

School of Engineering

Department of Electrical and Computer Engineering

**14:332:223 Principles of Electrical Engineering I Laboratory – Fall 2024**

**Lab Experiment #3**

**Laboratory objectives:**

1. Learn how operational amplifiers work
2. Design negative feedback loop with operational amplifiers
3. Use LTSpice to simulate the behavior of circuits

**PART A: Tutorials**

Please check relevant tutorial in lab 1 manual.

**PART B: Circuit Theory**

B.1 Operational Amplifiers (Op Amp)

**B.1.1 Op Amp Terminal Characteristics**

A 741 Op Amp is shown in Figure 1. Op amps have two input terminals (input port): one terminal is called inverting or negative terminal and the node voltage there is usually denoted as and the other terminal is called a non-inverting with a node voltage of . The input voltage is defined as the voltage across these terminals, such that:

The output is taken between (often called ) and ground. Additional terminals, such as or and or , are used for bias, offset, etc.

The realistic model of an operational amplifier is given in the course textbook and repeated below with equivalent notation. It involves separate input and output circuits. The input consists of an input resistance between the inverting and non-inverting terminal. The output consists of a voltage dependent voltage source (with voltage ) in series with an output resistance . Note that the only connection between the input and output is through the proportionality relation of the dependent source.



Figure 1: A 741 Operational Amplifier

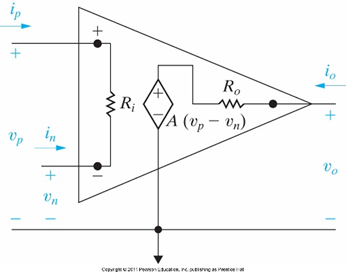


Figure 2: Op Amp modeling circuit

The parameters involved are as follows:

1. **Input Voltage** : Op amps could be considered differential amplifiers because they amplify this input voltage, which is the difference between the voltages at the input terminals .

2. **Output Voltage** : The output voltage of an Op Amp is proportional to the input voltage, provided it remains less in absolute value than the DC bias voltages or and or .

3. **Input Resistance** : The input resistance connected \ between the inverting and non-inverting terminals. represents the voltage drop across . The value of the input resistance can be found by dividing the input voltage by the current entering the non-inverting input terminal or exiting the inverting terminal .

4. **Open Loop Voltage Gain** : The open loop voltage gain is the proportionality constant in the dependent source equation where . Note that in general is not equal to the output whenever a load resistance is connected.

5. **Output Resistance** : The output resistance is a resistor in series with the dependent source that connects to the output node. In the presence of a non-zero output resistance , the output voltage across a load is not equal to and can be found by analyzing the voltage divider between and .

**B.1.2 Linear Operation and Saturation**

Op Amps have two regions of operation: linear and saturation. In the linear region, the voltage transfer characteristic, i.e. the mathematical relationship between the input and output voltages, is linear. This holds true when the output voltage lies in the range . From the definition of voltage gain given above, , one can see that this range corresponds to input voltages in the range of

. In this range the output voltage is directly proportional to the input voltage, with the proportionality factor being .

For input voltages outside this range, the Op Amp is said to be saturated, and its output is bounded by the DC bias voltages. In other words, the output voltage is clipped to when and to when .

**B.1.3 Characteristics of an Ideal Op Amp**

1. : According to the definition of input resistance given above, an infinite input resistance means that no current flows into or out of the input terminals. This greatly simplifies the analysis of Op Amp circuits.

2. : In this case the entire dependent source voltage appears across the load resistance or as the input of another device.

3. : it follows from the definition of voltage gain, that if than

So if is infinite than . This, however, assumes that there is some way for the input to be affected by the output. This will happen **only** *if there is a connection, namely a negative feedback mechanism, between the output and the inverting terminal (closed loop operation).* If such a connection does not exist, then the output will be saturated (open loop operation). For closed loop operation, it is said that a virtual short exists between the positive and negative input terminals (short because there is no voltage drop but virtual because unlike real shorts there is no current flowing; remember that : means that the input current is zero).

Thus, if an Op Amp is operating in its linear region (unsaturated) then or . This simplifies circuit calculations at the input terminals, because and can be represented by a single variable. When one of the two terminals is grounded, then the voltage at both the terminals is zero and the other terminal is called a virtual ground.

