EXPERIMENT 7

The Amplifier

Objectives

1) Understand the operation of the differential amplifier.
2) Determine the gain of each side of the differential amplifier.
3) Determine the gain of the differential amplifier as a function of frequency.
4) Determine the common mode rejection ratio of the differential amplifier.

Introduction

In this experiment it will be our goal to acquaint you with the differential amplifier and how the device can be used to measure small bio-electric signals. Before using the device as a tool in biological and physiological measurements, it will benefit you to have some idea of the basic structure of the differential "amp".

The differential amp compares two voltage signals with respect to 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 and muscle potentials.

A schematic diagram of a differential amp is shown in Figure 1.

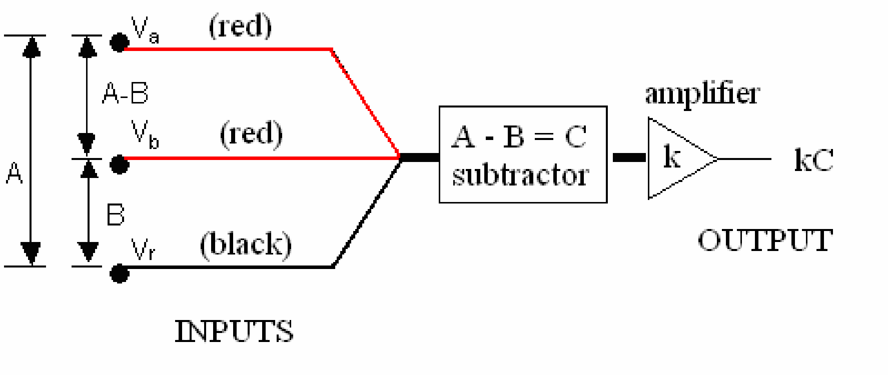


Figure 1

In the above diagram, the first red input lead has voltage V_a, the second has V_b, and the black lead defines a reference voltage V_r. The reference voltage is usually ground. The input signals can be thought of as the voltage differences between the inputs and the reference:

$$A = V_a - V_r \qquad B = V_b - V_r$$

The subtractor part of the differential amplifier forms the difference between the two input leads: $C = A - B = V_a - V_b$. The voltages here refer to voltages at any particular instant of time.

This signal (A - B) is then sent through an amplifier and its amplitude gets increased "k" times. The signal k×(A-B) becomes the output from the differential amp. The value "k" is the GAIN of the amp.

$$\text{GAIN} = \frac{output \cdot voltage}{input \cdot voltage}$$

The amplifier part of the differential amplifier makes voltages bigger at each moment. 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 C = A - B or on the shape as a function of time. It only changes its size. Of course, the signal A - B can be quite different from A or B by themselves.

It might appear as if the differential amplifier takes the hard way by amplifying $(V_a - V_r) - (V_b - V_r)$ instead of amplifying $(V_a - V_b)$ directly. Any real amplifier actually produces (as you will measure) an output related to not just the difference of its inputs, but also to their sum. So without the reference signal, we would have:

$$\text{Output} = k \times (V_a - V_b) + g \times \left(\frac{V_a + V_b}{2}\right)$$

where g is known as the "common mode" gain, the gain for an input presented in "common" to both inputs of the amplifier: if $V_a = V_b = V_{comm}$, $V_{comm} = (V_a + V_b) / 2$. An ideal differential amplifier would amplify *only* the difference, with g = 0 and k=100 or so. How close it comes to this is measured by the common mode rejection ratio. The common mode rejection ratio in percent is given by:

$$\%\text{CMRR} = (1 - g / k) \times 100\%$$

Stray electrical signals from outside sources, called noise, pervades 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 biological signals to be studied. Since part of this noise may be common to any signals measured in the same area (called common mode noise), we can make a third measurement, V_r, of just the noise:

$V_a = A + \mathit{noise}$ $\quad$ $V_b = B + \mathit{noise}$ $\quad$ $V_r = \mathit{noise}$

