably greater ruggedness and speed of response, and the ability to interface with analog or digital signal-handling circuitry. The most general and least troublesome, from the standpoint of circuit design and assembly, is to use package "system-solution" signal conditioning, which covers the gamut from card options associated with intelligent measurement-and-control systems* to packaged modules that include an adjustable-gain instrument amplifier, noise filtering, and (where the conditioning is for a single bridge) excitation.†

However, even if one opts for packaged solutions, it is still worthwhile to know what the alternatives are. Furthermore, for reasons of performance, cost, overall system requirements, (or sheer satisfaction), the user may be inclined towards specific circuit options applicable to his own system.

A simple and appealing circuit employing a single operational amplifier is shown in Figure 2-6. Though it maintains a voltage null across the bridge (like the circuit of Figure 2-4), current is not nulled; it has voltage gain, but the cost is high. The external resistances must be carefully chosen and matched to maximize common-mode rejection (CMR); the ideal case of everything equal, as shown in the figure, is hard to realize in practice. Also, it is difficult to switch the gain (and permit adjustments to maximize CMR), without a great deal of cost and trouble. Finally, depending on gain, the nonlinearity can be up to twice that of the bridge alone.

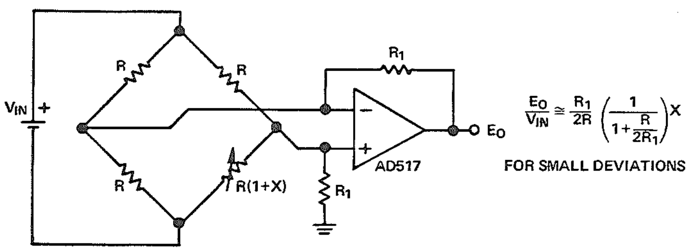


Figure 2-6. Single op-amp as a bridge amplifier

Perhaps the most widely used form of amplifier for reading bridge outputs is the *instrumentation amplifier*. The instrumentation amplifier (unlike the general-purpose op amp) is a committed gain block, generally characterized by low drift, high common-

*For example, MACSYM 2

†For example, 2B31, with self-contained excitation

mode rejection, high input impedance, and the capability of maintaining specified performance over a range of gains, typically from 1 to 1000 (Figure 2-7). Gain is a function of the ratio of two resistances, which do not have circuit connections in common with the inputs; the gain can be adjusted by adjusting or switching the resistance ratio. Some devices require that both resistors be connected externally; some require only a single external resistance, and some contain all the necessary resistors for a number of standard gains and require only external programming by jumpers, switches, or digital logic.

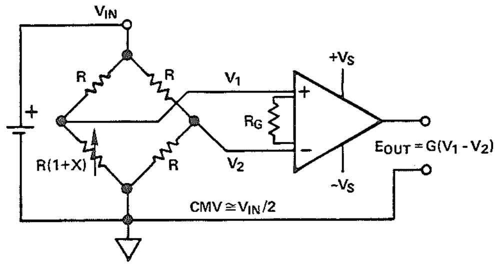


Figure 2-7. Differential-input instrumentation amplifier applied to bridge measurement

Common-mode errors and common-mode rejection will be discussed below and in the next chapter. When X is zero, the output should be zero. If the amplifier has been adjusted for zero output when $V_{IN} = 0$, then any error related to V_{IN} that appears at the output is known as a *common-mode-voltage error.* The ability of the amplifier circuit to minimize that error is known as *common-mode-rejection* (CMR), a quantity expressed logarithmically in decibels. CMR is usually specified at 60Hz with 1kΩ source unbalance.

The instrumentation amplifier has a balanced differential input. This means that the output voltage is proportional to the difference between the input voltages; and the input terminals, which present a high impedance to the input source, are electrically similar. High common-mode rejection means that the amplifier is sensitive only to the *difference* between the input voltages, even if they are swinging over a wide range, and the difference is quite small. For example, if the common-mode input is a voltage swinging over a ±10V range, the difference is a 10mV signal, the gain is 1000, and 1mV of common-mode error is desired, the *common-mode rejection ratio* (CMRR), the ratio of signal gain to common-mode gain, must be 1000/0.0001 = 10 million. Expressed logarithmically, *common-mode rejection* (CMR) is 20 $\log_{10}$ $(10)^7$ = 140dB, in this case.

