EE 233 Circuit Theory

Lab 2: Amplifiers

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1. Introduction

The objectives of this lab are to read and obtain data from integrated circuit (IC) component specifications, specifically operational amplifier (op-amp) specs, to learn SPICE simulation to predict behaviors of electronic circuits, and to analyze and measure characteristics of circuits built with op-amps.

Throughout the next three labs you will be constructing an audio mixer step-by-step. An audio mixer is an electronic device that combines multiple sounds into one channel. In the process of combining the sounds, the source signals' magnitude, frequency content, dynamics and panoramic position are manipulated. Audio mixers have a wide variety of applications, including music, film, television, and live sound. The process is generally carried out by a mixing engineer operating the audio mixer or audio console.

The characteristics of voltage follower, also called a buffer, and summing amplifier are going to be calculated, built, and measured in this lab. The circuits built can be kept on the board and reused in the following labs. Please read Supplemental Material Audio Mixer for more information on the entire project.

2. Precautions

None of the devices used in this set of experiments are particularly static sensitive; nevertheless, you should pay close attention to the circuit connections and to the polarity of the power supplies, operational amplifier and oscilloscope inputs.

3. Prelab

3.1 Recording Specified Op-amp Parameters for Analysis and Design

Go over the op-amp's specifications and write down the typical values of the following parameters: power supplies, input resistance, output resistance, open loop voltage gain, and slew rate. Use these values, when appropriate, in the subsequent parts of this laboratory. Read Reference 5.1 for more information on input resistance, output resistance (under frequency of 10 kHz and gain of 10), open loop gain (under frequency of 10 kHz), and slew rate. Over the course of the lab, your op-amp might burn out due to improper handling and usage. Read Reference 5.2 for more information of handling and using op-amps in order to avoid this.

3.2 Voltage Follower Circuit

1. Calculate the value for the gain, which is v_{out}/v_{in}, in Figure 3.1. Assume the op-amp is ideal. Read Reference 5.3 for more information on ideal op-amps.

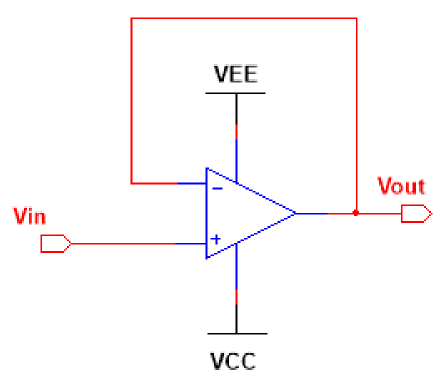

Figure 3.1 Voltage follower

2. Considering the slew rate you read from the datasheet, the output voltage cannot always follow the input voltage immediately. If a step wave from -10 V to $+10$ V is provided as an input signal, calculate the time that the output signal takes to reach the final value. Compare your result with the corresponding large signal pulse response in the datasheet and determine if they are the same.

3. The slew rate does not only appear for step functions; a sinusoidal wave may also be distorted if its frequency or amplitude is high enough. To find the maximum frequency or amplitude to avoid slew-rate limitations, first assume that the input signal is $v_{in} = A\cos(\omega t + \phi)$, where A is amplitude, ω is angular frequency and ϕ is the initial phase. Find the expression for $|dv_{out}/dt|$, assuming the op-amp is ideal and there is no slew rate. After that, find the maximum slope of output voltage, which is the maximum value of $|dv_{out}/dt|$. Finally, if the amplitude is given, which is A volts, find the maximum frequency to avoid slew rate limitation. If the frequency is given, which is f_0 Hz, find the maximum amplitude to avoid slew rate limitation.

   Hint: The relation between frequency and angular frequency is $\omega = 2\pi f$.

4. For audio signals, the range of frequencies is always between 20 Hz and 20 kHz. Calculate the maximum amplitude of the input signal to avoid slew rate limitation. Comment on your results.

   Hint: The voltage of audio signals is typically between 0.3 V and 2.0 V.

5. Assume small-signal inputs to avoid slew-rate limitations and also assume that the op-amp is not ideal (e.g. finite open-loop gain A_v).). You may still assume very large input resistance and very small output resistance for the opamp. Read Reference 5.3 for more information on non-ideal op-amps. Since the op-amp gain A_v is not ideal and varies as a function of frequency (see the op-amp specifications), the circuit in Figure 3.1 might not perform as a voltage follower. Using an equivalent circuit model for the op-amp in which the open-loop op-amp gain A is finite, analyze the circuit in Figure 3.1 to derive an equation for the circuit gain v_{out}/v_{in} as a function of A_v. At what value of A_v does v_{out}/v_{in} equal 0.5?