Without using the reference signal, the noise cancels in the difference term, but not in the sum term. Our imperfect amplifier would produce:

$$\text{Output} = k \times (A - B) + g \times \left(\frac{A + B}{2} + \mathit{noise}\right)$$

The differential arrangement uses as inputs A = (V_a+ noise) – (V_r+ noise) and B = (V_b+ noise) – (V_r+ noise). Now, the noise also cancels in the sum term and we get:

$$\text{Output} = k \times (A - B) + g \times \left(\frac{A + B}{2}\right) \qquad (1)$$

Note if all inputs are equal, $V_a = V_b = V_r$, then A = B = 0, and we expect zero output, aside from intrinsic noise produces by the amplifier.

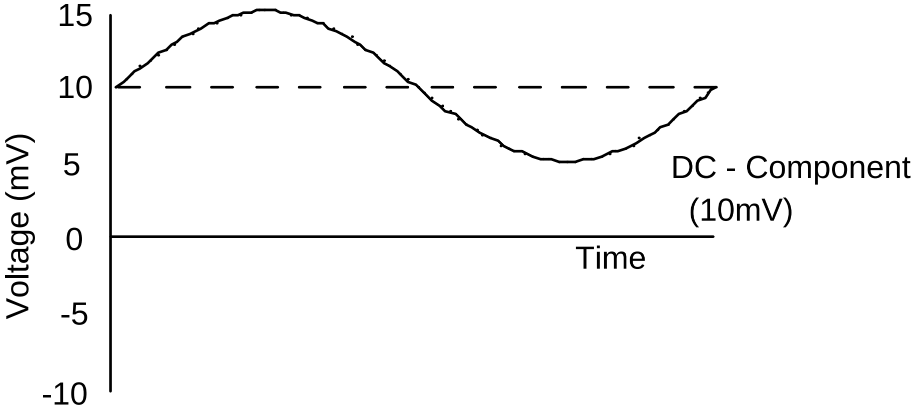
Since the noise may be much larger than the desired signals A and B, the arrangement which subtracts the reference voltage produces much less contamination of the output signal. The biological signals would be completely obscured if not for this property of the amplifier, which is known as Common-Mode Rejection, because it rejects signals sent in common to both of the input leads.

We will measure the characteristics of the amplifier by arranging input signals of A=0, then B=0, and finally A=B. From Equation (1), the output for these conditions should be

Out(A=0) = -B(k - g/2) if $g \ll k$, output ≈ -kB
Out(B=0) = A(k +g/2) if $g \ll k$, output ≈ kA
Out(A=B) = Ag

A second feature of the differential amplifier is that it can be "AC coupled". This means that there is an electronic circuit that passes only input potentials varying fairly rapidly in time. The AC coupling circuitry will not pass constant voltage DC or slowly varying voltage at frequencies below 1/2 Hz. AC coupling thus removes any DC component from an AC signal. For example, a signal that varies from 5 mV to 15 mV at, say, 10 Hz, is an AC signal with a DC component of 10 mV (See Figure 2). AC coupling will remove the 10mV DC component and pass an AC signal varying from -5 mV to +5 mV to the amplifiers. 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. It 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.

Before AC coupling



After AC coupling: (DC component eliminated)

