ECE 241L Fundamentals of Electrical Engineering

NAME ______________________

PARTNER ______________________

Experiment 3 Operational Amplifiers (Op-amps)

A. Objectives:

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I. Build and compare two inverting amplifier circuits
II. Build and test the voltage follower circuit, an integrator, and a Schmitt trigger
III. Investigate non-ideal op-amp behavior, (off-set voltage, clipping, slew rate, bias current compensation)
IV. After completing this lab you shoul;d know:
  (a) How to build a circuit that uses 741 op-amps
  (b) How to determine the practical limits of op-amps
  (c) The difference between ideal and non-ideal op-amps
  (d) How to use op-amps for wave-shaping and voltage amplification

B. Equipment:

Breadboard, wire, resistors, capacitors, 741 op amp
Oscilloscope: Tektronix TDS3043 Digital Storage Scope
Function Generator: Tektronix AFG310/320 Arbitrary Function Generator
Digital Volt-Ohm Meter (DVM): Fluke 189 (or equivalent)

C. Introductory Notes:

One of the most useful analog integrated circuits available is the operational amplifier (op-amp). The op-amp symbol is shown in Figure 1. The numbers at the terminals in Figure 1 are the pin numbers of the integrated circuit package for a 741 or 741 pin-compatible op-amp.

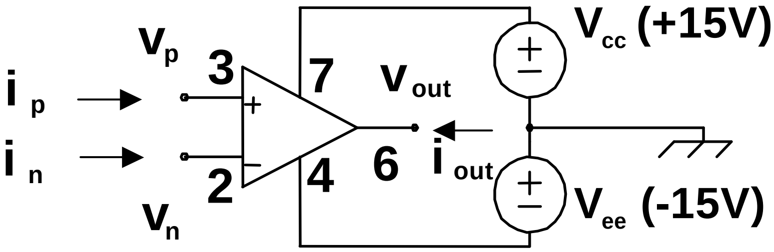
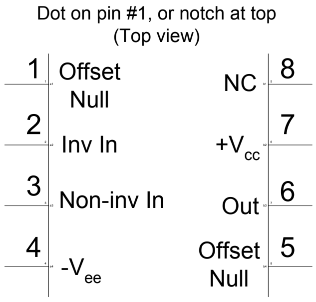
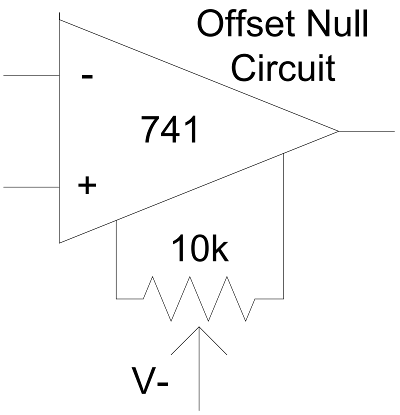


Figure 1 - 741 OPAMP Pinout w/ DC Supplies





Op-amps were first introduced in the 1940s as vacuum tube modules, which consumed large amounts of power. When transistors were introduced in the 1960s, op-amp size and power distribution were drastically reduced, making them cheaper and more efficient. The industry standard μA741 was introduced by Fairchild Semiconductor in 1968, and is still widely used today. Op-amps were first used to perform arithmetic operations in analog computers, (including addition, subtraction, multiplication, division, differentiation, and integration,) but modern uses have extended into signal processing (filters), communications, audio mixing, control systems, remote control, etc.

An op-amp operating in it's linear range is a voltage-controlled voltage source with voltage gain, A_0, such that the output voltage v_{out} is determined by

$$v_{out} = A_o v_{in} = A_o (v_p - v_n)$$

Equation 1

where v_{in} is the differential input voltage, $v_{\text{in}} = v_{\text{p}} - v_{\text{n}}$, v_{p} and v_{n}, respectively, are the voltages applied at the non-inverting and inverting input pins. (Note that v_{out}, v_{p} and v_{n} are measured relative to 'ground', i.e. to the zero volt reference.) To make this circuit work, *dc supply voltages* have to be applied from a power supply.

