EE 233 Circuit Theory
Lab 2: Amplifiers

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1 Introduction

This lab is designed to teach students how to read and obtain data from integrated circuit (IC) component specification (spec) sheets, through operational amplifier (op-amp) specs. This lab will also have students learn SPICE simulation, through Multisim, to predict behaviors of electronic circuits. And finally, the lab will have students 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 the music, film, television, and live sound industries. 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 should be kept on the board and reused in the following labs.** Please read **Overview of Audio Mixer.pdf** for more information on the entire project.

This lab is split into a prelab exercise and hardware implementation. Submit one prelab report and one lab report per group, with the members' names are clearly written on the front page. There is no template for the prelab report, and the lab report template is available on Canvas. These reports must be in pdf format. There are multiple apps, including CamScanner, for Apple and Android phones that turn photos into pdf's.

2 Precautions

Op-amps (and all other IC chips) can be easily damaged by static electricity, so make sure that you always store them with their prongs attached to plastic foam, which you can acquire (for free) at the EE store. In addition, make sure to ground yourself by touching a metallic surface before handling an op-amp.

Over the course of the lab, your op-amp might burn out due to improper handling and use:

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.

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 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 10mA 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.

You should also pay close attention to the circuit connections and the polarity of the power supplies, function generator, and oscilloscope inputs.

3 Prelab Exercises

3.1 LM348N Op-amp Parameters

Open **LM348N datasheet.pdf** on the class webpage. This is the datasheet for the op-amps in your lab kit; use information pertaining to "LM148", because "LMx48" is the family your op-amp belongs to. Before starting Prelab #1 read Reference 5.1 for more information on op-amp parameters.

Prelab #1:
Search through the op-amp's specifications and write down the typical values of the following parameters:

- Power supplies
- Input resistance
- Output impedance (this will be a graph)
- Open-loop voltage gain (this will also be a graph)
- Slew rate

Use these values, when appropriate, in the subsequent parts of this laboratory.

3.2 Voltage Follower Circuit Analysis

Voltage followers are useful to audio circuits because they serve as a buffer between the input signal and the rest of the circuit: if there is a sudden current or voltage surge in the input the high input resistance prevents that surge from damaging the rest of the circuit. The voltage follower is also able to completely transfer the input to the rest of the circuit, unless the signal is operating at a frequency higher than the op-amps slew rate. Figure 3.1 shows the circuit schematic for a voltage follower circuit.

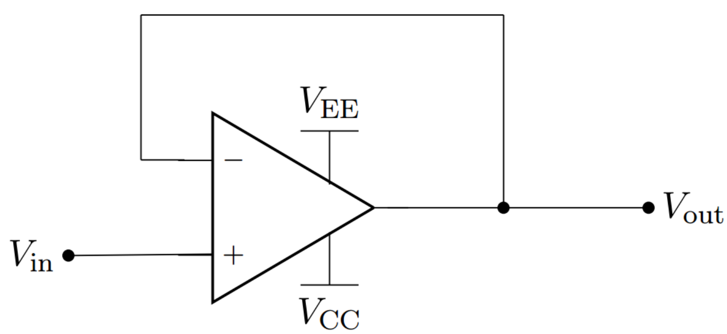

Figure 3.1: Voltage follower schematic

3.2.1 Ideal Op-amp

For an ideal op-amp, the positive and negative ports can be assumed to have the same voltage potential. Before starting Prelab #2 read Reference 5.2.1 for more information on ideal op-amp properties.

Prelab #2:
Calculate the value for the circuit's gain, which is V_{out}/V_{in}, in Figure 3.1. Assume the op-amp is ideal.

In a physical op-amp the output voltage cannot always immediately follow the input voltage. This “runtime delay” varies according to frequency, and is known as an op-amps *slew rate*, i.e. how long it takes an op-amp to respond to a sudden increase or decrease in input voltage.

Prelab #3:
If a square wave from -10V to $+10\text{V}$ is the input signal to the voltage follower:

a) Calculate the time that the output signal takes to reach the final value, using the slew rate you read from the datasheet.
b) Compare your result (using percent error) with the corresponding large signal pulse response in the datasheet and determine if they are the same. What factors could contribute to error between these values?

