University of California, Davis
Department of Electrical and
Computer Engineering

EXPERIMENT No. 6
THE OPERATIONAL AMPLIFIER

I. INTRODUCTION

The operational amplifier (op amp) is the most widely used linear integrated circuit and has many applications. In this experiment you will use an operational amplifier to build a low impedance driver, a voltage amplifier, a low pass filter, and a half wave rectifier. Non-ideal behavior and limitations of the operational amplifier will be investigated.

II. BACKGROUND

The operational amplifier features high gain, high input impedance, and low output impedance. A 741 operational amplifier has the following typical specifications:

Open Loop Voltage Gain=200,000
Input Resisitance=2 MΩ
Output Resistance=75 Ω
Maximum Output Current ≈ 10 mA
Gain-Bandwidth Product ≈ 1 MHz

See the data sheet for more details about the device. The pin configuration for the 741 op amp is shown in Figure 1.

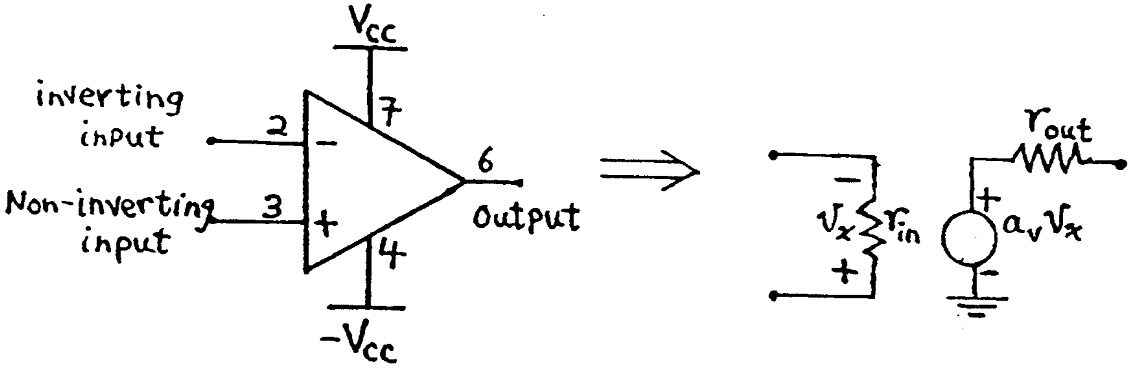


Figure 1.
Pin configuration and small signal model for the 741 op amp.

Nonideal Characteristics of Operational Amplifiers

Since differential amplifiers form the input stages of operational amplifiers, mismatch effects such as V_{OS} and I_{OS} (see lab 4) also apply to the 741 op amp. An equivalent circuit for the operational amplifier including these non-ideal D.C. effects is shown in Figure 2.

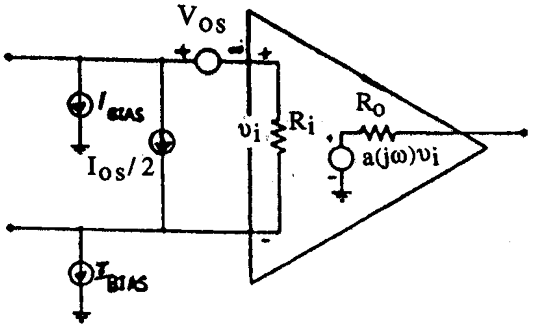


Figure 2. Equivalent circuit for the non-ideal op amp.

Note that V_{OS} and I_{OS} are random parameters (i.e., they are due to device mismatches and vary between different ICs), and their signs could be either positive or negative. I_{BIAS} is positive for an op amp with NPN input transistors and negative for an op amp with PNP input transistors.

Frequency limitations and feedback

The internally compensated 741 has a -3dB cutoff point at 5 Hz and -6 dB roll off from 5 Hz to about 1 MHz. However, by using feedback the cutoff frequency of an op amp amplifier can be increased by a factor of $(1+T_0)$, where T_0 is the low frequency loop gain of the feedback circuit ($T_0 = a_0 f$). The feedback also reduces the op amp's open loop gain by this same factor ($A_{CL} = a_0/(1+T_0)$), and thus the gain-bandwidth product remains constant. Figure 3 shows this effect.

