

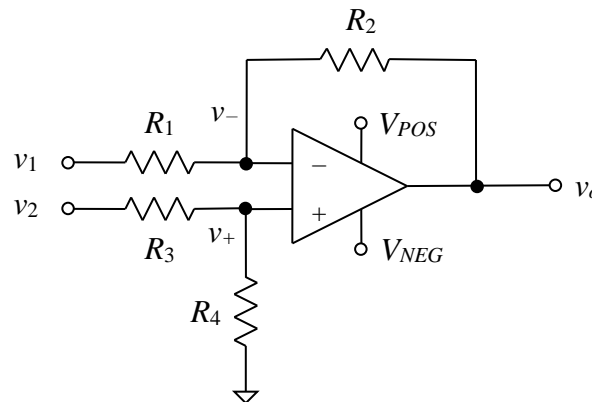
## Lab #2: The Basic Difference Amplifier

### 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 voltage values between 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.

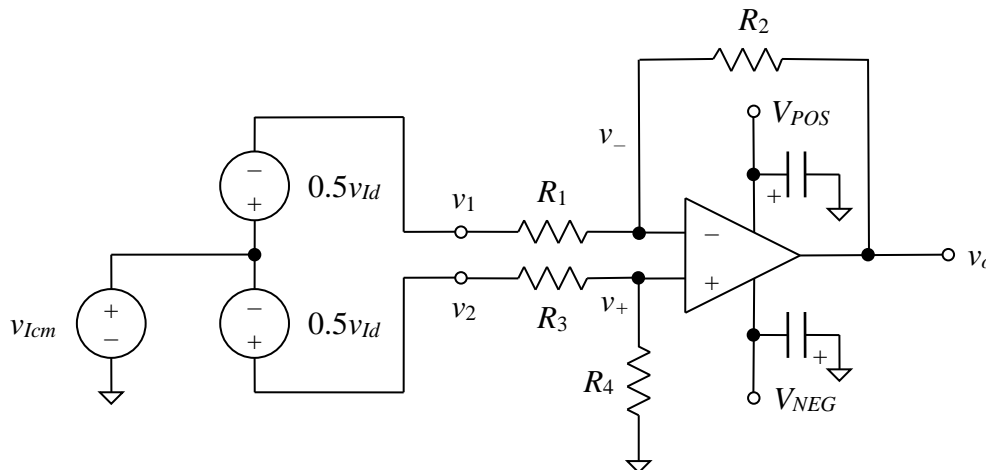
Difference amplifiers are widely used to boost signals arriving via long cables that are susceptible to common-mode noise pick-up. Analysis of the circuit is therefore aided by defining the differential and common-mode input signals as

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

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 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 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 together). 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.

### Design Specifications

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

Your assignment is to design, build, and test a difference amplifier like the one shown in Figure 1 or 2 that meets the following specifications as closely as possible. You should take notes throughout your design process.

Differential-mode gain ( $v_{od}/v_{Id}$ ):  $A_d = 15$  V/V

Min. differential-mode input resistance (see textbook):  $R_{id} = R_1 + R_3 = 20$  k $\Omega$

Power supply voltages: not critical, but at least  $\pm 12$  V or so to avoid clipping and below the maximum magnitude specified in the datasheet

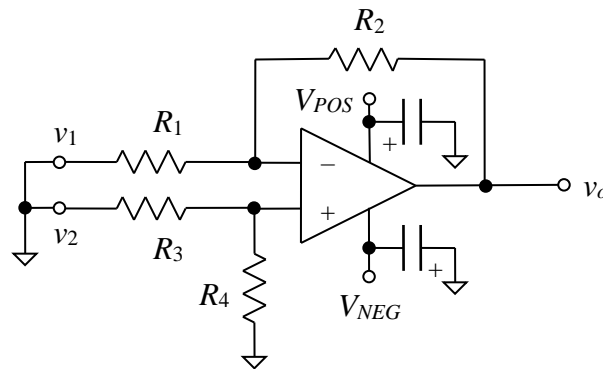
Input bias current effects and input offset voltage effect minimized as much as possible

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

You should also connect 10  $\mu$ F 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  $\mu$ F value is not available, then the next higher or lower value can be used.

One of the tasks you will be required to complete will be to measure the output voltage of the amplifier with the inputs driven by a purely common-mode signal. The resulting output voltage should be very low, as little as 1–10 mV, but the measurement could be corrupted by the presence of an output error voltage due to the combined effects of the input bias currents and the input offset voltage, so you will 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 mitigated the problem; your group will need to present these results during the post-lab meeting.



