# Phases and Filters

Objectives
1. Observe the phase relationships of current and voltage in a capacitor and an inductor.
2. Make some simple filters and plot their frequency response curves.

Parts: (Parts in **bold** are new to this lab)
1. **1 Ω**, 100 Ω, and 1 kΩ **resistor**s
2. **0.1 µF** (104) & **0.01 µF** (103) **capacitor**s
3. Inductor, 2 to 4 mH (probably 3.3mH)

Experiment 1, Current / Voltage phase shifts
Wire the circuit shown at right, including the scope probes, both set to 1x. Set the signal generator amplitude to 4 Vpp (which will actually give 8 Vpp) and it's frequency to about 10kHz.
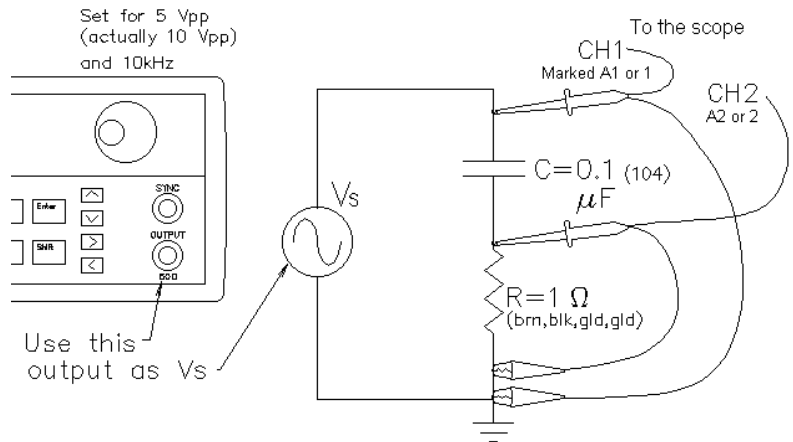

Measure both voltage and current with scope: Turn on the scope and adjust it to see both traces. Notice the small value of the resistor in this circuit (1Ω). This value will have very little effect on the CH1 signal, but will allow the CH2 signal to effectively display the current through the capacitor. Think of the CH2 trace as a measure of the capacitor current. (It may not always look like a nice sinusoid due to noise and scope/circuit irregularities, but try to ignore that in this lab.) You will want to trigger on the cleaner CH1 signal, which may require you to hit the "Edge" key in the "Trigger" section and then the A1 softkey or something similar.

Note the phase difference of the two traces. Is the current (CH2) leading (to the left of) the voltage?
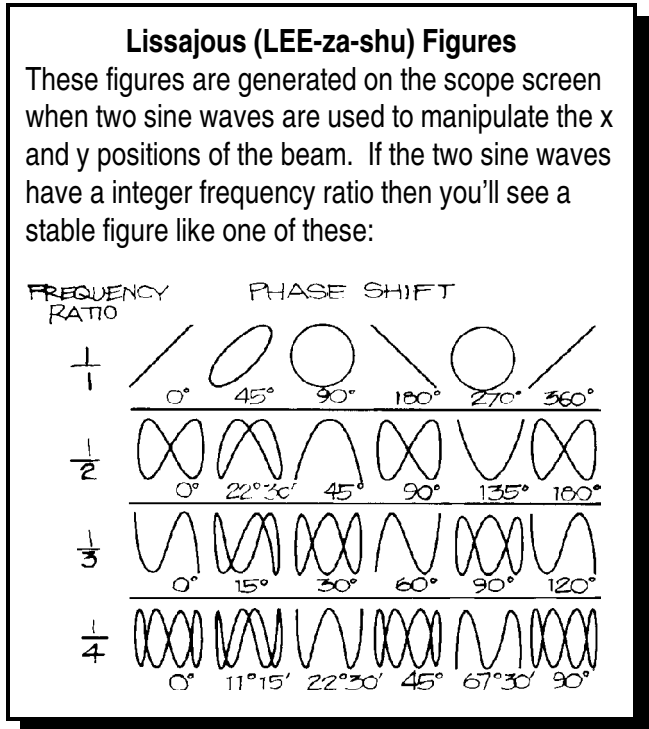

