The Operational Amplfier Lab Guide

COMPONENTS REQUIRED FOR THIS LAB :

1. LM741 op-amp integrated circuit (IC)
2. 1k resistors
3. 10k resistor
4. Wires, wire cutters and breadboard

1. Introduction

So far in this course you have been dealing with circuits that do not amplify the voltage input. That is, the voltages in the circuit are either equal to or less than the input voltage. In this lab, you are going to be introduced to the **voltage amplifier** – a circuit element that outputs voltage that is greater than or equal to the input voltage. There is an exception to this rule called railing that we will talk about later.

Mathematically, if the input to an amplifier is:

$$V_{¿} = \sin(2\pi f t) \quad \text{volts} \qquad (1)$$

the output may be something like:

$$V_o = 5sin(2\pi f t) \quad \text{volts} \qquad (2)$$

The amplifier you will be using is also an **operational amplifier** – you can use the device to perform common math operations like integration and differentiation. However, you will not be dealing with those operations in this lab, you will just be examining the amplifier functionality.

Operational amplifiers (op-amps) were first developed by George Philbrick when he was an employee for the National Defense Research Council in the early 1940s [1]. The op-amp later went through many transitions, Fairchild Semiconductor corp. developed a de-facto standard in 1962 – the µ741 [1]. This op-amp has lived on for over forty years and you will be using this op-amp in the lab. From now, on whenever I say “op-amp” think the µ741.

We mentioned that op-amps can be used to build circuits that perform mathematical operations and amplify voltage. Op-amps can also be used to build circuits that perform Analog-to-Digital (A/D) conversion, square-wave generators (oscillators) and a whole bunch of other stuff. The robustness of the op-amp is because the functionality of the op-amp can be extended by the use of feedback. Although a detailed description of feedback is beyond the scope of this guide, we will give you enough information to appreciate the usefulness of feedback. But first, let us look at the circuit symbol of the op-amp.

2. The Differential Amplifier

i. Circuit symbol and model

The circuit symbol for an op-amp is shown below:

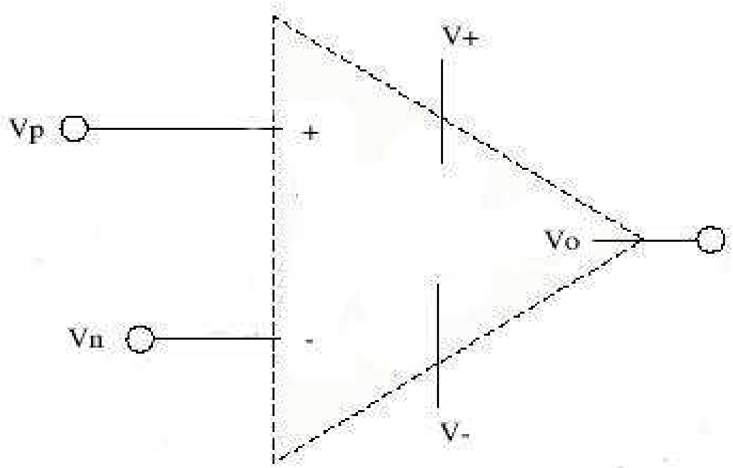

Figure 1. The circuit symbol for an op-amp

As you can see in figure 1, the op-amp has 5 terminals – two input terminals (+ and -, called the **non-inverting** and **inverting** terminals respectively), one output terminal (Vo) and two power supplies (V+ and V-). An op-amp is a **differential amplifier**, that is it amplifies the difference between the two input terminals. If we have a source with voltage Vp connected to the + terminal and Vn to the – terminal, the output is:

$$Vo = A\,(Vp - Vn) \qquad (3)$$

where A is a dimensionless constant (called **open-loop voltage gain**) specific to the op-amp. Vo is the output voltage, V+ and V- are the power supplies. The functionality of the terminals of an op-amp will be clear if we look at a circuit model shown in figure 2. Our goal is to derive equation (3) from figure 2.

Please note: the actual circuit inside an op-amp is complex and non-linear. The model below is an excellent linear approximation to the actual circuit inside an op-amp, and that is all you need to know for EECS 100.

