Unit 5: Negative Feedback and Operational Amplifiers

Xueqi Li*
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INTRODUCTION

An operational amplifier (opamp) can amplifie the input voltage by a large factor. Since it have a large gain, it might not stable in many case and the output is very uncontrollable, we usualy build up a circuits with it to achieve a much stable circuit.

An opamp, other than power-supply pins (V_{CC} and V_{EE}), have two input and one output, where the input are known as non-inverting input (+) and inverting input (−). The ouput is given as:

$$v_{\mathrm{out}} = A_0(v_+ - v_-) \tag{1}$$

where A_0 is a very large number. Usually it is higher than 10^5. The impedance of the opamp can be think as ideal.

Negative Feedback

A negative feedback is such that the output of the opamp connect to the inverting input. That is to say, $v_- = v_{\mathrm{out}}$. This leads to following equation:

$$v_+ = v_- \tag{2a}$$
$$i_+ = i_- = 0 \tag{2b}$$

Follower

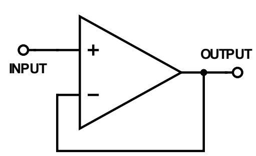


FIG. 1: A follower

The simplest negative feedback circuit is a follower, so as in Figure 1. From Equation 2a, we see that

$$V_{\mathrm{out}} = V_{\mathrm{in}} \tag{3}$$

Inverting Amplifier

An operational amplifier have to be able to be an amplifier! An Inverting Amplifier is presented as Figure 2.

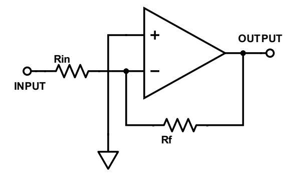


FIG. 2: An Inverting Amplifier

Since the non-inverting input is grounded, we must have $v_+ = v_- = 0\mathrm{V}$. Thus, we can find the current in the input side are given as

$$I_{\mathrm{in}} = \frac{V_{\mathrm{in}}}{R_{\mathrm{in}}}$$

Follow the Equation 2b, this current have to be also go through R_f, where the voltage drop on R_f just so happened to be output voltage ($v_- - V_{\mathrm{out}}$):

$$V_{\mathrm{out}} = -IR_f = -V_{\mathrm{in}}\frac{R_f}{R_{\mathrm{in}}} \tag{4}$$

where we see that the gain is just given as:

$$\mathrm{Gain} = -\frac{R_f}{R_{\mathrm{in}}}$$

Notice that for the inverting amplifier, the input impedance is give as:

$$Z_{\mathrm{in}} = \frac{\mathrm{d}V_{\mathrm{in}}}{\mathrm{d}I_{\mathrm{in}}} = R_{\mathrm{in}}$$

which is not a very high input impedance. In the other hand, easy to see the output impedance is ideal.

Non-inverting Amplifier

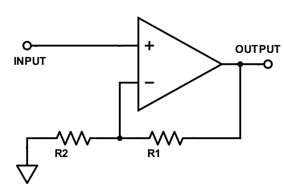


FIG. 3: An non-inverting Amplifier

It is nice to have a non-inverting amplifier. A non-inverting amplifier is shown as Figure 3. Since the input is directly connect to the non-inverting input, we have $V_{\mathrm{input}} = v_+ = v_-$. In the end of R_2, we must have 0V sicne it is grounded. Thuse we have:

$$I_2 = \frac{V_{\mathrm{in}}}{R_2}$$

From Equation 2b, this current have to go through R_1:

$$V_1 = IR_1 = V_{\mathrm{in}}\frac{R_1}{R_2}$$

where the other end of R_2 just so happened to be the output:

$$V_{\mathrm{output}} = V_{\mathrm{in}} + V_1 = V_{\mathrm{in}}(1 + \frac{R_1}{R_2}) \tag{5}$$

which give as a gain as:

$$\mathrm{Gain} = (1 + \frac{R_1}{R_2})$$

Integrator

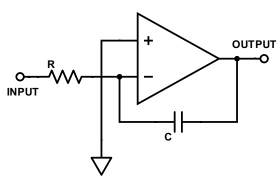


FIG. 4: An Integrator

The circuit presented in Figure 4 is an integrator. Since the non-inverting input is grounded, we have $v_- = v_+ =$ 0V. Thus we can find the current in the capacitor is the same as the current go through the resistor:

$$I = -C\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} = \frac{V_{\mathrm{in}}}{R}$$

solve the equation, we have:

$$V_{\mathrm{out}} = -\frac{1}{RC}\int V_{\mathrm{in}}\mathrm{d}t \tag{6}$$

However, there is a problem for the integrator. Usually, the input might have an offset. That is to say, there is a constent term in the input voltage. This will give us a growing or falling output after integration. To solve it, one can parallel a resistor with the capacitor.

