California State University, Fresno
Department of Electrical and Computer Engineering

ECE 90L Principles of Electrical Circuits Laboratory
Experiment No. 9: Bridge Circuits

Objective

Two DC bridge circuits and one AC bridge circuit will be built. Each of the DC bridge circuits permits accurate measurement of a resistance. These circuits can be used as transducers to sense environmental variables, such as temperature, light intensity, strain, and magnetic field strength. The AC bridge circuit permits the accurate measurement of capacitance.

Prelab

A number of devices are available that sense the physical environment and respond with a change in electrical resistance. The thermistor is an example of such a device. It has an electrical resistance that is a function of the temperature.

The resistance of a thermistor is given approximately by

$$R = R_0 + \Delta R$$

Here R_0 is the resistance of the thermistor at a reference temperature T_0. This T_0 is the nominal temperature at the location of the thermistor. ΔR is the change in resistance that is due to a change ΔT in temperature from its nominal value T_0. The actual temperature, denoted T, is therefore $T = T_0 + \Delta T$. For relatively small changes in temperature, ΔR is approximately proportional to ΔT:

$$\Delta R = k\,\Delta T$$

where k is the known constant of proportionality, having the units $\Omega/°\text{C}$. If we can measure ΔR, we can infer the actual, current temperature (at the location of the thermistor) as

$$T = T_0 + \Delta R/k$$

Other devices have been designed that experience a change in resistance in response to an environmental variable. A photoresistor responds to light intensity. A strain gauge responds to strain. A magnetoresistive sensor responds to magnetic field strength.

In principle, we could measure the resistance of a thermistor (or photoresistor, or strain gauge, or magnetoresistive sensor) using the ohmmeter function of a multimeter. However, there are two reasons why we don't usually do this.

First, an ohmmeter reading is not sufficiently accurate. If R_0 is 10,000 Ω and we need to determine ΔR with an accuracy of 5 Ω, then an accuracy of $(5/10{,}000) \times 100\% = 0.05\%$ is required of the ohmmeter. This is difficult to achieve. We will get better accuracy by measuring a quantity (such as a voltage) that is proportional to ΔR, rather than proportional to $R_0 + \Delta R$.

Second, we would like our measurement to produce a voltage. If we have a voltage, it can be periodically sampled and electronically written to a file, all without human intervention. The voltage can be sent to an electronic display. It can be sent to a processor that monitors it. If the temperature (for example) gets too large or too small, a warning light can be lit or an alarm can be sounded.

Two DC bridge circuits will be built. The first is a Wheatstone bridge. The second is a bridge amplifier. Each of these circuits will contain a variable resistor that is intended to mimic a thermistor (or photoresistor, or strain gauge, or magnetoresistive sensor). The output voltage from each of these circuits is at least approximately proportional to ΔR.

A circuit, such as a Wheatstone bridge or a bridge amplifier, that includes the sensor (a thermistor, or photoresistor, or strain gauge, or magnetoresistive sensor) and that produces a voltage that is proportional (at least approximately) to a change in an environmental variable, is called a transducer. The voltage produced by a transducer can be sampled and recorded, and from these sample values the change in the environmental variable can easily be calculated.

Wheatstone Bridge

A Wheatstone bridge is shown in Figure 1. Three of the four resistors in the bridge have the same resistance: R_0. The fourth resistance, which is meant to represent a sensor, will be varied during this experiment. The DC voltage source and the two resistors on the *left* side of the bridge form a voltage divider. The DC voltage source and the two resistors on the *right* side of the bridge form a different voltage divider. When $\Delta R = 0$ (that is, when the four resistances of the bridge match exactly), the bridge is said to be "balanced" and $V_B = 0$. When $\Delta R \neq 0$, V_B depends on ΔR (and, of course, the constant parameter values V_S and R_0).

Exercise: Analyze the Wheatstone-bridge circuit of Figure 1, finding an equation for V_B as a function of ΔR (with V_S and R_0 as parameters). You should find that V_B is a nonlinear function of ΔR. Next, make the assumption that $\Delta R \ll R_0$ and show that V_B is *approximately* proportional to ΔR.

