COLLEGE OF ENGINEERING
SUNY POLYTECHNIC INSTITUTE

**ECE 260**
**Name:________________________________________________**

**Date:_________________________________________________**

# Laboratory 6 – Operational Amplifiers

**Purpose:** In this lab, you will design amplifiers based on the 741 integrated-circuit op-amp.

**Equipment Required**

- Breadboard and variable power supply
- FLUKE Hand-held Digital Multimeter (DMM)
- Various resistors
  - Two 1 kΩ resistors
  - 4.7 kΩ resistor

**Learning Objectives**

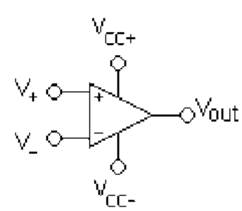
1. Discuss the purpose of an op-amp
2. Determine inverting and non-inverting circuit configurations
3. The effect of load resistances on an op-amp circuit

**Theory**

An operational amplifier (op-amp) is a device with two inputs and a single output. The output of the amplifier is given by $V_{out} = A\,(V_p - V_n)$, where A is the open-loop voltage gain (i.e. gain without feedback), $V_p$ is the non-inverting input voltage, and $V_n$ is the inverting input voltage. Typically, the open-loop voltage gain A is on the order of $10^3$ to $10^6$.

One important feature of op-amps is that a resistor can be placed between the output node and the inverting input to provide feedback and adjust amplification. While operating in its linear region ($-V_{cc} < V_{out} < +V_{cc}$), the op-amp adjusts its output current such that the voltage difference between the two inputs is nearly zero (i.e. $V_p = V_n$). When the output swings to $V_{out} = \pm V_{cc}$, however the op-amp is operating in its saturation region, and it cannot balance $V_p$ and $V_n$. Our general-purpose 741 op-amp requires two power supply voltages, ±15 V, for normal operation.

The 741 op-amp is a bipolar-junction-transistor-based amplifier, has an input resistance of about 2 MΩ. Because of this high input resistance, only a very small current (on the order of a μA) flows into either input of the op-amp and is essentially zero when we model it as an ideal op-amp (open-loop voltage gain A goes to infinity.




$I_p$ = current flowing into $V_+$ ($V_p$)
$I_n$ = current flowing into $V_-$ ($V_n$)
**Figure 1: An operational amplifier**

**Operational amplifier circuits**

Non-Inverting Amplifier

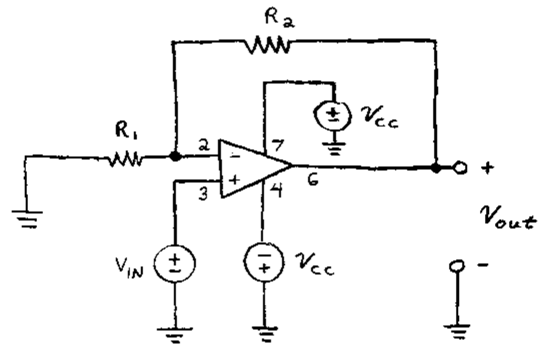



**Figure 2 – Non-inverting Amplifier**

The operational amplifier of Figure 2 is called a *non-inverting amplifier*. When a voltage is applied between the $V_p$ terminal (pin 3) and ground, the op- amp output $V_{out}$ (pin 6) will tend to become positive. This increase in voltage, which is measured relative to ground, is attenuated by the voltage divider formed by $R_1$ and $R_2$ and fed back to the op-amp's $V_n$ terminal (pin 2), where it also appears as a voltage with respect to ground. The positive voltage applied between $V_n$ and ground by $V_{out}$ counteracts the increase in $V_{out}$ by tending to force $V_{out}$ in the negative direction. The output voltage will thus reach an equilibrium in which the voltage of the $V_n$ terminal relative to ground rises to almost the same value as the voltage applied between the $V_p$ terminal and ground. In this state, with $V_n = V_p$, and with $V_n = V_{out} (R_1 + R_2) / R_1$ , the op-amp output becomes

$$V_{out} = V_{in} * (R_1 + R_2) / R_1$$

When $V_{out}$ reaches the value in this equation, the $V_n$ and $V_p$ terminals acquire nearly the same voltage. This condition is sometimes called a *virtual short circuit.*

