CIRCUITS LABORATORY

EXPERIMENT 9

Operational Amplifiers

9.1 INTRODUCTION

An ***operational amplifier*** ("op amp") is a direct-coupled, differential-input, high-gain voltage amplifier, usually packaged in the form of a small integrated circuit. The term "operational" dates back to the early days of analog computers when these devices were employed in circuits that performed mathematical operations such as addition, subtraction, integration, and the solution of differential equations. Today's op amps are used in a much wider variety of circuits and operate at considerably lower voltages and powers; however, the name remains.

The linear circuit which forms the heart of the operational amplifier is a fairly complicated device consisting of many (30 or more) active and passive devices integrated into silicon. (See schematic diagram in Section 9.11 at the end of this exercise). Such a complex device requires a team of experienced engineers many months to design! The beauty of operational amplifiers, however, is that to first order the input-output characteristics are very simple; the circuit designer using the op amp need not be overly concerned with the inner workings of the thing and can treat it like a "black box" with certain specified and very desirable properties. As such, the modern operational amplifier is a very useful and versatile building block for thousands of circuits in applications as diverse as audio, video, communications, process control, instrumentation, and biomedicine.

9.2 IDEAL CHARACTERISTICS

In this experiment, we will be concerned only with the "ideal" operational amplifier. It is this model, which is the simplest to analyze and which describes the operation that the circuit designer would consider "perfect" were it not for real-world limitations. The symbol for an operational amplifier is shown in Figure 9.1. V_+ and V_- are the input

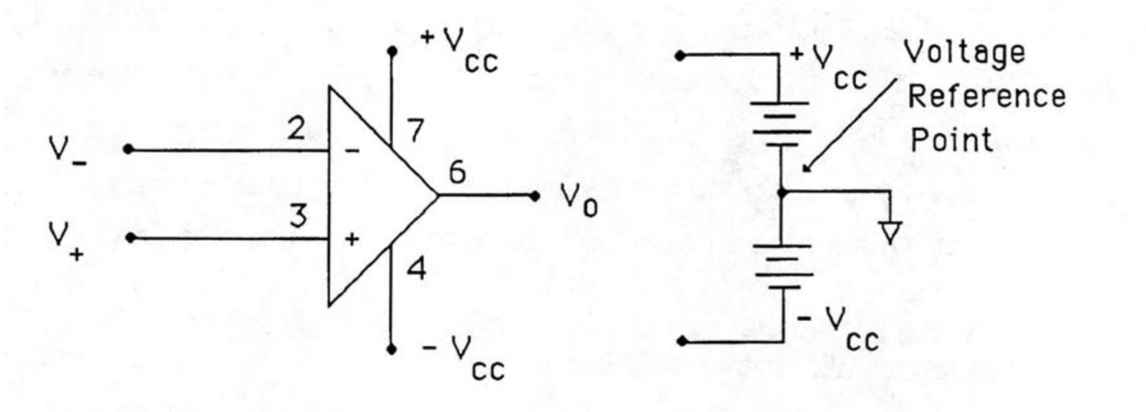


Figure 9.1: Operational amplifier symbols. Pin numbers are those of a 741 eight pin dual-inline package.

voltages and V_o is the output voltage. These are related by the simple expression

$$V_o = A_o\,(V_+ - V_-), \tag{9.1}$$

where A_o is the open-loop voltage gain and $+V_{CC}$ and $-V_{CC}$ are the positive and negative DC power supply voltages, respectively. There is no internal "ground" or "common" connection; voltages are measured relative to the common connection of the two power supplies. The numbers on the diagram refer to the pin numbers on the 741 integrated circuit (IC) package as shown in Figure 9.2. The pin numbers and the supply voltages are usually omitted in circuit diagrams as long as there is no ambiguity. Pin 8 is not used. Pins 1 and 5 do serve a useful purpose, but they will not be considered in this lab.

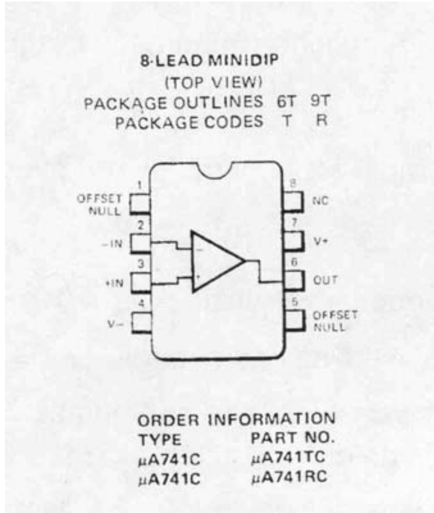


Figure 9.2: µA741 operational amplifier integrated circuit package

The ideal operational amplifier is characterized by the following three properties:

(1) The open-loop voltage gain A_o is very high. Typically, $A_o \geq 10^5$ and, in most simple analyses, you can assume $A_o = \infty$.

(2) The input impedance R_i is very high and can be assumed to be infinite. This means that there is no current into the op amp at input ports V_+ and V_- .

(3) The output impedance R_o is very low and can usually be assumed to be 0 Ω. This means that the output will drive any load without any drop in output voltage.

Of course, there are limitations to the above characteristics, especially with regard to (3). The output voltage v_o is limited to some significant fraction of the power supply voltage; the output current i_o is limited internally so that it does not overheat and destroy the device. However, for the range of voltages and currents to be experienced in this lab, these are very good approximations and you may assume them to hold.

When designing circuits with op amps, one ***never*** uses the op amp by itself as a high-gain amplifier. The gain is too high and the transfer function too non-linear. Instead, one designs ***practical*** circuits by using ***negative feedback*** from the output to the input. This concept will be emphasized throughout this lab.

Fig. 9.3 shows the input-output characteristics of a typical op amp. When the differential input voltage (V_+ - V_-) is in the range where the slope = A_o , the output v_o is equal to A_O (V_+ - V_-); otherwise the output is saturated at $\pm V_{sat}$. The "trick" in designing linear op amp circuits is to use of negative feedback to always force (V_+ - V-) to be suf - ficiently small so that the amplifier is operating in that very narrow linear region.

