Experiment 6

The Amplifier

6.1   Objectives

- Understand the operation of a differential amplifier.

- Determine the gain of a differential amplifier.

- Determine the gain of a differential amplifier as a function of frequency.

6.2   Introduction

When you go to purchase an audio amplifier for your home or car, there are a couple things you would like this amplifier (or just "amp") to do. First, it will take a small signal and make it larger. The amount of this amplification can be varied using the volume knob on the amp. As you increase the volume, you would like the various frequencies of sound coming out of your system's speakers to increase uniformly. That is, you don't want low frequencies to increase in loudness significantly more (or less) than high frequencies. Furthermore, you want your amp to amplify the desired signal while ignoring background noise.

The frequency response of an audio amplifier is available in the specifications of the amp. What does a frequency response of 20 Hz - 20 kHz $+/-$ 3 dB mean? Well, over this frequency range, the power output does not increase (or decrease) by more than 3 dB (decibels). Although we will

not measure gain in dB in this lab, decibels are commonly used when specifying amplifiers. The dB scale is a logarithmic scale and a variation of 3 dB represents a change in power output of a factor of two (+3 dB means the output power is doubled and −3 dB means the output power has been cut in half). The frequency response of all real amplifiers is not flat; they do not amplify all frequencies equally well. The speakers in our audio systems also have frequency responses that are not flat. Furthermore our ears cannot hear all frequencies equally well either.

Another frequently specified attribute of amps is the signal to noise ratio. This is the ratio of desired amplified signal to the (undesired) background noise. This too, is commonly specified in dB. For example, a signal to noise ratio of 90 dB represents an actual (desired) amplified signal that is 10^9 or one billion times larger than the undesired noise!

6.3   Key Concepts

For this lab, we'll be making extensive use of the oscilloscope, so you might want to review the previous lab where we learned how to use it. It would be good to review voltage, too.

There aren't many references to amplifiers in introductory texts, as it not is typically covered. However, we are learning about them so we can use one in the following experiment involving bio-electricity.

6.4   Theory

A differential amplifier compares two voltage signals with respect to a reference voltage (often ground), then takes their **difference** and amplifies this difference as its output. This allows the signal to be viewed on an oscilloscope or other recording device. We will see the usefulness of subtracting two voltage signals in next week's experiment when we use the differential amp to view cardiac signals.

A schematic diagram of a differential amplifier is shown in Fig. 6.1. The first red input lead has voltage V_a, the second red lead has voltage V_b, and the black lead defines a reference voltage V_r. The reference voltage is usually taken to be ground. The input signals can be thought of as the voltage differences between the inputs and the reference:
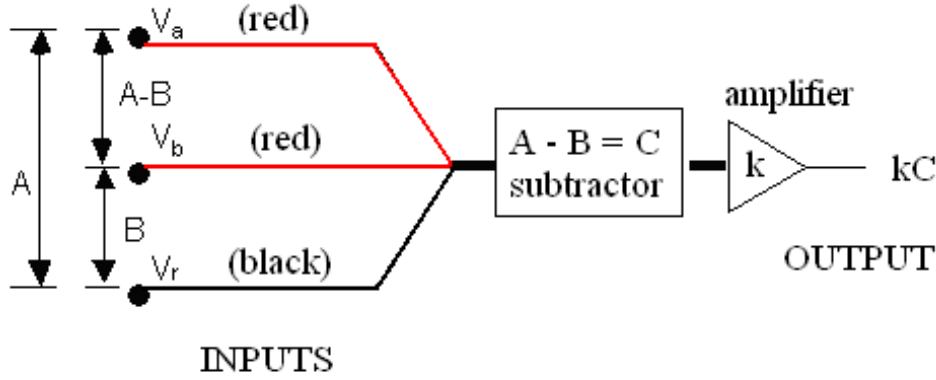
Figure 6.1: Schematic of a differential amplifier.

$$A = V_a - V_r \tag{6.1}$$

$$B = V_b - V_r \tag{6.2}$$

The subtractor part of the differential amplifier calculates the difference between the two input leads:

$$C = A - B = V_a - V_b \tag{6.3}$$

The voltages here refer to voltages at any particular instant of time.