Inverting Amplifier

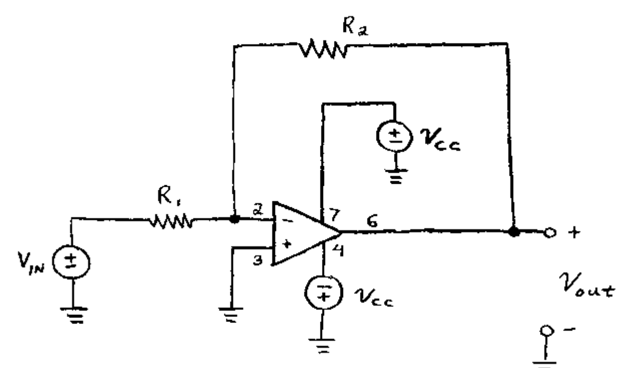



**Figure 3 – Inverting Amplifier**

The circuit of Figure 3 is called an *inverting amplifier*. The current flowing from $V_{in}$ into $R_1$ must also flow through $R_2$, because essentially zero current flows into the high resistance of the $V_n$ terminal (pin 2) of the op-amp. When a $V_{in}$ is applied, the output voltage of the op-amp adjusts itself until the voltage between $V_n$ and $V_p$ falls toward zero. With the $V_p$ terminal (pin 3) grounded, the $V_-$ terminal (pin 2) also remains at ground potential, causing all of $V_{in}$ to appear across $R_1$. The current flowing through $R_1$ determined by Ohm's Law, thus becomes $i_1 = V_{in}/R_1$. This same current must flow as $i_2$ through $R_2$. With $V_n$ at ground, the op-amp voltage becomes

$$V_{out} = - i_2R_2 = - V_{in} * (R_2/R_1)$$

The factor $-R_2/R_1$ multiplying $V_{in}$ is called the *gain* of the amplifier. This particular op- amp circuit has a negative gain. Positive increases in $V_{in}$ lead to negative increases in $V_{out}$; conversely, negative increases in $V_{in}$ lead to positive increases in $V_{out}$. The op-amp responds to any voltage difference between its $V_n$ and $V_p$ terminals by increasing the magnitude of $V_{out}$.

**Procedure**

1. **Non-inverting Amplifier with Given Resistors**
   - Obtain two resistors, $R_1 = 1$ kΩ and $R_2 = 1$ kΩ. Measure the values of these resistors and record their values in Table 1.
   - Build the circuit of Figure 2 with a 741 op-amp and these resistors. Refer to the datasheet in the appendix for the op-amp pin diagram. (Note that $V_{CC-}$ is $V_{EE}$ on the datasheet.)
   - Note: You'll need to place the op-amp across one of the gaps along a terminal strip such that you don't short any of the op-amp's pins together by placing them in the same row of 5 holes. Here is a checklist of the necessary connections for your circuit:
     - ⇒ $R_1$ to op-amp pin 2 and ground (one of the blue outer rails)
     - ⇒ op-amp pin 3 to variable power supply
     - ⇒ op-amp pin 4 to $-V_{cc}$ power supply (-15 or -12 V)
     - ⇒ op-amp pin 7 to $+V_{cc}$ power supply (+15 or +12 V)
     - ⇒ $R_2$ to op-amp pin 2 and op-amp pin 6
     - ⇒ ground bus to ground terminal of power supply
   - Calculate the gain of this op-amp circuit (with your measured resistor values) and record in Table 1.

**Table 1**

| Parameters | Calculated Values | Measured Values |
|---|---|---|
| $R_1$ | | |
| $R_2$ | | |
| Gain | | |

**What do you expect the value of $V_{out}$ for a given value of $V_{in}$?**

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- Set the variable power supply, $V_{in}$ = 1 V. Verify this value with the voltmeter (***always use verified values in your tables***).
- Measure $V_{out}$ (pin 6). Record this value. Calculate $V_{out}/V_{in}$ and record this value as well.
- Repeat for $V_{in}$ = 2V, 4V, 8V, and 16V

**Table 2**

| **$V_{in}$** | **Measured Values** | | |
|---|---|---|---|
| | **$V_{in}$** | **$V_{out}$** | **$V_{out}/V_{in}$** |
| **1** | | | |
| **2** | | | |
| **4** | | | |
| **8** | | | |
| **16** | | | |

**Does the experimental gain ($V_{out}/V_{in}$) match the gain you calculated earlier, for all values of $V_{in}$? Why or why not?**

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2. **Non-inverting Amplifier Design**
   - Design a non-inverting amplifier with a gain of approximately 4. ***Show how you determine the necessary resistor values.***
   - Measure the required resistor values and record them in your notebook
   - Build the circuit with a 741 op-amp and these resistors. (Again, note that $V_{cc}$- is $V_{EE}$ on the data sheet).
   - Apply +12V (or +15V) to $V_{cc+}$ (pin 7) and -12V (or -15V) to $V_{cc-}$ (pin 4).
   - Set $V_{in}$ = 0.5V. Verify this with a voltmeter (***always use verified values in your tables***).
   - Measure $V_{out}$. Record this value in Table 3. Calculate $V_{out}/V_{in}$ and record this value as well.
   - Repeat for $V_{in}$ = 1V, 1.5V, 2V, 3V.

