Lab #2: The Basic Difference Amplifier

Introduction

A common problem in the design of many communication and environmental monitoring systems is that the cables used to carry signals from one location to another pick up interfering signals and noise radiated or coupled by other devices. For example, the output from a medical sensor might be transmitted to a monitor via a cable, but that same cable might also pick up 60 Hz common-mode energy from the clinic's AC wiring. Unwanted signals can corrupt the desired sensor signal, leading to misleading displays on the monitor. Difference amplifiers are widely used to address this problem. Their ability to amplify differential-mode signals while suppressing common-mode noise makes them especially suitable for this type of application. In this lab exercise you will build a basic difference amplifier and investigate its performance capabilities. Group assignments are listed at the end of this handout.

Theoretical Background

A circuit diagram of a simple difference amplifier is shown in Figure 1. The circuit amplifies the difference in the single-ended voltages applied to inputs v_1 and v_2, giving the amplifier its name.

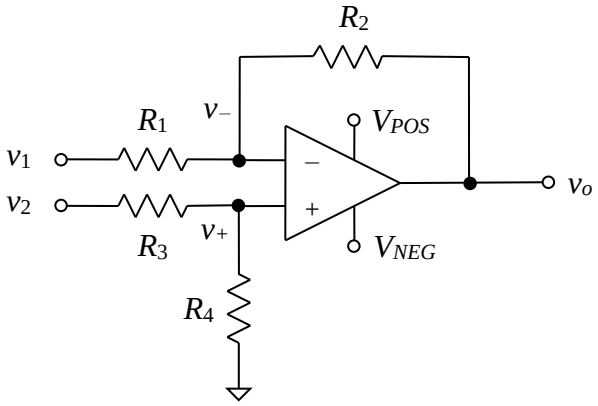

Figure 1. A simple difference amplifier. The nodes marked V_{POS} and V_{NEG} are the connections to the positive and negative power supplies, respectively. The small triangle represents a connection to the ground node. Power supply bypass capacitors are not shown here but should be included in a physical circuit.

The analysis of the circuit is most easily accomplished using the principle of superposition and leads to an expression for the output voltage given by

$$v_o = \left(1 + \frac{R_2}{R_1}\right)\frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} v_1 .$$

If the resistor ratios obey the relationship $R_4/R_3 = R_2/R_1$ exactly, then the output voltage expression reduces to

$$v_o = \frac{R_2}{R_1}(v_2 - v_1).$$

This ideal result depends on a perfect match between the two resistor ratios, a condition that cannot be achieved in practice with fixed resistors.

Difference amplifiers are widely used to boost signals arriving via long cables that are susceptible to common-mode noise pick-up. Analysis of the circuit is therefore aided by defining the differential and common-mode input signals as

$$v_{Id} = v_2 - v_1 \quad \text{and} \quad v_{Icm} = \frac{v_1 + v_2}{2}.$$

Solving these equations for v_1 and v_2 yields the equivalent relationships

$$v_1 = v_{Icm} - 0.5v_{Id} \quad \text{and} \quad v_2 = v_{Icm} + 0.5v_{Id}.$$

The latter set of expressions suggests a way to model the differential and common-mode voltages applied to a difference amplifier. Figure 2 shows a commonly used (but not the only) approach.

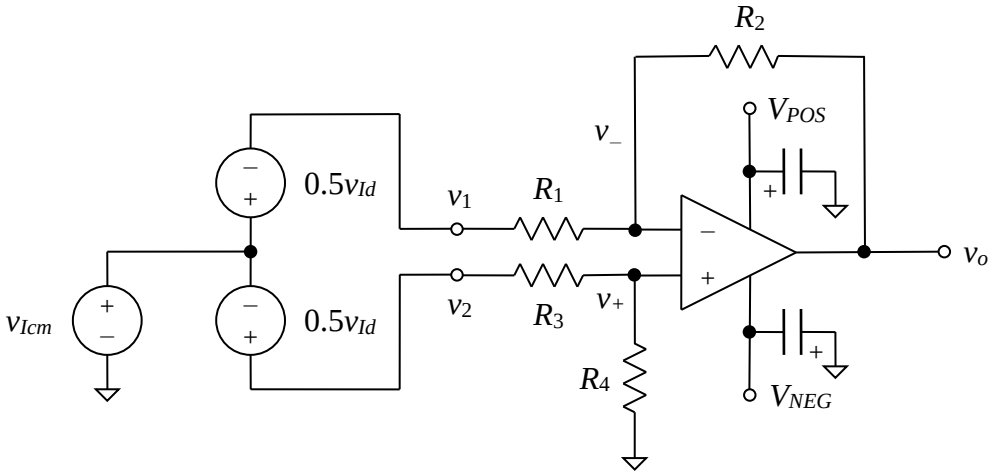

Figure 2. Circuit model of the differential-mode and common-mode signals at the input terminals of a difference amplifier. The electrolytic capacitors connected to the power supply terminals help eliminate noise that enters the circuit through the power leads. The two voltage sources labeled $0.5v_{Id}$ represent a single differential-mode input signal; the split voltage sources are merely a modeling convenience.

