ECE231: Introductory Electronics

Lab #3

Op-Amp Circuits

Version: 1.1

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Introduction

The objective of this first analog hardware lab is to acquire some familiarity with the lab equipment and to analyze several basic circuits. These building blocks are used in subsequent labs to construct larger and more complex circuits.

Checklist:

1. Read the Background section, ensuring that you understand the operation of each circuit.
2. Complete the preparation exercises and present your results to the TA at the start of the Lab (please **PRINT and TAPE** them to your own lab book. TAs do **NOT** mark any hand-sketching plots)
3. Use the LM741CM op-amp in the prep simulations. (Connect the two BAL pins to GND)
4. Refer to the datasheet of LM741 to find all the key specs:

   http://www.ti.com/lit/ds/symlink/lm741.pdf

Lab Preparations

PE1. Perform a transient (time domain) simulation of the 'Comparator with Hysteresis' circuit in Figure 1.9. using values from step E5 in the experiment section. Run the simulation for 20ms. For the input signal, use a 0.2 kHz triangular wave of 20 Vp-p, it should be symmetrical, same slope for rising and falling edges, with no offset (i.e. the average of the triangle wave is 0).

a) Record the threshold voltages at the input that cause the output to change.
b) Include a **PRINTED** plot of the input and output waveforms in your lab notebook.
c) Record the peak (max. and min.) output voltages and point out where these values are specified.

PE2. Perform a transient (time domain) simulation of the Astable Multivibrator in Figure 1.11 using values from step E6 in the experiment section and run the simulation for 20ms.

a) Record the oscillation frequency.
b) Describe the relationship between the oscillation frequency and the capacitor value.
c) Include a PRINTED plot of the input and output waveforms in your lab notebook.

IMPORTANT: This circuit is an oscillator that requires a 'kick-start'. Without the proper initial condition, the circuit would be stuck at zero and would produce no oscillating output waveform. The simplest solution is to set the initial capacitor voltage to be non-zero (e.g. 1V). NOTE: Setting initial conditions is not necessary in the real experiment because noise in the circuitry ensures the circuit oscillates.

Background

The op-amp schematic symbol, equation, and transfer characteristics are given below.

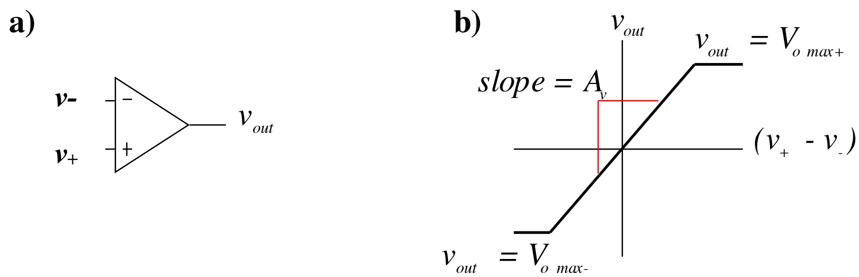
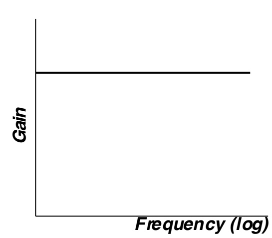
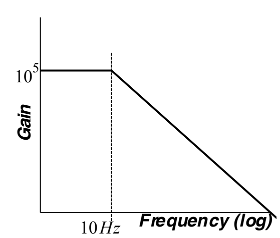


Figure 1.1: (a) Op-amp symbol; (b) Differential output characteristic.

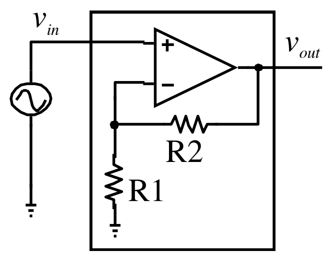
$$v_{out} = A_v \quad v_+ - v_- \tag{1.1}$$

In the following table, the characteristics of an ideal op-amp and the 741 op-amp are listed. When working with op-amp circuits, it is important to understand when the ideal characteristics are a sufficient approximation, and what are the maximum parameters it can handle (i.e. maximum voltage and current). For example, an output of 10 V that drives a 10 Ω load would require an output current of 1A! Since the 741 cannot drive that much current (the maximum is about 25mA), the output of 10 V would never be attained. Furthermore, the bandwidth or frequency response of any op-amp circuit is finite and limited by the open-loop frequency response of the op-amp.

