Operational Amplifiers

Operational amplifiers are high-gain amplifiers with a similar general description typified by the most famous example, the LM741. The LM741 is used for many amplifier varieties such as Inverting, Non-inverting, differential, voltage follower and summing amplifier. In addition to amplifiers, op amps are used as switches and even in some digital applications as comparators or A/D converters. Op amps make use of what is called open loop gain. This open loop gain is used to for the purposes of negative feedback. Negative feedback is when the output signal is feed back to the input terminals and the gain of the op amp can be controlled. This is done because the properties of the op amp become more predicable. Negative feedback also creates a more customizable frequency response for the desired amplifier. In turn there is also and increase in the input impedance of the amplifier is negative feedback is used. There is also what is called positive feedback, and the main use for this is to create an oscillator. The way this idea works is that instead of canceling the input to reduce gain, the output is combined in phase with the input to create oscillations. There are many different types of oscillators that can be created with op amps, one of which is the Colpitts Oscillator. In many cases, the op amp is thought of as an Ideal Op Amp. The Ideal Op Amp has a few basic rules that apply. These rules are as follows:

1. Infinite voltage gain
2. Infinite input impedance
3. Zero output impedance
4. Infinite bandwidth

Unfortunately there is no such device, and there are limits to the parameters of a real op amp. There are two rules of which an op amp will follow, too. These are that the output of the op amp will do whatever is necessary to make the input differential between the two input terminals exactly zero, and that the input terminals draw no current. Again, since there is no such device, the real op amp does not fit these rules. There is a limit to the gain on a real op amp (~10^6) and the input terminals do draw current (~.08 μA). The input current is so small, that it is thought to be zero.

Non-Inverting Amplifiers

The first op amp circuit that will be analyzed is that non-inverting amplifier. The non-inverting amplifier is called this because the input signal is connected to the non-inverting terminal. Also the output is in phase with the input. A special case of the non-inverting amplifier is that of the Voltage Follower. The voltage follower has the output signal connected to the inverting input terminal of the op amp as shown in Figure 1. The analysis of this device shows that $V_{out} = V_{in}$. The common use for a voltage follower is to create a buffer in a digital circuit. The follower isolates the output signal from the signal source with the very large input impedance. This is where the term 'buffer' came from. Notice that in the picture of the Voltage Follower the pin numbers of the device are listed. This is important for when the device is connected on a breadboard that the device pins are connected to the correct locations. The pin assignments for any device can be found on the data sheets that are available online or in paper form. This information will be provided one way or another.

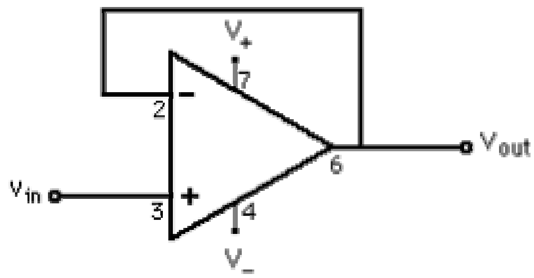

Figure 1: Voltage Follower

The voltage follower does not hold much interest right now, so the next amplifier that will be looked at is a non-inverting amplifier with a gain. This amplifier is shown in Figure 2. By doing the analysis of this device using KCL and KVL, the transfer function, or gain, can be found.

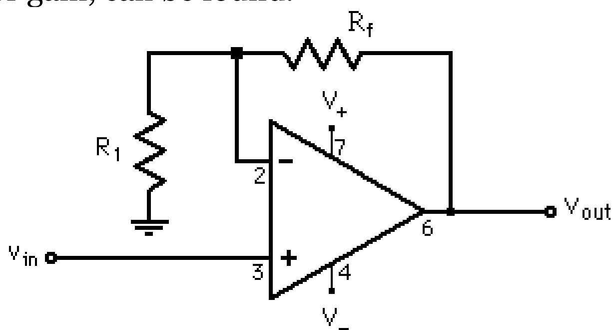

Figure 2: The non-inverting voltage amplifier with feedback resistor R_f.