Constant voltage supplies V_{cc}=+15V and V_{ee}=-15V are shown connected in Figure 1 at pins 7 and 4. The op-amp's internal electronic circuitry limits the amplitude of the output voltage to a little less than supply voltages: in this case, $|v_{out}| < 15$ V. There is provision for nulling out the DC offset voltage, as shown, but you will not use this unless absolutely necessary.

The voltage gain of an op-amp at low frequencies is very large, typically $A_0 > 10^5$. Since the output voltage is limited by the power supplies, (in this case $|v_{out}| < 15$V), it follows from Equation 1 that

$$\left|V_{in}\right|_{\max} = \left|\frac{v_{out}}{A_o}\right|_{\max} \leq \frac{15}{10^5} = 150\mu V$$

Equation 2

if the op-amp is to act as a *linear* amplifier (i.e. there be a linear relationship between V_{in} and V_{out}.) This means that to be in the *linear* range the input voltage is limited by

$$\left|v_{in}\right|_{\max} \approx \frac{V_{cc} - V_{ee}}{2A_o}$$

Equation 3

If the input voltage is larger than the limit imposed by Equation 3, the output will saturate and stay close to V_{cc} or V_{ee}. This relation is illustrated by the *dc transfer curve* in Figure 2.

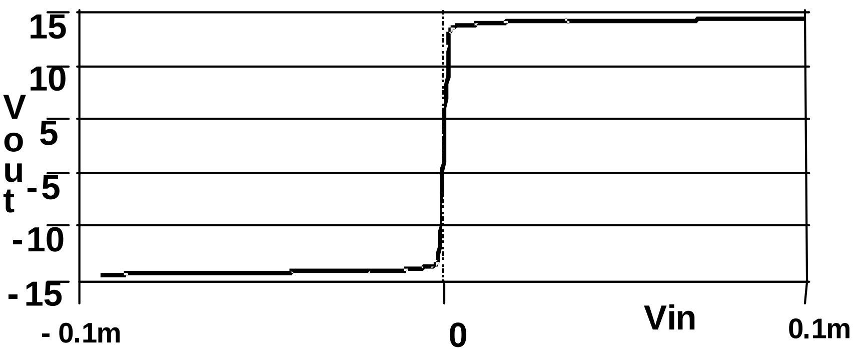


Figure 2 - Typical OPAMP DC Transfer Curve

Note the different scales on the vertical and horizontal axes, because of the influence of the large gain A_0.

If the op-amp is to work in its linear range, it is necessary to apply *negative feedback* from its output to its input, i.e. some electrical network, such as a resistor, *must* be connected from the op-amp 's output to the *inverting* input if linear operation is to be achieved.

Since $|V_{in}|_{max} < 0.15\text{mV}$ is normally much less than any other voltage in the circuit, one may make the approximation that in an ideal op-amp the gain A_0 is infinite and

$$v_{in} = 0 \quad i.e. \quad v_p = v_n$$

Equation 4

Further approximations of an ideal op-amp are that the currents i_p and i_n in Figure 1 are zero. This implies the input resistance at the inverting and the non-inverting inputs is infinite,

$$R_{inp} = \frac{\partial v_p}{\partial i_p} \to \infty \quad R_{inn} = \frac{\partial v_n}{\partial i_n} \to \infty \,.$$

Also the output resistance is assumed zero,

$$R_{out} = \frac{\partial v_{out}}{\partial i_{out}} = 0$$

i.e., the op-amp output looks like an ideal voltage source, controlled by v_{in}, whose voltage is unchanged by the output current. In real op-amps one measures $R_{in} > 10^6\Omega$ and often $R_{in} > 10^8\Omega$, and $R_{out} < 100\Omega$.

