BEE 233 Circuits
Fall 2015
Lab 3: Opamp circuits

1 Objectives

1. Determine opamp specifications from the manufacturer's datasheet.
2. Analyze and measure characteristics of circuits built with opamps.
3. Use the opamp as a component in the design of simple circuits.
4. Analyze the effect of open fault in manufacturing.

2 References

Opamp characteristics and methods for analyzing circuits using the simple opamp model are covered in the textbook. You will also need a datasheet from the manufacturer describing the part you'll be using.

You'll be using the dual output power supply in series mode. The convention is to use VCC to denote the positive supply and VEE to denote the negative supply.

3 Circuits

Figure 1 shows a simple voltage follower circuit whose step and sine wave response you will study in this lab.

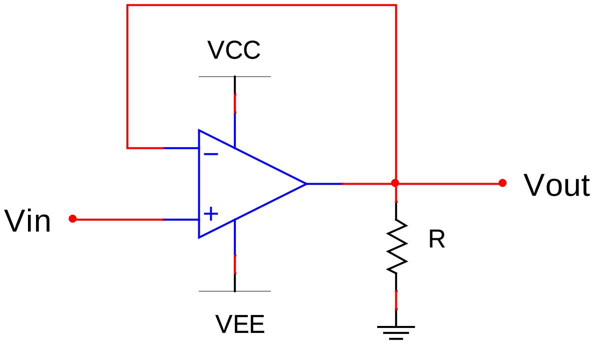

Figure 1. Simple voltage follower.

Figure 2 shows an interesting gain circuit, designed by the technical staff at National Semiconductor to provide variable gain with an interesting twist. You will analyze this circuit to find out what it does, measure its performance in the lab, and then re-design it to meet another specification.

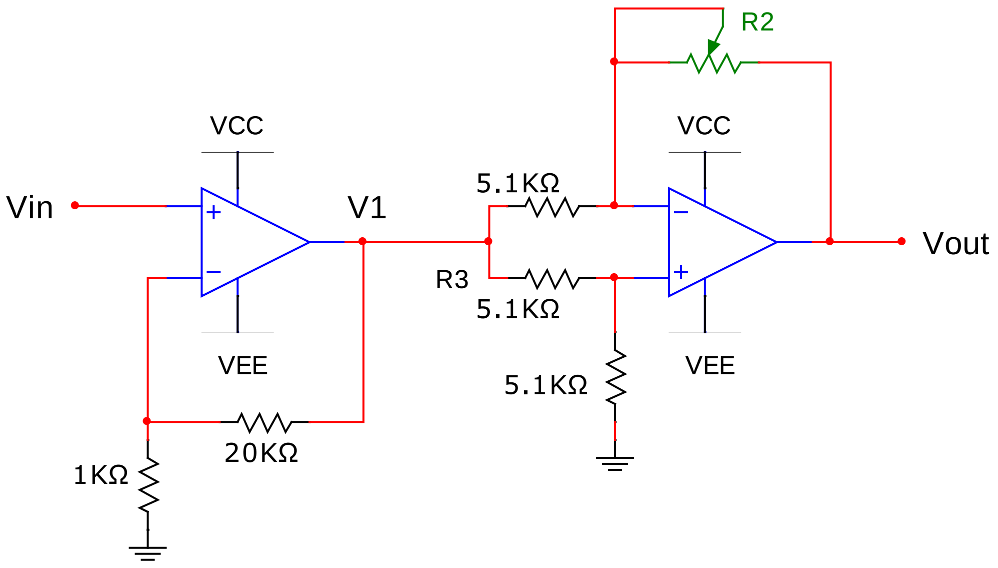

Figure 2. Interesting gain circuit by National Semiconductor.

4 Components

These are the components you'll need. You should record the measured values of your resistors.

Quantity	*Description*
2	LM 348 opamp
1	1 KΩ resistor
3	5.1 KΩ resistor
1	20 KΩ resistor
1	10 KΩ potentiometer

The LM 348 is a common part made by several manufacturers. Their datasheets describing this opamp are easily found on the web. You'll need one that has graphs on it.