**Table 3**

| $V_{in}$ | Measured Values | | |
|---|---|---|---|
| | $V_{in}$ | $V_{out}$ | $V_{out}/V_{in}$ |
| 0.5 | | | |
| 1.00 | | | |
| 1.50 | | | |
| 2.00 | | | |
| 3.00 | | | |

**Does the experimental gain ($V_{out}/V_{in}$) match your desired gain, for all values of $V_{in}$? Why or why not?**

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3. **Inverting Amplifier with Given Resistors**
   - Obtain two resistors, $R_1 = 1.2\ k\Omega$ and $R_2 = 5\ k\Omega$. Measure the values of these resistors and record their values in Table 4.
   - Build the circuit of Figure 3 with a 741 op-amp and these resistors. Refer to the datasheet in the appendix for the op-amp pin diagram.
   - Calculate the gain of this op-amp circuit (with your measured resistor values) and record in Table 4.

**Table 4**

| Parameters | Calculated Values | Measured Values |
|---|---|---|
| $R_1$ | | |
| $R_2$ | | |
| Gain | | |

**What do you expect the value of $V_{out}$ for a given value of $V_{in}$?**

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- Set the variable power supply, $V_{in} = 1$ V. Verify this value with the voltmeter.
- Measure $V_{out.}$ Record this value in Table 5. Calculate $V_{out}/V_{in}$ and record this value as well.
- Repeat for $V_{in}$ = 1.5V, 2V, 2.5V, and 3V

**Table 5**

| $V_{in}$ | Measured Values | | |
|---|---|---|---|
| | $V_{in}$ | $V_{out}$ | $V_{out}/V_{in}$ |
| 1 | | | |
| 1.5 | | | |
| 2 | | | |
| 2.5 | | | |
| 3 | | | |

**Does the experimental gain ($V_{out}/V_{in}$) match the gain you calculated earlier, for all values of $V_{in}$? Why or why not?**

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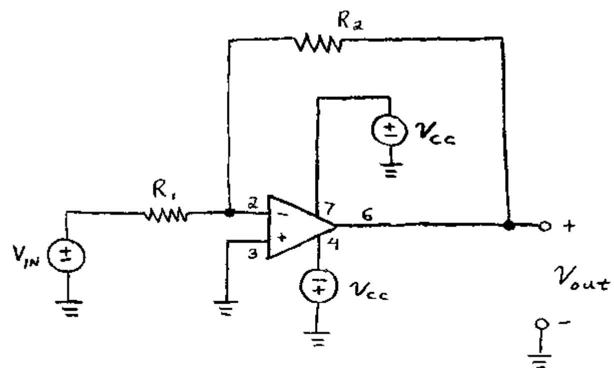
4. **Inverting Amplifier Design**
   - Design a inverting amplifier with a gain of approximately -1. ***Show how you determine the necessary resistor values.***
   - Measure the required resistor values and record them in your notebook
   - Build the circuit with a 741 op-amp and these resistors. (Again, note that $V_{cc}$- is $V_{EE}$ on the data sheet).
   - Apply +12V to $V_{cc+}$ (pin 7) and -12V to $V_{cc-}$ (pin 4).
   - Set $V_{in}$ = 0.5V. Verify this with a voltmeter (***always use verified values in your tables***).
   - Measure $V_{out}$. Record this value in Table 6. Calculate $V_{out}/V_{in}$ and record this value as well.
   - Repeat for $V_{in}$ = 1.5V, 2.5V, 3.5V, 4.5V.

**Table 6**

| $V_{in}$ | Measured Values | | |
|---|---|---|---|
| | $V_{in}$ | $V_{out}$ | $V_{out}/V_{in}$ |
| 0.5 | | | |
| 1.5 | | | |
| 2.5 | | | |
| 3.5 | | | |
| 4.5 | | | |

**Does the experimental gain ($V_{out}/V_{in}$) match your desired gain, for all values of $V_{in}$? Why or why not?**

5. **Inverting Amplifier with a Load Resistor**
   - Redraw figure 3 with a load resistor




   - Determine $V_{out}$ as a function of $V_{in}$. Show this derivation in the notes.