Observe from Equation 4 that in linear operation, ideally $v_p = v_n$, that is, the inverting and non-inverting input terminals are at the same voltage, referred to as a *virtual short*. This means that if v_p is connected to ground ($v_p = 0$) as is often the case, then $v_n = 0$ also. But because $R_{in} \to \infty$, we have also $i_n = 0$. Such a terminal is referred to as *virtual ground*. These concepts are very useful when analyzing ideal op-amp circuits. This simple model is adequate to explain and understand the experiments in this laboratory.

In practice, for any application above the low audio range, the simple model needs considerable refinement. In particular it must be remembered that the op-amp gain is a function of frequency: it decreases with frequency approximately like the function 1/f, as shown in Figure 3.

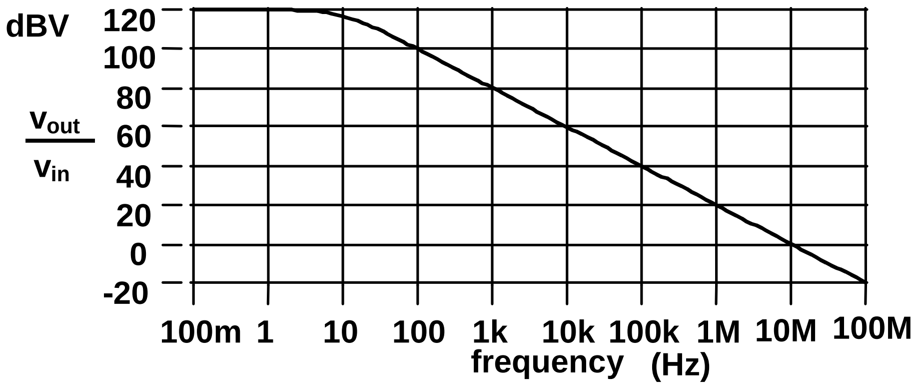


Figure 3 - Typical OPAMP Gain vs. Frequency

PROCEDURE

In order to build the circuits in this lab, you will have to use OUT1 and OUT2 of the PS250 Programmable Power Supply in series tracking mode. **Error! Reference source not found.** shows how to connect the power supply to the rails and the schematic for the connection.

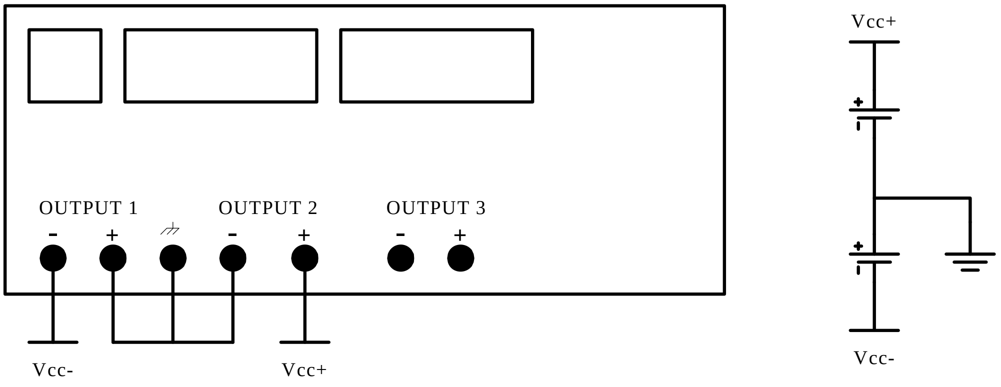
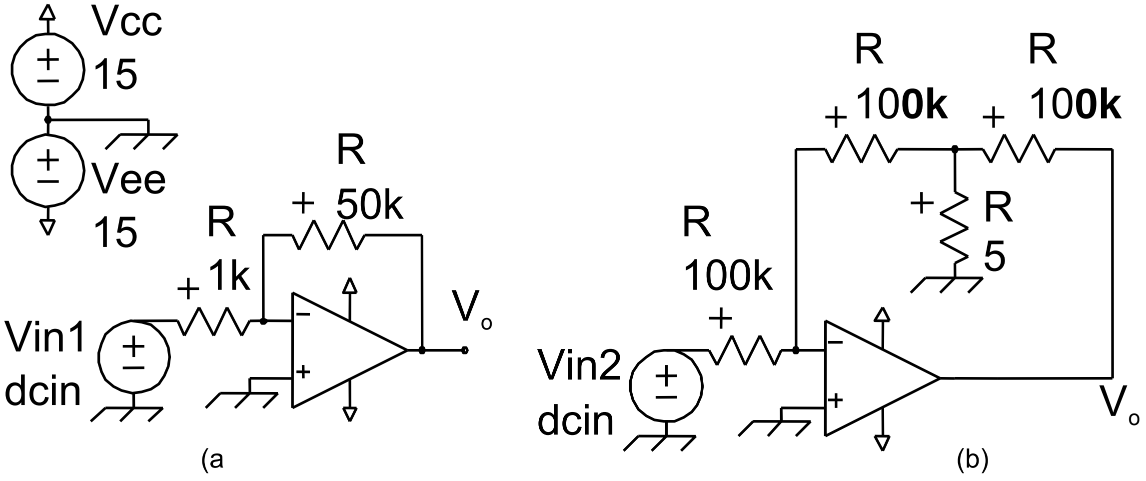


