Operational amplifiers

1. Objectives

· Read IC component specifications and get data from them for circuit analysis and design.
· Analyze and measure characteristics of circuits built with opamps.
· Use the opamp as a component in the design of simple circuits.
· Analyze the effect of open fault in manufacturing.

2. Reference

The opamp characteristics and circuits are covered in the textbook. Make sure you know how to analyze circuits using the simple ideal opamp model.

Review the usage of the programmable power supply that can set two supply values. The convention is to use VCC to denote the positive supply and VEE to denote the negative supply.

3. Circuits

Figure 1 shows the simple voltage follower circuit whose step response and sine-wave response will be studied in this lab. Figure 2 shows an interesting gain circuit, designed by a 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.

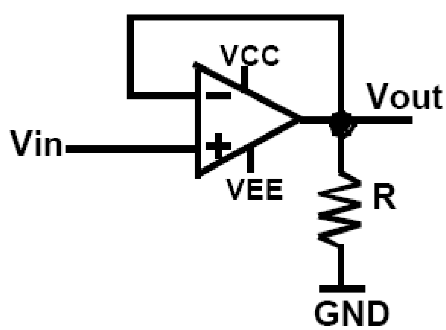

Figure 1. Voltage follower circuit.

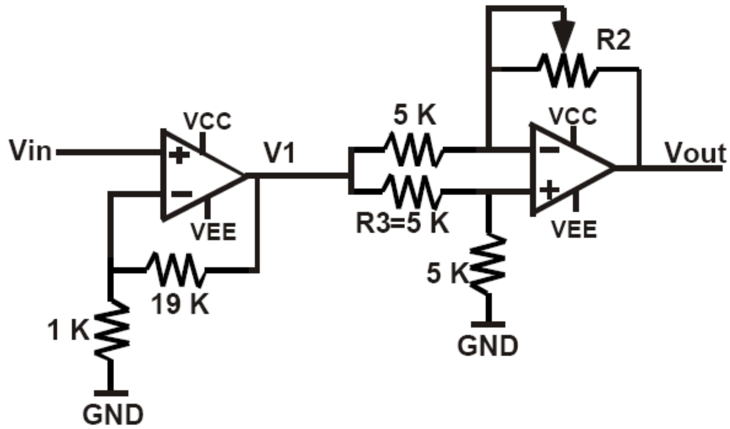

Figure 2. Interesting gain circuit (© National Semiconductor).

4. Components and specifications

Quantity	***Description***	***Comments***
2	LM 348 opamp	or equivalent.
1	1 KΩ resistor	
3	5 KΩ resistor	
1	19 KΩ resistor	
1	10 KΩ resistor	3-terminal potentiometer

Opamp specifications are available from the laboratory web site of this course or manufacturers' web sites. Check your component and download the appropriate specifications.

5. Discussion

5.1 Opamp parameters

There are many parameters for simple opamp components. For this experiment, only a few parameters are pertinent, which will be briefly discussed in this section. Other parametric specifications are important in higher-level design courses. Use the opamp datasheets to find out the values of the parameters below.

5.1.1 Power supplies

Never exceed the specified power supply limits. The most frequently used supplies are: ±15 V, ±12 V, ±10V, ±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 should be as high as possible (to approach the ideal opamp model). This gain is usually specified in dB unit and varies as function of frequencies. If a voltage gain is A, the dB value of A is defined by:

$$A\ (dB) = 20\ \log A$$

This equation can be used to convert a gain to dB value or vice versa. For example, a gain A = 100 is the same as A (dB) = 40 dB. The specification sheets provide both a typical value as well as several plots of the voltage gain as function of frequency or other parameters.

Note that the "open-loop voltage gain" refers to the opamp gain by itself. When the opamp is used in a circuit, the voltage gain of the entire circuit is different than the open-loop opamp gain, depending on the topology of the circuit.

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 of amplitude 10V) 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 and the maximum rate of change of the voltage output as function of time is called the slew rate (dVo/dt). The slew rate depends on a specific opamp design, the power supplies, and loading conditions. Look up the specifications of the opamp to find a typical value of the slew rate.