The signal C is then sent through an amplifier and its amplitude is increased k times. The output signal of the amplifier is

$$\text{output} = k \times (A - B) = k \times C \tag{6.4}$$

The value k is the "gain" of the amplifier and is defined as:

$$\text{gain} = \frac{\text{output voltage}}{\text{input voltage}} = \frac{V_{\text{out}}}{V_{\text{in}}} \tag{6.5}$$

The amplifier part of the differential amp makes voltages bigger at each moment but it cannot make the input voltage vary more or less quickly. Thus, an ideal amplifier has no effect on the frequency of its input signal or on its shape as a function of time. It only changes its size. Of course, the signal $C = A - B$ can be quite different from either A or B by themselves.
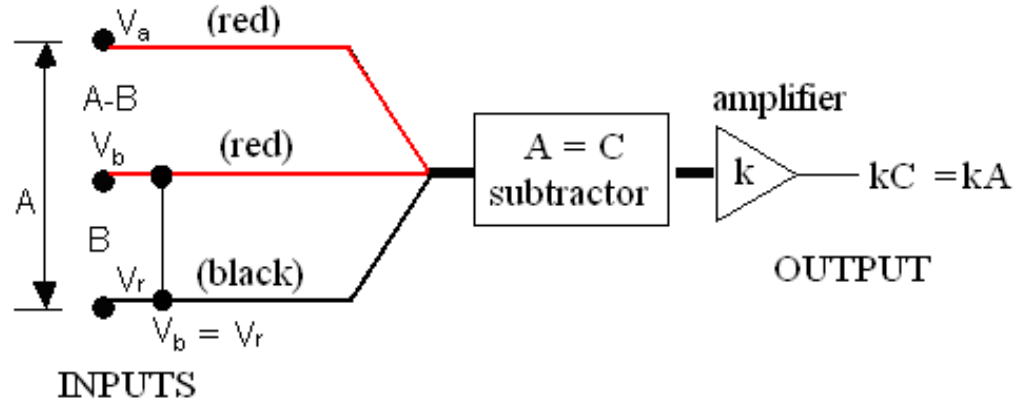
Figure 6.2: Schematic of an amplifier with the input signal B set to zero.

Stray electrical signals from outside sources, called noise, pervade the room where voltages V_a and V_b are measured. The amplitude of this noise is often much greater than the amplitude of the signals we wish to study. Since the noise may be much larger than the desired signals A and B, the arrangement that subtracts a reference voltage produces much less contamination of the output signal. The biological signals we will study in the next experiment would be completely obscured if not for this property of the amplifier. This feature is known as Common Mode Rejection (CMR) because it rejects signals sent in common to both of the input leads.

We will measure the characteristics of the amplifier by setting the input signal of B to zero ($B = 0$) by connecting it directly to the reference (ground) as shown in Fig. 6.2. The inputs to the differential amplifier are:

$$A = V_a \qquad (6.6)$$

and

$$B = V_b = V_r = 0 \qquad (6.7)$$

The output signal is then:

$$\begin{aligned}
\text{output} &= k \times (A - B) \\
&= k \times (V_a - 0) \qquad (6.8) \\
&= k \times V_a
\end{aligned}$$

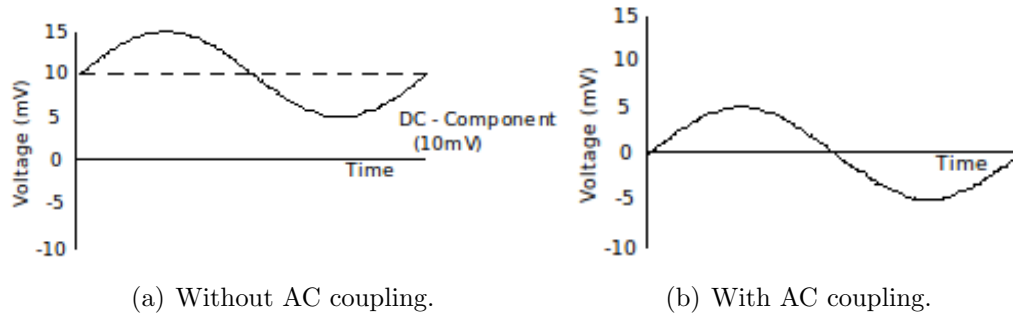(a) Without AC coupling. (b) With AC coupling.

