Electronic Instrumentation
ENGR-4300 Fall 2004 Sec _______

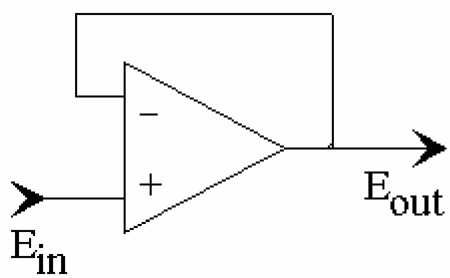
Experiment 8
Op Amp Configurations – Integrator, Differentiator, Voltage Follower

Purpose: In this experiment, we will look at two of the standard op amp configurations that give us the mathematical operations of differentiation and integration. Also we will see how we can add just about any kind of load to an amplifier and not change its performance by using a voltage follower.

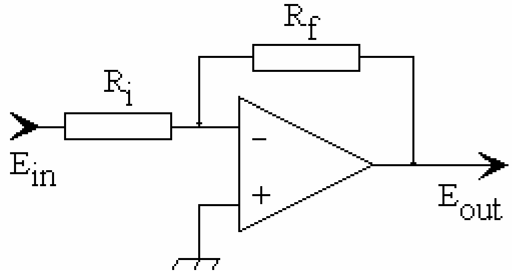
Background: Before proceeding, please review pg 76-79, 88-99, 127,128 in *The Essence of Analog Electronics* which he describes various mathematical operations that can be performed with op amps. You will see that it is quite easy to perform additions, subtractions, derivatives and integrals. That is why collections of op amp circuits have been used in the past to represent dynamic systems in what is called an analog computer. There are some very good pictures of analog computers and other computers through the ages at H. A. Layer's Mind Machine Web Museum at http://userwww.sfsu.edu/~hl/mmm.html
Finally, check out the websites listed in the helpful info section of the course web page. Some of the highlights of these pages have been extracted below. *Please note that both V and E are used to represent voltage.*

Op-Amp Configurations

We will be considering several basic op-amp configurations. The first is the voltage follower



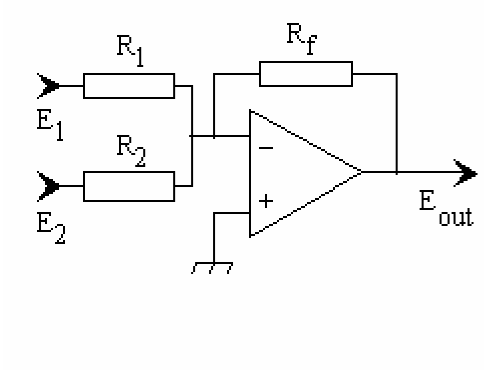
where E_{in} is the input voltage and E_{out} is the output voltage. The non-inverting voltage follower is a configuration that can serve as an impedance matching device. For an ideal op-amp, the voltages at the two input terminal must be the same and no current can enter or leave either terminal. Thus, the input and output voltages are the same and $Z_{in} = E_{in}/I_{in} \to \infty$. In practice Z_{in} is very large which means that the voltage follower does not load down the source. The second is an inverting amplifier



(*Another note on notation: The symbol with the three legs connected to the non-inverting input is another symbol for ground.*) The inverter with voltage gain amplifies the signal and changes its sign, $E_{out} = -E_{in}(R_f/R_i)$. It is possible to select $R_i = R_f$ which just changes the sign of the input. More than one input can be used if we wish to add signals. To construct this circuit, use two or more input resistors in parallel. The resistors are all connected to the common or summing point of the circuit. By using the basic design rules for operational amplifiers, it is easily shown that the output voltage will be

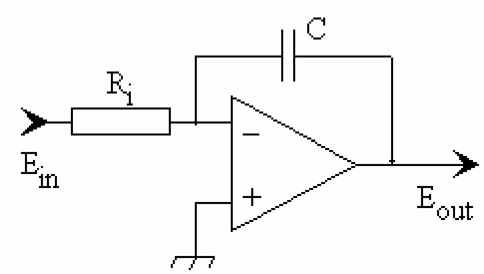
$$E_{out} = -R_f \sum_{i=1}^{n} \frac{E_i}{R_i}$$

where n is the number of input resistors. The input resistors can have any values but this circuit generally uses the same values for the R_{in}.

