Lab Assignment 1: Equipment Familiarity and First Order Electrical Circuits

Revision: September 17, 2018

Summary

First order circuits are mathematically modeled in the time domain by a first order differential equation with a time constant τ. The steady state response of first order circuits to sinusoidal inputs models the circuit using an impedance analysis approach, resulting in an algebraic governing equation for the circuit. Specifically, we will characterize the circuit by its magnitude response as a function of frequency. In this lab, we will get familiar with the lab instruments and their limitations, and we will investigate the effect of those physical limitations on your measurements.

Learning Outcomes: After completing this lab, you should be able to:

- Generate time-varying signals using the function generator.
- Measure time-varying signals using the oscilloscope.
- Calibrate oscilloscope probes.
- Experimentally measure the step response of a first order electrical circuit and find the time constant of the circuit from the measured step response.
- Experimentally measure the frequency response of a first order electrical circuit and find the cutoff frequency from the measured frequency response.
- Use experimental data to estimate unknown parameters in a mathematical model of a first order electrical circuit.

Required Equipment

- EE352 analog parts kit
- Breadboard
- Function generator, oscilloscope
- DMM
- DC power supplies

Bench Inventory

1. In your lab notebook, record the manufacturer's name and model number of the equipment at your workstation. Items to be inventoried include:

    - Oscilloscope
    - Digital Multimeter (DMM)
    - Function Generator
    - Power supply

    Additional equipment used in later experiments should be listed in your lab notebook entries for that experiment. It is important to document the equipment used in an experiment; a knowledgeable engineer should be able to replicate your experiment, including the equipment used, from the notes in your lab notebook.

2. Also inventory the probes and connectors at your workbench station. These do not have to be listed in your lab notebook, but you should have at least two each of the following:

    - Oscilloscope probes
    - BNC to BNC connecters

I. Getting Familiar with Function Generator and Oscilloscope

In EE352, you will often be concerned with the *time varying* response of electric circuits. Hence, two necessary instruments are needed. The function generator will be used to generate time-varying signals, and the oscilloscope will be used to measure and display time varying signals. This experiment will re-acquaint you with the basic operation of these instruments using hands on exploration.

The following instructions are intended as guidelines to help you to understand the operation of the function generator and oscilloscope. However, abbreviated manuals for most of the available lab equipment can be downloaded from the manufacturer's websites. Feel free to expand upon the procedures listed as you investigate the accuracy, appropriate frequency ranges, and general characteristics of equipment and components.

Pre-lab: None.

Lab Procedures:

1. Using two BNC coaxial leads and a Tee BNC splitter connect CH1 of the function generator to two channels (CH1 & CH2) of the oscilloscope. Both channels should show identical displays on the oscilloscope screen. Explore the oscilloscope and function generator controls. Use the function generator to generate various wave shapes (sinusoidal, square & triangular) over the available frequency range for a range of amplitudes. You should conclude that both BNC coaxial leads generate the same signal using Tee BNC splitter. In later experiments, one side of the splitter will be used to measure the function generator signal using the oscilloscope while the other side will be used to send the input signal to the tested circuits.

2. To investigate the maximum and minimum ranges of the function generator and the oscilloscope, set the oscilloscope for X1 and adjust the Volt/DIV control and the Time/DIV scale as you change amplitude and the frequency. You should be able to conclude what is the maximum and minimum amplitude and frequency that is supplied by the function generator and what are the limits for the scope to measure the sinusoidal, square and triangular waves. Expect the display to deteriorate at small amplitudes (e.g., mV) and high frequencies (e.g., MHz). Make sure that you can read time scales and amplitudes from the oscilloscope display using your eyeball. At this point you should know the minimum and maximum voltages and frequencies that are generated by the function generator and measured by the scope.

3. In your lab notebook record the minimum and maximum frequencies and amplitudes at which the waveform begins to deteriorate. This information can be valuable when evaluating results in other lab experiments. A table listing the max/min frequencies is useful, as are example waveform sketches.

