BME 3512 Bioelectronics
Laboratory Five - Operational Amplifiers

Learning Objectives:

Be familiar with the operation of a basic op-amp circuit.
Be familiar with the characteristics of both ideal and real op-amps.
Be able to calculate the gain for both inverting and non-inverting inputs.

Laboratory Equipment:

Agilent Oscilloscope Model 54622A
Agilent Function Generator Model HP33120A
Agilent Power Supply Model E3631A
Multimeter

Supplies and Components:

Breadboard
1 KΩ Resistor
2 KΩ Resistor
3 KΩ Resistor
10 KΩ Resistor
Diode 1N4001
Op-Amp 741 or 1458

Pre-Lab Questions

1. What is meant by the term op-amp?
2. List at least practical applications for op-amps.
3. Sketch an inverting amplifier circuit using only an op-amp and two resistors.
   Calculate Vout in terms of Vin and R1 & R2.
4. Sketch a non-inverting amplifier circuit using only an op-amp and two resistors.
   Calculate Vout in terms of Vin and R1 & R2.

Post-Lab Questions

1. What are the differences between a 741 and a 1458.
2. What are the characteristics of an ideal op-amp?
3. Compare the characteristics of a real op-amp to those of an ideal op-amp.
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Background

The standard symbol for an op-amp is shown in the figure below.

![Op-Amp Symbol](image)

**Figure 1a. Standard Op-Amp Symbol**

**Figure 1b. Op-Amp symbol including bipolar power supply**

Bipolar Supply - The Op-Amp has a single output terminal plus two input terminals, one of which is inverted (-) and one is not inverted (+). The reference terminal for each active terminal mentioned above is the ground (0 V). The two power terminals labeled ±V in Figure 1b highlight the fact that the op-amp is an active device requiring an independent power source in addition to the two inputs. Notice that the op-amp requires two DC supply voltages, one at +V and one at -V. This use of bipolar supply voltages is to allow the amplified output voltage to swing in both positive and negative directions (as would be required in the amplification of AC signals.)

Pin Connections - In this lab you will use an 8-pin 741 op-amp as shown below.

![Pin Connections](image)

**Figure 2. Pin connections of op-amp 741**

Notice that the two inputs are connected to pins 2 and 3. Pin 2 is the inverted input and pin 3 is the non-inverting input. The output is at pin 6. The bipolar power leads are connected to pins 4 and 7 as indicated. Pins 1 and 5 can be used to offset any null voltage which can arise due to variations between the transistors contained within the op-amp chip. Pin 8 is not connected (NC) to the op-amp electrically, but can be used as a heat sink.
**The Ideal Op-Amp** - When analyzing op-amp circuits, one usually begins by treating it as an ideal op-amp.

1. The ideal op-amp has infinite input impedance (open) and so does not draw any power or current from the driving source.
2. The ideal op-amp has zero output impedance.
3. The ideal op-amp has infinite voltage gain.
4. The ideal op-amp has infinite bandwidth.

In the real world, op-amps have limitations. The practical op-amp has high (but not infinite) input impedance, low output impedance, high voltage gain and wide bandwidth. The output voltage can never exceed the bipolar supply voltage ±V. The maximum positive and negative output voltages are called the saturation limits and tend to be very near ±V. A simplified graph of output voltage against differential input voltage is shown below. The straight portion between the saturation limits is called the linear region and its slope gives the gain of the amplifier.

![Graph showing linear and saturation regions of the input-output relation of an op-amp](image_url)

Figure 3. Linear and saturation regions of the input-output relation of an op-amp
Laboratory Procedures

1) Lab Experiment with Inverting Amplifier

a) Step 1. Build the circuit shown above. The +10V and -10V power supply will be obtained from DC Power Supply. The terminal 'COM' should be connected to the ground of your circuit.

