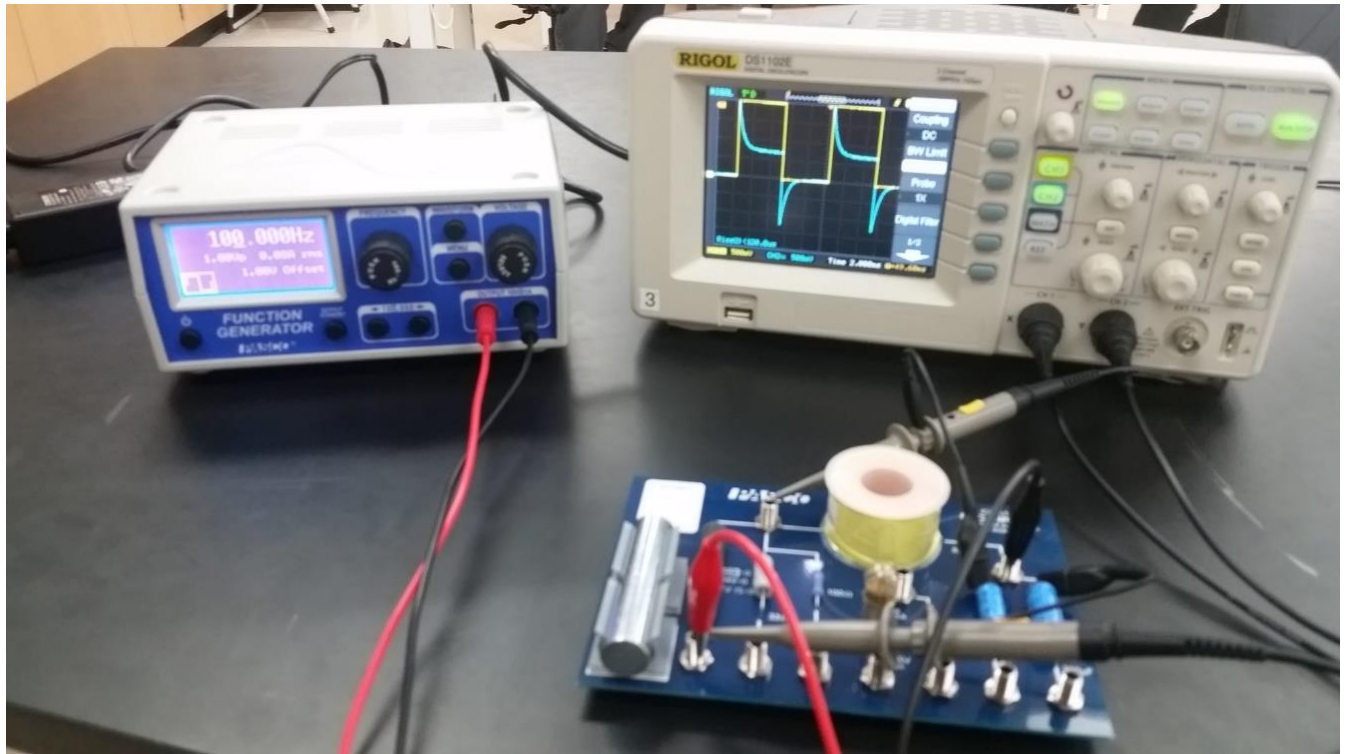


Physics 196 Lab 11: Circuits with Inductors

Equipment:

Function Generator (PASCO), Power cord + Adapter for Function Generator, RLC Circuit Board (PASCO C1-6512), Two Channel Oscilloscope (RIGOL DS1102E), Power Cord for Oscilloscope, Oscilloscope Probes (2), Banana-Banana Leads for Function Generator (2).

Layouts:



Equipment used for Lab 11.

Summary:

Students will use an oscilloscope with two probes to monitor voltages in circuits with inductors, capacitors and resistors which are driven by square waves or sine waves from a function generator. In the first experiment (shown in photo) a square wave with a period longer than any time constants to be measured will be used to drive a resistor and inductor in series. The L/R time constant will be measured for 3 resistor values and compared to theory. The qualitative effect on the time constant of changing the inductance with variable insertion of a ferrite cylinder will also be explored. In the second experiment, an LC circuit (inductor in series with a capacitor) will be excited with a (slow) square wave, and its measured oscillation period will be compared with theory. In the third experiment, the LC circuit (which also contains a significant resistance R in the inductor) will be driven with sine waves of various frequencies to investigate resonance, and the change in behavior from low frequencies (where most of the applied voltage is dropped across the capacitor) to high frequencies (where most of the applied voltage is dropped across the inductor) will be investigated.

