Lab 7

Operational Amplifiers (Op-amps)

REFERENCE: Horowitz and Hill — Sections 4.01-4.09,4.11; Appendix K: `411 datasheet

INTRODUCTION

" The operational amplifier (op amp):

- is an integrated circuit, i.e., "chip."
- is a multistage transistor amplifier with a differential input.
- has a high input impedance (10^{12} Ω for J-FET input op-amps).
- is usually used with an external feedback network.
- can amplify or perform mathematical and logical operations.
- can operate from DC to MHz frequencies, depending on the op-amp model.
- requires bi-polar power supply, typically ± 15 V.

" Note: The student will need software to make graphs, or log-log or semi-log graph paper with 5 cycles.

EQUIPMENT

Prototyping board	
Digital Oscilloscope	
Function generator	
Digital Multimeter	
Op-amp (2)	LF411CN (or equivalent 8-pin DIP)
Resistors:	1 k (2), 10 k (4), 22 k, 100 k, 5 M
Decade box	
Capacitor:	0.01 μF, 50 pF

log-log and semi-log paper (alternatively, use a computer to plot data)

" The `411 is a general-purpose internally-compensated op-amp that costs about a dollar. Compared to the old `741, the`411 is better because it has JFET transistors, lower offset error, lower drift, and is faster.

PROCEDURE

0. Things to know

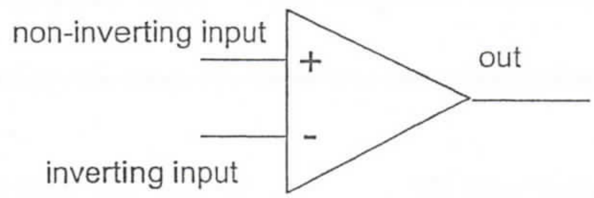


Figure 7-1 Symbolic representation of an operational amplifier

" An op-amp ideally obeys the rules:

(1) The output voltage does whatever necessary to make the two inputs at the same voltage.
(2) The current drawn by the two inputs is zero.

Also, an external feedback network must be provided that connects the output to the inverting input; this provides negative feedback.

The pin configuration for an 8-pin DIP op-amp is shown in Figure 7-2, as viewed from the top.

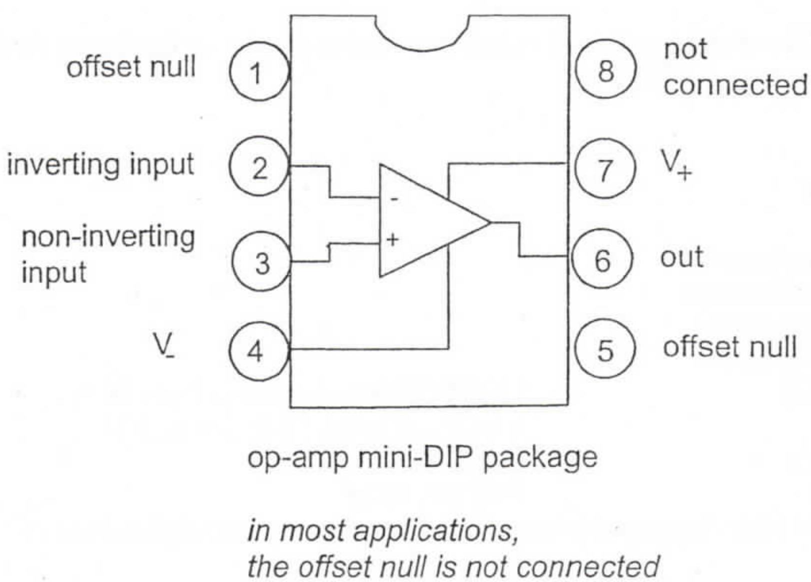


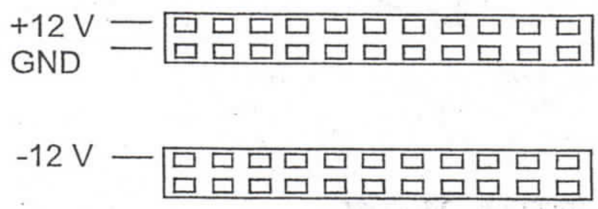
Figure 7.2 Op-amp pin configuration

❝ Note that an op-amp is an active component that must be powered to work. Most models need a bi-polar power supply. On a schematic diagram, the power-supply connections to an op-amp are often not shown.

