Lab 2: AC fundamentals, RC circuits, filters

Objectives:

- become familiar with the features of the Tektronix oscilloscopes and HP/RIGOL function generators
- investigate the properties of RC circuits
- investigate the properties of RC filters (high-pass and low-pass)
- see how filters can be used as differentiators and integrators

Important note: The function generator and scope have their grounds referenced to true (earth) ground. For this reason, in any circuit, these grounds should always be connected to the same point in the circuit. Any other true grounds (e.g. a powered breadboard ground) should also be connected to that point. Note that the "common" jack of the BK meter is not referenced to earth ground, so it can be connected anywhere with no harm to the circuit.

2-1 Oscilloscope and function generator

Get familiar with the Tektronix scope and HP/RIGOL function generator by producing and observing sine, triangle, and square waves of various frequencies and amplitudes.

Make sure you understand what each of the following controls do:

- vertical gain (V/Div)
- horizontal sweep (time/ Div)
- trigger level

Set the function generator to put out a sine wave of any frequency you wish. Use the scope to measure its peak-to-peak voltage and its frequency. Compare to the function generator readings. If there is a significant difference (there may appear to be a factor of 2 difference in voltage), ask me about it.

What comes out of the function generator's SYNC output? Look at a sine wave from the function generator on channel 1 and the SYNC signal on channel 2. Change the frequency, amplitude, and waveform of the signal. How is the SYNC signal related to the signal from the function generator? (What might the SYNC signal be useful for?)

Connect the output (center tap) of a 6 V transformer to the scope (ask me for help if it's not clear how to do it). Use the scope to measure the frequency. How well does it compare to what you expect? (Since the electric company regulates the frequency of AC power very precisely, this measurement gives you an idea of how well the scope is calibrated.)

Use the scope to measure the transformer's output voltage amplitude. Use a DMM (BK meter) to measure the transformer's output voltage (AC volts). How are the voltage measurements with the scope and the DMM related? In what sense is this a "6V" transformer?

2-2 Impedance of test instruments
Use the scope as part of a voltage divider with a known resistor to determine its (input) resistance. Since you want to measure its resistance, you should use a low-frequency signal (about 60 Hz is fine) from the function generator with an amplitude of a few volts. If you use both channels of the scope, you can measure V_{in} and V across the scope at the same time.

Now increase the frequency (at least into the kHz range) and see what happens to the voltage across the scope. Explain this frequency dependence in terms of the scope having resistance in parallel with capacitance.

Now use the x10 probe. Look at pp. 6-8 in the manual or have me show you how to compensate the probe and set up the scope so it reads properly with the x10 probe. Repeat the low-frequency resistance measurement. Then see what happens to the voltage across the scope as the frequency is increased. What does this mean about the frequency dependence of the scope's impedance when used with the x10 probe?

Summarize: What are the advantages of using the x10 probe?

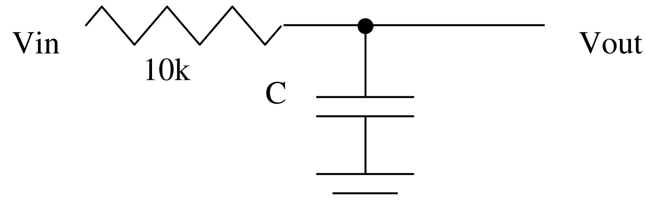
From now on, use the (compensated) probe with the scope instead of a regular cable whenever possible.

Next, use the function generator as part of a voltage divider with a known resistor to determine the (output) resistance of the function generator. (Hint: the function generator serves as the unknown resistor and as the voltage source.) Use a fairly low frequency (below 1 kHz) so that the inductance of the coaxial cable doesn't play a role. Sketch the setup you use and show how you determined the function generator's output resistance. Check your results with the documentation for the function generator.

Summarize: For the oscilloscope, is the impedance high or low? Why is this a desirable thing, given how it's used? In what cases would you have to worry about the oscilloscope impedance?

For the function generator, is the impedance high or low? Why is this a desirable thing, given how it's used? In what cases would you have to worry about the function generator impedance?

