

ECEN4618: Experiment #3 Design of a Voltage-Controlled Waveform Generator

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In this lab assignment your task is to design a waveform generator shown in Fig. 1.

The generator is to produce two periodic output waveforms: a triangular-wave output $v_{oi}(t)$ and a square-wave output $v_{os}(t)$. There is one input voltage v_m that controls the frequency f of the output waveforms. The duty ratio D of the output is to be controlled by an adjustable potentiometer R_1 . The two controls should be independent: when R_1 is turned, only the duty ratio should change while the frequency should remain constant; when v_m changes, only the frequency should vary, while the duty ratio should remain constant. Both outputs should have constant amplitudes independent of the duty ratio or frequency settings.

A laboratory pulse generator can perform functions similar to what is described above. Frequency can be adjusted by an external knob, or modulated by an external input voltage. The duty ratio can also be adjusted independently. The lab generator usually allows independent control of the waveform amplitudes, and has a much wider frequency range than what we can achieve in the lab (given generic components, time and breadboard constraints).

The waveform generator belongs to a class of circuits called voltage-controlled oscillators (VCO), where frequency of the generated waveforms is proportional to a voltage input. The VCO is a key component in phase-locked loops (PLL) which in turn are the key components in communication systems. PLL and its applications will be the topic of the lab experiments #4 and #5.

1 Design Specifications

Here is the set of design specifications and constraints for the waveform generator shown in Fig. 1:

1. Only one supply voltage (+15V) is available.
2. Frequency f of the output waveforms is related to the input voltage v_m as:

$$f = K_o v_m$$

$$K_o = 5\text{kHz/V}$$

$$0.5V \leq v_m \leq 10V$$

Therefore, the generator should produce the outputs at the frequency f in the range $2.5\text{kHz} \leq f \leq 50\text{kHz}$. Constant K_o is called the gain of the VCO.

3. By turning R_1 , the duty ratio can be adjusted in the range $0.1 \leq D \leq 0.9$ at any frequency f in the specified range.
4. Turning R_1 should not affect the frequency f . Changing v_m should not affect the duty ratio D .

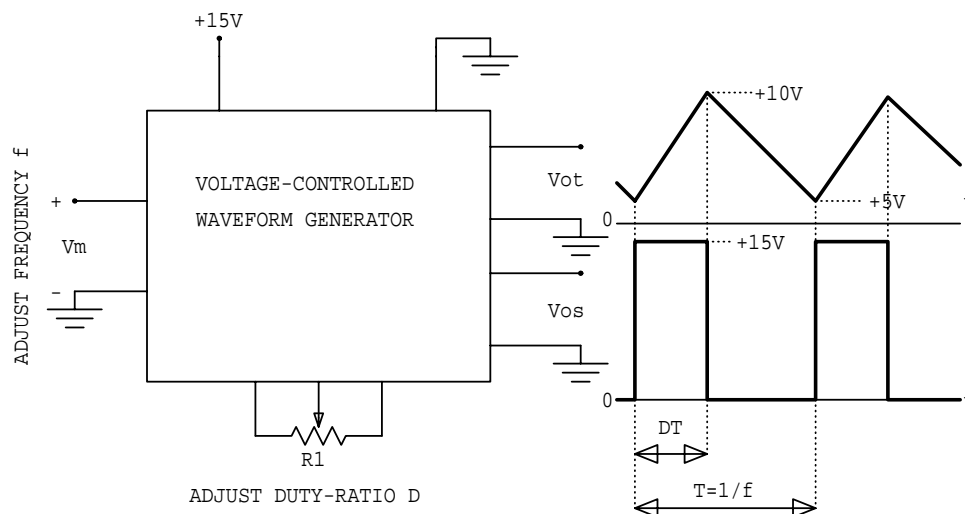


Figure 1: A voltage-controlled waveform generator.

5. The square-wave v_{os} amplitude is 0V to +15V.
6. The rise and the fall times of v_{os} are less than $1\mu s$.
7. The triangular-wave v_{ot} is between +5V and +10V.

2 An Approach to Constructing the Voltage-Controlled Waveform Generator

There are many possible approaches to constructing the generator. This handout outlines only one of the approaches. You are welcome and encouraged to explore other options using general-purpose integrated and discrete components.

The solution outlined in this section can be implemented using a voltage comparator (such as LM311), operational amplifiers (such as LF353) and discrete MOS transistors (such as NMOS ZVN3310A and PMOS ZVP3310A), resistors and capacitors.

The solution is based on the use of a voltage comparator with hysteresis, and an integrator built around an op-amp. Similar circuits were used in the pulse-width modulator design.