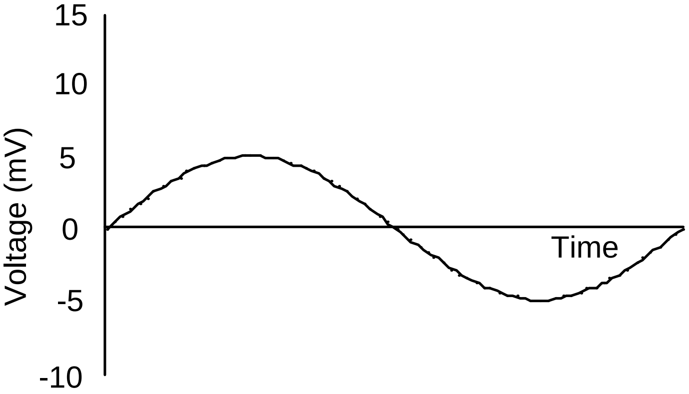


Figure 2

In next week's experiment we will look at a specific biological measurement, the electrical potentials produced by the human cardiac muscles. The heart puts out a signal varying from about -4 mV to +4 mV at a frequency of about $\frac{72\,beats}{60\sec} = 1.2$ Hz corresponding to the contractions of the cardiac muscles. Customarily, placing an electrode on the skin of each arm makes this measurement. There is an arm-to-arm DC potential of about 20 mV due to the biceps and shoulder muscles. In addition, the whole body acts as an antenna picking up electromagnetic waves from the surrounding space. These signals are mostly 60 Hz from the 60-Hz power lines in the building. In a typical situation this may produce a potential between any two points on the body of 50 - 60 mV with a dominant frequency of 60 Hz. Thus, the cardiac signals are completely lost in the noise.

If the differential amplifier is connected to a subject as in Figure 3 with an electrode on each arm and one on a leg, which is the common reference point, the cardiac muscle signals can be monitored. The AC coupling feature will remove the DC level from the input due to the large muscles in the body. The inputs to the amplifier are the AC potential differences between the right arm and right leg, and between the left arm and right leg. The difference will be the AC potential difference between the right arm and the left arm. The noise induced by EM waves passing through the body is common to both arm-leg inputs and thus is removed by the common mode rejection feature, with the leg input as the reference. The output is the amplified cardiac signals alone.

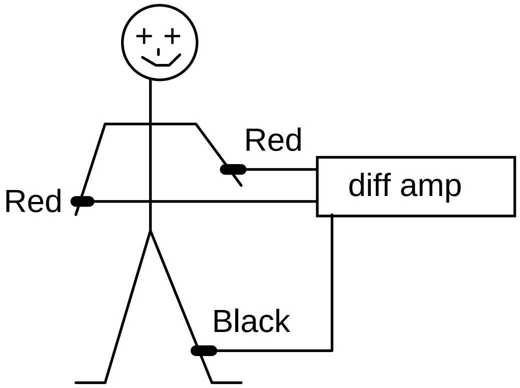


Figure 3

Apparatus

The apparatus that we will use today consists of a differential amp, a signal generator, an attenuator and an oscilloscope, shown schematically in Figure 4. The attenuator is a device which decreases the amplitude of a signal. Here, it allows small adjustments to the input voltage.

