THE AMPLIFIER

OBJECTIVES:

1) Explain 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 percentage 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 is basically a device that takes the "difference" between two voltage signals. The result of this subtraction is then amplified (or increased) so that it can be conveniently viewed on an oscilloscope or other recording devices. 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.

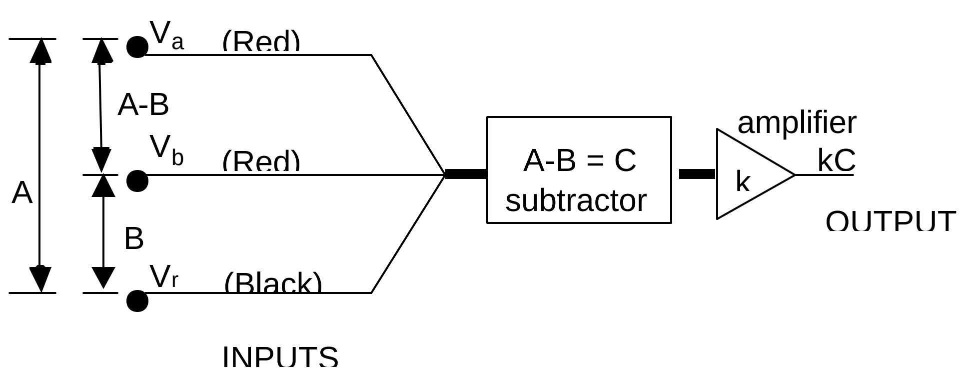


Figure 1

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 input signals can be thought of as the voltage differences between the input lead and the reference voltage:

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

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.

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

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,

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

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 this noise is common to any signals measured in the same area, we can make a third measurement, V_r, of just the noise:

$$V_a = A + noise \qquad V_b = B + noise \qquad V_r = noise$$

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

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

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:

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

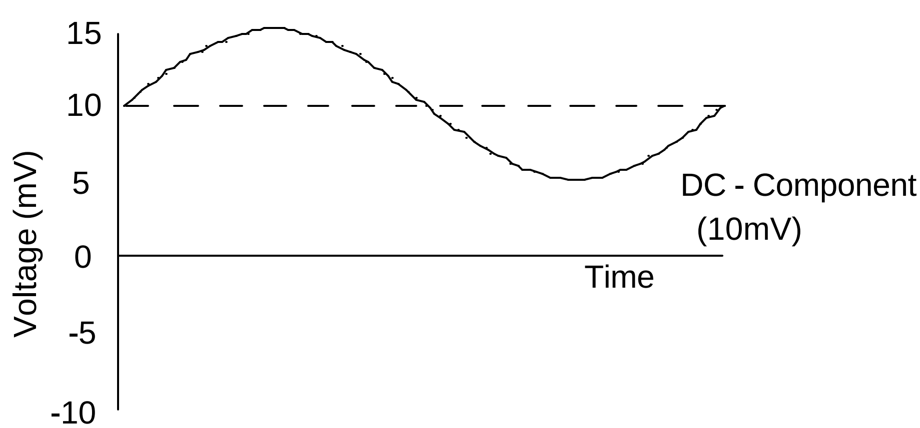
Note if all inputs are equal, $V_a = V_b = V_r$, then A = B = 0, and we expect zero output.
Since the noise is much larger than the desired signals A and B, the arrangement which subtracts the reference voltage produces much less contamination of the output signal. The biological signals would be completely 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 the equations above, the output for these conditions should be

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

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 cycle per second. AC coupling also 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.) The AC coupler 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 switch under the input connector.

Before AC coupling



After AC coupling: (DC component eliminated)

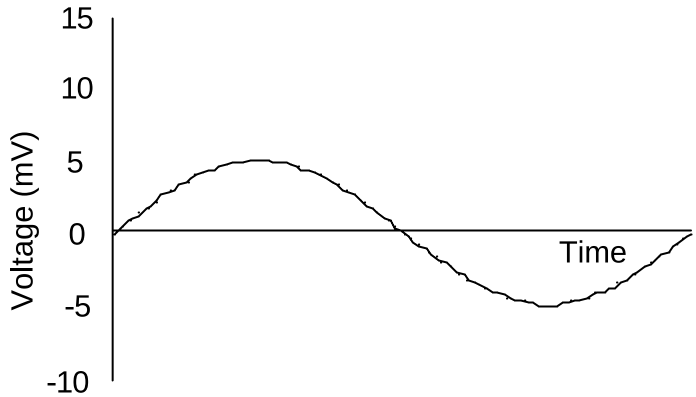


Figure 2

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. The output is the amplified cardiac signals alone.