5 Discussion

5.1 Opamp parameters

Opamps are typically characterized by a large number of parameters. In this experiment, we will consider only these basic parameters:

1. Power supply limits
2. Input resistance
3. Open-loop voltage gain
4. Slew rate

5.1.1 Power supply limits

A given integrated circuit is designed to be used only within certain power supply limits. The most frequently used supplies are: ±15 V, ±12 V, ±10V and ±5 V.

5.1.2 Input resistance

The input resistance should be as high as possible to approach the ideal opamp model and must be at least 10 times larger than the resistance of components immediately connected to the inputs of the opamp. Otherwise, the finite input resistance of the opamp must be taken into account in analysis and design.

5.1.3 Output resistance

The output resistance should be as low as possible to approach the ideal opamp model and must be at least 10 times smaller than the resistance of the opamp load at the output. Otherwise, the finite output resistance must be taken into account in analysis and design.

5.1.4 Open-loop voltage gain

The open-loop voltage gain refers to the opamp gain by itself. In an actual application, negative feedback is used and the voltage gain of the entire circuit will be far lower.

The open-loop voltage gain should be as high as possible to approach the ideal opamp model. This is critical to our simplifying assumption about opamp circuits that the voltage across the inputs will always be zero, no matter what the output. The open-loop gain is usually specified in dB and varies as function of frequency. If the voltage gain is A_V, the gain in dB is calculated as:

$$A_{db} = 20\ log_{10}(\ A_v)$$

For example, a gain A_V = 100 is the same as A_{db} = 40 dB. The datasheet should provide both a typical value as well as several plots of the voltage gain as a function of frequency or other parameters.

Datasheets sometimes use these phrases to describe open-loop voltage gain: large-signal voltage gain, differential voltage gain, open-loop frequency response, etc.

5.1.5 Slew rate

When a large signal, e.g., a step signal = 10Vpp, is applied to the input of the opamp, the opamp cannot respond fast enough to follow the input signal. The output signal rises at a fixed slope. The maximum rate of change of the voltage output is a function of time is called the slew rate (dVout/dt). The slew rate depends on a specific opamp design, the power supplies, and loading conditions.

Opamps need to operate well below the slew rate limitations so that the output waveform is not distorted. This means that there is an upper limit on the frequency of the input signals to ensure that the opamp can respond faithfully to changes in the input.

5.2 Handling and using opamps

Real opamps may be damaged by improper handling and usage.

5.2.1 Static discharge damage

Your finger may carry a high static charge (up to hundreds of volts) due to a combination of the clothing you wear (synthetic or wool is worse), humidity (dry is worse) or other factors. Most modern devices are pretty well protected against static but it's still good practice to exercise care by touching a grounded metal surface before picking up an IC.

5.2.2 Applying out-of-range input values

The input signals must be in the range of the power supply limits. If the input signal exceeds the power supply limits, the circuit can be burned out.

Damaged chips look the same as good ones and you can waste a lot of time trouble-shooting your circuit. Two signs of a burned-out opamp are excessive current drawn from the power supply (greater than about 10 mA with no load) or an opamp that's hot to the touch. But a blown-out opamp might not exhibit either of these symptoms. If you suspect that your opamp is faulty, try another. If that still doesn't fix your problem, you likely still have a wiring error.

5.3 Manufacturing test issue: open-fault

In manufacturing testing of large-scale systems on IC or board or multi-chip modules (MCMs), a broken wire between two nodes in a circuit is a common failure. The wire might break due to improper soldering on a circuit board, bad contact, over-etching of conductor lines on an IC or MCM, etc. This type of fault is called "open" fault since the broken wire is equivalent to an open circuit (no connection). We will study one example of open fault with respect to the circuit in Figure 2 in this experiment.

6 Pre-lab

6.1 Recording specified opamp parameters for analysis and design

Go over the specifications of the opamp and write down the typical values of the following parameters assuming the power supplies are ± 12V: input resistance, output resistance, voltage gain, and slew rate. Use these values, where appropriate, in the subsequent parts of this laboratory. (Output resistance of the LM 348 can be determined from the chart of output impedance under the conditions of 1.0 KHz and gain (Av) = 10.)