Figure 4. Op Amp Rails Connection.

In all your experiments set the power supply to ±15V, connect a load R_L=10kΩ from op-amp output to ground and use only resistors larger than 1kΩ. Refer to Figure 1 for pin numbers. To avoid parasitic oscillations in your circuit, use 10µF shunt capacitors located as close to the op-amp as possible for both the plus and the minus power supplies (i.e. in parallel with the power supplies.) Be careful to install the capacitors in the proper polarity, i.e. '-' terminal at the more negative voltage. The purpose of these capacitors is to prevent high frequency currents from flowing through the power supplies via long inductive wires, i.e. high frequency currents are drawn from the capacitor, rather than directly from the power supply. When hooking up the circuits don't forget to connect the ground of the power supplies. One should have the grounds of the signal generator, the oscilloscope and power supplies connected all together as one common node. Please note that there is no ground pin on a 741 op-amp but often one of the input pins is grounded. If your circuit does not work as expected, check first that you have power and ground everywhere you should have it

Unless stated otherwise, for each circuit, connect a sinusoidal signal with a frequency of 1 kHz and a peak-to-peak amplitude of 0.5 V to the input V_{in} and observe input and output using the oscilloscope, set to 1MΩ input impedance.



(a

(b)

Figure 5 - Inverting Amplifiers

1. Build the circuit of Figure 4(a). (Use two 100k resistors in parallel for R2.) Verify its performance experimentally by comparing input and output amplitudes. Before measuring, make sure your output waveform is not distorted, compared to your input. (Turn down your input amplitude until the output is undistorted.) Record undistorted sinusoidal amplitudes.

V_{in1} = ________________________________ volts V_0 = _________________________________ volts

Gain V_0/V_{in1} = ________________________

2. Build a unity gain circuit, using the topology of Figure 5(a) (with $R_1=R_2=10k\Omega$). This will be used to estimate the slew rate of the op-amp. Apply a 10 $V_{peak\text{-}to\text{-}peak}$ square-wave with a frequency of 5 kHz at the input. Adjust the time-base of the oscilloscope so that only one edge of the output signal is visible; either a rising or falling edge can be used. Measure the time the output waveform takes to pass through the 10% and 90% points of its voltage change. Record the Δt and ΔV from this measurement. The slew rate of the op-amp may be approximated by this $\Delta V/\Delta t$. Slew-rate (*SR*), in units of V/μs, is a measure of how fast the output voltage $v_o(t)$ of the op-amp can change, given a large differential signal at its input. It is the highest possible rate of change $dv_o(t)/dt$ that the amplifier output can provide. For large output signals, the slew rate is a limitation on the frequencies that can be

amplified without distortion.

ΔV = ________________________ volts Δt = _______________________ sec

$\Delta V / \Delta t$ = ______________________V/μs

Increase the signal frequency to 20 kHz. Sketch the shape of the output signal. Do you still get the expected amplitude?

