SECTION 4-2: BRIDGE CIRCUITS

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An Introduction to Bridges

This section of the chapter, 4-2, discusses more fundamental bridge circuit concepts. To gain greatest appreciation of these ideas, it should be studied along with those sections discussing precision op amps within Chapters 1 and 2. The next section (4-3) focuses on the detailed application circuits relating to strain-gage-based sensors. These sections can be read sequentially if the reader already understands the design issues related to precision op amp applications.

Resistive elements are some of the most common sensors. They are inexpensive, and relatively easy to interface with signal-conditioning circuits. Resistive elements can be made sensitive to temperature, strain (by pressure or by flex), and light. Using these basic elements, many complex physical phenomena can be measured, such as: fluid or mass flow (by sensing the temperature difference between two calibrated resistances), dew-point humidity (by measuring two different temperature points), etc.

◆ **Strain Gages** $120\Omega, 350\Omega, 3500\Omega$

◆ **Weigh-Scale Load Cells** $350\Omega - 3500\Omega$

◆ **Pressure Sensors** $350\Omega - 3500\Omega$

◆ **Relative Humidity** $100k\Omega - 10M\Omega$

◆ **Resistance Temperature Devices (RTDs)** $100\Omega, 1000\Omega$

◆ **Thermistors** $100\Omega - 10M\Omega$

Figure 4-4: Sensor resistances used in bridge circuits span a wide dynamic range

Sensor element resistance can range from less than 100Ω to several hundred kΩ, depending on the sensor design and the physical environment to be measured. Figure 4-4 indicates the wide range of sensor resistance encountered. For example, RTDs are typically 100Ω or 1000Ω. Thermistors are typically 3500Ω or higher.

Resistive sensors such as RTDs and strain gages produce relatively small percentage changes in resistance, in response to a change in a physical variable such as temperature or force. For example, platinum RTDs have a temperature coefficient of about 0.385%/°C. Thus, in order to accurately resolve temperature to 1°C, the overall measurement accuracy must be much better than 0.385Ω when using a 100Ω RTD.

4.7

Strain gages present a significant measurement challenge because the typical change in resistance over the entire operating range of a strain gage may be less than 1% of the nominal resistance value. Accurately measuring small resistance changes is therefore critical when applying resistive sensors.

A simple method for measuring resistance is to force a constant current through the resistive sensor, and measure the voltage output. This requires both an accurate current source and an accurate means of measuring the voltage. Any change in the current will be interpreted as a resistance change. In addition, the power dissipation in the resistive sensor must be small and in accordance with the manufacturer's recommendations, so that self-heating does not produce errors. As a result, the drive current must be small, which tends to limit the resolution of this approach.
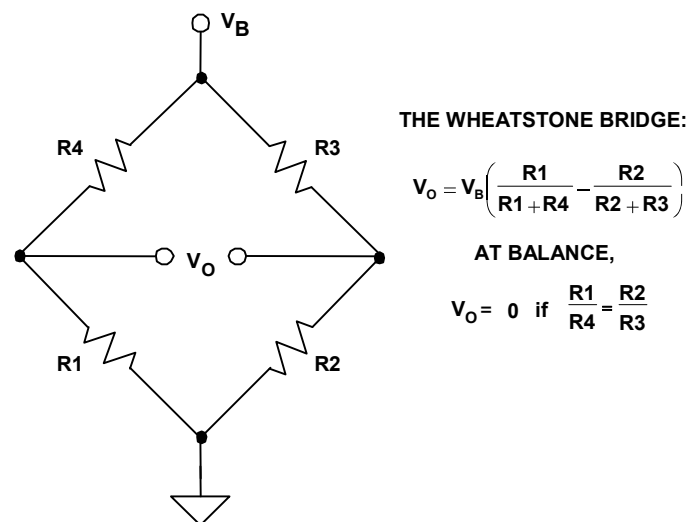
THE WHEATSTONE BRIDGE:

$$V_O = V_B \left(\frac{R1}{R1+R4} - \frac{R2}{R2+R3} \right)$$

AT BALANCE,

$$V_O = 0 \quad \text{if} \quad \frac{R1}{R4} = \frac{R2}{R3}$$

Figure 4-5: *The basic Wheatstone bridge produces an output null when the ratios of sidearm resistances match*

A *resistance bridge,* shown in Figure 4-5, offers an attractive alternative for measuring small resistance changes accurately. This is a basic Wheatstone bridge (actually developed by S. H. Christie in 1833), and is a prime example. It consists of four resistors connected to form a quadrilateral, a source of excitation voltage V_B (or, alternately, a current) connected across one of the diagonals, and a voltage detector connected across the other diagonal. The detector measures the difference between the outputs of the two voltage dividers connected across the excitation voltage, V_B. The general form of the bridge output V_O is noted in the figure.