The current rule will force the current to the inverting terminal (-) to be zero. Also remember that the voltage at the inverting terminal (-) needs to match the voltage at the non-inverting terminal (+). This gives the node equations to be $\frac{V_{in}}{R_1} = \frac{V_{out} - V_{in}}{R_f}$. Solving this equation, the transfer function can be found to be $A = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$. Therefore the gain of a non-inverting amplifier has an automatic gain of 1 in the system. This is believable due to the voltage follower just discussed. If the gain resistor is set to zero ($R_f = 0\ \Omega$) then the circuit becomes a voltage follower and $V_{out} = V_{in}$ and the gain of 1.

Inverting Amplifier

Next the discussion will turn to what is called an inverting amplifier. The inverting amplifier is so called because the input is connected to the inverting terminal of the op amp. The name also gives away the form of the output. The output of an inverting amplifier is 180° out of phase of the input, thus the output in inverted. The common inverting amplifier is shown in Figure 3. The analysis of this amplifier follows the same logic as the non-inverting amplifier. The input terminals need to have zero difference between them, so there has to be zero volts at the inverting terminal (-) due to the fact that the non-inverting terminal (+) is grounded. This leads to the node equation of $\frac{V_{in}}{R_1} = \frac{-V_{out}}{R_f}$. Notice that the negative sign appears in this equation and not in the non-inverting case. Solving this equation, the transfer function comes out $A = \frac{V_{out}}{V_{in}} = \frac{-R_f}{R_1}$.

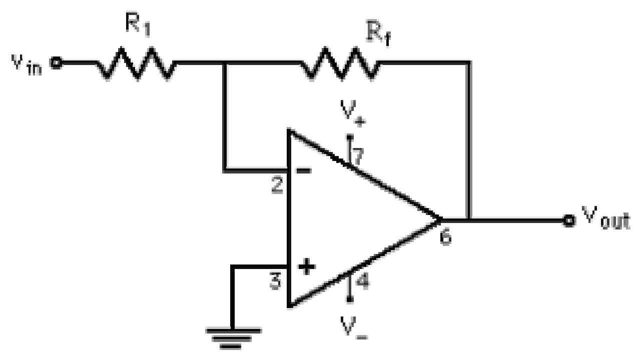

Figure 3: Inverting amplifier with the non-inverting (+) terminal grounded

Therefore the gain of an inverting amplifier does not have an automatic gain of 1 in the system. The resistor values have to be chosen such that $R_f = R_1$ to get the inverting gain of 1. There are many uses for the inverting amplifier configuration some of which will be discussed further. Two other uses of the inverting configuration are the integrator and the differentiator. The integrator (as the name suggests) integrates the input signal over time. The integral of the input is the output waveform. And the counterpart of the integrator is the differentiator which as the name implies again, differentiates the input as the output. These two configurations as well as the input and output waveforms are shown below in Figure 4 and Figure 5.

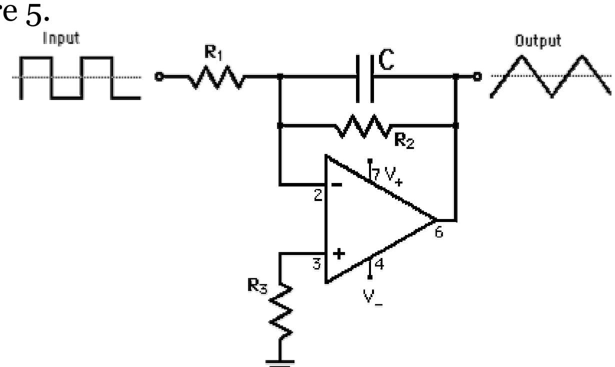

Figure 4: Integrator circuit set up in the inverting amplifier case

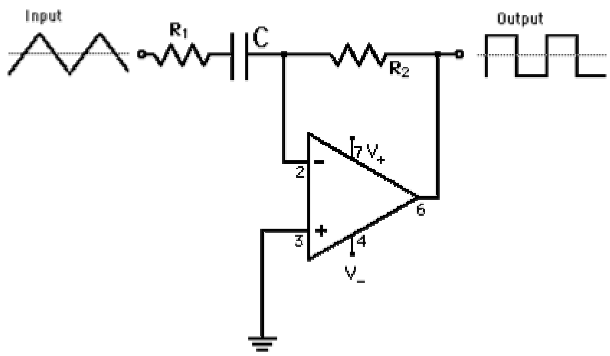

Figure 5: Differentiator set up in the inverting amplifier case

Difference Amplifier

The last configuration that will be discussed is the difference amplifier. The main point of this amplifier is that there are two input voltages and the output is a function of the difference of the two inputs. The configuration shown in Figure 6 is that of the difference amplifier. If the resistor values are chosen such that $R_1 = R_2 = R_3 = R_4$ the difference amplifier will act as a unity gain amplifier. There can also be a gain to the amplifier, and in this case $R_1 = R_2$ and $R_3 = R_4$ with the gain being a function of these combinations.