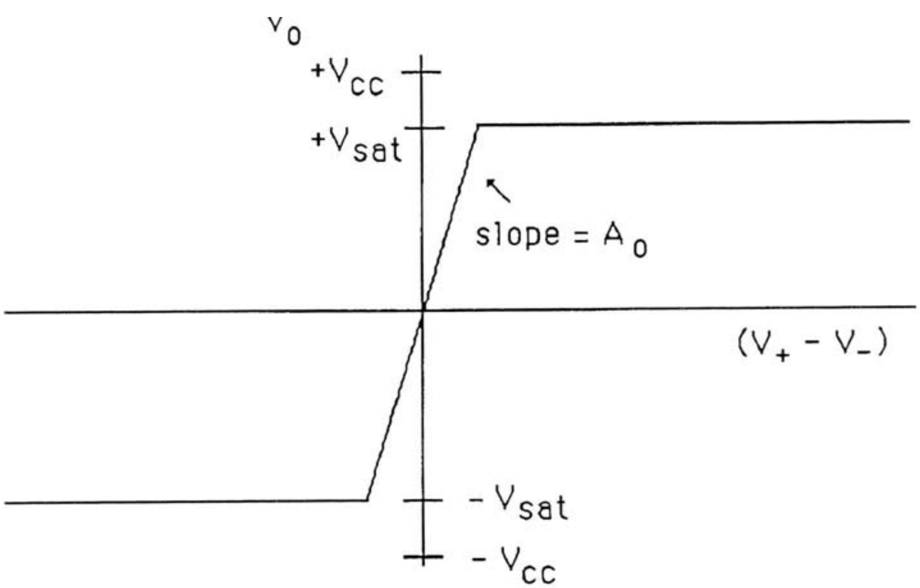


Figure 9.3: Ideal op amp input-output characteristic.

There is a simple algorithm for the analysis of an op amp circuit. This algorithm is valid only when there is some path from Vo to V-, i.e., negative feedback is being used to force the op amp to operate in its linear region.

(1) Assume that the input currents to the op amp are zero.

(2) Assume that the differential input voltage is zero and (this is the crucial part) that the output v_o always adjusts itself to force the differential input voltage to be zero, which is called a ***virtual short***.

(3) If for whatever reason (2) cannot be satisfied, then the output voltage is ± Vsat, depending on the polarity of the differential input.

Let us apply this algorithm to the simplest op amp circuit of all: the unity gain

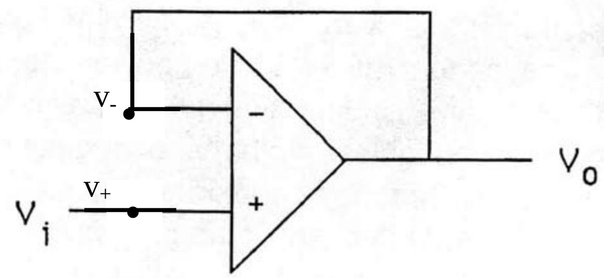


Figure 9.4: Operational amplifier connected as a voltage follower

voltage follower of Figure 9.4. The input voltage is V_i,. The *virtual short* forces $v_- = v_+$ and, therefore, $V_o = V_i$. Hence, it is termed a voltage follower. Now you may be thinking that this is a circuit that serves no function since the output voltage merely equals the input voltage. On the contrary, this circuit acts as a buffer between V_i and V_o. The input may have a high source impedance or be incapable of providing any significant power. Examples are a microphone or guitar pick-up. Here the input supplies no power at all, since $i = 0$. Instead, it is the op amp which provides current and therefore power to the load resistor, R_L, in such a way that $V_o = V_i$. Of course, this power is ultimately derived from the power supply via $\pm V_{CC}$.

In this laboratory you will assemble and test a variety of simple circuits which are built around operational amplifiers. These have been grouped into three categories: (1) inverting and non-inverting amplifiers, (2) integrators and differentiators, and (3) function generators. The following section contains some general information on assembling op amp circuits. Read it carefully before building anything!

9.3 OPERATIONAL AMPLIFIER CIRCUITS - GENERAL INFORMATION

It is assumed that you are familiar with assembling circuits using the solderless wiring fixture and ordinary passive components. The 741 IC op amp can also be inserted in this fixture for building op amp circuits. Insert the 741 integrated circuit so that the pins straddle the center horizontal gap in the wiring fixture and the notch is to the left. The pins are numbered 1 through 8, counter-clockwise beginning with the pin at the lower left.

All operational amplifiers require an external power supply to operate. The 741 requires two power supplies, one positive and one negative. This will not be shown on subsequent diagrams, but is always assumed. Use the left power supply for +16 V, and the right for -16 V. Connect the negative floating terminal on the left power supply to chassis ground, and connect the positive floating terminal on the right power supply to chassis ground. Use cables with banana plug connectors to supply the +16V, -16V, and ground to separate terminals on your solderless wiring fixture. *Be sure to connect the ground cable to the ground terminal on the fixture*. Then connect the +16 V to pin 7 and the -16 V to pin 4 of the 741. Although there is no connection for ground on the 741 IC, you will use chassis ground as a reference point later in your circuits. Do not turn on the power supplies until after you have made these connections. In general, it is a good idea <u>not</u> to assemble any circuits with the power supplies on. Pins 1, 5, and 8 should be left disconnected. Once you have inserted the 741 op amp in your wiring fixture and connected the power supplies, it should be possible to leave this particular configuration assembled for the rest of the lab.

9.4 EQUIPMENT LIST

Solderless Breadboard

Cables & Wires

741 IC Operational Amplifier

Several 1/4-Watt Resistors

Decade Capacitor Box (0-10 μF)

9V Battery

9.5 INVERTING AND NON-INVERTING AMPLIFIERS

9.5.1 Non-Inverting Amplifier - Circuit 9.5.1 Using the 741 op amp with power supplies connected as described Section 2, page 9.2, assemble Circuit 9.5.1 as shown.

