LABORATORY 7

RC Oscillator

Guide

The Waveform Generator Lab Guide

1. Objective

In this lab you will first learn to analyze negative resistance converter, and then on the basis of it, you will learn to build a square wave and a triangular wave generator.

2. Introduction

To introduce the waveform generators, we shall first introduce the mechanism of **negative resistance converter** and **RC oscillator**.

2.1. Negative Resistance Converter

Consider the op-amp circuit shown below:

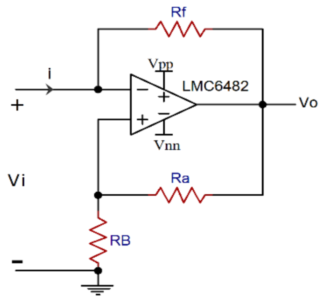


Fig. 1. A Negative Resistance Converter

This circuit realizes a negative resistance converter incorporating both a negative feedback path (via R_f) and a positive feedback path (via R_a). We will derive its driving characteristic by inspecting both the linear and the saturation regions as well. First assuming that the circuit works in the linear region, in an op-amp you know that no current flows into the inverting terminal, so we can easily find the relationship between i, V_o andV_i using Ohm's law:

$$i = \frac{V_i - V_o}{R_f} \quad \cdots\cdots\cdots\cdots(1)$$

You should understand from the passive sign convention why the numerator is $V_i - V_o$, not $V_o - V_i$. Equation (1) above does have an i-v relationship. However, we need to eliminate V_o.Here is where the positive feedback helps us. Again, the current flowing into the non-inverting terminal of the op-amp is zero. The trick is to spot the voltage divider at the non-inverting terminal. Since no current is flowing into the non-inverting terminal, R_a and R_b are in series as shown below:

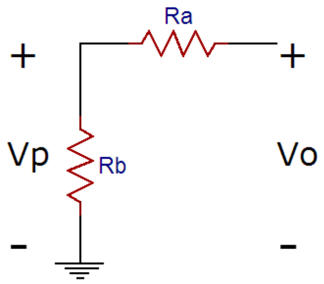


Fig. 2. The voltage divider

V_p (the voltage at the non-inverting terminal) can be easily found using the voltage divider:

$$V_i = \frac{R_b}{R_a+R_b} \times V_o \quad \cdots\cdots\cdots\cdots \quad (2)$$

$$V_o = \frac{R_a+R_b}{R_b} \times V_p \quad \cdots\cdots\cdots\cdots \quad (3)$$

But, $V_p = V_n$ (we are assuming the op-amp is in the linear region). Notice however from figure 1 that $v_i = V_n$. Substituting in (3):

$$V_o = \frac{R_a+R_b}{R_b} \times v_i \quad \cdots\cdots\cdots\cdots \quad (4)$$

Substituting (4) in (1) and simplifying, we get an i-v relationship for the op-amp operating in the linear region:

$$i = \frac{-R_a}{R_b R_f} \times v_i \quad \cdots\cdots\cdots\cdots \quad (5)$$

The i-v graph for the circuit when the op-amp is operating in the linear region is shown below:

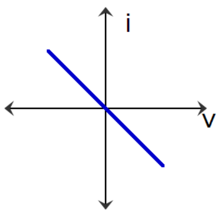


Fig. 3. The i-v graph of the circuit in the linear region

You can see why the circuit is called a “negative-resistance converter” because it converts positive resistance R_a, R_b, and R_f into a negative resistance equal to $-R_f \frac{-R_b}{R_a}$ Ω in the linear region. The i-v graph is a straight line but unlike a resistor, it has a negative slope. Also notice the circuit is still “linear” - the graph is a straight line. Intuitively, this makes sense.

