EXPERIMENT NUMBER 7
Properties of the Operational Amplifier

Preface:
- Preliminary exercises are to be done and submitted individually.
- Laboratory hardware exercises are to be done in groups.
- Work done in notebooks to be submitted individually.
- The laboratory notebooks to be submitted immediately following the laboratory.
- The laboratory notebooks must include all settings, steps and observations in the exercises. All statements must be in complete sentences and all tables and figures must have a caption.
- This laboratory requires technical memorandum to be submitted individually. The technical memorandums require a specific format, must include specific appendix tables, and must address the listed questions. Review the associated guidelines.
- Review the guidelines for plagiarism to be aware of acceptable laboratory and classroom practices.

Operational amplifiers, or OpAmps, are versatile elements in many amplifier circuits. This laboratory explores the characteristics of OpAmps and their use in basic amplifier configurations.

Objectives:
- To observe the characteristics of an OpAmp and
- To learn how to construct a buffer, inverting, and non-inverting amplifier circuit.

References:
- EE 121 Handouts.
- Cunningham, David R. and Stuller, John A., *Circuit Analysis*, 2nd ed., (John Wiley & Sons, Inc., Chichester, New York, 1995) Chapter 6.

Background:
An operational amplifier, or OpAmp, is an electronic device composed of various internal circuit components (e.g. transistors, capacitors, and resistors). It has two input terminals, two power terminals, and one output terminal. The input resistance between the two input terminals is large (ideally infinite), and thus negligible current flows into the OpAmp. The output terminal acts as a dependent voltage source with small (ideally zero) output resistance. Constant power must be supplied to the OpAmp to power it on. An example of an OpAmp chip is shown in Figure 1(a).

The input terminals of the OpAmp are the (+) terminal, or non-inverting, and the (-) terminal, or inverting. A positive voltage between the (+) and (-) terminals produce a positive voltage at the output and a negative voltage between the (+) and (-) terminals produce a negative voltage at the output. The output voltage is an amplified version of the input difference voltage. Note that an output of zero results for a voltage difference of zero. However, the gain is large such that a small input difference can produce a large output voltage magnitude. The effective gain of an OpAmp circuit typically depends on a feedback arrangement. A connect from the output terminal back to the (-) terminal provides negative feedback and quickly the circuit reaches a stable operating point. (If positive feedback in used, the OpAmp can produce oscillations, overloads, etc.) Consider the buffer circuit in Figure 1(b). As a positive input v_S increases, the output increases and the difference between the (+) and (-) terminals is reduced. As the input v_S decreases, the output decreases and the difference between the (+) and (-) terminals is again reduced. The output v_o is drive to match the input v_S. Hence, the feedback causes allows the output to drive the input voltage difference to zero and a stable operating point reached.

(a) (b)