T Network

To achieve a large parallel resistor, one can use a T network, so as in Figure 5. Ignore the capacitor, we can

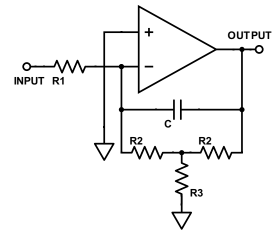


FIG. 5: An Integrator with T network

just calculate the effect of the T network. First, we still have the current on the R_1 will go through the left R_2:

$$I_1 = \frac{V_{\mathrm{in}}}{R_1} = I_{2\mathrm{L}} = I_{2\mathrm{R}} + I_3$$

On the other hand, the voltage between R_1 and $R_{2\mathrm{L}}$ is 0V. Thus we can find the voltage between two R_2:

$$V_2 = 0 - I_1R_2 = -V_{\mathrm{in}}\frac{R_2}{R_1}$$

And this voltage will dorp to zero once it go through R_3:

$$I_3 = \frac{V_2}{R_3} = -V_{\mathrm{in}}\frac{R_2}{R_1R_3}$$

In the output end, we can write the current go through R_2 as following:

$$I_2 = \frac{V_2 - V_{\mathrm{out}}}{R_2} = -\frac{V_{\mathrm{in}}}{R_1} - \frac{V_{\mathrm{out}}}{R_2}$$

This relate the output voltage to the current. Now we have $I_1 = I_2 + I_3$:

$$\frac{V_{\mathrm{in}}}{R_1} = -V_{\mathrm{in}}\frac{R_2}{R_1R_3} - \frac{V_{\mathrm{in}}}{R_1} - \frac{V_{\mathrm{out}}}{R_2}$$

Solve the equation, we find

$$V_{\mathrm{out}} = -V_{\mathrm{in}}\frac{R_2}{R_1}(2 + \frac{R_2}{R_3})$$

This give us the impedance of the T network:

$$Z_f = R_2(2 + \frac{R_2}{R_3})$$

Thus, we can achieve a high impedance if we just chose two two small resistor with a large ratio.

Differentiator

By interchange the resistor and capacitor of integrator, one can achieve a differentiator, as in Figure 6. Since the non-inverting input is grounded, we have to have 0V on v_-. This means the current go through the capacitor and the resistor are the same:

$$V_{\mathrm{out}} = -IR = -RC\frac{\mathrm{d}V\mathrm{in}}{\mathrm{d}t} \tag{7}$$

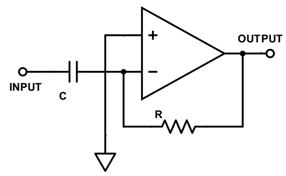


FIG. 6: An Differentiator

Limit of the Opamp

A realistic opamp are not ideal. There are a few importent things we have to consider when use it:

1. The voltage gain (A_0) will drop linearly to the frequency in logarithm scale;

2. There might be a phase shift in the output;

3. For the feedback loop, Equation 2b is approximate, i.e., i_+, $i_- \approx 0$;

4. For the feedback loop, Equation 2a is approximate, i.e., $v_+ \approx v_-$;

5. There is a small delay to the output. When input voltage change suddenly, the output voltage will learly increase and reach the theoretical value. This is called slew rate.

DATA AND CALCULATION

Follower

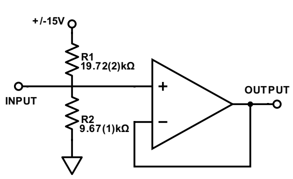
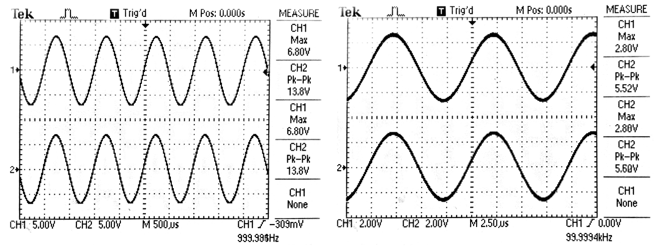


FIG. 7: An follower with changeable DC input

In this part we build a follower as in Figure 7. The resistor is actualy changeable so that we can achieve different voltage. By let the ratio of two resistor is up to 1:2, we can change our input DC voltage from -5V to 5V. The data obtained is in appendix, where the frequency is record as "DC". We can also remove the voltage divider and directly use a input from signal generator so as in Figure 1, the data obtained also presented in the appendix.