The op-amp is the device in the circuit that causes the nonlinearity. This will occur if the op-amp is saturated. Since we derived the segment in figure 3 by assuming the op-amp is linear, the i-v graph is a straight line.
Let us see what happens when the op-amp saturates. Let us take consider the negative saturation region. That is $V_o = V_{nn}$. Equation (1) is still valid since no current enters the inverting or non-inverting terminal even if the op-amp is saturated:

$$i = \frac{V_i - V_{nn}}{R_f} \quad \cdots\cdots\cdots\cdots \quad (6)$$

However, to plot the function above we have to figure out for what value of v is the op-amp saturated.
Intuitively, you know any op-amp obeys the op-amp equation in the linear region:

$$V_o = A(V_p - V_n) \quad \cdots\cdots\cdots\cdots \quad (7)$$

where Vo is the voltage at the output, A is the open loop gain (usually huge like 10^6), V_p is the voltage at the inverting terminal and V_n is the voltage at the noninverting terminal. The op-amp will then rail to V_{nn} if $V_p < V_n$. In our circuit, V_n is V_i (refer to figure 1). Therefore, if $V_i > V_p$, then the circuit will rail to the V_{nn}. That is, $V_o = V_{nn}$. Then, V_p becomes $V_p = \frac{R_b}{R_a + R_b} \times V_{nn}$ (from equation (2)). Therefore, the point when the op-amp switches from linear to saturation is when $V_n = V_p$ or $V_i = \frac{R_b}{R_a + R_b} \times V_{nn}$. Now, V_{nn} is usually negative. That is why in figure 3 I have extended the graph to the negative v region.

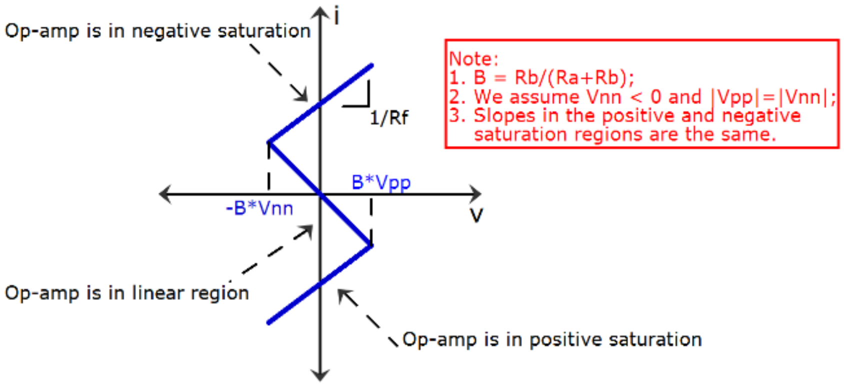


Fig. 4. The i-v graph of the negative resistance converter

Which way does the i-v graph extend when the op-amp is saturated? If you look at equation (6), you can see that if V_{nn} is negative then i has to be positive. The reason is: v will always be smaller than V_{nn}. Therefore, the numerator in equation (6) is always positive. If you stare at figure 3 long enough you will realize that when the op-amp is saturated with $V_o = V_{nn}$ then V_o is at the lowest possible voltage in the circuit. Therefore current i in figure 3 has to flow from left to right, since V_i is higher than V_o. This is in the direction of positive current. By symmetry, the argument(s) above apply for the positive saturation and hence we can complete figure3, as shown in Figure 4.

That concludes the derivation of the i-v graph for the negative resistance converter. An important observation is the manner in which we derived the graph. We really did not use any "step-by-step" method to derive the result. Rather, we used our intuitive knowledge of how the op-amp works. This is what is called "real-world engineering".

2.2. RC Oscillator

In this section, we will analyze the negative resistance converter with a capacitor connected across the v terminal. We will assume the capacitor is initially uncharged, i.e., v(0) = 0 volts. The circuit is shown in figure 5 below.

