EE431 Lab 1
Operational Amplifiers

Dec. 27, 2014

Report all measured data and show all calculations

Introduction

The purpose of this laboratory exercise is for the student to gain experience with measuring and observing the effects of common op-amp imperfections. In addition, the student is introduced to several common op-amp applications.

Although op-amps are generally very easy to work with, the typical haywire construction methods used by students on proto boards often leads to problems such as oscillation. A number of problems can be prevented by observing the following:

- The circuit must have a definite ground that is connected to the common terminal on the power supply. There should be three wires from the power supply: +15V, -15V, and common. Do not use the terminal labeled ground on the power supply.
- If the proto board has a metal plane (all good ones do, all bad ones do not) then it must be connected to the circuit common or ground. This lowers the overall impedance level of the wiring and makes the circuits less susceptible to noise pickup and feedback oscillations.
- It is highly recommended that all ground connections be made to one of the long horizontal strips. Chaining grounds from point to point is a very bad practice that often causes many problems.
- All op-amps should have the RC decoupling networks discussed in the notes on their power supply leads as shown in Figure 1. These networks should be as physically close to the part as practical. Typical good values to use are 47 to 100 Ohms for the resistors and 0.01 to 0.1 microfarrads for the capacitors. The path to ground should be as short as practical. Failure to use this network on a proto board makes the op-amp susceptible to oscillation.
- Never connect a meter lead or scope probe directly to the input or output of an op-amp as this is likely to make it oscillate as discussed in the notes. Always put a resistor (1K is good) located close to the op-amp pin and connect the DVM or scope probe to the other end of the resistor. The resistor serves as a damper and has no effect on low frequency signals that students use. This resistor is not shown in the lab figures but you should know to use it.

Use the general circuit in Figure 1 for the entire lab and also for subsequent labs. For clarity the power supply circuits are not shown in the rest of the lab figures. You will need the data sheet for the LM741 op-amp. This can be found in numerous places on the Internet. For all circuits in this lab use +15 volts for VCC and -15 volts for VEE.

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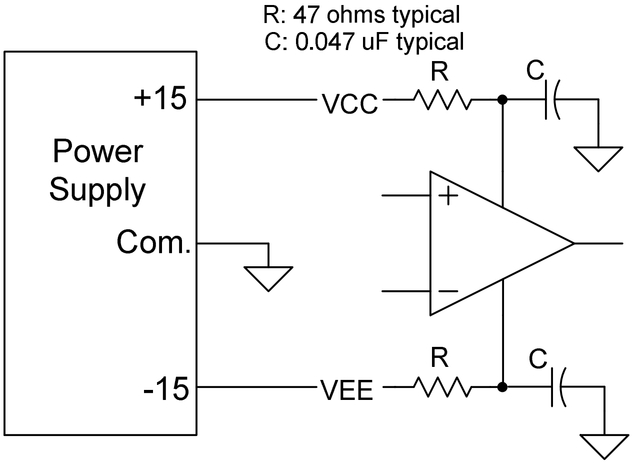

Figure 1: RC decoupling network for op-amp circuits

Part 1: Inverting amplifier

The purpose of this first part of the experiment is to gain experience with inverting amplifiers and also verify that you op-amp is working properly prior to subsequent steps. Build the circuit in Figure 2. Use 100K for Rf and 1K for Ri.