Prelab: A capacitor is a circuit element based on the concept of two charged parallel conducting plates, which stores energy in the electric field between the plates. If the capacitor is hooked to an external load (a resistor, for instance), the energy is transferred to the load with a time constant which depends on the resistance. As a circuit element, a capacitor (capacitance C in Farads) is used like a reservoir to store charge, and to resist sudden changes in voltage. An inductor is a circuit element based on the concept of a current conducting solenoid which stores energy in the magnetic field inside the solenoid. Because the solenoid resists changes in this magnetic field, an inductor (inductance L , Henrys) is used as a circuit element which resists sudden changes in the current. If a capacitor were to be charged, and then instantaneously attached in a loop circuit with an inductor, and if there were no resistance or other energy loss mechanisms in the circuit, energy would be transferred back and forth between the electric field in the capacitor and the magnetic field in the inductor, sloshing back and forth forever at an angular frequency ω_0 given by $\omega_0 = (LC)^{-1/2}$. The larger L or C is, the lower the oscillation frequency, because a larger capacitor or inductor provides more of a barrier to a change in voltage or current. Real inductors (if they are not superconducting) have internal resistance, and there is also resistance in the external circuit. This resistance causes the oscillatory energy transfer to dampen out, since the energy is dissipated in the resistor. The smaller the circuit resistance, the more slowly the energy is dissipated, and the longer the oscillation can continue.

For an Alternating Voltage applied across a resistor the current is in phase with the voltage, and Ohm's law applies; that is $V=IR$. For an inductor or capacitor, the magnitude of the AC voltage divided by the magnitude of the AC current is called the reactance, X . For a capacitor, where $V=IX_C$, the reactance $X_C = 1/\omega C$, and varies inversely with the angular frequency of the AC voltage with $\omega=2\pi f$. The voltage across a capacitor lags the current by 90° . For an inductor, where $V=IX_L$, the reactance $X_L = \omega L$, varying directly with the angular frequency. The voltage across an inductor leads the current by 90° .

Imagine an inductor and capacitor connected in series, as they will be in Experiment 3. At high frequencies, the inductor has a high reactance and the capacitor has a low reactance, meaning that most of the circuit voltage will be across the inductor (and the capacitor will act sort of like a wire). At low frequencies, the capacitor has a high reactance and inductor has a low reactance, meaning that most of the circuit voltage will be across the capacitor (and the inductor will act sort of like a wire, which makes sense because it is one for a fixed voltage).

If $L=37$ mH and $C=100$ μF for an inductor and Capacitor in series, Calculate X_L and X_C at $f=20$ Hz, 400 Hz, and at the resonant frequency $\omega_0 = (LC)^{-1/2}$. Remember that $\omega=2\pi f$. What f_0 corresponds to ω_0 ? At that frequency the reactances should be equal. If we apply a sinusoidal voltage across the LC circuit at 20 Hz, f_0 and 400 Hz, what do you expect the ratio of the voltages across the inductor and capacitor to be at those frequencies?

Lab:

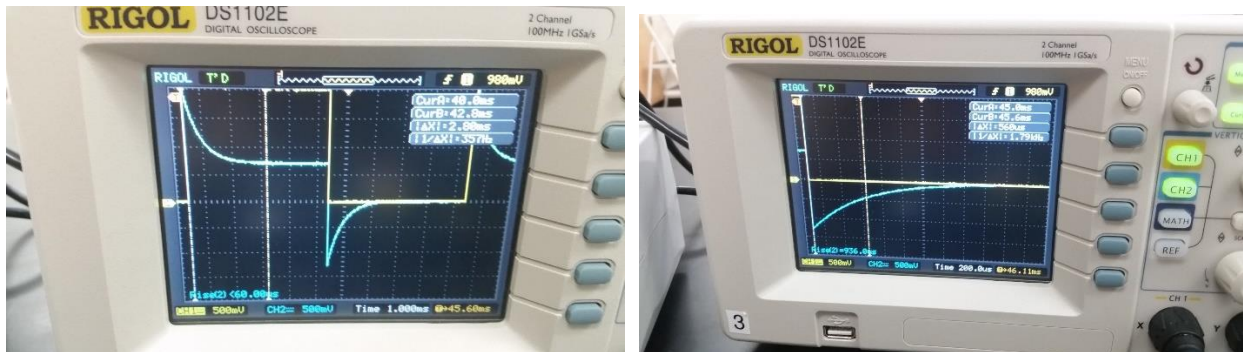
In your lab notebook, please include a description and labelled diagram of each experiment, a data table, graphs as appropriate, and a discussion of the results including comparisons between data and expected results and a conclusion. For the first page of the lab, please tape in the cover page of this write-up which includes an equipment list, a photograph of the layout, and a summary. The Resistor values, Inductor value and Capacitor values to be used in this experiment are labelled on the circuit board shown in the photograph below.



Pasco RLC Circuit Board

The resistors have $R=10\Omega$, $R=33\Omega$ and $R=100\Omega$. The Inductor has $L=8.2$ mH without the ferrite cylinder inserted. The cylinder increases the inductance by about a factor of 4.5. The capacitors have $C=100\mu\text{F}$ and $C=330\mu\text{F}$.

Experiment 1, RL time constant. If a DC voltage is switched onto a resistor and inductor in series, the voltage will initially appear across the inductor, and then as current begins to flow through the resistor the voltage across the inductor will decay exponentially as $V=V_0e^{-t/\tau}$, where the characteristic time constant $\tau=L/R$. Set the function generator for a 100 Hz square wave with a 1V peak and a 1V offset (so it goes from 0 to 2 V). Attach the output of the function generator with red (signal) on the lower end of the 10Ω resistor and black (ground) to the right of the inductor (without the Ferrite cylinder). Measure the voltage across the resistor and inductor together with an oscilloscope probe (x1 setting) inserted into channel 1 (left BNC connector) on the oscilloscope. (Attach the black ground alligator clip on the probe to the same location as the black lead from the function generator). Measure the voltage across the inductor alone with a second oscilloscope probe inserted into channel 2 (middle BNC connector). With appropriate voltage and time scale settings on the oscilloscope, you should be able to see waveforms something like those at left below. (Yellow waveform, channel 1, input voltage across RL circuit, blue waveform, channel 2, voltage across L by itself).



Notice that when the square wave voltage switches on, the inductor voltage rises to the square wave voltage, and then decays. It does not decay to zero because the inductor has an internal resistance. The ratio of the steady blue voltage to the steady yellow voltage should be the ratio of the inductor resistance to the combined resistance of the inductor and resistor. Sketch the waveforms from the oscilloscope in your notebook, and calculate the internal inductor resistance from the voltage ratios.

Now measure the L/R time constant. One way to do this is to use the negative going inductor voltage waveform which decays back to zero, and expanding the trace on the oscilloscope as in the right hand picture above. Using the two cursors, you should be able to measure the time it takes the voltage to drop from its peak value to $1/e$ times that peak value. Compare your measured value to the expected value of L/R . If you are not close, did you remember to include the resistance of both the external 10Ω resistor and the internal resistance of the inductor in your calculation of R ?

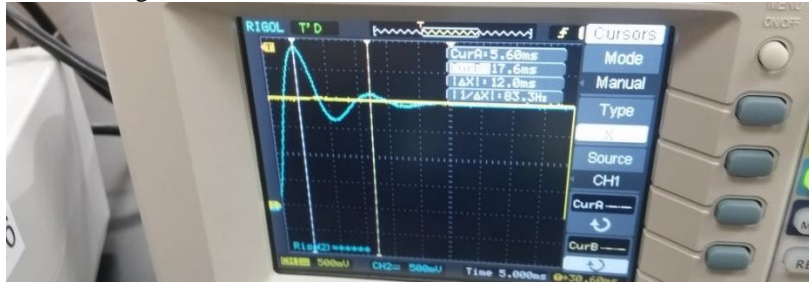
Now re-expand the display on the oscilloscope to show a full cycle (as in the left photograph above), and observe the voltages when the Ferrite Core is inserted into the inductor. Make a sketch in your lab notebook showing the shape of the decay curve (top half cycle) for about 4 cases from having no core, through partial insertion, to complete insertion. (Put the curves on the same sketch for easy comparison). Since the time constant is changing, what can you say about the effect of the core on the inductance?

