## Basic operational amplifier circuits

In this lab exercise, we look at a few op amp circuits and become familiar with our at-home lab equipment.

### Prior to Lab

- Look over the introductions and instructions or the using the Digilent Analog Discovery 2 systems for setting up and doing labs.
- Become familiar with the multimeter. Pick out the parts that will be used for various circuits and measure the values with the meter.
- Look over the data sheets for the 324 and 660 op-amps. Even though they are different parts, they have identical pin connections, making it easy to swap them. In a future lab, we will look at some of the differences between between the two op amps. For now, we will treat them as being essentially interchangeable.

  Suggestion: Since we will use the op amps frequently in EE 230, you might want to make a small copy of the pin-outs for each and tape them to the lid of your parts box.

## A. Standard Inverting & non-inverting amps.

Build the two amplifier circuits shown in Fig. 1 using op-amps from an LMC660 chip. Use ±5 V power supplies from the DAD. Build the two circuits, so that both are available on the circuit board at the same time. Calculate the expected gain for each circuit.

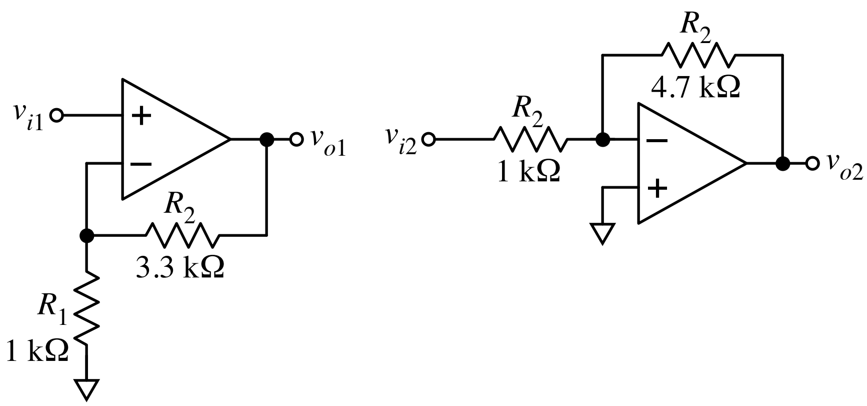


Figure 1. Simple non-inverting and inverting amplifier circuits

- Measure the gain of the non-inverting amp. Do this by using one of the function generators from the DAD to apply a sinusoid with an amplitude of 0.5 V and frequency of 1 kHz at the input. Confirm the operation of the source by observing the waveform with the DAD oscilloscope. Then use the other channel of the oscilloscope to view the output. Use the oscilloscope readings to calculate the gain, $G = v_{o1}/v_{i1}$. Then measure the gain again using the multimeter. (Remember to set the meter to AC volts and recall that it reports the AC voltage in RMS.) Save a copy of the oscilloscope traces — input and output together on the same axes — for the report. Try some different source frequencies — for example 100 Hz, 500 Hz, 5 kHz, 10kHz, 20 kHz. Are there any changes in the output amplitude?
- Repeat all of the previous measurements using the inverting amp.
- Now cascade the two amps with the non-inverting amp first followed by the inverting amp. To do this, connect the input of the inverting amp to the output of the non-inverting amp and attach the sinusoidal source to the input of the non-inverting amp. Lower the amplitude of the source to 0.25 V. The output of the inverting amp is the output for the cascaded pair.

  Observe the input and output together on the oscilloscope and measure the gain of the cascade. Save a copy of the oscilloscope traces for the report.
- Now repeat the cascade, but swap the order — the inverting amp is first and the non-inverting amp follows. (You should only need to swap a couple of wires.) Repeat the measurements and save a copy of the traces. Can you detect any differences when the order has been changed?

Do not remove the circuits from the circuit board — they will be used in part B.

## B. Unity-gain buffer — part 1

Wire up a potentiometer in a simple voltage divider configuration, as shown in Fig. 2(a).