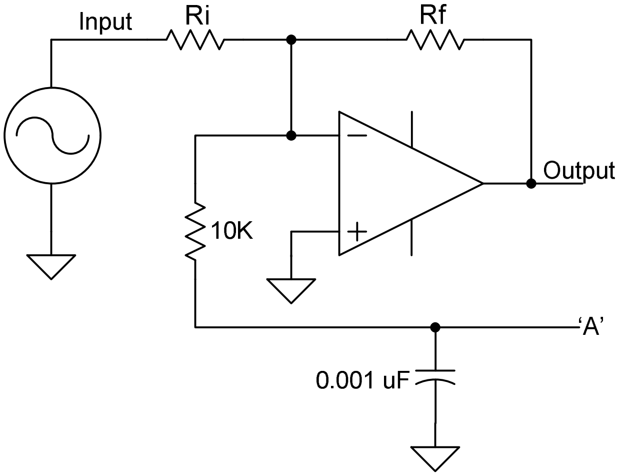

Figure 2: Inverting amplifier

Apply a 1 kHz sine wave of 0.2 volts peak-peak to the input and measure the peak-peak output voltage – which should be as perfect a sine wave as the eye can see. Calculate and report the expected voltage gain of the circuit and confirm that the output signal is what would be expected. If not then determine what is wrong before proceeding with the lab as you will be wasting time.

Using both channels of the oscilloscope, connect channel 1 to the input signal and channel 2 to the output signal. Confirm that the output signal in phase inverted from the input.

Connect the scope to point ‘A’ in the circuit and measure the peak-peak waveform. Note – the resistor and capacitor in the circuit form a low-pass filter to minimize noise and interference from the small measurement amplitude. If the gain of the op-amp were infinite then this voltage would be zero. Expect a signal amplitude roughly in the 20 mVpp range – this is the differential input voltage to the op-amp. Calculate the open-loop gain of the op-amp at 1 kHz – don’t be concerned with phase – just magnitude. Expect a gain roughly in the 1,000 range.

Increase the input signal amplitude to 0.3 Vpp and observe clipping on the output waveform of the op-amp. Measure and report the positive and negative clipping levels.

Connect the scope to point ‘A’ in the circuit and note the differential waveform. Observe that when the waveform becomes large when the op-amp output is in clipping. Explain why this is.

Use a scope to measure the amplitude at the inverting input of the amplifier and confirm that it is practically zero. Increase the amplitude of the applied signal until the output just starts to clip at both peaks. Measure the amplitude of the signal at the inverting input of the amplifier to see that there is a waveform associated with the output clipping. Explain why this is.

Part 2: Non-inverting amplifier

Build the circuit in Figure 3. Use 100K for Rf and 1K for Ri. Apply a 1 kHz sine wave of 0.2 volt peak-peak to the input and measure the output voltage of the op-amp – which should be as perfect a sine wave as the eye can see. Calculate and report the expected voltage gain of the circuit and confirm that the output signal is what would be expected.

Using both channels of the oscilloscope, connect channel 1 to the input signal and channel 2 to the output signal. Confirm that the output signal is in phase with the input.

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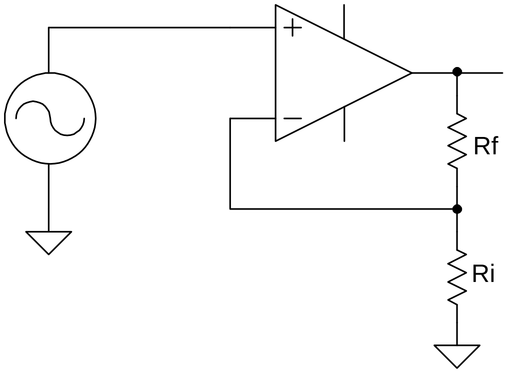

Figure 3: Non-inverting amplifier

Part 3: Measuring op-amp DC error terms

This part assumes you are using an op-amp proven to be working in parts 1 and 2. Use the same op-amp for all sections of this part – otherwise your end results will make no sense. In this section of the lab you will be measuring the DC error terms – input offset voltage, input bias current, and input offset bias current. Normally we only deal with these error terms in magnitude only and typically use the maximum values from the data sheet of the op-amp. In this special case you will know the actual magnitude and polarity of each because you are specifically making the measurement.