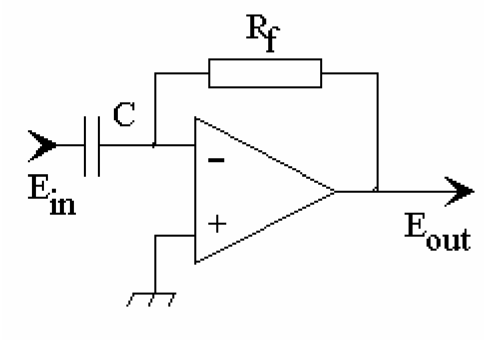


Also recall that there is an op-amp configuration which will not invert the output. This is called a non-inverting amplifier and was introduced to you in experiment 4.

The next configuration is known as the ideal integrator. The circuit is similar to the voltage inverting amplifier, only the feedback resistor is replaced with a capacitor. As a practical device, this configuration does not work unless there is also a resistor included in parallel with the feedback capacitor, as is discussed below.



An analog differentiator circuit can be constructed by using a capacitor as the input element and a resistor in the feedback position of the inverter circuit.

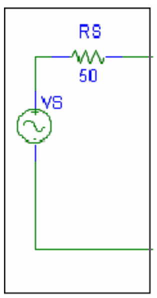


Basic Circuit Blocks

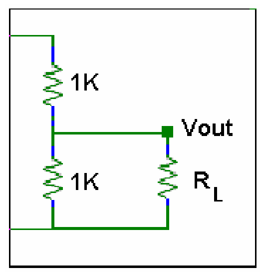
In this experiment, we will be connecting a voltage divider to the function generator, but not directly. We will first modify the source signal using a circuit that will introduce enough impedance to adversely affect the function of the voltage divider. Then we will add a voltage follower and demonstrate that we can isolate the voltage divider from the rest of the circuit to make it work correctly.

In order to do this, we need a circuit with components that can represent impedances we have placed in our circuit on purpose or parasitic impedances that come from interactions between wires. The circuit we have chosen is a combination of an integrator and a differentiator. It performs neither of these functions (because it tries to do both), but it has the impedance that we need to demonstrate the usefulness of a voltage follower.

There are several basic circuit blocks that we will use in this experiment: the function generator, the circuit with impedance, the voltage follower (optional), the voltage divider, and a load. Rather than drawing the entire circuit at once, it is more instructive to show the blocks separately, so that each function can be identified. First there is the function generator, that we will represent as a Thevenin equivalent, followed by the voltage divider with a load at the center pin. We know that R_L will affect the voltage at Vout depending upon its size. Calculate what Vout should be when R_L is equal to 1 Meg, 1K and 100 ohms.

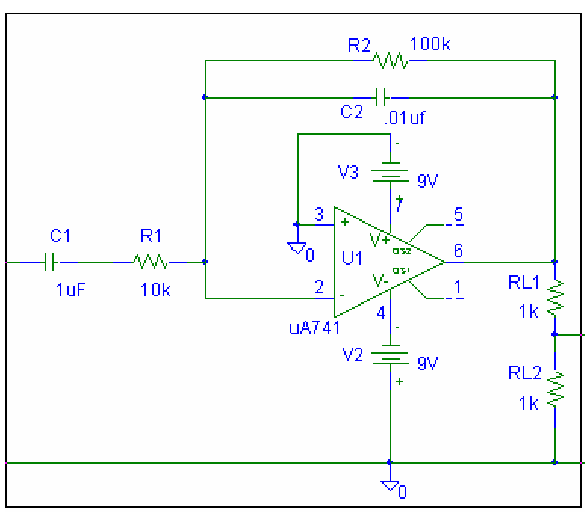


Function Generator



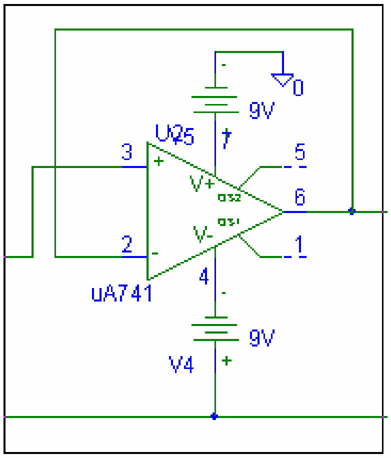
Load

Next is our circuit with impedance. This is the basic op amp configuration with enough components to be either an integrator or differentiator.