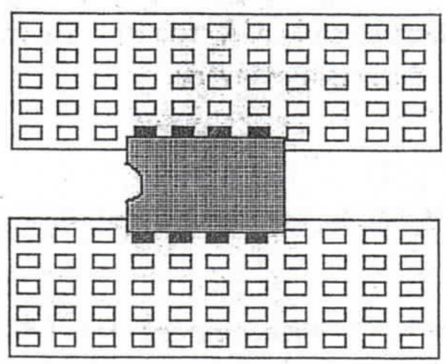
Connect the two terminals V_+ and V_- to a ±15 V power supply (or ± 12 V on your prototyping board).

The prototyping board

A prototyping board is made especially for DIP (dual-inline package) ICs. Many models have built in power supplies that you may use. Use wires to connect the outputs of the ± 12 V power supply and ground (three wires in all) to a couple of narrow strips that look like:



Insert the ICs (carefully to avoid bending their leads) into the wider strips, like this:



1. Inverting amplifier

❝ To measure the amplitude of a sine wave, measure peak-to-peak and divide by two.

☞ Set up the oscilloscope to show a dual trace, one for the input of the op-amp and one for the output. Use DC input coupling. Set up the function generator to produce a sine wave with an amplitude ≈ 0.2 V and frequency 1 kHz. (Use the –20 dB button on your function generator, if necessary, to reduce your function generator output to such a low amplitude.) Make sure that the grounds of the function generator, oscilloscope, and prototyping board are somehow connected.

☞ Measure the values of your resistors, then using the prototyping board, wire up the inverting amplifier shown in Figure 7-3.

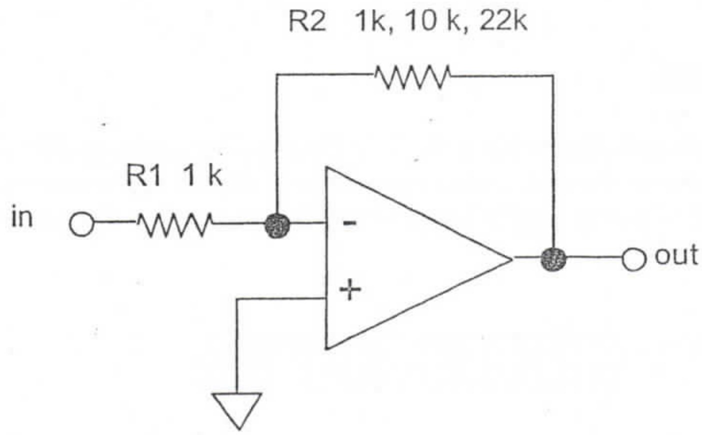


Figure 7-3 Inverting amplifier

(a) Gain

☞ ✍ (i) Measure the gain A_V for $R_2 = 1$ k, 10 k, and 22 k.
(ii) Using measured values of R_2 and R_1, compare to $A_V = - R_2 / R_1$.
(iii) Verify that the amplifier inverts.

(b) Saturation

☞ For the circuit with $R_2 = 22$ k , increase the input signal amplitude to observe clipping.

☞ Calculate the ratio $Vout / Vin$ that corresponds to -3 dB.

☞ ✍ Measure the input amplitude that results in clipping of 3 dB at the output. What is this amplitude as a ratio of V_{CC}?

(c) Frequency response

(i) roll-off frequency

☞ ✍ For the circuit with $R_2 = 22$ k, vary the frequency from a low value (≈ 100 Hz) upward to find f_{3dB}, the frequency at which the gain drops by 3 dB. Compare to the value given by Figure 4.31 in the text.

(ii) graph of frequency response

☞ ✍ For the circuit with $R_2 = 100$ k, measure the gain A_V at the logarithmically-spaced frequencies of 100 Hz, 300 Hz, 1 KHz, 3 kHz,..., 1 MHz, 3 MHz. Repeat for $R_2 = 10$ k.

