

NORTHWESTERN UNIVERSITY TECHNOLOGICAL INSTITUTE

ECE 270

Experiment #7 OPERATIONAL AMPLIFIERS

An operational amplifier is an integrated circuit consisting of transistors, resistors and capacitors. It has two inputs and one output, and the output is an amplified version of the difference between the input signals ($v_{OUT} = A(v_1 - v_2)$ where $A \sim 10^4$). This feature makes the op amp extremely flexible among other nice features such as: low cost, high input impedance, low output impedance, and the ability to amplify both AC **and** DC signals.

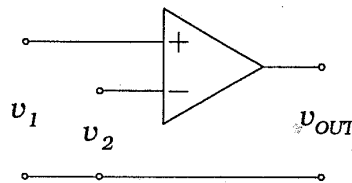


Figure 1

Op amps require two DC power supplies (which are generally not shown in a schematic). The output signal is always constrained to be less than the positive supply and greater than the negative supply. Note that the output can be less than zero: $V^- < v_{OUT} < V^+$.

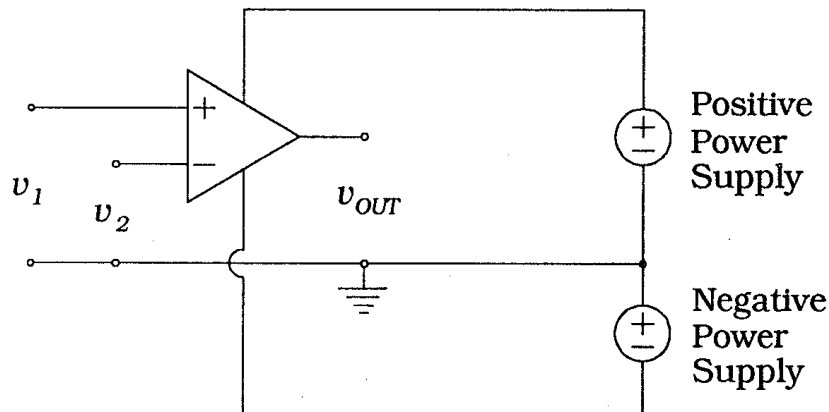


Figure 2

To enhance circuit characteristics, such as stability, and to increase the versatility of the device, an external feedback line is often added to the basic op amp. By choosing the proper passive components for this feedback line, the op amp can be made to perform a variety of mathematical functions (add, subtract, multiply, divide, differentiate, and integrate) and also be converted into low and high pass filters and sinusoidal and non-sinusoidal oscillators. Some of these feedback circuit applications are illustrated in Figure 3 through Figure 8.

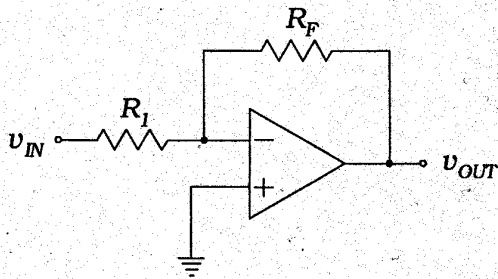


Figure 3: $v_{OUT} = -\left(\frac{R_F}{R_1}\right)v_{IN}$

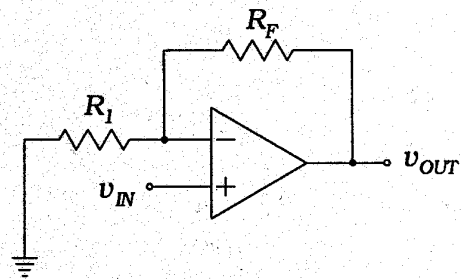


Figure 4: $v_{OUT} = \left(1 + \frac{R_F}{R_1}\right)v_{IN}$

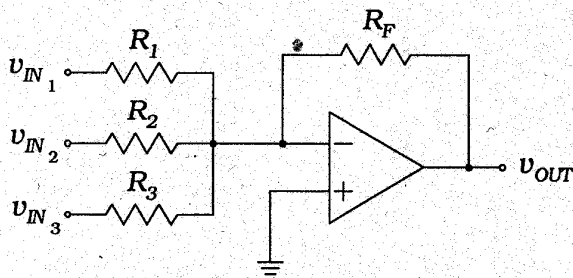


Figure 5

$$v_{OUT} = -\left(v_{IN1} \frac{R_F}{R_1} + v_{IN2} \frac{R_F}{R_2} + v_{IN3} \frac{R_F}{R_3}\right)$$

