ECE 214 - Lab #5
OpAmp Circuits with Positive Feedback

21 February 2022

Introduction

Two LM741 Operational Amplifiers (OpAmps) are used to produce an oscillator. A block diagram, showing the inputs and outputs, is shown in Figure 1. The input to the circuit is a DC voltage of $+V_{SUP}$. The output of the circuit consists of a ~ 10 V_{pp} square wave and a ~ 5 V_{pp} triangular wave. The oscillator is formed by connecting the output of a Schmitt trigger, shown in Figure 2, to the input of an inverting integrator (see Lab #4), and then connecting the output of the inverting integrator back to the input of the Schmitt trigger. The complete oscillator circuit is shown in Figure 3.

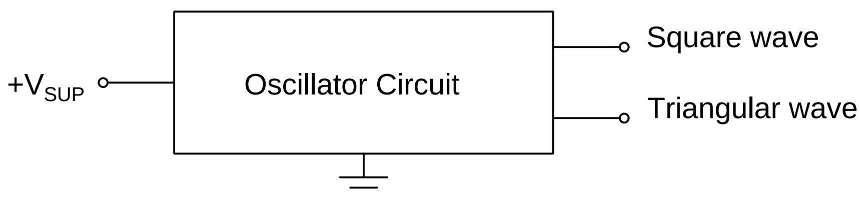


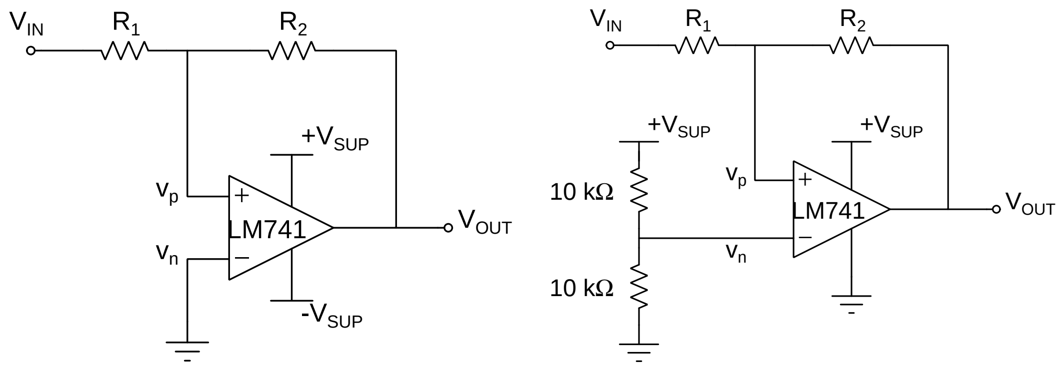
Figure 1: Block diagram of the oscillator circuit showing the inputs and outputs.

Parts List

1. 0.1 μF capacitor (1)
2. 20 kΩ potentiometer (1)
3. Resistor values needed to satisfy the design specification

Circuit Specifications

1. Input: $+V_{SUP} = 12$ V DC
2. Outputs:
   (a) Square wave (10 ± 1 V_{pp})
   (b) Triangular wave (5 ± 0.25 V_{pp})
   (c) Frequency $= 1.5 \pm 0.1$ kHz
   (d) Duty cycle $= 50 \pm 2$%



(a) Schmidtt trigger with dual rail voltages.

(b) Schmitt trigger with a single rail voltage.

Figure 2: Schmitt trigger circuit using an Op Amp with positive feedback.

Pre-Lab

1. There are many ways to implement a Schmitt trigger. One method uses an OpAmp configured with positive feedback as shown in Figure 2(a), for a dual-rail OpAmp, and Figure 2(b) for a single-rail OpAmp. In these circuits, the output of the OpAmp (V_{OUT}) is connected through resistor R_2 to the **non-inverting** input (v_p) of the OpAmp. This results in an amplifier circuit with positive feedback.

   When an OpAmp is configured with positive feedback, $v_p \neq v_n$. Rather V_{out} takes on one of only two values, $+V_{SUP}$ or $-V_{SUP}$. The output voltage $V_{OUT} = +V_{SUP}$ when $v_p > v_n$, and $V_{OUT} = -V_{SUP}$ when $v_p < v_n$. V_{OUT} transitions between $-V_{SUP}$ and $+V_{SUP}$ when $v_p = v_n$. The input voltages V_{IN} that cause the output to switch between $-V_{SUP}$ and $+V_{SUP}$, and between $+V_{SUP}$ and $-V_{SUP}$, are called the trigger levels.

   Assume the OpAmp in Figure 2(b) is ideal. Analyze this circuit and derive an equation for the two trigger levels in terms of the resistor values R_1 and R_2. When $R_1 = 3\ k\Omega$ and $R_2 = 12\ k\Omega$, calculate the trigger levels that cause the output to switch from zero to $+V_{SUP}$, and from $+V_{SUP}$ to zero, and

   (a) Sketch the transfer function as Vin increases from 0 V to $+V_{SUP}$ V,

   (b) Sketch the transfer function as Vin decreases from $+V_{SUP}$ V to 0 V.

   Make sure the two trigger levels are labeled on the sketch.

2. For the Schmitt trigger circuit in Figure 2(b), determine values for resistors R_1 and R_2 so that the separation of the Schmitt trigger levels are 5 ± 0.25 V. Assume the OpAmp is ideal and $+V_{SUP} = 12$ V. With the chosen values of R_1 and R_2, what are the two Schmitt trigger levels?