☞ ✍ Plot your results on log-log graph paper. (You will need 5 cycles for the log paper on the frequency axis.) Also show on this graph the theoretical gain $|A_V| = R_2 / R_1$.

“ Note that high gain is achieved at the expense of frequency bandwidth.

2. Voltage Follower (Unity Gain Non-Inverting Amp)

“ The circuit in Figure 7-4 has a voltage gain of unity but a very high current gain.

(a) Input impedance

☞ ✍ Use a 5 MΩ resistor in series with the function generator at the input to measure the input impedance. If it is too high to measure, report it as $Z_{in} >> 5$ MΩ.

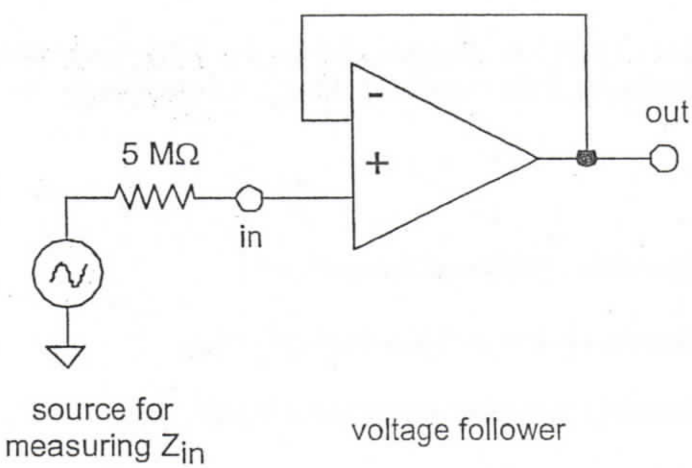


Figure 7-4 Unity gain non-inverting amplifier (Voltage Follower)

3. Summing Amp

☞ Build the circuit shown in Figure 7-5. Choose $R_1 = 10$ k.

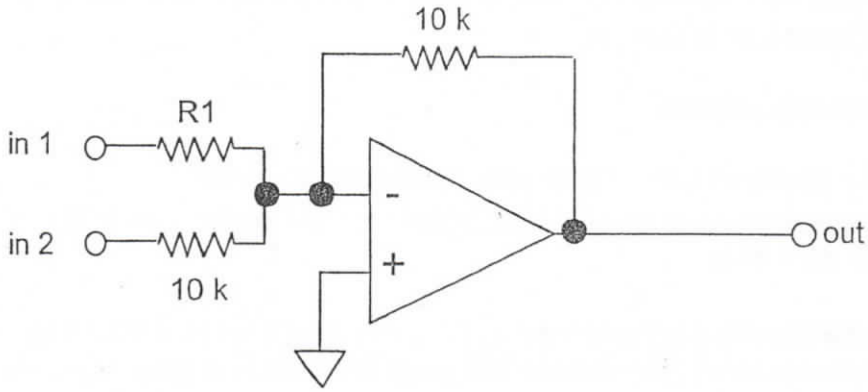


Figure 7-5 Summing Amplifier

☞ Use a 4 Volt P-P sine wave for input 1. Use a + 5 V dc voltage from a power supply (your prototyping board is ok) for input 2. Connect the oscilloscope, using DC input coupling, to monitor input 1 and the output.

(a) Summing

☞ ✍ Confirm that the output is (minus) the sum of the inputs. Sketch the waveforms.

(b) Clipping

☞ ✍ Use the DC offset on your function generator to raise the dc input voltage until you see a pronounced clipping of the waveform. Sketch the waveforms.

4. Difference Amp

“ The circuit in Figure 7-6 is a differential amplifier.