**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

- After you have completed your design, 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 the appropriate information from the “Theoretical Background” section. Carefully record your results. During the post-lab meeting, you will be required to present all of your calculations and measurements in tabular form. The data must be complete and well organized.
- After the difference amplifier has been assembled and the effects of the input bias currents and input offset voltage eliminated, 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 in reality its output resistance (i.e., its internal or Thévenin equivalent resistance) is about 50  $\Omega$ . To determine the amplitude of the output voltage more easily, you might need to use the “BW Limit” feature of the oscilloscope, which is accessed by pressing the appropriate channel on/off key. This feature adds in a low-pass filter with a cut-off frequency of about 20 MHz; 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. Demonstrate your common-mode gain measurement to the instructor before moving on to the next item (**In-lab Demo #1**).

- 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.

Use the function generator to determine the common-mode gain as before, but this time adjust the circuit (if you are able to) 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.

- Now apply a differential-mode DC input signal to the amplifier and 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 cannot do this using the bipolar part of the bench-top power supply because it is being used to supply the operating voltages for the op-amp. However, you should be able to devise a simple circuit to do the job using one or two op-amps and a few resistors. Other options are also possible. Remember to 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 within the rated limit. Alternatively, you may use the 6 V power supply as the differential input if you can correctly apply it as a truly floating voltage. You should measure the actual input voltages that you apply to the circuit (using the multimeter since this is DC); you cannot assume that they exactly match the expected values. 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 in your post-lab meeting.
- When you are confident that your results are correct, schedule a 30-minute post-lab meeting with me at a mutually agreed time before the deadline posted on the Laboratory page at the course web site. The following guidelines apply:
  - All group members must be present.
  - The meeting will take place in the Maker-E if Dana 307 is not available at the scheduled time.
  - Meetings will be scheduled in the order that requests are received.
  - 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.
  - Preparation instructions are given in the “Post-Lab Meeting” section below. **Read them carefully!** Note that you will need to prepare a set of visual aids to refer to during the meeting.
- The visual aids that your group intends to use must be combined into a single PDF document and **e-mailed** to me before the post-lab meeting begins. Include a list of the measured values of  $R_1$  through  $R_4$  to allow verification of the gain quantities. Use a file name of the form

“LName1\_LName2\_LName3\_Lab2\_fa23.pdf,”

where “LName1,” “LName2,” and “LName3” are the group members’ last names. Include the underscore ( \_ ) characters. 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\_fa23.pdf

**The file size must be less than 5 MB.** Keep a copy of your documentation if you wish to use it to prepare for the next exam or need it for future reference.

### Post-Lab Meeting

Each group member must respond to one of the following prompts (a different prompt for each person) and possibly answer a few follow-up questions. This part will constitute each member’s individual demonstration score. Your group may decide how the prompts are assigned. All visual aids may be prepared by hand, but they must be very neat and legible. You should strongly consider using software to prepare data tables. Each person will have a time limit of **five minutes** to respond.

1. Explain how you reduced the effects of the input bias currents and the input offset voltage and how you verified that your chosen method is practical and working properly. Your visual aids must include a high-quality circuit diagram that shows the method you used and a table summarizing the results before and after the mitigation method was applied.
2. Demonstrate a common-mode gain measurement and compare the result to the calculated common-mode gain. Also explain how you ensured that the results were as accurate as possible. Your visual aids must include a high-quality table summarizing your results. The table must include the calculated worst-case CMRR given by the expression below. Explain the relationship between it and the calculated and measured CMRR values.

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

where  $\varepsilon$  is the fractional resistor tolerance, and  $R_{1\text{nom}}$  and  $R_{2\text{nom}}$  are the nominal values of  $R_1$  and  $R_2$ .

3. Demonstrate a differential-mode gain measurement and compare the result to the calculated differential-mode gain. Include a concise explanation of how you generate an effective differential-mode test signal. Either describe the supplemental circuitry 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 table summarizing your results.

In a four-person group, one person must:

4. Demonstrate how you modified the circuit to reduce the common-mode gain to the minimum possible value. This is the bulleted activity above that is required of four-person groups. Note that 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 shows the modifications that you made and a table summarizing the results before and after the circuit was modified.

Each lab member's prompt response score will be based on the extent to which they understand the circuit's design and operation and on the quality of their visual aids. The latter must include a well-organized presentation of results and legible circuit diagrams with clearly labeled component values. A good demo must have excellent oral and visual components; thus, it will be challenging to achieve a perfect prompt response score.

After the individual responses, there could be some general discussion of your design process and measurements, your circuit's function, how you handled any uncertainties, and other related topics. If you made unusual choices, you must be prepared to defend them.

### 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 two criteria. The score for 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 be used to determine the various scores.

0, 10, 20, 30, 40 pts	Functional diff amp w/appropriate component values (group)
0, 10, 20 pts	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.)

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 circumstance apply. No credit for the two 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 first two (group) criteria if at least one group member demonstrates a functional circuit and working measurement procedures within a week of the deadline.

## Group Assignments

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

Jeong-Miller-Sagoe

Freedenberg-Jiorle-Piper

Beebe-Ren-Tuncel

Baganski-Flynn-Samuels

Beaudette-Hackett-Regec

Bailey-Youn-Zhang

Andrews-Ashnault-Powick

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