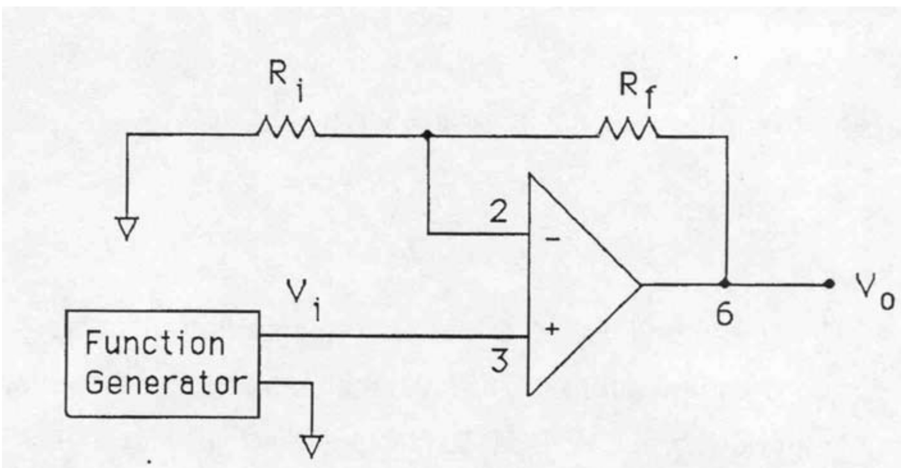


Figure 9.5: Non-inverting amplifier circuit 9.5.1.

The input- output relationship for this circuit is given by

$$V_o = \left(1 + \frac{R_f}{R_i}\right) V_i \tag{9.2}$$

Start with R_i = 10 kΩ and R_f = 33 kΩ. Before inserting resistors R_i and R_f , record and measure their actual resistance using the DMM. Use the function generator

LOW OUTPUT to supply a 1 kHz 0.4 V peak-to-peak sine wave to the input (V_i) to pin 3. Use oscilloscope CH1 to measure V_i and CH2 to measure V_o. You may find it useful to trigger the oscilloscope sweep using the function generator SYNC OUTPUT as an external trigger.

Observe and record the input and output voltages using the oscilloscope noting the phase relationship, peak-to-peak voltages and period. Now, measure the rms values of the input and output voltages. Compare your measurements to those predicted by Equation (9.2) above.

Repeat the above exercise for R_f = 0 Ohms, i.e., a short circuit.

Next, choose values for R_i and R_f such that the closed-loop gain (V_o / V_i) is 2. Repeat your measurements.

Finally, choose values for R_i and R_f such that the closed-loop gain is 11. Repeat your measurements.

Now switch the function generator to provide a 10 kHz, 4V peak-to-peak, zero offset squarewave input with the amplifier having a gain of 11. Observe and record the input and output voltages and determine the slew-rate (slope) of both the rising and falling transitions of the output voltage.

9.5.2 Inverting Amplifier - Circuit 9.5.2 Assemble the circuit shown in Figure 9.6, again measuring the actual resistance values first. The input-output relationship for this circuit is given by

$$V_o = -\frac{R_f}{R_i} V_i \tag{9.3}$$

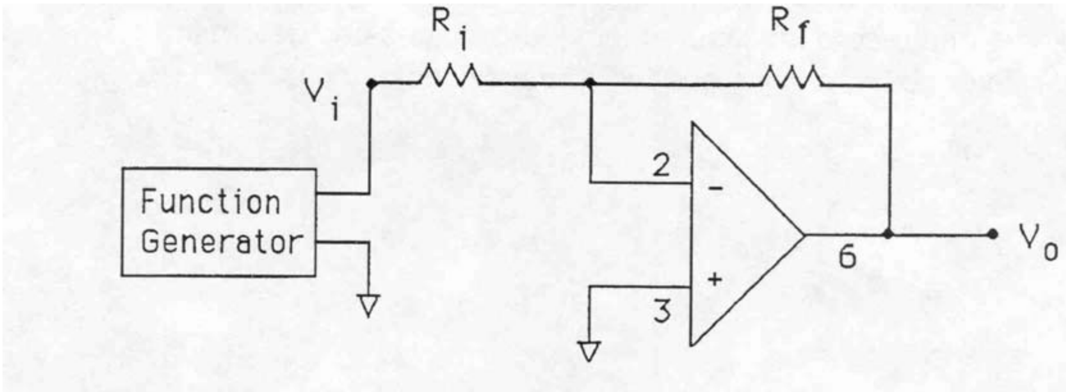


Figure 9.6: Inverting amplifier circuit 9.5.2.

Start with R_i = 1kΩ and R_f = 10kΩ . Use the function generator LOW OUTPUT to supply a 1 kHz 0.4 V peak-to-peak sine wave input as V_i. Observe and record the input and output voltages as before for a closed-loop gain of -10, -2.2, and -1. You will need to choose values of R_i and R_f for gains of -2.2 and -1. Note particularly the phase relationship between the function generator output (which is the amplifier input) and the amplifier output. Compare your measurements to those predicted by Equation (9.3) above.