4. Apply a 10V peak-to-peak sine wave at 1kHz using the function generator. Set the oscilloscope for X1, adjust the Volt/DIV control and the Time/DIV scale. Measure the peak-to-peak voltage using your eyeball, and using the measure key. (Save data on a Thumb Drive)

5. Using the function generator, apply a 10V peak-to-peak sine wave at 1kHz with 5V DC offset. Examine the effect of the DC & AC coupling of the oscilloscope. Explore the effect of varying the DC offset of the signal. Note that a sine-wave signal with DC offset may give a clipped display. (Save data on a Thumb Drive).

II. <u>Digital Multimeter (DMM) Verses Oscilloscope</u>

The internal impedance of a measuring instrument, such as an oscilloscope or DMM, can sometimes be comparable to the impedances of the circuit under measurement; when this is the case, the instrument's connection to the circuit can significantly affect the currents and voltages in the circuit. This experiment provides a qualitative yet hands on exploration of these effects.

Pre-lab: None.

Lab Procedures:

1. *Using the x10 oscilloscope probes*: The oscilloscopes are equipped with both ×1 and ×10 probes. Some of these probes have both ×1 and ×10 settings. (Note: BNC connectors can be considered as ×1 probes.) *A common mistake in the lab is to use a x10 probe while the oscilloscope is set for x1, or vice-versa.* The procedure to use the x10 probe is as follows:
    a. Select the channel to be displayed (CH1 or CH2), and then select "x10". You should see "x10" displayed on the menu.
    b. If you are using a probe with both x1 and x10 settings, then set the switch on the side of the probe to "x10".

2. *Calibrating the scope probe:*
    a. Set the scope and the probe to x10.

b. Connect the probe ground to the ground connector on the front of the oscilloscope.
c. Connect the probe to the square-wave generator on the front of the oscilloscope.
d. The scope should display a square wave with amplitude 5V. (If the amplitude is not 5V, then recheck whether both scope and probe are set to x10).
e. If the displayed square wave does not have square edges, adjust the set screw on the side of the probe until the displayed wave is square.

3. Use the Signal Generator to apply an 80 Hz, 3 volt zero-to-peak sine wave to the voltage divider shown in Figure 1. Use the oscilloscope with a $\times 10$ probe to measure V_{in} and V_o. With the oscilloscope still connected to V_o, use the DMM to measure V_o. Note any effect on the oscilloscope readings resulting from connecting the DMM to the circuit. Compare the DMM readings with the values measured by the oscilloscope, on the basis of a percentage change in the readings. Record the measurements before and after adding DMM. Based on your observations, what should you conclude?

4. The voltage divider circuit should not be affected by the frequency. Now, increase the frequency; note any discrepancies without and with the DMM added. Based on your observation, what should you conclude?

5. With only the oscilloscope still connected across V_o of the voltage divider of Figure 1, apply a 300 KHz, 3 volt zero-to-peak sine wave to the circuit. Now, use the DMM to measure V_o. Note any effect on the oscilloscope readings resulting from connecting the DMM to the circuit. Save your data before and after adding the DMM. Repeat these observations with a square wave input and observe the waveforms. Comment on your observations in your lab notebook and the report.

6. Disconnect the oscilloscope from the circuit and replace the 200 KΩ resistors in Figure 1 with 10 MΩ resistors. Now, use the DMM to measure V_o, for an 80Hz, 3 volt zero-to-peak input. Comment on the measured voltage, relative to your expectations.

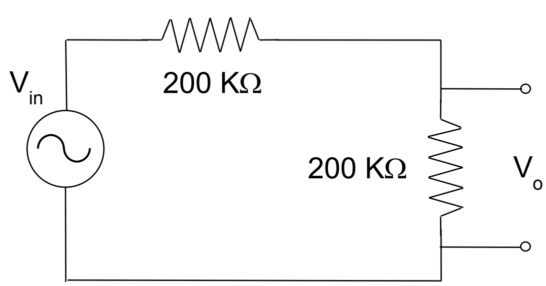

Figure 1. Voltage divider circuit for Part II.