6. Using the op-amp specifications (plot of op-amp gain A as function of frequency) and the result in item 5 above, at what frequency do you expect v_{out}/v_{in} to equal 0.5? Find the range of gain v_{out}/v_{in} for the audio signal and comment on whether the gain significantly changes in terms of frequency.

3.3 Summing Amplifier Circuit

A summing amplifier is essential for mixing signal channels. The audio mixer then utilizes potentiometers to control the ratios among channels. It also behaves as a filter to remove the white noise in the audio frequency. Now consider a summing amplifier with three input channels.

1. Derive the equation for v_{OUT} in the frequency domain for the circuit in Figure 3.2, assuming the op-amp is ideal. Then find the magnitude of the output signal in terms of frequency. Assume that the input voltages are V_1, V_2, and V_3, in frequency domain.

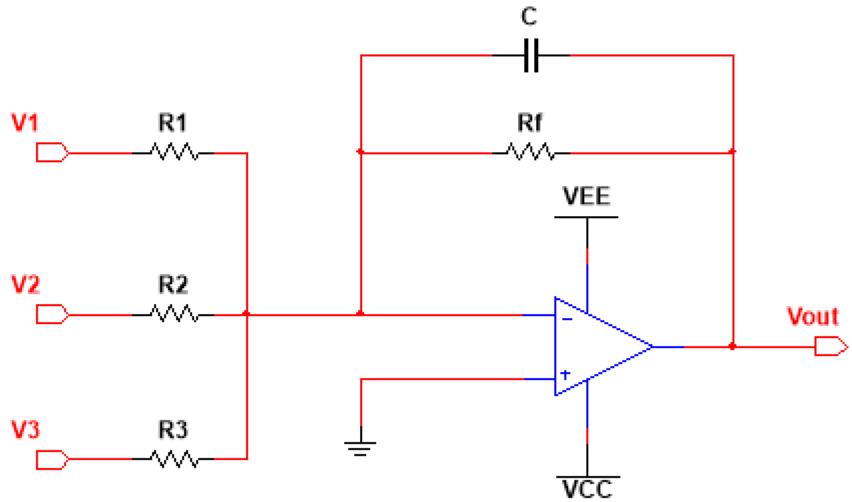

Figure 3.2 Summing amplifier circuit

2. Suppose the input voltages V_1, V_2, and V_3 are independent of frequency. When the input signals are DC, find the expression for V_{OUT}.

   Hint: The relation between angular frequency and frequency is $\omega = 2\pi f$.

3. Suppose the input voltages V_1, V_2, and V_3 are independent of frequency. Find the frequencies, as a function of R_f and C, at which the output voltage is 70% of the value when the inputs are DC. What are the frequencies for 50%, 30% and 10%?

4. Assume $v_1 = \cos(2\pi \times 1000 \times t)\, V$, $v_2 = 0.1\cos\left(2\pi \times 1000 \times t - 30^{\circ}\right) V$, and

   $v_3 = 0.1 \times \cos\left(2\pi \times 1000 \times t + 30^{\circ}\right) V$. Find v_1, v_2, and v_3 in the phasor domain.

5. Assume $R_1 = R_2 = R_3 = R_f = 100$ kΩ and $C = 22$ pF and use the voltages from item 4. Plot the magnitude and phase of the output signal in the range from 10 Hz to 1 MHz. Use a log scale for both the frequencies and magnitude.

6. If the capacitor is removed, does the magnitude of output voltage still depend on frequency? Comment on the function of the capacitor in the circuit. Assume the frequency is low so that slew-rate limitation and non-ideal effects of the op-amp are negligible.

3.4 SPICE Simulation

SPICE is a powerful tool to design, simulate and predict the behavior of circuits. You will be using MultiSim a powerful SPICE tool to simulate and verify your calculations. Keep the diagrams from the MultiSim program and turn them in with your prelab.

1. For the circuit in Figure 3.1, with power supplies $V_{CC} = 12\ V, V_{EE} = -12\ V$, use MultiSim transient analysis to simulate this circuit in the time domain using a square wave input with an amplitude going from −10 V to +10 V, a frequency of 3 kHz, and a duty cycle of 50%. From the MultiSim output plot of the input and output waveforms, measure the time interval for the output to reach the steady state after an input transition. Then calculate the slew rate. Compare the waveforms in the MultiSim program to the corresponding waveforms given in the datasheet.