Phase angle Measurement
Note: On most scopes the Volts/div knob is above BNC connector and the Position knob is below it. Use the Ch1 position knob to move the tiny ground symbol on the left side of the screen to the center line of the screen. Repeat for the Ch2 position. Refer to the figure at right. Adjust the VOLTS/DIV knobs and the TIME/DIV knob on the scope to get two good, big traces. This may not always be possible, but do the best you can. Find the "Measure" section on the scope. Hit the "Time" and "Cursors" keys (New Agilent MSO-X 3014A scope: "Cursors" key, "Cursors"
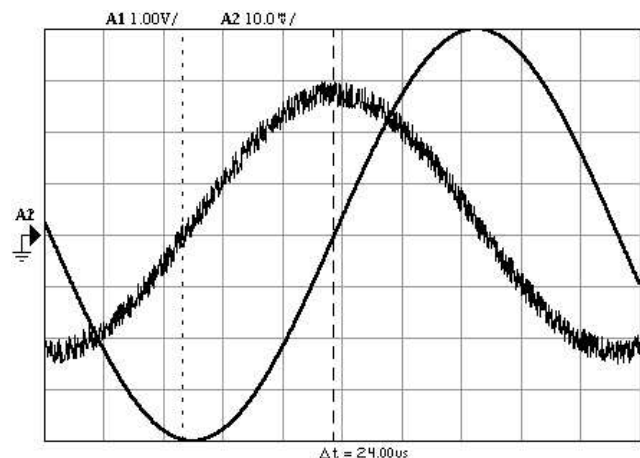
softkey several times until the checkmark is at X1) and adjust the vertical, dotted line with the "Entry" knob to one of the zero-crossing points on the scope screen. Hit the "Cursors" key (or softkey) again and repeat for the other zero-crossing point. The Δt is shown on the screen. Use this measurement and the period (either measured or calculated from frequency) to calculate the phase shift of the current relative to the voltage. Is this 90° as expected?

Circle
Hit the "Main/Delayed" key in the "HORIZONTAL" section and then the "XY" softkey. (New scope: "Horiz" key, "Time Mode" softkey until the checkmark is at "XY".) In this position the left-right movement of the scope beam is controlled by CH2 rather than scope sweep circuits. CH1 works as normal, making the beam move up and down. If the CH1 and CH2 are both sine waves and are truly 90° out of phase, then you should be able to adjust the VOLTS/DIV knobs to get a perfect circle. You may also have to fine-adjust one channel. Sketch this in your notebook and explain why it's (almost) a circle. Restore your scope to its normal operation by hitting the "Main" softkey (or "Time Mode" softkey until the checkmark is at "Normal").

Lissajous (LEE-za-shu) Figures
These figures are generated on the scope screen when two sine waves are used to manipulate the x and y positions of the beam. If the two sine waves have a integer frequency ratio then you'll see a stable figure like one of these:

Other frequencies: Adjust the function generator frequency down to 1kHz. Does the phase angle change? Check again at 30 kHz. Also note that the current magnitude does change with frequency. Considering that the impedance of a capacitor is inversely proportional to the frequency, is it changing as expected? Return your frequency to 10 kHz.

Repeat with Inductor: Replace the capacitor with your inductor and repeat this entire section, including the detailed phase angle measurement at 10 kHz. Note that the current now lags the voltage by 90°. (You don't need to explain the circle again, but do everything else including the other frequencies.)

Experiment 2, Simple Filters
The impedance of an inductor is proportional to frequency and the impedance of a capacitor is inversely proportional to frequency. These characteristics can be used to select or reject certain frequencies of an input signal. This selection and rejection of frequencies is called *filtering*, and a circuit which does this is called a *filter*. The bass and treble or equalizer controls on your stereo are frequency filters. So are the tuners in TVs and radios.

You've already made a simple filter in the Capacitors lab. We called it a frequency-dependent voltage divider. Almost any circuit where a capacitor or an inductor is part of a voltage divider is a filter. The magnitude of the output voltage is a function of frequency. Look back at the frequency response curve you made in the Capacitors lab.

If a filter passes high frequencies and rejects low frequencies, then it is a *high-pass* filter. Conversely, if it passes low frequencies and rejects high ones, it is a *low-pass* filter. A filter that passes a range or *band* of frequencies and rejects frequencies lower or higher than that band, is a *band-pass* filter. The opposite of this is a *band-rejection* filter, or if the band is narrow, a *notch* filter or *trap*. What type of filter did you make in the Capacitors lab? How about the Resonance lab (look at the frequency response curve)?

Filters, like most things, aren't perfect. They don't absolutely pass some frequencies and absolutely reject others. In fact there are large gray areas between pass and reject that make it somewhat arbitrary to say just what *is* and what *isn't* passed. For filters, you measure the pass and reject areas by using a constant magnitude of input signal and varying its frequency. A frequency is considered passed if it's magnitude (voltage amplitude) is within 70% of the maximum amplitude passed, and rejected otherwise. The 70% frequencies are known as *half-power* points, *3-dB-down* points, or *roll-off* points. (Square 0.7 on your calculator to see why they're called half-power points).