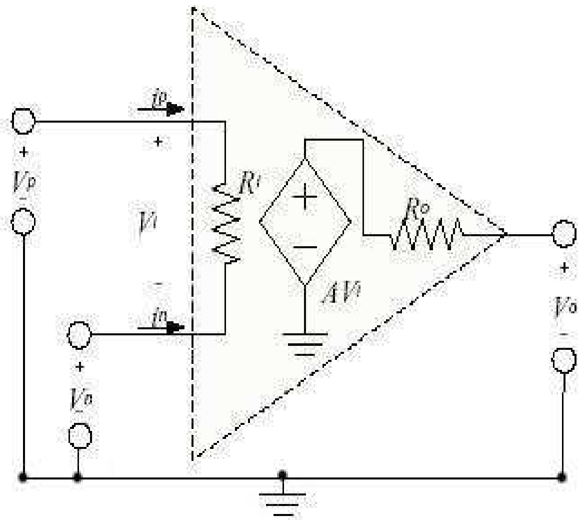

Figure 2. An approximate linear circuit model for an op-amp

I have annotated two extra currents in figure 2 to make the discussion clear. i^p is the current into the non-inverting terminal of the op-amp, i^n is the current into the inverting terminal. Let us analyze the figure above, ignoring the power supplies V+ and V- for the moment. First, we can re-draw the circuit in figure 2 to the one shown in figure 3.

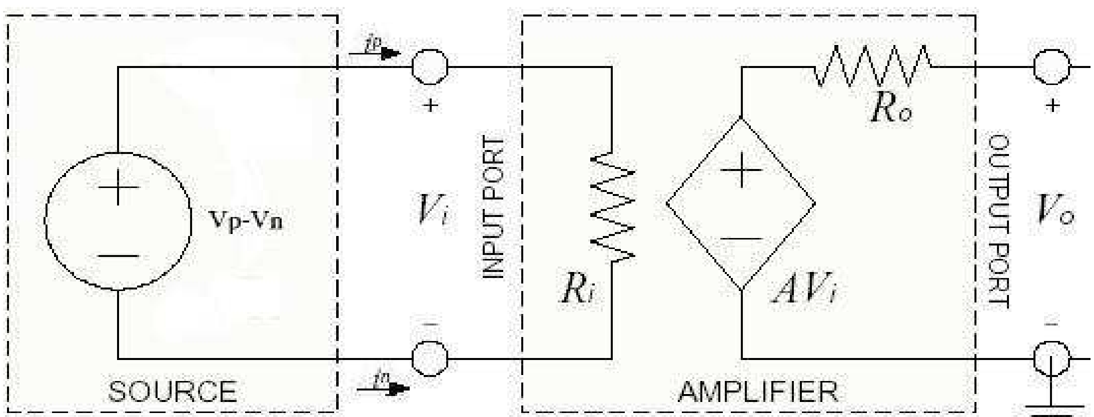

Figure 3. Redrawing the circuit in figure 2

Our goal is to obtain Vo as a function of Vp – Vn. From your knowledge of basic-circuit analysis:

$$Vi = Vp - Vn \quad \text{(parallel rule)} \qquad (5)$$

Thus:

$$Vo = AVi = A(Vp - Vn) \quad \text{(output is open, no current flows through Ro)} \quad (6)$$

If we graph Vo as a function of Vp-Vn, we get the **Voltage Transfer Characteristic (VTC)** of an op-amp, as shown below:

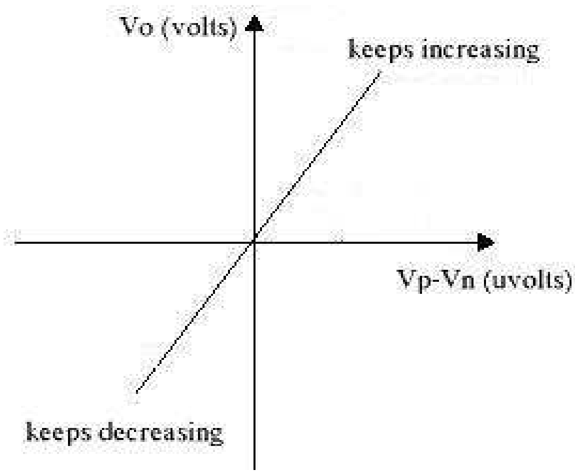

Figure 4. Ideal VTC of an op-amp

The graph shows that Vo varies linearly as a function of Vp-Vn[1]. This should be obvious from equation 6 since A is a constant. In reality, we all know that you cannot get infinite gain – the amplifier cannot amplify if we input a trillion volts. This is where the functionality of the power supplies comes into play. A real op-amp will have a VTC shown below:

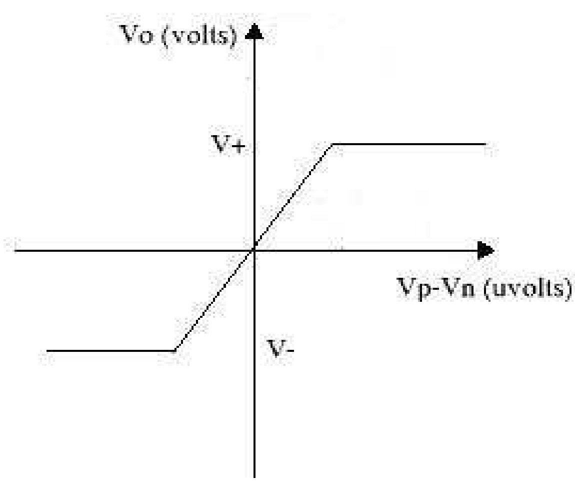

Figure 5. Non-ideal VTC of an op-amp

As you can see, the op-amp cannot output a voltage greater than its positive power supply

1 The careful reader would have noted the scale of Vp-Vn is in microvolts. We will discuss this later.

(V+) or lower than its negative power supply (V-), a phenomenon called **railing**. Remember this when you use an op-amp. In this lab, your V+ is set to +10 V and V- to -10 V as shown in the figure below.

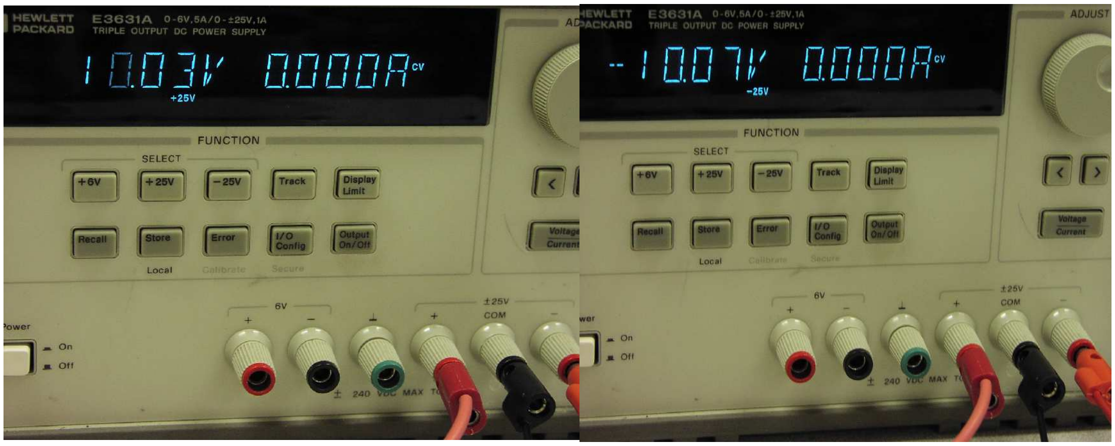

Figure 6. The +10 V supply is on the left and the -10 V supply is shown on the right

Before we move on, a note about the power supplies. This is one of the most confusing aspects new students encounter with an op-amp. Please be very careful about your power supply values and where you hook em up. If you connect the positive supply to V- and the negative supply to V+, what you are going to have is a very light paper-weight. In order to set the power supply inputs, turn on the power supply. Your output will probably be set to OUTPUT OFF as shown below.