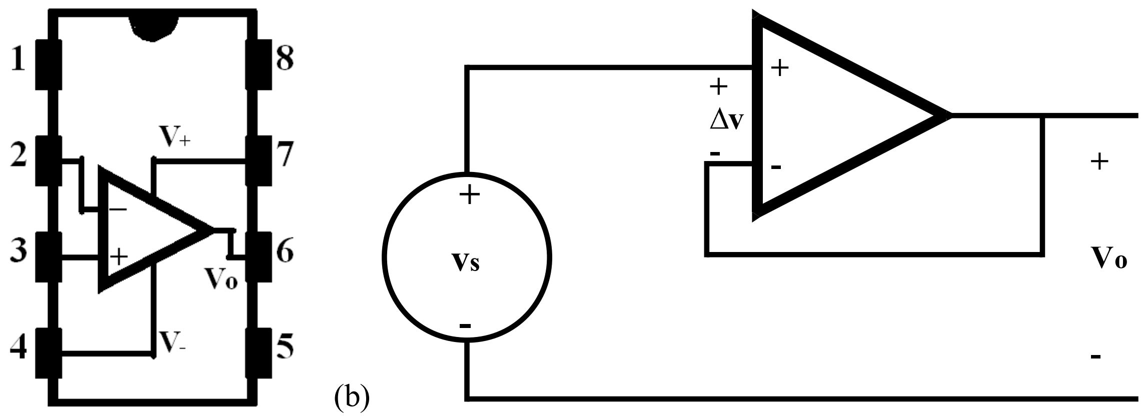
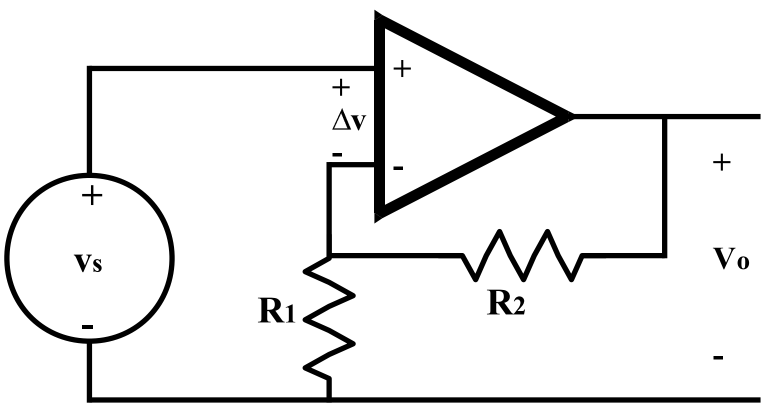


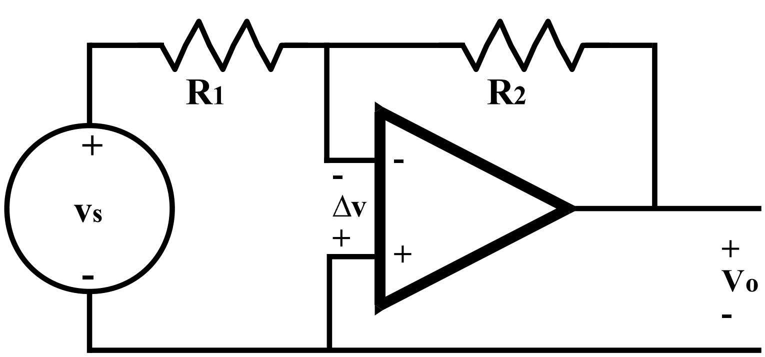
Figure 1 – (a) OpAmp Chip and (b) Buffer OpAmp Circuit

Other common OpAmp circuits are non-inverting and inverting configurations, see Figure2 and Figure 3. (A resistor is sometime placed between the (+) terminal and the reference for the circuit in Figure 3.) Circuit analysis shows the effective gains as shown.



$v_o/v_S = 1 + (R_2/R_1)$

Figure 2 – Non-Inverting OpAmp Circuit



$v_o/v_S = -(R_2/R_1)$

Figure 3 – Inverting OpAmp Circuit

Preliminary:

(Work on separate paper and turn in at the beginning of the laboratory session.)

- Print the data sheets for a LM741 OpAmp. Using these data sheets, identify the value of the voltage gain, maximum positive output voltage, and minimum negative output voltage.
- Consider the non-inverting OpAmp circuit in the Background. Let the (+) terminal be V_1, the (-) terminal be V_2, and the output be V_3. If the OpAmp is modeled with $R_{in} = \infty$, $R_{out} = 0$, and dependent-source gain of A, (a) determine the node-voltage equations (express in matrix form). Assume that the currents into the (+) and (-) terminal are zero. (b) Determine the determinant Δ of the **a** matrix. (c) Find V_3 using Cramer's rule. (d) Determine V_3/V_{in} as A goes to infinity.

Equipment:

- OpAmp LM741 Chip
- DC Power Supply
- DMM
- Resistors (1 kΩ, 2 kΩ, and 5 kΩ)
- Breadboard
- Oscilloscope
- Function Generator

Experimental Procedure:

(Record specifics in the Laboratory Notebook.)