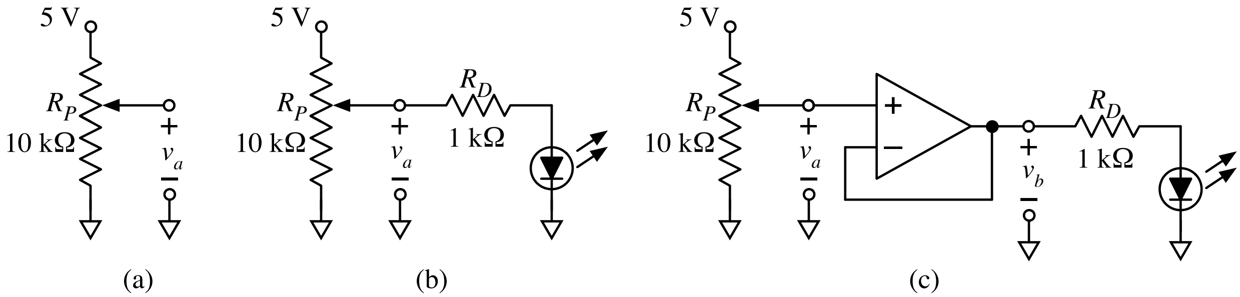


Figure 2. Various voltage divider circuits.

- Use the multimeter to measure the voltage $v_a$, which is the voltage on the wiper (center terminal) of the potentiometer with respect to ground. Adjust the potentiometer setting up and down and note that $v_a$ changes smoothly as the potentiometer setting is changed, varying from 0 V to 5 V as the potentiometer is adjusted through its full range. Adjust the potentiometer so that $v_a$ is exactly 2.5 V.
- Attach an LED (any of the ones from your kit is OK) and a 1-kΩ current-limiting resistor as shown in Fig. 2(b). Measure $v_a$ again. Can you explain the change? Re-adjust the potentiometer until $v_a = 2.5$ V. Disconnect the resistor/diode combination and measure $v_a$ once more. Obviously, the voltage divider does not work as expected when a load is attached.
- Now insert a unity-gain buffer between the potentiometer and the LED/resistor pair as shown in Fig. 2(c). Use another amp from the LMC 660 chip that was used to build the amps in part A above. Before connecting the potentiometer to the amp input, adjust the setting until $v_a = 2.5$ V. Connect the amp and measure $v_b$. Try several other potentiometer settings, measuring $v_a$ and then $v_b$. The benefit of the buffer should be obvious.

## C. Unity-gain buffer — part 2

In audio amplifier applications, a potentiometer can serve as a simple volume control.