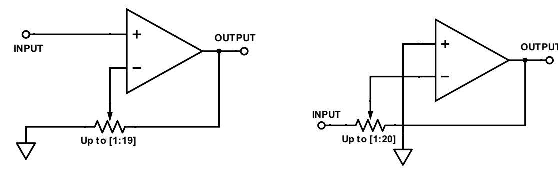
On the other hand, to see that the impedance of the circuit is ideal, we can link a 1.12(1)kΩ load resistor in the output end of the Figure 7. The value of the resistor for this part is shown in the Figure 7: $R_1 = 9.67(1)\mathrm{k}\Omega$, and $R_2 = 19.72\mathrm{k}\Omega$. When we use this circuit, wee find the input voltage is 15.2(2)V with a 10.6(2)V output. However, when we remove the follower, we have a 1.42(2)V output.



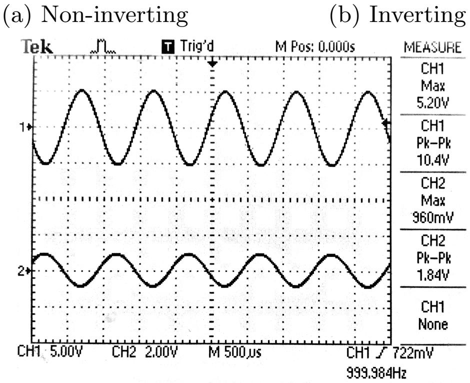
(a) 1kHz (b) 100kHz

FIG. 8: The input and the ouput voltage for the follower in different frequency

Amplifier



(a) Non-inverting (b) Inverting



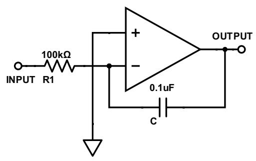
(c) The output of inverting Amplifier at 1kHz

FIG. 9: The amplifier circuit used in lab and its output

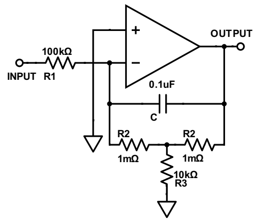
In the lab we use a 10kΩ potentiometer to achieve the amplifier with different gain. In here we want to achieve the highest gain is 26dB, i.e., the gain is around 20. Following the Equation 4 and Equation 5, we want the ratio of the resistor is up to 1:19 for the non-inverting amplifier and is up to 1:20 for the inverting amplifier. THe circuit used in the lab is presented in the Figure 9.

In the lab, we measure the 3 different set of data for different gain for each amplifier. The data obtained is in the appendix.

Integrator



(a) Without T network



(b) With T network

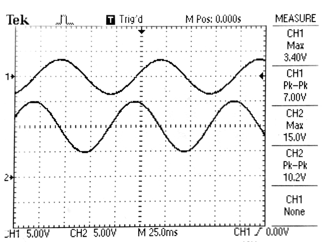
FIG. 10: Integrator used in lab

We have used two integrator shown in Figure 10. One is with T network and the other one does not use T network. We chose a 0.1μF capacitor and a 100kΩ resistor for the both case.

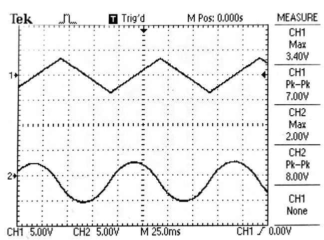
For the one without T network, when we connect the input to the ground, we see a upgoing line. On the other hand, we can connect the signal generator to the input. The output voltage shift up and down for different wave form. When frequency increase, the output peak to peak voltage drop significantly. We observed that the output voltage droped below 1V at 100Hz and unrecognizable for the higher frequency.

For the one with T network, we observed the same shift but the shift is slower. When frequency increase, the output drop below to 1V at 300Hz, and unrecognizable for the higher frequency.