Figure 6.3: Output voltage with and without AC coupling, for input voltage that varies between 5 and 15 mV.

If instead, we had connected the signal into channel A to the reference (with our input signal connected to B) we would get essentially the same result but with a minus sign, i.e. output $= k \times (A - B) = k \times (0 - V_b) = -k \times V_b$. For AC signals, this minus sign presents itself as a 180° phase shift in the output signal.

A second feature of the differential amp is that it can be **AC coupled**. This means that there is an electronic circuit that passes only input voltages varying rapidly in time. The AC coupling circuitry will not pass a constant, DC voltage or slowly varying voltage at frequencies below 0.5 Hz. Thus, AC coupling removes any DC component from an AC signal. For example, a signal that varies from 5 mV to 15 mV at 10 Hz is an AC signal with a DC component of 10 mV (See Fig. 6.3(a)). AC coupling will remove the 10 mV DC component and pass an AC signal varying from −5 mV to +5 mV to the amplifier, as in Fig. 6.3(b). AC coupling is accomplished by capacitors in the input circuit that act as a large resistance to DC signals. The differential amplifier may also be **DC coupled** with no restriction on the input. DC coupling amplifies whatever it sees at the input: AC, AC + DC, or pure DC. Note that the oscilloscope may also be AC coupled; using the AC/DC button toggles the scope between AC coupling and DC coupling.

6.5 In today's lab

In this experiment it will be our goal to acquaint you with the differential amplifier. Before using this device as a tool in biological measurements, it

will benefit you to have some idea of the basic structure of the differential amp.

6.6 Equipment

- Differential amplifier

- Signal generator

- Oscilloscope

- Attenuator

6.7 Procedure

Setup

The apparatus that we will use consists of a differential amplifier, a signal generator, an attenuator and an oscilloscope. The setup is shown schematically in Fig. 6.4 and a photo is shown in Fig. 6.5. The attenuator is a device which decreases the amplitude of a signal. Today, we will use it to make small adjustments to the input voltage.

The differential amp is contained in an opaque plastic box. On the back of the box (see the upper photo in Fig. 6.7) there are three banana jacks: two of them are red and the other one is black. The two red jacks are the INPUTS of the differential amp. The black jack is the ground or reference for the signals sent into the two red jacks. On the left side of box, there is a BNC connector for the OUTPUT of the amplifier. On the front of the amplifier (see Fig. 6.6), starting from the left, there is an OFFSET adjust knob, a connection jack to charge the amplifier's battery, the High/Low gain selection switch, and the DC/AC coupling selection switch.

Retrieve an amplifier from the charger at the front of the room. If the amplifier is not connected to the charger, you should connect it to the charger and wait about 2 minutes for the amp's battery to charge. Record the number on the back face of your amplifier in your Excel Spreadsheet. You will need to know which amplifier you used for next week's lab. When you are finished with the experiment, return your amplifier to the front of the room and connect it to the charger.
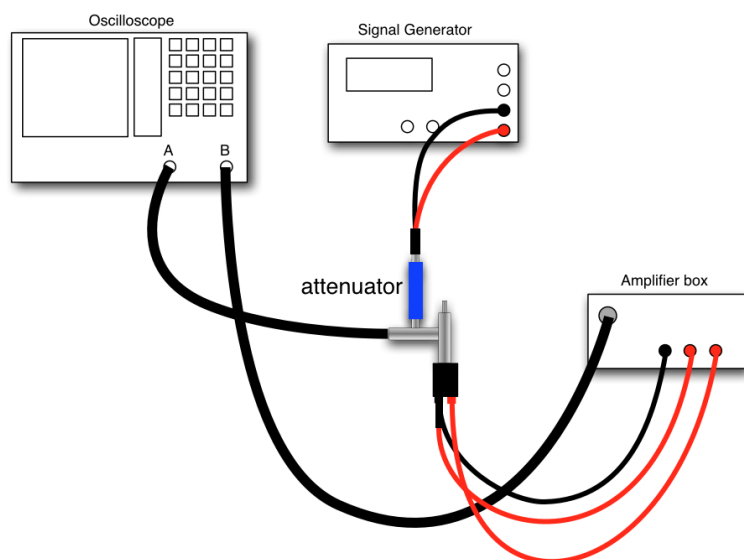
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Figure 6.4: Schematic of setup.