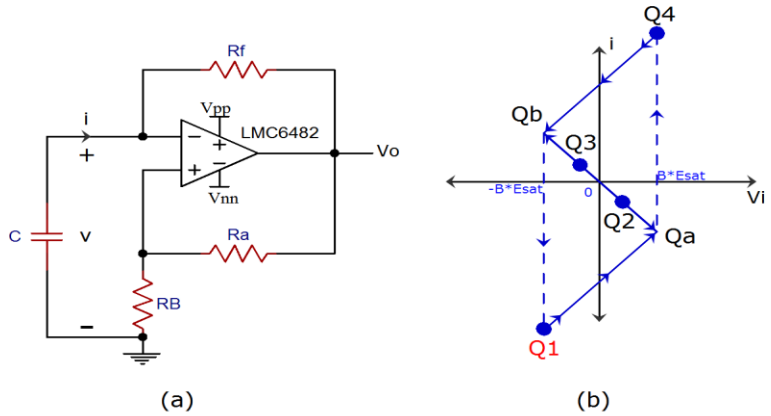


Fig. 5. An oscillatory circuit

Let us consider the four different initial points Q_1, Q_2, Q_3 and Q_4 (corresponding to four different initial capacitor voltages at t = 0) on this characteristic. Since $\dot{v}_{in}(t) = \dot{v}_c(t) = -\frac{i(t)}{C}$ and C > 0, we have

$$\dot{v}_{in}(t) > 0 \text{ for all } t \text{ such that } i(t) < 0,$$
$$\dot{v}_{in}(t) < 0 \text{ for all } t \text{ such that } i(t) > 0.$$

Hence the *dynamic route* from any initial point must move *toward the left in the upper half plane*, and *toward the right in the lower half plane*, as indicated by the arrow headsin Figure 5 (b). Observe that there is no stable equilibrium point in the circuit because the zero *i* current belongs to an unstable equilibrium (opposite arrowheads diverging from zero). This equilibrium point cannot be observed in practice, because any small amount of noise will drive out the circuit from this point. Also, the breakpoints Q_a, and Q_b cannot be equilibrium points because $i \neq 0$. Since, arrowheads towards $Q_a$and Q_b are oppositely directed it is impossible to continue drawing the dynamic route beyond Q_a or Q_b. In other words, an *impasse* is reached whenever the solution reaches Q_a or Q_b. The dotted arrows show that a sudden *instantaneous transition* will occur (also called *jump*). For an *RC* circuit this transition should be always a vertical jump (assuming in the *v-I* plane that *i* is the vertical axis) because the voltage across a capacitance cannot be changed suddenly such that $V_c(T_+) = V_c(T_-)$. Applying jumps at the two *impasse* points Q_a and Q_b, we obtain a closed dynamic route. This means that the solution

waveforms become *periodic* after a short transient time (starting from any initial capacitance voltage) and the op-amp circuit functions as an *oscillator*. Note that the oscillation is not sinusoidal. Such oscillators are usually called *relaxation oscillators*.
To figure out what kind of waveforms will be generated note that the closed dynamic route operates always in the saturation regions (except for the short transient time at the very beginning). These are the segments Q_1-Q_a, and Q_4-Q_b. It means that the output voltage (V_o) will alternate between the two saturation levels, $+E_{sat}$ and $-E_{sat}$. The output will be a square wave with a duty cycle of 50 % if the saturation levels are symmetrical. Since the output voltage will be either $+E_{sat}$ or $-E_{sat}$, then the non-inverting input of the op-amp will be biased at $\beta * E_{sat}$ or $-\beta * E_{sat}$. This will drive the circuit to behave as a comparator. Until the voltage of the capacitance is lower than $\beta * E_{sat}$ the output will remain at $+E_{sat}$ (Q_1 to Q_a) , and similarly until the voltage of the capacitance is larger than $-\beta * E_{sat}$ the output will be always $-E_{sat}$ (Q_4 to Q_b). The capacitor voltage will change exponentially because it is charged or discharged through the resistor $-R_f$ from a constant voltage $+E_{sat}$ or $-E_{sat}$, respectively.
Observe that this RC op-amp circuit is *autonomous* in the sense that it produces periodic oscillatory signal without any external driving periodic signal.

2.3. Additional Remarks

Now, you can see how the circuit oscillates. If we start at (0, 0), we will eventually reach one of the impasse points. Then, we have an instantaneous jump. After a while, we will reach another impasse point and the cycle continues.
Intuitively, why does this circuit oscillate? We know the dynamics of the circuit leads to the impasse points. Turns out once the circuit reaches an impasse point, the power supply provides the necessary energy to overcome the impasse point. In other words, you cannot have an oscillator without a power supply. Mechanically, think about a simple pendulum. Physically, you always need to give it "a push" to sustain the oscillation.