9.5.3 Inverting Amplifier with Multiple Inputs - Circuit 9.5.3. Assemble the circuit shown in Figure 9.7. Use the function generator to supply a 0.4 V peak-to-peak 1 kHz,

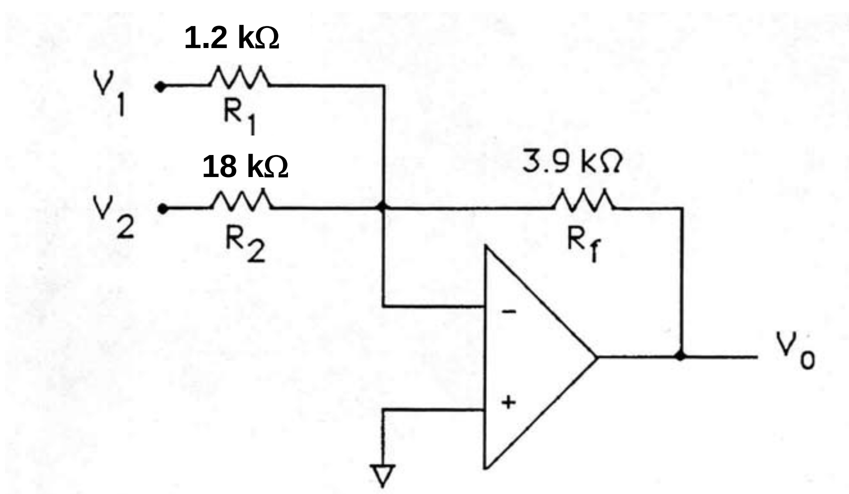


Figure 9.7: Inverting amplifier citrcuit 9.5.3 with multiple inputs.

zero offset, triangle wave to input V_1, and use the battery to supply a 9 V DC signal to input V_2 .

The input-output relationship for this circuit is

$$V_o = (G_1V_1 + G_2V_2), \tag{9.4}$$

where G_1 and G_2 are the negative gains associated with inputs 1 and 2, respectively.

The requirement is to observe the composite output V_o on CH2 of the digital scope while observing V_1 on CH1. Sketch the waveforms, V_o , with respect to V_i. Make sure that the ground reference point (on the oscilloscope) is the same for CH1 and CH2. Also, make sure you measure the actual battery voltage using the DMM. Finally, in order to measure the gains of the circuit more accurately, it is better to use superposition; that is, only apply one signal at a time (with the other input grounded) and measure the respective output voltage and gain independently.

9.6 INTEGRATORS AND DIFFERENTIATORS.

9.6.1 Integrator - Circuit 9.6.1 Use the assembled circuit of Figure 9.8 having R_i = 1Meg Ω and C = 1 μF. Do not connect the 1kΩ resistor. The theoretical input-output

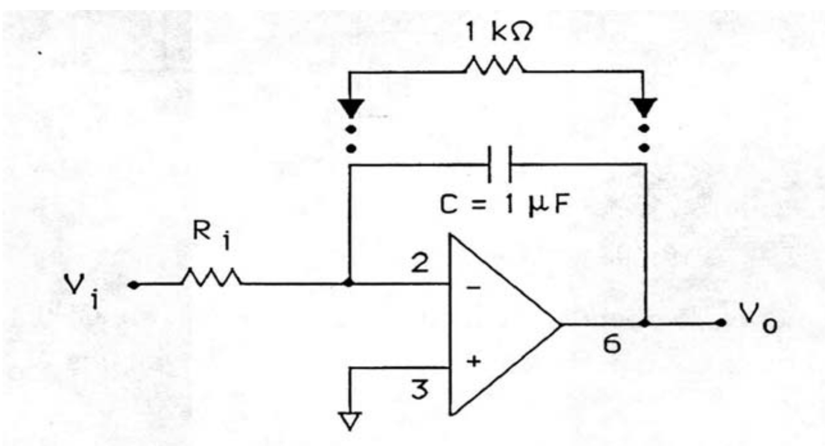


Figure 9.8: Integrator circuit 9.6.1.

relationship for this integrator circuit is

$$v_o(t) = -\frac{1}{R_i C}\int_0^t v_i(\tau)\,d\tau \; + v_o(0) \qquad (9.5)$$

You will need a 1 V DC input for this exercise. This input can be derived from the $+V_{CC}$ power supply using the voltage divider shown in Figure 9.9. Adjust the $+V_{CC}$ power supply slightly until V_i is exactly 1.0 V. Connect V_o to oscilloscope CH1 and

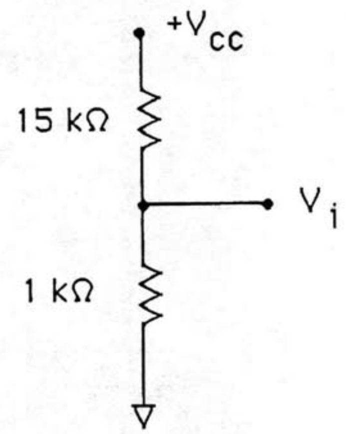


Figure 9.9: Voltage divider.

set the sweep rate to be 1 sec/div and the zero reference to the top on the scope. Continue using the external trigger so that the oscilloscope is in effect free-running. To reset the integrator to zero, connect the 1kΩ resistor in parallel with the capacitor C. This discharges the capacitor and sets v_o = -1mV ≈ 0 Volts.

Now disconnect the 1kΩ resistor so that the circuit begins to integrate the input voltage. Stop the scope trace by pressing RUN/STOP button when the trace reaches –8 V. Observe and record v_o. Note the length of time needed for v_o to reach -8 V. Compare this to the time you obtain using Equation (9.5) above. If you want to repeat the above excercise, simply discharge the capacitor C using the 1kΩ resistor as described previously. Note that the capacitor C will not discharge by itself.

9.6.2 Differentiator. - Circuit 9.6.2 Assemble the circuit shown in Figure 9.10 The input-output relationship for this circuit is given by

$$v_o(t) = -RC\frac{dv_i(t)}{dt}. \tag{9.6}$$

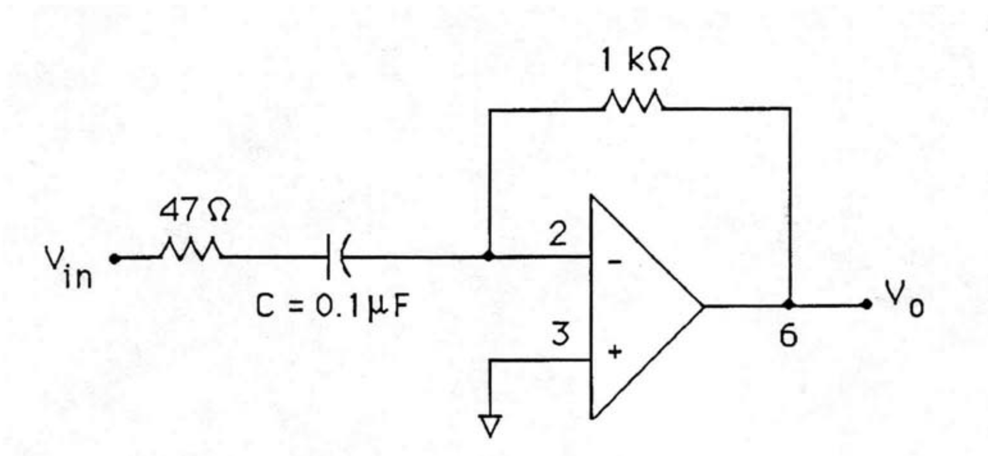


Figure 9.10: Differentiator circuit 9.6.2.