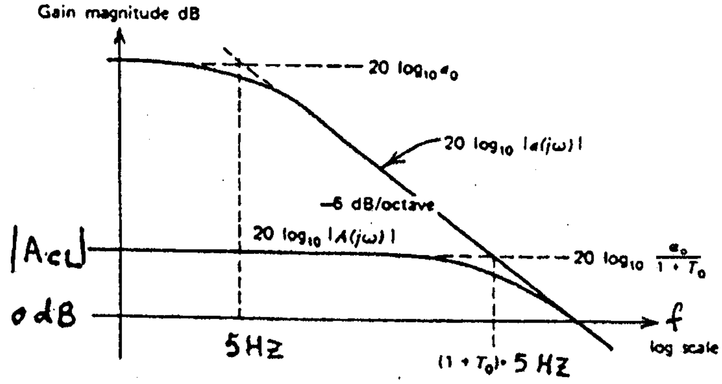


Figure 3. Effect of feedback on the 741 op amp.

III. OP AMP WITH CLASS-B OUTPUT STAGE

An external class B output stage can be added to an op amp to increase its current output capability (recall from the data sheet that the 741 can only source or sink ≈ 10mA. The addition of the class B stage increases this to $\beta \cdot 10$mA).

1) Build the class B output stage as shown in Figure 4. Obtain and sketch the V_{out} vs. V_{in} transfer characteristic by using the x-y function on the oscilloscope. Use a 1 kHz sine-wave input. How large is the "dead band" around V_{in}=0 v? What is the gain of the output stage outside of the dead band?

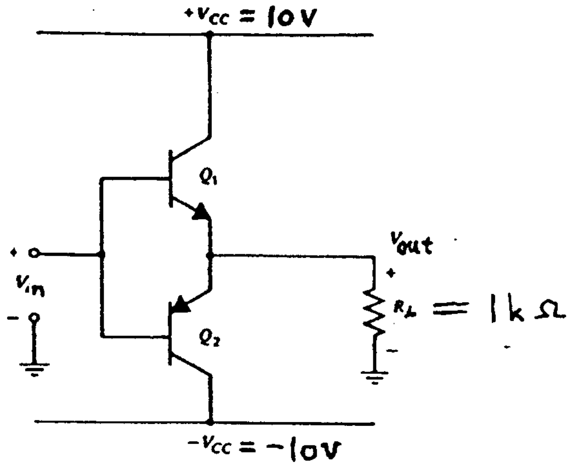


Figure 4. Class B output stage

2) Build a voltage buffer by connecting the class B output stage to the op amp (see Figure 5). As before, obtain and plot the $Vout$ vs. Vin transfer characteristic. What is the gain of your circuit? How has the deadband changed ? Why? What are the output swing limits?

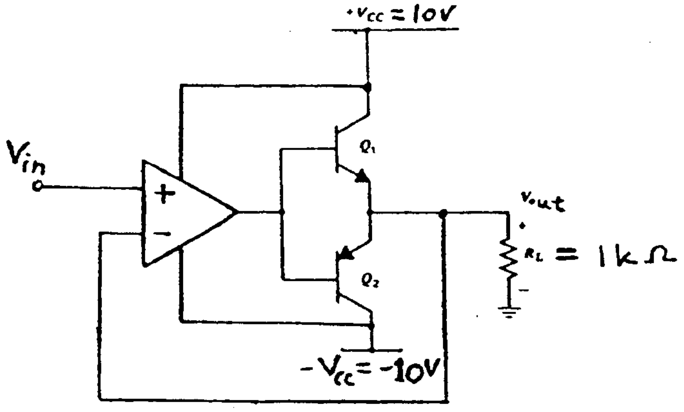


Figure 5 op amp with class B output stage.

IV. OP AMP AMPLIFIER-PRACTICAL CONSIDERATIONS

V_{OS}, I_{OS}, and I_{BIAS} (see figure 2) will cause D.C. errors in op amp circuits. For example, the circuit in Figure 6 will give a gain $|v_{out}/v_{in}|=100$, but will also amplify V_{OS} by 101 (show that this is true).