1. Build the buffer OpAmp circuit with V_{CC} = 5 V centered at 2.5 V or greater. Connect the function generator to the input with a sine wave of 1 V peak-to-peak and 1.0 kHz. Observe the output voltage with the oscilloscope and plot or sketch the output voltage ~~curve~~. Increase the input voltage amplitude until the output voltage curve is no longer a sine wave. Record the input voltage magnitude and the maximum and minimum output voltage values. Measure the input current by adding a resistor R_{input} = 1 kΩ between the function generator and the OpAmp input. Measure the voltage across the resistor and calculate the input current.

   Q1: Does the circuit operation match the theoretical expectations? What limits the output magnitude?

2. Build the non-inverting OpAmp circuit with V_{CC} = 5 V centered at 2.5 V or greater, resistor R_1 = 1 kΩ (between the (-) terminal and the reference), and resistor R_2 = 2 kΩ (between the (-) terminal and the output). Connect the function generator to the input with a square wave of 1 V peak-to-peak and 1.0 kHz. Observe the output voltage with the oscilloscope, record the peak-to-peak output voltage, and plot or sketch the output voltage curve. Calculate the percent difference between the actual peak-to-peak output voltage and the theoretical voltage value. Place a load resistor R_L = 5 kΩ between the output and the reference and observe the output voltage again.

   Q2: Does the circuit operation match the theoretical expectations, i.e. is the output not inverted and is the amplification correct? Does the output voltage change for different loading resistances? Explain.

3. Build the inverting OpAmp circuit with V_{CC} = 5 V centered at 2.5 V or greater, resistor R_1 = 1 kΩ (between the (-) terminal and the signal connection), resistor R_2 = 2 kΩ (between the (-) terminal and the output), and resistor R_3 = 5 kΩ (between the (+) terminal and the reference). Connect the function generator to the input with a square wave of 1 V peak-to-peak and 1.0 kHz. Observe the output voltage with the oscilloscope, record the peak-to-peak output voltage, and plot or sketch the output voltage curve. Calculate the percent difference between

the actual peak-to-peak output voltage and the theoretical voltage value. Replace the R_2 resistor with a 5-kΩ resistor. Again, observe the output voltage with the oscilloscope, record the peak-to-peak output voltage, and plot or sketch the output voltage curve. Calculate the percent difference between the actual peak-to-peak output voltage and the theoretical voltage value. Place a load resistor R_L = 5 kΩ between the output and the reference and observe the output voltage again.

Q3: Does the circuit operation match the theoretical expectations, i.e. is the output inverted and is the amplification correct? Does the output voltage change for different loading resistances? Explain.

Technical Memorandum:

- Memorandum discussion:

(1) Describe, based on your observations, the operation of the buffer OpAmp circuit. Does the operation match theoretical expectations? (Q1) How is the output voltage limited?

(2) Describe, based on your observations, the operation of the non-inverting OpAmp circuit. Does the operation match theoretical expectations? (Q2) Does the loading resistor effect the operation? Explain.

(3) Describe, based on your observations, the operation of the inverting OpAmp circuit. Does the operation match theoretical expectations? (Q3) Does the loading resistor effect the operation? Explain.

- Appendix 1: Record or sketch the output voltage curve for the buffer OpAmp circuit with 1 V peak-to-peak input. Record or sketch the output voltage curve for the buffer OpAmp circuit as the input produces a limited output. Calculate the input current from the voltage across the input resistor
- Appendix 2: Record or sketch the output voltage curve for the non-inverting OpAmp circuit without and with a load resistor. Calculate the percent difference between the actual peak-to-peak output voltage and the theoretical voltage value. Record or sketch the output voltage curve for the inverting OpAmp circuit for both resistor cases. Also, plot or sketch the curve with an added load resistor. Calculate the percent difference between the actual peak-to-peak output voltage and the theoretical voltage value for all three curves.