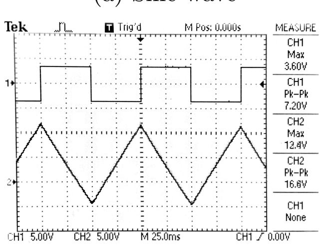
For both case, when input voltage have a large amplitude, the output usually be cut off on the ±15V.



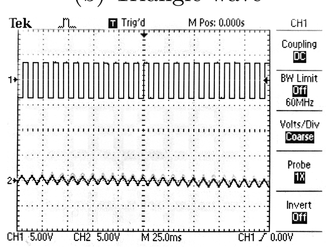
(a) Sine wave



(b) Triangle wave



(c) Square wave



(d) Square wave on high frequency

FIG. 11: Result of different wave form for integrator

Differentiator

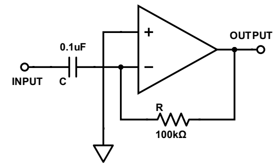


FIG. 12: Differentiator used in lab

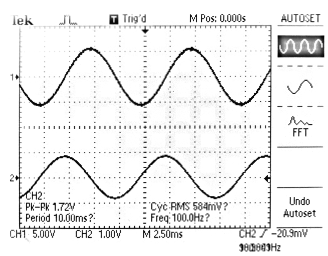
In the lab we use a Differentiator as in Figure 12. We chose a 0.1μF capacitor and a 100kΩ resistor. We use a 5V amplitude on the input for all the wave fomr.

Slew Rate

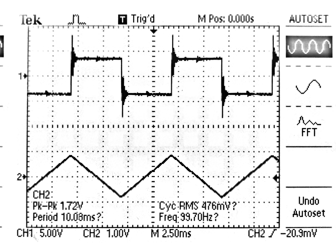
To measure the slew rate, there are two different way.

Disform of sine wave

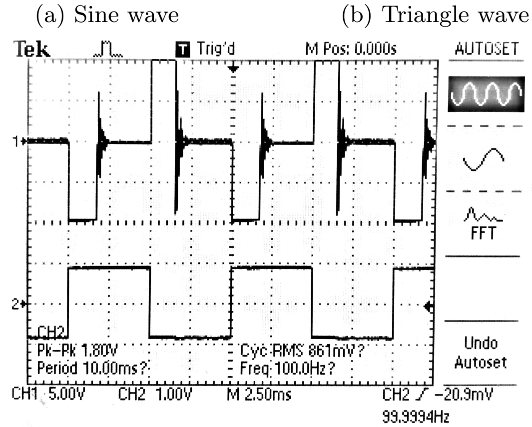
To measure the slew rate, we notice the change for a sinewave is hugh near the point $V(t) = 0$. At a high frequency, the voltage chagne is too quick such that the



(a) Sine wave

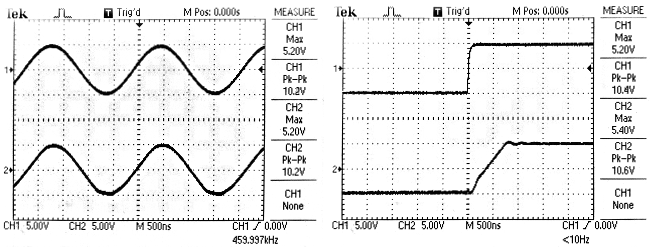


(b) Triangle wave



(c) Square wave

FIG. 13: Result of different wave form for differentiator



(a) Disform of sine wave (b) Sudden voltage change

FIG. 14: Measure the slew rate

opamp cannot follow, which cause a disform of sine wave in the output. This can help us to find the slew rate.

In this part, we use a follower as Figure 1. We use a sine wave as input and find out when the disform happen. We see the peak of the sine wave is start to disform at a frequency of 450kHz and 5V amplitude, as in Figure 14a.

Sudden voltage change

A sudden voltage change can also give us a chance to observed the slew rate. In the lab, we use a follower as in Figure 1. We apply a square wave in the input and find hot how the output delay when the voltage jump from $-V_0$ to V_0. THe result obtained is in Figure 14b. We see that the voltage change is 10V and the time it takes is $0.8(1)\mu$s.

ANALYSIS

CONCLUSION

* Partner: Tianming Hai