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 $V_{\text{in}} = A\cos(\omega t + \varphi)$, where A is amplitude, ω the angular frequency, and φ the initial phase.

Prelab #4:

a) Find the expression for the slope of the output voltage, $|dV_{\text{out}}/dt|$, in terms of the amplitude A and the signal frequency f. Assume the op-amp is ideal and there is no slew rate.
   Hint: The relation between frequency and angular frequency is $\omega = 2\pi f$.
b) Find the maximum slope of output voltage, which is the maximum value of $|dV_{\text{out}}/dt|$, in terms of the amplitude A and the signal frequency f.
c) Find the maximum frequency that avoids the slew rate limitation if the input amplitude A is constant.
d) Find the maximum amplitude that avoids the slew rate limitation if the input frequency f_0 is constant.

For audio signals the range of input frequencies is always between 100Hz and 5kHz, since those are the frequencies detected by human ears.

Prelab #5:
Calculate the maximum amplitude needed to avoid the slew rate limitation when the input frequency f_0 is 100Hz, and then when it’s 5kHz. Comment on your results. Should you be concerned about slew rate limitation when using audio signals in your mixer?
Hint: The voltage of audio signals is typically between 0.3V and 2V.

3.2.2 Non-Ideal Op-amp

Now that you have analyzed the voltage follower under the assumption that the op-amp is ideal, it is time to determine how the circuit will behave if the op-amp is non-ideal (e.g. finite open-loop gain A_v). When using the non-ideal model assume that you will only encounter small-signal (small amplitude) inputs, to avoid slew-rate limitations. You may still assume very large input resistance and very small output resistance for the op-amp. Read Reference 5.2.2 for more information on non-ideal op-amps.

Since the op-amp gain A_v is not ideal, is finite, 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.

Prelab #6:

a) Analyze the circuit in Figure 3.1 to derive an equation for the circuit gain $V_{\text{out}}/V_{\text{in}}$, as a function of A_v. Assume the op-amp is non-ideal.

Hint: The positive and negative ports are at different voltage potentials when the op-amp is non-ideal.

b) At what value of A_v does $V_{\text{out}}/V_{\text{in}}$ equal 0.5?

Using the op-amp specifications (plot of op-amp gain A as function of frequency) and the result above:

c) At what frequency do you expect $V_{\text{out}}/V_{\text{in}}$ to equal 0.5?

d) Find the range of gain $V_{\text{out}}/V_{\text{in}}$ for the audio signal and comment on whether or not the gain significantly changes in terms of frequency. Can we reasonably assume that the op-amp is ideal for all audio signals?

3.3 Summing Amplifier Circuit Analysis

A summing amplifier is essential for mixing signal channels. The audio mixer uses potentiometers to control the ratios between channels, while also filtering the white noise in the audio frequency. Now consider a summing amplifier with three input channels, as shown in Figure 3.2.

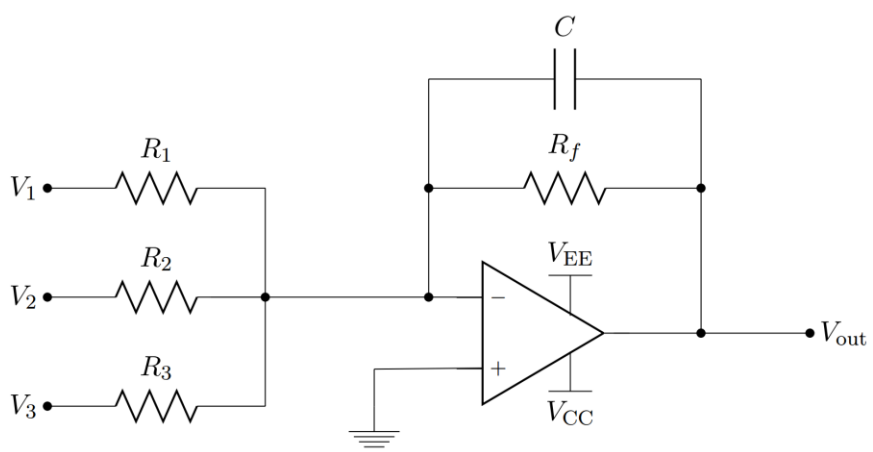

Figure 3.2: Summing amplifier schematic

Prelab #7:

Assuming that the input voltages V_1, V_2, and V_3, are in the frequency domain, and that the op-amp is ideal:

a) Derive the equation for V_{out} in the frequency domain, in terms of frequency.

b) Derive the expression for the magnitude of the output signal, $|V_{\text{out}}|$, in terms of frequency.