**Is this equation you used to derive $V_{out}$ different from the equation derived for an amplifier circuit without a load? Why or why not?**

**Using the inverter circuit you designed in part 4…**

- Obtain a 4.7 kΩ resistor. Measure and record its value.

**Table 7**

| Parameters | Calculated Value | Measured Value |
|---|---|---|
| $R_{load}$ | | |

- Connect this resistor between the op-amp output ($V_{out}$) and the ground bus (be sure the ground bus is connected to ground on your power supply).
- Apply +12V to $V_{cc+}$ (pin 7) and -12V to $V_{cc-}$ (pin 4).
- Set $V_{in}$ = 0.5V. Verify this with a voltmeter (***always use verified values in your tables***).
- Measure $V_{out}$. Record this value in Table 8. Calculate $V_{out}/V_{in}$ and record this value as well.
- Repeat for $V_{in}$ = 1.5V, 2.5V, 3.5V, 4.5V.

**Table 8**

| $V_{in}$ | Measured Values | | |
|---|---|---|---|
| | $V_{in}$ | $V_{out}$ | $V_{out}/V_{in}$ |
| **0.5** | | | |
| **1.5** | | | |
| **2.5** | | | |
| **3.5** | | | |
| **4.5** | | | |

**Does the load resistor affect the gain of the amplifier? Why is this useful?**

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## 6. Operational Amplifier Non-Idealities

**What is the voltage difference $V_p - V_n$ for an ideal op-amp?** Record your results in Table 9.

**What are the input currents ($I_p$ and $I_n$) for an ideal op-amp?** Record your results in Table 9.

**Using the same inverting amplifier circuit from Part 5…**

- Measure the voltage difference between $V_p$ and $V_n$ (pins 3 and 2). Record this value in Table 9.

**Does this voltage reading match your answer above? Why or why not?**

- Measure the currents flowing into these op-amps ($I_p$ and $I_n$). Record these values in Table 9. ***Be careful not to blow the fuse in the multimeter!!***

**Do these current readings match your answer above? Why or why not?**

**Table 9**

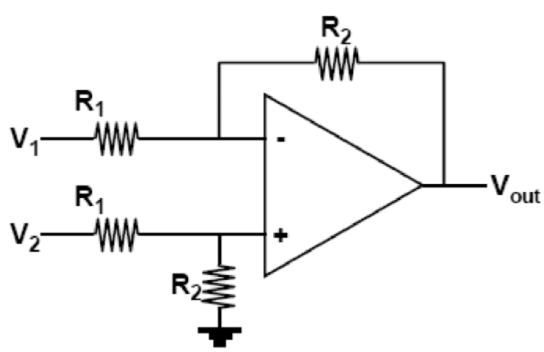
| Parameter | Expected Value | Measured Value |
|---|---|---|
| $V_+ - V_-$ | | |
| $I_+$ | | |
| $I_-$ | | |

**Questions:**

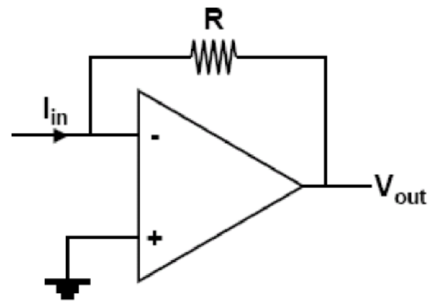
(1) Why do we need $V_{cc}$? What is its function?

(2) When does an op-amp operate within its *linear* region? When does an op-amp operate in its *saturation* regions?

(3) What is the purpose of the following circuit? (Determine $V_{out}$ as a function of $V_1$, $V_2$, $R_1$, and $R_2$.)



(4) What is the purpose of the following circuit? (Hint: What is the *input* to the “system” and what is the *output* of the “system”?)