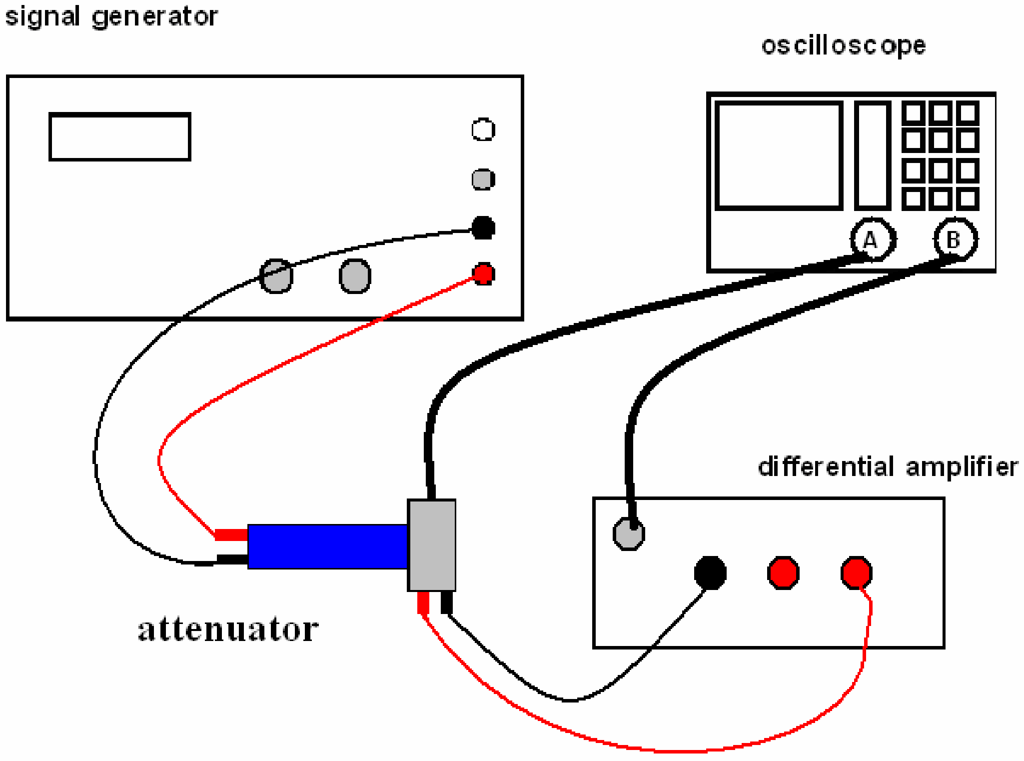


Figure 4

The differential amp is contained in an opaque plastic box. On the back of the box, there are three banana jacks. Two of them are "red" and the other one is "black". The two red jacks are the INPUT to 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 amp. On the front, from the left, there are the OFFSET adjusting knob, a connection jack to charge the amplifier's battery, the High/Low gain selection switch, and the DC/AC coupling selection switch.

PROCEDURE:

Preparations:

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.

Turn the OFFSET knob all the way to the left.

1. Set everything to AC coupling (both channels of the oscilloscope AND the amplifier). Make the following connections:
    a) Set the amplifier coupling switch to AC
    b) Set the amplifier to LOW gain.
    c) 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.
    d) Connect the differential amplifier to the out put of the attenuator using banana plug cables as follows: One red jack on the amplifier is connected to the red jack on the attenuator. The other red jack on the amplifier is connected to the black jack on the attenuator. The black jack (reference) on the amplifier is also connected to the black jack on the attenuator.
    e) Using a BNC cable, connect the output of the amplifier to Channel B of the oscilloscope.
    f) Set the oscilloscope to AC coupling for both Channels A and B. The LCD panel should now show AC for both channels.

The scope is now set up to view the input signal on channel A and the output signal on channel B.

2. Triggering: 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). Use should use the TRIG COUPL button on the oscilloscope until P-P is visible on the LCD panel. Then, push the TRIG x SOURCE button on oscilloscope until "B" is visible just below the P-P on the LCD panel. Set the trigger level knob to the middle of its range.
3. With the current set up, turning the OFFSET knob on the amplifier should not affect the vertical position of the output trace on the oscilloscope (except momentarily).

4. If during any of your measurements the output signal looks clipped looks clipped (that is, either the top or the bottom is cut off), you will have to adjust the OFFSET knob, until the entire signal is visible. If both the top and bottom are cut off, you most likely have the amplifier set to high gain – switch it back to low gain.

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

First, we wish to determine the GAIN of each side of the differential amp. To do this, we connect one input jack (red) of the amplifier to the OUTPUT of the attenuator; both the other input jack (also red) of the amplifier and the black reference jack of the amplifier to the GROUND of the attenuator. That gives one input voltage (say B) = 0 and we measure kA, swapping the location of the red leads gives kB.

