Function Generator
Op-amp Summing Circuits
Pulse Width Modulation
LM311 Comparator

Objective

The main purpose of this lab is to gain familiarity with use of the op-amp in a non-linear circuit configuration. The LM741 is used as a comparator in a function generator circuit that produces square and triangle wave outputs. A high speed function generator using the LM311 comparator is used to create a pulse-width-modulated waveform. A summing circuit is also investigated.

A word of advice:

This lab involves very high speed signals. For these circuits to work properly, it is extremely important that the layouts you construct in the lab are as neat and physically compact as possible! Power supply bypass capacitors (see Labs 1 and 2) are essential. Running power and ground on the "rail" contacts of your breadboard is strongly recommended. Put some thought into the placement and connection of devices and components on your breadboard to keep connections short.

Prelab

P1.   Function generator: Figure 3.1 shows a function generator circuit that produces both square wave and triangular wave outputs.
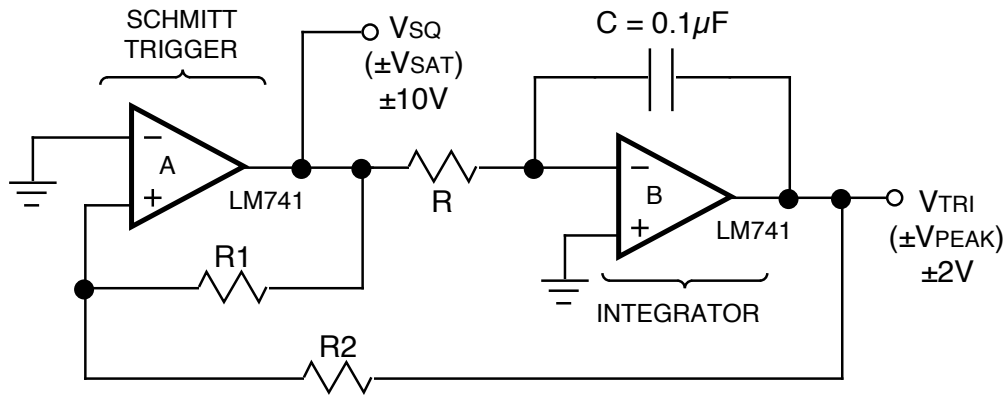

Figure 3.1. Function Generator.

Note that op-amp "A" is connected with **positive** feedback, so that it operates as a comparator (or, more specifically, a Schmitt trigger). We have seen that negative feedback tends to keep the op-amp input voltages close to each other, so that the op-amp operates in its linear region. Conversely, positive feedback tends to drive the op-amp input voltages away from each other, so that the op-amp output is saturated near one of the supply rails at $\pm V_{SAT}$.

Op-amp "B" is connected with negative feedback in the integrator configuration.

P1.1   Determine the waveform frequency as a function of the component values.

There are many ways to analyze this circuit - many complicated, some simple. In general, the simplest analysis results from **intuitively** understanding the function of **each block**. Only from this foundation can we write the appropriate equations for making a formal analysis of the circuit's physical performance. Try the following general procedure:

a)   **Qualitatively** analyze the circuit - no equations yet! How does the circuit function? In this case, for example, assume that the comparator has just switched to one of its two stable states. Then see what the integrator will do in response. Then see if the integrator output will eventually cause another change in the comparator state. Repeat this qualitative analysis and see if the circuit will return to the state from which you began your analysis.

b)   At this point, a sketch of waveforms in the circuit can be extremely helpful. For example, since the goal of the analysis is to determine the output frequency, you might draw the periodic waveforms of interest:
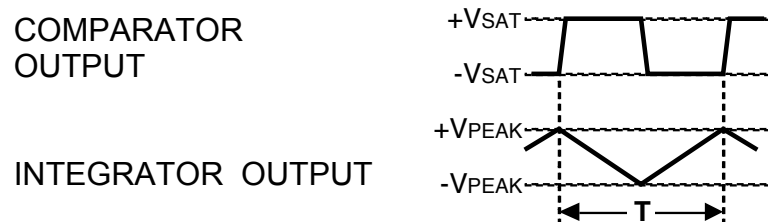
Note that the **shapes** of the waveforms are determined entirely by **qualitative** means: The comparator output will be essentially a digital signal at $+V_{SAT}$ or $-V_{SAT}$; the inverting integrator will ramp up or down in response to a negative or positive input. Ultimately your goal is to write equations for various voltages (such as the maximum integrator output V_{PEAK}) and times (such as the waveform period T), but for now all that is required is to label these variables to gain a clear qualitative understanding of how the circuit functions.