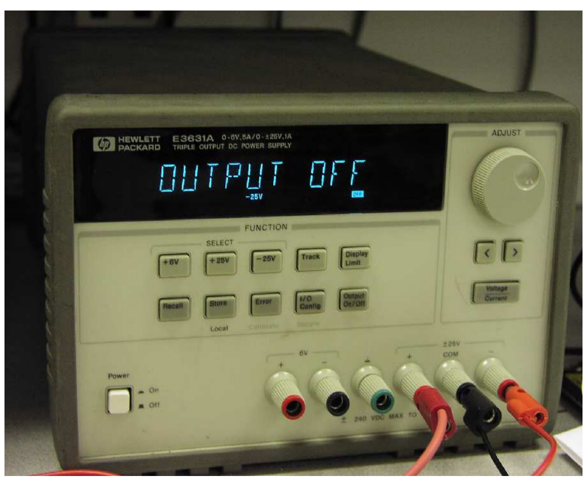

Figure 7. You need to turn the output on before you can set the power supply inputs

If so, hit the Output On/Off button and then press the +25 V button on your power supply. Use the dial to set the output value to +10 V. Then, press the -25 V button and set the output voltage to -25 V. If you don't know how to hook up an op-amp, feel free to ask the TA. Also note this is the power supply input. To actually provide a signal input to the op-amp you are going to be using the function generator. More on this when we talk about the actual experiment setup.

Great, how do you use an actual op-amp? A real op-amp does not look like the triangle above. Rather, it comes in the form of Dual-inline-package Integrated Circuit (DIP IC) as shown below:

Figure 8. Comparing the op-amp IC to a whiteboard marker

As you can see, the actual op-amp is very tiny indeed! In order to use the op-amp above, you refer to the product's **datasheet**. A datasheet (as the name suggests) has important data describing the many features of your product. The datasheet for the μ741 op-amp can be downloaded off the EECS 100 Lab Guides homepage[2]. It contains a lot of information. Feel free to skim through it before the lab and ask the TA questions you may have. The most important information are on the first couple of pages, and understanding these pages should suffice for this lab. They contain the **pinout** and power supply requirements of your op-amp. The pinout describes how the actual op-amp corresponds to the model shown earlier in figure 2.

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2 The op-amp you have is the LM741 – it is functionally equivalent ot the u741.

In figure 9, I have shown an annotated version of the pinout for the op-amp:

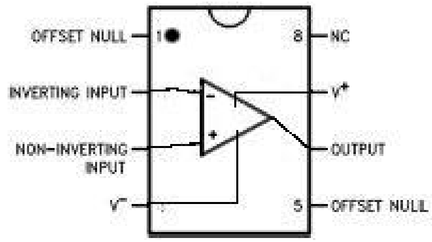

Figure 9. This should help you visualize how the op-amp is connected internally

In order to correctly read the pin numbering on the op-amp IC: hold the op-amp with its top-side (the LM741 lettering side) facing you. You will see a notch corresponding to the notch in figure 9 AND/OR you will see the circle shown in figure 9. The pin to the left of the notch or circle is pin number 1, and it increases going down. On the right side (as shown in figure 9), the bottom pin is 5 and it increases going up. Don't worry about the NC and the Offset Null pins. You can leave them disconnected when you breadboard your op-amp. More on breadboarding when we talk about the actual experiment setup.

We are almost done with the theory part. The final concepts we have to learn are a few simple rules for analyzing an op-amp circuit and the concept of negative feedback. Both these concepts arise out of the constant A in equation 6.

ii. Op-amp golden rules

As stated earlier, the scale of Vp-Vn in the VTC of an op-amp is in microvolts. This is because the open-loop gain (the constant A in equation 6) is usually in the order of 10^6. For all practical purposes, you **approximate the open-loop gain of an ideal op-amp as infinity**.

$$A \to \infty \tag{7}$$

You also make the following approximations for an ideal op-amp:

$$\mathbf{R_{in}} \to \infty \tag{8}$$
$$\mathbf{R_{out}} \to \mathbf{0} \tag{9}$$

