EE052

PRINCIPLES OF EE1 LAB

Lab 4

Operational Amplifiers

Full name: ……………………………………………

Student number: …………………………………….

Class: ………………………………………………....

Date: ………………………………………………….

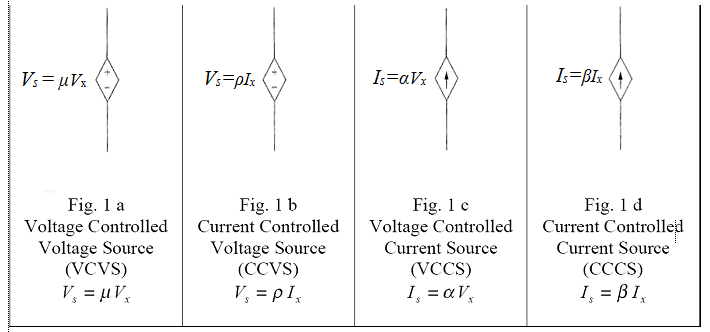
1. OBJECTIVES
2. To introduce operational amplifiers and dependent sources
3. To explore those circuit connections that allow operational amplifiers to operate in their linear region.
4. INTRODUCTION

Ideal operational amplifiers (Op-Amps) are two-ports that can produce an output voltage which is directly proportional to their input voltage (linear operation). Op-Amps can be operated in two ways: open loop and closed loop. The latter circuit connection is the only one that can force the Op-Amp to operate in its linear region. An *equivalent circuit model* can be used to model or simulate the ideal Op-Amp or to incorporate deviations from ideality. The standard *inverting* and *non-inverting configurations* are explored.

The lab experiments include the realization of both configurations and the experimental determination of the circuit parameters that demonstrate the function of the circuit and allow for Op-Amp parameter derivation.

1. Dependent Sources

Dependent sources are sources whose value varies as a function of a specified voltage or current elsewhere in the circuit. The relationship could be of any form, but in this course we will introduce only those sources whose value is proportional to a voltage or current elsewhere in the circuit. Since the output quantity can be voltage or current and so can the controlling quantity, there are four types of such dependent sources, whose names, characteristic equations, and symbols are shown in Fig. 1.



1. Operational Amplifiers
2. Op Amp Terminal Characteristics

A 741 Op-Amp is shown in Fig. 2 below. Op-Amps have two input terminals; the input voltage Vi to the Op-Amps is taken across these terminals. One terminal is called inverting or negative and the voltage there is usually denoted as Vn and the other as noninverting (Vp) so that *Vi=(Vp-Vn)*. The output is taken between Vo and ground. Additional terminals (such as +Vcc, or -Vcc) are used for bias, offset etc.



The realistic model of an operational amplifier is given in your text and repeated below with equivalent notation. It involves separate input and output circuits. The input consists of an input resistance Ri between the inverting and noninverting terminals. The output consists of a voltage dependent voltage source (with voltage AvVi) in series with an output resistance Ro. Note that the only connection between the input and output is through the proportionality relation of the dependent source.



The parameters involved are as follows:

1. Input Voltage Vi: *V(a,b)=Vi=(Vp-Vn).*
2. Output Voltage Vo: 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 Vcc and -Vcc.
3. Input Resistance Ri : The input resistance appears between the inverting and noninverting terminal (so that Vi appears across Ri) and can be found by dividing the input voltage Vi by the current entering the non-inverting input terminal Vp or exiting the inverting terminal Vn.
4. Open Loop Voltage Gain μ or Av: The open loop voltage gain is the proportionality constant in the dependent source equation where V = AvVi (or V=μV(a,b)).
5. Output Resistance Ro: The output resistance appears as a resistor in series with the dependent source. In the presence of a non-zero output resistance Ro, the output voltage across a load RL is not all of V = AvVi and can be found by analyzing the voltage divider between Ro and RL.
6. 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

-*Vcc ≤ V0 ≤ Vcc*

From the definition of voltage gain given above, i.e. *Vo = AvVi*, 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, by the factor Av.

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 clamped to -Vcc when Vi < -Vcc/Av and to Vcc when Vi > Vcc/Av.