Use the following equation (without absolute value) which comes from the class notes. This equation is only valid if the actual magnitude and polarities of all the error terms are known – which is the special case for this lab. It does not work in general. Observe that there are three small terms inside the brackets. In your report calculations, show the value of each term and then the sum. Observe how the terms combine either favorably or unfavorably to affect the output DC error voltage. This is crucial for understanding.

$$V_o = \left[-V_{os} - \left(I_{B+} \times R_p\right) + \left(I_{B-} \times \left(R_f || R_i\right)\right)\right] \times \left(1 + \frac{R_f}{R_i}\right) \tag{1}$$

Build the circuit in Figure 4. Measure and report the output voltage – should be at most only a few millivolts either positive or negative. This is the negative of the input offset voltage including polarity. Report the polarity adjusted input offset voltage.

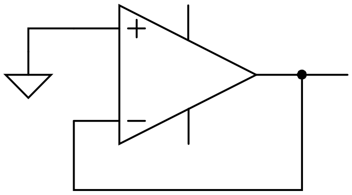

Figure 4: Measuring input offset voltage, Vos

The input bias current is in the nanoampere region and it is a challenge to directly measure such small currents. So, this lab step will introduce the student to a powerful technique using integration to facilitate the measurement of very tiny signals. The bias current will charge a known capacitor over an easily measured time period to an easily measured voltage. By knowing the voltage, capacitance, and time period, it is a simple physics calculation to determine the bias current. You will measure the bias current of each op-amp input and then average them to compute the composite IB, and take the difference to compute Ibos. For reference:

$$\Delta V = \frac{I \times \Delta T}{C} \tag{2}$$

Build the circuit in Figure 5. Parallel non-polarized capacitors in the 0.1 to 1.0 uF range to make a composite capacitor nominally around 1.0 uF. Don't worry about achieving a specific capacitance as that will not matter. Measure and report the net capacitance and use that in the calculations. The switch is a jumper wire across the capacitor that you will pull out of the breadboard at time zero. Connect the digital voltmeter (DVM) to the output of the op-amp.

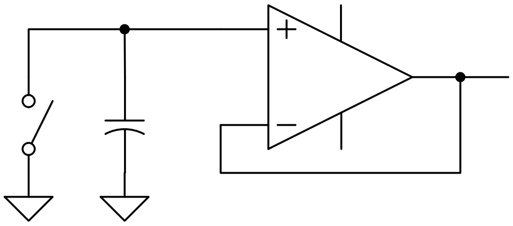

Figure 5: Circuit to measure IB+

Before starting, confirm that the DVM indicates at most only a few millivolts. If not then correct whatever is wrong. Pull the jumper wire and measure the time required for the voltage at the output of the op-amp to reach 5 volts in magnitude – the polarity might be plus or minus. This might be as little as about ten seconds if the op-amp has high bias current or many tens of seconds if the op-amp has low bias current. Since bias current is defined as positive for current into the op-amp then the capacitor will charge to a negative voltage for positive bias current – understand why. The -5 in the following equation takes that into account. Report the required time and report the computed IB+ current.

$$I_{B+} = \frac{-5 \times C}{T} \tag{3}$$

Build the circuit in Figure 6 using the same capacitance as in the previous step. The switch is a jumper wire across the capacitor that you will pull out of the breadboard at time zero. Connect the digital voltmeter to the output of the op-amp.

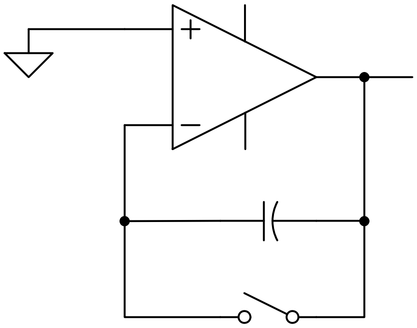

Figure 6: Circuit to measure IB-

Before starting, confirm that the DVM indicates at most only a few millivolts. If not then correct whatever is wrong. Pull the jumper wire and measure the time required for the voltage at the output of the op-amp to reach 5 volts in magnitude – the polarity might be plus or minus. This might be as little as about ten seconds if the op-amp has high bias current or many tens of seconds if the op-amp has low bias current. Since bias current is defined as positive for current into the op-amp then the capacitor will charge to a negative voltage relative to the op-amp output for positive bias current – understand why. This means that the output of the op-amp will be rising for a positive bias current. Report the required time and report the computed IB- current.