In deriving Equation (9.6) the 47Ω resistor is ignored; it is included in the circuit only to prevent certain phenomena whose analysis is beyond the scope of this course. Use the function generator to set v_i to a 2 V peak-to-peak triangle wave. Using both channels of the oscilloscope as before, observe and record the relationship between input and output for input frequencies of 500 Hz, 1kHz, and 5kHz. Compare this to what you obtain using Equation (9.6). Repeat the above experiment using a sine-wave input. Be sure to note the phase relationship between input and output.

9.7 FUNCTION GENERATORS

In this section of this laboratory exercise, you will see how an operational amplifier can be used, not as a linear device, but as a "digital" device whose output is either $\pm V_{sat}$ and is used to indicate the polarity of the differential input. An operational amplifier used in this way is called a ***comparator***. The basic model of the comparator is the same as that of the op amp, although the design of the actual device may be different so that certain properties that are desirable in comparators are emphasized more than those properties desirable in operational amplifiers. The 741 op amp is not the world's best comparator, but it will perform adequately for the experiments in this exercise.

9.7.1 Square-Wave Generator - Circuit 9.7.1 Use the already assembled circuit shown in Figure 9.11. Observe and record the output v_o. You will have to use the internal trigger on Ch 1 of the scope since this circuit has no input and is not synchronized with anything.

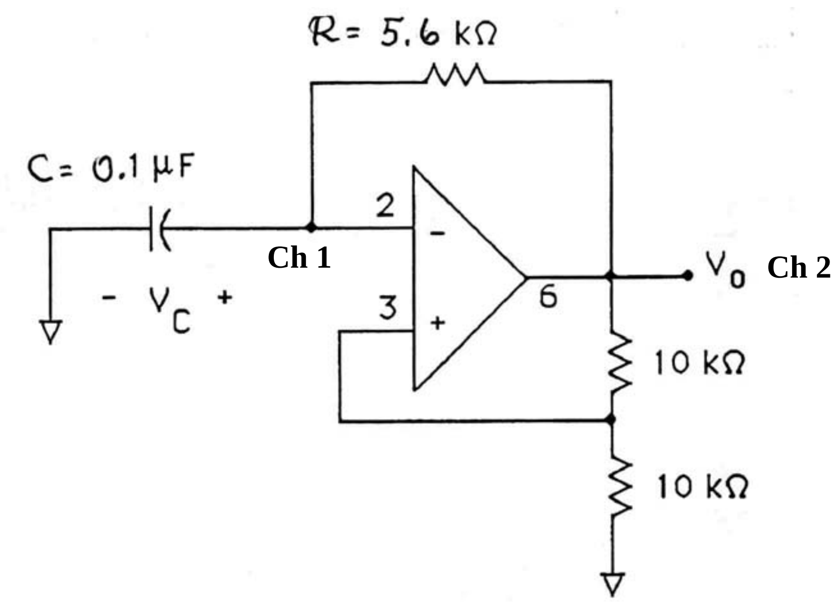


Figure 9.11: Square wave generator circuit 9.7.1.

Circuit 9.7.1 is analyzed as follows. Suppose at $t = 0$, $v_o = +V_{sat}$ and $v_C = 0$. Then $V_+ = V_{sat} / 2$. This is greater than v_C so the output is consistent with the input. The capacitor C charges through the feedback resistor. When v_C reaches V_+ (actually just slightly larger), the polarity on the input is reversed, and the output switches to -$V_{sat.}$ Now V_+ = - V_{sat}/2 and the capacitor charges to the opposite polarity. When v_C reaches -V_{sat}, the output switches again. This process is repeated *ad infinitum*. As is evident, the period of the oscillation is determined by the values of R and C. An analysis based on the above description result in the oscillation period T given as

$$T = 2RC \ln(3) = 2.2RC. \tag{9.7}$$

Record the waveforms at pins 2 and 6 of the amplifier noting appropriate values.

9.7.2 Triangle-Wave Generator - Circuit 9.7.2. This circuit is slightly more complicated, as it requires two op amps. Use the already assembled circuit having a two 741 op amps and having power supplied to it by connecting pins 4 of both devices together and then connecting pins 7 of both devices. The assembled circuit is shown in Figure 9.12. Observe and record V_{o1} and V_{o2} using both channels of the oscilloscope.