The common-mode signal is modeled as a single voltage source v_{Icm} referenced to ground, and the differential-mode signal is modeled as split voltage sources each of value $0.5v_{Id}$ connected to the two input terminals. The use of two differential-mode sources does not mean that there are two separate differential-mode signal sources; it simply allows the common-mode and differential-mode input signals to be modeled using a symmetrical structure. The common-mode gain can be determined by finding the output voltage with the two $0.5v_{Id}$ sources set to zero (in

which case the inputs v_1 and v_2 are connected, becoming a single node). Similarly, the differential-mode gain can be determined by finding the output voltage with the v_{Icm} source set to zero. In the latter case, the connection to ground between the two $0.5v_{Id}$ sources should be preserved to facilitate the analysis.

The complete expression for the output voltage in terms of the differential and common-mode input signals is (as derived in a separate set of course notes)

$$v_o = v_{od} + v_{ocm} = \frac{1}{2}\left[\left(1+\frac{R_2}{R_1}\right)\frac{R_4}{R_3+R_4}+\frac{R_2}{R_1}\right]v_{Id} + \left[\left(1+\frac{R_2}{R_1}\right)\frac{R_4}{R_3+R_4}-\frac{R_2}{R_1}\right]v_{Icm},$$

where v_{od} and v_{ocm} are the components of the output voltage due to the differential-mode input voltage v_{Id} and the common-mode input voltage v_{Icm}, respectively. If the relationship $R_4/R_3 = R_2/R_1$ is satisfied exactly, the first coefficient (the differential-mode gain) reduces to R_2/R_1, and the second coefficient (the common-mode gain) reduces to zero. In a practical amplifier, the variations of the resistor values from their nominal values and other imperfections prevent complete cancellation of the common-mode signal. As shown in the notes on diff amps, the common-mode gain expression can be modified so that the output voltage can also be expressed as

$$v_o = v_{od} + v_{ocm} = \frac{1}{2}\left[\left(1+\frac{R_2}{R_1}\right)\frac{R_4}{R_3+R_4}+\frac{R_2}{R_1}\right]v_{Id} + \left[\frac{R_4}{R_3+R_4}\left(1-\frac{R_2}{R_1}\frac{R_3}{R_4}\right)\right]v_{Icm}.$$

Formulas for the differential and common-mode gains can be isolated from the expressions above, which yields

$$A_d = \frac{v_{od}}{v_{Id}} = \frac{1}{2}\left[\left(1+\frac{R_2}{R_1}\right)\frac{R_4}{R_3+R_4}+\frac{R_2}{R_1}\right]$$

and

$$A_{cm} = \frac{v_{ocm}}{v_{Icm}} = \left(1+\frac{R_2}{R_1}\right)\frac{R_4}{R_3+R_4}-\frac{R_2}{R_1} = \frac{R_4}{R_3+R_4}\left(1-\frac{R_2}{R_1}\frac{R_3}{R_4}\right).$$

Design Specifications

IMPORTANT: Read *all* of the following design specifications. You will save a lot of time if you have a complete picture in your mind of what you need to do before you get started.

Design, build, and test a difference amplifier like the one shown in Figure 2 that meets the following specifications as closely as possible.

- Differential-mode gain (v_{od}/v_{Id}): A_d = 15 V/V
- Min. differential-mode input resistance (see textbook): $R_{id} = R_1 + R_3$ = 20 kΩ
- Power supply voltages: not critical, but at least ±12 V to avoid clipping; do not exceed the maximum magnitude specified in the datasheet
- Input bias current effects and input offset voltage effect minimized as much as possible (see recommendation #4 below)

- Each resistor in the circuit must be a single fixed unit. That is, you may not combine multiple resistors in parallel or in series to obtain a total resistance close to the exact value that you need. This restriction is typical in real-world design situations. Using more resistors than necessary adds cost, weight, and bulkiness to a circuit.