Preparing the circuit.

1. On the differential amplifier turn the OFFSET knob all the way counterclockwise. Set everything to AC coupling (both channels of the oscilloscope **and** the amplifier).

   Now make the following connections:

   a) Set the amplifier coupling switch to AC and the gain of the amplifier to LOW as shown in Fig. 6.6.

   b) The signal generator should be connected to the attenuator. Use a BNC cable to connect the output of the attenuator to channel A of the oscilloscope.

   c) Connect the differential amp to the output of the attenuator using banana plug cables as follows: 1) One red jack on the amplifier is connected to the red jack on the attenuator. 2) The other red jack on the amplifier is connected to the black jack on the attenuator. 3) The black jack (reference) on the amplifier is also connected to the black jack on the attenuator.
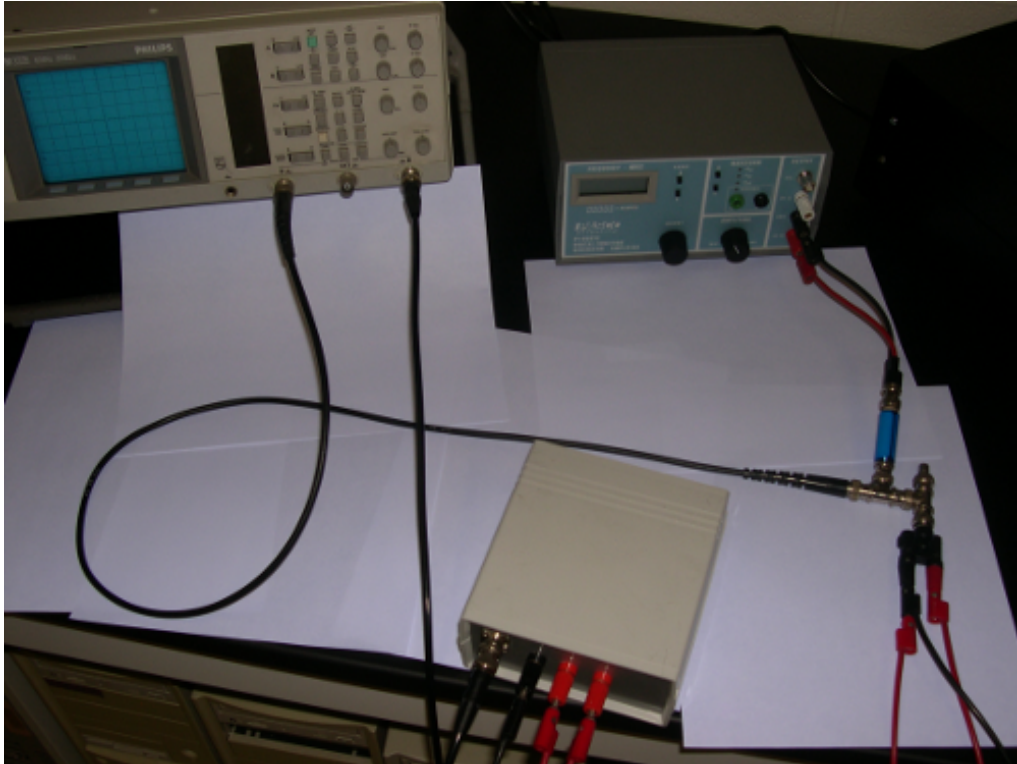
Figure 6.5: Photo of setup.