General Op-Amp Configuration

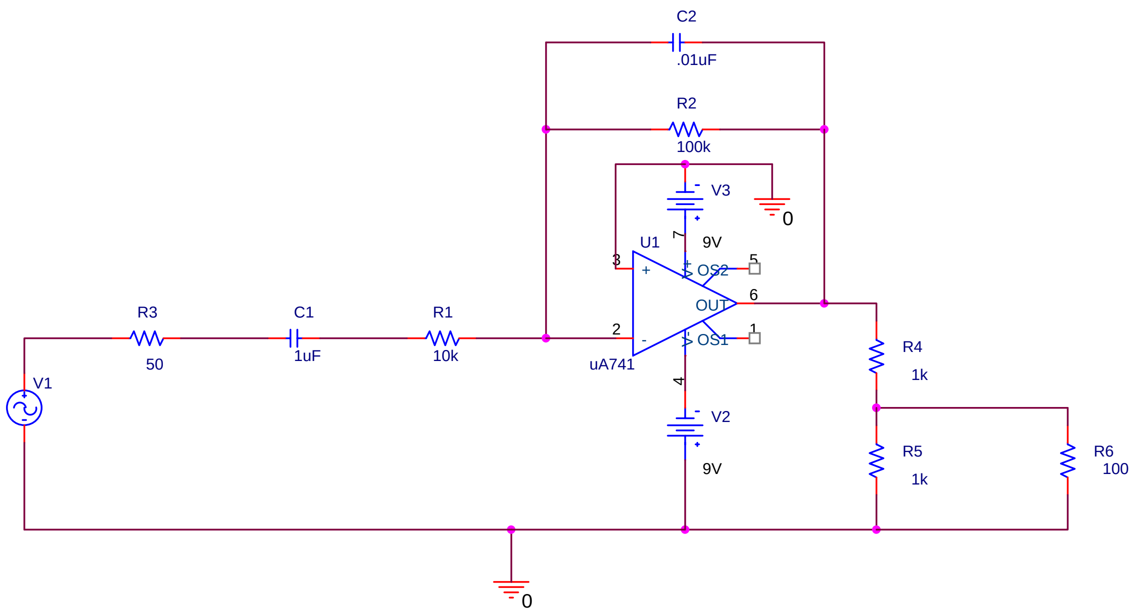
Finally, the voltage follower:



Voltage Follower

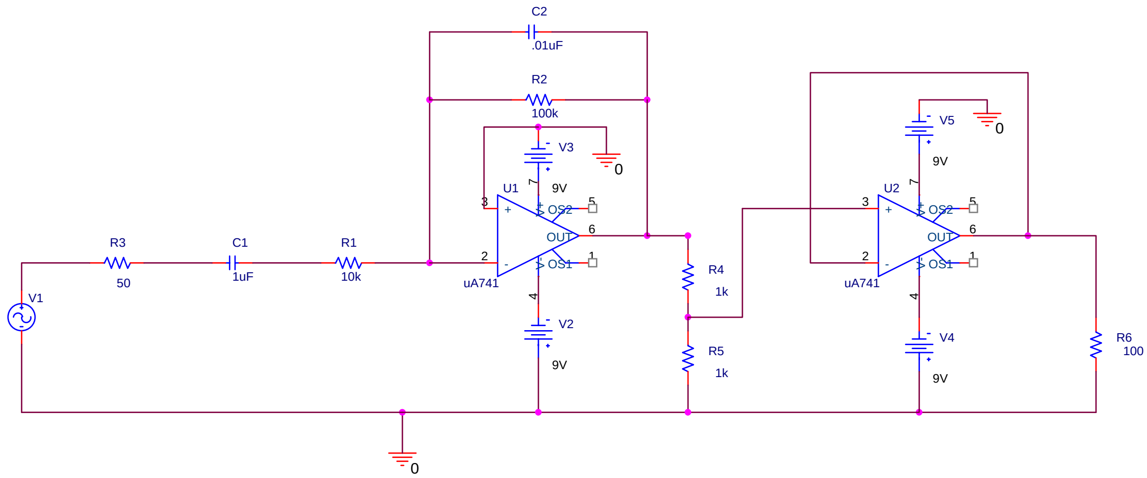
Part A The Voltage Follower

Begin by simulating the circuit consisting of the source, the impedance op amp circuit, the voltage divider, and the load. We will add the voltage follower next. Use a source voltage of 1 volt and a frequency of 1kHz. Do an AC Sweep from 1 Hz to 100 kHz. *Obtain a plot* of the output showing the voltages at the output of the function generator (before the first capacitor), at pin 6 of the op amp, and at the center of the voltage divider. Note that you are plotting the input signal, the output of the op amp circuit (pin 6), and the voltage across the 100 ohm load resistor. Is the amplitude of the voltage across the load relative to the voltage at pin 6 consistent with your expectations for a 100 ohm load resistor?



Now we can demonstrate the way a voltage follower can isolate a load from the rest of the circuit. Add the voltage follower circuit between the voltage divider output and the load (see below). Do the same AC sweep and obtain a plot of the output. What similarities and differences do you observe between the two sweep outputs? It is said that the voltage follower (also called a buffer amplifier) is used to isolate a signal source from a load. From your results, can you explain what that means?

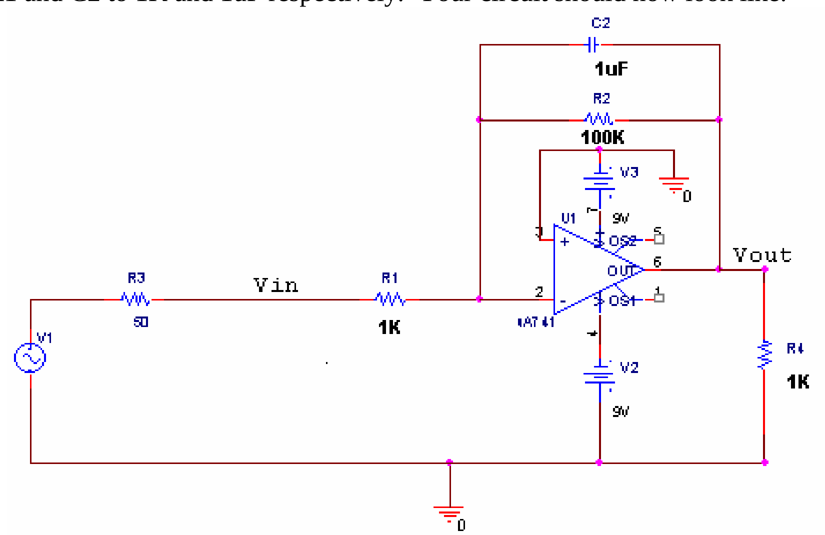
Voltage followers are not perfect. They are not able to work properly under all conditions. To see this, do a transient analysis of the circuit in steps of 10 us for a total time of 10 ms. You should see the circuit working more or less as you would expect. Now change the load resistor to 10 ohms and do the transient analysis again. What do you observe now? Can you explain it? Refer to the spec sheet for the 741 op amp. How have we changed the current through the chip by adding a smaller load resistance?



Finally, it was noted above that the input impedance of the voltage follower should be very large. Determine the input impedance by finding the ratio of the input voltage to the input current for the follower. That is, find the ratio of the voltage to the current for the non-inverting input of this device. Since PSpice tries to be as realistic as possible, you should get a large but not infinite number. Recall that R=V/I. We can obtain the voltage we need by placing a voltage marker at the non-inverting input. However, it is not as easy to identify current. Fortunately, we can use what we know about basic circuits to figure it out. The current we need is the difference between the current through R4 and R5. From your AC sweep results, plot V(U2:+)/(I(R4)-I(R5)). Note that your voltage divider resistors might have different names if you placed them on the schematic in a different order. You will note that we are getting into the noise levels for the simulation, so that the plot will be ragged. Around what value is the input impedance? Is this “a large but not infinite” number? Include this plot.

Part B Integrator

In this section, we will observe the operation of an integrator. Modify your circuit from part A. Remove the voltage divider and the voltage follower. Replace them with a 1k load resistor. Remove C1 and change the values of R1 and C2 to 1K and 1uF respectively. Your circuit should now look like:



Repeat the transient analysis of this circuit and obtain a plot of your results. Just like in mathematical integration, integrators can add a DC offset to the result. Adjust your input so that it is centered around zero by adding a trace that adds or subtracts the appropriate DC value. Print this plot.