Recommendations

1. Take notes throughout your design process. Record when ideas work, when they do not, and what happened in each case.
2. Remember that the voltage sources v_{Icm} and $0.5*v_{Id}$ in Figure 2 are only models used to simulate the common-mode and differential-mode input voltages. They might or might not be valid representations of test circuits.
3. Consider connecting 10 μF electrolytic capacitors between the op-amp's power supply pins and ground to suppress noise arriving through those paths. (Watch the polarities!) Bypass capacitors should be mounted as close to the IC as possible using short leads. The use of power supply bypass capacitors is a good design practice and should be employed in almost all circuits. If the 10 μF value is not available, then the next higher or lower value can be used.
4. One of your required tasks will be to measure the output voltage of the amplifier with the inputs driven by a purely common-mode signal. The resulting common-mode output voltage is likely to be very low, as little as 1–10 mV, but the measurement could be corrupted by the presence of a DC output error voltage due to the combined effects of the input bias currents and the input offset voltage. You will therefore need to take steps to minimize it. The error voltage can be measured using the test configuration shown in Figure 3. You will need to add some components to mitigate the error voltage. Those components are not shown in Figure 3. Consult the op-amp's datasheet for details on how to mitigate output error voltage, or devise a method of your own. Take measurements of the output error voltage before and after you mitigate the problem; your group will need to present these results during the post-lab meeting. Finally, keep in mind a recent ungraded homework problem that showed that the resistor pair R_1 and R_3 and the pair R_2 and R_4 should each have the same nominal value; that is, not only should the ratios R_4/R_3 and R_2/R_1 match, but the resistors' respective values should match as well to help mitigate the effects of the input bias currents.

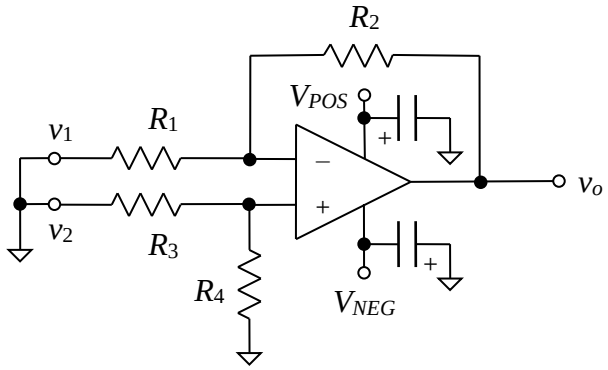

Figure 3. Test configuration for measuring the effects of the input offset voltage and input bias currents on the output voltage. Both inputs of the diff amp are shorted to ground. Note that bypass capacitors have been added to help reduce noise entering the circuit through the power supply leads.

Experimental Procedure

BEFORE YOU BEGIN: Two demonstrations will be required during the lab sessions. To ensure that you complete the lab exercise on time, you should strive to complete Demo #1 during the first lab meeting. Both demonstrations **must** be completed during the first two lab sessions; otherwise, there will be a 5-point score reduction.

- After you have completed your design and assembled your amplifier circuit, test your chosen method for minimizing the effect of the input bias currents and input offset voltage. Using the test configuration shown in Figure 3, measure the output voltage without the mitigation applied and record the voltage. Then add the mitigation circuitry and confirm that you can reduce the measured output voltage to nearly zero (to the extent that the noise on the output allows). Demonstrate your mitigation method to the instructor before moving on to the next item. **(In-lab Demo #1)**

- Measure the exact values of resistors R_1 through R_4, record their values, and calculate accurate expected values for the differential-mode gain (v_{od}/v_{Id}) and common-mode gain (v_{ocm}/v_{Icm}) using your measurements. Use the appropriate information from the "Theoretical Background" section as a guide. Carefully record your results. During the post-lab meeting, you will be required to present all of your calculations and measurements. The data must be complete and well organized.

- Devise a way to apply a differential-mode DC signal to the amplifier's input terminals, and use it to verify that the amplifier has the specified differential-mode gain. As shown in Figure 2, to do this properly you will need to simulate two equivalent voltage sources with the positive terminal of one and the negative terminal of the other connected to ground. You should be able to design a simple circuit to accomplish this task using one or two op-amps and a few resistors. Other options are also possible. Use modest resistor values in the new circuit to avoid output error voltages due to the input offset voltage and input bias currents, but make the resistors large enough to keep the op-amps' output currents below the rated limit. Measure the actual differential input voltage that you apply to the circuit using the multimeter since it is a DC voltage. Do not assume that the input voltage exactly matches the expected value. Before proceeding to the next item, ask the instructor to check your differential-mode test circuit. **(In-lab Demo #2)**

- Calculate the differential-mode gain (v_{od}/v_{Id}) from your measured data, and verify that it is close to the design value. Carefully record your measurements and calculations so that you can present them during your post-lab meeting.

