ECE 214 - Lab #5
OpAmp Circuits with Positive Feedback

25 February 2019

Introduction: Two LM741 Operational Amplifiers (OpAmps) are used to produce an oscillator. A system level block diagram is shown in Figure 1. The oscillator is formed by connecting the output of a Schmitt trigger Figure 2 to the input of an inverting integrator, and connecting the output of the inverting integrator back to the input of the Schmitt trigger. The entire oscillator circuit is shown in Figure 3. The only input to the circuit is a DC voltage $+V_{SUP}$. The circuit produces both a square wave and a triangular wave output signal. You are to design an oscillator which meets the following specification:

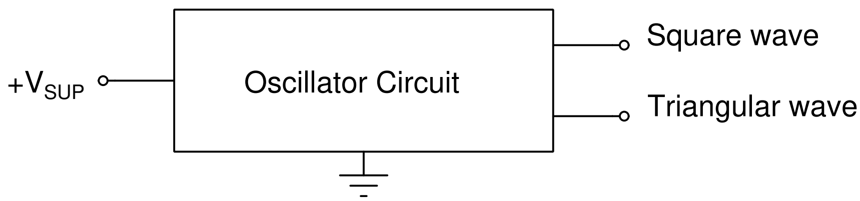


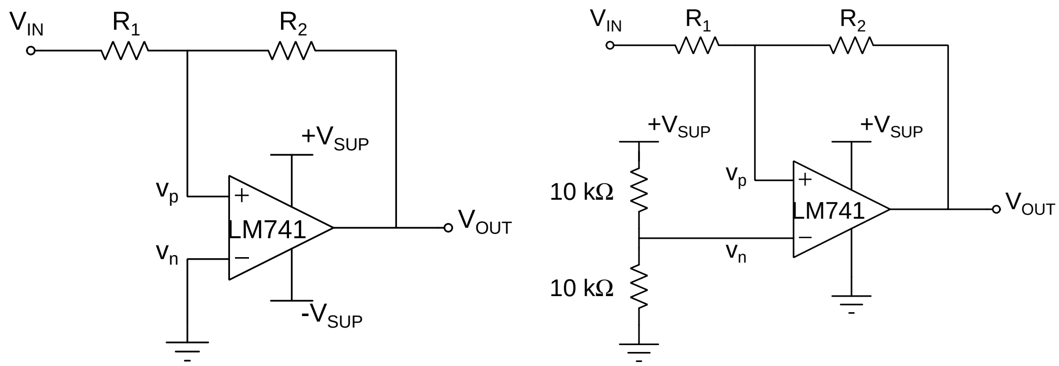
Figure 1: Block diagram of the oscillator circuit.

Circuit Specification:

1. Input: $+V_{SUP} = 10$ V DC
2. Outputs:
   (a) Square wave and triangular wave
   (b) Frequency $= 1.0 \pm 0.05$ kHz
   (c) Duty cycle $= 50 \pm 2\%$

Pre–Lab:

1. There are many ways to implement a Schmitt trigger. One method uses an OpAmp with positive feedback as shown in the circuits in Figure 2. In these circuits, the output (V_{OUT}) is connected through resistor R_2 to the non-inverting input (v_p) of the OpAmp. When an Op Amp 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} which cause the output to switch between $-V_{SUP}$ and $+V_{SUP}$, and between $+V_{SUP}$ and $-V_{SUP}$ are known as the trigger levels.
2. Assume the OpAmp in Figure 2(a) is ideal and $R_1 = 3$ kΩ and $R_2 = 10$ kΩ.
   (a) Sketch the transfer function as Vin increases from $-V_{SUP}$ V to $+V_{SUP}$ V.
   (b) Sketch the transfer function as Vin decreases from $+V_{SUP}$ V to $-V_{SUP}$ V.



(a) Schmidtt trigger circuit with dual rail voltages. (b) Schmitt trigger with a single rail voltage.