Op-amp Characteristics

Parameter	Ideal	741
DC Gain	Infinite	200 V/mV
Z_{in}	Infinite	2M Ω
Z_{out}	0 Ω	<1k Ω
Max Output Current	Infinite	25mA
V_{omax} (Max Output Voltage)	Infinite	15V
Frequency Response		

1. **Non-inverting amplifier** (Ref: §2.3 Non-inverting Configuration)



$$\textbf{Gain} = \frac{v_{out}}{v_{in}} = 1 + \frac{R2}{R1}$$

Figure 1.2: Circuit schematic of a non-inverting amplifier.

The non-inverting amplifier configuration as shown in Figure 1.2 uses two resistors (R1 and R2) and a negative feedback path to both amplify the circuit and act as a low-pass filter.

2. **Inverting Integrator** (Ref: §2.5.2 Inverting Integrator)

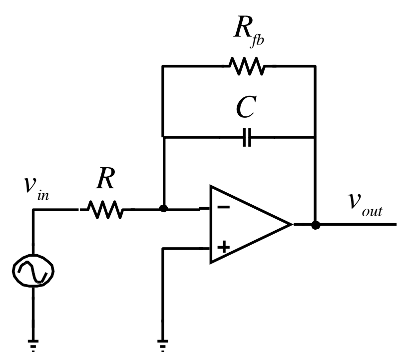


Figure 1.3: Circuit schematic of an inverting integrator

The inverting integrator uses a capacitor in the feedback path to integrate the signal at certain frequencies. R_{fb} is also in the feedback path to make sure that a DC signal cannot drive the op-amp into saturation. Also, since real op-amps in the lab are not ideal, a small DC offset is present. If that DC offset is amplified, it could also drive the op-amp into saturation. The transfer function of the integrator in Figure 1.3, assuming an ideal op-amp, is

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{-\frac{R_{fb}}{R}}{R_{fb}Cs + 1}, \tag{1.2}$$

and when $|R_{fb}Cs| \gg 1$, it can be approximated by

$$\frac{V_{out}(s)}{V_{in}(s)} \quad \frac{-\frac{R_{fb}}{R}}{R_{fb}Cs} = \frac{-K}{s}. \tag{1.3}$$

where $K = 1/(RC)$. Thus, we see that this circuit does operate as an integrator with a response of 1/s (which represents the integration operation) and a scaling factor of K. This approximation is apparent on the Bode Plot in the figure below.

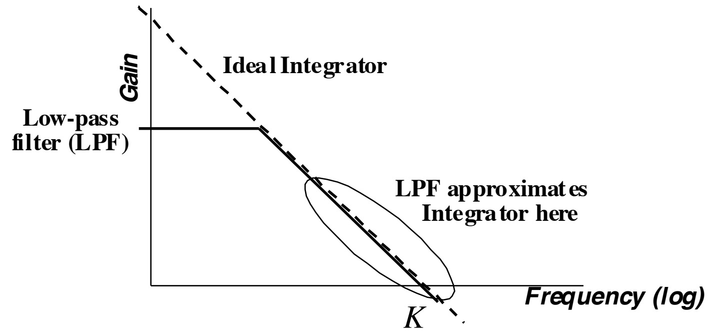


Figure 1.4: Bode Plot of an op-amp integrator

To illustrate how the circuit integrates in the time domain, we will use a 1 ms pulse as an input and determine the output based on certain parameters. In this case, we will use the values of R_{fb} = 100 kΩ and C = 22 nF which will give us a time constant of $R_{fb}C$ = 2 ms. Ideally, the output will ramp down to -4.5V and then hold at that voltage. However, in the actual circuit the output ramp is in fact a curved line and not straight because of the RC time constant in the circuit. In Figure 1.5, we can see that the output ramp is close to the ideal for short pulse widths that are much less than the time constant. This is also suggested by the bode plot in Figure 1.4 because shorter pulses contain more energy at higher frequencies where the LPF acts as an integrator.

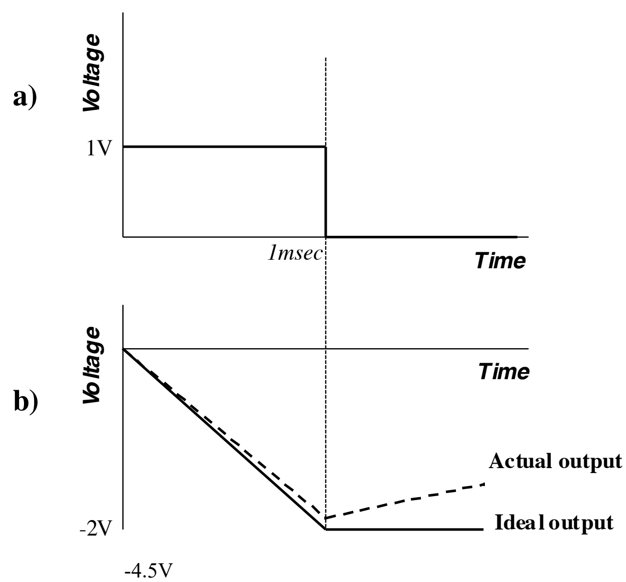
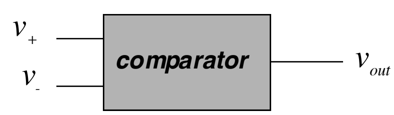