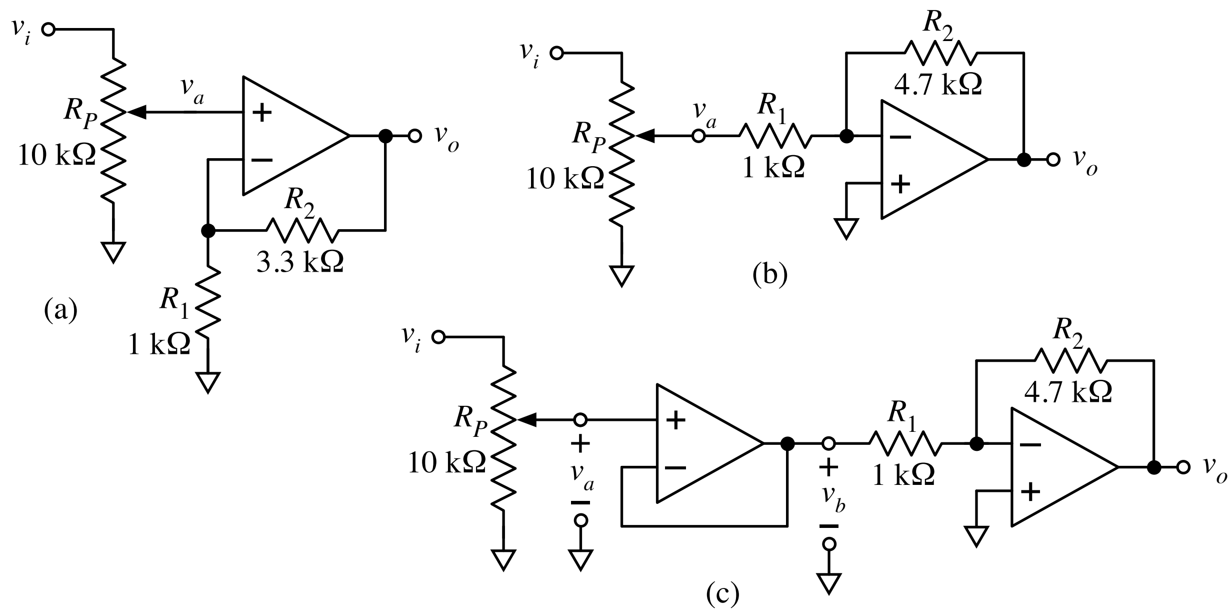


Figure 3. Inverting and non-inverting amps with potentiometers as signal-level adjustors.

- A non-inverting version is shown in Fig. 3(a). The circuit is a combination of the non-inverting amp used in Part A and the simple voltage voltage divider of Part B. Apply a sinusoid with an amplitude of 1V and frequency of 1 kHz at the input to $v_i$. Prior to connecting the circuits, set the potentiometer so that $v_a$ has an amplitude of 0.5 V (= 0.353 $V_{RMS}$ if measuring with the multimeter). Then, connect the circuits together, and measure $v_i$, $v_a$, and $v_o$. Show that everything is working as expected by calculating the voltage divider ratio, $v_a/v_i$, and the gain of the amp $v_o/v_a$. Observe the input and output together on the oscilloscope and and save a copy for the report. Vary the potentiometer setting to see the how the potentiometer controls the output amplitude. The circuit works nicely because there is no current drawn at the non-inverting input and the voltage divider is not "loaded'.

- Now repeat with the potentiometer and the inverting amp from part A. Use the same sinusoid for $v_i$, and, before connecting the amp, set the potentiometer so that $v_a = v_i/2$. Without changing the potentiometer setting, connect the amp to the divider and measure $v_i$, $v_a$, and $v_o$. Calculate the voltage divider ratio, $v_a/v_i$ and the amplifier gain, $v_o/v_a$. Now things are not so simple — the potentiometer has, in effect, become part of the feedback loop. The divider is loaded by $R_1$ and the gain of the amp depends on the potentiometer setting. Observe the input and output together on the oscilloscope and and save a copy for the report. Vary the potentiometer setting to see that the output amplitude does indeed change, but the situation is more complicated than in the non-inverting case.

- The inverting situation can be improved by adding a buffer between the potentiometer and the input of the amp. Build the circuit and repeat the previous measurements to show that the divider and the amplifier are isolated and work together as expected.

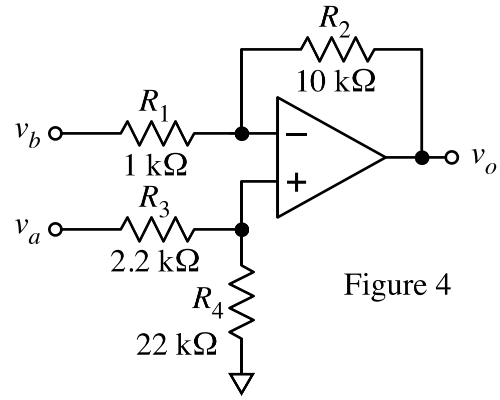

Figure 4

### D. Difference amplifiers

A basic difference amplifier circuit is shown in Fig. 4. Build the circuit using an LM324 op amp with ±5-V power supplies. Also, use the multimeter to measure the values of the resistors and calculate the actual ratios of $R_2/R_1$ and $R_4/R_3$.

Calculate the expected output function, $v_o = f(v_a, v_b)$, for the amp, assuming that the resistor ratios are matched.