The attenuator and the connections to the amplifier are shown in Fig. 6.7.

   d) Using a BNC cable, connect the output of the amplifier to Channel B of the oscilloscope.

   e) Push the A/B button (circled in Fig. 6.8) until both channels are displayed on the oscilloscope. The scope is now set up to view the input signal on channel A and the output signal on channel B.

   f) Use the AC/DC buttons (also circled) on **both** channels of the oscilloscope to set both Channels A and B to AC coupling. The LCD panel should now show AC for both channels (also circled).

2. **Triggering.** The triggering on an oscilloscope lets the oscilloscope know where on the signal it should start its trace. When set properly,
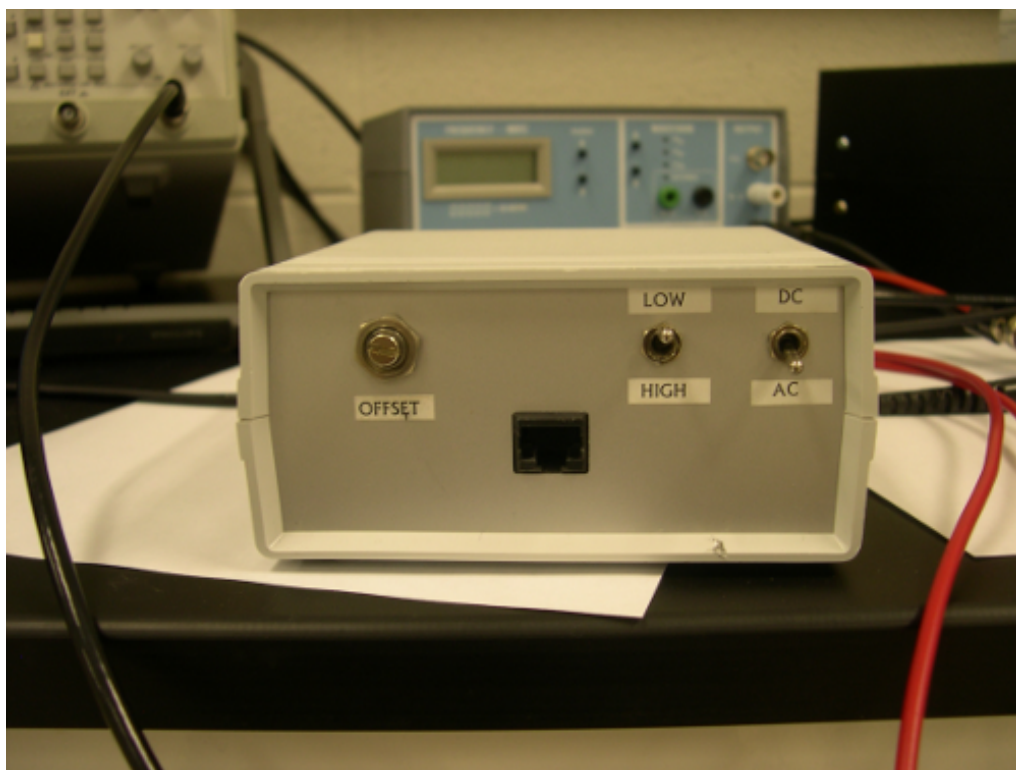
Figure 6.6: Settings on the front of the amplifier.

the signal will start each trace in the same location. If not set properly, the signal will be very erratic and it will be extremely difficult to make any measurements. The output signal in this experiment is significantly larger than the input signal. Therefore, you want to set the oscilloscope to trigger on the output signal (channel B). Push the "TRIG COUPL" button on the oscilloscope until "P-P" is visible on the LCD panel. Then, push the "TRIG or x SOURCE" button on the oscilloscope until "B" is visible just above the "P-P" on the LCD panel. Set the trigger level knob (in lower right-hand corner) to the middle of its range.