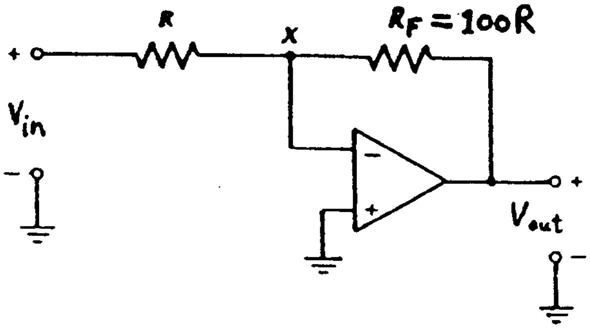


Figure 6. A basic op amp gain circuit

These D.C. offset errors can be minimized in many ways. For example, the multiplication of V_{OS} can be eliminated by A.C. coupling the input, and the effect of I_{BIAS} can be minimized in Figure 6 by placing a resistor in series with the non-inverting input terminal (see figure 7).

1) Build the amplifier circuit shown in Figure 6 (with R=1 kΩ). Measure V_{OUT} with V_{IN}=0 volt. This V_{OUT} is produced by the D.C. sources shown in Figure 2. Now add C and another resistor of value R_F as shown in Figure 7 (with R=1 kΩ and C=0.047 μF). Again, measure V_{OUT} with V_{IN}=0 volt. How has the D.C. output changed? Why?

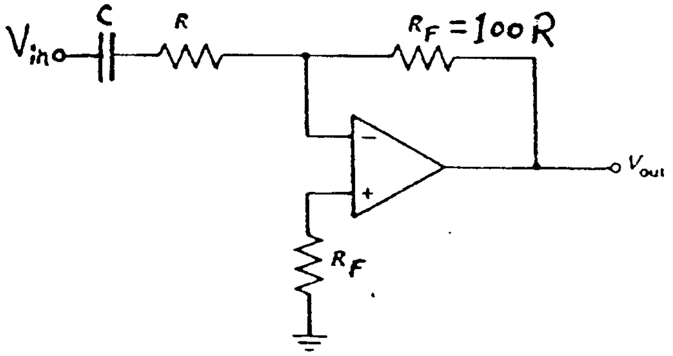


Figure 7. Op amp gain stage with D.C. error nulling

2) For the circuit in Figure 7, compute and select R so that the midband A.C. input resistance is larger than 4 kΩ. Calculate and select capacitor value C so that the circuit will amplify signals above 400 Hz with gain = 40dB±3dB (a midband gain of 100). (Hint: use virtual ground approximation). Build your circuit using standard resistor and capacitor values. Measure and plot the A.C. gain v_{out}/v_{in} (in dB) vs. log frequency for your circuit from f=10Hz to 1MHz. How do the low and high -3dB corner frequencies agree with expected values?

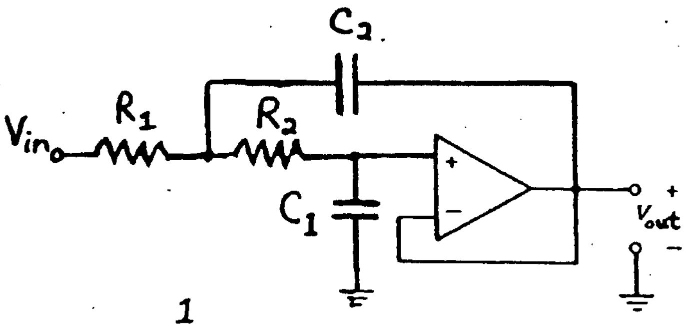
3) Output Swing. For the circuit shown in Figure 7, with an input of 1 kHz, increase the amplitude of V_{in} until output V_{out} clips. What are the positive and negative clipping limits? Compare measured values with data sheets values.

4) Slewing. Due to the finite current available to charge and discharge the internal compensation capacitor, the maximum rate of voltage change at the output of the 741 op amp is limited. For an input of 50 KHz, increase the amplitude of V_{in} until slewing is observed (under severe slewing conditions, you will see a triangular wave output for a sine-wave input). Measure the slew rate. Compare this value with the data sheet value.

NOTE: Choose either part V or part VI for the remainder of this lab.