III. Low pass RL circuit

For part III of this lab, consider the circuit shown in Figure 2. The input voltage is $V_i(t)$ and the output voltage is $V_o(t)$.

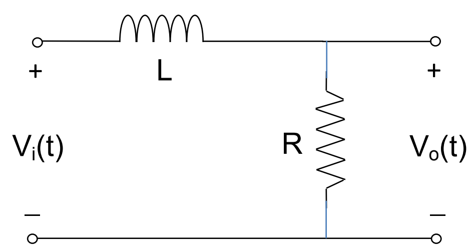

Figure 2. Low-pass RL circuit.

Pre-lab:

(a) Find an analytical expression for the amplitude of the frequency response of the circuit in Figure 2. Your response will be a function of frequency ω, as well as R and L. Determine the low-frequency (*ω=0)* gain*,* high frequency (*$\omega \to \infty$)* gain, and the frequency at which the gain $20\log_{10}(|V_o|/|V_i|) = 20\log_{10}(1/\sqrt{2}) = -3\mathrm{dB}$ (also called the *half power point, corner frequency, break frequency, 3dB frequency* or *cutoff frequency*).

(b) Find an analytical expression for the time constant τ of the circuit. What is the relationship between the time constant and the cutoff frequency? What percentage of the final value of the step response is achieved τ seconds after the start of the step?

(c) Let L = 1mH and R = 300Ω, and include a 50Ω internal resistance to an AC voltage source as an input, and then use AC sweep (Frequency Response) to simulate the circuit using either LTSPICE or ORCAD SPICE. Plot the amplitude of the gain in dB.

(d) Let L = 1mH and R = 300Ω and include a 50Ω internal resistance to a Vpulse input source, and then use transient analysis to simulate the unit step response of the circuit. Determine the time constant of the circuit. Select the pulse width to be greater than the settling time of the circuit.

Lab Procedures:

Construct the circuit shown in Figure 2 using nominal values of R=300Ω and L=1mH. Using the DMM and the RLC meter, measure the <u>actual</u> values of R and L that you use in your circuit, and record these values in your lab notebook for later analysis. (Note: The instructor or TA will show you how to use the RLC meter.)

1. *Experimental amplitude response*: Hook the signal generator's sine wave output to the circuit input V_{in}.
   a. Starting from a frequency of 10 Hz and a V_{in} amplitude of 4 volts zero-to-peak, set the frequency of the signal generator to progressively higher values; at each

frequency, use the oscilloscope to measure and record V_{in}, V_o, and the gain V_o/V_{in} as a function of frequency, and record the results in a table in your lab notebook.

b. Also in your notebook, plot the measured amplitude response $20\log_{10}(|V_o(\omega)|/|V_i(\omega)|)$ of the circuit (in dB) as a function of frequency; a hand-written plot is OK for your lab notebook.

c. Be sure to measure the amplitude response at enough different frequencies (typically 10 to 20, with the ending frequency at least 10 times the 3 dB cutoff frequency) to allow you to create a meaningful plot.

d. As you take the data, keep in mind that you need to *experimentally* determine the 3 dB cutoff frequency for this circuit. In your lab report, you should plot the data using, e.g., Microsoft Excel or MATLAB.

e. In your lab notebook, and in your lab report, explain how you experimentally find the 3dB frequency for the circuit.

2. *Experimental step response*: Using a square wave input as V_{in}, measure the step response of the system. Your input will need to have a low enough frequency to allow the system to reach a steady-state value. Sketch the step response in your lab notebook; estimate the time constant and steady-state response of the system. Comment on the agreement between the measured step response and the theoretical step response determined in the pre-lab. Note that the 50Ω internal resistance of the function generator will affect the time constant of the circuit. Explain how you estimated the circuit's time constant from your experimental measurements.