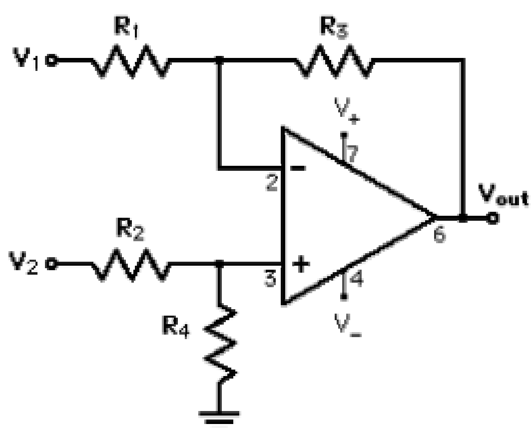

Figure 6: The difference amplifier with generic resistor values

The analysis of the difference amplifier still follows the game general rules. The input will match at the inverting (-) and the non-inverting (+) terminals and the output will do what it can to make that happen.

Frequency Response

The amplifier characteristics that were listed above talked about an infinite bandwidth. It would be great if a device existed but there is no such thing. The bandwidth is the range of frequencies that the device can operate in without distortion to the output. In many cases the bandwidth is listed on the data sheet of the device. For the LM741 op amp, the bandwidth is listed on the data sheet along with many of the other important characteristics, such as input offset voltage and input offset current. To determine the bandwidth experiments are preformed on amplifiers with a gain (not equal to 1, but less than that to make the device saturate) and measurements are made at different frequencies. Once the gain has fallen back down to 1, the frequency is called the Unity Gain Frequency. This is usually the bandwidth of the device. If the frequency of operation is increased the device will begin to show attenuation of the signal, rather and amplification. Many devices such as filters make us of the different frequencies and have special names depending on the way the response is shaped. The discussion of filters will take place in the second part of the Op Amp lab next week.

Along with this discussion is another important parameter known as the Slew Rate. The slew rate is the rate at which the voltage is allowed to change and is measured in V/μsec. The slew rate is different for each generation of op amps and even for different gains of amplifiers.

Hand-in Requirements

1. Pre lab exercises sheet(at the beginning of class)
2. Simulation output waveforms from pre lab (at beginning of class).
3. Data sheet with TA's signature
4. Lab report with detailed answers to post lab exercises.

Pre Lab Exercises

1. Read the data sheet for the LM741 Operational Amplifier and fill in the following parameters.

Supply Voltage:	Bandwidth:
Input Offset Current:	Slew Rate:
Input Offset Voltage:	Input Voltage:
Input Resistance:	Supply Current:
Output Short Circuit Current:	Power Consumption:

2. Using any analysis technique desired, find the transfer function of the difference amplifier shown in Figure 6. Show your work for credit.

3. Look up definition of Gain-Bandwidth product and write the description in the space provided.

4. Simulate the circuit of Figure 3 for gain values of 1, 10, and 100 for values of frequency between 10 Hz and 100 MHz. Comment on the gain-bandwidth product and the 'cutoff' frequencies. Obtain printouts of the gain vs. frequency curves for each value of gain.

Lab Exercises

1. Construct the circuit of Figure 3 with a gain of 2. Make sure that the op amp is powered with connections to pin 4 (-15 V) and pin 7 (+15 V). The pin out assignment is shown in Figure 7 for the LM741 Operational Amplifier.

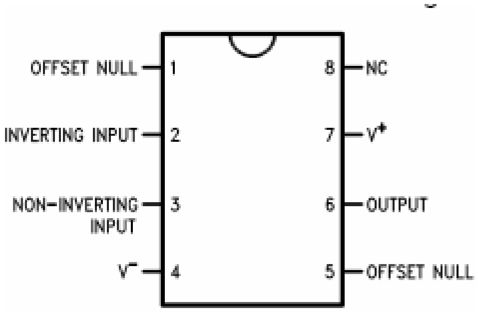

Figure 7: Pin out assignments for the LM741 Operational Amplifier

2. Use the function generator to apply an input voltage of 5 Vpp to the amplifier with a frequency of 10 Hz with a 0 dc offset.