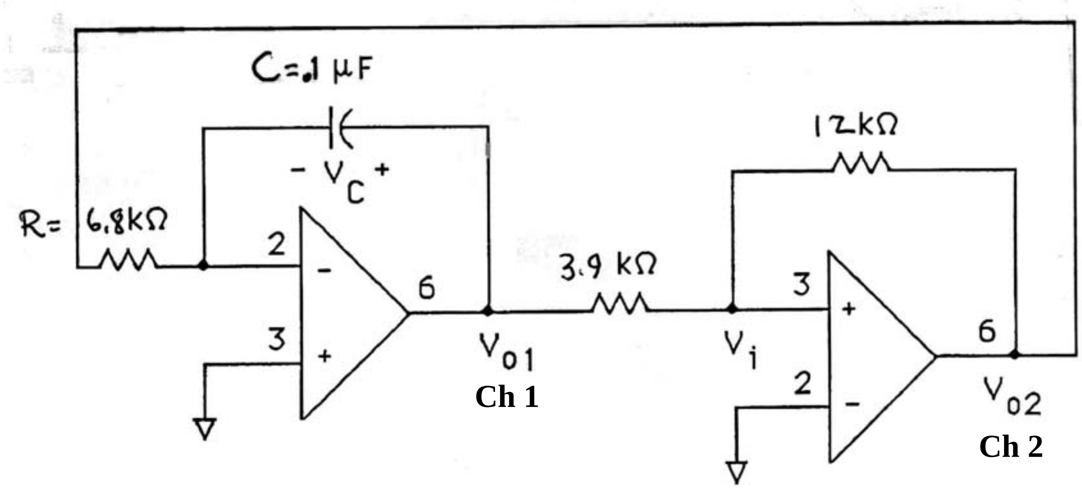


Figure 9.12: Triangle wave generator circuit 9.7.2.

This circuit consists of a comparator and an integrator connected in a feedback loop. Suppose at t = 0, v_C = 0 and v_{o2} = +V_{sat} . Now v_{o2} is the input to the integrator circuit, so v_{o1} is a ramp that decreases linearly. When v_{ol} reaches a value which makes v_i negative (What is this value?), v_{o2} switches to -V_{sat}. This causes the integrator to ramp up linearly until v_{ol} causes the comparator to switch states again, and the cycle repeats. The period of this oscillator is determined by the R-C combination in the integrator, which determines the rate of change of v_{ol}, and the resistor combination of the comparator, which determines the threshold that v_{ol} must reach before the comparator switches states. With comparator resistor values as shown, the value of the period T is

$$T = (1.3)RC. \tag{9.8}$$

9.8 ANALOG SIMULATION CONCEPTS

In analog simulation, also termed analog computation, electronic circuits with op amps are used to solve differential equations. The heart of the technique is the op amp integrator circuit shown in Figure 9.8. Based on Equation (9.5), equating the input to an op amp integrator v_i equal to dy/dt, then the output of the integrator v_o is $-(1/R_iC)\ y(t)$. Thus, the voltages in the op amp circuit, i.e., v_o and v_i, can be "analogs" of other physical parameters such as distance (feet), velocity (ft/sec), force (lb), temperature (°C), etc.

As an example, suppose we have a mechanical spring-damper system described by the following first order differential equation, where *y(t)* is displacement in feet,

$$\frac{dy}{dt} + 5y = 2 \quad \text{for } t \geq 0 \text{ and } y(0) = -1 \text{ foot.} \tag{9.9}$$

As an analog, we can let the output of the integrator be proportional to displacement, i.e.,

$$v_o(t) = K\ y(t). \tag{9.10}$$

Note that in order to maintain linear operation and obtain an accurate solution, we must always be careful to scale output voltages so as not to saturate the op amp. Assuming that $v_{SAT} \approx 10$ Volts for the op amp and that the maximum displacement of $y(t) \leq 10$ feet, we can design an op amp circuit to simulate the system by scaling the output voltage of the integrator to be 1 Volt/foot, i.e., $v_o(t) = y(t)$ or K = 1 Volt/foot.

Figure 9.13 shows one of many possible op amp circuits that can be used to simulate the differential equation given in Equation (9.9) above. Note that three op amps are used: one as a summing amplifier, one as an integrator, and one as an inverting amplifier. Also, switches and DC voltages, shown as batteries, are included in the circuit in order to apply bias voltages representing (1) the initial condition of *y(0) = -1 foot* ($v_{o2}(0) = -1V$) to the feedback capacitor during "reset", i.e., t < 0, and (2) the step input of *2 feet* ($v_1 = 2V$) to the input of the integrator during "operation", i.e., $t \geq 0$.

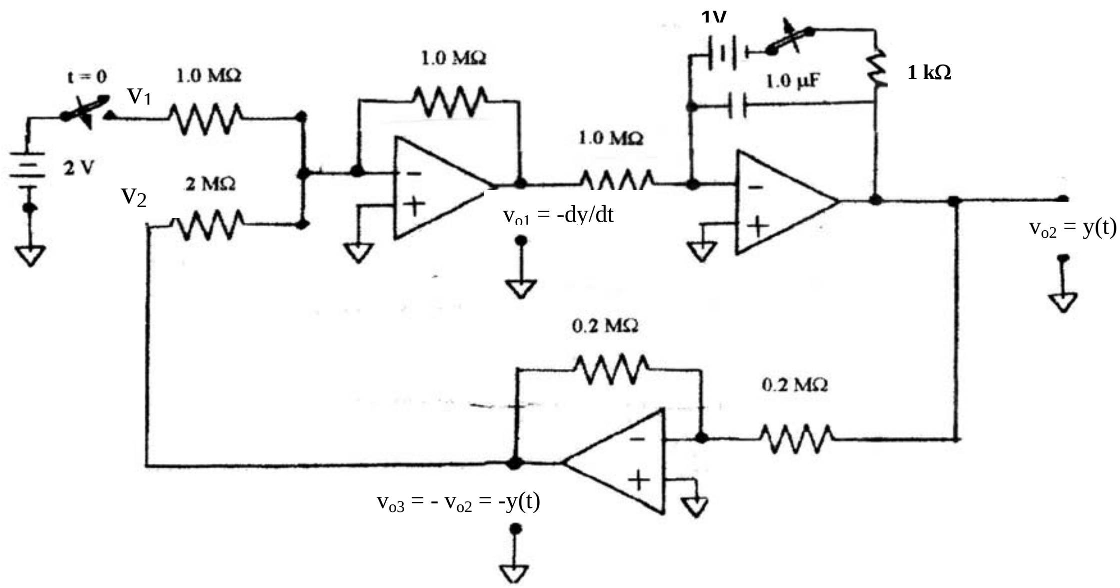


Figure 9.13 Analog Computer Simulation Circuit for a First Order System Using Three Operational Amplifiers.