**B.1.4 Building Amplifier Circuits Using Op Amps**

There are two standard closed-loop connections for an Op Amp. Both have in common the feedback connection through a resistance between the output terminal to the inverting input terminal. This connection provides the negative feedback and ensures the virtual short. The analysis is simple for ideal Op Amps since:

1. the two input terminals are at the same voltage

and

(b) there is no current into the input terminals

The analysis usually derives a gain or amplification. Such analysis can be found in the course textbook and will be discussed in class. It is important to note that this is the gain of the whole stage (or the closed loop gain) and should not be confused with the gain of the Op Amp alone. In here, we will use for the open loop gain, and for the gain of the whole stage.

**Note:** negative feedback does not guarantee that the amplifier will not saturate. If the input is such that the output, based on the amplification of the whole stage, is expected to be larger than the bias voltage in absolute value, or , then the output will be clipped to or .

**B.1.5 The Inverting Amplifier**

Circuit analysis of the inverting amplifier in Figure 3 yields the equation,

( eq. 1)

Thus, the theoretical gain of the whole stage is given by

(eq. 2)

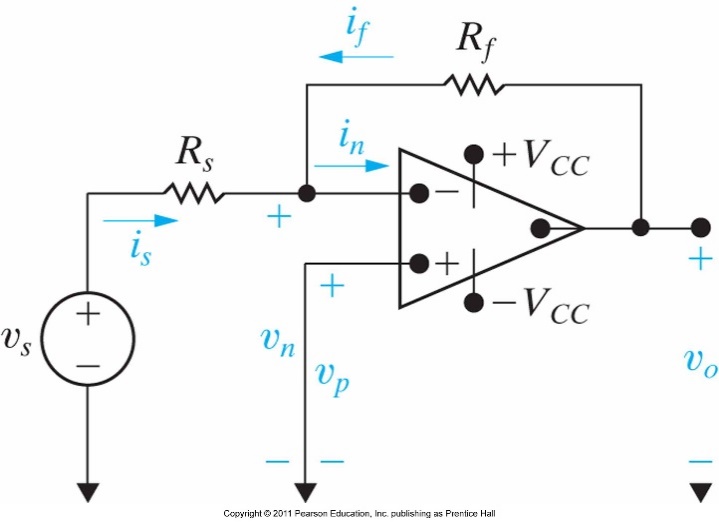


Figure 3: Inverting Op Amp

**B.1.6 The Non-Inverting Amplifier**

Circuit analysis of the non-inverting amplifier shown in Figure 4 yields the equation,

( eq. 3)

Thus, the theoretical gain of the whole stage is given by

(eq. 4)

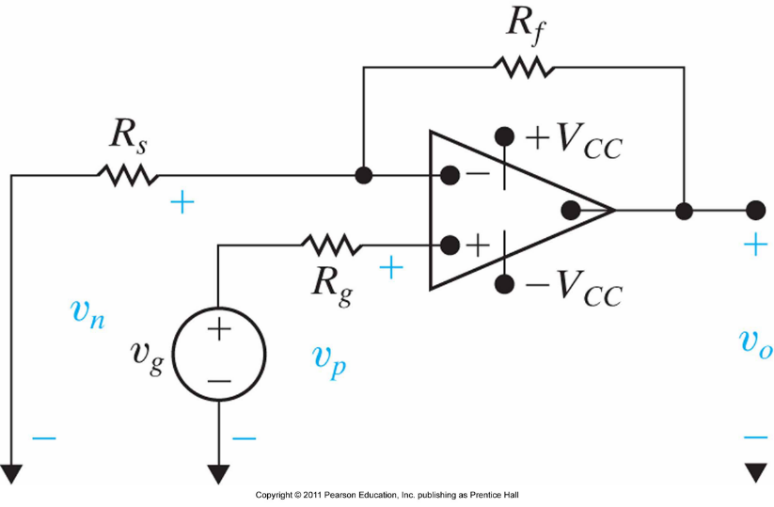


Figure 4: Non-Inverting Op Amp

**B.1.7 The Inverting Summing Amplifier**

Circuit analysis of the inverting summing amplifier shown in Figure 5 yields the equation,

( eq. 5)

A summing amplifier circuit shows an op amp with a resistor and three input voltages.
The op amp has a positive supply voltage, V sub CC and a negative supply voltage, minus V sub CC. A resistor R sub f is connected between the output terminal and inverting input terminal, and carries a current, i sub n into the output terminal. The non-inverting input terminal is short circuited with the common node, and shows a voltage, v sub n. The voltage across the output terminal and common node is marked as v sub o.
Three input voltages--v sub a, v sub b, and v sub c are connected along with series resistors--R sub a, R sub b, and R sub c, respectively between the inverting input terminal and the common node.