Now increase the signal frequency to 50 kHz. Sketch and comment on the shape and the amplitude of the output signal. Why is the amplitude different?

3. Build the circuit of Figure 4(b) and determine its voltage gain.

V_{in1} = _______________________________ volts V_0 = ________________________________ volts

Gain V_0/V_{in1} = ________________________

4. Build the integrator shown in Figure 5(a). Record the output waveforms for input square waves of (a) +/-10v at 10kHz, and (b) +/-1v at 100Hz..

(a) (b)

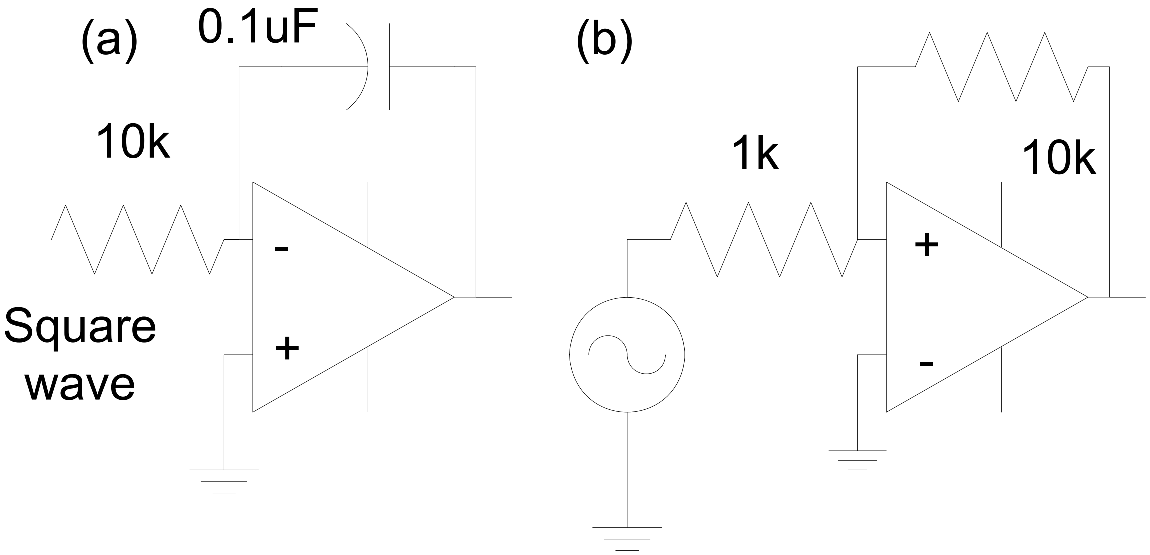


Figure 5: (a) Integrator, and (b) Schmitt trigger.

4. Build the Schmitt trigger circuit of Figure 5(b). Verify its performance experimentally by sketching the output waveform for a 5v pk-pk input sine wave. Note the input signal amplitudes when the output changes state.

Output changes when

v_{IN} = __________________________________ V

& __________________________________ V

SUMMARY

1. If the typical input offset voltage for the 741 is 1mV (from the data sheet), how is the plot of Figure 2 affected?

____ (Maximum is 5mV.)

2. Did you observe any offset voltage or bias/offset current effects with the circuit of Figure 4(a)?

3. Compare gain with theory for the circuit of Figure 4(a). ____

2. What is the amplifier input impedance (as seen by the source)? R_{in} = ____________________________

3. Why do the output amplitudes for the modified (unity gain) circuit vary with frequency, as tested in Part 2?

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4. Compare the voltage gain of the circuit of Figure 4(b) with theory.

5. What is the input impedance for this circuit? R_{in} = ____

What are the relative advantages of the circuits of Figures 4(a) & (b)?t____________________________

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5. Compare the integrator output ramp rates with theory:

(a) ____

(b) ____

1. Compare the Schmitt trigger transistion point with theory. ____