6.2 Analysis of simple opamp voltage follower circuit

For the circuit in figure 1 with R = 5.1 KΩ, VCC = +12 V, VEE = –12 V, and the parameter values in section 6.1, answer the following questions:

1. What is the voltage gain of the circuit at low frequency?
2. If Vin is a square wave with an amplitude of 2.5 Vpp from –1.25 V to +1.25 V, how long will the output signal take to reach the final value after each input transition? Calculate this time and keep it for comparison with the experimental value to be measured in the lab.
3. Assume Vin is a sine wave = 3 Vpp. Derive an equation for the maximum rate of change of the output voltage |dVout/dt| as function of the input amplitude and frequency. From this equation and the opamp slew rate, determine the input frequency at which the slew rate of the opamp begins to limit its ability to act as a voltage follower?
4. Assume small-signal inputs to avoid slew-rate limitations and that the opamp is not ideal, i.e., it has a finite open-loop gain A_V. You may still assume very large input resistance and very small output resistance for the opamp. Since the opamp gain A_V is not ideal and varies as a function of frequency (see the opamp specifications), the circuit in Figure 1 might not perform as a voltage follower. Using an equivalent circuit model for the opamp in which the open-loop opamp gain A_V is finite, analyze the circuit in Figure 1 to derive an equation for the circuit gain Vout/Vin as a function of A_V. At what value of A_V does Vout/Vin equal 0.5?
5. Using the opamp specifications (plot of opamp gain A_V as function of frequency) and the result in item 4 above, at what frequency do you expect Vout/Vin = 0.5?

6.3 Analysis of the gain circuit in Figure 2

Use the techniques in the text and what you've learned about opamp circuits, analyze the gain circuit in Figure 2 following this procedure:

1. What is the function of the first opamp stage? Find the voltage gain V1/Vin of this stage?
2. What is the function of the second opamp stage? Find the voltage gain Vout/V1 of this stage as a function of the variable resistance R2.
3. With the results from items 1 and 2 above, what is the overall voltage gain Vout/Vin of this circuit as a function of R2? Plot the gain as function of R2. Use the linear scale for the gain.
4. You should now be able to see what is interesting about this circuit. Explain its feature in one sentence.

6.4 Design of another gain circuit

Re-design the circuit in Figure 2 so that the new overall gain has the opposite sign, i.e. if the circuit in Figure 2 has a gain G, the new circuit has gain –G over the entire range of the resistor R2. Use as few components as possible and keep the design simple.

1. Show the schematic of your circuit with all components completely specified (component types and values, component part numbers, power supply values, etc.).
2. Analyze your circuit to prove that it has the gain as specified. If you find out that the magnitude of the gain somehow is not large as the gain magnitude for the circuit in Figure 2, explain why this is so.
3. Plot the gain of this new circuit as a function of R2. Use the linear scale for the gain.

6.5 Open fault in circuit in Figure 2

Assume that the circuit in Figure 2 has an open fault at the R3 (5.1 KΩ) resistor. The effect of this open fault is to remove R3 totally from the circuit.

1. Re-draw the circuit diagram in Figure 2, omitting the resistor R3 to simulate the effect of the open fault.
2. Analyze this new circuit to find the overall voltage gain Vout/Vin in one particular case when R2 = 8 KΩ.
3. Is this gain different than the gain when the circuit has no fault? The good (no fault) circuit is also called the “fault-free” circuit.

7 Experimental procedures

7.1 Instruments needed for this experiment

The instruments needed for this experiment are: a power supply, an arbitrary waveform generator, a multimeter, and an oscilloscope.

Throughout this experiment, Vin should always be on channel 1 of the oscilloscope, Vout should be on channel 2, and both channels should be set for DC coupling. Add some useful on-screen measurements and adjust the timescale appropriately for each of the various measurements you take.

7.2 Opamp voltage follower circuit

1. Build the circuit in Figure 1 using R = 5.1 KΩ, VCC = +12 V and VEE = –12V. Set Vin to be a square wave as follows and capture a screenshot.
    a. Frequency = 40 KHz
    b. Amplitude = 2.5 Vpp

   c. DC offset = 0 V

2. Use the cursors on the oscilloscope to measure the time it takes for the output to reach the steady state after an input transition. Capture a screenshot.