Using equations (8) and (9), we can re-draw figure 2:

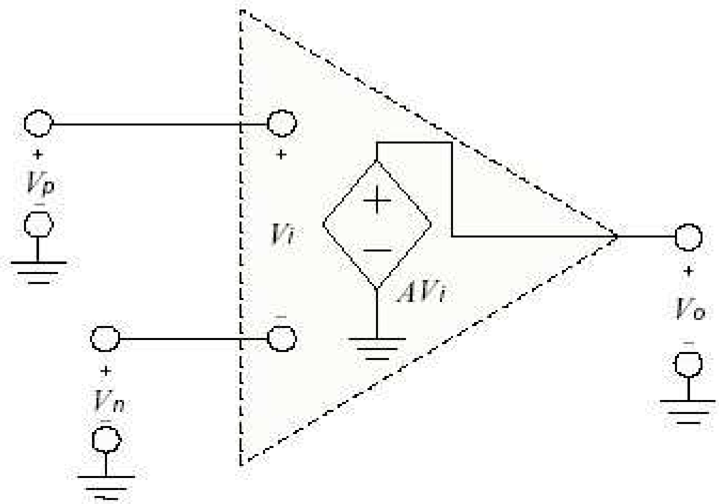

Figure 10. The ideal op-amp

Based on equation (8), the currents going into Vp and Vn are approximately 0.

$$ip = in = 0 \text{ A} \qquad (10)$$

Also, since the open loop gain is infinity and Vo has to be finite, we have:

$$Vp - Vn = Vo/A = \text{finite quantity/infinity} = 0$$

$$Vp = Vn \qquad (11)$$

Although equations 7, 8 and 9 constitute the **ideal op-amp assumptions**, **equations 10 and 11 are used to analyze op-amp circuits**. **Unless otherwise stated, you will assume the op-amp is ideal. The only non-ideality you have to deal with is the railing phenomenon.** In order to understand op-amp analysis, let us look at a common amplifier obtained from the op-amp: the inverting amplifier.

iii. Concept of negative feedback and the gain of an inverting amplifier

You have seen that an op-amp as a differential amplifier discussed above has infinite gain. Hence, if you apply an input such as 1 Volt, you are going to get an infinite output – in reality the op-amp will hit the positive power supply and will thus rail. In order to use it in a practical circuit, you make use of **negative feedback**. That is, we take the output and feed it back to the inverting input. Figure 11 shows such an application - the inverting amplifier configuration.

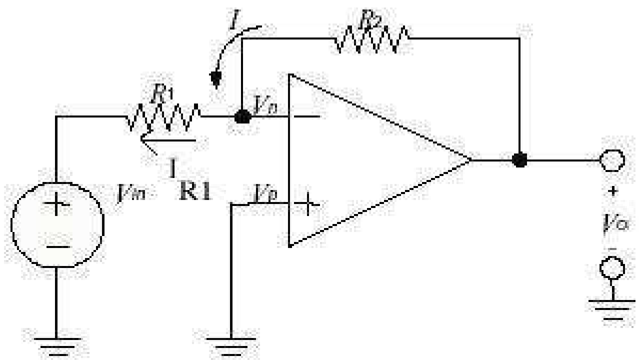

Figure 11. The inverting amplifier circuit

Noitce how the output is connected to the inverting input through R2. A detailed discussion of feedback is beyond the scope of this guide. However, a qualitative idea can be obtained by looking at equation 6:

$$Vo = A(Vp - Vn)$$

Assume R2 = 0 in figure 11. Then, we get:

$$Vo = A(Vp - Vo)$$

The equation above is a **recursive equation**. As you all know, A is huge (tends towards infinity for an ideal op-amp). Hence, Vp = Vo. Suppose Vo increases a little bit. Then, Vp < Vo now and A(Vp-Vo) < 0 since A is positive. Hence, if Vo tries to increase the negative feedback immediately[3] causes Vp to move towards Vn, thereby stabilizing the circuit.

Let us go back to figure 11 and assume R2 is not zero. We want Vo as a function Vin in the circuit in figure 11 and obviously this is not going to be equation 3 because of the negative feedback. The corresponding gain we are going to get is called the **closed-loop gain**[4]of the op-amp.