Now suppose the input voltages V_1, V_2, and V_3 are independent of frequency.

Prelab #8:

a) Find the expression for $|V_{\text{out}}|$ if all the inputs are DC.

b) 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.

Hint: Set the expression you got in Prelab #7b equal to 0.7 times the expression you got in part (a) above, then simplify.

c) What are the frequencies for 50%, 30% and 10% the DC value?

Now assume:

$$v_1(\text{t}) = \cos(2000\pi t)\text{V}, v_2(\text{t}) = 0.1\cos\left(2000\pi t - 30^{\circ}\right)\text{V}, v_3(t) = 0.1\cos\left(2000\pi t + 30^{\circ}\right)\text{V}$$

$$R_1 = R_2 = R_3 = R_f = 100\text{k}\Omega, C = 22\text{pF}$$

Download **Lab2_prelab.m** and **lab2plot.m** from the class webpage, place them in the same folder, then open **Lab2_prelab.m**. Follow the instructions to complete Prelab #9b.

Prelab #9:

a) Find V_1, V_2, and V_3 in the phasor domain.

b) Plot the magnitude and phase of the output signal in the range from 10Hz to 1MHz. Make sure the frequency is in Hertz and the output's magnitude is in dB.

c) 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 SPICE to simulate and verify your calculations. Keep the diagrams from the SPICE program and turn them in with your prelab. You may use any SPICE program you wish: PSPICE, HSPICE, Multisim, LT-SPICE, or something else; however, Multisim is the preferred software for you to use, and can be found on any EE lab computer or through the EE remote desktop.

Refer to **Lab 2 Multisim Tutorial.pdf** for a step-by-step tutorial on how to create the circuit simulations.

3.4.1 Voltage Follower Simulation

Use SPICE transient analysis to simulate the circuit in Figure 3.1, with power supplies $V_{\text{CC}} = 12\text{V}$ and $V_{\text{EE}} = -12\text{V}$. The input should be a square wave with an amplitude of -10V to $+10\text{V}$, a frequency of 3kHz, and a duty cycle of 50%.

Prelab #10:

From the SPICE 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 SPICE program to the corresponding waveforms given in the datasheet

3.4.2 Summing Amplifier Simulation

Simulate the circuit in Figure 3.2, with power supplies $V_{CC} = 12V$ and $V_{EE} = -12V$. Use the circuit and input values from Prelab #9.

> **Prelab #11:**
> Use SPICE AC analysis to plot the output voltage from 10Hz to 1MHz. Compare this plot with the one from Prelab #9b.

4 Experimental Procedure and Data Analysis

4.1 Voltage Follower

Note: Instructions for using the lab equipment are found in **Lab Equipment.pdf**, on the class webpage.

Build the circuit in Figure 3.1 with power supplies $V_{CC} = 12V$ and $V_{EE} = -12V$. Set the function generator to provide a square wave with an amplitude of $-10V$ to $+10V$, a frequency of 3kHz, and a duty cycle of 50%.

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 around 3 complete cycles of the signals. Capture the output from the scope display with both the waveforms and the measured values. **Turn this oscilloscope waveform in as part of your lab report.**

> **Analysis #1:**
> Measure the time needed for the output to reach steady state after a drastic change in the input, then use this information to calculate the slew rate. Compare the result with the typical slew rate in the specifications. Compare the oscilloscope waveforms with those in the datasheet and SPICE program.

Clear all the measurements. Change the input signal to a sine wave with an amplitude of 3V ($-3V$ to $+3V$ peak-to-peak) and a frequency of 1kHz. 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.

> **Analysis #2:**
> What is the frequency for the onset of this distortion? Compare it with the theoretical result calculated in Prelab #4c.