“ Recall that the common mode rejection ratio is defined as:

CMRR = differential mode gain / common mode gain, i.e.,

CMRR = A_D / A_C

" Using Op-amp rules 1 and 2 as described in the text, one can derive that the output is

$$V_{out} = -\frac{R_2}{R_1} V_{in\,1} + V_{in\,2} \frac{R_4}{R_1}\left(\frac{R_1+R_2}{R_3+R_4}\right) \qquad (4.1)$$

Note that if $R_1 = R_2 = R_3 = R_4$, then the output is a simple difference

$$V_{out} = V_{in2} - V_{in1}. \qquad (4.2)$$

More generally, we can find expressions that are valid even if the resistor values are not all exactly identical, which of course they won't be in practice, due to resistor tolerances. Substituting $V_{in1} = - V_{in2}$, we find that the "differential mode gain" is

$$A_D = - R_2 / R_1 \qquad (4.3)$$

Substituting $V_{in1} = V_{in2}$, we find that the "common mode gain" is

$$A_C = -\frac{R_2}{R_1} + \frac{R_4}{R_1}\left(\frac{R_1+R_2}{R_3+R_4}\right) \qquad (4.4)$$

which is zero if $R_3 = R_1$ and $R_4 = R_2$. So, the CMRR = A_D / A_C is perfect (infinity) if $R_3 = R_1$ and $R_4 = R_2$. However, resistors actually have a tolerance of typically 5%, and therefore the common mode gain will not actually be zero, and the CMRR will not be infinity.

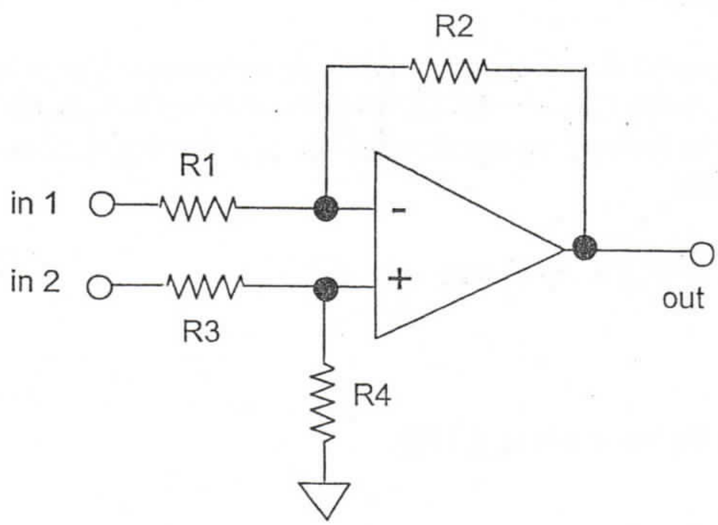


Figure 7-6 Differential Amplifier

☛ Connect the circuit in Figure 7-6, using resistor values
$R_1 = R_2 = R_3 = R_4 = 10$ k.

(a) Differencing

☛ ✍ Use the setup with a sine wave and a dc signal set-up that you used for the summing amp. Verify that the output is the difference of the two inputs, as predicted by Eq. (4.2).

(b) Differential mode gain

☛ ✍ Apply the sine wave to input 1 and connect input 2 to ground. Measure $A_D = V_{out} / V_{in1}$. Compare to the value predicted by Eq. (4.3), using actual measured values for the resistors.

(c) Common-mode gain

☛ ✍ Connect both inputs to the sine wave. Measure $A_C = V_{out} / V_{in}$. Compare to the value predicted by Eq. (4.4), using actual measured values for the resistors.

(d) CMRR

✍ Compute CMRR $= A_D / A_C$. Compare this value to your result using discrete transistors in Lab 5. Which difference amplifier has the highest (best) CMRR?

5. Integrator (low-pass filter)

“ The circuit in Figure 7-7 is an integrator, which is also a low-pass filter with a time constant $= R_1$ C. Resistor R_2 provides DC feedback for stable biasing, since without it there would be feedback through the capacitor only, and that would not provide any DC feedback.

The output is $V_{out} = -\dfrac{1}{R_1 C} \int V_{in}\, dt + \text{const}$

(a) Integration

☛ ✍ Print waveforms for V_{in} and V_{out} at 1 kHz.

(b) DC stability

☛ ✍ Remove the 5 MΩ resistor, and see if anything unfortunate happens. Be sure to use DC coupling on your oscilloscope input.