V. OP AMP LOW PASS FILTER

The op amp is widely used as a filter building block. A second order low pass filter is shown below in Figure 8. Calculate and choose the resistor and capacitor values using standard values to give $f_{-3\,dB}\approx 1$ kHz and $Q\approx 0.707$. (Find $v_{out}(s)/v_{in}(s)$ in terms of R's and C's. Arrange this transfer function into the form of equation (1) in Figure 8. For Butterworth type low pass filters, $w_o=2\pi \cdot f_{-3\,dB}$).
Build the filter and measure the A.C. gain for frequencies from 100 Hz to 500 kHz. Plot the gain (in dB) versus log frequency. How well does the cutoff frequency agree with your design?



Equation (1)

$$H(s) = \frac{1}{\left(\frac{S}{\omega_o}\right)^2 + \frac{S}{Q\omega_o} + 1}$$

Figure 8. An op amp low pass filter

VI. HALF WAVE RECTIFIER

A precision half wave rectifier is shown below in Figure 9. Its transfer characteristic is shown in Figure 10. Construct the half wave rectifier and verify its operation by connecting a 1 kHz, 1volt peak to peak sinewave input and observing the output. Sketch the input and output waveforms. What are the regions of operation of D1 , D2 and the op amp for Vin<0 and for Vin>0 volt?

Now disconnect D1, and again input a 1 kHz, 1 volt peak to peak sinewave input. Sketch the input and output waveforms. What happened to your output? What kind of rectifier have you built?

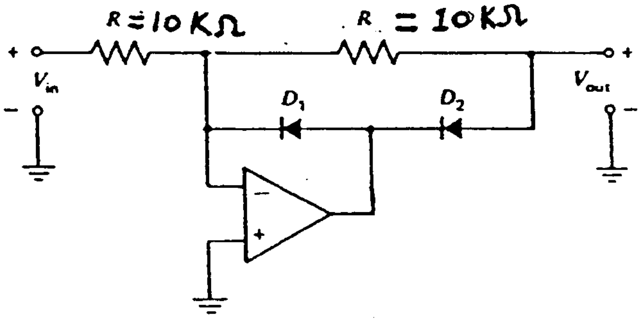


Figure 9. Precision half wave rectifier

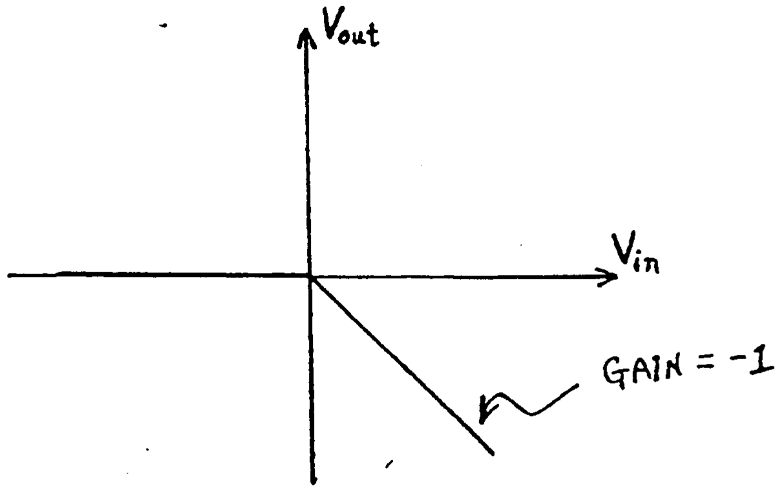


Figure 10. Precision half wave rectifier transfer characteristic

Lab Results:

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III. OP AMP WITH CLASS-B OUPUT STAGE

(1) deadband= ________ A_v= ________

(2) A_v= ________ $V_{out(max)}$= ________ $V_{out(min)}$= ________

IV. OP AMP AMPLIFIER - PRACTICAL CONSIDERATIONS

(1) V_{out}(circuit 1)= ________ V_{out}(circuit 2)= ________

(2) R= ________ C= ________

(3) $V_{out(max)}$= ________ $V_{out(min)}$= ________

CHOOSE EITHER PART V OR VI

V. OP AMP LOW PASS FILTER

R_1= ________ R_2= ________

C_1= ________ C_2= ________

VI. HALF WAVE RECTIFIER

Rectifier Type: ______________