3. Demonstrate the operation of your circuit to the TA or instructor for both the sinusoidal input and step input cases. *Have the TA initial the lab checklist.*

IV. Oscilloscope Characterization

When measuring a physical quantity, the response of the instrumentation system often has an effect on the measurement. Sometimes this effect is negligible; at other times it can significantly change the measurement. In this part of the lab, we will characterize the oscilloscope's frequency response, and observe how it can effect circuit measurements.

Consider the circuits in Figures 3 and 4 below. Our goal is to measure the output voltage $V_o(t)$ of the voltage divider shown in Figure 3 in response to a sinusoidal input $V_{in}(t)$. Ideally the voltage divider circuit gain V_o/V_{in} should not be a function of frequency. However, it will be seen that the oscilloscope introduces loading effects (R & C) on the circuit which result in potentially erroneous measurements. The oscilloscope loading effects will be modeled by the first-order circuit in Figure 4.

When the output of the voltage divider is hooked across the input to the oscilloscope loading circuit, the resulting combined circuit is a first order lowpass filter. (Why?) Therefore, the circuit response can be characterized by its DC gain and cutoff frequency or time constant.

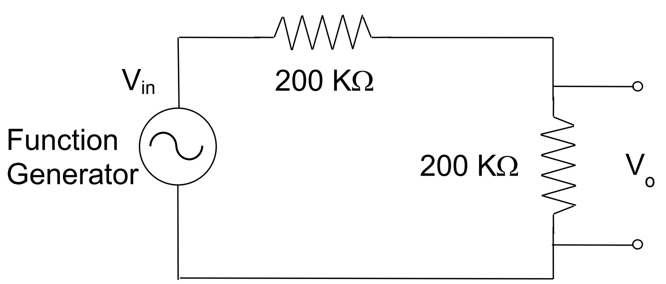

Figure 3. Voltage divider.

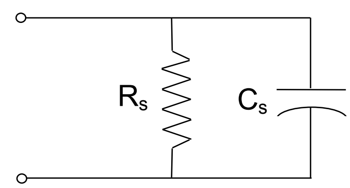

Figure 4. Oscilloscope loading circuit.

Pre-lab:

(a) From the probes manuals, obtain the values of R_s and C_s for the x1 and x10 probes.
- x1 has an internal resistance of 1MΩ and an internal shunt capacitance of 95 pF
- x10 has an internal resistance of 10MΩ and an internal shunt capacitance 16 pF

(b) Use LTSPICE or ORCAD AC analysis to simulate the voltage divider circuit with the oscilloscope loading circuit hooked across V_o. Determine the cutoff frequency (3dB frequency) for the both x1 and x10 loading equivalent circuits.

(c) Use LTSPICE or ORCAD transient analysis with a Vpulse input voltage with proper pulse width to simulate the voltage divider circuit with the oscilloscope loading circuit. Determine the time constant for both x1 and x10 loading equivalent circuits.

Lab Procedures:

Construct the circuit shown in Figure 3. Record the actual values of resistance used in your circuit.

1. Measure the input and output voltage amplitudes of the circuit of Figure 3 by connecting one channel of the oscilloscope to V_{in} and the other to V_o using x1 BNC and alligator connector cables. Estimate the DC gain and cutoff frequency of the circuit by applying sinusoidal input signals over a range of frequencies from 100 Hz to 1MHz to the circuit and computing the dB gain $20\log_{10}(|V_o(\omega)|/|V_i(\omega)|)$ as a function of frequency.

2. Using a square wave input, measure the step response of the system. Estimate a time constant and steady-state response for the system based on the square wave data you acquired. Are these values consistent with the DC gain and cutoff frequency you found in step 1 above?

3. Demonstrate operation of your circuit using the x1 probe to the TA or instructor for both the sinusoidal input and step input cases. *Have the TA initial the lab checklist.*

4. Replace the x1 lead with the x10 probe on the channel connected to V_o. Calibrate the probe using the square waveform from the oscilloscope front-panel. (See step 2 of Part II above). Then, using a sine wave input, estimate the DC gain and cutoff frequency of the system with the x10 probe.