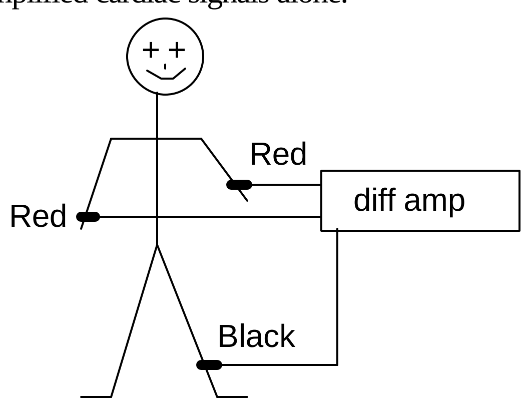


Figure 3

APPARATUS:

The apparatus that we will use today are a differential amp, a signal generator, and an oscilloscope, shown schematically in figure 4.

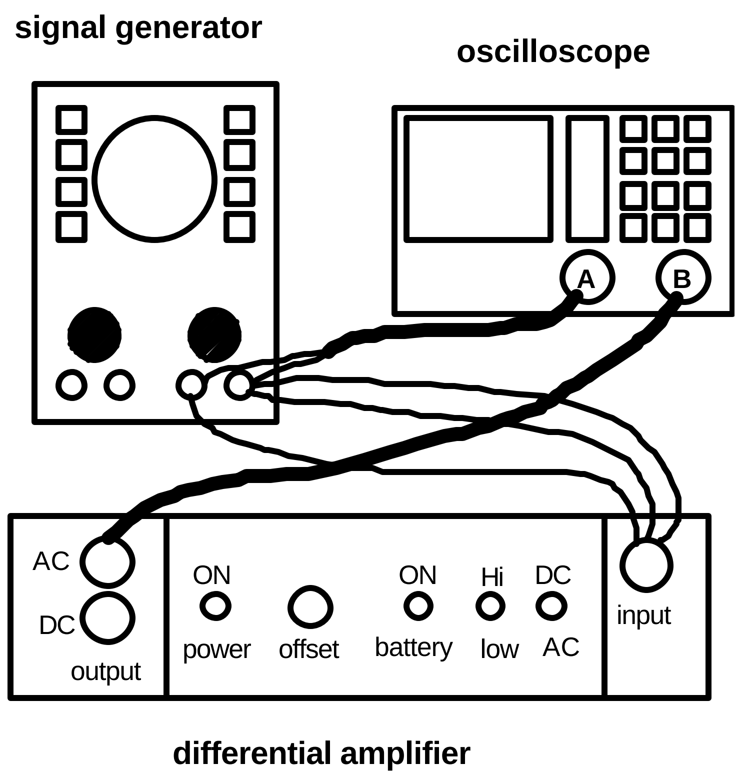


Figure 4

The differential amp is contained in a transparent plastic box. On the right side of the box, there is a connector with three wires with alligator clips attached. Two of them are "red" and the other one is "black". The two red leads are the INPUT to the differential amp. The black lead is the ground or reference for the signals sent into the two red leads. On the left side of box, there are two BNC connectors for the OUTPUT of the amp. They are labeled "AC" and "DC", for AC and DC coupling, respectively. On the front, from the left, there are a power switch, the OFFSET adjusting knob, the battery switch, the High/Low gain selection switch, and the DC/AC coupling selection switch.

Reference material: review section of introduction on Making Graphs.

Partners ______________________ Name ______________________

______________________ Section ______________________

PROCEDURE:

Preparations:
Please ensure that the amplifier and its power supply (or battery if used) are turned ON.