The analog computer simulation shown in Figure 9.13 was obtained as follows. First, the output of the integrator was chosen to represent the displacement, i.e., $v_{o2} = y(t)$. Choosing $R_i = 1$ MΩ and C = 1 μF so that $R_iC = 1$ second, Equation (9.5) inplies that

$$v_{i2} = - dv_{o2}/dt = - dy/dt. \quad (9.11)$$

Noting that $v_{i2} = v_{o1}$ and solving Equation (9.9) for - dy/dt, we get

$$v_{o1} = - dy/dt = -2 + 5\ y = - 2 + 5\ v_{o2}. \quad (9.12)$$

From Figure 9.7, we get that

$$v_{o1} = -\frac{R_f}{R_1}v_1 - \frac{R_f}{R_2}v_2 \tag{9.13}$$

Letting R_f = 1 MΩ, v_1 = + 2V, $v_2 = -v_{o2}$, and equating terms in Equations (9.12) and (9.13), we get R_1 = 1 MΩ and R_2 = 0.2 MΩ. Using an inverting amplifier with input and feedback resistances chosen as 0.2 MΩ each to obtain $v_{o3} = -v_{o2}$, we get the analog computer simulation of the mechanical system shown in Figure 9.13.

Analog simulations with fewer components can often be obtained if the summing and integration functions are combined as shown in Figure 9.14.

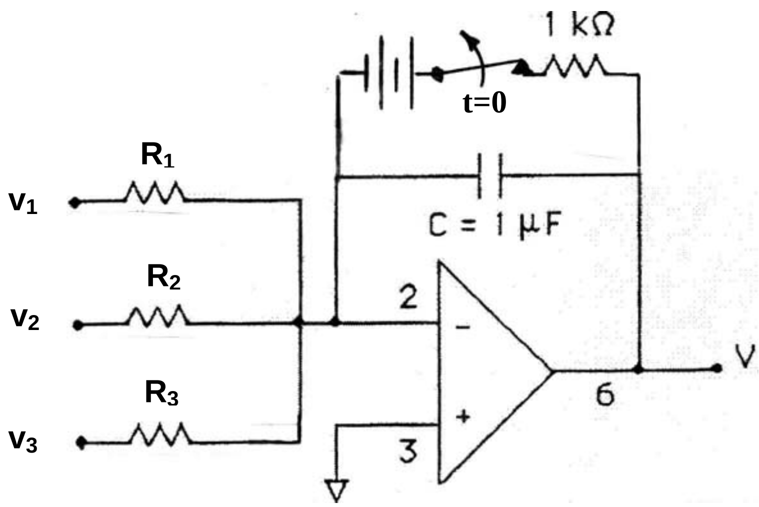


Figure 9.14 Summing Integrator Circuit

Again assuming an ideal op amp, the equation for the output of this summing integrator is

$$v_o(t) = \int_0^t \left(-\frac{v_1}{R_1C} - \frac{v_2}{R_2C} - \frac{v_3}{R_3C} \right) * d\tau + v_o(0) \tag{9.14}$$

or

$$dv_o/dt = -[v_1/R_1 + v_2/R_2 + v_3/R_3]C. \tag{9.15}$$

Choosing C = 1 μF, and performing steps analogous to the previous example, the resulting analog computer simulation is shown in Figure 9.15.

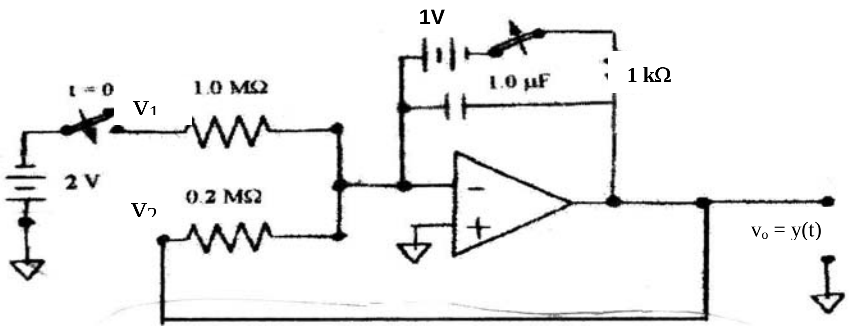


Figure 9.15 Analog Simulation circuit Using One Summing Integrator

Comparing Figures 9.13 and 9.15, it is clear that the number of op amp integrators needed is equal to the order of the differential equation, but the number of inverting amplifiers needed is somewhat arbitrary.

9.9 REPORT

9.9.1 Non-inverting Amplifier - Circuit 9.5.1

(a) Derive the theoretical input-output relationship shown in Equation (9.2). Compute the gains for the first two circuits (where R_i = 10kΩ and R_f = 33 kΩ and 0 Ohms). What did you use for R_i and R_f for the last two circuits?

(b) Show the input and output waveforms for the case where R_i = 10kΩ and R_f = 33 kΩ. Comment on the phase relationship and describe how you measured the gain for this circuit.

(c) Record the observed gain for all four circuits and compare the measured results to the computed results and determine the percent error.

(d) Show the input and output waveforms for the case where you were required to measure the slew rate (i.e., gain of 11 and Vi was a 10 kHz, 4V peak-to-peak square wave). Carefully describe how you measured the slew rate. Compare your slew rate measurements to those provided in the MCI 741 specifications.

9.9.2 Inverting Amplifier - Circuit 9.5.2

(a) Derive the theoretical input-output relationship shown in Equation (9.3). Compute the gain for the first circuit (R_i = 1kΩ and R_f = 10kΩ). What did you use for R_i and R_f for the last two circuits?

(b) Show the input and output waveforms for the case where the gain is -2.2. Again, comment on the phase relationship and describe how you measured the gain for this circuit.

(c) Record the observed gains for all three circuits and compare the measured results to the computed results and determine the percent error.

9.9.3 Inverting Amplifier with Multiple Inputs - Circuit 9.5.3

(a) Derive Equation (9.4), including the values for G_1 and G_2 as a function of R_f, R_1, and R_2.