Now make a second sketch of the decay curve with the core inserted, and change the resistor value from its original 10Ω to 33Ω and 100Ω . (When you change resistors you need to move the probe and input voltage). Notice that the decay time gets shorter (since R is in the denominator of the time constant), and also the voltage drops back closer to zero (since the ratio of the inductor resistance to the external resistance gets smaller).

Discuss what you learned in your lab notebook. Make sure you have included a circuit diagram with voltage measurement locations.

Experiment 2, LC Oscillation. Change the function generator output frequency to 10 Hz. Connect the black output (ground) of the function generator below the $100\ \mu\text{F}$ capacitor and the red output (signal) to the left end of the inductor (with the ferrite core). With the Channel 1 probe, monitor the voltage across the LC combined circuit, and with the Channel 2 probe measure the voltage across the capacitor only. (Remember to connect the black alligator clips on the probes to the same ground as the black function generator lead below the capacitor). Make sure to

include a circuit diagram (showing inductor, capacitor, input voltage and measurement voltage locations) in your lab notebook. After adjusting the voltage and time scales on the oscilloscope, the display should look something like the following:



Measure one full period of the oscillating voltage across the capacitor (first to second peak). Notice that the voltage goes higher than the external drive voltage. The oscillation decays quickly because of the internal resistance in the inductor. Compare what you measure to what you would expect ($1/f_0$ calculated in prelab, assuming $L=37$ mH with core inserted). Sketch a copy of the display in your lab notebook, and write your time measurement onto it. Now make a new sketch of one top half cycle in your lab notebook, and add sketches of what you observe when you remove the ferrite core, and when you change the capacitance to $330 \mu\text{F}$ (with the core reinserted). Comment on what is happening to the LC oscillation time and why. (When you change the capacitor, you will also have to move the ground location and leads).

Experiment 3, Changing Reactance. Connect the function generator across the inductor (core inserted) and $100 \mu\text{F}$ capacitor in series, as at the beginning of experiment 2. (Remember to change the oscilloscope probe ground lead locations back as well). Change the output of the function generator to be a 1V peak sine wave with no voltage offset (symmetric plus and minus voltages). Vary the input frequency to the following values (20, 40, 60, 80, 100, 120, 150, 200, 300, 400 Hz), graphing and discussing what you observe for the peak of the sinusoidal voltage across the capacitor (Channel 2) compared to the 1V peak of the sinusoidal input voltage (Channel 1). At what frequency does the capacitor voltage peak? Is this consistent with what you expect from the prelab and experiment 2? What happens at low and high frequencies? The oscilloscope traces should look like the following around 80 Hz (yellow is voltage across whole LC circuit, blue is across C):



Now reverse the function generator and probes so the grounds (black leads) are located to the left of the inductor, and the signal (red lead) is located below the capacitor. Measure the input signal with the channel 1 probe below the capacitor. Measure the voltage across the inductor with the channel 2 probe placed to the right of the inductor. Vary the input frequency from 20 Hz to 400 Hz (use same values as before), and sketch and discuss what you observe for the peak of the sinusoidal voltage across the inductor. At what frequency does the inductor voltage peak? What happens at low and high frequencies? Are your observations consistent with what you expect?

Note that the signals applied to the LC circuit were the same in both cases above. The leads were reversed so that the oscilloscope probe would properly measure the voltage across either the capacitor or inductor. At all frequencies, the actual voltage across the capacitor added to the voltage across the inductor should equal the voltage across the LC circuit combined. At low frequencies, we see that this happens because the voltage dropped across the inductor (acting like a wire) goes to zero. At high frequencies, we see that this happens because the voltage across the capacitor goes to zero (a capacitor passes high frequency signals through, but blocks low frequencies). At resonance, it appears that both the peak capacitor voltage and the peak inductor voltage can be higher than the peak input voltage. How can this be true if $V_C + V_L = V_{L-C}$ at all frequencies?