Capacitors and inductors in circuits

In this final lab, we take a brief look at transient effects caused by capacitors and inductors and examine a few examples of sinusoidal circuits with impedances.

Note: We will be using the oscilloscope extensively in this lab. Before recording screenshots, take a moment to adjust time and voltage scales to obtain a good set of traces.

1. Capacitor / inductor values and measurements

Capacitors have two pre-dominant varieties: *ceramic* and *electrolytic*. Ceramic capacitors usually have smaller values (1 pF to 1 μF) and have very small physical sizes. Electrolytic capacitors typically have bigger values and come in larger packages. Ceramic capacitors are *unpolarized,* meaning that they have no preferred direction — like a resistor. In contrast, electrolytic capacitors are polarized — there are specific positive and negative terminals. If there is a constant DC voltage across an electrolytic capacitor, the negative terminal must always be at the lower voltage. If the polarity is reversed — with the negative terminal at a higher voltage, the capacitor may fail, perhaps in the form of a small explosion. It is important to pay attention to the polarity of an electrolytic.

The capacitance value for ceramic capacitors is indicated in a manner similar to resistors, but instead of using color bands, the value is given by three digits printed directly on the capacitor package. Ceramic capacitors are very small, and the printed numbers are ridiculously small — it can be a challenge to read them. (Using a cell phone flashlight can help.) The digits have the same interpretation as the color bands on a resistor — the first two digits give the basic value and the third digit is the base-10 exponent. The base units are picofarads. For example, a capacitor marked 332 would have a value of 33×10^2 pF = 3300 pF = 3.3 nF. A 104 capacitor would have a value of 10×10^4 = 100,000 pF = 100 nF = 0.1 μF. The scheme is fairly easy to interpret — the hardest part is reading the minuscule printing.

Since electrolytic capacitors have bigger packages, the labeling is simpler — the value is stamped right on the package. A 22-μF capacitor will have "22uF" printed on the metal "can". In addition, there will be a negative sign printed next to the negative terminal. We should pay attention to it. (Unless the possibility of surprise mini explosions seems like fun.)

Although reading the value of a capacitor can be a challenge, measuring it is a simple matter.[1] There are a couple of options for measuring capacitance. Many multi-meters have a capacitance function. For the Keysight meters in the lab, choose the capacitance function by pressing the blue shift button and then the "Freq" button. The connections are the same as for measuring voltage or resistance. It is quite simple. Alternatively, there is an LCR meter in the lab. As the name implies, it can measure inductance, capacitance, and resistance. This is probably a better tool for measurements, because it can measure basic capacitance along with any parasitic resistances. To measure capacitance with the LCR meter, put it into "Cp" mode, plug the capacitor into the measurement leads, and the instrument will automatically measure the capacitance along with any parallel resistance (conductance).

Inductors are simpler. They are always unpolarized, like resistors. It doesn't matter which lead is positive and which is negative. The labeling uses the same three-digit code as ceramic capacitors, with

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[1] Sometimes, I just give up on trying on read the value and go straight to the meter, which is probably more reliable. - GT

the base unit being micro-henries. For example, the inductor in the lab kit (there is only one) is labeled 153, meaning $15\text{x}10^3\ \mu\text{H} = 15{,}000\ \mu\text{H} = 15\ \text{mH} = 0.015\ \text{H}$.

Inductors always have some series resistance, due to the long copper wire winding of the coil. It is always a good idea to measure the inductor resistance so that we have some idea of the potential errors that it may result. Inductor resistance can be measured with the ohm-meter or with the LCR meter (described below). The kit inductors have ≈10 Ω of series resistance, which is rather bad. Good inductors will have less than an 1 Ω of resistance. However, low-resistance inductors will be bigger (because bigger wire is needed to achieve low resistance) and are more expensive because there is more copper.

The only way to measure inductance in lab is with the LCR meter. Put the meter into "Ls" mode, plug the inductor into the measurement leads, and the meter will report the inductance along with the series resistance.

It is always good practice to measure the capacitors and inductors used in the circuits. Typical tolerances are ±20%, so the difference between that nominal value and the actual value can be significant.