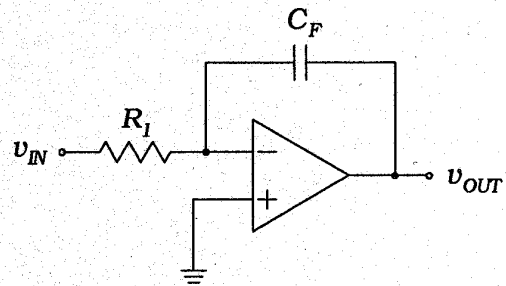


Figure 6

$$v_{OUT} = -\frac{1}{R_1 C_F} \int v_{IN} dt + K$$

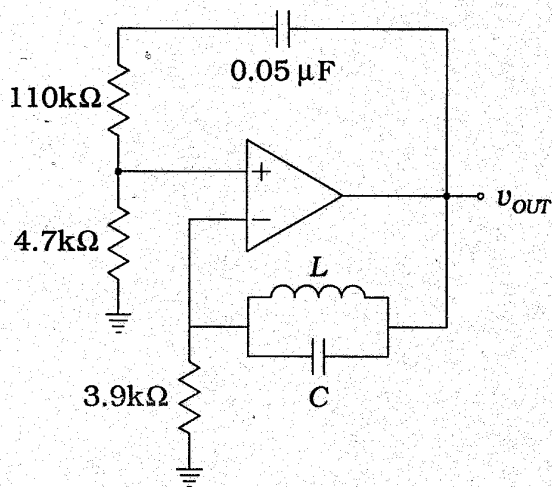


Figure 7

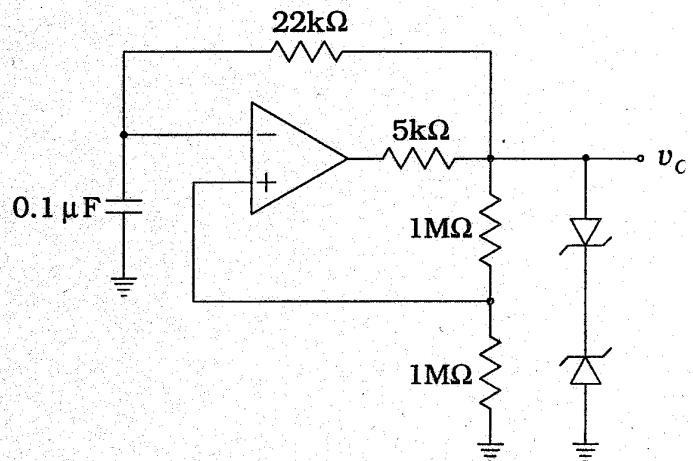


Figure 8

Figure 3: Inverting Amplifier

Figure 4: Non-inverting Amplifier

Figure 5: Summing Amplifier

Figure 6: Integrator

Figure 7: Sinewave Oscillator at $f = \frac{1}{2\pi\sqrt{LC}}$

Figure 8: Square Wave Oscillator

AMPLIFICATION WITH FEEDBACK

An operational amplifier is a high gain feedback amplifier circuit which is used to perform mathematical operations. The basic circuit configuration is as shown in Figure 9.

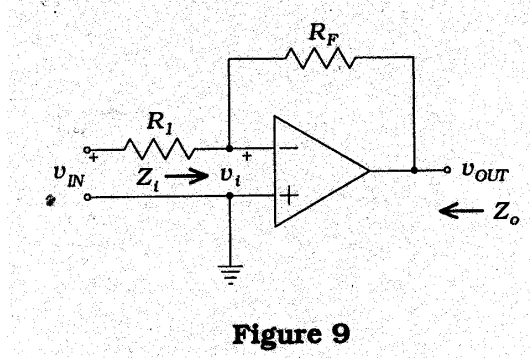


Figure 9

In ideal form, the input impedance (Z_i) is infinite, the output impedance (Z_o) is zero, and the output voltage is $v_{OUT} = Av_i$ where A is the amplifier open loop gain (the gain the amplifier would have when there is no feedback). Under these conditions there is no current into the amplifier. Therefore, the current through R_I also must flow through R_F . This current can be expressed in terms of either v_{IN} and v_i or in terms of v_i and v_{OUT} as follows:

$$\frac{v_{IN} - v_i}{R_I} = \frac{v_i - v_{OUT}}{R_F}$$

If v_i is eliminated using $v_i = v_{OUT}/A$, then one can solve for the output voltage in terms of v_{IN} to obtain:

$$v_{OUT} = \frac{-\frac{R_F}{R_I} v_{IN}}{1 - \frac{1}{A} \left(1 + \frac{R_F}{R_I} \right)}$$

For $A \rightarrow \infty$, this simplifies to:

$$v_{OUT} = -\frac{R_F}{R_I} v_{IN}$$

so that the overall amplification with feedback (A_F) is given by:

$$A_F = -\frac{R_F}{R_I}$$

and is dependent only on the ratio of R_F to R_I . However, the output is an inverted form of the input. More generally, R_F and R_I can be replaced by capacitors, inductors or combinations of resistors, capacitors and inductors to obtain a wide variety of mathematical operations. As examples: If R_F is changed to a capacitor (C_F), the circuit becomes an integrator. If R_I is changed to a capacitor (C_I), the circuit is a differentiator. If multiple inputs, each input having its own series resistance, are used, then the output is a weighted sum of the inverted inputs.