Because the instrumentation amplifier has differential inputs, it is useful as a readout of signals from transducers in wide variety, whether balanced (as bridges generally are) or unbalanced (single-ended, with a ground return having questionable stability). It is available in a variety of forms, ranging from monolithic amplifiers, to hybrids, to discrete modules; it is also at the heart of signal-conditioning modules.* With specifications such as 0.5μV/°C for offset temperature coefficient, 100–140dB common-mode rejection, and better than 0.01% nonlinearity, they can serve well in the majority of bridge-measurement applications. In very high-precision applications, problems arise when even these low levels of drift and common-mode error are excessive. Instrumentation amplifiers may also prove marginal or inappropriate in applications calling for high CMRR with potentially destructive high voltage under either fault or operating conditions.

It is possible to reconfigure circuits so as to improve one or more aspects of performance by simple level shifts. For example, Figure 2-8 shows how the use of split supplies can effectively reduce the dc common-mode voltage to zero. This is a neat trick which works well in many situations: but it does nothing to reduce drifts with time and temperature, and it provides no improvement with respect to dynamic common-mode variations.

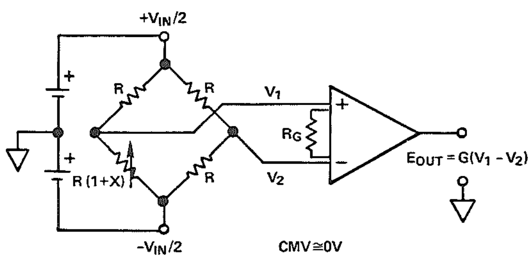


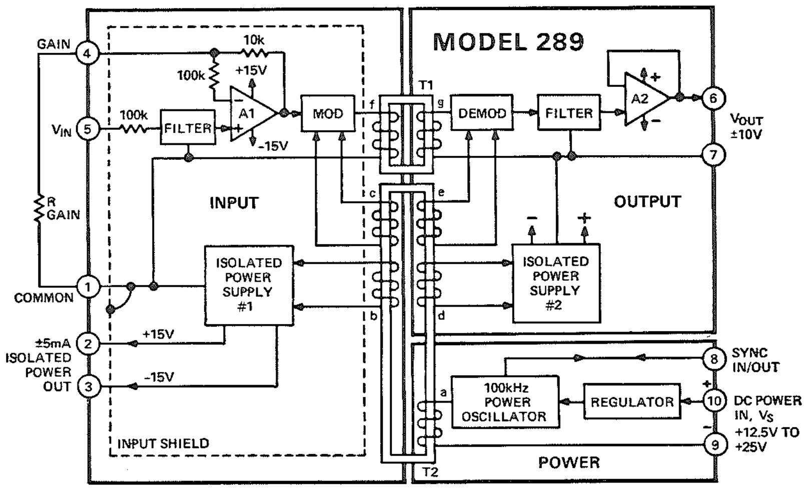
Figure 2-8. Using center-tapped supply to minimize common-mode voltage

An *isolation amplifier* is useful for applications where the bridge may be at a high potential with respect to the signal-conditioning circuitry, or where there must be no galvanic connections between the bridge and grounded instrumentation circuitry (for example in patient monitoring).

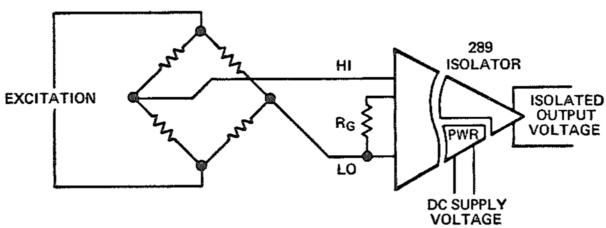
*An example of each: AD521, AD522, Model 610, Model 2B30 signal-conditioner

An isolation amplifier is one in which there is no galvanic path, and very low capacitance, between some combination of input, output, and power supply, hence no possibility for dc current flow, and minimal ac coupling. The usual combination isolates the input from both the power supply and the output (2-port isolation); but some devices have isolation between all three sections (3-port isolation). Isolation can, in concept, be provided via any means of energy transfer, from acoustics and lasers to magnetics and microwave. The easiest-to-implement and most widely used isolators today are electromagnetically coupled.

Figure 2-9 shows a basic configuration in which an isolation amplifier is providing the readout for a bridge. DC power is converted to high-frequency ac and coupled across the isolation



a. Block diagram of isolator



b. Typical application

Figure 2-9. Isolated bridge measurement. Gain is controlled by R_G. Bridge excitation may be low-frequency ac (transformer coupled) or dc.

barrier to the input section, where the ac is rectified to provide power for the input stage and for external isolated circuitry. The input signal modulates the ac carrier and is coupled to the output stage, where it is synchronously demodulated (using a sync signal coupled from the oscillator) and provided at the output.