There are two principal ways of operating a bridge such as this. One is by operating it as a null detector, where the bridge measures resistance indirectly by comparison with a similar standard resistance. On the other hand, it can be used as a device that reads a resistance difference directly, as a proportional voltage output.

When R1/R4 = R2/R3, the resistance bridge is said to be 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 of R2/R3 is fixed at K, a null is achieved when R1 = K·R4. If R1 is unknown and R4 is an accurately determined variable resistance, the magnitude of R1 can be found by adjusting R4 until an output null is achieved. Conversely, in sensor-type measurements, R4 may be a fixed reference, and a null occurs when the magnitude of the external variable (strain, temperature, etc.) is such that R1 = K·R4.

Null measurements are principally used in feedback systems involving electromechanical and/or human elements. Such systems seek to force the active element (strain gage, RTD, thermistor, etc.) to balance the bridge by influencing the parameter being measured.

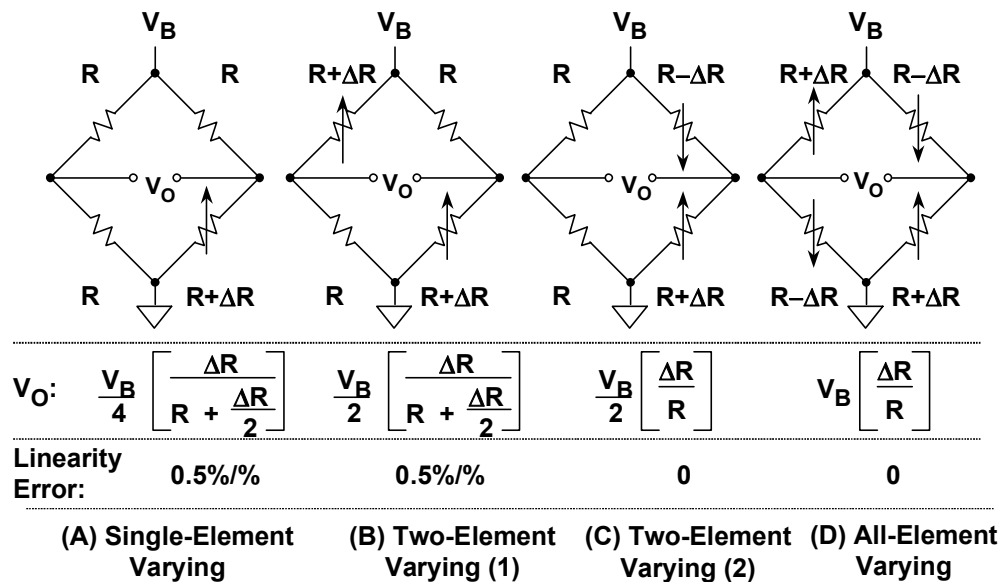|	(A) Single-Element Varying	(B) Two-Element Varying (1)	(C) Two-Element Varying (2)	(D) All-Element Varying
V_O:	$\dfrac{V_B}{4}\left[\dfrac{\Delta R}{R + \dfrac{\Delta R}{2}}\right]$	$\dfrac{V_B}{2}\left[\dfrac{\Delta R}{R + \dfrac{\Delta R}{2}}\right]$	$\dfrac{V_B}{2}\left[\dfrac{\Delta R}{R}\right]$	$V_B\left[\dfrac{\Delta R}{R}\right]$
Linearity Error:	0.5%/%	0.5%/%	0	0

Figure 4-6: The output voltage sensitivity and linearity of constant voltage drive bridge configurations differs according to the number of active elements

For the majority of sensor applications employing bridges, however, the deviation of one or more resistors in a bridge from an initial value is measured as an indication of the magnitude (or a change) in the measured variable. In these cases, the output voltage change is an indication of the resistance change. Because very small resistance changes are common, the output voltage change may be as small as tens of millivolts, even with the excitation voltage V_B = 10V (typical for a load cell application).

In many bridge applications, there may not just be a single variable element, but two, or even four elements, all of which may vary. Figure 4-6 above shows a family of four voltage-driven bridges, those most commonly suited for sensor applications. In the four cases the corresponding equations for V_O relate the bridge output voltage to the excitation voltage and the bridge resistance values. In all cases we assume a constant voltage drive, V_B. Note that since the bridge output is always directly proportional to V_B, the measurement accuracy can be no better than that of the accuracy of the excitation voltage.