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 might be burned out due to improper handling and usage.

5.2.1 Static discharge damage

Your finger might carry a high static voltage (up to hundreds of volt) due to a combination of clothing you wear (synthetic or wool is worse) and the environmental humidity (dry is worse), or other factors. Picking up an IC package could burn out the circuit inside due to this static voltage. Remember to touch a grounded piece of metal (usually a wrist-strap attached to test benches) to discharge the static voltage before handling the IC.

5.2.2 Applying out-of-range input values

The input signals must be in the range set by the power supplies (see the specifications). If the input signal exceeds the power supplies (either more negative or more positive), the circuit might be burned out.

Burned-out chips look the same as a good one 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 hot to the touch. Of course a blown-out opamp may exhibit none of these symptoms. If you suspect that your opamp is faulty, replace it.

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. (For output resistance of LM 348, you can get it 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 KΩ, power supplies 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 a step signal from –1.25 V to + 1.25 V is applied to the input of the circuit, how long will the output signal take to reach the final value? Calculate this time and keep it for comparison with the experimental value to be measured in the lab.

3. Assume a sine wave input with 3 V amplitude is applied to the circuit. Derive an equation for the maximum rate of change of the output voltage $|dV_{out}/dt|$ as function of the input amplitude and frequency. From this equation and the opamp slew rate, at what input signal frequency does the output slew rate of the opamp begin to limit the voltage follower action?

4. Assume small-signal inputs to avoid slew-rate limitations and that the opamp is not ideal (e.g. finite open-loop gain A). You may still assume very large input resistance and very small output resistance for the opamp. Since the opamp gain A 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 is finite, analyze the circuit in Figure 1 to derive an equation for the circuit gain V_{out}/V_{in} as a function of A. At what value of A does V_{out}/V_{in} equal 0.5?

5. Using the opamp specifications (plot of opamp gain A as function of frequency) and the result in item 4 above, at what frequency do you expect $V_{out}/V_{in} = 0.5$?

6.3 Analysis of the gain circuit in Figure 2

Use the techniques in the text and what you 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 V_1/V_{in} of this stage?

2. What is the function of the second opamp stage? Find the voltage gain V_{out}/V_1 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 V_{out}/V_{in} of this circuit as a function of R2? Plot the gain as function of R2. Use the linear scale for the gain.

You can now find out 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 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. Is this gain different than the gain when the circuit has no fault? The good circuit (no fault) 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.

7.2 Opamp voltage follower circuit

1. Build the circuit in Figure 1 using R = 5 KΩ, programmable power supply 1 = 12 V and programmable power supply 2 = -12 V. Set the arbitrary waveform generator to provide a square wave input as follows (display on channel 1 of the scope):
   a. Frequency = 40 kHZ
   b. Amplitude: 2.5 Vpp and DC offset = 0 V.
   c. Set both ch1 and ch2 probe gain to 1X and DC coupling. Do not select “on trigger”.

2. Use Channel 2 of the oscilloscope to display the output signal waveform. Adjust the timebase to display 2 complete cycles of the signals.

3. From the oscilloscope, use the timing cursor to measure the time interval for the output to reach the steady state after an input transition.

4. **Calculate the slew rates high-to-low and low-to-high** using this data and compare with the typical slew rate in the specifications.

5. **Save a screenshot** output from the scope display with both waveforms and the measured slew rate. Turn these screenshots in as part of your lab report.

7. Change the input signal to a sine wave with amplitude 3 Vpp, DC offset 0 V, and frequency 500Hz. Disable the trigger. Check the output signal to make sure the voltage follower functions as expected. Now increase the frequency of the input signal (keep the input amplitude the same) until the output signal starts to get distorted from a sine or cosine wave. When you increase the frequency, adjust the timebase to display about 2 complete cycles of the signals. What is the frequency for the onset of this distortion?

8. **Save a screenshot** from the scope display with both waveforms and the measured input signal frequency at the onset of distortion. Turn this screenshot in as part of your lab report.