1. Set signal generator frequency at 200 Hz.
2. Set the peak-to-peak voltage of the input signal to 10 mV. To set this, view channel A. Adjust the output amplitude knob on the signal generator to set the desired voltage. Measure your peak-to-peak signal with the cursors. Adjust the amplitude knob on the signal generator to increase or decrease your signal, then re-measure (it may be necessary to change the output amplitude coarse setting). Repeat until you reach the desired voltage. Be sure to change scales on the oscilloscope to get a good view of the signal if necessary.
3. Measure the peak-to-peak voltage of the output. To measure the output voltage, view channel B on the scope and use voltage cursors to measure V_{pp}. Record the data in your Excel spreadsheet data table (under INPUT 1 = V_{IN}). Make sure the signal on Channel B 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 steps 2 and 3 for other input voltages shown in the data table.
5. Plot the output (vertical axis) vs. input (horizontal axis) voltage.
6. Interchange the two red leads and repeat steps 2 through 5. Record the data in the table (under INPUT 2 = V_{IN}).

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

1. Set the input to 10 mV peak to peak. Measure and record the uncertainty in the input voltage (δV_{IN}) in your Excel spreadsheet.
2. Measure the output of the differential amp for each frequency shown in your Excel spreadsheet.
3. Calculate the gain and its uncertainty of the differential amp for each frequency. Adjust the input if necessary to return it to 10mV.

$$\delta(GAIN) = GAIN\left(\frac{\delta V_{IN}}{V_{IN}} + \frac{\delta V_{OUT}}{V_{OUT}}\right)$$

4. Plot gain (vertical axis) vs. frequency (horizontal axis) on a semi-logarithmic 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.

Part III. Common-mode rejection

To measure the percentage of common-mode rejection, we connect both input leads (red) to the OUTPUT of the signal generator. Attach the black lead to GROUND.

1. Set the input to 1.0 volt and 200 Hz. Measure the peak-to-peak voltage of the input and its uncertainty by using the voltage cursors (channel A). Record your measurement in your Excel spreadsheet.
2. Measure the peak-to-peak voltage of the output by using the voltage cursors (channel B). Record your measurement (in volts) in your Excel spreadsheet.
3. Have Excel calculate the common mode gain (g) and its uncertainty

$$g = \text{OUTPUT}/\text{INPUT}$$

$$\delta g = g\left(\frac{\delta V_{IN}}{V_{IN}} + \frac{\delta V_{OUT}}{V_{OUT}}\right)$$

4. Using the gain determined from either side of the amplifier in Part I, have Excel calculate the % common-mode rejection ratio (CMRR) and its uncertainty.

$$\%\ \text{CMMR} = (1 - g/k) \times 100 = \left(1 - \frac{common\_mode\_gain}{gain\_of\_one\_side}\right) \times 100$$

$$\delta(\%\text{CMRR}) = \%CMRR\left(\frac{\delta g}{g} + \frac{\delta k}{k}\right)$$

Questions

Part 1

1. When one of the red jacks on the amplifier, say INPUT 1 is connected to the GROUND on the attenuator, what is the signal going into that side of the amplifier (again, INPUT 1)?
2. If the common mode gain g is much less than k, and INPUT 2 is set to ground, then $V_{out} = k*V_1$. This predicts a linear relation between V_1 and V_{out}. Does your data support this? If yes, what does the slope represent and what are its units?
3. Find the gain of each side from the slopes, including their uncertainties (you will need the gain of your amplifier for next week's experiment).
4. Are the gains from the two sides of the amplifier consistent with each other?

Part 2

5. Is your measured at 200 Hz consistent with your measurement in part 1?
6. What happens to the gain of the differential amp at high frequencies?
7. Estimate the highest and lowest frequency signal one would encounter when looking at cardiac signals. Is this amplifier adequate? Hint: To see good detail in the shape of the heartbeat, following all the wiggles in the signal, the gain of the amplifier should be relatively flat (i.e. constant) up to a frequency of roughly 100f, where f = the basic heart frequency (see page 4).

Part 3

8. When both input leads (red) are connected to the output of the signal generator, what should be the output of the differential amplifier ideally?
9. Ideally, what should be the % CMRR for the differential amplifier? Is this value consistent with the value you obtained for your amplifier?