V_{out} from pin 6 should be connected to CH1 input of the oscilloscope. The input signal V_{in} is a sine waveform generated by Function Generator. The frequency of the signal is 1000 Hz, and the peak-to-peak (p-p) amplitude is initially 0.2 V. In addition to connecting V_{in} to R_{1} of the circuit, you should also connect V_{in} to Channel 2 input of the oscilloscope so that the input and output of the circuit can be displayed simultaneously on the screen. Use the upper half of the screen to display V_{out} and use the lower half of the screen to display V_{in}.

b) Step 2. Observe the two sine waveforms displayed on the screen. Notice, there is a 180-degree phase difference between the two waveforms. Measure the p-p amplitudes of both input and output by the oscilloscope. If the amplitude of the input waveform is significantly different from 0.2 V, adjust the Function Generator to make the p-p amplitude of V_{in} as close to 0.2 V as possible.

c) Step 3. Save the input and output signals.

Determine the gain of the circuit based on:

\[
G \text{ (measured)} = \frac{V_{out}}{V_{in}}
\]

Compare this gain with the gain determined by the theoretical equation:

\[
G \text{ (predicted)} = -\frac{R_{2}}{R_{1}}
\]

(the negative sign is due to the 180° phase difference between V_{out} and V_{in})

d) Step 4. Change R_{2} to 20 K, and repeat Step 3.

e) Step 5. Increase the p-p amplitude of V_{in} until the clipping (due to saturation) of V_{out} occurs. Save the waveforms of both V_{in} and V_{out}. Indicate the voltage of V_{out} where clipping occurs.
2) Lab Experiment with the Non-Inverting Amplifier

a) Step 1. Build the circuit shown below.

The input signal $V_{in}$ is the same as used in Part A. Again, use Channel 1 of the oscilloscope to display $V_{out}$ and Channel 2 to display $V_{in}$. Notice, now the two signals are in-phase.

b) Step 2. Record on your lab notebook the values of the input and output signals.

Determine the gain of the circuit based on:

$$G \text{ (measured)} = \frac{V_{out}}{V_{in}}$$

Compare this gain with the gain determined by the theoretical equation:

$$G \text{ (predicted)} = 1 + \frac{R_2}{R_1}$$

c) Step 3. Change the value $R_2$ to 20 K and repeat Step 2.

d) Step 4. Increase the p-p amplitude of $V_{in}$ until the clipping (due to saturation) of $V_{out}$ occurs. Sketch the waveforms (with correct vertical scale) of $V_{in}$ and $V_{out}$ on your lab notebook. Indicate the voltage of $V_{out}$ where clipping occurs.
3) Use Op-Amp to build a full-wave rectifier

Due to the 0.7V forward-biased voltage of the diode, a simple rectifier built on silicon diodes is not suitable for low-level signals. To rectify low-level signals, such as EMG signal, the following circuit can be used.

The principle of the above circuit is first explained. When $V_{in}$ is in the negative half cycle ($V_{in} < 0$), $V_0 > 0$ and D is conducting. As a result, the circuit acts as an inverting amplifier with a gain of $-0.5 (-R_2/R_1)$. Therefore, $V_{out} = -0.5 V_{in}$. When $V_{in}$ is in the positive half cycle ($V_{in} > 0$), $V_0 < 0$ and D is disconnected. As a result, the op-amp acts as disconnected and $V_{out} = V_{in} R_3/(R_1+R_2+R_3) = 0.5 V_{in}$ (or, the gain is +0.5).

a) Step 1. Build the circuit shown above using an op-amp 741 and a diode 1N4001. The values of $R_1$, $R_2$ and $R_3$ should be as close as possible to the values shown in the figure.

b) Step 2. $V_{out}$ should be connected to CH1 input of the oscilloscope. The input signal $V_{in}$ is a sine waveform generated by Function Generator. The frequency of the signal is 1000 Hz and the peak-to-peak (p-p) amplitude is initially 1 V. Again, $V_{in}$ is also to Channel 2 input of the oscilloscope so that the input and output of the circuit can be displayed simultaneously on the screen. Use the upper half of the screen to display $V_{out}$ and use the lower half of the screen to display $V_{in}$.

c) Step 3. Observe the waveforms on the screen. Sketch the waveforms (with the correct vertical scale) of both $V_{in}$ and $V_{out}$ on your lab notebook. Determine the actual gain of the circuit for both positive half cycle and negative half cycle of $V_{in}$. 
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I) Circuit Diagrams (Circuit Maker Only)