Reference

[1] University of California, Berkeley EE100 Spring, 2013.
[2] University of California, Berkeley EE100 Fall, 2004.

Report

Name ____________ TA Checkoff ________________________

Teammate ____________ Score ________________________

You are required to do simulate, build and analyze the aforementioned RC oscillator circuit.

Note: **You are suggested to finish the simulation tasks before class**. Otherwise, it may be difficult for your group to finish all tasks in 3 hours.

3.1 Simulations

- **Task 1: The Relaxation Oscillator**

Detailed parameter requirements and questions please find the prelab document.

- **Task 2: The Triangle Wave Generator**

In this task, the square wave output of the relaxation oscillator (Fig. 5.) will be fed into the triangle wave generator. The triangle wave generator is actually just a simple integrator shown below.

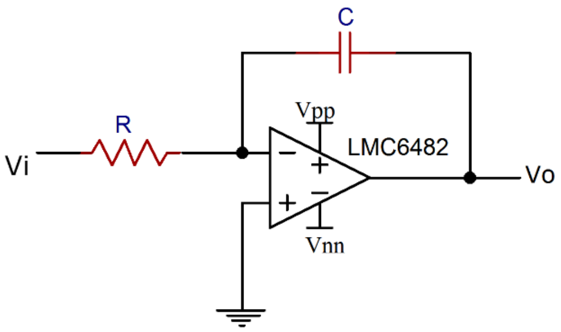


Fig. 6. Inverting Integrator

The output of the above circuit actually integrates and inverts the input signal.

$$V_o = -\int_0^t \frac{V_i}{RC} dt$$

This circuit generates a triangle wave from a square waveform. You do not need to prove this statement but we are going to ask you to simulate it. If V_i is a 20Hz square wave with 6V amplitude, how would you pick the value of R and C to generate a triangle waveform with 4V amplitude? For V_i, you can use a pulse generator or even the output of your relaxation oscillator. Simulate the circuit in Multisim and attach it to the **prelab report**.

3.2. Experiments

- **<u>Task 1: The Relaxation Oscillator (60%)</u>**

Build an RC oscillator shown in Figure 5. This is composed of a negative resistance converter and a capacitor connected across its input port. You will be provided a breadboard and other elements. Let R_a, R_b and R_f be 10k, 10k, and 4.7k, respectively. Connect a 1μF monolithic ceramic capacitor across the inverting terminal of the op-amp and the ground. This circuit will serve as a time-base generator.
Hint: use V_{DD} = +6V (i.e. V_{pp}= +6V) and V_{ss}= -6V (i.e. V_{nn}= -6V) (on the datasheet these are called +V_S and –V_S) as power supply for LMC6482. Read LMC6482 datasheet to know the functionality of each of its 8 pins. Refer to the basic lab experiment on how the power supply should be connected.

1-a) Output measurement (20pt): Switch on the circuit. Observe and show the output waveform to your TA for check off. Characterize it (amplitude, frequency, duty cycle) in the following block. Is it possible to change the duty cycle? How?

Check Off: ____________

1-b) Driving-point characteristic (15pt): Measure the input current versus to the input voltage. Set the scope to display the driving-point characteristic (X/Y mode). What does the driving-point characteristic look like? Which parts of the driving-point characteristic are visible? Explain the reasons of this behavior. **Hint**: Figure 5-b can help.

1-c) Parameter dependency measurement (15pt):

Follow the following steps and record the value in the table below:

1. Change R_b to 4.7k, measure the frequency and the comparator level V_C.
2. **Set back $\boldsymbol{R_b}$ to 10k** and change R_f to 10k. Repeat the measurement.
3. Now change the capacitance to 10μF. Repeat the measurement.