An op amp has two inputs, one that gives an inverted output and the other that gives a non-inverted output. These devices are, therefore, differential amplifiers. In addition to their use as linear operational amplifiers, these op amps can be combined with non-linear circuit elements in circuits which generate non-sinusoidal waveforms.

A differential amplifier, ideally, only responds to the difference between the inverting and non-inverting inputs, one of which may be held fixed. Actually, when both inputs are equal, there is a small output and hence a gain, which is called the *common mode gain* (A_{cm}). The ratio of the *differential mode gain* (A_d) to the *common mode gain* (A_{cm}) is called the *common mode rejection ratio* (CMRR). Typical values for CMRR range from 50dB to 100dB. The total output voltage, using the assumption of linearity and the Superposition Theorem, is then given by:

$$v_{OUT} = A_d v_d + A_{cm} v_{cm}$$

where

$$v_d = v_p - v_n \text{ and } v_{cm} = (v_p + v_n) / 2$$

where v_p and v_n are the voltages on the positive and negative input terminals with respect to ground.

PROCEDURE

1) UNITY GAIN INVERTING AMPLIFIER

A 741 operational amplifier is a very common op amp and is generally packaged as shown in Figure 10. Connect a 741 operational amplifier as shown (Figure 11):

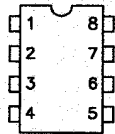


Figure 10

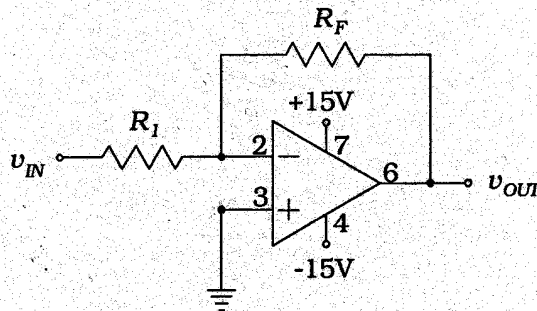


Figure 11

Be sure that you connect the ground (or common) terminal of your DC power supply to the ground terminal shown in Figure 11 above. Use $R_F = R_I = 100k\Omega$ to obtain a unity gain inverting amplifier. Use the function generator to supply a small sinusoidal input v_{in} and measure v_o for frequencies of:

$$f = 100\text{Hz}, 1\text{kHz}, 10\text{kHz}, 100\text{kHz}, 1\text{MHz}$$

Recalling that $A_v = \left| \frac{v_o}{v_{in}} \right|$ and $A_v(\text{dB}) = 20 \log \left| \frac{v_o}{v_{in}} \right|$, plot the gain $A_v(\text{dB})$ vs. $\log(f)$.

2) VECTOR SUMMING AMPLIFIER

Add another input through a $100\text{k}\Omega$ resistor to the inverting input terminal. Use the output of the function generator at $f = 1\text{kHz}$ for both inputs, but with one of the inputs place a phase shifting low-pass RC circuit between the function generator and the $100\text{k}\Omega$ resistor as shown in Figure 12.

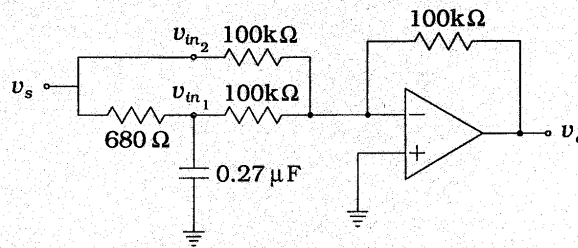


Figure 12

Check the output while each input is applied individually and the other input is grounded (disconnect source from the grounded input) and for when both inputs are applied simultaneously. Sketch these three waveforms in relative phase and amplitude. To accomplish this, first connect the left input channel on the oscilloscope to v_s and trigger off the left channel. Do not disconnect the oscilloscope from v_s or switch the trigger source for the rest of this part of the experiment. Then connect v_s to the 680Ω resistor **only** and connect v_{in2} to ground as shown in Figure 13.