2. Set the input signal to a sine wave with an amplitude of 100 mV (-100 mV to $+100$ mV peak-to-peak) and a frequency of 10 Hz. Check the output signal to make sure the voltage follower functions as expected. Use the AC analysis function in the MultiSim program and find the frequency at which the voltage gain decreases to half of its maximum value. Compare this result with 3.2 item 5.

3. For the circuit in Figure 3.2, with power supplies $V_{CC} = 12\ V, V_{EE} = -12\ V$, use MultiSim AC analysis (log scales for both the frequencies and magnitude) to plot the output voltage from 10 Hz to 1 MHz. Use the same parameters as in 3.3 items 4 and 5 and compare the result with the theoretical result.

4. Experimental Procedure and Data Analysis

4.1 Voltage Follower

1. Build the circuit in Figure 3.1 with power supplies $V_{CC} = 12\ V, V_{EE} = -12\ V$. Set the function generator to provide a square wave as follows:

   a. Frequency: 3 kHz, 50% duty cycle

   b. Amplitude: -10 V to $+10$ V

   Use the oscilloscope to display this waveform on Channel 1 and make sure the amplitude is correct. Now use Channel 2 of the oscilloscope to display the output voltage. Adjust the time base to display 3 complete cycles of the signals. Get a hardcopy output from the scope display with both waveforms. Turn this hardcopy in as part of your lab report.

   Question-1: Measure the time interval for the output to reach the steady state after an input transition and calculate the slew rate. Compare the result with the typical slew rate in the specifications. Compare the waveforms with that in the datasheet and in SPICE program.

2. Clear all the measurements. Change the input signal to a sine wave with an amplitude of 3 V (-3 V to +3 V peak-to-peak) and a frequency of 1 kHz. Check the output signal to make sure the voltage follower functions are 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.

   Question-2: What is the frequency for the onset of this distortion? Compare it with the theoretical result calculated in above 3.2 item 3.

3. Clear all measurements. Set the input signal to a sine wave with an amplitude of 100 mV (-100 mV to +100 mV peak-to-peak) and a frequency of 10 Hz. Check the output signal to make sure that the voltage follower functions as expected. Then increase the frequency of the input signal, while keeping the input amplitude the same, until the voltage gain decreases to exactly half of the low-frequency gain. Record this frequency.

   Question-3: What is the gain of the circuit at 10 Hz (which is called “low-frequency gain”) and the frequency at which the voltage gain is half of the low-frequency gain? Compare this result with 3.2 item 5 and 3.3 item 2.

4.2 Summing Amplifier

1. Build the circuit in Figure 4.1 with power supplies $V_{CC} = 12$ V, $V_{EE} = -12$ V. Set the function generator to provide $v_1 = \cos(2\pi \times 1000 \times t)$ V, $v_2 = v_3 = 0$ V. Set $R_1 = R_2 = R_3 = R_f = 100$ kΩ and $C = 22$ pF. Sweep the frequency of V_1 from 10 Hz and varying it using 1-2-5 sequence up to 1 MHz while keeping the amplitude the same. Record the amplitude of the output signals.

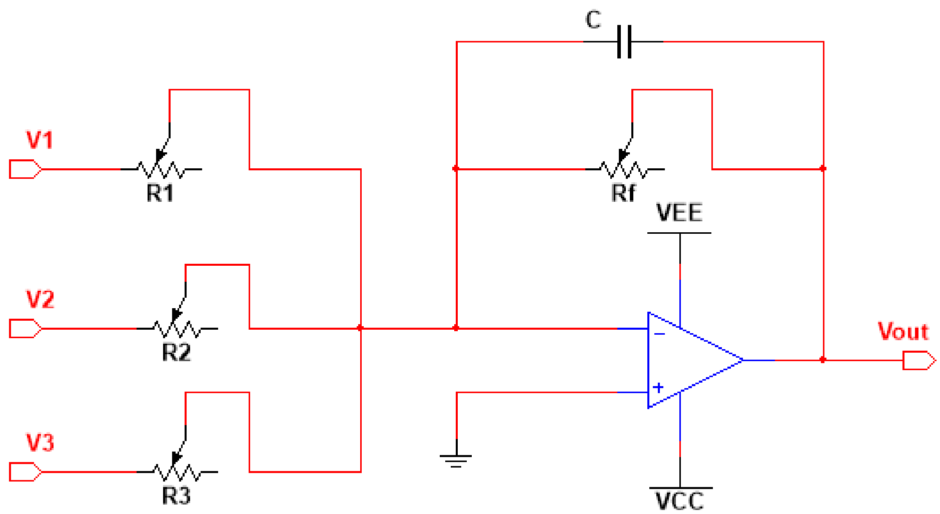

Figure 4.1 Summing amplifier with potentiometers

Question-4: Plot the output voltage in terms of frequency and compare it with the result in 3.3 item 5.