Figure 1.5: (a) Input waveform (b) Integrator output

3. **The Comparator** (Ref: §17.4.6 Application of the Bistable Circuit as a Comparator)

The comparator shown in Figure 1.6(a) is a block that performs the simple operation of comparing two input voltages and producing a logic output based on the relation in Figure 1.6(b).

a)



b)

$$\text{Is } v_+ > v_- ? \qquad v_{out} = \begin{cases} High & \text{if TRUE} \\ Low & \text{if FALSE} \end{cases}$$

Figure 1.6: (a) Block diagram; (b) Governing equation

This can be represented by the curve shown in Figure 1.7 below.

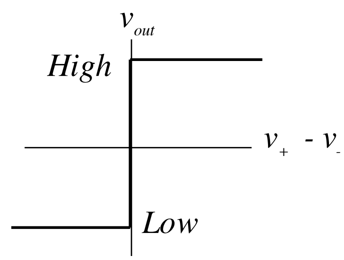


Figure 1.7: Transfer curve of a comparator

The important thing to notice in Figure 1.7 is that the transfer curve is identical to an ideal op-amp in open-loop mode. For example, in Figure 1.8(a), if the input voltage is above 0 V, V_{out} will quickly saturate to the maximum output voltage, V_{omax+}. Similarly, if the input voltage of Figure 1.8(b) goes below 3 V, then the output will quickly saturate to V_{omax-}.

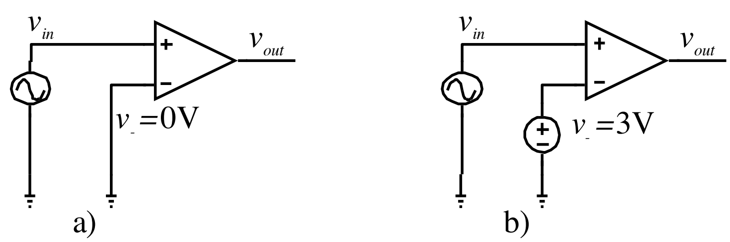


Figure 1.8: (a) and (b) Circuit schematic of two comparators

4. **Comparator with Hysteresis** (Ref: §17.4 Bistable Multivibrator)

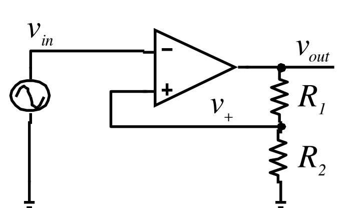


Figure 1.9: Comparator with hysteresis

In the previous examples, the threshold has been set by the voltage (v-) and has remained fixed. In practice, it is often useful to change the threshold depending on the present state of the output. Hysteresis means that the transfer characteristic is not the same whether the input is increasing or decreasing. Specifically, the comparator's threshold changes depending on the variation of the input as shown in Figure 1.10. In this case, the dotted line represents the transfer function when the input is increasing, and the solid line represents the transfer function when the input is decreasing.

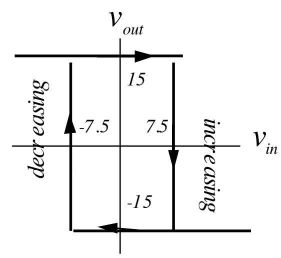


Figure 1.10: Transfer function of a comparator with hysteresis.

Now consider the circuit in Figure 1.9. To illustrate the functionality, consider an input V_{in} of -15 V, and assume that the output v_{out} is saturated at V_{omax+} = 15 V. Then, with $R_1 = R_2 = 100\ \text{k}\Omega$, we have v_+ = 7.5 V because of the voltage divider. Thus, for v_{out} to switch to V_{omax-} = -15 V, v_{in} has to increase over v_+ = 7.5 V. Assume that v_{in} has gone over 7.5V and is now at 8 V. Then, v_{out} will switch to -15 V and v_+ will now be -7.5 V. Thus, for v_{out} to switch back to V_{omax+}, v_{in} now has to decrease below v_+ = -7.5 V. This is how the switching threshold changes depending on whether v_{in} increases or decreases.