We will use the dual-source feature of the DAD to measure some of the properties of the difference amp. (Note that the single-source function generators used in our the usual on-campus lab would require that these measurements be done in a different manner.)

- Channel 1 of source will be used for $v_a$. Set channel 1 to be a sinusoid with amplitude of 0.25 V and frequency of 1 kHz. Also, set the DC offset to be +2 V. Channel 2 will be $v_b$ — set it to be a sinusoid with $f$ = 1 kHz. However, set the amplitude to be zero and the DC offset to be +2V. The inputs are $v_a$ = (0.25 V)·sin $\omega t$ + 2V and $v_b$ = 2V. Choose "Synchronized" from the pull-down menu, so that there will be no phase difference between the sources. Connect the sources to the inputs of the difference amp and activate them. Observe $v_a$ and $v_o$ together on the oscilloscope. Record a copy of the two traces together and note the amplitude of the output sinusoid and the DC value of the output.

- Now set $v_a$ = 2 V (sinusoid amplitude is zero) and $v_b$ = (0.25 V)·sin $\omega t$ + 2V. (Basically, the two inputs are swapped.) Observe $v_b$ and $v_o$ together on the oscilloscope. Record a copy of the two traces together and note the amplitude of the output sinusoid and the DC value of the output.

- Set $v_a$ = (0.2 V)·sin $\omega t$ + 0.2 V and $v_b$ = 0. (Amplitude and offset of vb are both zero. Or, in the circuit, connect $v_b$ to ground.) Save an oscilloscope trace and record the DC and AC values of the output.

- Next, set $v_a$ = (2 V)·sin $\omega t$ + 0.1 V and $v_b$ = (2 V)·sin $\omega t$ – 0.1 V. (Note the sign on the DC part of $v_b$.) Save an oscilloscope trace and record the DC and AC values of the output.

The behavior the difference amp should be fairly clear now. To finish, we should measure the common-mode rejection ratio, CMRR = $G_d/G_c$. (See the class notes for the definitions.)

- To measure $G_c$, apply the same signal to both inputs (inputs are common). Set $v_a = v_b$ = (2 V)·sin $\omega t$, with no offset. Save an oscilloscope trace of the input and output together and record the DC and AC values of the output. Use the results to calculate the common-mode gain, $G_c$. (It should be small.)

- To measure $G_d$, set $v_a$ = (0.2 V)·sin $\omega t$ and $v_b$ = 0. (Again, no offsets.) Save an oscilloscope trace of the input and output together and record the DC and AC values of the output. Use the results to calculate the difference-mode gain, $G_d$. (It should be small.)

- Calculate CMRR.

An improved version of difference amp is the instrumentation amp shown in Fig. 5. (See the notes for analysis of the circuit and discussion of the advantages.)

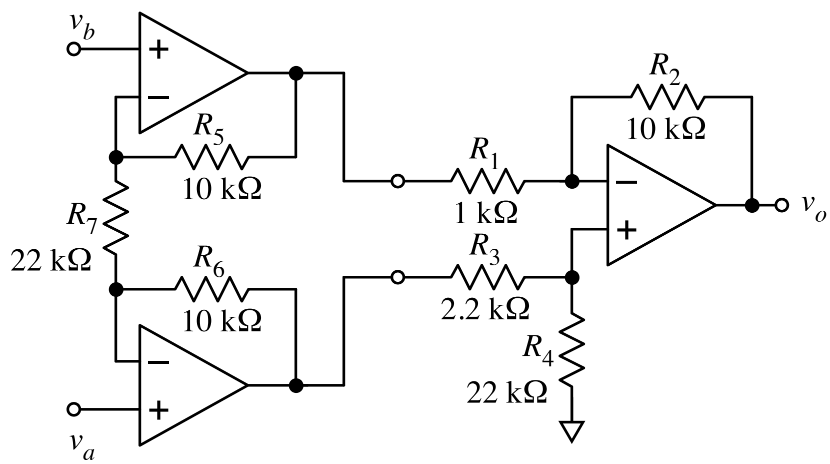


Figure 5. Instrumentation amp.

