Laboratory 9: Op Amp Oscillators

Concept

Operational amplifiers can be used as comparators, that is, the output will be either $+V_{cc}$ or $-V_{cc}$ when $V_+ > V_-$ or vice versa. It is possible to devise a comparator with both positive and negative feedback such that there is no stable state of the system. If a time delay is introduced in both feedback circuits, it is possible for such a system to oscillate. This concept is the basis for the square-wave oscillator known as the astable multivibrator. If the astable configuration is modified to introduce an asymmetry in the feedback circuit to one of the inputs, then there will be one stable and one unstable state of the system. This is the basis for the monostable multivibrator, or the one-shot, which will produce the unstable state for a short period of time after a trigger signal is applied.

An inverting integrator and a comparator can be combined to form a potential-controlled sawtooth oscillator commonly known as a “voltage-controlled” oscillator or VCO. The basic concept is to use the output of the comparator to drive a switch which discharges the integrating capacitor. VCOs are used extensively as a parts of very stable oscillator circuits in devices from computers to cell phones.

An operational amplifier circuit also can exhibit oscillation if there is positive feedback at a particular frequency and sufficient gain at that frequency. One way to achieve this condition is to pass the output of an inverting ideal amplifier through a series of CR or RC filters which provide a total phase shift of 180° and then connect it back to the input. The product of gain of the amplifier and the transmission function of the filters must be slightly greater than 1. The internal phase shift of a real amplifier varies with frequency and must be taken into account.

Helpful hints and warnings

Operational amplifiers are integrated circuits (consisting of many internal transistor, diodes, resistors and capacitors) which require a bipolar power source. It is imperative that symmetric positive and negative potentials be applied to the + and - power pins, such as ±12.0 V or ±14.7 V. The power supply should provide ±15 V or less. Check the specification sheet for the absolute maximum power supply potential. Unlike the passive devices encountered in previous laboratory experiments, opamps can be destroyed by the application of excessive potential differences. Remember to connect the power supply ground to the oscilloscope ground. Besides the limitation on the power pins, the two signal inputs also have a limitation on the maximum applied potential. Check the specification sheet. The output of an op amp can be sensitive to changes in the potentials provided by the power supply, $\pm V_{cc}$. It is generally wise to include 100 nF capacitors between each power supply line and the system ground to dampen any such variations.

If you need to create an input signal or DC level using a potential divider, be sure that the *source resistance* of the divider is at least 10 times less than the *input resistance* of the entire opamp circuit. If this condition is not satisfied, then the source you have created will be distorted by the opamp circuit.

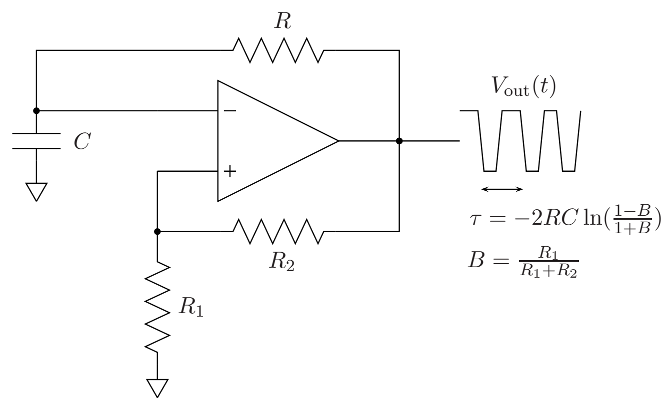
Experimental Instructions

9.1 Astable Multivibrator

Background:
As described in class, this circuit will oscillate when the values of the components are chosen carefully.

Instructions:

1. Construct this circuit choosing values for the resistors and capacitor such that it will oscillate at 1 kHz.
2. Capture the waveforms for $V_{-}(t)$, $V_{+}(t)$ and $V_{out}(t)$, and graph them together. Limit the number of cycles on the graph to at most 2.