5. **Astable Multivibrator** (Ref: §17.5.1 Operation of the Astable Multivibrator)

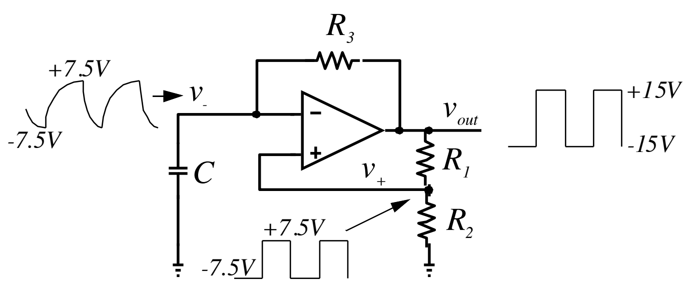


Figure 1.11: Circuit schematic of the astable multivibrator.

Finally, consider what happens when we place a capacitor and a resistor as shown in Figure 1.11. This circuit will provide a periodic signal by switching back and forth between the maximum positive and negative output voltages (V_{omax}). To analyze this circuit, first assume that v_{out} = +15V, thus making v_+ = 7.5V. Since v_{out} is positive, capacitor C will charge through $R3$ until v_- reaches v_+. At that moment, v_{out} will switch to -15V and v_+ will be -7.5V. The negative v_{out} discharges the capacitor and v_- decreases. When v_- reaches v_+, v_{out} will switch back to +15V and the cycle starts all over again.

It is important to note that v_- is simply v_{out} which has been low-pass filtered by the RC network created by R_3 and C. Since this circuit does not stabilize at a certain state (output value) it is called an astable multivibrator.

Lab Experiments

Throughout this lab, use a 741 op-amp (LM741 or similar) and use ±15 V dual power supplies to power the op-amp. **Set the current limit to 0.2 A** to avoid damage in the circuit.

Building and Debugging Tips:

1. If you have no output or if your output resembles your input (but is not supposed to), it probably means that the power supplies are off or are not properly connected.
2. Don't forget to connect all grounds together. That is, connect the grounds of the signal generator and the oscilloscope probes to the ground line on your protoboard.
3. When using the oscilloscope, think about the waveform that you expect to see, and adjust the settings accordingly. The "auto set" button and the automatic measurements may help, but they cannot think for you. See *Appendix C* for tips on using the digital oscilloscope.
4. Check ***Appendix C*** and **our tutorial videos on YouTube** for more information (get links on Quercus).

E1. Oscilloscope Measurements and Triggering Test

1. With no components connected, apply a 1 kHz sine wave with roughly 1 Vpeak-peak directly to the BNC input of the breadboard. Using the oscilloscope, measure the period and amplitude by counting the divisions on the screen. Verify the results by using the oscilloscope's built-in measure function.

   Hint: Use BW Limiting on the oscilloscope for more stable results.
2. Using the offset dial on the function generator, add a noticeable dc offset (say 2 V) to the sine wave. Use the oscilloscope to DC coupling mode (from the channel menu, see *Appendix C* to measure the dc offset voltage (a rough measurement is adequate). Next, switch to the AC coupling mode, and measure the peak-to-peak voltage of the sine wave (again, a rough measurement is adequate). Notice how in AC coupling mode, the dc offset is removed, allowing you to quickly centre the waveform on the display.
3. Reduce the amplitude of the input sine wave to roughly 0.01 Vpeak-peak. (-20 dB button gives ×0.1 gain and -40 dB button gives ×0.01 gain) What is most noticeable about the output at this point? Using the divisions on the screen, measure the actual amplitude of the wave, and then verify it by using the built-in function. In your lab book, explain how you could stabilize the waveform on the screen.

   Hint: use the "sync" output of the function generator as the external trigger signal for the oscilloscope.

E2. Non-inverting Amplifier

1. Build a non-inverting amplifier with a gain *A* of 11, as shown in Figure 1.12. Apply a 10 kHz sine wave that is roughly 0.5 Vpeak-peak at the input of the amplifier and make sure you obtain Vout of same shape but with an amplitude of 5.5 Vpeak-peak. (Rule of thumb: when making small-signal measurements, we want the output voltage swing to be less than 20% of the maximum output voltage swing)
2. Measure and record the -3 dB frequency of the non-inverting amplifier by sweeping the frequency range. Calculate the gain-bandwidth product (i.e., DC gain x f_{3db}). How does this compare with the specified gain-bandwidth product of 1 MHz for the 741 opamp?

   Hint: What is the gain of the circuit at -3 dB frequency? Calculate the amplitude of Vout at this frequency (feel free to simulate with Multisim).