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

3. Analyze the Schmitt trigger circuit in Figure 2(b) and determine the values of resistors R_1 and R_2 such that the Schmitt trigger levels are separated by more than 3.5 V, but less than 4.5 V. Assume the OpAmp is ideal and $+V_{SUP} = 10$ V. With the chosen values of R_1 and R_2, what are the two Schmitt trigger levels?

4. Simulate the transfer function of the Schmitt trigger circuit in Figure 2(b) with the resistor values you calculated in step 3. Use DC analysis to sweep the input voltage from 0 to 10 V. Set the power supply voltage to 10 V, and the input to a DC voltage. A MATLAB® template file and an hspc template file are available on the course web site. Analyze the behavior of this circuit using both the ideal OpAmp and the LM741 OpAmp.

   (a) Simulate the output voltage as the input voltage is increased from 0 V to $+V_{SUP}$ V.
   (b) Simulate the output voltage as the input voltage is decreased from $+V_{SUP}$ 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.

5. Do the simulated results for the LM741 OpAmp meet the requirement that the trigger levels are separated by more than 3.5 V, but less than 4.5 V? If not, adjust the values of R_1 and R_2 so that the trigger levels meet this requirement. Record the final values of R_1 and R_2 in your notebook.

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

7. 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. Make an entry in the table of contents indicating the page where the derivation and formula are located.

8. With C$= 0.1\,\mu$F, $+V_{SUP} = 10$ V, and the variable resistor set at the mid-point, use the formula from step 7, and the values of R_1 and R_2 determined in step 3, to determine the value of R_3 needed to produce an oscillation frequency of 1 kHz.

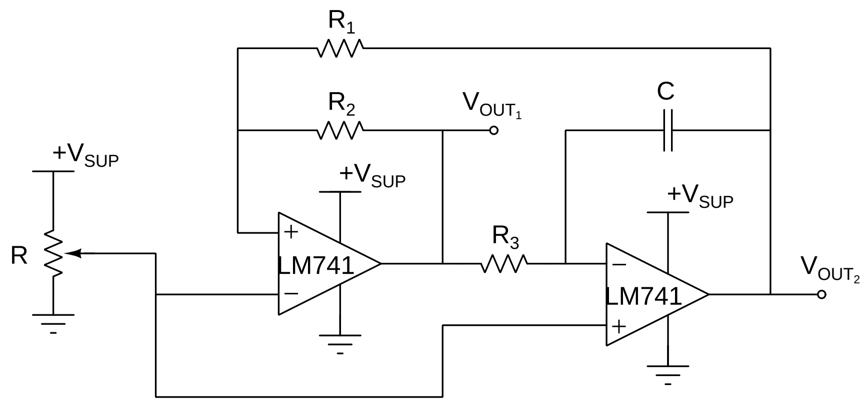


Figure 3: Oscillator circuit using a Schmitt trigger and an inverting integrator.

9. Perform a transient simulation of the circuit of Figure 3 with the LM741 OpAmp. What is the simulated value of the oscillation frequency? What is the duty cycle? You will need to generate your own MATLAB® file and `hspc` file, but can use the MATLAB® and `hspc` files from previous labs as templates.

   For the transient simulation, you may need to add an "initial condition" to ensure that the oscillator starts properly. To add an "initial condition" to the simulation, add the following line of code to the `hspc` file:
   `.ic v(out1)=5`
   where `out1` is the name of the output node of the Schmitt trigger.

10. 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, if needed, to produce an oscillation frequency of 1 ± 0.05 kHz.

11. Since the saturation voltages of the opamp are not 0 V and 10 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 ± 0.05 kHz.

12. 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 12.

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? Include images of V_{OUT_1} and V_{OUT_2} as a function of time in your notebook.

2. Use the FFT function of the scope to examine the output signals in the frequency domain. Include images of V_{OUT_1} and V_{OUT_2} as a function of frequency domain in your notebook.

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 FFT signal on the scope, 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 ± 0.05 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? Include images of V_{OUT_1} and V_{OUT_2}, in both the time domain and the frequency domain, in your notebook.

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. Record the results in a table in your notebook. Reference this table in your table of contents.

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?