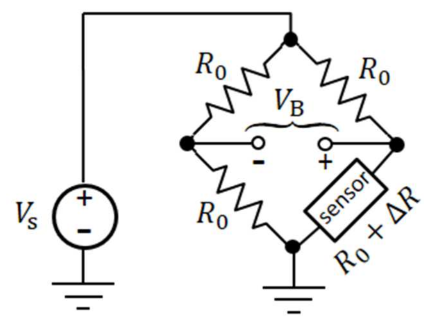

Figure 1: Wheatstone bridge

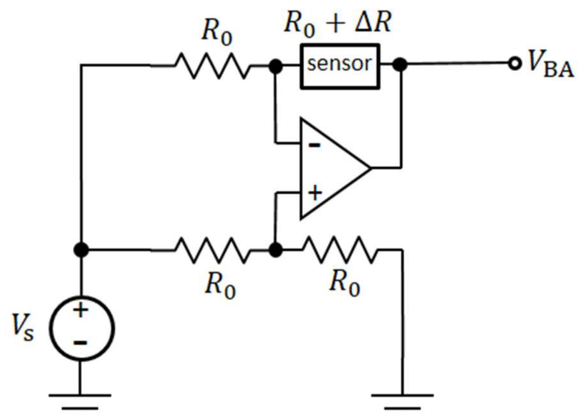

Figure 2: Bridge amplifier

Bridge Amplifier

A bridge amplifier is shown in Figure 2. Three of the four resistors in the bridge amplifier have the same resistance: R_0. The fourth resistance, which is meant to represent a sensor, will be varied during this experiment.

It is worthwhile to compare the bridge amplifier of Figure 2 with the Wheatstone bridge of Figure 1. The two resistors on the left side of the Wheatstone bridge appear in the lower voltage divider of the bridge amplifier. The resistor plus sensor on the right side of the Wheatstone bridge appear in the upper voltage divider of the bridge amplifier. We can view the bridge amplifier as having been created from the Wheatstone bridge with the following two changes:

1. The terminals where V_B is measured in the Wheatstone bridge have now been placed at the inverting and non-inverting inputs of an op amp.

2. The "bottom" of the sensor in the Wheatstone bridge has now been removed from ground and is instead connected to the output of the op amp. Thus, the negative feedback path for the op-amp circuit passes through the sensor.

How does this bridge amplifier work? The negative feedback of the op-amp circuit causes the mid-point of the upper voltage divider (the op amp's inverting input) to have the same voltage as the mid-point of the lower voltage divider (the op amp's non-inverting input), and this voltage is $V_S/2$. This mimics the operation of the Wheatstone bridge when $\Delta R = 0$ (that is, when the Wheatstone bridge is balanced). The bridge amplifier is balanced when $\Delta R = 0$; in this special case, $V_{BA} = 0$. But this circuit should produce a voltage V_{BA} that is proportional to ΔR even when $\Delta R \neq 0$.

In general, the current through the sensor equals the current through the resistor R_0 in the upper voltage divider; this is because the current has nowhere else to go (as there is no current on the op amp's inverting input). When $\Delta R > 0$, the voltage drop across the sensor is greater than that across the resistor R_0. (The current is the same through both resistances, but the sensor has more resistance.) Since the left side of the sensor has a voltage of $V_S/2$ and the voltage drop across the sensor is more than $V_S/2$ (when $\Delta R > 0$), $V_{BA} < 0$. On the other hand, when $\Delta R < 0$, $V_{BA} > 0$.

Exercise: Analyze the bridge-amplifier circuit of Figure 2, finding an equation for V_{BA} as a function of ΔR (with V_S and R_0 as parameters). You should find that V_{BA} is proportional to ΔR, but with a minus sign.

In the equation relating V_{BA} to ΔR, there is a minus sign. In other words, a positive ΔR results in a negative V_{BA}. If it is desired to have a positive V_{BA} produced by a positive ΔR (and a negative V_{BA} produced by a negative ΔR), then the bridge amplifier of Figure 2 can be followed by an inverting amplifier. We won't bother to do that in this experiment.

