Wheatstone bridge & differential amplifiers: Procedure

ME 240: Fundamentals of Instrumentation & Measurement • D. H. Kelley and I. Mohammad

Introduction

Most mechanical systems integrate with electrical systems —from simple electric motors and sensors to huge industrial instrumentation. Therefore, measuring and controlling current and voltage is vital. This lab introduces four types of circuits: voltage divider, current divider, Wheatstone bridge, and differential amplifier.

A voltage divider circuit is based on the principle that when two resistors are connected in series such that the same current flows through both, proportionally more voltage is dropped across the resistor with the higher resistance. This can be useful for creating a reference voltage or as a signal attenuator. Figure 1a shows a voltage divider with resistors having values R_1 and R_2. Taking the total voltage drop, V_{in}, as the input, Kirchoff's laws show that the voltage across resistor R_1 is

$$V_1 = \frac{R_1}{R_1 + R_2} V_{\text{in}}, \tag{1}$$

and the voltage across resistor R_2 is

$$V_2 = \frac{R_2}{R_1 + R_2} V_{\text{in}}. \tag{2}$$

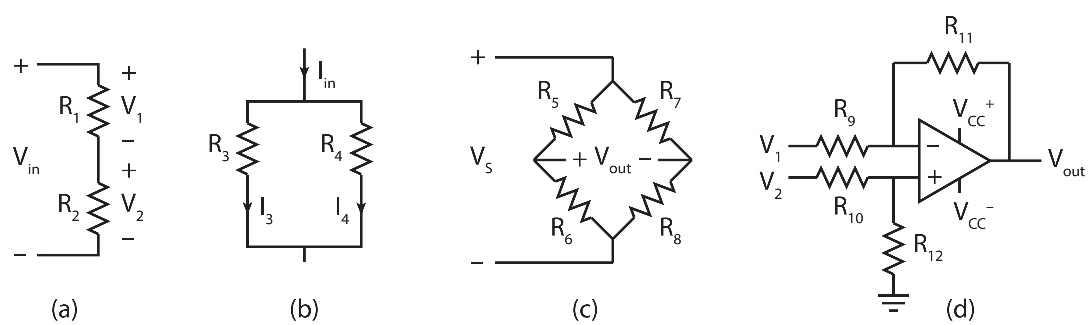

Figure 1: (a) Voltage divider. (b) Current divider. (c) Wheatstone bridge. (d) Differential amplifier made with an op-amp. In the amplifier circuit, the op-amp input pins are labeled "+" and "–", and all voltages are referenced to ground.

A current divider is based on the principle that when two resistors are connected in parallel such that the voltage drop across both is the same, proportionally more current flows through the resistor with the smaller resistance. A current divider can be used, for example, to split a current to power two or more components. Figure 1b shows a current divider with resistors having values R_3 and R_4. Taking the total current, I_{in}, as in the input, Kirchoff's laws show that the current through resistor R_3 is

$$I_3 = \frac{R_4}{R_3 + R_4} I_{\text{in}}, \tag{3}$$

and the current through resistor R_4 is

$$I_4 = \frac{R_3}{R_3 + R_4} I_{\text{in}}. \tag{4}$$

A Wheatstone bridge is a circuit used to determine an unknown resistance by balancing it against known resistances. Wheatstone bridges are essential for determining small variations of large resistances, which occur when working with thermistors and strain gauges, for example. A Wheatstone bridge is composed of four resistors forming two parallel voltage dividers. In the bridge shown in Fig. 1c, resistors with values R_5 and R_6 form one voltage divider, while resistors with values R_7 and R_8 form another. Suppose R_5 is the unknown resistance you wish to determine, and that $R_5 = R + \delta R$, with $\delta R \ll R$. That is, R_5 differs only slightly from some known value R, and the difference (δR) is what you wish to determine. Now if you choose $R_6 = R_7 = R_8 = R$, apply a voltage V_{S}, and measure a voltage V_{out}, Kirchoff's laws show that the two voltages are related by

$$V_{\text{out}} = -\frac{\frac{\delta R}{R}}{4 + 2\frac{\delta R}{R}} V_{\text{S}}. \tag{5}$$

The fact that $\delta R \ll R$ implies $2\delta R/R \ll 4$, so it is accurate to make the approximation

$$\delta R = -4R\frac{V_{\text{out}}}{V_{\text{S}}}, \tag{6}$$

which shows that δR varies linearly with V_{out}.