The isolation results in extremely high common-mode rejection, with drift that is comparable to that of some instrumentation amplifiers. Because the amplifier's front end is truly floating, it is possible to withstand thousands of volts of common-mode voltage (CMV).

For the lowest drifts with time and temperature, amplifiers that employ *choppers* are used. Maximum drift, for modules such as the 261K, is $0.1\mu V/^\circ C$. A noninverting chopper amplifier is an op amp in which the dc offset between the feedback point and the input modulates a high-frequency carrier, which is then ac-amplified and demodulated, to produce an offset-corrected dc output level. Because of their internal circuit architecture, most chopper-type amplifiers are unbalanced single-ended-input devices; that is, the input and output voltage share a common terminal. This might appear to inhibit their ability to take a differential measurement across a bridge. However, if the bridge excitation is derived from a floating source, such as a battery or an isolated dc-to-dc converter, or an ac signal coupled via a transformer, then the output, though grounded, can be viewed as floating with respect to the excitation.

As Figure 2-10 shows, only the signal voltage appears at the amplifier input; as long as the supply floats, there is no common-mode voltage presented to the amplifier. Thus, this approach yields very low drift and high common-mode rejection. The remaining

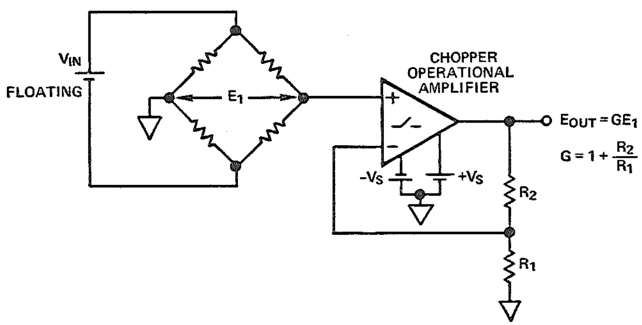


Figure 2-10. Chopper-stabilized bridge amplifier

source of concern is the accuracy and stability of the floating excitation source. A floating supply with regulation and stability *better than the required measurement accuracy* must be employed. Since the purpose of the chopper was to get high precision, it is reasonable to expect that the required measurement accuracy in such applications is high. The design and construction of highly stable floating power supplies, while certainly feasible, may be an unnecessarily high price to pay.

A better arrangement is shown in Figure 2-11, which provides very high accuracy, limited principally by the isolator's gain stability, at reasonable cost. Here a chopper amplifier is used as a freely floating preamplifier via an isolation amplifier. Power for the chopper is obtained from the isolation amplifier's isolated front-end supply (which is made available at a set of terminals on many models*). Since the preamplifier is isolated, it performs an essentially floating measurement of the bridge output, yet the bridge may be referenced to the same ground as the rest of the system. Because of this, a single grounded supply may be used to drive the bridge and also to provide a ratiometric measurement at the output (Figure 2-5c).

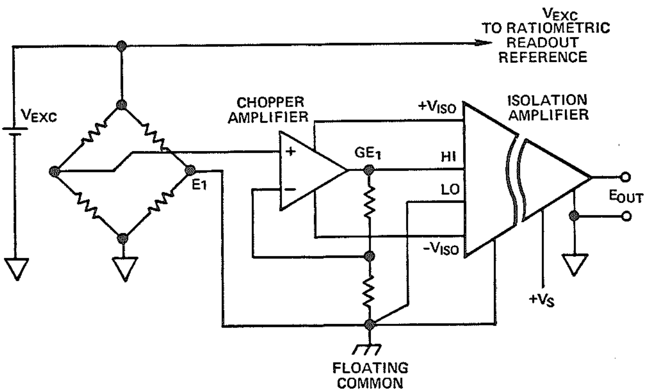


Figure 2-11. Chopper-stabilized, isolated bridge amplifier, using floating supply voltage from isolation amplifier front-end to power chopper amplifier

For most bridge applications, an instrumentation amplifier or a packaged signal conditioner will provide sufficient accuracy and resolution. However, it is worthwhile to be aware of the tools

*For example, Model 289

that are available for isolation, increased stability, and increased accuracy. Examples of applications in which they may be required are provided in the Applications section, in somewhat greater detail.

Bridges are perhaps the most pervasive element found in electrical measurement. This chapter has sought to provide a preliminary and practical acquaintance with their architecture, excitation, and readout. More information, in the more-general context of transducer interfacing, will be found in the chapters that follow.