In order to derive the closed-loop gain, let us start with equation 10. From equation 10, we know the current into the inverting input is zero. Hence, by applying KCL at the inverting input, the current I flowing through R2 in figure 11 is the same current which flows through R1:

$$I = I_{R1}$$

Applying Ohm's law:

3 In an actual circuit, there is obviously some delay between a change in Vo and the negative feedback taking effect. We can safely neglect this effect in our case.

4 It is called a “closed loop gain” because you have a loop from the output to the inverting input.

$$\frac{(Vo - Vn)}{R2} = \frac{-Vin}{R1} \qquad (12)$$

From equation 11, we know:

Vp = Vn = 0 (since Vp is grounded)

Substituting the value of Vn in (12) and rearranging:

$$Vo = \left(\frac{-R2}{R1}\right)Vin \qquad (13)$$

The quantity within paranthesis in equation 13 is the closed loop gain for the inverting amplifier. This is awesome – by using negative feedback you eliminated the dependence of gain on A and designed the gain of the op-amp to depend only on R2 and R1. Obviously, you can now control the gain of an op-amp using only two resistors. If R2 is twice the value of R1, you get two times the gain and so on. The gain is negative, you will design an amplifier with positive gain in the prelab. In summary, for analyzing a circuit with an op-amp in negative feedback:

1. Use equation (10) and KCL at the inverting and/or non-inverting inputs.
2. Use equation (11) to eliminate the value of Vp or Vn.

Please note that (1) and (2) are not hard-and-fast rules. They just serve as a guide – use them wisely!

As a concluding remark to this section, what happens when you feedback Vo to the non-inverting input? Turns out you get **positive feedback.** By using the same qualitative recursion argument above, you can show that positive feedback leads the circuit towards instability. This is not useless – you use positive feedback to make square wave generators and other kinds of oscillators. You will see how to build a square wave generator in a later lab.

Thats all for the theory! Now, its your turn. Before we go on to the experiment, you should finish the prelab.

3. The Experiment

The TA will demonstrate how to wire the op-amp using the breadboard. **PLEASE NOTE: WIRE NEATLY! THIS IS THE MAGIC ASPIRIN THAT WILL REDUCE A LOT OF HEADACHE WILL DEBUGGING.**

i. The Voltage Follower

The function generator settings for this part are shown below. Use a sine wave as the input.

Figure 12. Function generator settings for parts i and ii.

Construct the voltage follower shown in figure 13. Your Vin is from your function generator.

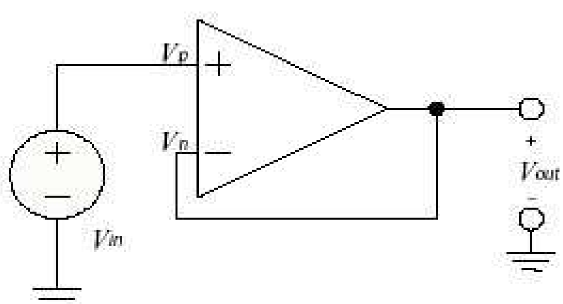

Figure 13. Voltage follower

a. Verify the output is the same as the input using the scope. Ask your TA to check you off on the lab report question i. a.

Now, answer the lab report questions i. b. and i. c.

ii. The Inverting Amplifier

Use the same function generator settings as in part i. Hook up the inverting amplifier circuit from figure 11. Choose R1 = 1k. Now, I want you to choose R2 so the closed loop gain is -2 and answer lab report question ii. The input voltage and output voltage scope plot from my circuit is shown below for your reference:

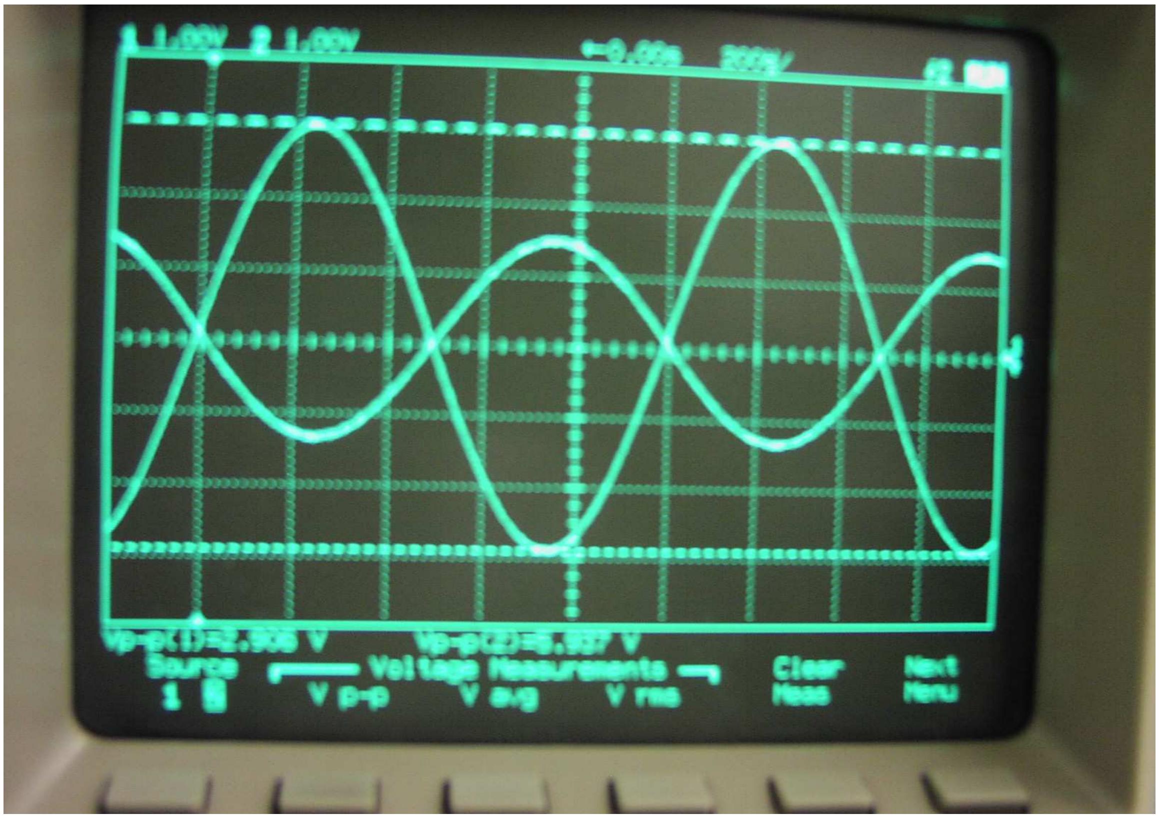

Figure 14. Output from inverting amplifier. My input is on probe 1 and output on 2

iii. The Non-inverting amplifier

a. Change Vpp to show 250 mV on the scope. Hook up the non-inverting amplifier circuit shown in figure 15. Use R2 = 10k and R1 = 1k. Answer the lab report question iii. a.

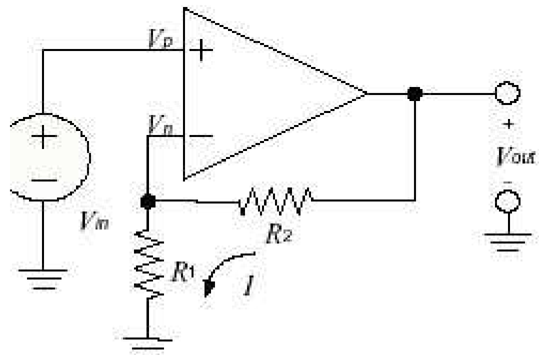

Figure 15. The non-inverting amplifier, signal input is from the function generator

b. Change Vpp to 1.34 V and answer the lab report question iii. b.

c. Answer lab report question iii. c.

5. References

1. Multimedia Tutorial on Operational Amplifiers, Fundamentals and Applications. *http://fie.engrng.pitt.edu/fie98/papers/1089.pdf. February 14th 2004.*