Simplified circuit diagram of a basic triangle-wave and square-wave generator is shown in Fig. 2, together with typical waveforms $v_s(t)$ (square wave) and $v_i(t)$ (triangle wave). At $t = 0$, $v_i(0)$ is equal to the upper threshold voltage V_H of the comparator with hysteresis. The comparator output v_s jumps to $+V_X$. As a result, constant current $+V_X/R$ through R discharges the capacitor C , so that

$$v_i(t) = V_H - \frac{V_X}{RC}t, \quad t \geq 0. \quad (1)$$

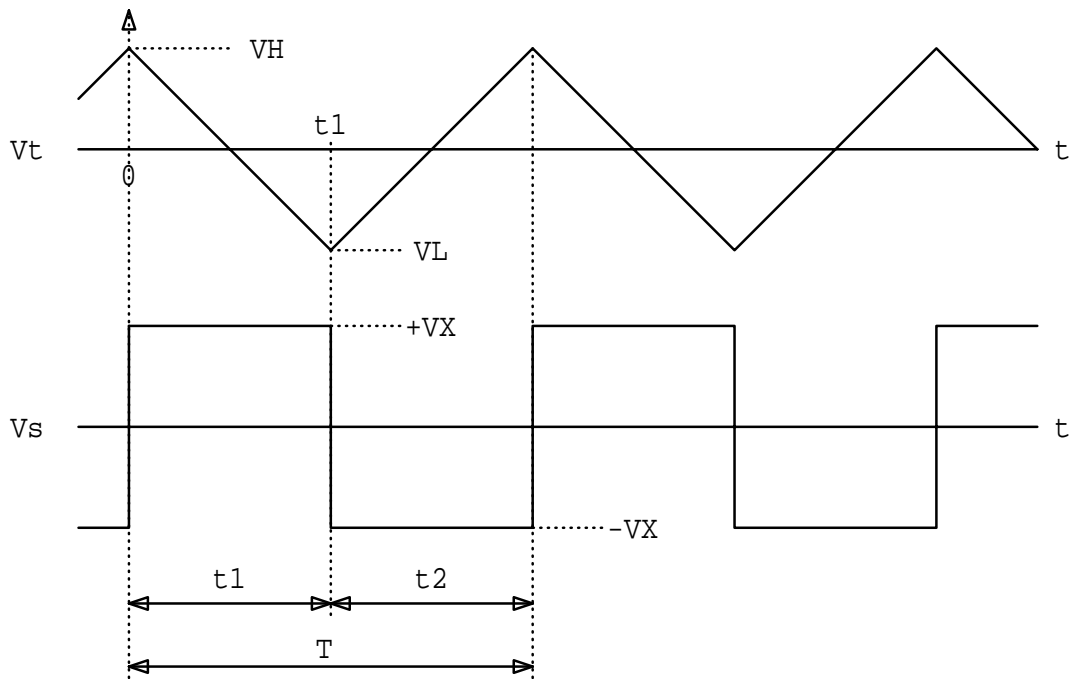
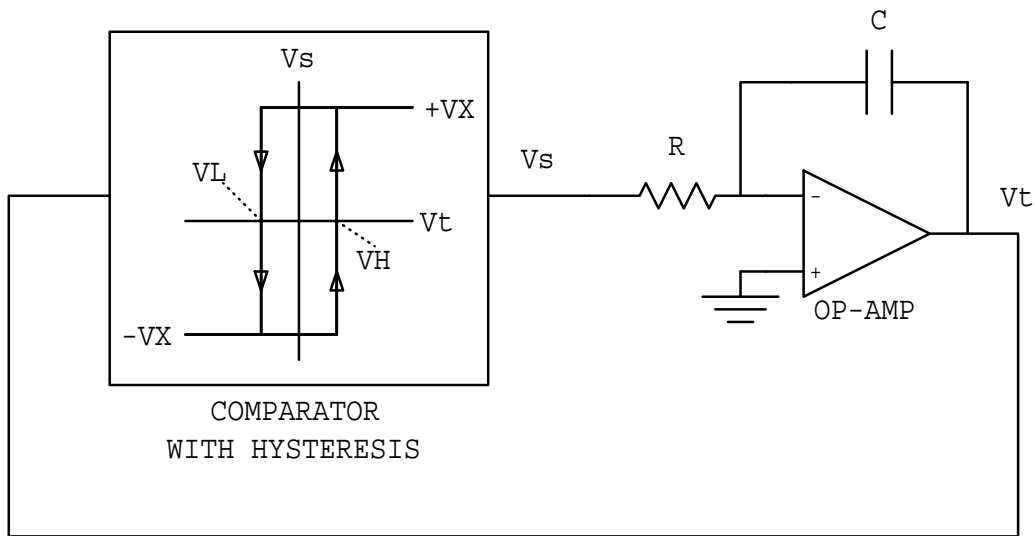


Figure 2: Simplified circuit diagram of a basic triangle-wave/square-wave waveform generator.