3. Simulate the transfer function of the Schmitt trigger circuit in Figure 2(b) with the resistor values you calculated in item 2. Set the power supply voltage ($+V_{SUP}$) to 12 VDC, and the input voltage (V_{IN}) to a DC voltage source. Use DC analysis to sweep the input voltage between 0 to 12 V. A MATLAB® file for NGspice is available at `https://ece214.davidkotecki.com/docs/Matlab/ECE214_2022_Lab5_Schmitt.m`. Analyze the simulated behavior of the circuit using both the ideal OpAmp and the LM741 OpAmp.

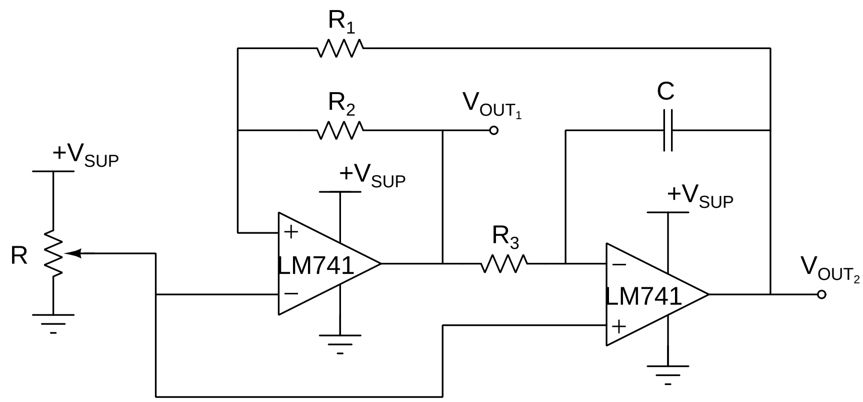


Figure 3: Oscillator circuit using a Schmitt trigger and an inverting integrator.

(a) Simulate the output voltage as the input voltage is increased from 0 V to 12 V.

(b) Simulate the output voltage as the input voltage is decreased from 12 V to 0 V.

(c) What are the trigger levels for the Ideal and LM741 OpAmps?

(d) How does the LM741 OpAmp compare with an ideal OpAmp?

Make sure all axes on your graphs are properly labeled.

4. Do the simulated results for the LM741 OpAmp meet the requirement that the trigger levels are separated by 5 ± 0.25 V? If not, adjust the values of R_1 and R_2 so that the trigger levels meet this requirement.

5. Describe the function of the circuit shown in Figure 3. Assume the variable resistor is set to the mid-point resistance. Sketch the shape of the expected output signals V_{OUT_1} and V_{OUT_2} as a function of time.

6. Assume the OpAmps are ideal. Derive the formula that relates the oscillation frequency to the values of the components R_1, R_2, R_3, and C.

7. With C$= 0.1\,\mu$F, $+V_{SUP} = 12$ V, the variable resistor set at the mid-point, and the values of R_1 and R_2 determined in step 4, use the formula from step 6 to determine the value of R_3 needed to produce an oscillation frequency of 1 kHz.

8. Perform a transient simulation of the circuit of Figure 3 using the Ideal OpAmp. What is the simulated value of the oscillation frequency? What is the duty cycle? A MATLAB® file for NGspice is available at `https://ece214.davidkotecki.com/docs/Matlab/ECE214_2022_Lab5_Osc.m`.

   For the transient simulation, an "initial condition (ic)" is added to ensure that the oscillator starts properly. The following line of code sets the initial condition:
   `.ic v(out1)=5`
   where `out1` is the name of the output node of the Schmitt trigger.

9. Perform a transient simulation of the circuit of Figure 3 using the LM741 OpAmp. Since the OpAmp is not ideal, the value of R_3 you calculated may be off by as much as 20%. Adjust the value of R_3 to produce an oscillation frequency of 1 ± 0.1 kHz.

10. Since the saturation voltages of the opamp are not 0 V and 12 V, the duty cycle of the waveform may not be 50%. If this is the case, adjust the reference voltage produced by the variable resistor to produce a 50 ± 2% duty cycle. You may also have to readjust the value of R_3 to keep the frequency in the range of 1 ± 0.1 kHz.

11. Record in your notebook the final schematic of your oscillator circuit, listing all of the component values.

Lab Procedure

Build the oscillator circuit you recorded in your notebook in Pre-Lab step 11. Include plots of all measured results in your notebook.

1. Measure V_{OUT_1} and V_{OUT_2} on the scope, and compare the measured results to the simulated results. Are the frequency and duty cycle what you expected?

2. Use the FFT function or the Spectrum Analyzer of the AD2 to examine the output signals in the frequency domain.

3. Do you observe both even and odd harmonics in the frequency spectrum? If so, your duty cycle is not 50%. The duty cycle can be adjusted by changing the DC reference voltage that is controlled by the variable resistor. While observing the signal from the spectrum analyzer, adjust the variable resistor to minimize the even harmonics. Determine the reference voltage that minimizes the even harmonics.

4. Because the spice model of the LM741 is only an approximation to the actual opamp, both the oscillation frequency and duty cycle may differ from the specification. If necessary, redesign the oscillator circuit to generate a 1 ± 0.1 kHz output signal with a duty cycle of 50 ± 2%. What are the final values of resistors R_1, R_2, and R_3, and the DC reference voltage at the opamp?

5. Measure the magnitude of the first five harmonics for both the triangular– and square–wave outputs and compare these results to the theoretical values based on the coefficients of the Fourier series.

Post-Lab

Compare the performance of the simulated design with the actual design. How did the final component values of the actual design compare with the simulated design. Did the simulation provide you with a good prediction of the actual circuit performance?