1. Characteristics of an *Ideal* Op-Amp
2. Ri = ∞: 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.
3. Ro = 0: In this case the entire dependent source voltage appears across the load resistance or as the input of another device.
4. μ =AV = ∞: If the output voltage is to be finite it follows from the definition of voltage gain, that *Vi = Vo / Av* will go to zero if Av is infinite. This, however, assumes that there is some way for the input to be affected by the output. Indeed this will only happen if there is such a connection namely a *negative feedback mechanism* in the form of *a connection between the output and the inverting terminal* (closed loop operation). If such 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. This means that if an Op-Amp is operating in its linear region (if it is *unsaturated*) then Vi ≈ 0, or equivalently Vp ≈ Vn. This also simplifies the circuit calculations at the input terminals, because Vp and Vn can be represented by a single variable. When one of the two terminals is grounded, then the voltage at both terminals is zero and the other terminal is called a *virtual ground*.
5. Building Amplifier Circuits Using Op-Amps

There are two standard closed-loop connections for an Op-Amp. Both have in common the connection (Rf) from 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
  2. there is no current into the input terminals.

The analysis usually derives a gain or amplification. 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.

One last 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 (*Vo> +Vcc* or *Vo< -Vcc*) then the output *will* be clamped to *Vcc* (or *-Vcc*).

1. The Inverting Amplifier



Circuit analysis of the inverting amplifier in Fig. 4 yields the equation,

*V2 = K V1 = (-Rf / R)V1* (1)

Thus, the theoretical gain K of the whole stage (that is, the entire Op-Amp circuit of Fig 4.) is given by

*K = V2/V1= (-Rf / R).*

1. The Non-Inverting Amplifier

Circuit analysis of the non-inverting amplifier shown in Fig. 5 yields the equation,

*V2 = (1+Rf / R)V1* (2)

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

*K = V2/V1= (1 + Rf / R)*.



1. Simulating Op Amps in PSpice



Figure 6

Using a VCVS, one can construct a model of the Op-Amp for use in SPICE. The circuit of Fig. 2b can be used to model a *non-ideal1* Op-Amp using two resistors and a dependent voltage source.

The circuit of Fig. 6 can be used for simulating an *ideal* Op Amp and is derived from Fig. 2b by shorting out the output resistor Ro (which is equivalent to setting its value equal to zero) and by picking large values for the input resistor Ri and for the Op-Amp voltage gain μ (or A). Typical such values for approximating an ideal Op-Amp in PSpice are Ri=1010Ω and μ =106.

1. PRE-LABRATORY
2. Theory
3. Briefly explain why one can assume *Vp=Vn* for an ideal Op-Amp. What connection has to be present for this to occur?
4. What is the gain of an amplifier circuit? How is it different from the Op-Amp gain?
5. Experiment 1
6. Calculate the gain K for the non-inverting amplifier circuit in Fig. 8 (from section 5.1 below) assuming that the Op-Amp is ideal and using the resistance values specified in 5.1.1.
7. Calculate the theoretical range of the input voltage for linear operation of the circuit in Section 5.1.
8. Simulate the experimental procedure of Section 5.1 in PSpice by choosing 3 different points in the linear operating range, and calculating the circuit gain at each of these points.
9. The PSpice Op Amp model presented in Section 3.2.5 does not account for the effects of saturation, so this portion of the experiment cannot be simulated in PSpice. Describe how you would expect the circuit to behave outside its range of linear operation.
10. Experiment 2
11. Calculate the gain K for the inverting amplifier circuit of Fig. 9 (from Section 5.2 below) assuming that the Op-Amp is ideal. The answer should be in terms of R and Rf.
12. Given the results of question 4.7, calculate the values of R and Rf that produce a circuit gain of -4.545 and a voltage Vi=0.5V when Vs=5V.
13. Simulate the experimental procedure from Section 5.2 in PSpice by choosing 3 different points in the linear operating range, and calculating the circuit gain at each of these points.
14. EQUIPMENT AND PARTS LIST

* Electronic board with Power Supply
* Digital Multimeter
* 741 Operational Amplifier
* 10KΩ, 2.2KΩ, 15kΩ, 20kΩ, 4.7kΩ Resistors

1. PROCEDURES

Part 1. Non-Inverting Amplifier



Figure 7 Op Amp 741

You will be using the "741" Op-Amp which is biased at +15V and -15V. The chip layout is shown in Fig. 7. The standard procedure on such chip packages (DIP15) is to identify pin 1 as the one to the left of the notch in the chip package. The notch always separates pin 1 from the last pin on the chip. In the case of 741, the notch is between pins 1 and 8. Pins 2, 3, and 6 are the inverting input Vn , the non-inverting input Vp, and the amplifier output Vo respectively. These three pins are the only three terminals that usually appear in an Op-Amp circuit schematic diagram.