It is worthwhile to consider the relative advantages of the Wheatstone bridge and the bridge amplifier. The Wheatstone bridge is a simpler circuit, especially if it is necessary that the output voltage have the same algebraic sign as ΔR. On the other hand, the bridge amplifier voltage V_{BA} is exactly proportional to ΔR (assuming the permanent resistors are all matched), as opposed to the Wheatstone bridge for which V_B is only *approximately* proportional to ΔR. This means that the bridge amplifier's output voltage is easily and accurately converted to a change in the environmental variable.

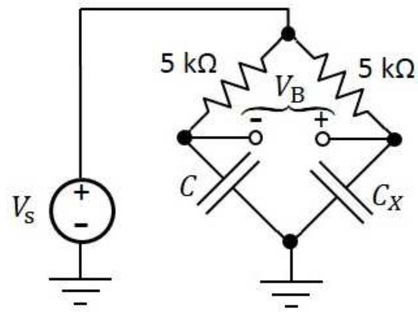

Figure 3: AC bridge

Another advantage of the bridge amplifier is that we have more flexibility in measuring its output voltage V_{BA}. This is because V_{BA} is referenced to earth ground. V_{BA} can be measured accurately by an instrument that has one of its input terminals connected to earth ground. For the Wheatstone bridge, on the other hand, we need a differential measurement for V_B. In other words, V_B must be measured with neither terminal connected to earth ground.

AC Bridge

Unlike the two bridge circuits described above, the bridge circuit of Figure 3 uses an AC source (which shall generate a sinusoid in this case) and a mix of resistors and capacitors. The purpose of this AC bridge is to measure accurately the capacitance C_X. This will be accomplished by using a precision, adjustable capacitor for C. In our experiment, C will be the capacitance produced by a capacitor decade box; its capacitance is not only adjustable but also known to excellent accuracy. C_X, on the other hand, will be a fixed, physical capacitor whose exact value is unknown. (Nominally, the capacitor C_X used in this experiment will be 33 nF; but there is some manufacturing tolerance on this value.)

The experimental procedure is to adjust C so as to minimize the root-mean-square of V_B. The value of C that achieves this minimization can then be considered as the measured value of C_X. We justify this conclusion with the following reasoning. If $C = C_X$, both the right side and the left side of the bridge are identical. Each consists of a series combination of a resistor and a capacitor, where the resistances match and the capacitances match. Therefore, the voltage at the resistor/capacitor node should be the same for both sides of the bridge, and the voltage V_B will be zero. We call this a balanced bridge.

Procedure

Wheatstone Bridge

Construct the Wheatstone bridge shown in Figure 1. Use the precision, adjustable resistances from the resistance decade boxes. Set three of these precision resistances to

$$R_0 = 10\ \text{k}\Omega$$

You should use the ohmmeter to verify that each of these resistors has, at least approximately, the correct value.

You will use an adjustable, precision resistor to represent the sensor.

You will use

$$V_S = 5\ \text{V}$$

This voltage will come from CH1 of the Siglent power supply. Set the current limit to 0.2 A.

First set ΔR to 0. In other words, the adjustable, precision resistor representing the sensor should, initially, be set equal to $R_0 = 10\ \text{k}\Omega$. In this case, V_B should be close to 0 V. If it is not close to 0 V, then you have troubleshooting to do.

Test your Wheatstone bridge for each of the following values for ΔR: -1 kΩ, -0.5 kΩ, 0 kΩ, $+0.5$ kΩ, and $+1$ kΩ. For example, $\Delta R = -1\ \text{k}\Omega$ is implemented by setting the adjustable, precision resistor that represents the sensor to 9.0 kΩ. For each value of ΔR, measure V_B using the DC voltmeter.

Bridge Amplifier

Place an LM741 op amp on the solderless breadboard. The pin-out of this op amp is illustrated in Figure 4.