The equation that governs the behavior of this integrator at high frequencies is given by:

$$if \quad \omega_c >> \frac{1}{R_2C_2} \quad then \quad v_{out}(t) \approx -\frac{1}{R_1C_2}\int v_{in}(t)dt$$

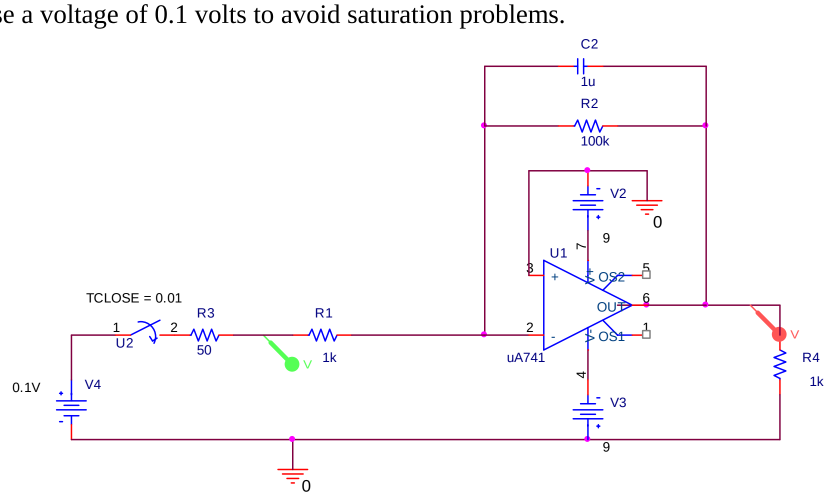
Recall that the integration of sin(ωt) = (-1/ω)cos(ωt). Therefore, the circuit attenuates the integration of the input by a constant equal to -1/ωR1C2. The negative sign means that the output should also be inverted. What is there about the transient response that tells you that the circuit is working correctly? Is the phase as expected? The amplitude? Above what frequencies should we expect this kind of behavior?

Now we can look at the behavior of the circuit for all frequencies. Repeat the AC sweep you did in part A. In addition to the voltage, plot the phase of the voltage at Vout. What should the value of the phase be (approximately) if the circuit is to be working more or less like an integrator. Print this plot. Mark the frequency fc=1/2πR2C2. Also mark the frequency above which the circuit is within 5 degrees of the desired phase shift.

We can also use PSpice to check the magnitude to see when this circuit acts best as an integrator. Using the equation above, we know that at frequencies above fc, $V_{out} = -V_{in}/(\omega RC)$, where R = R1, C = C2, and ω=2πf. In our PSpice simulation, V_{in} is the output voltage of the function generator (voltage between R3 and R1), while V_{out} is the voltage at pin 6 of the op-amp. Change the plot for the AC sweep to show just V_{out} and $-V_{in}/(\omega RC)$. Note that you need to input the frequency ω as 2*pi*Frequency in your PSpice plot. (Pspice recognizes the word “pi” as the value of π and the word “Frequency” as the current input frequency to the circuit.) When are these two signals approximately equal? It is at these frequencies that the circuit is acting like an integrator. Print out this plot and indicate fc=1/2πR2C2. How close are the amplitudes of the two signals at that frequency? Also indicate on the plot the approximate frequency above which the two signals are equal.

What will happen if we change the value of the capacitor? Try increasing C2 to 10μF. Run the transient analysis at 1k Hz. What happens to the phase and the amplitude? Print this plot. Now decrease C2 to 0.01μF. Run the transient analysis again. What happens to the phase and the amplitude this time? Print this plot. (Note that the op-amp is saturating for part of this plot. What feature of the output signal tells us this?)

As indicated below, a more direct way of demonstrating that integration can be accomplished with this circuit is to replace the source with a DC source and a switch. Note that the switch is set to close at time t=0.01 sec. Use a voltage of 0.1 volts to avoid saturation problems.



Do the transient analysis for times from 0 to 50ms with a step of 10us. Rather than plotting the output voltage (voltage at Vout), plot the negative of the output voltage. You should see that this circuit does seem to integrate reasonably well. Indicate on your plot how close it has come to doing what it is designed to do. Calculate the approximate slope of the output. Write it on your output plot. Also write the theoretical slope on the plot. What should the integral of a constant input of 0.1 volts be? Does it do its job for the entire simulation time?