$$I_{B-} = \frac{5 \times C}{T} \tag{4}$$

Calculate and report the following:

$$I_B = \frac{I_{B+} + I_{B-}}{2} \tag{5}$$

$$I_{Bos} = I_{B+} - I_{B-} \tag{6}$$

Part 4: Effect of DC error terms

Build the circuit in Figure 7 using the same op-amp as in Part 3. Compute and report the expected output voltage using your measured values for Vos, IB+ and IB-. Normally, the calculation of output error terms is done with magnitude only but in this particular case you know the correct polarities. So do not use the absolute value in the calculation. Because of the low resistor values this circuit is sensitive only to Vos and the effect of bias current is minimal.

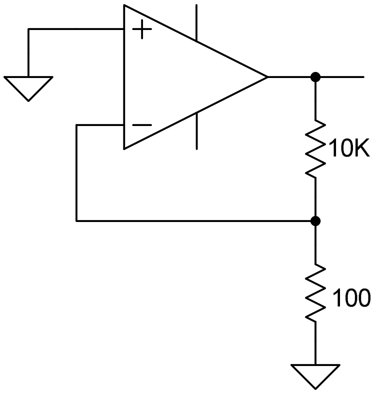

Figure 7: Effect of Vos

Measure and report the actual measured output voltage of the op-amp. Do not compute a percent error as that is meaningless for values that could be of either polarity – why? While your calculated and measured values are unlikely to match, they should definitely be same polarity and be of similar magnitudes. Correct whatever is wrong (perhaps an error in a previous step) so that general agreement is achieved. It would not be unusual for there to be a ten percent or more difference in magnitudes (observe that in this case the polarities are the same).

Build the circuit in Figure 8 using the same op-amp as in Part 3. Compute and report the expected output voltage using your measured values for Vos, IB+ and IB-. Normally, the calculation of output error terms is done with magnitude only but in this particular case you know the actual polarities. So do not use the absolute value in the calculation. Because of the high resistor values this circuit is sensitive to bias current as well as offset voltage.

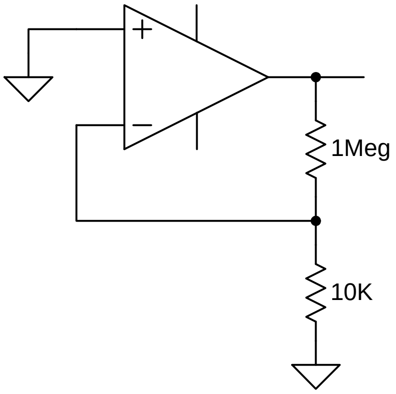

Figure 8: Effect of Vos and bias current

Measure and report the actual measured output voltage of the op-amp. Do not compute a percent error as that is meaningless for values that could be of either polarity. This circuit has numerous opportunities for small errors to be magnified so do not expect good agreement between your calculated and measured values – although that is a possible output. In general what you should notice is that the output DC error term is larger in magnitude than in the previous step (although it is possible for the output DC error to be smaller if the polarities of the error terms combine in a favorable way – not generally the case).

Modify your circuit to be as in Figure 10. This will illustrate the effect of bias current compensation. Compute and report the expected output voltage using your measured values for Vos, IB+ and IB-. Normally, the calculation of output error terms is done with magnitude only but in this particular case you know the actual polarities. So do not use the absolute value in the calculation. Because of the high resistor values this circuit is sensitive to bias current as well as offset voltage.