1. Fine-adjust the DC OFFSET knob of the amplifier.
   a) Set the amplifier coupling switch to DC
   b) Connect the DC output to channel B of the oscilloscope.
   c) Set the oscilloscope to DC coupling (LCD panel should show DC for channel B).
   d) Turn the signal generator off. You should see a horizontal trace on the scope.
   e) Press the GND (ground) button on the scope to give a 0 volt input, and adjust the Y position knob (channel B) on the scope so that the line is in the middle of the screen. This is where the oscilloscope itself thinks 0 volts is.
   f) Now press the GND button again to look at the amplifier output when it has no input. This is where the amplifier thinks that 0 volts is. Adjust the OFFSET knob so that the line is also in the middle of the screen. If you can't see the trace, the OFFSET knob is badly out of adjustment. Switch to the coarse-voltage sensitivity scale of 10 V/cm, center the trace with the amplifier. Continue to center with finer and finer sensitivity scales.
   g) Turn the signal generator back on.

2. a) Turn the amplifier OFFSET knob *just a little*. Is the vertical position of the trace on the scope (channel B) affected by turning the OFFSET knob?

3. Put everything back to AC coupling.
   Make the following settings and connections
   a) Set the amplifier coupling switch to AC.
   b) Set amplifier to LOW gain.
   c) Connect signal generator output to channel A of the oscilloscope.
   d) Connect differential amp input (alligator clips) to signal generator output. One red lead goes to OUTPUT (red connector) of the signal generator, the other red lead and the black lead to GROUND (black connector) of the signal generator.
   e) Connect the AC output to channel B of the oscilloscope.
   f) Set oscilloscope to AC coupling (LCD panel should show AC for channel B).
      Now, the scope is set up to view the input signal on channel A and the output signal on channel B. The amplifier is set up for AC coupling.

4. With the amplifier set up for AC coupling, turning the OFFSET knob should not affect the vertical position of the output trace (channel B) on the scope except momentarily. (Only turn the knob a little, otherwise you will need to repeat step 1.)

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 lead (red) to OUTPUT of the signal generator, and the other input lead (also red) and the black reference lead to the GROUND of the signal generator. That gives one input voltage (say B) = 0, and we measure k_A; swapping the location of the red leads gives k_R .

1. Set signal generator frequency at 200 Hz.
2. Set the peak-to-peak voltage of the input signal to 5 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 remeasure (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 oscilliscope 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 the table below (side 1).
4. Repeat steps 2 and 3 for other input voltages shown in the table below.
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 (side 2).

INPUT (mV)	OUTPUT (side 1) (mV)	OUTPUT (side 2) (mV)
5.		
10.		
15.		
20.		
25.		
30.		

Questions:

1. Do the data points on the graph form approximately a straight line? If yes, what does the slope of the line represent?

2. What units does the slope have?

3. Find the gain of each side from the slopes.
   Gain (side 1) = ____________________
   Gain (side 2) = ____________________

4. When one of the red leads is connected to the GROUND on the signal generator, what is the signal that is going into that side of the amplifier?

5. Are there any units associated with the gain of the amplifier? Why?

Part II. Gain as a function of frequency (at a constant INPUT=10 mV)

1. Set the input to 10 mV peak to peak.
2. Measure the output of the differential amp for each frequency shown in the table below.
3. Calculate the gain of the differential amp for each frequency. Adjust the input if necessary to return it to 10mV.
4. Plot gain (vertical axis) vs. frequency (horizontal axis) on a semi-logarithmic graph.

FREQUENCY (Hz)	OUTPUT (mV)	GAIN
20		
50		
100		
200		
400		
600		
700		
800		
900		
1000		
1300		
1600		
2000		
5000		
10000		

<u>Questions:</u>

1. Is the gain you measured at 200 Hz consistent with your measurement in part 1?

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

3. 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, you would need a frequency range of roughly .1f to 100f, where f = the basic heart frequency. See page 4.)

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 by using the voltage cursors (channel A).
   INPUT = ________________ volts

2. Measure the peak-to-peak voltage of the output by using the voltage cursors (channel B).
   OUTPUT = _______________ mV = _________________volts

3. Calculate the common-mode gain.
   Common-mode gain = g = OUTPUT/INPUT = __________________

4. Calculate the % common-mode rejection ratio (CMRR).

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

   = _________________ %

   (Use the gain of either side that you determined from Part I).

Questions:

1. When both input leads (red) are connected to the output of the signal generator, what should be the output of the differential amplifier ideally?

2. Ideally, what should be the % CMRR for the differential amplifier?

3. Compare your value for the %CMRR with the ideal value. Are they close?