The comparator output stays at $v_s = +V_X$ as long as the comparator input voltage v_t is greater than the lower threshold V_L . In the circuit of Fig. 2 it is assumed that the threshold voltages are symmetrical around zero, $V_L = -V_H$. At $t = t_1$, $v_t(t_1) = V_L$, and the output v_s of the comparator with hysteresis jumps to $-V_s$. The time interval t_1 can be found from

$$v_t(t_1) = V_H - \frac{V_X}{RC}t_1 = V_L = -V_H, \quad (2)$$

$$t_1 = RC \frac{2V_H}{V_X}. \quad (3)$$

After the comparator output v_s jumps to $-V_X$, the current through R becomes $-V_X/R$, and this current charges the capacitor. As a result, the op-amp output $v_t(t)$ increases as a linear function of time:

$$v_t(t) = V_L + \frac{V_X}{RC}(t - t_1), \quad t \geq t_1. \quad (4)$$

At $t = T$, the triangle-wave output v_t reaches the upper threshold V_H again, and the comparator output v_s returns to $+V_X$, starting a new period. Period $T = 1/f$ can be found from the condition $v_t(T) = V_H$, or

$$T - t_1 = t_2 = RC \frac{2V_H}{V_X} = t_1, \quad (5)$$

$$T = RC \frac{4V_H}{V_X}. \quad (6)$$

The frequency of the output waveforms is given by

$$f = \frac{1}{T} = \frac{1}{RC} \frac{V_X}{4V_H}. \quad (7)$$

If we compare the operation of the basic triangle-wave/square-wave waveform generator with the actual design requirements, we have the following conclusions:

- The frequency f is *linearly* proportional to the voltage V_X that determines the charging/discharging current through the capacitor. Therefore, V_X could be used to achieve the desired voltage control $f = K_o v_m$. Note, however, that in the circuit of Fig. 2 both $+V_X$ (for discharging) and $-V_X$ (for charging) are needed.
- The amplitude of the triangle wave v_t is determined directly by the threshold voltages V_H and V_L of the comparator with hysteresis.
- The square-wave amplitude is $\pm V_X$, and frequency is proportional to V_X , while the specifications require a constant-amplitude square wave v_{os} .
- The basic circuit has no provisions for changing the output duty ratio. Since the charging and the discharging currents are the same, $t_1 = t_2$, and the output duty ratio is always equal to 50%. To control the duty ratio, the circuit should be modified to include a potentiometer R_1 that would change the ratio of the charging/discharging currents.
- Positive and negative supply voltages are needed to implement the circuit of Fig. 2, while the specifications allow for only one +15V supply voltage.

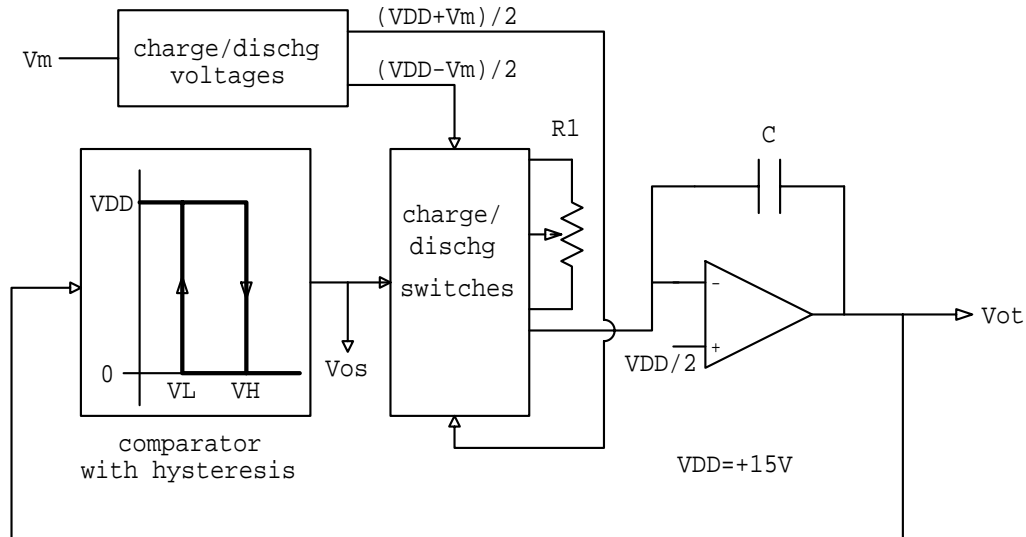


Figure 3: A block diagram of the voltage-controlled triangle-wave/square-wave waveform generator.

To proceed with the design, the basic circuit of Fig. 2 should be modified to generate the required charging/discharging voltages from the input v_m , allow for the duty ratio control using R_1 , and operate from a single +15V supply. A block diagram of one possible solution is shown in Fig. 3.