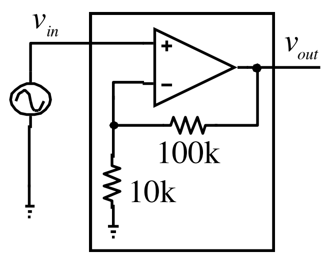


Figure 1.12: Non-inverting amplifier (*A* = 11).

E3. Inverting Integrator

1. Build the inverting integrator of Figure 1.13 using R_{fb} = 100 kΩ, R = 10 kΩ and C = 22 nF.

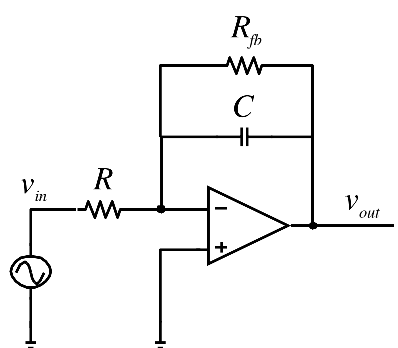


Figure 1.13: Circuit schematic of an inverting integrator.

2. Apply a 2 Vpeak-peak, square wave input at a frequency of 1 kHz. In your lab book, draw the input and output waveforms. Change the input frequency to 100 Hz and draw the input and output waveforms. Does the circuit still integrate? By sweeping the signal frequency, what would you suggest is the minimum input frequency for this circuit to act as an integrator?

E4. Comparator

1. Build the circuit of Figure 1.14(a)

2. Apply at the input a 20 Vpeak-peak triangular wave with a frequency of roughly 100 Hz (no need for accuracy). In your lab book, draw the input and output waveforms. Then, put the oscilloscope display in XY mode (see *Appendix C*) and draw the curve of the output voltage versus the input voltage (called the transfer characteristic). What is the threshold of this comparator (i.e., at what input voltage does the output switch from the positive maximum voltage to the negative maximum voltage)? You may need to vary the frequency of the triangular wave to clearly see the sweeping motion.
3. Connect the negative input of the op-amp to a 3 V power supply, as shown in Figure 1.14(b). Draw the transfer characteristic in your lab book. What is the new threshold value?

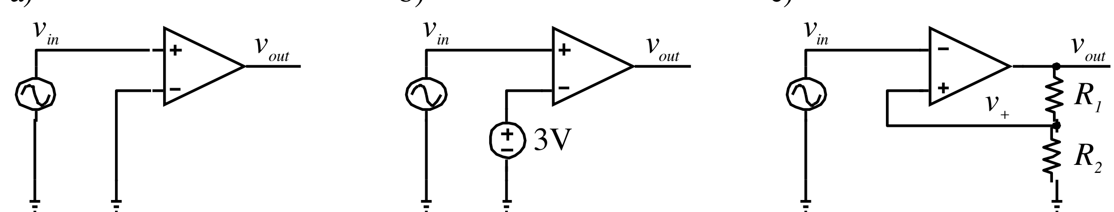


Figure 1.14: (a) and (b) Circuit schematic of two comparators; and (c) one with hysteresis.

E5. Comparator with hysteresis

1. Build the circuit of Figure 1.14(c) (notice the positive feedback), using $R_1 = R_2 = 100$ kΩ. Use the same input as in E4.2 and keep the oscilloscope in XY mode. Turn on the 'persist' option using the Display button and set it to 1 second. To better see the curve sweep, you can steadily lower the frequency of the triangular wave.
2. Draw the transfer characteristic in your lab book. What are the **two** threshold values? Describe in your lab book the difference between this transfer characteristic and that of E4.2.
3. Reduce the input amplitude to 10 Vpeak-peak. In your lab book, describe what happens and explain why.

E6. Astable multivibrator

1. Build the circuit of Figure 1.15 using $R_1 = R_2 = R_3 = 100$ kΩ and $C = 10$ nF.

   NOTE: this circuit does not have an input because it is used to generate a waveform.
2. Set the oscilloscope display from XY mode back to normal 'voltage-in-time' (YT) mode. Turn off the 'persistence' option. In your lab book, draw the waveforms of nodes v_{out}, v_+ and v_- and measure the frequency of oscillation. Can you modify the circuit to half the oscillation frequency?

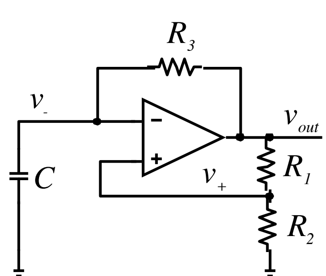


Figure 1.15: Circuit schematic of the astable multivibrator.