3. With the current setup, turning the OFFSET knob on the amplifier should not affect the vertical position of the output trace on the oscilloscope (except momentarily).
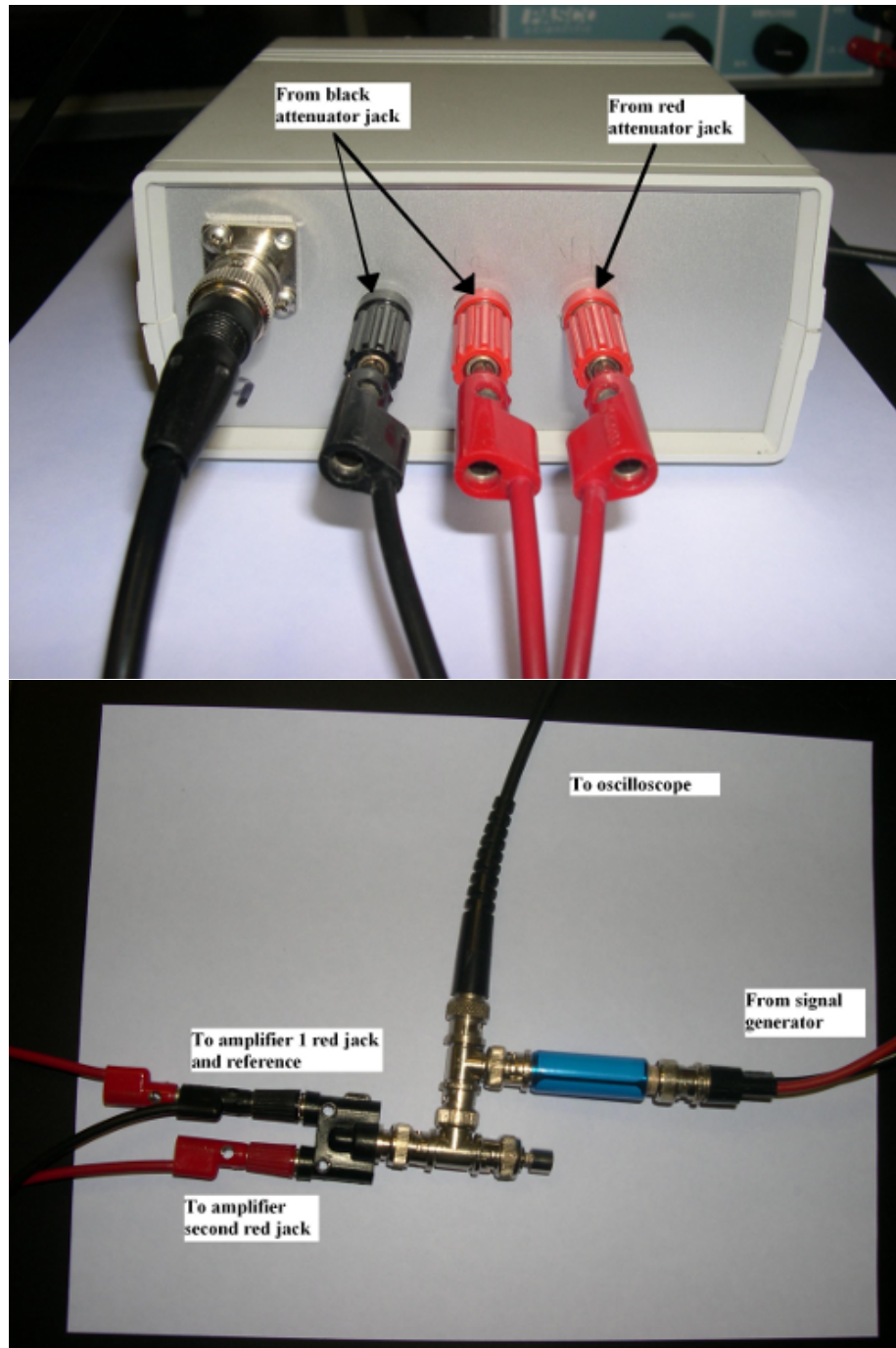
Figure 6.7: Connecting the cables to the amplifier (top) and attenuator (bottom).

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Figure 6.8: Front panel of the oscilloscope with the circled buttons indicating how to get channels A and B displayed simultaneously and in the AC coupling mode.