2-3 RC circuit: time constant

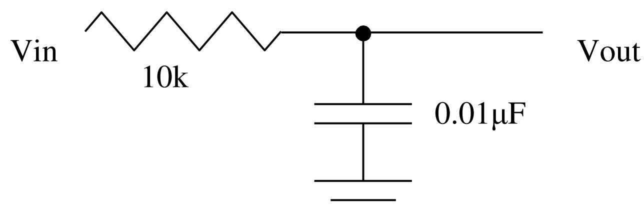


Construct the circuit above (I'll give you a capacitor to use). Drive the circuit with a 500 Hz square wave from the function generator. You might want to use some reasonably large voltage (on the order of a volt peak-to-peak) to make the signal easier to find.

Use the scope to look at the output signal (be sure to use the scope's DC input setting). Sketch V_{in} and V_{out}. Measure the time constant for the circuit (defined as the time for the output to rise or fall to $1-e^{-1}$ (63%) of its asymptotic value). From the measured time constant, figure out what the value of the capacitor is and see how well it agrees with the marked capacitance value. (You may also use the BK meter to measure the capacitance directly.)

Change the frequency of the square wave and observe the output. What happens to the output when the frequency is very high (at least several kHz)? (A sketch might help.) Explain your observations.

2-4 RC low-pass filter



Yes, this is the same circuit, but now we're looking at the attenuation (V_{out}/V_{in}) as the frequency changes! Drive it with a sine wave of a few volts amplitude; start with a low frequency and increase the frequency. How does the output amplitude change as the input frequency is changed? Make several measurements of V_{out}/V_{in} and plot them vs. frequency to show the shape of the attenuation curve.

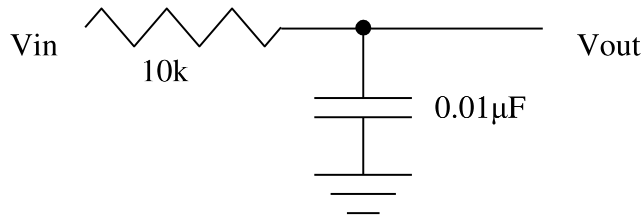
Calculate the expected breakpoint (or -3dB) frequency f_0. Then find it experimentally, (hint: what does V_{out}/V_{in} equal when $f=f_b$?) and compare the measured and calculated values.

Find the limiting phase shift at high frequencies and at low frequencies (be sure to indicate whether V_{out} leads or lags V_{in}, and by how much). Do your results agree with what you expect? Explain your reasoning.

Will f_0 increase, decrease, or stay the same if the 10k resistor is replaced with a 1k resistor? Try it and summarize the results.

If the capacitor is replaced by a 10 mH inductor, how will the general behavior of the circuit change? Make a prediction and then try it out. Summarize the results.

2-5 RC circuit: integrator



Put together the circuit shown above. Drive it with a fairly large (several volts amplitude) square wave of frequency 100 kHz. Sketch input and output (don't forget to indicate time and voltage scales). Try a triangle wave of the same frequency. Try a sine wave of the same frequency. Describe the output. In what sense is this circuit an integrator?

A low-pass circuit will also work as an integrator if $RC \gg T_s$ (where T_s is the period of the signal). Another way of saying this is that $f_b \ll f_s$ (that is, the signal frequency is well <u>above</u> the breakpoint frequency). Check that expectation experimentally by calculating the breakpoint frequency and then determining the frequency range in which the circuit acts like a good integrator.

In the frequency region in which the circuit acts as a good integrator, how does the magnitude of v_{out} compare to that of v_{in} (much larger, much smaller, about the same)? Does this make sense, given the discussion in the previous paragraph?

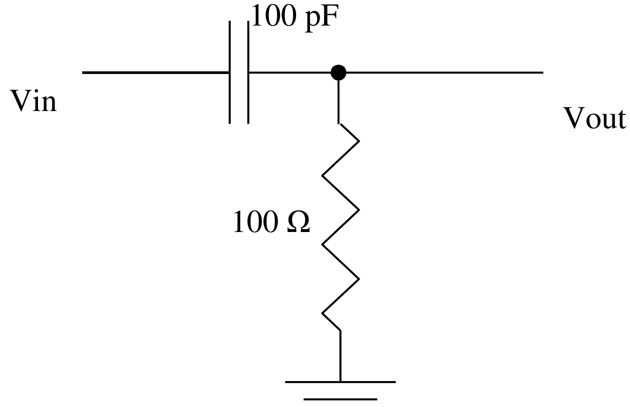
Summarize: under what condition is the circuit a good integrator? Why is it a good integrator only when this condition is met?