Finally, as its name would suggest, a differential amplifier amplifies the difference between two input signals. This type of amplifier is particularly useful for reducing noise that is common to both signals. Such "common mode" noise often occurs in instrumentation, where wires tend to pick up common noise from ground connections and nearby sources of wireless noise (like other wires). Figure 1d shows a simple differential amplifier circuit that uses an operational amplifier (op-amp) device. Kirchoff's laws, along with a few rules for modeling the op-amp, show that the output voltage V_{out} is related to the two input voltages V_1 and V_2 by

$$V_{\text{out}} = \left(\frac{R_{12}}{R_{10} + R_{12}}\right)\left(\frac{R_9 + R_{11}}{R_9}\right) V_2 - \frac{R_{11}}{R_9} V_1. \tag{7}$$

If the circuit is designed such that $R_9 = R_{10}$ and $R_{11} = R_{12}$, the expression simplifies to

$$V_{\text{out}} = \frac{R_{11}}{R_9}(V_2 - V_1). \tag{8}$$

That is, the output voltage is proportional to the difference between the two input voltages.

An op-amp has two input pins for signals, labeled "+" and "–" in Fig. 1d. In order to amplify a signal, an op-amp requires a ground connection (not shown in Fig. 1d) and two power connections, V_{CC}^+ and V_{CC}^-, which are positive and negative, respectively. The power connections limit the range of possible output voltages: $V_{\text{CC}}^- < V_{\text{out}} < V_{\text{CC}}^+$. (In practice, the range is a bit smaller.)

Learning goals

- Measure voltage, current, and resistance using a multimeter.
- Build a voltage divider on a breadboard referring to a circuit diagram.
- Build a current divider on a breadboard referring to a circuit diagram.
- Build and balance a Wheatstone bridge for sensitive resistance measurements.
- Build a differential amplifier circuit with a negative feedback referring to a circuit diagram.
- Gain familiarity with amplifier gain.

Materials

- **Voltage divider:** Breadboard, two random resistors, 2.2 kΩ resistor, 5.6 kΩ resistor, breadboard wires, power supply, multimeter
- **Current divider:** Breadboard, 10 Ω resistor, 47 Ω resistor, breadboard wires, power supply, multimeter
- **Wheatstone bridge:** Breadboard, three 120 Ω±0.1% resistors, potentiometer, breadboard wires, power supply, multimeter, screwdriver
- **Differential amplifier:** Breadboard, two 2.2 kΩ resistors, two 5.6 kΩ resistors, μA741 operational amplifier, breadboard wires, two power supplies (or one dual power supply), function generator, oscilloscope

Safety

Closed-toed shoes are required. Power supplies must be handled with caution to avoid electric shock and burns.

Voltage divider measurement and analysis

Resistors are painted with stripes that indicate their nominal resistances, according to a standard color code, available here (or use the QR code in Fig. 2). To practice its use, choose two random resistors, photograph them together, use the code to determine their nominal resistances, measure their resistances with a multimeter, and then calculate the percent differences between the nominal and measured resistances. Record your results in the Deliverables.

Build the voltage divider circuit shown in Fig. 1a using a breadboard like the one in Fig. 4 and resistors $R_1 = 2.2$ kΩ and $R_2 = 5.6$ kΩ. Use Eqs. 1 and 2 to calculate the voltages V_1 and V_2 expected if $V_{\text{in}} = 7$ V, recording your results. Apply an input voltage $V_{\text{in}} = 7$ V using a power supply. Measure V_1 and V_2 using a multimeter (refer to Fig. 3). Determine the percent difference between the calculated and measured values of both. Reduce the input μA741 data sheet

resistor color code

Figure 2: QR codes linking to relevant documentation.

voltage to $V_{\text{in}} = 3.5$ V and measure the new values of V_1 and V_2. Comment briefly on the changes to V_1 and V_2 caused by altering V_{in}.