Figure 5: Inverting Summing Op Amp

PART C: Pre-Lab

## C.1 What is the gain of an entire amplifier circuit in closed, negative, loop and how is it different from the open loop gain of Op Amp?

## The closed loop gain is the negative ratio of the feedback resistor and the source resistor. The open loop gain of an ideal Op Amp would be infinite, but in real life it is just a very high value.

## C.2 For the circuit of Figure 3:

## a. Calculate the gain for the inverting amplifier if . Assume that the Op Amp is ideal.

## K = -2

## b. Calculate the theoretical linear operating range of the input voltage for the circuit (before the output reaches saturation): for which values of will the output stays within the linear range.

## -7.5 <= Vs <= 7.5

## 

## C.3 For the circuit of Figure 4:

## a. Calculate the gain for the non-inverting amplifier if . Assume that the Op Amp is ideal.

## K = 3

## b. Calculate the theoretical linear operating range of the input voltage for the circuit (before the output reaches saturation): for which values of will the output stays within the linear range.

## -5 <= Vs <= 5

## C.4 Derive Equation 5 for the voltage output of a Inverting Summing Amplifier with three

## inputs Va, Vb, and Vc.

## Vo = -Rf(Va/Ra + Vb/Rb + Vc/Rc)

## PART D: In Lab Experiments

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**Lab Experiment #3**

## Date of lab experiment: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

## Lab section: \_\_\_\_\_\_\_\_\_\_ GROUP (A/B): \_\_\_\_\_\_

## Team members: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

## 

**Laboratory instruments:**

* Power supply: Keithley 2231-30-3
* Digital Multimeter (DMM): Keysight (Agilent) 34461A
* Breadboard/Arduino set
* 1 k or higher resistors by design
* Op-amps (741)
* Variable 10k resistor

## Experiment # 3.1: Inverting Amplifier

## Design:

## Use the following circuit for this experiment:

## Figure 6: Circuit for experiment 3.1

## Note: this circuit is identical to the inverting amplifier circuit shown in Figure 3, except for the voltage divider at the inverting input terminal whose purpose is to decrease the input voltage and keep the Op Amp from saturating. The connections to the DC power supplies and the pins are labeled along with their pin numbers.

## Power supply to the *V*+ =15V, and *V*- =15V should be connected as follows:

## A close up of a map Description generated with high confidence

## Choose the resistors values to design a gain of a maximum gain of 2.5 (not accounting for the variable resistor *R*var, i.e. assuming that *R*var=0 position):

## *R*=\_\_\_\_\_\_\_\_\_\_\_

## *Rf*=\_\_\_\_\_\_\_\_\_\_\_

***R*var=** Variable 10k resistor

## If *R*var=0 , Calculate the proportionality constants:

## =\_\_\_\_\_\_\_\_\_\_\_

## Given that *VS*=5V, *V*+ =15V, and *V*- =15V, If *R*var=0 , calculate the output voltage:

## *V*out =\_\_\_\_\_\_\_\_\_\_\_

## Wiring: wire the network in Figure 6 you designed on the breadboard. Make sure the voltage sources initial value is set to 0V.

TA Verification: \_\_\_\_\_\_\_\_\_\_\_\_\_

## Measurements:

**Important:** ***Do not connect your board to the source BEFORE the instructor has approved your connections!***

* Set the power supply to 5V for the source . Measure and record in Table 1. Change in in steps of 0.25V by changing between 0  to 10 k and record these values in Table 1

**Table 1: Set values and measured values** vout

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Vi (measured) | Vout (measured) | Rvar (measured) | K.Vi (calculated) | %error |
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* For an input voltage of your choice that keeps the Op Amp in the linear region, place an ammeter in series with . Record the value of the current I.

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* Disconnect the ammeter. Keep the input voltage the same as before. Attach a load resistance between the output terminal of the Op Amp and ground. In so doing one can study the output resistance characteristics of the Op Amp.

1. Place a 20 k resistor between the output terminal of the Op Amp and ground and set the supply voltage to 5V.
2. Measure the output voltage and compare with the results obtained for the same input voltage in the previous step.

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* This item involves the study of the relationship between the load resistance and output voltage (and thus voltage gain): Keeping the source voltage at 5V, measure (the current through the load resistance ) for three values of in the range of 4 k to 20 k. Record the resistor values and measured currents in Table 2.