2-6 RC high-pass filter

Rearrange the components of the low-pass filter to make a high-pass filter. Drive it with a sine wave. How does the output amplitude change as the input frequency is changed? Calculate the breakpoint or 3dB frequency f_b (hint: you've already done this!) Then find f_b experimentally, and compare with your prediction.

Find the limiting phase shift at high frequencies and at low frequencies (be sure to indicate whether V_{out} leads or lags V_{in}, and by how much). Do your results agree with what you expect?

2-7 RC circuit: differentiator



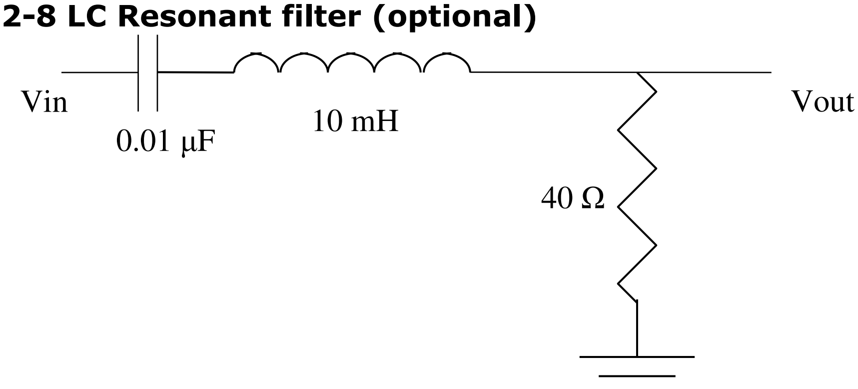
Put together the circuit shown above. Drive it with a square wave of frequency 100 kHz. Sketch input and output. Try a triangle wave of the same frequency. Try a sine wave of the same frequency. In each case, is the output waveform the derivative of the input?

A high-pass circuit will also work as a differentiator if $RC \ll T_s$ (where T_s is the period of the signal). Another way of saying this is that fb >> f_s (that is, the signal frequency is well <u>below</u> the breakpoint frequency). Check that expectation experimentally by calculating the breakpoint frequency and then determining the frequency range in which the circuit acts like a good differentiator.

In the frequency region in which the circuit acts as a good differentiator, how does the magnitude of v_{out} compare to that of v_{in} (much larger, much smaller, about the same)? Does this make sense, given the discussion in the previous paragraph?

Summarize: under what condition is an RC high-pass filter also a good differentiator? Why is it a good differentiator only when this condition is met?

2-8 LC Resonant filter (optional)



Build the circuit above. Predict the resonance frequency. Drive the circuit with a sine wave, varying the frequency and looking at the response (V_{out}/V_{in}). How closely does the resonant frequency match your prediction?

Estimate the circuit's quality factor Q, defined as the ratio of the resonance frequency f to the width of the resonance peak between the half-power points (where $V_{out}/V_{in}=1/\sqrt{2}$), Δf.

If there's time, try a larger resistor and see what that does to the resonant frequency and the quality factor.

2-9 Design problem: garbage detector, garbage cleaner

When you looked at the output of the transformer, you may have noticed that it was not a very clean sine wave, due to high-frequency noise that distorts the signal from the AC power line. Design an RC filter that will let you look at the high-frequency "garbage" on the AC power line by discarding most of the 60 Hz signal. You should put the line frequency of 60 Hz well below the 3 dB point, but pass frequencies in the kHz range. Build your filter and try it on the output of the 6 V transformer (the oscilloscope will not enjoy trying to look at a 110 V line signal). Sketch the signal from the transformer with and without the filter. Does your filter do what it's supposed to? Estimate the factor by which you've reduced the 60 Hz signal.

Optional: If there's time, design a filter that will clean up the garbage, but pass the 60 Hz. Try it and sketch the results.