<table>
<tr><td>Changes of component</td><td>Frequency</td><td>Comparator level</td><td>Sth. else changed?</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">How the waveform has changed (frequency, comparator levels, etc.)? Explain the reasons of these changes.</td></tr>
</table>

1-d) Frequency adjustment (10pt): Without doing other changes (R_b is 10k, C is 10 μF), just replace R_f with a 10k potentiometer. Tune the potentiometer until the frequency is 20Hz and **show it to you TA for check off**. Measure the resistance of your potentiometer **(Pay attention that you need to measure the part which is connected into the circuit)** and check whether it's the same of the theoretical value, if not, try to explain the reason. (The following equation may help)

$$f = \frac{1}{2\ln(3)R_f C}$$

Measured Resistance = ___________ **Theoretical Resistance =** ___________

Task 2: The Triangle Wave Generator (20%)

2-a) (10pt) Build the triangle wave generator (Fig. 6). The input comes from the square wave generated by your relaxation oscillator built in Task 1. Pick R, C based on your previous calculation. Note that our lab doesn't have the capacitors of any value you want. So it's better to choose an appropriate capacitor and use a potentiometer for R. In this task, a 10μF capacitor and a 10k potentiometer is recommended. Tune the potentiometer until the amplitude is 4V. **Show it to your TA for check off and attach the input and output waveform in your report.**

Note: You may want to put 100k resistor across C to discharge excess charge.

Check Off:___________

2-b) (8pt) Once you have finished the oscillator, it would be nice to see some indication that it works. To accomplish this, we can attach an LED to the outputs.

Add and LED to the output of your relaxation in series with an appropriate resistor. Usually a resistor between 0.2k and 1k do the trick. You should now have a blinking LED at 20Hz. Turn the potentiometer and show the LED blink at different frequencies. Now connect a second LED and resistor to the output of your triangle wave generator. Does the intensity of the LED change with time? **Show your set up to TA for check off**.

2-c) (2pt) According to the preceding experiment, could you give an application of the relaxation oscillator?

Prelab

Name ___________ TA ______________________

Teammate ___________ Score ______________________

1. Determine the slope of the linear region of a negative resistance converter in Fig.1 (R_a, R_b, R_f are 10k, 10k, and 4.7k). What is the maximum current in the linear region if E_{sat} equals to 8 V? Please show your steps.

*Answer:*_________________ **/2pt**

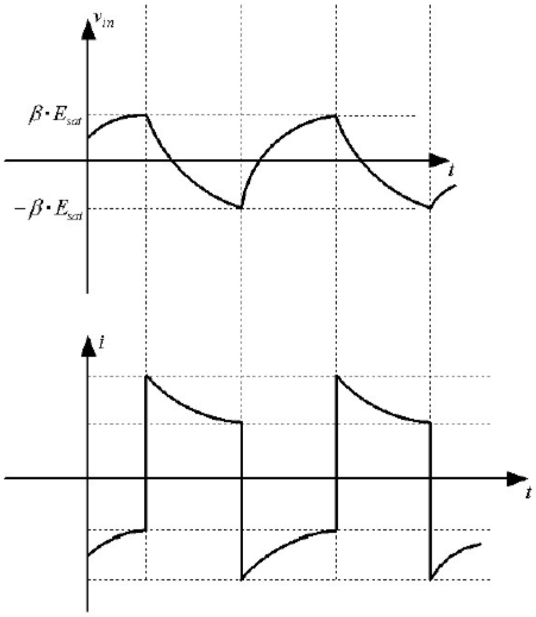
2. Connecting a capacitor across the input of the negative resistance converter produces an oscillatory circuit. Does this circuit work in the linear region, in the saturation region, or in both of them?

Answer: ____ **/1pt**

3. What is the maximum current flowing through the capacitor? (R_a, R_b, R_f are 10k, 10k, and 5.1k, respectively, and E_{sat} is 12V.) Does it depend on the value of the capacitor? Please show your steps below. (Figure 3 may help).

Answer: _______________ **/2pt**

4. Plot the expected $V_o(t)$ waveform of the relaxation oscillator in Fig. 1 of Lab 7 Guide, with respect to the following input waveform i(t) and $V_{in}(t)$.