4. If during any of your measurements the output signal looks clipped (that is, either the top or the bottom is cut off as in Fig. 6.9), you will have to adjust the OFFSET knob, until the entire signal is visible (see Fig. 6.10). Notice the amplifier output on the screen of the oscilloscope appears smaller than the input. This is because the voltage sensitivity for the output and the input are NOT set to the same level. If both the top and bottom are cut off (see Fig. 6.11), you most likely have the amplifier set to high gain, so switch it back to low gain (see Fig 6.6).

5. Please note that the amplifier is very sensitive to noise. Make sure to keep the amp away from the signal generator (whether it is on or
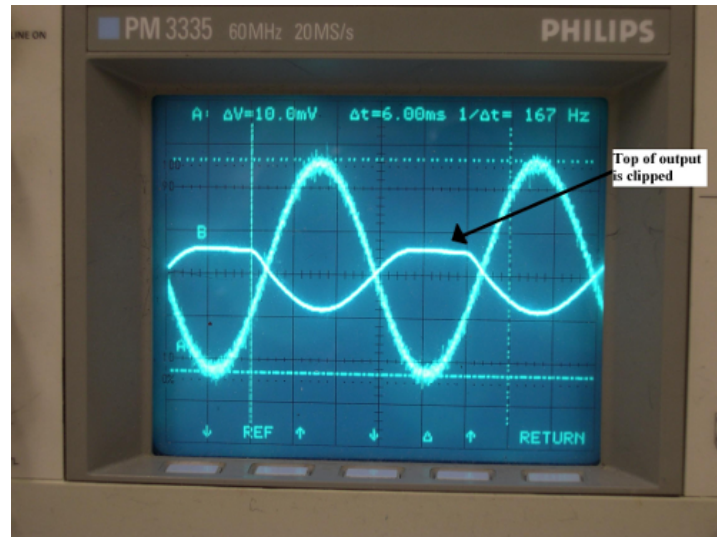
Figure 6.9: Output of amplifier is clipped.

off) as well as the oscilloscope and various power cords. If the amp is placed on top of the signal generator the signal displayed on the oscilloscope will bounce up and down. Before taking any measurements move the differential amplifier at least a foot away from the signal generator and oscilloscope.

Part I. Gain of the differential amp (at a constant frequency of $f = 200$ Hz)

1. Set the signal generator frequency to 200 Hz.

2. Set the peak-to-peak voltage (V_{pp}) of the input signal, V_{IN}, to 5 mV. To do this, view channel A and set the cursors so the peak-to-peak limits are 5 mV. Adjust the amplitude knob on the signal generator to increase or decrease your input signal until it fits the cursor settings.

3. Measure the peak-to-peak voltage of the output, V_{OUTPP}. To measure the output voltage, view channel B on the scope and use the voltage cursors to measure V_{pp}. Record the data, including an uncertainty, in
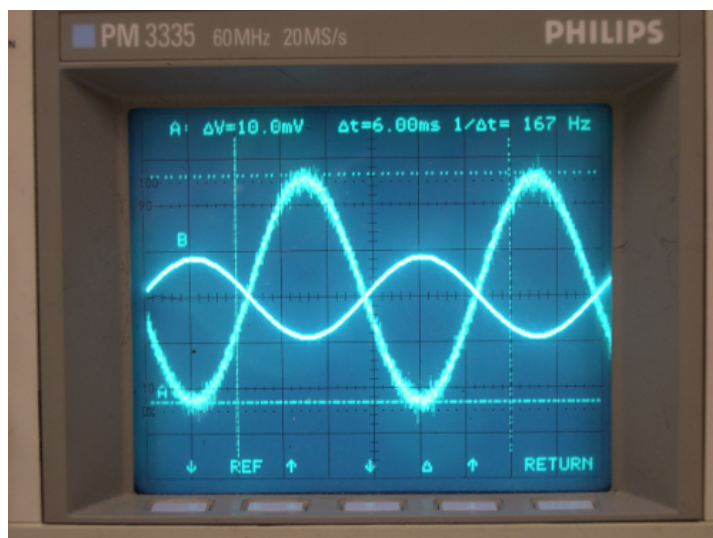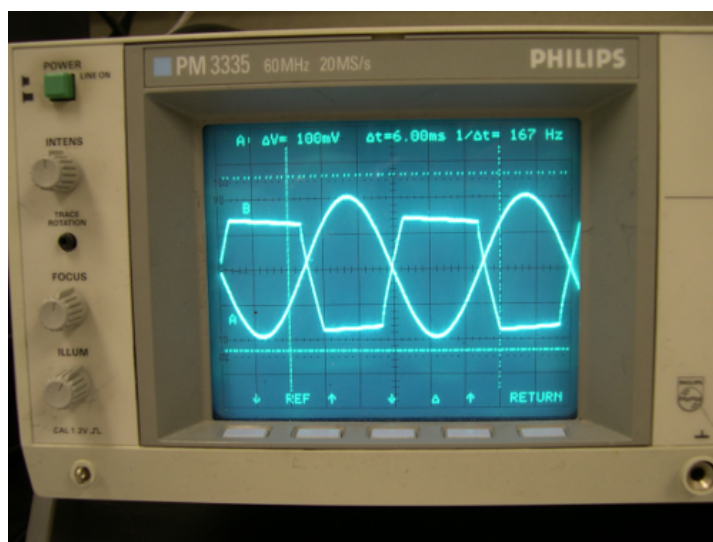
Figure 6.10: After adjusting OFFSET knob, output is no longer clipped.