2. RC and RL transients

Build the *RC* and *RL* circuits shown in Fig. 1. The source for each will be a square wave from the function generator. Set the amplitude so that the square wave oscillates between 0 V and +10 V. (Set the "high" and "low" values directly. Or set the amplitude to 10 V_{pp} and introduce an offset of +5V. Don't forget to put the FG output into "High-Z mode".)

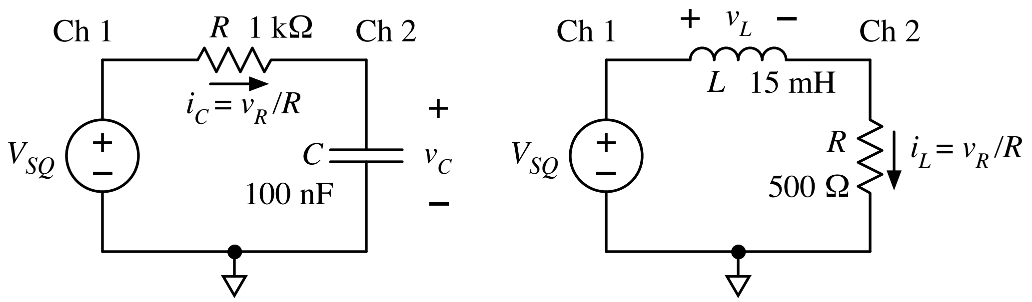

Figure 1. Circuits for observing *RC* (left) and *RL* (right) transients. For the *RL* circuit, the 500-Ω resistor can be made with two 1-kΩ resistors in parallel.

Start with the *RC* circuit.

1. Calculate the *RC* time constant for the circuit. Attach the function generator to the circuit, and set the frequency to 250 Hz.
2. Use two probes to observe the both the source voltage and capacitor voltage with respect to ground. Adjust the time and voltage settings so that there is at least one full period on the screen and the rising and falling transients of the capacitor are clearly displayed. Save a screenshot of the oscilloscope traces for the report.

3. Using the cursors, measure the time required for the capacitor voltage to reach the half-way point of the rising transient. Measure the difference between the time when the input goes high and the time when the capacitor voltage crosses 5 V. (Or we could use the falling transient — the rise and fall times should be the same.)
4. Use the math function to display a trace of the resistor voltage (channel 1 minus channel 2), which provides a measure of the current in the circuit. Display the calculated resistor voltage together with the source and capacitor voltage. Save a screenshot of the three traces on the oscilloscope for the report.

Now perform similar measurements for the *RL* circuit. Note that the circuit is not in "standard" form with a current source, resistor, and inductor all in parallel. If needed, we can use a source transformation to make the circuit more recognizable when doing calculations.

1. Calculate the *RL* time constant. Attach the function generator to the circuit and set the frequency to 1500 Hz.
2. Use two probes to observe the source voltage and resistor voltage together on the oscilloscope. (The resistor voltage is proportional to current and provides a measurement of the inductor current.) Adjust the time and voltage settings so that there is at least one full period on the screen and the rising and falling transients of the capacitor are clearly displayed. Save a screenshot of the oscilloscope traces for the report.
3. Using the cursors, measure the time required for the inductor current to reach the half-way point of the rising transient. (Again, we could use the falling transient, since the times will be the same.)
4. Use the math function to display a trace of the inductor voltage (channel 1 minus channel 2). Display the calculated inductor voltage together with the source and resistor voltage. Save a screenshot of the three traces together for the report.

3. RLC transient

Next, build the *RLC* circuit shown in Fig. 2. For the source, use a square wave that switches between 0 V and 10 V at a frequency of 500 Hz.

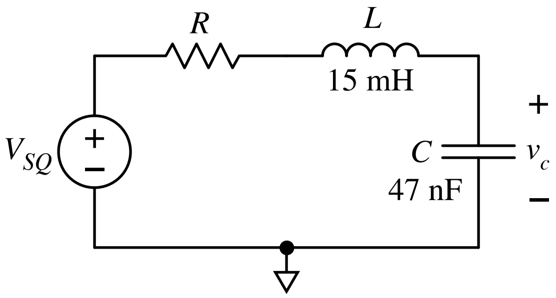

Figure 2. *RLC* circuit for transient measurements.