c) Now, based on your understanding of the circuit block functions, superimpose the waveforms on the same time scale in the correct phase relationship. Use plenty of space to avoid clutter and confusion. If necessary, the waveforms can be drawn on separate vertical scales (a "timing diagram").

Now you are ready for quantitative work - writing equations. In this case,

d) For the integrator, determine the period T of the waveform in terms of V_{PEAK}, V_{SAT}, R, and C. It may be more convenient to work with a fraction of the period, T/2, and work from there to an expression for T.

e) For the comparator, determine how the peak integrator level is related to V_{SAT}, R_1, and R_2. Note that the key variable here is the voltage V_X, since the comparator output makes a digital transition whenever V_X crosses zero volts.

f) Finally, combine the above two relationships to get an expression for the period T of the waveform in terms of R_1, R_2, R, and C. The frequency is then $f = 1/T$.

P1.2 Design a circuit, for construction in the lab, to the following specifications:

a) Integrator output: $\pm 2V$.

b) Comparator output: $\pm 10V$.

c) Frequency: 100Hz

All resistor values should be $\geq 10k\Omega$.

P1.3 Which resistor can be used as a frequency control without affecting the triangle wave amplitude? What value would give a frequency of 500Hz?

P1.4 Can the triangular wave amplitude be adjusted independently of frequency by changing only one resistor? If so, which one? If not, what approach would you suggest to realize this capability? (Hint: in the lab we will be using a "quad op-amp": 4 op-amps in one package).

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P2.   Pulse Width Modulation

An interesting (and useful) property of this function generator is that the square wave duty cycle δ can be modulated by an external waveform V_{ext} as shown in Figure 3.2:
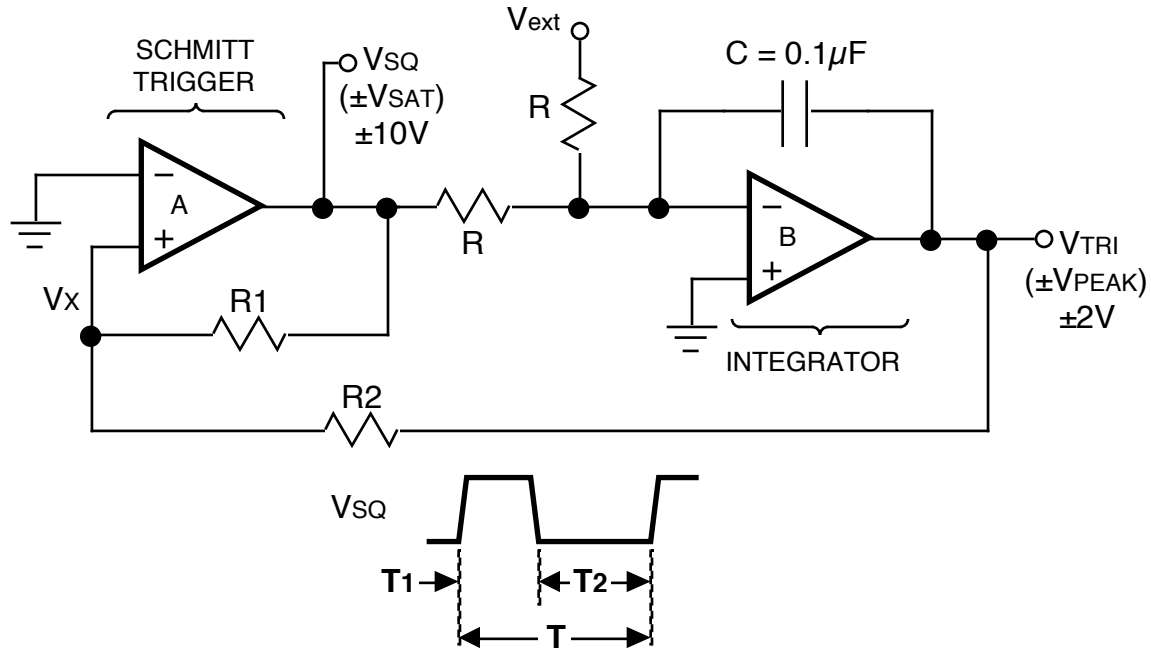