- Use the bench-top function generator to apply a purely common-mode AC voltage at a frequency of 60 Hz to the amplifier, and determine the common-mode gain (v_{ocm}/v_{Icm}) from the measured input and output voltage values. Use the oscilloscope to make these measurements, and display the input and output waveforms simultaneously. Use a common-mode voltage amplitude that will allow you to make the most accurate measurement possible; think about the implications of using low voltages. You may assume that the function generator acts as an ideal voltage source, although its output resistance (i.e., its internal or Thévenin equivalent resistance) is about 50 Ω.

If the displayed waveform is noisy, try using the "BW Limit" feature of the oscilloscope, which is accessed by pressing the appropriate channel on/off key. This feature activates a low-pass filter with a cut-off frequency of about 20 MHz at the oscilloscope's input; it is useful for reducing the interference from campus radio station WVBU. Make sure that you understand how to determine the peak or peak-to-peak voltage level of a noisy oscilloscope trace. Carefully record your measurements and calculations, and clearly identify whether the voltages are in peak (pk) or peak-to-peak (pp) units. You will need to report your measurements in your post-lab meeting.

- Compare the measured common-mode gain to the calculated common-mode gain determined earlier from the actual values of resistors R_1 through R_4. If the two gain values do not match relatively closely (within 20–30% or so), examine your circuit carefully. If you are confident that the circuit is wired correctly, think of plausible reasons why the discrepancy might have occurred.

- **[This item is required for a four-person group and optional for a three-person group.]** Devise a way to make the resistor ratios R_4/R_3 and R_2/R_1 match as closely as possible in order to reduce the common-mode gain to a much lower value. You may replace one of the fixed resistors with a potentiometer with an appropriate range. You might also consider wiring a fixed resistor and potentiometer in series to obtain finer control.

  Apply the same common-mode gain measurement procedure as before, but this time adjust the circuit (if possible) while monitoring the output voltage on the oscilloscope. There might be some interaction with your hand due to stray capacitance effects, so make observations when your hand is away from the circuit. Make sure that you understand what you observe as it relates to the common-mode gain expression. You will need to demonstrate and explain your results during the post-lab meeting if you are in a four-person group.

- Schedule a post-lab meeting (length up to 30 min) with me to take place during the Tuesday, Sept. 30 lab session. The following guidelines apply:

  - Read these guidelines and the "Post-Lab Meeting" section below well in advance of the meeting. You will need to prepare a set of visual aids.
  - **All equations, variables, and other mathematical content must be formatted according to the guidelines posted on the Laboratory page at the course web site.**
  - All group members must be present, but you do not have to remain in the lab room after your group's meeting has ended.
  - Meetings will be scheduled either in the order that requests are received or by random assignment.
  - Meetings will not be rescheduled if the first one reveals circuit problems, wiring failures, errors in the test procedure, or a lack of preparation.
  - Deadline extensions will generally be approved for confirmed illnesses or other extenuating circumstances. Make-up meetings will be scheduled at a mutually agreed time before the end of Friday, Oct. 3 but not during a lecture, lab, or recitation section for another course or during important work, athletic, rehearsal, or similar commitments. Make-up meetings will take place in the Maker-E if Dana 307 is not available at the scheduled time.

- Compile the visual aids that your group intends to use into a single PDF document (size less than 5 MB) and **e-mail** it to me before the post-lab meeting begins. Use a file name of the form

  LName1_LName2_LName3_Lab2_fa25.pdf,

  where "LName1," "LName2," and "LName3" are the group members' last names. Include the underscore (_) characters. Omit "LName3" if your group has two members, or add "LName4" if your group has four members. For example, if students Alvarez, Zhang, and Smith are lab partners, then their Lab #2 documentation would have the file name

  Alvarez_Zhang_Smith_Lab2_fa25.pdf.