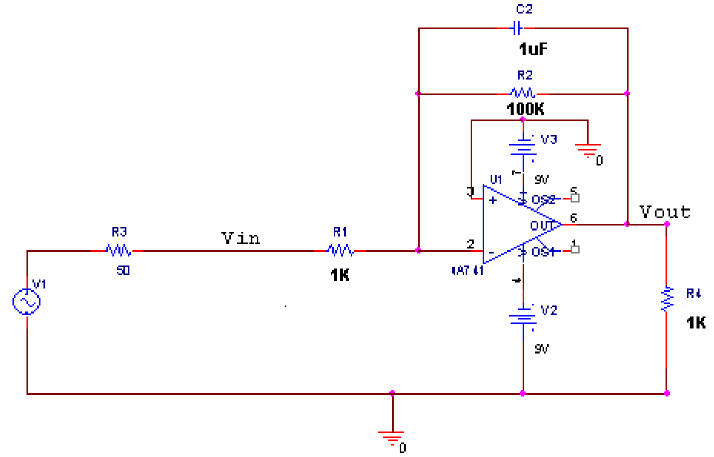
To show what our problem was before when it did not produce an output proportional to the integral, decrease C2 to 0.01μF and repeat the simulation. Don't forget to plot the negative of the output voltage. Print your output. Mark the theoretical slope on the plot. Describe the performance of the circuit. That is, does it integrate -- even approximately -- for any period of time? Can you think of any reason why we might prefer to use a smaller capacitor in the feedback loop, even though the circuit does not integrate quite as well?

Please note that the ideal integrator does not have a feedback resistor. We have been looking at the configuration with such a resistor because it is more practical. This configuration is often called a "Miller Integrator". In this course we also refer to it as a "Real Integrator". Now we will look at why, although an ideal integrator works in theory, we need to include the feedback resistor in any real circuit to get it to work.

Set the feedback capacitor back to its initial value of 1uF. Remove the resistor from the feedback loop and run your transient analysis again. You should see that the circuit no longer works. Negate the output voltage again and plot your results. Indicate what is wrong with the output The circuit will operate on both the AC and DC inputs; and -- in any real circuit and no matter how good your equipment is -- there will always be a small DC offset voltage at the inputs. The problem with this circuit is that there is no DC feedback to keep the DC offset at the input from being integrated. Therefore, the output voltage will continuously increase and, in addition, it will be amplified by the full intrinsic gain of the op-amp. This immediately saturates the op-amp.

Part C Hardware Inplementation

Using a 741 op amp, set up the integrator configuration with the 1μf capacitor as shown below. Do not include the voltage divider and the buffer. Use the sine wave from the function generator for the voltage source, set the amplitude to 0.1 V (remember to use the 'scope to set the amplitude correctly). Obtain measurements of the input and output voltages at frequencies of 10Hz, 100Hz, and 1kHz. Add your experimental points to your PSpice plot (AC sweep plot with phase from part B). Obtain a picture of each of these signals with the Agilent Intuilink software.

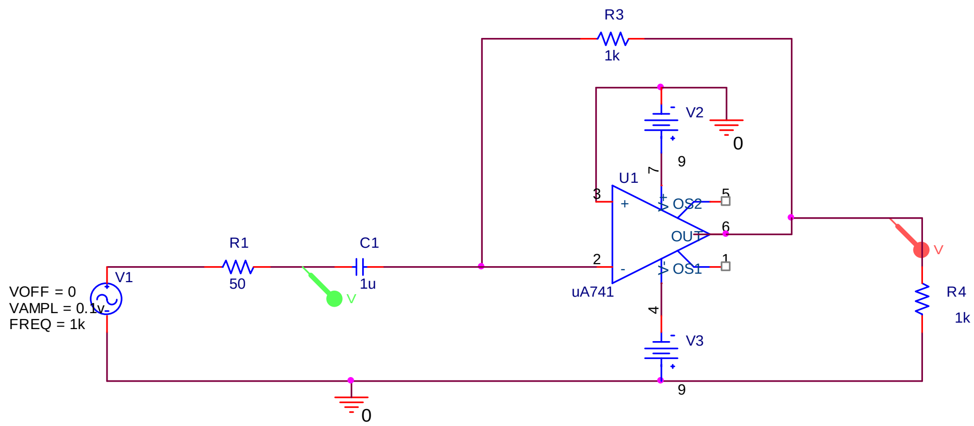


Set the function generator to a frequency which gives a reasonable signal amplitude and integrates fairly well. This is somewhat subjective, we just want you to see the shapes of the outputs for different input wave shapes. You can use this to verify that the circuit does indeed integtrate. Set the function generator to the following types of inputs:

1. sine wave
2. triangular wave
3. square wave

Take a picture of each situation with the Agilent software.