Figure 3.2. PWM Circuit.

The duty cycle δ is defined as the ratio of (the time the signal is in its high state) to (the total period):

$$\delta = \frac{T_1}{T_1 + T_2}$$

P2.1   Show that the duty cycle δ is related to V_{ext} by

$$\delta = \frac{1}{2}\left(1 - \frac{V_{ext}}{V_{SAT}}\right)$$

where $V_{SAT} = +10V$, and $|V_{ext}| < V_{SAT}$. The analysis of the circuit is similar to section 1.1 of the prelab, except that now the positive and negative intervals of the square wave are of different duration and must be determined separately. Assume that the external input V_{ext} is constant during the period T; then derive expressions for T1 and T2 as in prelab part P1.1; finally plug into the expression for duty cycle. Note that when we substitute $V_{ext} = 0$, $\delta = 50\%$ as expected.

If you end up with the incorrect expression

$$\delta = \frac{1}{2}\left(1 - \frac{V_{SAT}}{V_{ext}}\right)$$

you've made a sign error, most probably in the expression for integrator current.

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This form of analog-to-digital conversion is called "pulse-width modulation" (PWM), since the value of the analog signal V_{ext} is encoded in the width of the digital pulse signal V_{SQ}. To function effectively, the frequency of the square wave must be much greater than the maximum frequency of V_{ext}.

When a signal is encoded using PWM, it is usually necessary to have the frequency of the square wave much higher (100X or more) than the maximum frequency of the signal to be encoded. With a square wave frequency of only 100 Hz from P1.2(c), the maximum input signal frequency would be severely limited.

P2.2. For your design from prelab part P1.2, using the same R, R_1, and R_2 values, what value of C would be necessary to result in a 50 kHz square wave?

P3.   Summing amplifier

For this part, we want a circuit to sum the square and triangular waveforms. The sum is to be inverted in phase and scaled as follows:

$$V_{OUT} = -[(0.5)V_{SQ} + (2.5)V_{TRI})]$$

P3.1   Design the circuit to perform this function. One op-amp is to be used; the minimum resistor value is 2kΩ.

P3.2   If this circuit is used with the V_{SQ} and V_{TRI} signals from your function generator design of prelab part P1.2, sketch the expected V_{out} output signal from this summing circuit.

Lab

Function Generator

1. Construct the circuit of Figure 3.1 with your design values from prelab section P1.2. Use the LM348 quad op-amp, which contains four independent LM741 op-amps in a 14-pin package. Begin with the supply voltages at ±12V. Once the circuit is operating, adjust the supplies independently for comparator outputs of $\pm V_{SAT} = \pm 10V$.

    Use three scope channels to look at V_{SQ}, V_{TRI}, and the + input of the op-amp used as a comparator in the Schmitt Trigger.

1.1 Verify your expression for frequency from prelab section P1.2. How well does the measured frequency agree with your prediction? How well does the V_{TRI} amplitude agree with your design prediction? Be sure to record all relevant waveforms in the circuit, dimensioned with appropriate voltages and times.

1.2 Frequency control: Verify frequency control of your circuit by changing frequency to 500Hz using the resistor value you designed for in prelab section P1.3. Does the V_{TRI} amplitude remain the same? Explain.

1.3 How long does it take for the LM741 "comparator" to change states (from $+V_{SAT}$ to $-V_{SAT}$)? What limits is speed? **Estimate** a maximum possible frequency for this function generator when using the LM348 as a comparator.