Questions to answer:

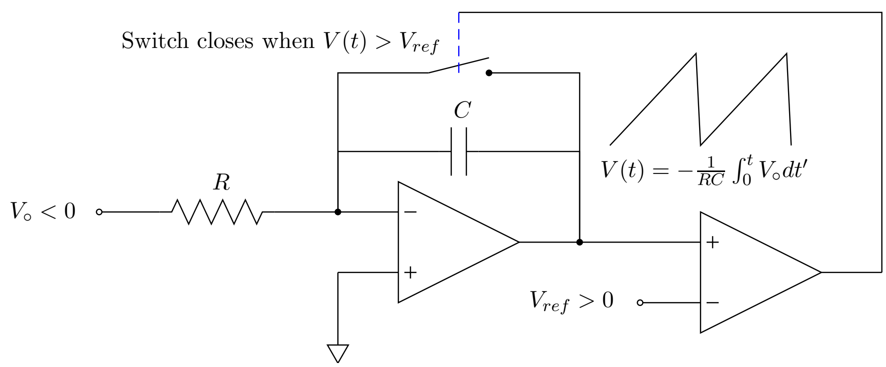
1. Use the combined graph from instruction 2 to explain how this circuit functions.
2. Derive the expression for the period τ, and compare your measured value with the theoretical prediction.
3. What is the maximum frequency at which this circuit can oscillate, and what property of the circuit is responsible for this limit?
4. What is the lowest frequency at which you can make your circuit oscillate?

9.2 Voltage-Controlled Oscillator

Background:
As described in class, the combination of an integrating op amp circuit, a comparator, and a switch that discharges the integrating capacitor in response to the output of the comparator will behave as a potential-controlled (voltage-controlled) oscillator. The frequency changes as V_{ref} and $V_\circ$ change. The sawtooth output can be transformed into a step-function or square-wave form using another comparator. If the output of this oscillator is compared to a very stable reference oscillator using a phase-comparator, the error signal can be used to control V_{ref}. This constitutes a phase-locked loop (PLL) which is a means to generate an oscillating signal with little variation in frequency and phase. PLLs are used extensively in device requiring an oscillator, such as computers, cell phones and radios.

Instructions:

1. Construct this circuit choosing values for the resistors and capacitor such that it will oscillate at 1 kHz.
2. Capture the output waveform graph it. Limit the number of cycles on the graph to at most 2.



Questions to answer:

1. Use the graph from instruction 2 to explain how this circuit functions.
2. Derive the expression for the period τ, and compare your measured value with the theoretical prediction.
3. What is the maximum frequency at which this circuit can oscillate, and what property of the circuit is responsible for this limit?
4. What is the lowest frequency at which you can make your circuit oscillate?

9.3 Phase-Shift Oscillator

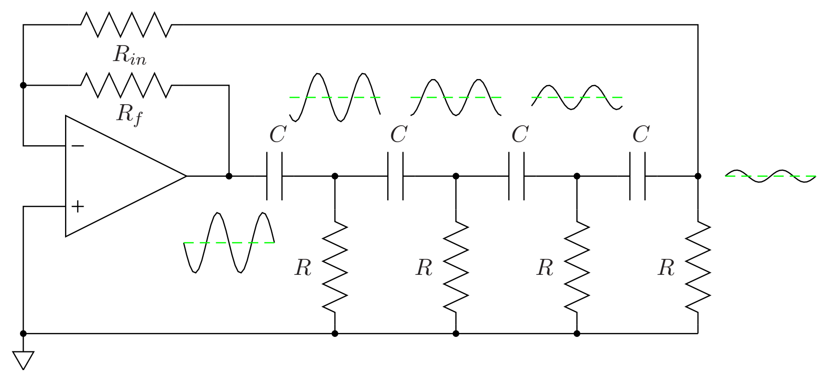
Background:
As described in class, this circuit with a 741 op amp will oscillate. For an ideal op amp with no internal phase shift, the phase shift due to passage through the four CR filters must be 180° for positive feedback to occur in this inverting amplifier configuration. If the filters are identical, then the phase shift per stage must be 45°. To choose the frequency, the fact that the gain of some op-amps falls off rapidly with frequency must be considered. Since the four filters attentuate the signal, the gain of the inverting amplifier might need to be a high as 100. A reasonable frequency is 250 Hz.

Prep Questions:

1. Mathematically show that $\tan^{-1} 1/\omega RC = 45°$ and that the frequency for which this occurs is $\omega = 1/RC$.
2. Show that R =10 k and C =70 nf yields the desired 250 Hz frequency.
3. To choose the gain of the inverting amplifier, you must first determine the attentuation of the four stage filter. Show theoretically that the total transmission amplitude is simply 1/4. The gain of the amplifier will have to be greater than -4.
4.