Turn in: a table of rise time, fall time, calculated slew rate, frequency for the onset of distortion, and screenshots

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 (record this value) and programmable power supply 1 = 12 V and programmable power supply 2 = -12 V. Apply a sine wave input signal with amplitude 200 mV, DC offset 0V, gain low (1x), and frequency 20 Hz. Display the input signal on channel 1 of the oscilloscope use the continuous start" data capture. Set channe1 1 to gain X1 and DC coupling.

2. Display V_{out} on Channel 2 and set probe gain to X10 and DC coupling. Adjust the timebase to display 2 complete cycles of the signals.

3. **Record the overall gain** at this setting of R2 (i.e. record in a table the value of R2 and the corresponding value of the voltage gain).

4. Now **vary R2** to take on these values: 1 KΩ, 2 KΩ, 3 KΩ, up to 10 KΩ at 1 KΩ step. At each setting of R2, measure the gain and record it in the same table for subsequent plotting.

5. **Save a screenshot** from the scope display with both waveforms at each of these settings of R2: 2 KΩ and 8 KΩ. Turn these screenshots in as part of your lab report.

Turn in: a table of resistor values, output voltages, and gains and screenshots

7.4 Performance of your own gain circuit

1. Build the circuit you designed in the pre-lab, section 6.4 above and programmable power supply 1 = 12 V and programmable power supply 2 = -12 V. Apply a sine wave input signal with amplitude 200 mVpp, DC offset 0 V, gain low (1x) and frequency 20 Hz. Set channe1 1 to gain X1 and DC coupling. Display the input signal on channel 1 of the oscilloscope.

2. Use Channel 2 of the oscilloscope to display the output signal waveform and set probe gain to X10 and DC coupling. Adjust the timebase to display 2 complete cycles of the signals.

3. **Collect "sufficient" data** to show convincingly that your circuit performs as designed. Turn in the data you collect (scope display of waveforms, tables of data points, plots, etc.).

Turn in: a table of resistor values, output voltages, and gains

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. Apply a sine wave input signal with amplitude 200 mVpp, DC offset 0 V, gain low (1x) and frequency 20 Hz. Set channe1 1 to gain X1 and DC coupling. Display the input signal on channel 1 of the oscilloscope.

2. Display V_{out} on Channel 2 and set probe gain to X10 and DC coupling. Adjust the timebase to display 2 complete cycles of the signals.

3. **Save a screenshot** from the scope display with both waveforms. Turn these screenshots in as part of your lab report.

4. **Measure and record the overall voltage gain** of the circuit for this case.

Turn in: overall gain and screenshot

8. Data analysis

8.1 Opamp voltage follower circuit

1. From the pre-lab section 6.2 item 2 and the measured value in section 7.2 item 3, compare the calculated and measured values of the time for the output to reach the steady state.

2. With regard to the frequency at which the output starts to be distorted due to slew rate limitations, compare the value calculated in the pre-lab section 6.2 item 3 and the measured value in section 7.2 item 7. Explain any difference between these two values.

8.2 Performance of the circuit in Figure 2

1. Plot the data collected in section 7.3 item 4: voltage gain versus the setting of the resistor R2. Use linear scale on both axes.

2. Compare this plot with the plot using calculated data in the pre-lab section 6.3 item 3. Explain any difference.

8.3 Performance of your own gain circuit

1. Justify the specific data you collected in section 7.4 (i.e. if you collect voltage gain as function of frequency, explain why you think this data is important to support your conclusion that the 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. Discuss in detail if your circuit does not work as designed or if there are significant differences between the theoretical and the measured results.

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 item 4, gain value for the case R2 = 8 KΩ) and the faulty circuit (section 7.5 item 4). Are they different?

2. Compare the waveforms of the output signals for the fault-free circuit (section 7.3 item 5, plot for the case R2 = 8 KΩ) and the faulty circuit (section 7.5 item 3). 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 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 is used to build systems, which eventually leads to system failures.