1. Start with $R = 2.2\ \text{k}\Omega$. Do a calculation showing that the circuit is over-damped. Then observe the source voltage and the capacitor voltage together on the oscilloscope. Save a screenshot of the traces for the report. Use the cursors to measure the 50% rise time. (Or the fall time — the two should be the same.)

2. Now change the resistor to R = 220 Ω. Do a calculation showing that the circuit is underdamped. Calculate the expected damped oscillation frequency and the decay time constant. Then observe the source voltage and the capacitor voltage together on the oscilloscope. Save a screenshot of the traces for the report. Use the cursors to measure one period of the ringing oscillation and determine the corresponding frequency. Compare the measured oscillation frequency to the calculated value. (Note that the source resistance of the FG, R_S = 50 Ω and the series resistance of the inductor, $R \approx$ 10 Ω, also both contribute to the effective series resistance.)
3. Finally, use a 10-kΩ potentiometer for R. Observe the capacitor voltage together with the source voltage on the oscilloscope. Note that the transient behavior can be controlled by adjusting the pot.

4. AC measurements (RC and RL)

Set up the two circuits shown in Fig. 3 on the breadboard. Use the function generator as the source voltage, set to produce sinusoids. (For convenience, change the units to V_{RMS}. And don't forget to set the output to High-Z.)

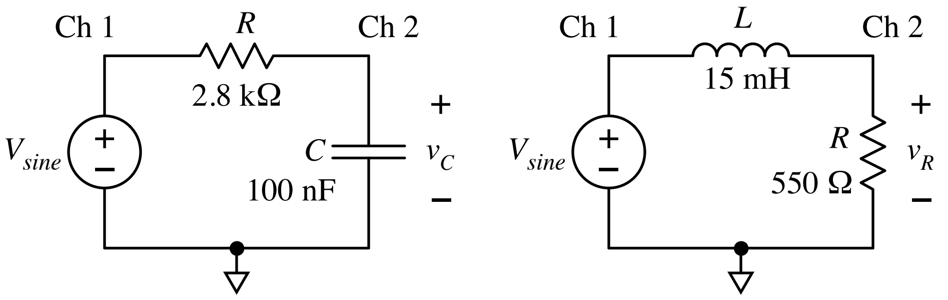

Figure 3. *RC* and *RL* circuits for AC measurements. A 2.8-kΩ resistance can be realized with a 6.8 kΩ and 4.7 kΩ resistors in parallel. A 550-Ω resistor can be made with 220 Ω in series with 330 Ω.

Start with the *RC* circuit.

1. Connect the FG — set the amplitude to 5 V_{RMS} and the frequency to 100 Hz. Use the AC voltmeter to confirm the amplitude of the source.
2. Then use the voltmeter to measure the capacitor AC amplitude.
3. With the voltmeter still in place across the capacitor, use the oscilloscope to observe the source and capacitor voltages together. Save a screenshot of the oscilloscope display for for the report. Then change the frequency to each of the values listed in Table 1 below, measuring the amplitude of the capacitor voltage at each frequency. Save a copy of the oscilloscope traces at 1 kHz and 10 kHz. (We can save more traces if we want, but these three— one low, one middle, and one high — are sufficient for the report.)

Now repeat the measurements with the *RL* circuit. Note the higher frequencies. Record the AC resistor voltages at each frequency. Save copies of the oscilloscope traces at 1 kHz, 10 kHz, and 100 kHz.

Table 1. *RC* and *RL* AC amplitude measurements.