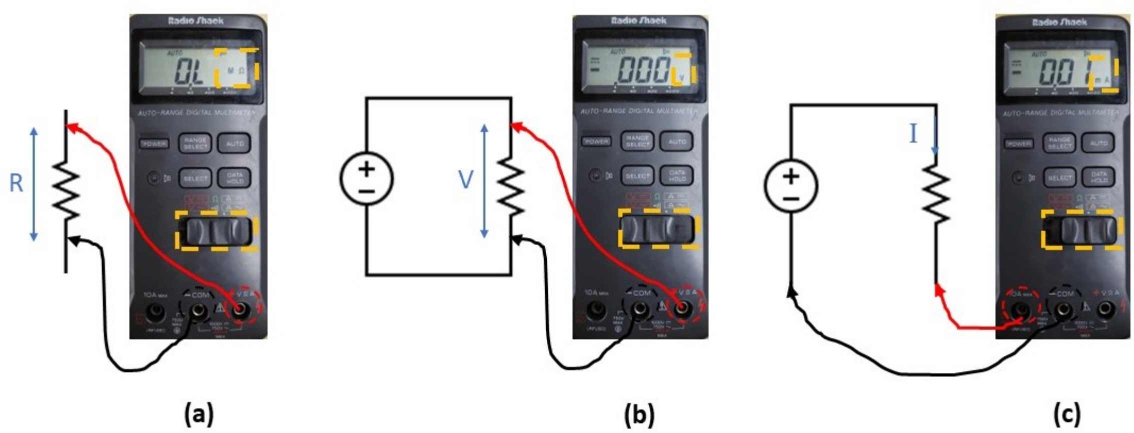

Figure 3: Multimeter as (a) an ohmmeter, (b) a voltmeter, and (c) an ammeter.

Current divider measurement and analysis

Build the current divider circuit shown in Fig. 1b using a breadboard and resistors $R_3 = 10\ \Omega$ and $R_4 = 47\ \Omega$. Use Eqs. 3 and 4 to calculate the currents I_3 and I_4 expected if $I_{\text{in}} = 50$ mA, recording your results. Apply an input current $I_{\text{in}} = 50$ mA using a power supply, being sure to measure I_{in} with a multimeter (refer to Fig. 3c), which is more precise than a power supply. Measure I_3 and I_4 using a multimeter. Determine the percent differences between the calculated and measured values of both. Reduce the input current to $I_{\text{in}} = 25$ mA and measure the new values of I_3 and I_4. Comment briefly on the changes to I_3 and I_4 caused by altering I_{in}.

Wheatstone bridge measurement and analysis

Build the Wheatstone bridge circuit shown in Fig. 1c using a breadboard and resistors $R_6 = R_7 = R_8 = R = 120\ \Omega \pm 0.1\%$. The Wheatstone bridge will work well only if $R_6 = R_7 = R_8$ with good accuracy, so be sure to choose precision resistors with values specified to be accurate to 0.1%; common resistors have values accurate only to 5%. Use a potentiometer,

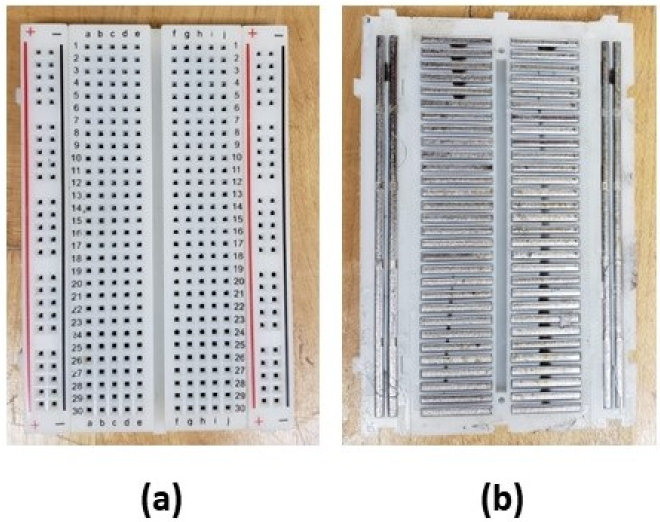

Figure 4: A breadboard, seen (a) from above and (b) from below, with its cover removed to reveal electrical connections. Breadboards make it easy to connect electronic devices (e.g., resistors, potentiometers, and op-amps), as each hole accommodates one lead or pin from a device. Most of the holes in the breadboard are electrically connected in rows. For example, holes 1a – 1e are all connected, and holes 1f – 1j are all connected. The edges, however, are meant for power supplies and are electrically connected in columns. For example, all of the holes in the left column labeled "+" are connected.