- Calculate the expected difference mode gain for this instrumentation amp.
- Build the circuit and measure the difference-mode gain. Set $v_a$ = (0.2 V)·sin $\omega t$ and $v_b$ = 0. Save an oscilloscope trace of the input and output together and record the AC value of the output. Use the results to calculate the difference-mode gain, $G_d$.
- Measure the common-mode gain. Set $v_a = v_b$ = (2 V)·sin $\omega t$, with no offset. Save an oscilloscope trace of the input and output together and record the AC value of the output. Use the results to calculate the difference-mode gain, $G_d$.
- Calculate CMRR.

As discussed in the notes, CMRR is a function of the resistor matching in the difference amp. If the resistors were perfectly matched, the difference amp would reject common-mode signals ($G_c = 0$) and CMRR → ∞. In a real circuit with imperfect resistors, $G_c$ will not be zero and the CMRR will be something less than infinity. However, CMRR can be probably improved with some tweaking. Change $R_4$ from the 22-kΩ fixed resistor to a series combination of a fixed 15-kΩ resistor and a 10-kΩ potentiometer. Set $v_a = v_b$ = 4 V (DC only, AC amplitude = 0.) While measuring the DC output, adjust the potentiometer setting and attempt to minimize the output. The tweaking of the resistance value improves the resistor matching and reduce the common-mode gain. Using the minimum output voltage found by tweaking, calculate the minimum $Gc$ and the corresponding maximum CMRR. (Assume $G_d$ is unchanged from the prior measurement.)

One feature of the instrumentation amp is that the gain can be varied with a single resistor. (In the simple difference amp, any adjustments require changing two matched resistors, which is much tricker.) In the instrumentation-amp circuit, Change $R_7$ from the 22-kΩ fixed resistor to a series combination of a fixed 15-kΩ resistor and a 10-kΩ potentiometer. Apply a difference signal — for example $v_a$ = (0.2 V)·sin ωt and $v_b$ = 0 — observe the output together with the $v_a$ input and show that adjusting the $R_7$ potentiometer changes the gain without adding any common-mode signal.

## E. Integrating amplifier

The integrating amplifier circuit shown in Fig. 6 uses an LM324 op amp with ±5-V power supplies. The voltage signal used for the inputs is a 500-Hz square wave with 6-V peak-to-peak amplitude. (It switches back and forth between +3 V and –3 V.)

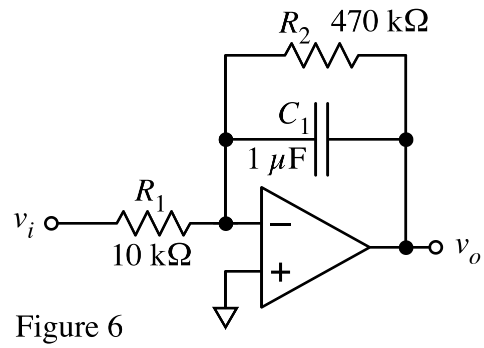


Figure 6

(Note: $R_2$ is included to reduce errors in the operation of the circuit. Without $R_2$, the amplifier has essentially infinite gain at DC, and so any small DC voltages present at the input will cause the output to be shifted up or down by a possibly large amount. After you have completed your measurements, try removing $R_2$ to see the effect on the output waveform.)

- Make a good sketch (with numbers) of the expected output of the integrator with square wave input as described above.
- Build the circuit.
- Observe the input and output together on the oscilloscope. Note from the oscilloscope trace the maximum and minimum values of the amplifier output. Save a good copy of the trace to include in the mini-report.
- Change the input from a square wave to a ramp with the same amplitude and frequency. (The input ramps from –3V to 3 V in 1 ms and then back down at the same rate.) Observe the input and output together and save a copy for the report.
- Change the input to a sinusoid with the same amplitude and frequency. Observe the input and output together and save a copy for the report.

## Reporting

Prepare and submit a report after you have finished the lab. Beside to include all required oscilloscope traces and calculations.