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II) Data and Results

1) Experiment 1- Inverting Amplifier

| Points | a. Graph of $V_{IN}$ and $V_{OUT}$ ($R_2 = 10 \, k\Omega$) | __ / 4 |
|        | b. Measured Values of $|V_{IN}|$ and $|V_{OUT}|$ | __ / 2 |
|        | c. Equation and Calculation for Actual Gain, $G$ (Based on $|V_{IN}|$ and $|V_{OUT}|$) | __ / 2 |
|        | d. Equation and Calculation of Predicted Gain, $G$ (Based on $R_1$ and $R_2$) | __ / 2 |
|        | e. Graph of $V_{IN}$ and $V_{OUT}$ ($R_2 = 20 \, k\Omega$) | __ / 4 |
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|        | h. Equation and Calculation of Predicted Gain, $G$ (Based on $R_1$ and $R_2$) | __ / 2 |
|        | i. Measured Value of $|V_{IN}|$ and $|V_{OUT}|$ when $V_{OUT}$ Clips | __ / 2 |
|        | j. Graph of $V_{IN}$ and $V_{OUT}$ When $V_{OUT}$ Clips | __ / 4 |

2) Experiment 2- Non-Inverting (Follower) Amplifier

| Points | a. Graph of $V_{IN}$ and $V_{OUT}$ ($R_2 = 10 \, k\Omega$) | __ / 4 |
|        | b. Measured Values of $|V_{IN}|$ and $|V_{OUT}|$ | __ / 2 |
|        | c. Equation and Calculation for Actual Gain, $G$ (Based on $|V_{IN}|$ and $|V_{OUT}|$) | __ / 2 |
|        | d. Equation and Calculation of Predicted Gain, $G$ (Based on $R_1$ and $R_2$) | __ / 2 |
|        | e. Graph of $V_{IN}$ and $V_{OUT}$ ($R_2 = 20 \, k\Omega$) | __ / 4 |
|        | f. Measured Values of $|V_{IN}|$ and $|V_{OUT}|$ | __ / 2 |
|        | g. Equation and Calculation for Actual Gain, $G$ (Based on $|V_{IN}|$ and $|V_{OUT}|$) | __ / 2 |
|        | h. Equation and Calculation of Predicted Gain, $G$ (Based on $R_1$ and $R_2$) | __ / 2 |
|        | i. Measured Value of $|V_{IN}|$ and $|V_{OUT}|$ when $V_{OUT}$ Clips | __ / 2 |
|        | j. Graph of $V_{IN}$ and $V_{OUT}$ When $V_{OUT}$ Clips | __ / 2 |

2) Experiment 3 – Full-Wave Rectifier

| Points | a. Graph of $V_{IN}$ and $V_{OUT}$ | __ / 4 |
|        | b. Gain for Positive Half-Cycle of $V_{IN}$: |
|        | i. Equation/Calculation for Predicted Gain Based on Resistors | __ / 3 |
|        | ii. Equation/Calculation of Measured Gain Based on $|V_{IN}|$ and $|V_{OUT}|$ | __ / 3 |
|        | c. Gain for Negative Half-Cycle of $V_{IN}$: |
|        | i. Equation/Calculation for Predicted Gain Based on Resistors | __ / 3 |
|        | ii. Equation/Calculation of Measured Gain Based on $|V_{IN}|$ and $|V_{OUT}|$ | __ / 3 |
### III) Discussion

1) **Experiment 1- Inverting Amplifiers**
   
   a. **Estimate** the phase shift between the input and output waveforms.
   
   b. What does the negative sign (-) in the equation for predicted gain indicate? Explain why this op-amp configuration is referred to as an “inverting” amplifier.

2) **Experiment 2 – Non-Inverting (Follower) Amplifier**
   
   a. **Estimate** the phase shift between the input and output waveforms.
   
   b. Explain why this op-amp configuration is referred to as a “non-inverting” amplifier (also known as a “follower” amplifier).

3) **Experiment 1 and 2 – Limitation on Amplifier Output Voltage**
   
   a. What limits the output voltage that can be produced by the amplifier?
   
   b. If you needed a larger output voltage than your amplifier is capable of producing, what could you change in the amplifier circuit?

### IV) Post-Lab Questions

   **Post Lab Question #3**

### V) References