Configure the Siglent DC power supply to be the source of $+12$ V for pin 7 and -12 V for pin 4. But do not apply live voltages to the op amp until ready to make measurements. Set the maximum current to 0.2 A for both sources. Place the DC power supply in series mode. Set the CH1 voltage to 12 V, causing the CH2 voltage to be 12 V also. Connect the CH2 $-$ terminal, which is internally connected to the CH1 $+$ terminal while in series mode, to ground. With this configuration, the CH2 $+$ terminal is at $+12$ V relative to ground and the CH1 $-$ terminal is at -12 V relative to ground.

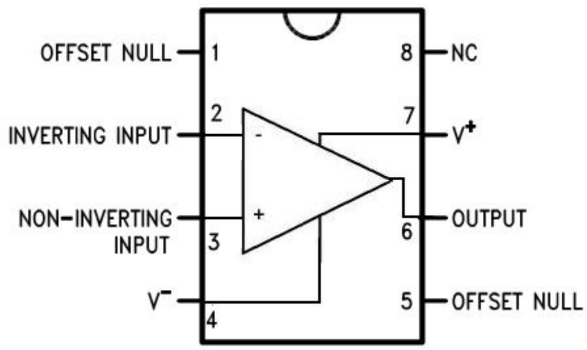

Figure 4: LM741 pin-out

Construct the bridge amplifier shown in Figure 2. The $\pm 5\%$ (fourth color band = gold) tolerance resistors available in our lab are not precise enough for this application. Instead, use the precision, adjustable resistances from the resistance decade boxes. Set three of these precision resistances to

$$R_0 = 10 \text{ k}\Omega$$

You should use the ohmmeter to verify that each of these resistors has, at least approximately, the correct value.

You will use an adjustable, precision resistor to represent the sensor.

You will use

$$V_S = 5 \text{ V}$$

For V_S use the third source on the Siglent DC power supply. With the sources still turned off, connect the $+$ terminal of the third source to the point in the circuit of Figure 2 where V_S is supposed to be applied. Connect the $-$ terminal of the third source to ground.

Now, with the bridge amplifier circuit complete and in anticipation of making measurements, turn on the sources.

Test your bridge amplifier for each of the following values for ΔR: -1 kΩ, -0.5 kΩ, 0 kΩ, $+0.5$ kΩ, and $+1$ kΩ. For each value of ΔR, measure V_{BA} using the DC voltmeter.

AC Bridge

Construct the AC bridge of Figure 3. Use resistance decade boxes for the two resistors. Use a capacitance decade box for C. Initially, set C to 30 nF. Use a 33-nF physical capacitor from the components drawer for C_X. This fixed capacitor should bear the marking “333”. This stands for 33×10^3 pF or, equivalently, 33 nF or 0.033 μF. Set the synthesized frequency generator to produce a sinusoid of frequency 1 kHz and amplitude 5 V.

Connect the voltage at the “top” of C_X (that is, the voltage at the resistor/capacitor node on the *right* side of the bridge) to channel 1 of the oscilloscope. Connect the voltage at the “top” of C (that is, the voltage at the resistor/capacitor node on the *left* side of the bridge) to channel 2. Set the math channel of the oscilloscope to display channel 1 minus channel 2. Therefore, the math channel will display V_B. Using the Measure menu, have the oscilloscope display the math-channel rms voltage.

Using trial and error, adjust C so as to minimize the rms value of V_B. When this is accomplished, identify the measured value of C_X as the value of C that minimizes V_B. Since C_X is advertised as 33 nF, you should find that the measured value of C_X is close to 33 nF.

Lab Report

Define the terms *sensor* and *transducer*.

For the Wheatstone bridge, plot V_B as a function of ΔR. This figure should contain both a solid curve for the theory (your Wheatstone bridge equation from the Prelab) and discrete points for your measured data.

For the bridge amplifier, plot V_{BA} as a function of ΔR. This figure should contain both a solid curve for the theory (your bridge amplifier equation from the Prelab) and discrete points for your measured data.