Figure 8

* + 1. Construct the circuit in Fig. 8 with R =2.2kΩ, Rvar=20kΩ and Rf =15kΩ.
    2. Use the fixed 5V power supply of the power source for Vs. Vary Rvar’s value so that you can change Vi. Take readings for the output voltage Vout for values of Vi from -3.5V to +3.5V in increments of 0.5V and record them in Table 1. Calculate KVi for each Vi using the calculated gain K found in prelab item 4.3 above. Calculate the % error for each row in the table.

K = 7.82

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| V nominal | Vi | Kvi | Vout | Error |
| -3.5 | -3.5157 | -15 | -14.241 | 5.33% |
| -3 | -3.064 | -15 | -14.241 | 5.33% |
| -2.5 | -2.5568 | -15 | -14.239 | 5.34% |
| -2 | -2.0529 | -15 | -11.996 | 25.04% |
| -1.5 | -1.5142 | -11.841 | -11.837 | 0.034% |
| -1 | -1.0069 | -7.874 | -7.946 | -0.91% |
| -0.5 | -0.5024 | -3.9288 | -3.973 | -1.11% |
| 0 | 0 | 0 | 0 | 0% |
| 0.5 | 0.5052 | 3.9507 | 3.9525 | -0.046% |
| 1 | 1.0081 | 7.8833 | 7.863 | 0.26% |
| 1.5 | 1.5085 | 11.7965 | 11.827 | -0.26% |
| 2 | 2.0034 | 15 | 13.509 | 11.04% |
| 2.5 | 2.5040 | 15 | 13.508 | 11.04% |
| 3 | 3.0062 | 15 | 13.508 | 11.04% |
| 3.5 | 3.5009 | 15 | 13.508 | 11.04% |

* + 1. For an input voltage of your choice that keeps the Op-Amp in the linear region, place an ammeter in series with Rf. Record the value of the current I.

Vi = \_\_\_\_1.5017\_\_\_\_\_\_\_\_ . I = \_\_\_\_\_\_0.6874\_\_\_\_\_\_\_\_ .

* + 1. Disconnect the ammeter. Keep the input voltage the same as in 5.1.3 above. Place a 10kΩ load resistor between the output terminal of the Op-Amp and ground. In so doing one can study the output resistance characteristics of the Op-Amp. Measure the output voltage Vout with the DVM, and compare with the results obtained for the same input voltage in item 5.1.2. Explain any discrepancies by assuming a non-zero Op-Amp output resistance. Later you will be asked to calculate the output resistance of the Op Amp based on these results.

Vi = \_\_\_\_\_\_1.5\_\_\_\_\_\_\_. Vout = \_\_\_\_\_\_\_11.732\_\_\_\_\_. K = \_\_\_\_\_\_7.8213\_\_\_\_\_.

* + 1. This item involves the study of the relationship between the load resistance and output voltage (and thus also voltage gain). Keeping the source voltage at 5V, measure IL (the current through the load resistance RL) for each value of RL in Table 2. Later, you will be asked to analyze this data.

|  |  |
| --- | --- |
| RL | IL |
| 10kΩ | 1.1774 mA |
| 15kΩ | 0.7924 mA |
| 20kΩ | 0.5914 mA |

Part 2: Inverting Amplifier



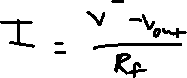
Figure 9

1. In prelab item 4.7 you should have calculated the values of Rf and R that yield a circuit gain of -4.545 and Vi=.5V when Vs=5V and Rvar=20kΩ. Get your TA to check your calculations and correct them if necessary, then build the circuit of Fig. 9 with the correct values of Rf and R.
2. Use the fixed 5V power supply of the power source for Vs. Vary Rvar’s value so that you can change Vi. Take 21 readings for the output voltage Vout at each value of Vi from -5V in increments of 0.5V and record them in Table 3. Calculate KVi for each Vi in Table 3 using the calculated gain K found in prelab item 4.7 above. Calculate the % error for each row in the table. If the measured Vout differs from KVi by more than 10% you probably have an error in the circuit. Troubleshoot the circuit until it is operating properly.