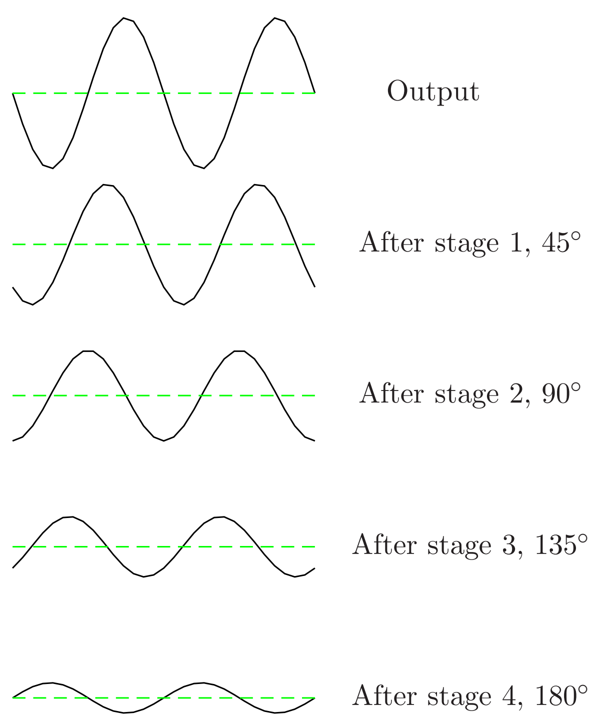
Instructions:

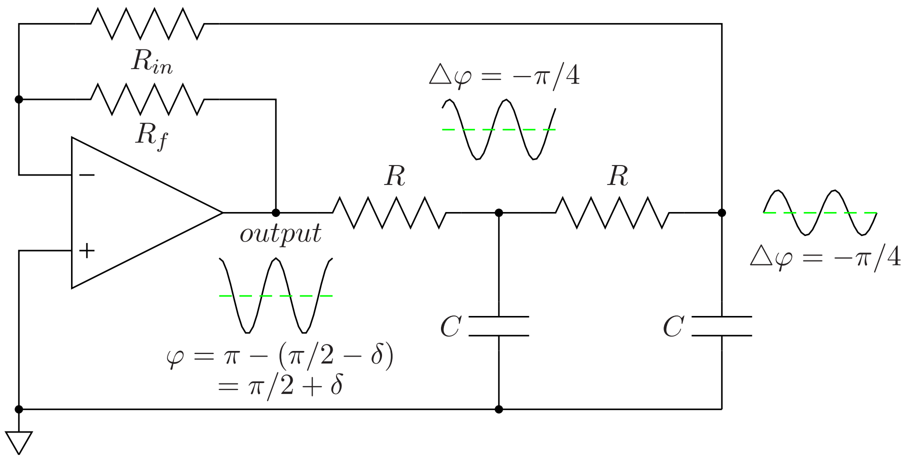
1. Build this circuit with these suggested values of R and C. For a real op-amp circuit, the behavior will deviate significantly from the ideal behavior. In fact, the gain will need to be about -60. Some adjustability can be included by using a fixed resistor and pot combination for either R_f or R_{in}.
2. Adjust your circuit for oscillation and measure the frequency. If the waveform is not sinusoidal, try lowering the gain to improve the shape.
3. Lower the gain to the threshhold for oscillation and observe the behavior. Can you see the oscillation slowly build when the power is turned on? Measure R_f and R_{in} and determine the actual gain of your circuit.
4. Measure the waveforms at the points indicated in the diagram, and determine the change in phase and amplitude that occurs as the signal passes through each stage.
5. Try to push the frequency of oscillation higher. One possibility is to try to reach the high end of the frequency response of the op-amp by utilizing the fact that, since the op amp open-loop gain exhibits the frequency dependence of an RC low-pass filter, there is an additional phase shift approaching $-\pi/2$ as $\omega \to \infty$. Only two low-pass RC stages can be used to provide an additional phase shift of $-\pi/2$. For each filter, $\tan^{-1} \omega RC = \pi/4$, so the frequency of oscillation should be $\omega = 1/RC$. 200 kHz oscillation might be possible.



Questions to answer:

1. Compare the observed and calculated frequencies.
2. Determine the total phase change and transmission amplitude for your four stage filter.
3. What is the product of your measured gain and transmission amplitude?
4. Can you account for all the phase shifts in this circuit?




R_{in}
R_f
$\triangle\varphi = -\pi/4$
R
R
output
$\triangle\varphi = -\pi/4$
C
C
$\varphi = \pi - (\pi/2 - \delta)$
$= \pi/2 + \delta$