***RC* circuit**		***RL* circuit**	
***f* (kHz)**	**v_C (V_{RMS})**	***f* (kHz)**	**v_R (V_{RMS})**
0.1		1	
0.15		1.5	
0.22		2.2	
0.33		3.3	
0.47		4.7	
0.68		6.8	
1		10	
1.5		15	
2.2		22	
3.3		33	
4.7		47	
6.8		68	
10		100	

5. AC measurements (RLC)

1. Build the *RLC* circuit shown in Fig. 4.

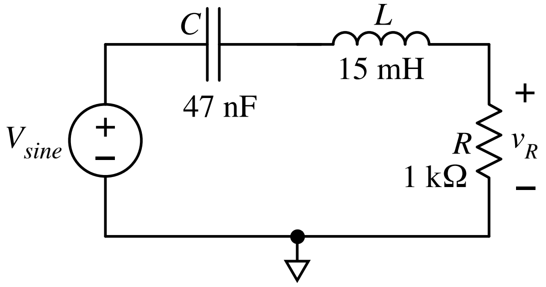

Figure 4. RLC circuit for AC measurements.

2. Connect the FG, with the amplitude set to 5 V_{RMS} and the frequency to 300 Hz. Use the AC voltmeter to confirm the amplitude of the source.
3. Then use the voltmeter to measure the AC voltage of the resistor.
4. Leave the AC voltmeter connected across the resistor, and use the oscilloscope to observe the source and resistor voltage waveforms together. Save a good screenshot of the oscilloscope display for the report.

5. Then change the frequency in succession to 2.4 kHz, 15 kHz, and 30 kHz. At each frequency measure the AC resistor voltage and save a screenshot of the oscillscope display showing source and resistor sinusoids together. From the oscilloscope traces, note the how the phase difference changes as the frequency increases.
6. Finally, go back and set the source frequency to 6 kHz. Measure the AC resistor voltage using the multimeter. Then measure the voltages across the inductor and capacitor. When considered altogether, the voltages may pose a conundrum, if we believe KVL. Can we explain what is happening? Hint: the circuit is at (or near) resonance. Observe the source and resistor voltages together on the oscilloscope and save a screenshot for the report.

Table 2. *RLC* AC amplitude measurements.

RLC circuit	
f (Hz)	**v_R (V_{RMS})**
300	
2400	
6000	
15000	
30000	

6. AC measurements (op amp)

This exercise is optional. Do this only after completing all of the earlier required measurements and if there is sufficient time remaining in the lab period.

1. Using the LM324 op amp with ± 10 V power supplies, build the op-amp circuit shown in Fig. 5. (Note: We will see this circuit again in EE 230 — it is a very common form of low-pass filter.)

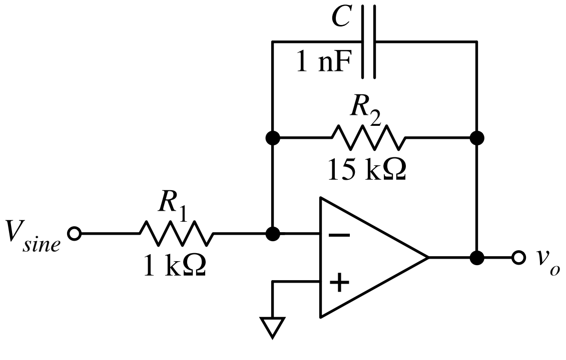

Figure 5. Simple op-amp circuit for AC measurements.

2. Connect the FG to the input, with the amplitude set to 0.25 V_{RMS} and the frequency to 100 Hz. Confirm the source amplitude with the voltmeter.
3. Use the AC voltmeter to measure the amplitude of the output voltage.

4. Use the oscilloscope to observe the phase difference between the input and output waveforms. Save a screenshot of the oscilloscope display shown the two traces together.
5. Repeat for the other frequencies shown in Table 3. Save copies of the oscilloscope traces at *f* = 1 kHz and *f* = 10 kHz for the report. (In addition to the traces at *f* = 100 Hz.)

Table 3. Op-amp *RC* circuit AC amplitude measurements.

op-amp RC circuit	
f (Hz)	**v_o (V_{RMS})**
100	
500	
1000	
2000	
10,000	

Report

Prepare a report describing your work and results. If you did the optional work of part 6, include a description of that, as well. Note the due dates for report on the class web site or by consulting the assignment listing on Canvas.