Clear all measurements. Set the input signal to a sine wave with an amplitude of $100mV$ ($-100mV$ to $+100mV$ peak-to-peak) and a frequency of 10Hz. Check the output signal to make sure that the voltage follower functions as expected.

Now 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.**

Analysis #3:
What is the gain of the circuit at 10Hz (which is called "low-frequency gain")? And what is the frequency at which the voltage gain is half of the low-frequency gain? Compare these results with those found in Prelab #6.

4.2 Summing Amplifier

Build the circuit in Figure 4.1 with power supplies $V_{CC} = 12\text{V}$ and $V_{EE} = -12\text{V}$. Set the function generator to provide $v_1(t) = \cos(2000\pi t)\,\text{V}$, $v_2(t) = v_3(t) = 0\text{V}$. Set $R_1 = R_2 = R_3 = R_f = 100\text{k}\Omega$ and $C = 22\text{pF}$.

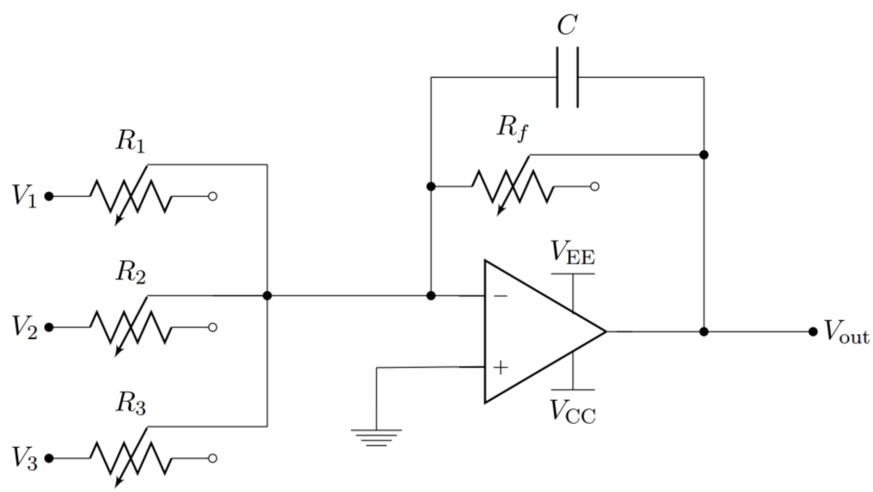

Figure 4.1: Summing amplifier with potentiometers

Sweep the frequency of V_1 from 10Hz to 1MHz, varying it using the 1-2-5 sequence, while keeping the amplitude the same. **Record the amplitude of the output signals.**

Analysis #4:
Using Microsoft Excel, plot the output voltage in terms of frequency and compare it with the results from Prelab #9b and Prelab #12.

For the next procedure you will need to rent a speaker from the EE store (free if you give them your UW ID) and download the supplemental audio files from the class website.

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

Analysis #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 1kHz sine wave and hear how it sounds.

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

Analysis #6:
Comment on the function of the four potentiometers.

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

5 Reference Material

5.1 Op-amp Parameters

There are many parameters for simple op-amp components, but only a few parameters are pertinent to the lab procedure, and will be briefly discussed in this section. Other parametric specifications are important in higher-level design courses.

5.1.1 Power Supplies

Never exceed the specified power supply limits. The most frequently used supplies are: ± 15V, ± 12V, ± 12V and ± 5V.

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 Impedance

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:

$$A(\text{dB}) = 20\log_{10}A$$

This equation can be used to convert a ratio gain into a dB value or vice versa.

Example: If *A* = 100:

$$A(\text{dB}) = 20\log_{10}(100) = 40\text{dB}$$

If *A* = 40dB:

$$40 = 20\log_{10}A \rightarrow A = 10^{40/20} = 100$$

The datasheets 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 10V) 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_0/dt). The slew rate depends on the specific op-amp design, the power supplies, and loading conditions. Use the op-amp datasheet 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 Op-amp Properties

5.2.1 Ideal Op-amps

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

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

5.2.2 Non-Ideal Op-amps

Non-ideal op-amps differ from the ideal model in the following ways:

- 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 $V_{\text{in}} \neq 0$, 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