Post-Lab Meeting

Each group member must respond to one of the prompts from the numbered list below and possible follow-up questions. Each member's response will determine the individual portion of their score for Lab #2. The following guidelines apply:

- Each person will have a time limit of **five minutes** in which to respond.
- You may assign the prompts to group members before the meeting.
- Each response must be supported by high-quality visual aids prepared by the respondent, including a properly labeled circuit diagram (or diagrams). **All equations, variables, and other mathematical content must be formatted according to the guidelines posted on the Laboratory page at the course web site.** Graphics such as circuit diagrams may be prepared by hand, but they must be very neat and legible. You should strongly consider using software to prepare data tables.
- Include a list of the measured values of R_1 through R_4 to allow verification of the gain quantities.
- Visual aids must be complete enough for understanding but not so information-packed that they are overwhelming or create visual clutter that detracts from clarity.
- Organize the physical circuit layout and connections to equipment so that group members can switch between demonstrations quickly.
- Excessive delays will affect group and/or individual scores as appropriate.

The four prompts are listed below. A two-person group must address Prompts #2 and #3:

1. [Omit for 2-person group:] Explain how you reduced the effects of the input bias currents and the input offset voltage and how you confirmed the effectiveness of your chosen method. Your visual aids must include a high-quality circuit diagram that depicts the method and a summary of the measured results before and after it was applied.

2. Demonstrate a differential-mode gain measurement and compare the result to the calculated differential-mode gain. Express both gain values in multiplying factor form and in decibels. Briefly explain how you generated an effective differential-mode test signal. Either describe the supplemental circuitry that you designed or explain how you were able to apply an appropriate signal another way, whichever is relevant. You will need to thoroughly understand how the test equipment is used for this type of measurement. Your visual aids must include a high-quality circuit diagram and a comparison of the calculate and measured results.

3. Demonstrate a common-mode gain measurement and compare the result to the calculated common-mode gain. Also explain how you ensured that the measurements were as accurate as possible. Calculate the worst-case CMRR using the expression given below. Explain the relationship between it and the calculated and measured CMRR values and brief implications of the results. Express all CMRR values in multiplying factor form and in decibels.

$$\mathrm{CMRR}_{\min} = \frac{1 + \dfrac{R_{2\mathrm{nom}}}{R_{1\mathrm{nom}}}}{4\varepsilon},$$

where ε is the fractional resistor tolerance, and $R_{1\mathrm{nom}}$ and $R_{2\mathrm{nom}}$ are the nominal (labeled) values of R_1 and R_2.

In a four-person group, one person must:

4. Demonstrate how the circuit was modified to reduce the common-mode gain to the minimum possible value. (See second bullet on page 6.) This will require you to rewire the circuit quickly. Include a concise explanation of your design process. Your visual aids must include a high-quality circuit diagram that accurately depicts the modifications that you made and a comparison of the results before and after the circuit was modified.

After the response to each prompt, there will be a follow-up discussion of the design process, the circuit's function, measurement results, and other related topics.

Lab Scoring Criteria

Each group member will receive a score based on the following criteria quantized at the indicated point values. The first two criteria constitute a group base score; that is, each group member will receive the same score for those criteria. The remaining criteria will be assessed independently and will be determined by that person's contribution to the post-lab meeting. The rubrics posted on the Laboratory page at the course web site will guide the assignment of scores.

0, 10, 20, 30, 40 pts	Functional diff amp w/appropriate component values (group)
0, 5, 10, 15, 20 pts	Satisfactory completion of in-lab demos (group)
0, 8, 15, 23, 30 pts	Quality of response to prompt (indiv.)
0, 2, 5, 8, 10 pts	Quality and effectiveness of supporting visual aids (indiv.)
−5 pts/demo	Reduction if demo(s) not completed during first two lab sessions

A good presentation must be technically accurate but must also have excellent oral and visual components that are well integrated. Above all, the presentation that you give during your post-lab meeting should demonstrate that you have engaged deeply with the material and achieved a high level of understanding. It will be challenging to achieve a perfect score.

If the meeting is completed after the deadline, a 10% score deduction will be applied for every 24 hours or portion thereof that it is late (not including weekend days) unless extenuating circumstances apply. No credit for the individual criteria will be given four or more days after the deadline; however, up to 60 pts will be assigned to each member of the group for the group criteria if at least one member demonstrates a functional circuit within one week of the deadline.

Group Assignments

The randomly generated groups for this lab exercise are listed below.

1:00 pm section:
Prevuznak-Foster-De La Cruz
Cherniske-Golden

3:00 pm section:
Pan-Vaccaro-Wu
Chernova-Manicke-Ortiz-RiosSaldivar
Bui-Charles-English-Kraiker