3. Measure the following parameters: input voltage, output voltage, voltage at pin 2, and the voltage between pin 2 and pin 3.

4. Measure the input and output voltage for frequencies up to 100 MHz. Calculate the amplitude gain, and the gain in dB. The measurement in dB will allow us to create a graph of the gain vs. frequency.

5. Reset the input signal to $1V_{pp}$ and change the amplifier to a gain of 20 and repeat steps 2 – 4. Take a minute to consider why the input signal needs to be reduced.

6. Setup the amplifier with unity gain.

7. Change the input voltage to 10 Vpp, 1 kHz square wave with zero offset.

8. Using the oscilloscope display the rising edge of the output square wave on most of the screen. Use the vertical (voltage) knobs to get the waveform to the top and bottom of the screen and use the horizontal (time base) knob to make the waveform display across most of the screen.

9. Measure the difference in voltage from peak to peak, and the time from minimum to maximum voltage. Record these numbers on the data sheet.

10. Reset the input voltage to 1 Vpp, 1 kHz square wave with zero offset and the gain to 100. Measure the change in voltage and time again.

Post Lab Exercises

1. Was the voltage at the input terminals of the op amp zero? If not, how does it compare to data sheet specifications?

2. How does the gain compare to the theoretical gain of each of the amplifiers? Explain any differences that might have occurred.

3. Create a plot of the gain vs. frequency for the data collected in steps 4 and 5. Use the gain in dB to create the plot.

4. The gain bandwidth product is a constant for an amplifier, and changes depending on the gain. The gain bandwidth product listed on the data sheet is for a unity gain configuration. Using the data that was collected in steps 4 and 5 calculate the measured gain. Determine the cutoff frequency of the amplifier (usually -3 dB down from the maximum gain). Calculate the gain bandwidth product for steps 4 and 5 and compare them to the data sheet specification. Explain any differences that may have occurred. Compare to the simulation performed in the pre lab and comment on any similarities or differences.

5. Using the data collected in steps 9 and 10 calculate the slew rate of the amplifier. The slew rate is calculated as $\Delta t/\Delta V$. Compare the slew rates of steps 9 and 10 to the data sheet specifications. Compare the slew rate of step 9 to step 10. Are they the same? Should they be the same? Explain any differences that may have occurred.

Data Sheet

1. Construct the circuit of Figure 3.

TA INITIAL ____________

2. Input Voltage:___________

   Output Voltage:___________

   Pin 2 Voltage:_____________

   Voltage between Pin 2 and Pin 3:_________________

3. Measure the gain for different frequencies between 10 Hz and 100 MHz. **Theoretical gain A = -2.**

Frequency	Input Voltage	Output Voltage	Measured Gain	Gain (dB)
10 Hz				
100 Hz				
1 kHz				
5 kHz				
10 kHz				
25 kHz				
50 kHz				
100 kHz				
200 kHz				
400 kHz				
500 kHz				
700 kHz				
800 kHz				
1 MHz				
2 MHz				
5 MHz				
10 MHz				
50 MHz				

75 MHz				
100 MHz				

TA INITIAL _______________

Theoretical Gain A = -20.

Frequency	Input Voltage	Output Voltage	Measured Gain	Gain (dB)
10 Hz				
100 Hz				
1 kHz				
5 kHz				
10 kHz				
25 kHz				
50 kHz				
100 kHz				
200 kHz				
400 kHz				
500 kHz				
700 kHz				
800 kHz				
1 MHz				
2 MHz				
5 MHz				
10 MHz				
50 MHz				
75 MHz				
100 MHz				

TA INITIAL _______________

9. Measure Δt and ΔV with 10 Vpp, 1 kHz square wave with unity gain.
   Δt: _______________
   ΔV: _______________
10. Measure Δt and ΔV with 1 Vpp, 1 kHz square wave with a gain of 100.
   Δt: _______________
   ΔV: _______________

TA INITIAL _______________