Figure 6.11: Top and bottom of output are both clipped (check input voltage and gain setting on the amplifier).

your Excel spreadsheet Data Part 1. Make sure the signal on Channel B of the oscilloscope has the same waveform as the input signal. If clipping occurs, adjust the OFFSET on the amplifier. Do not exceed an input voltage of 30 mV on Channel A.

4. Repeat the previous 2 steps for the other input voltages, V_{IN}, shown in the data table.

5. **Plot** the output voltage V_{OUTPP} with error bars vs. the input voltage V_{IN}. If you don't remember how to plot error bars please refer to Part 2 in Appendix D.

Part II. Gain as a function of frequency (at a constant input voltage of $V_{\text{IN}} = 10$ mV)

1. Refer to your Excel spreadsheet Data Part 2 for the lowest frequency setting and set the signal generator to that value. Set the input peak-to-peak voltage V_{IN} to 10 mV. Measure and record the input voltage, including an uncertainty δV_{IN}, in your Excel spreadsheet.

2. Measure the output voltage V_{OUTPP} of the differential amp for each frequency shown in the Excel spreadsheet.

3. Calculate the gain and its uncertainty of the differential amp for each frequency. Adjust the amplitude knob if necessary to maintain an input voltage V_{IN} of 10 mV. The equation for the uncertainty in gain is:

$$\delta(\text{gain}) = \text{gain} \left(\frac{\delta V_{\text{IN}}}{V_{\text{IN}}} + \frac{\delta V_{\text{OUT}}}{V_{\text{OUT}}} \right) \tag{6.9}$$

4. **Plot** the gain including error bars vs. frequency on a semi-logarithmic[1] graph. Use a logarithmic scale on the frequency axis. To do this select "AXIS OPTIONS" from the PLOT pull-down menu in Kaleidagraph and then change the scale setting from linear to log.

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[1] "semi-logarithmic" means that one axis is in log scale and the other is not.

6.8 Questions

Part I.

1. In practice, the goal is to have an amplifier whose gain is linear. This predicts a linear relation between V_{IN} and V_{OUT}. How did your amp do? Does your data support a linear gain? How can you tell this from your data and graph?

2. Find the gain, including its uncertainty, of your amplifier from the slope. You will need the gain of this amplifier for next week's experiment! Also, make sure you have written down the number of your amplifier so you can find the same one next week.

Part II.

3. When you varied the frequency in Part II you "passed by" 200 Hz, which you used in Part I. Is your measured gain at 200 Hz in Part II consistent with the gain obtained from the slope of your graph in Part I? If not, suggest a possible explanation for the inconsistency.

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4. What happens to the gain of the differential amp at high frequencies?

5. Over what frequency range is the amplifier gain most reliably constant?