2. Use supplemental audio sounds as input signals to V_1, V_2 *and* V_3. Use a speaker to play the audio sound. Then display the output signal voltage with oscilloscope. Get a hardcopy output from the scope display with the waveform. Turn this hardcopy in as part of your lab report.

   Question-5: Comment on the sound of the audio signal and the waveform displayed in oscilloscope. Is it a pure sinusoidal wave? If not, use the function generator to provide a 1 kHz sine wave and hear how it sounds.

3. The function of this summing amplifier is to mix sounds of all tracks in the audio mixer. Use supplemental audio sounds as three input tracks. Adjust the four potentiometers and hear the change in the output sound.

   Question-6: Comment on the functions of the four potentiometers.

   Hint: Which potentiometer controls the whole volume? How do potentiometers control the volume of each track?

5. Reference

5.1 Op-amp Parameters

There are many parameters for simple op-amp 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 op-amp 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, ± 10 V and ± 5 V.

5.1.2 Input Resistance

The input resistance should be as high as possible (to approach the ideal op-amp model) and must be at least 10 times larger than the resistance of components immediately connected to the inputs of the op-amp. Otherwise, the finite input resistance of the op-amp 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 op-amp model) and must be at least 10 times smaller than the resistance of the op-amp 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 op-amp model). This gain is usually specified in dB units and varies as function of frequency. 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 ratio gain into a dB value or vice versa. For example, a gain $A = 100$ is the same as $A(\text{dB}) = 40$ 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 op-amp gain by itself. When the op-amp is used in a circuit, the voltage gain of the entire circuit is different than the open-loop op-amp 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 10 V) is applied to the input of the op-amp, the op-amp 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 (dv_{OUT}/dt). The slew rate depends on the specific op-amp design, the power supplies, and loading conditions. Look up the specifications of the op-amp to find a typical value of the slew rate.

Op-amps 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 op-amp can respond faithfully to changes in the input.

5.2 Handling and Using Op-amps

Real op-amps might become 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 volts) due to a combination of the clothing you wear (synthetic or wool is worse), 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 get burned out.

Burned-out chips look the same as a good ones, and you can waste a lot of time trouble-shooting your circuit. Two signs of a burned-out op-amp are excessive current drawn from the power supply (greater than about 10 mA with no load) and/or an op-amp hot to the touch. Of course, a blown-out op-amp may exhibit none of these symptoms. If you suspect that your op-amp is faulty, replace it.

5.3 Operational Amplifier

5.3.1 Equivalent Circuit of an Operational Amplifier

The model for operational amplifier is in Figure 5.1.

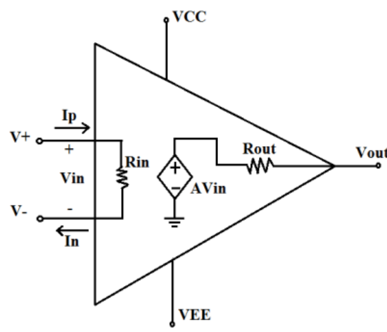

Figure 5.1 Circuit model for operational amplifier

5.3.2 Ideal Op-amps

An ideal op-amp is usually considered to have the following properties:

- Infinite open-loop gain $A \to +\infty$
- Infinite input impedance $R_{in} \to +\infty$, so zero input current $I_p = I_n = 0$
- Zero output impedance $R_{out} = 0$
- Zero input offset voltage $v_{IN} = 0$, so $V_+ = V_-$

5.3.3 Real Op-amps

Real op-amps differ from the ideal model in the following aspects:

- Finite open-loop gain A as function of frequency
- Finite input impedance R_{in}
- Non-zero output impedance R_{out}
- Non-zero input current $I_p = I_n \neq 0$
- Non-zero input offset voltage $v_{IN} \neq 0$, so $V_+ \neq V_-$
- Saturation, so output voltage is limited to a minimum and maximum value close to the power supply voltages V_{CC} and V_{EE}.
- Slew rate, which is the maximum rate of change for the amplifier's output voltage