K = -6.82

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Vi | Vi | KVi | Vout | Error |
| -5 | - 5.067 | 15 | 13.480 | 11.28% |
| -4.5 | -4.517 | 15 | 13.486 | 11.23% |
| -4.0 | -4.007 | 15 | 13.490 | 11.19% |
| -3.5 | -3.5138 | 15 | 13.492 | 11.18% |
| -3.0 | -3.0469 | 15 | 13.493 | 11.17% |
| -2.5 | -2.5011 | 15 | 13.535 | 10.82?% |
| -2.0 | -2.0581 | 14.0362 | 13.538 | 3.68% |
| -1.5 | -1.5648 | 10.6719 | 10.737 | -0.61% |
| -1.0 | -1.0411 | 7.1003 | 7.139 | -0.54% |
| -0.5 | -0.5389 | 3.6753 | 3.6888 | -0.37% |
| 0 | 0 | 0 | 0 | 0% |
| 0.5 | 0.5345 | -3.6452 | -3.695 | -1.35% |
| 1 | 1.0027 | -6.8384 | -6.916 | -1.12% |
| 1.5 | 1.5122 | -10.3132 | -10.415 | -0.98% |
| 2 | 2.0111 | -13.7157 | -13.846 | -0.94% |
| 2.5 | 2.5078 | -15 | -14.224 | 5.46% |
| 3.0 | 3.0502 | -15 | -14.229 | 5.42% |
| 3.5 | 3.5035 | -15 | -14.218 | 5.5% |
| 4.0 | 4.035 | -15 | -14.215 | 5.52% |
| 4.5 | 4.560 | -15 | -14.213 | 5.54% |
| 5.0 | 5.123 | -15 | -14.213 | 5.54% |

1. REPORT
2. Derive the relationship between the current I and the resistor Rf in the non-inverter circuit of Fig. 8.



1. Compare the theoretical value of the gain K = Vout /Vi of both the inverting and the non-inverting circuits of Sections 5.1 and 5.2 that you calculated in the prelab exercises with the experimentally obtained values of gain.
2. Calculate the theoretical value of the current I for the resistor Rf in Section 5.1. Compare with the experimental one.
3. Calculate the theoretical values of the current IL for all three values of RL in Section 5.1.5. Compare with the experimental ones.
4. Plot the experimental values of IL vs. 1/RL in a graph with rectangular coordinates. From your graph, how does your output voltage depend on the load? How does the gain K= Vout /Vi depend on the load? Note that if Vout does not change with the load RL, and since IL = Vout (1/RL), then the slope is Vout and it should be constant and thus the graph of IL vs. 1/RL should be a straight line passing through the origin.
5. Draw two graphs of the experimentally obtained Vi vs. Vout, one for the inverting amplifier circuit and one for the non-inverting amplifier circuit (5.1 and 5.2). On each graph identify the transition between saturated and linear regions of operation for these amplifier circuits. Label the mode of operation for each of these regions. For the linear regions and for both circuits, discuss the possible sources of discrepancies between the experimentally obtained value of Vout and the calculated values of KVi.
6. Simulate the non-inverter circuit of Fig. 8 in PSpice for Rf = 10kΩ, Rvar=20 kΩ and R=2.2 kΩ. Find the output voltage Vout and the current I in Rf. Assume a μA741 Op Amp.
7. Simulate the non-inverter circuit of Fig. 8 in PSpice for Rf = 10kΩ with a load RL = 10kΩ applied between the output terminal of the Op-Amp and ground. Find the current in RL.
8. Simulate the inverter circuit in Fig. 9 in PSpice for Rf = 10kΩ, Rvar=20kΩ and R=2.2 kΩ. Find the output voltage Vout and the current in Rf.