In each case, the value of the fixed bridge resistor "R" is chosen to be equal to the nominal value of the variable resistor(s). The deviation of the variable resistor(s) about the nominal value is assumed to be proportional to the quantity being measured, such as strain (in the case of a strain gage), or temperature (in the case of an RTD).

The *sensitivity* of a bridge is the ratio of the maximum expected change in the output voltage to the excitation voltage. For instance, if $V_B = 10V$, and the fullscale bridge output is 10mV, then the sensitivity is 1mV/V. For the four cases of Figure 4-6, sensitivity can be said to increase going left-right, or as more elements are made variable.

The *single-element varying* bridge of Figure 4-6A is most suited for temperature sensing using RTDs or thermistors. This configuration is also used with a single resistive strain gage. All the resistances are nominally equal, but one of them (the sensor) is variable by an amount ΔR. As the equation indicates, the relationship between the bridge output and ΔR is not linear. For example, if $R = 100\Omega$ and $\Delta R = 0.1\Omega$ (0.1% change in resistance), the output of the bridge is 2.49875mV for $V_B = 10V$. The error is 2.50000mV – 2.49875mV, or 0.00125mV. Converting this to a % of fullscale by dividing by 2.5mV yields an end-point linearity error in percent of approximately 0.05%. (Bridge end-point linearity error is calculated as the worst error in % FS from a straight line which connects the origin and the end point at FS, i.e., the FS gain error is not included). If $\Delta R = 1\Omega$, (1% change in resistance), the output of the bridge is 24.8756mV, representing an end-point linearity error of approximately 0.5%. The end-point linearity error of the single-element bridge can be expressed in equation form:

> Single-Element Varying
> Bridge End-Point Linearity Error $\approx$ % Change in Resistance ÷ 2

It should be noted that the above nonlinearity refers to the nonlinearity of the bridge itself and not *the sensor*. In practice, most sensors themselves will exhibit a certain specified amount of nonlinearity, which must also be accounted for in the final measurement.

In some applications, the bridge nonlinearity noted above may be acceptable. But, if not, there are various methods available to linearize bridges. Since there is a fixed relationship between the bridge resistance change and its output (shown in the equations), software can be used to remove the linearity error in digital systems. Circuit techniques can also be used to linearize the bridge output directly, and these will be discussed shortly.

There are two cases to consider in the instance of a *two-element varying* bridge. In Case 1 (Figure 4-6B), both of the diagonally opposite elements change in the same direction. An example would be two identical strain gages mounted adjacent to each other, with their axes in parallel.

The nonlinearity for this case, 0.5%/%, the same as that of the single-element varying bridge of Figure 4-6A. However, it is interesting to note the sensitivity is now improved by a factor of 2, vis-à-vis the single-element varying setup. The two-element varying bridge is commonly found in pressure sensors and flow meter systems.

A second case of the two-element varying bridge, Case 2, is shown in Figure 4-6C. This bridge requires two identical elements that vary in *opposite* directions. This could correspond to two identical strain gages: one mounted on top of a flexing surface, and one on the bottom. Note that this configuration is now linear, and like two-element varying Case 1, it has twice the sensitivity of the Figure 4-6A configuration. Another way to view this configuration is to consider the terms R+ΔR and R−ΔR as comprising two sections of a linear potentiometer.

The *all-element varying* bridge of Figure 4-6D produces the most signal for a given resistance change, and is inherently linear. It is also an industry-standard configuration for load cells constructed from four identical strain gages. Understandably, it is also one of the most popular bridge configurations.

Figure 4-7 circuit values:

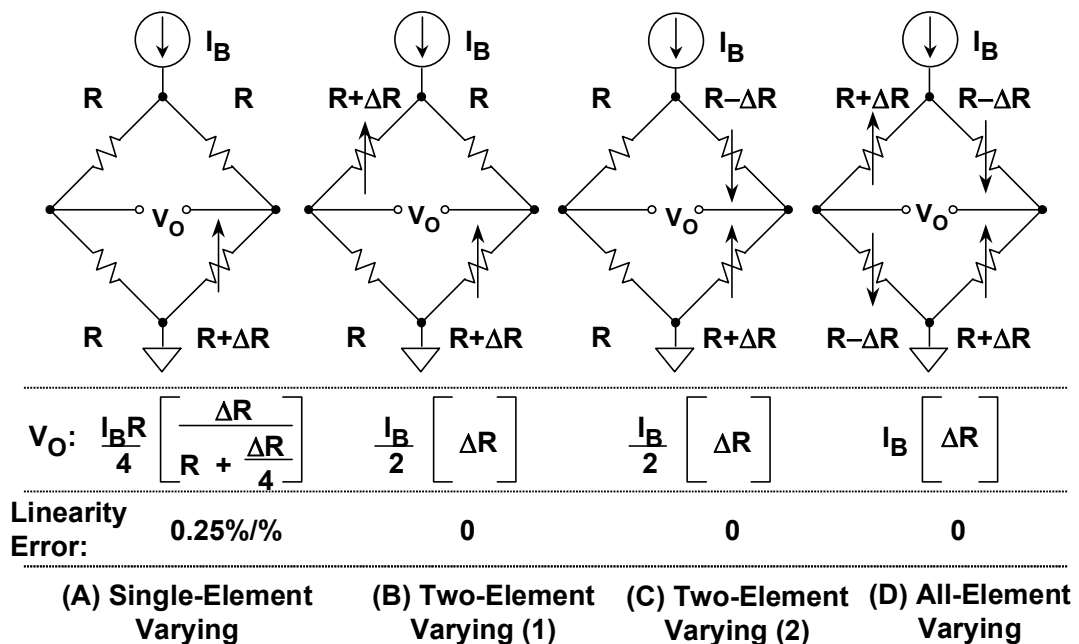|	(A) Single-Element Varying	(B) Two-Element Varying (1)	(C) Two-Element Varying (2)	(D) All-Element Varying
V_O:	$\dfrac{I_B R}{4}\left[\dfrac{\Delta R}{R + \dfrac{\Delta R}{4}}\right]$	$\dfrac{I_B}{2}\left[\Delta R\right]$	$\dfrac{I_B}{2}\left[\Delta R\right]$	$I_B\left[\Delta R\right]$
Linearity Error:	0.25%/%	0	0	0

Figure 4-7: The output voltage sensitivity and linearity of constant current drive bridge configurations also differs according to the number of active elements

Bridges may also be driven from constant current sources, as shown in Figure 4-7, for the corresponding cases of single, dual, dual, and four active element(s). As with the voltage-driven bridges, the analogous output expressions are noted, along with the sensitivities.

Current drive, although not as popular as voltage drive, does have advantages when the bridge is located remotely from the source of excitation. One advantage is that the wiring resistance doesn't introduce errors in the measurement; another is simpler, less expensive cabling. Note also that with constant current excitation, all bridge configurations are linear except the single-element varying case of Figure 4-7A.

In summary, there are many design issues relating to bridge circuits, as denoted by Figure 4-8 below. After selecting the basic configuration, the excitation method must be determined. The value of the excitation voltage or current must first be determined, as this directly influences sensitivity. Recall that the fullscale bridge output is directly proportional to the excitation voltage (or current). Typical bridge sensitivities are 1mV/V to 10mV/V.

Although large excitation voltages yield proportionally larger fullscale output voltages, they also result in higher bridge power dissipation, and thus raise the possibility of sensor resistor self-heating errors. On the other hand, low values of excitation voltage require more gain in the conditioning circuits, and also increase sensitivity to low level errors such as noise and offset voltages.

◆ **Selecting Configuration (1, 2, 4 - Element Varying)**

◆ **Selection of Voltage or Current Excitation**

◆ **Ratiometric Operation**

◆ **Stability of Excitation Voltage or Current**

◆ **Bridge Sensitivity: FS Output / Excitation Voltage**
   1mV / V to 10mV / V Typical

◆ **Fullscale Bridge Outputs: 10mV - 100mV Typical**

◆ **Precision, Low Noise Amplification / Conditioning**
   Techniques Required

◆ **Linearization Techniques May Be Required**

◆ **Remote Sensors Present Challenges**

Figure 4-8: A number of bridge considerations impact design choices

Regardless of the absolute level, the stability of the excitation voltage or current directly affects the overall accuracy of the bridge output, as is evident from the V_B and I_B terms in the output expressions. Therefore stable references and/or *ratiometric* drive techniques are required, to maintain highest accuracy.

Here, ratiometric simply refers to the use of the bridge drive voltage of a voltage-driven bridge (or a current-proportional voltage, for a current-driven bridge) as the reference input to the ADC that digitizes the amplified bridge output voltage. In this manner the absolute accuracy and stability of the excitation voltage becomes a second order error. Examples to follow illustrate this point further.