(c)Frequency response

☞ ✍ Vary the frequency while observing the input and output waveforms on the oscilloscope. It is not necessary to record data for this step. Discuss in one sentence how your observations are consistent with the description "low-pass filter."

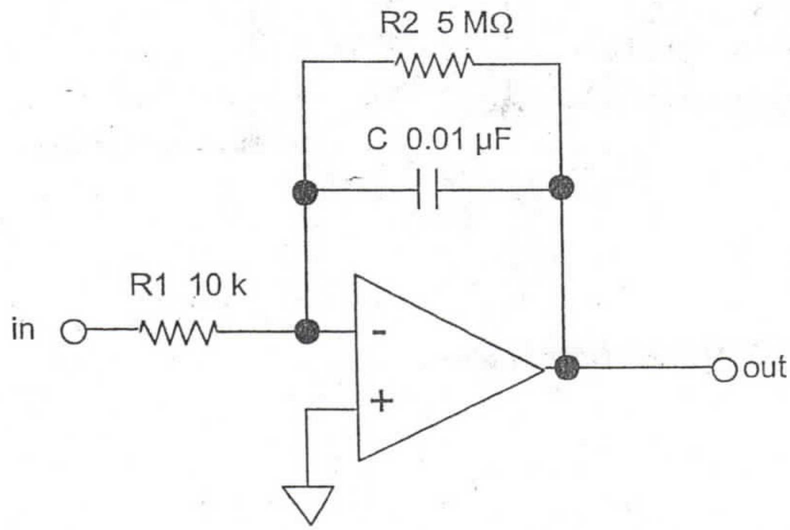


Figure 7-7 Op-Amp Integrator

6. Differentiator (high-pass filter)

❝ The configuration in Figure 7-8, with the main components C_1 and R_2, is a differentiator. Differentiators always have difficulty with high frequency noise, so a low-pass filter combination C_2 and R_1 is added to reduce the noise.

☞ Connect the circuit shown in Figure 7-8, and apply a sine wave to the input.

(a) Differentiation

- Print the outputs of the differentiator circuit for a sine wave input at frequencies 100 Hz and 10 kHz. Explain how your waveforms are consistent with the circuit taking the "derivative" of the input.

(b) Frequency response

☞ ✍ Vary the frequency while observing the input and output waveforms on the oscilloscope. It is not necessary to record data for this step. Discuss in one sentence how your observations are consistent with the description "high-pass filter."

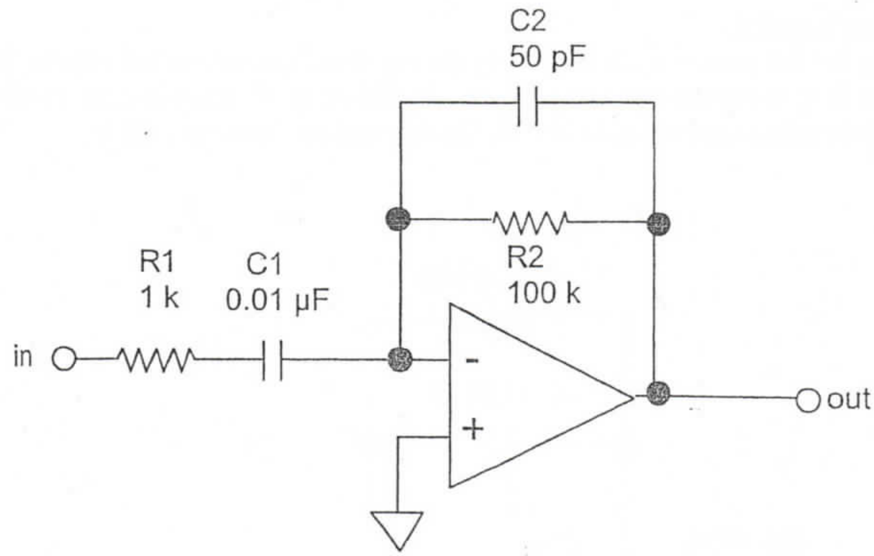


Figure 7-8 Op-Amp Differentiator