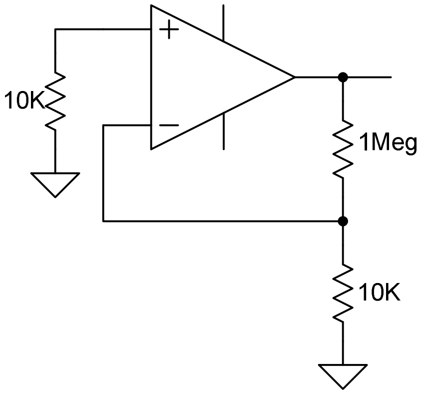

Figure 10: Bias current compensation

Measure and report the actual measured output voltage of the op-amp. Do not compute a percent error as that is meaningless for values that could be of either polarity. This circuit has numerous opportunities for small errors to be magnified so do not expect good agreement between your calculated and measured values – although that is a possible output. In general what you should notice is that the output DC error term is smaller in magnitude than in the previous step. However, it is possible for the output DC error term to be larger if the polarities of the error terms combine in an unfavorable way – not generally the case).

Part 5: Op-amp as integrator

Build the circuit in Figure 11. Use 2.2K for R1 and 0.1 uF for C and apply a 100 Hz, 1 volt peak-peak sine, triangle (use the **ramp function** with **duty cycle set to 50%** -- the waveform is symmetrical like a sine wave – you will lose points if you apply the wrong waveform), and square waves and simultaneously view the applied and output signals on a scope. Are the output signals as predicted by the math – use the course notes and calculate the expected peak-peak output voltages for each waveform.

Note: The integral of a sine wave is a cosine wave, the integral of a triangle wave is a parabolic wave – looks similar to a sine wave but isn't, and the integral of a square wave is a triangle wave.

Note: The 1Meg resistor is to stop the integrator from drifting so you better observe the scope signals – note that there will likely be a small DC offset term (the constant in integral math) on the output signal.

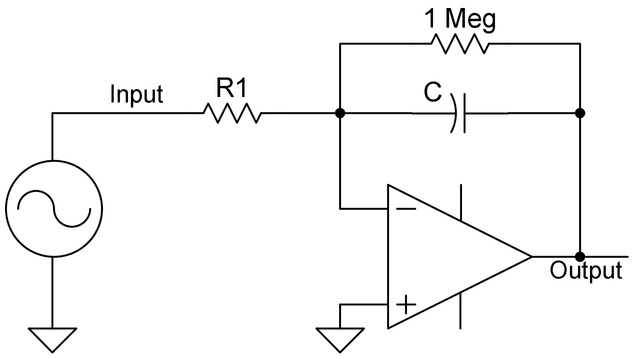

Figure 11: Integrator

Part 6: Op-amp as differentiator

Build the circuit in Figure 12. Use 0.1 uF for C and 100K for R. Apply a 100 Hz, 1 volt peak-peak sine, triangle, and square waves and simultaneously view the applied and output signals on a scope. Are the output signals as predicted by the math – use the course notes and calculate the expected peak-peak output voltages for each waveform except the square wave because the derivative of a square wave is a series of positive and negative spikes the op-amp cannot accurately produce?.

Note: The derivative of a sine wave is a cosine wave, the derivative of a triangle wave is a square wave, and the derivative of a square wave is a spike wave.

Note: The 4.7K resistor in series with the capacitor is to limit the input current for a square wave to something the op-amp can make a reasonable effort to accommodate.

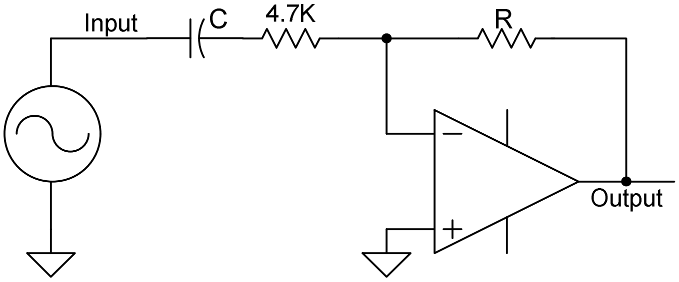

Figure 10: Differentiator