**Table 2**: Data collected for load resistor

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## Experiment # 3.2: Non-Inverting Amplifier

## Design:

## Use the following circuit for this experiment:

## Figure 7: Circuit for experiment 3.2

## Note: this circuit is identical to the non-inverting amplifier circuit shown in Figure 4, except for the voltage divider at the non-inverting input terminal whose purpose is to decrease the input voltage and keep the Op Amp from saturating. The connections to the DC power supplies and the pins are labeled along with their pin numbers.

## Choose the resistors values to design a maximal gain of 2.5 (not accounting for the variable resistor *R*var, i.e. assuming that *R*var=0 position):

## *R*=\_\_\_\_\_\_\_\_\_\_\_

## *Rf*=\_\_\_\_\_\_\_\_\_\_\_

***R*var=** Variable 10k resistor

## If *R*var=0 , Calculate the proportionality constants:

## =\_\_\_\_\_\_\_\_\_\_\_

## Given that *VS*=5V, *V*+ =15V, and *V*- =15V, If *R*var=0 , calculate the output voltage:

## *V*out =\_\_\_\_\_\_\_\_\_\_\_

## Wiring: wire the network in Figure 7 you designed on the breadboard. Make sure the voltage sources initial value is set to 0V.

TA Verification: \_\_\_\_\_\_\_\_\_\_\_\_\_

## Measurements:

**Important:** ***Do not connect your board to the source BEFORE the instructor has approved your connections!***

* Set the power supply to 5V for the source . Measure and record in Table 3. Change in in steps of 0.25V by changing between 0  to 10 k and record these values in Table 3

**Table 3: Set values and measured values** vout

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Vi (measured) | Vout (measured) | Rvar (measured) | K.Vi (calculated) | %error |
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|  |  |  |  |  |
| Vi (measured) | Vout (measured) | Rvar (measured) | K.Vi (calculated) | %error |
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* For an input voltage of your choice that keeps the Op Amp in the linear region, place an ammeter in series with . Record the value of the current I.

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

* Disconnect the ammeter. Keep the input voltage the same as before. Attach a load resistance between the output terminal of the Op Amp and ground. In so doing one can study the output resistance characteristics of the Op Amp.

1. Place a 20 k resistor between the output terminal of the Op Amp and ground and set the supply voltage to 5V.
2. Measure the output voltage and compare with the results obtained for the same input voltage in the previous step.

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* This item involves the study of the relationship between the load resistance and output voltage (and thus voltage gain): Keeping the source voltage at 5V, measure (the current through the load resistance ) for three values of in the range of 4 k to 20 k. Record the resistor values and measured currents in Table 4.

**Table 4**: Data collected for load resistor

|  |  |
| --- | --- |
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## PART E: Post-Lab Report

The lab report should include a filled and signed copy of part D and analysis of the data based on the following questions and required simulation.

1. **Analysis for experiment 3.1** (*show all work for calculations and explain the experimental results versus calculated ones in each of the relevant sections*):
   1. For the resistor values chosen in the lab for experiment 3.1, calculate the theoretical value of the gain and compare it with the measured using the data collected in Table 1.
   2. Calculate the theoretical value of the current for the resistor . Compare with the experimental one.
   3. Calculate the theoretical values of the current for all three values of . Compare with the experimental ones you obtained.
   4. Simulate the inverter circuit in Figure 6 in LTSpice for the values chosen (, . Find the output voltage and the current flowing through the resistor .
2. **Analysis for experiment 3.2** (*show all work for calculations and explain the experimental results versus calculated ones in each of the relevant sections*):
   1. For the resistor values chosen in the lab for experiment 3.2, calculate the theoretical value of the gain and compare it with the measured using the data collected in Table 3.
   2. Calculate the theoretical value of the current for the resistor . Compare with the experimental one.
   3. Calculate the theoretical values of the current for all three values of . Compare with the experimental ones you obtained.
   4. Simulate the inverter circuit in Figure 7 in LTSpice for the values chosen (, . Find the output voltage and the current flowing through the resistor .
3. **Simulation:**

a. The circuit in Figure 8 has been designed to implement a certain relationship between

the input and output. Find the relationship between , , and , i.e. .



Figure 8: Circuit for LTSpice

## b. Simulate in TinkerCAD the circuit in Figure 7 and measure Vout with a Voltmeter. Please

## provide a URL for your circuit and attach the circuit schematic to your Post Lab report.