Now we will create a differentiator. Remove the feedback capacitor, C2. Replace R1 with an input capacitor, C1=1μF . Replace the 100K feedback resistor with a 1K resistor. Your circuit should now look like this:



Set the function generator to a frequency which gives a reasonable signal amplitude and differentiates fairly well. Take a picture of the output and the input when the function generator is adjusted to the following types of inputs:

1. sine wave
2. triangular wave
3. square wave

Take a picture of each situation with the Agilent software.

Results and Conclusions

The following should be included in your report. Everything should be labeled and easy to find. Partial credit will be deducted for poor labeling or unclear presentation.

Part A:

Include the following plots:

1. PSpice AC sweep without voltage follower (1 pt)
2. PSpice AC sweep with voltage follower (1 pt)
3. PSPice plot of voltage follower input impedance (1 pt)

Answer the following questions:

1. Compare the AC sweep outputs with and without the buffer circuit in place. What is the function of the buffer circuit? (1 pt)
2. Why is the follower unable to work properly with a small load resistor? (1 pt)
3. What is the typical value of the input impedance of the voltage follower when it is working properly? (1 pt)

Part B:

Include the following plots:

1. PSpice transient plot of integrator (C2=1uF) (1 pt)

2. AC sweep plot of integrator voltage (with three points marked) and phase (with three points marked). Also the loacation of fc and the place where the phase becomes close to ideal should be indicated. (1 pt)
3. PSpice plot of Vout vs. -Vin/ωRC. On this plot, fc and the frequency, where the output and input become equal, should be marked..(1 pt)
4. PSpice transient plot of integrator (C2=10uF) (0.5 pt)
5. PSpice transient plot of integrator (C2=0.01uF) (0.5 pt)
6. PSpice plot of integrator with DC source (C2=1uF) with slope and theoretical slope (if any) indicated on plot. (0.5 pt)
7. PSpice plot of integrator with DC source (C2=0.01uF) with slope and theoretical slope (if any) indicated on plot. (0.5 pt)
8. PSpice plot of ideal integrator (without feedback resistor) (1 pt)

Answer the following questions:

1. Derive the relationship between V_{out} and V_{in} for the integrator circuit, as described above. (1 pt)
2. What are the features of the AC sweep and transient analysis of an integrator that shows it is working more-or-less correctly? Consider the phase shift and the change in amplitude of the output in relation to the input. (1 pt)
3. Why would we prefer to use the 1uF capacitor in the feedback loop, even though the circuit does not integrate quite as well? (1 pt)
4. Why is the integrator also called a low-pass filter? Take the limits of the transfer function at high and low frequencies to demonstrate this. (1 pt)

Part C:

Include the following plots:

1. Agilent Intuilink pictures of your circuit trace (input vs. output) at 100 Hz, 1K Hz and 2K Hz. (3 plots) (1 pt)
2. Agilent Intuilink pictures of your integrator output with sine wave, triangular wave and square wave inputs (input vs. output) (3 plots) (1pt)
3 Agilent Intuilink picture of your differentiatoroutput with sine wave, triangular wave and square wave inputs (input vs. output) (3 plots) (1pt)

Answer the following questions:

1. In the hardware implementation, you should have used a square-wave input to demonstrate that the integrator was working approximately correctly. If it was a perfect integrator, what would the output waveform look like? (1 pt)
2. When we built the differntiator, what did the ouptput waveform look like for the square-wave input? What did the differentiator circuit output look like for a triangular wave input? If it was a perfect differentiator, what would the output waveform look like? (1 pt)
3. Does a *differentiator* need an additional resistance to be added in parallel with the capacitor in order to function effectively? Why or why not? (Hint: Find H(jω) at low and high frequencies.) (2 pt)

Summarize key points (1 pt)

Discuss mistakes and problems (0.5 pts)

List member responsibilities (0.5 pts)