Summing Amplifier

2. Return the function generator circuit to your component values for f = 100Hz

2.1 Construct the summing amplifier you designed in prelab section P3.1. Use the fourth scope channel to record the measured output signal. How does it compare with what you expect based on prelab section P3.2?

Pulse Width Modulation

This circuit requires a higher speed square wave (about 50kHz), so the LM311 (a fast comparator) is used instead of the LM348 for the comparator function. Construct the function generator circuit shown in Figure 3.3, with the LM311 as the comparator. Use the capacitance value you designed for in prelab part P2.2.
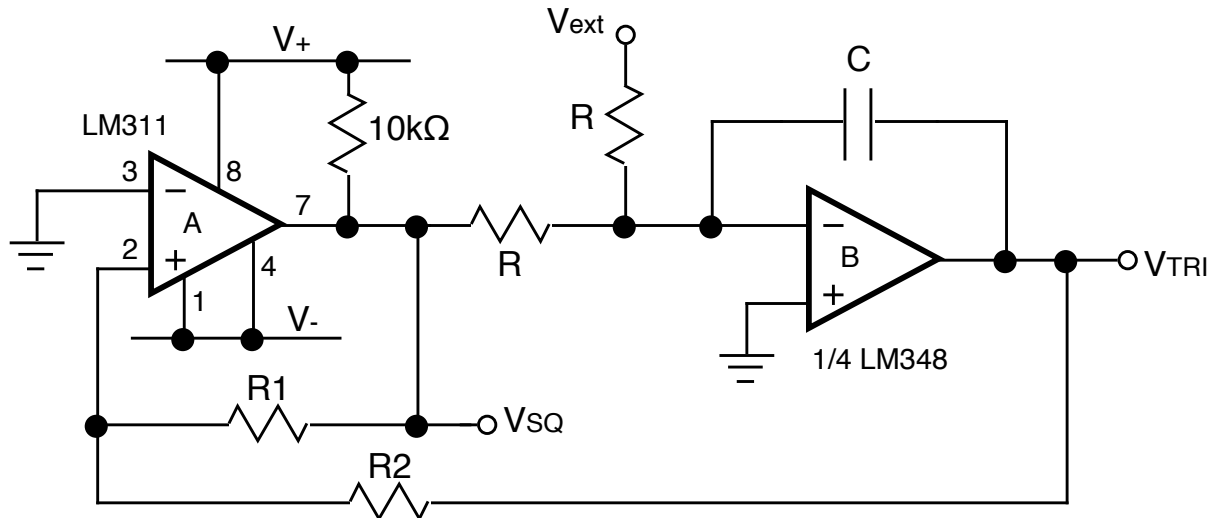

Figure 3.3. 50kHz PWM circuit.

Again, adjust the V_+ and V_- supplies independently for comparator outputs of $\pm V_{SAT} = \pm 10V$.

3.1   With $V_{ext} = 0V$, verify the frequency of approximately 50kHz for V_{SQ}.

3.2   For V_{ext}, use your function generator set to a very low frequency, (about 0.1 Hz) and an amplitude of about 5V peak. On the scope, observe V_{ext} and V_{SQ} and see how varying V_{ext} changes the square wave duty cycle. Also, look at the integrator output to get an intuitive understanding of why the duty cycle is affected by V_{ext}. Use as many of the scope's four channels as necessary to get a good visual indication of how waveforms in this circuit are related to each other.

Since the average value of a square wave is proportional to the duty cycle, the input waveform can be restored with a simple averaging network.

3.3   For V_{ext}, increase the function generator frequency to about 200 Hz. Construct the averaging network (low-pass filter) shown in Figure 3.4. Compare V_{demod} with the PWM input V_{ext}. Explain.
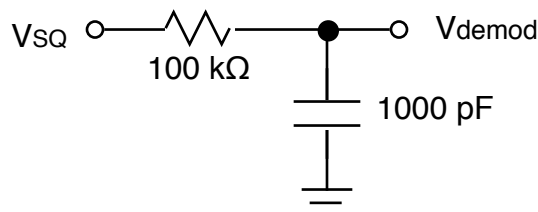

Figure 3.4. Averaging network to demodulate PWM signal.