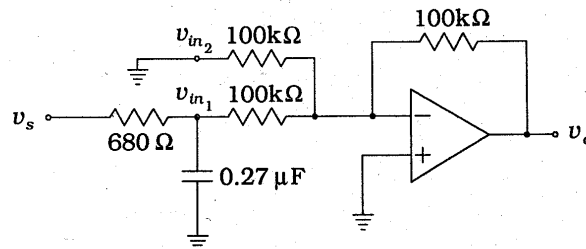


Figure 13

Use the right input channel on the oscilloscope to monitor the output voltage. If the signal is not stationary, you can adjust the trigger LEVEL at this point. This output voltage is your first sketch. Also, choose two points in time on your sketch and, using the oscilloscope, measure the amplitude of this signal at those two points. The trigger LEVEL should **not** be adjusted for the second and third sketches and the signal should not be shifted in time. Next connect v_s to v_{in2} **only** and connect v_{in1} to ground as shown in Figure 14.

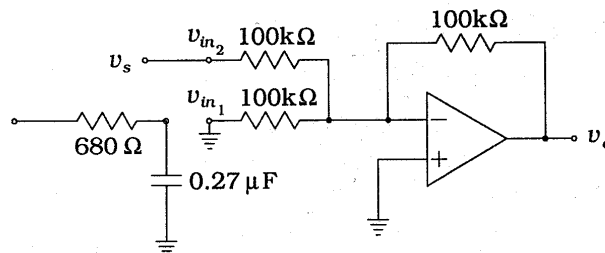


Figure 14

The output for Figure 14 is your second sketch. At the same two points in time chosen previously, measure the amplitude of this signal. Finally, apply v_s to both v_{in2} and the 680Ω resistor (Figure 12) and sketch the output waveform. At the same two points in time chosen previously, measure the amplitude of this signal. For each point in time, use the data points measured to show that the third sketch is the summation of the first two sketches. It is possible to simply measure v_{in1} , v_{in2} and v_o to show the summation, however v_o is equal to $-(v_{in1} + v_{in2})$ as shown in Figure 5. Repeat the test using a square wave for the input function.

3) LOW-PASS FILTER

The operational amplifier can function as a low-pass filter if a capacitor is placed in parallel with R_F . The half power frequency ($f_{1/2}$) or cutoff frequency (f_{co}) is given by:

$$f_{co} = \frac{1}{2\pi R_F C_F}$$

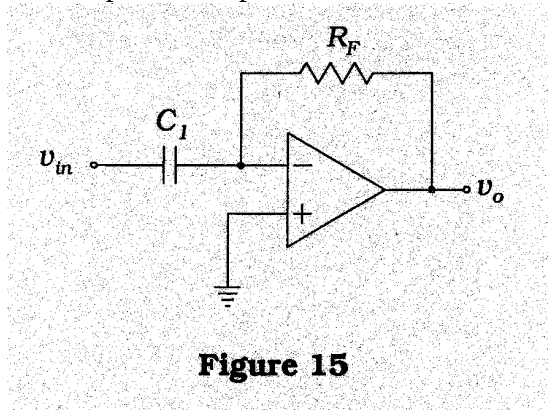
Make $R_I = 10k\Omega$, $R_F = 47k\Omega$ and $C_F = 0.002\mu F$. Plot the gain $A_v(\text{dB})$ vs. $\log(f)$. Be sure to measure the frequency at which the response is -3dB from the maximum gain and take enough measurements to cover at least 3 decades of frequency (ie: 50Hz to 50kHz). Compare the measured f_{co} to the calculated one.

4) INTEGRATOR

Form an integrator as shown in Figure 6, with $R_I = 10k\Omega$ and $C_F = 0.27\mu F$. To allow C_F to discharge, place a feedback resistor in parallel with it ($R_F = 100k\Omega$). Also decouple the function generator from your circuit by placing a $1\mu F$ capacitor in series with R_I , between the function generator and R_I . Use square wave and triangular wave (ramp) function inputs and sketch the input and output for each. Is the integration function realized? Explain.

5) DIFFERENTIATOR

Form a differentiator as shown in Figure 15, with $C_I = 0.05\mu F$ and $R_F = 1k\Omega$. Use square wave and triangular wave (ramp) function inputs and sketch the input and output for each. Is the differentiation function realized? Explain.



6) SINEWAVE OSCILLATOR

Connect the circuit shown in Figure 7. Using a $0.005\mu F$ capacitor and the variable inductor, measure the frequencies generated for the various inductor values (10mH to 100mH) and compare to the expected frequencies.

7) SQUARE WAVE OSCILLATOR

Connect the circuit shown in Figure 8 and sketch the output. Explain how this circuit operates to give a square wave output