With $V_{DD} = +15V$, charging and discharging voltages are generated as $(V_{DD} + v_m)/2$ and $(V_{DD} - v_m)/2$, symmetrical around $V_{DD}/2$. These are the voltages that replace $\pm V_X$ in Fig. 2. Note that the + input of the op-amp is also set to $V_{DD}/2$.

The characteristic of the comparator with hysteresis is constructed so that the output triangle wave is between $V_L = +5V$ and $V_H = +10V$. LM311 can be used to implement the comparator with hysteresis.

A block “charge/discharge switches” is inserted between the comparator output and the op-amp integrator, to allow for switching of the charging and discharging voltages and to allow for duty ratio adjustments. Discrete MOS transistors can be used to implement this block. The potentiometer R_1 should be connected so that turning R_1 changes the *balance* of the charging and the discharging current through the capacitor.

3 Experiment

Your main task in the lab is to design and verify operation of the voltage-controlled waveform generator according to the specifications in Section 1. The next task is to make an improvement or modification of the circuit, as discussed in Section 3.1.

Try to follow the modular design/verification approach as in Lab 2: start with constructing and verifying operation of simpler blocks and proceed only when the simpler blocks work as expected. Do not forget about proper power supply decoupling !

In your report you should describe how you arrived at your final circuit: the experiments you performed to verify operation of the blocks and any design modifications you made. Include a complete and labeled circuit diagram of your final solution.

Once you are satisfied with operation of the circuit, do the following experiments:

1. Set the duty ratio at 50% and measure the output frequency f as a function of the input voltage v_m . Include a plot of $f(v_m)$ in your report. Find the actual K_o of your circuit. Test and explain what happens if v_m goes below or above the specified limits.
2. Measure and report the actual amplitudes of v_{ot} and v_{os} at the extremes of the frequency range, for $v_m = 0.5\text{V}$, and for $v_m = 10\text{V}$, with the duty ratio equal to 50%. Measure and report the actual rise and fall times of v_{os} .
3. Set the frequency to the minimum value, for $v_m = 0.5\text{V}$. Measure and report the actual range of duty-ratios that you can obtain by turning R_1 . Repeat the measurement at the highest frequency, for $v_m = 10\text{V}$. Include *labeled* sketches or printouts of the triangular and square-wave output waveforms at the extremes of the frequency and duty-ratio settings (total of 4 sets of waveforms).

In the report, include the corresponding PSpice simulation results and compare the simulation waveforms to the actual measured waveforms. If necessary, make appropriate simplifications of the simulated circuit so that the results can be obtained with the available evaluation version.

4. In (3), you may notice that adjusting the duty ratio introduces some (undesirable) frequency variations and variations in the amplitude of v_{ot} , especially at the highest frequency setting. If this is so, explain why it happens, measure and report how much the frequency and the amplitude change while the duty ratio is adjusted from the minimum to the maximum value. Suggest how this error could be reduced.

3.1 Modifications

After you complete and verify your design, do at least one modification of the waveform generator as described below, or suggest and pursue a modification on your own. Extra-credit will be given for particularly original/good solutions.

1. Modify the generator to allow independent control of the triangle-wave peak-to-peak amplitude, while keeping all other design specifications the same. The triangle wave should be centered around $V_{DD}/2$ but the amplitude should be adjustable by another potentiometer. Adjusting the amplitude should not affect the duty ratio nor the frequency of the output waveforms. Design, on paper, the additional circuitry and experimentally verify its operation. Include a complete, labeled circuit diagram and results of experimental verification in your report.
2. Modify the original design to increase the VCO gain to $K_o = 15\text{kHz/V}$, while keeping all other specifications the same. Include a complete labeled circuit diagram, and test results that illustrate performance of the modified generator.

3. Modify the generator so that the triangle-wave output swings between 0V and +5V, while keeping all other design specifications the same. Include a complete labeled circuit diagram, and test results that illustrate performance of the modified generator.
4. Modify the generator so that it also has a sinusoidal output centered around $V_{DD}/2$, with 2V peak-to-peak amplitude. Include a complete labeled circuit diagram, and test results that illustrate performance of the modified generator.

4 Prelab Assignment

The prelab assignment is due in the lab on the day when you start working on the experiment.

Read the complete Lab 3 handout.

Design (on paper) the voltage-controlled waveform generator shown in Fig. 1, according to the design specifications given in Section 1.

Turn in the complete circuit diagram with all component values. Label the pin numbers on all active devices. Show how you found the component values.

Do PSpice simulations to verify your design. If your design exceeds the number of components allowed by the PSpice evaluation version, you will need to make appropriate simplifications of the simulated circuit. Turn in a sketch of the simulated circuit and the plots of the output waveforms at the maximum output frequency and the two extreme values of the duty ratio.

Make a copy of your prelab work so that you can use it during the Lab sessions.