For RC (resistor-capacitor) filters, roll-off is where:

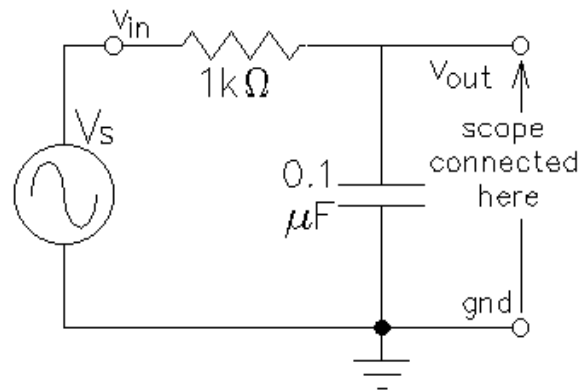$$R = \frac{1}{\omega_c C} \qquad \omega_c = \frac{1}{RC} \qquad f_c = \frac{1}{2\pi RC}$$

For RL (resistor-inductor) filters, roll-off is where:

$$R = \omega_c L \qquad \omega_c = \frac{R}{L} \qquad f_c = \frac{R}{2\pi L}$$

RC low-pass: The filter shown at right is the same one that you built in the Capacitors lab. Look back at that lab now and find the frequency response curve for this filter. Determine what the roll-off frequency (f_c) was from this curve (the frequency where $v_o/v_{in} = .70$).

Calculate the theoretical roll-off frequency for this filter and compare this to what you found from the frequency response curve.

Frequency response curves: Calculate the roll-off points for the three filters shown on the next page. You may want to measure the actual value of your inductor and use that value in your calculations instead of 3.3 mH. Your lab TA can show you how to use the HP LCR meter to measure your inductor. If you don't measure your inductor, remember that it probably isn't exactly 3.3 mH when you compare calculations to measurements.
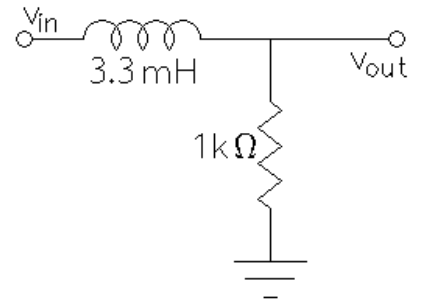
Make one of the RC or RL filters shown on the next page. Use the signal generator to supply v_{in}, and the scope to observe both v_o and v_{in}. This should result in a circuit that looks like the one on the first page of this lab, although the parts will be different. Measure the frequency response of your filter and plot the results on a log plot. You can make your log plot (frequency response curve) in several different ways; use a 1, 3, 10,... pattern of frequencies like you did in the Capacitors lab, use a $\log_2$ pattern like you did in the Resonance lab, use log paper, or use a computer program. In the last two cases you'll tape or paste the plot in your notebook. Be sure to find the roll-off point and compare it to your calculated roll-off frequency.
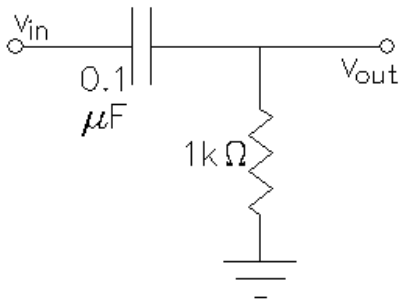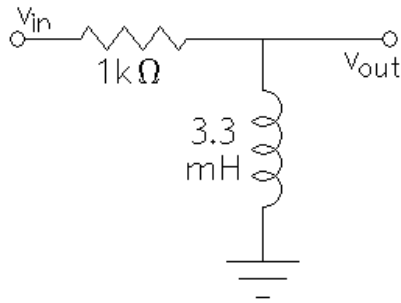
High-pass RC — High-pass RL — Low-Pass RL

Make one of the other two filters. Confirm that it is high-pass or low-pass as advertised. Find its roll-off point and compare that to your calculated roll-off. You **don't** need to make another curve.

Repeat for the last filter. Again, just confirm that it is high-pass or low-pass as advertised. Find its roll-off point, compare it to your calculation, and **don't** make another curve.
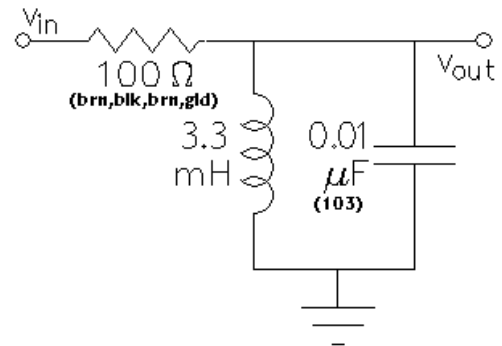
Band-pass filter: Make the band-pass filter shown below. Measure its frequency response and plot the results on a log plot, you'll need quite a few data points. This will be your second curve for this lab. Find the two roll-off point(s) for each, and compare to calculations.

Low frequency roll-off: $f_L = \dfrac{R}{2\pi L}$

High frequency roll-off: $f_H = \dfrac{1}{2\pi RC}$

Conclude
As always, check off and write a conclusion.