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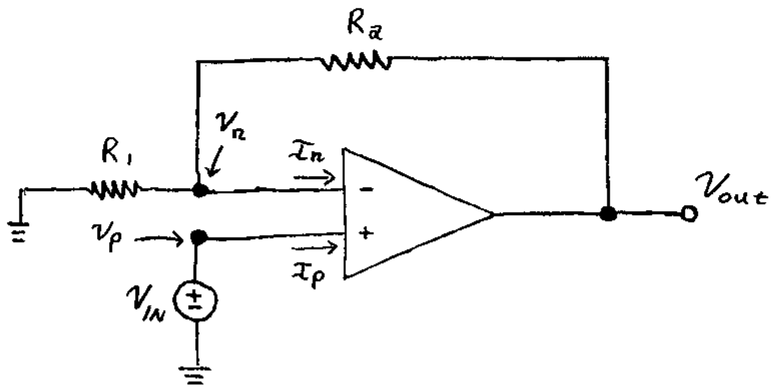
# NON-INVERTING AMPLIFIER




ideal characteristics : $I_n = I_p = 0$

$V_n = V_p$

KCL @ node $V_n$ : $$\frac{V_n - 0}{R_1} + \frac{V_n - V_{out}}{R_2} = 0$$

@ node $V_p$ , $V_p = V_{IN}$

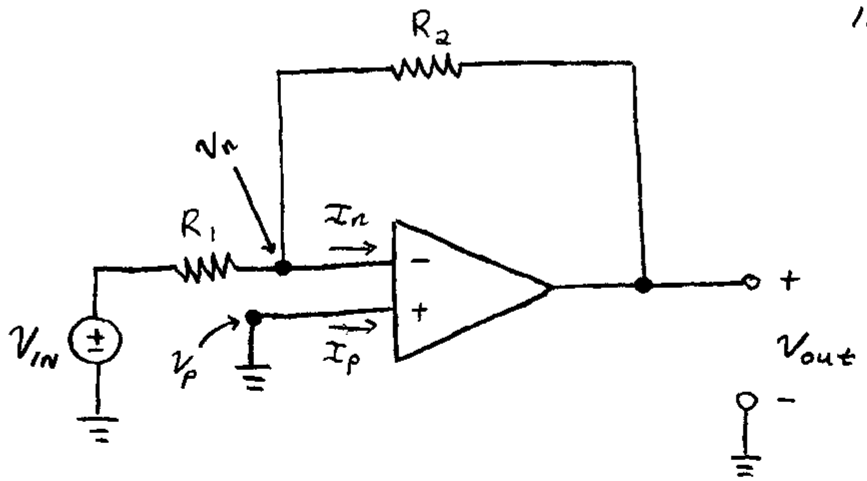
$$\therefore \quad \frac{V_{IN}}{R_1} + \frac{V_{IN} - V_{out}}{R_2} = 0$$

$$R_2 V_{IN} + R_1 ( V_{IN} - V_{out} ) = 0$$

$$R_2 V_{IN} + R_1 V_{IN} = R_1 V_{out}$$

$$\boxed{\frac{V_{out}}{V_{IN}} = \frac{R_2 + R_1}{R_1}}$$

INVERTING AMPLIFIER




ideal characteristics : $I_p = I_n = 0$

$V_p = V_n$

KCL @ node $V_n$ : $\dfrac{V_n - V_{IN}}{R_1} + \dfrac{V_n - V_{out}}{R_2} = 0$

@ node $V_p$ : $V_p = 0$

$$\therefore \quad \frac{0 - V_{IN}}{R_1} + \frac{0 - V_{out}}{R_2} = 0$$

$$-R_2 V_{IN} = R_1 V_{out}$$

$$\boxed{\frac{V_{out}}{V_{IN}} = \frac{-R_2}{R_1}}$$

**NOTES**

# HA17741/PS

General-Purpose Operational Amplifier
(Frequency Compensated)

HITACHI

ADE-204-043 (Z)
Rev. 0
Dec. 2000

## Description

The HA17741/PS is an internal phase compensation high-performance operational amplifier, that is appropriate for use in a wide range of applications in the test and control fields.

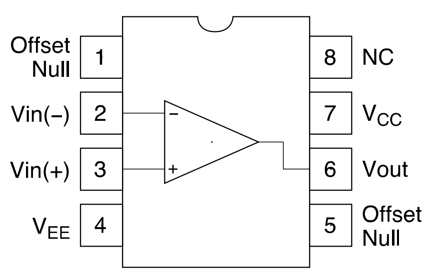
## Features

- High voltage gain : 106 dB (Typ)
- Wide output amplitude : ±13 V (Typ) (at $R_L \geq 2$ kΩ)
- Shorted output protection
- Adjustable offset voltage
- Internal phase compensation

## Ordering Information

| Application | Type No. | Package |
|---|---|---|
| Industrial use | HA17741PS | DP-8 |
| Commercial use | HA17741 | |

## Pin Arrangement




(Top view)

Hitachi semiconductor