a device with adjustable resistance, in place of R_5. A potentiometer typically has three pins, and the resistance between the middle pin and either end pin can be changed by spinning the knob on top. Before connecting it to the circuit, adjust the potentiometer until its resistance, as measured with a multimeter, is about 123 Ω, and record the corresponding value of δR. Then connect the potentiometer to the circuit and apply a source voltage $V_S = 7$ V using a power supply. Measure V_{out} and record its value. Use that value in Eq. 6 to determine δR, recording the result. How different is the result from the value of δR you determined using the multimeter? Now remove the potentiometer from the circuit and adjust its knob until its resistance, as measured with a multimeter, is about 117 Ω. Record the corresponding value of δR. Return the potentiometer to the circuit. Again measure V_{out} and record its value. Again use Eq. 6 to determine δR. How different is the value from the one you determined by measuring the potentiometer's resistance with a multimeter?

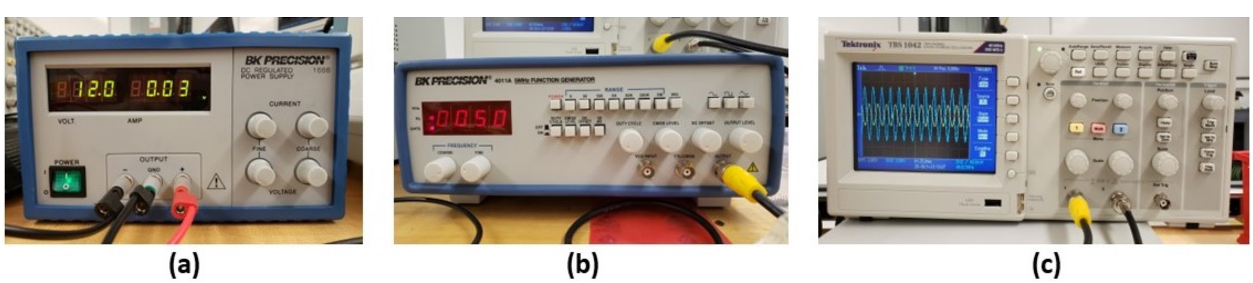

Figure 5: (a) Power supply. (b) Function generator. (c) Oscilloscope.

Differential amplifier measurement and analysis

Build the differential amplifier circuit shown in Fig. 1d using a breadboard, a μA741 op-amp, resistors $R_9 = R_{10} = 2.2$ kΩ, and resistors $R_{11} = R_{12} = 5.6$ kΩ. Check the op-amp manual, available here (or use the QR code in Fig. 2) for the pin configuration. Using the nominal resistances and assuming that the input voltage $(V_2 - V_1)$ has peak-to-peak amplitude 500 mV, calculate the peak-to-peak amplitude of the output voltage V_{out}. Calculate the differential gain $V_{\text{out}}/(V_2 - V_1)$. Use two power supplies (or one dual power supply) to provide $V_{\text{CC}}^{+} = 12$ V and $V_{\text{CC}}^{-} = -12$ V. Use a function generator (see Fig. 5) to apply a sinusoidal signal with frequency 50 Hz and peak-to-peak amplitude 500 mV across the V_1 and V_2 pins. Be sure that the ground nodes of the power supply, function generator, and op-amp are all connected (breadboards are handy for this). Connect channel 1 of an oscilloscope to the function generator and channel 2 to the output voltage V_{out}. Read the peak-to-peak amplitude of the output voltage from the oscilloscope and record it in the Deliverables. Calculate the percent difference between the expected and measured the peak-to-peak output amplitude and record it in Deliverables. Adjust the function generator such that the input voltage has frequency 1 kHz and peak-to-peak amplitude 250 mV. Read the peak-to-peak amplitudes of the input and output voltages from the oscilloscope and record them in the Deliverables. Comment briefly on the changes to V_{out} caused by altering $(V_2 - V_1)$.