(b) Show the output waveforms you observed for V_2 of 0 V and 9 V. What was the measured battery voltage? Also, clearly describe the procedure used to measure gains G_1 and G_2

(c) Record the observed gains for this circuit and compare the measured results to the computed results and determine the percent error.

9.9.4 Integrator - Circuit 9.6.1

(a) Derive Equation (9.5).

(b) Show $v_o(t)$ that your observed on the scope with R_i = 1MegΩ. Compare the slope of this curve to what you obtain from Equation (9.5).

(c) Assume R_i = 15kΩ and C = 0.5μF in Circuit 9.6.1. Determine the peak-to-peak value of the output voltage and make a sketch of v_o compared to the input voltage, assuming v_i is a 10 V peak-to-peak square wave with 0V dc average (i.e., it switches between ± 5V) at a frequency of 1 KHz. Finally, determine the peak-to-peak voltage of v_o assuming v_i is at a frequency of 2 kHz, 5 kHz, and 10 kHz, and compare these to the value predicted at 1 KHz.

9.9.5 Differentiator - Circuit 9.6.2

(a) Derive Equation (9.6).

(b) (Triangle input). Sketch the input and output waveforms for the 1 kHz case. Record the output peak-to-peak amplitudes for all three frequencies. Compare these results to what you obtain from Eq. (9.6).

(c) Repeat part (b) for the sinewave input.

9.9.6 Square-Wave generator - Circuit 9.7.1

(a) Derive the theoretical relationship between *R*, *C*, and the oscillator period T.

(b) Show the waveforms that you observed.

(c) What was the period of the oscillator that you observed experimentally? Compare it with the theoretical value.

9.9.7 Triangle-Wave Generator - Circuit 9.7.2

(a) Derive the theoretical period T of this oscillator.

(b) Show the waveforms that you observed.

(c) What was the period of the oscillator that you observed experimentally? Using your actual circuit values, calculate the expected value for the period and compare it with the observed value.

9.9.8 Design Problem

Design an analog computer simulation circuit having two integrators and one inverter that will solve the following second order differential equation for a mechanical spring-mass-damper system assuming the maximum displacement y(t) is 10 feet and the maximum displacement rate dy/dt is 10 feet/sec. The differential equation for the system is

$$d^2y/dt^2 + 8\, dy/dt + 20\, y = 100 \text{ for } t \geq 0,\ \ y(0) = 4 \text{ ft}, dy/dt(0) = -3 \text{ ft/sec.} \quad (9.16)$$

Assume that the MC1741C Integrated Circuit will be used as the operational amplifier.

Document your design as follows:

8.1 Briefly describe your design process and indicate the analogs selected, i.e., $v_{o2} = y(t)$.

8.2 Provide a circuit diagram showing all op amps, resistors, capacitors, switches, and DC voltages needed. Include all "Reset" and "Operate" switches on the diagram.

8.3 Define the values you selected for all resistors, capacitors, and DC voltages.

8.4 If the maximum displacement is changed to 100 feet, the maximum displacement rate is changed to 100 feet/sec, and the step input is changed to 10 feet, what changes would you make to the analog computer simulation?

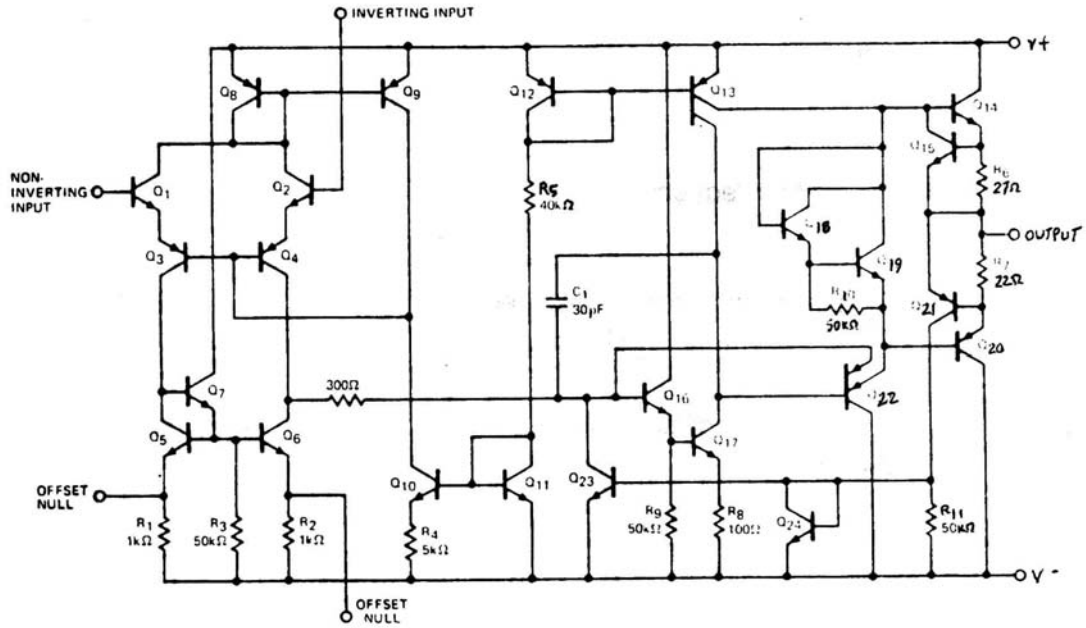
9.10 References

1. Sedra, Adel S. and Smith, Kenneth C., **Microelectronic Circuits,** 4th Edition, Oxford University Press, New York, 1998

2. Phillips, Charles L., and Harbor, **Royce D., Feedback Control Systems,** 4th Addition, Prentice Hall, New Jersey, 2000

3. Johnson, Clarence L., **Analog Computer Techniques,** 1st Edition, Mcgraw-Hill Book Co., New York, 1963

9.11 Appendix I - μA741 CIRCUIT DIAGRAM



741 Integrated Circuit Schematic Diagram