5. Using a square wave input, measure the step response of the system. Estimate a time constant and steady-state response for the system based on the square wave data you acquired. Are these values consistent with the DC gain and cutoff frequency you found in step 4 above?

6. Demonstrate operation of your circuit using the x1 probe to the TA or instructor for both the sinusoidal input and step input cases. *Have the TA initial the lab checklist.*

<u>Lab Report:</u>

In your lab report, provide a summary of the results of this lab assignment. You should include, at a minimum, all items indicated on the lab checklist. Append the lab checklist sheet <u>with teaching assistant initials indicating completed lab demos</u> to your report.

Lab 1 Checklist

Name:_________________

I. Function Generator, Oscilloscope (10 pts total)

1. Highest measurable amplitude: sine, square, triangle wave.
2. Lowest measurable amplitude: sine, square, triangle wave.
3. Highest measurable frequency: sine, square, triangle wave.
4. Lowest measurable frequency: sine, square, triangle wave.

II. Digital Multimeter (DMM) (20 pts)

1. 80 Hz
   (a) Diagram of Figure 1.
   (b) x10 probe measurement of V_{in} and V_o.
   (c) DMM measurement of V_o.
   (d) Percent change in readings?
   (e) One sentence conclusion.
2. 300 KHz
   (a) DMM measurement of V_o.
   (b) Effect on oscilloscope readings?
   (c) Observations with square wave.
   (d) One sentence conclusion.
3. Using 10 MΩ @80 Hz
   (a) DMM measurement of V_o.
   (b) Expected value?
   (c) One sentence conclusion.

III. Low pass RL circuit. (35 points total)

1. Diagram of the circuit (Fig. 2). Circuit diagrams can be cut from the lab assignment and pasted into your report.

2. Theoretical amplitude response. Using your <u>measured</u> values for R and L and your result from part (a) of the prelab, plot the circuit's <u>theoretical</u> amplitude response. Plot should be in dB vs. $\log_{10}$ of the frequency. Calculate or estimate (from the plot) the 3dB frequency.

3. Theoretical step response. Using your <u>measured</u> values for R and L and your result from part (b) of the prelab, plot the circuit's <u>theoretical</u> step response. Calculate or estimate the time constant τ.

4. **DEMO**: Have your TA or instructor initial this sheet, indicating that they have observed your circuit's operation for sinusoidal and step inputs.
   ____
   - Circuit operates; input applied and output measured correctly.
   - Circuit operation matches expected theoretical high and low frequency responses. (Show TA pre-lab analysis of frequency response.)
   - Measured time constant, measured cutoff (3 dB) frequency, and relationship between the two. (Show TA pre-lab analysis giving relationship between time constant and cutoff frequency).

Name:__________________

5. Plot of measured frequency response (using, e.g., MATLAB or Excel). Measured data points should be indicated by symbols on the plot.

6. Plot of measured step response data points (using, e.g., MATLAB or Excel) used to compute the time constant, and an explanation of how the time constant was computed. Measured data points should be indicated by symbols on the plot.

7. Comment on agreement between theory and data. Include % difference between theory and data for both the time constant and the 3dB frequency.

8. Briefly discuss how this circuit works as a low pass filter.

IV. Oscilloscope Characterization. (35 points total)

1. Estimated DC gain and cutoff frequency with $\times 1$ probe.

2. Estimated steady-state response with $\times 1$ probe.

_______ 3. **DEMO**: Have a TA initial this sheet, indicating that he/she has observed your circuit's operation for sinusoidal and step inputs using the $\times 1$ probe.

4. Estimated DC gain and cutoff frequency with $\times 10$ probe.

5. Estimated steady-state response with $\times 10$ probe.

_______ 6. **DEMO**: Have a TA initial this sheet, indicating that he/she has observed your circuit's operation for sinusoidal and step inputs using the $\times 10$ probe.

7. Compare the cutoff frequencies of the $\times 1$ and $\times 10$ probes. Which probe should you use to measure a high-frequency signal?