Your Plot: **/2pt**

5. Find the schematic of the relaxation oscillator in Fig. 1 of Lab 7 Guide. The frequency of the output signal of the relaxation oscillator is given by:

$$f = \frac{1}{2\ln(3)R_f C}$$

For the purpose of this lab, please simulate this circuit in Multisim and attach it to this prelab report. Pick **REASONABLE** values for R_f and C that will give you an oscillation frequency of **about** 20Hz. Note that this part will be implemented in your Lab Session, so **you should avoid to choose some strange values for $\boldsymbol{R_f}$ and C** (e.g. R=95.6 kOhm; C=3.5uF), as a result, don't worry that the frequency may not be accurately 10Hz. Searching on the Internet to find the common values of resistor and capacitor which we often use is recommended. (Hints: You may pick 20k resistors for R_a&R_b and a 10uF resistor for C and solve for R_f using the above formula.)

If you replace $\boldsymbol{R_f}$ with a 10k potentiometer, what happens to the frequency when you turn $\boldsymbol{R_f}$ lower with the same C? You do not need to derive the formula. Please record your resistor value and capacitor value below.

Answers:

R_f = _________ C = _________ Frequency = ____________ **/2pt**

What happens to the frequency when you turn R_f lower? **/1pt**

Please attach the simulation chart, **indicating the frequency of output waveform**.

Tips: You could attach your chart in the end of the Prelab, but you have to **LABEL IT CLEARLY**. (e.g. Fig-5 is corresponding to this problem) **/3pt**

6. In Lab 7 guide 3.1 Task 2, you are required to pick the value of R and C of the inverting integrator and simulate the circuit. Please attach the simulation chart and **LABEL IT CLEARLY.** Indicating the value of R and C in your chart.

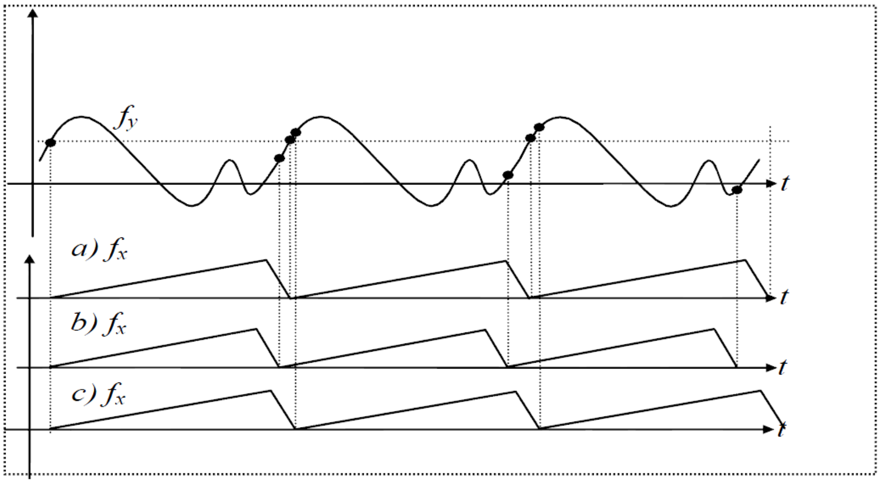
Answers:

R = ________________ C = _________________ **/2pt**

simulation chart: **/2pt**

7. To display a periodic signal stationary on the oscilloscope screen, it is necessary that the input signal (vertical draw) and the sawtooth waveform (horizontal draw) be "synchronized" at all times. This means that the beginning of each sweep must occur at the same position on the input waveform.

1) Consider the following periodic signal f_y and find the f_x sawtooth waveform which is synchronized with the input signal.



Answer: ________________ **/1pt**

2) If the sawtooth waveform is not synchronized to the input signal (frequencies differ slightly) then the displayed waveform will drift slowly to the left or to the right. Find the answer for each case (stationary, drifts left, drifts right).

Answers: **/2pt**

a) ____________________

b) ____________________

c) ____________________