3. Calculate the slew rates from high to low and from low to high using this data and compare these results with the typical slew rate in the specifications.

4. Change Vin to be a sine wave as follows and capture a screenshot.

   a. Frequency = 500 Hz
   b. Amplitude = 3 Vpp
   c. DC offset = 0 V

5. Increase the frequency of the input signal (keeping the input amplitude the same) until the output signal starts to get distorted. Capture a screenshot.

6. Construct a table of rise time, fall time, calculated slew rate, frequency for the onset of distortion.

7.3 Performance of the gain circuit in Figure 2

1. Build the circuit in Figure 2, with the initial setting of the resistor R2 = 0 Ω (record the measured value) and VCC = +12 V and VEE = –12 V. Adjust Vin to be a sine wave as follows and capture a screenshot.

   a. Frequency = 20 Hz
   b. Amplitude = 200 mVpp
   c. DC offset = 0 V

2. Create a table of measurements of gain versus R2 as you vary R2 from 0 Ω to 10 KΩ in 1 KΩ steps, measuring R2 at each step.

3. Capture screenshots for R2 = 2 KΩ and 8 KΩ.

7.4 Performance of your own gain circuit

1. Build the circuit you designed in the pre-lab, section 6.4 above with VCC = +12V and VEE = –12 V. Adjust Vin to be a sine wave as follows and capture a screenshot.

   a. Frequency = 20 Hz
   b. Amplitude = 200 mVpp
   c. DC offset = 0 V

2. Collect sufficient data (screenshots, tables of data points, etc.) to show convincingly that your circuit performs as designed.

7.5 Open fault effect measurement

1. Build the circuit in Figure 2 but omit the resistor R3 to simulate the open fault. Set R2 = 8 KΩ. Adjust Vin to be a sine wave as follows and capture a screenshot.
    a. Frequency = 20 Hz
    b. Amplitude = 200 mVpp
    c. DC offset = 0 V
2. Measure and record the overall voltage gain of the circuit.

8 Data analysis

8.1 Opamp voltage follower circuit

1. Compare the calculated and measured values of the time for the output to reach steady state from sections 6.2 and 7.2.

2. Compare the calculated and measured frequencies at which the output starts to become distorted due to slew rate limitations from sections 6.2 and 7.2. Explain any difference.

8.2 Performance of the circuit in Figure 2

1. Plot voltage gain versus R2 using the data collected in section 7.3. Use a linear scale on both axes.

2. Compare this graph with the graph made using calculated data in the pre-lab section 6.3. Explain any difference.

8.3 Performance of your own gain circuit

1. Explain why the data you collected in section 7.4 supports your conclusion that your circuit works as designed.

2. How much data is sufficient to demonstrate the performance of your circuit? This issue is critical in real-life testing. If too much data is collected, the test cost is higher and the profit per product is lower. If too little data is collected, your circuit might not really work as designed since it has not been well tested. So what is “sufficient data” for this specific design? Justify your answer.

3. Analyze your data to demonstrate that the circuit works as designed. Show plots, equations, differences between calculated and measured results, etc. If your circuit does not work as designed or if there are significant differences between the theoretical and the measured results, explain.

8.4 Open fault comparison

We will compare data between a fault-free circuit and a faulty circuit to study the effect of the open fault at the resistor R3 in the circuit in Figure 2. Note that R2 = 8 KΩ is fixed for both cases.

1. Compare the overall voltage gain values for the fault-free circuit (section 7.3 for R2 = 8 KΩ) and the faulty circuit (section 7.5). Are they different?

2. Compare the waveforms of the output signals for the fault-free circuit (section 7.3 for the case R2 = 8 KΩ) and the faulty circuit (section 7.5). Are they different? If the outputs of the fault-free and faulty circuits are different, the fault is “detected”, i.e., the circuit is shown to fail and will be discarded. In large-scale systems, there are cases where the fault-free and faulty circuits have the same outputs under test. In these cases, the fault is not detected and a bad circuit used to build a product, which eventually fails.