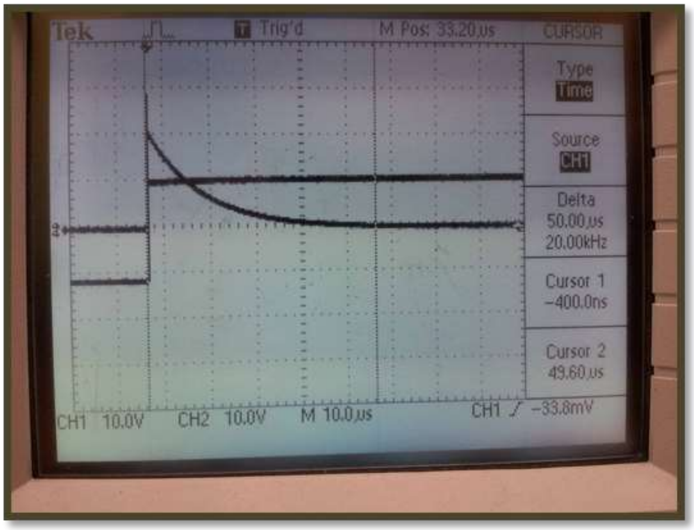
Electrical Engineering 110L Circuits Measurements Lab

Lab 4: Digital Oscilloscopes & Frequency Response



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November 5, 2012

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Objective

In electrical engineering the oscilloscope is one of the most important device electrical engineer's laboratory cannot go without. In this lab we will explore the technical usage for the oscilloscope and measure parameters for the low and high pass alternating current (AC) circuits. This lab consist of two part and will take two weeks to perform. The first objective is to learn the basic function of the oscilloscope and use its ability for measuring voltage, phase shift, time delay, and plotting Lissajous figures for collecting circuit's data.

Part B will force the students to operate the oscilloscope and measure the frequency response for simple filter circuits. Student will work with both high-pass and low-pass filter and finding the -3dB location on the dB vs. frequency plot.

Theory

In this lab we will be using the following governing equations to conduct experiments and verify principles:

Governing Equations	Equations Information
[1] $P = I^2R = V^2/R = VI$	I = current (A), P = power (W), R = resistance (Ω)
[2] $V = IR$	V = voltage (V)
[3] $V=V_{0\text{-peak}}\sin(\omega t+\theta)+/-V_{DC}$	General AC voltage sine wave
[4] $V = (P*R)^{1/2}$	Max voltage can be applied to resistor (derive from [1])
[5] $f = 1/T$	f = frequency (Hz) and T = period (s)
[6] Gain = 2b/2c	Amplified amount
[7] $dB = 20*\log(V_{in}/V_{out})$	Voltage ratio to dB conversion
[8] $\frac{1}{j\omega C}$	Capacitor's Impedance
[9] $j\omega L$	Inductor's Impedance
[10] Gain = V_{out}/V_{in}	Gain of the circuit
[11] BW = $\omega_{HI}-\omega_{LO}$	Bandwidth (ω are usually obtain from 3dB drop from maximum)
[12] $Q = \omega_R/(BW) = \|\|Z_c\|\|/R = \|\|Z_L\|\|/R$	Quality factor of the circuit

Table 1: Governing Equations for the experiments that follow.

Reading resistor's value will require understanding of the color values. This is the general equations that give the resistor's resistance. $R = (1^{st}2^{nd}) \times 10^{3rd}\,\Omega \pm 4^{th}$
The 1st denote the first color band, 2nd denote the second color band and so on. Plugging in the values into the respective location will give the resistance and tolerance of the resistor. The 4th is the tolerance of the resistor normally in percentage and needs to be converted to Ω for finding the range of resistance.

Voltage Division – provide the necessary equation to compare the input voltage with the output voltage. The voltage division in this case can be used for capacitors, inductors, and resistors. The technique is still the same with R being replace with equation [8] or [9] as if the resistor was at that location instead.

Procedure

Part A lab is to become familiar with the oscilloscope and be able to operate it for part B

Lab experiment 1:

After familiarizing oneself with the oscilloscope the next step is to setup the circuit A as described in the pre-lab. Proceed to the stock room an grab the 10nF capacitor and 500 Ω +/- 5% resistor. Measure each components resistance or capacitance for the circuit obtained. Place these parts in series with the resistor before the capacitor. With the oscilloscope connect the channel 1 across the power supply and channel 2 across the V_{out} (in this circuit A channel 2 should be across the capacitor). Base on the circuit design in the pre-lab V_{out} is always across the second component.

(NOTE: Circuit B, C, and D will be constructed later. Inductor → L = 3.9mH for C and D circuit. Resistance for inductor should be measured.)

Step 2 –

In this step, measure the voltage using the oscilloscope at different frequencies provided by the professor. The best method is to measure using the visible peak to peak AC voltage.

Step 3 –

Recording both input and output voltages from channel 1 and 2. When collecting the data it is recommended to record at least 2 data points at frequency when amplitude remain constant. Recording the point when the -3dB drop occurs is also useful in the experiment. Frequencies are chosen beforehand for the experiment. Just follow the recommended frequency and collect the data for successful graphing later.

Step 4 –

For following figure record the following data:
Circuit A – V_{in}, V_{out}, time delay, and 2a
(Note that 2a is measured from the Lissajous figure.)
Circuit B – 2a, V_{in}, and V_{out}
Circuit C – V_{in}, V_{out}, and time delay
Circuit D – 2a, V_{in}, and V_{out}

Afterward in the post lab the data is plot between output and input voltages as a function of frequency.

Experiment 2:

In the second experiment construct a low-pass filter with its -3dB frequency at the month and day of your birthday e.g. (mmdd). Add a zero to make it 4 digit if necessary. The potentiometer can be used to tune the resistor to get the correct frequency. Be sure to record the resistance and capacitance used in the low-pass filter.

Experiment 3:

With the oscilloscope's probe remove the cap and touch it while monitoring the AC signals from the screen (do a screenshot for easier reading of the frequency). Changing the trigger controls and time base (s/div) will help achieve better stable display. Measure the frequency (ignore the high frequency noise).

Data, Data Analysis, Error Analysis, and Discussion

Error Analysis

If the general equation is F(x_1, x_2,…, x_n) then the error for F (identified as σ_F) would be given by the following error propagation equation:

$$\sigma_F = \sqrt{\left(\frac{dF}{dx_1}\sigma_{x_1}\right)^2 + \left(\frac{dF}{dx_2}\sigma_{x_2}\right)^2 + \cdots + \left(\frac{dF}{dx_n}\sigma_{x_n}\right)^2}$$

Lab experiment 1:

For all of experiment 1 with the four circuit we used the following resistor, capacitor, and inductor with the following values:

R = 512+/-.5 Ω || C = 10.32+/-.005 nF || L = 2.44+/-.005 mH (with R = .543+/-.0005 Ω)

Since the resistance in the inductor is much smaller than the resistor's resistance it can basically be ignored for simpler error calculation.

Circuit A

Data & Error Analysis

Frequency (kHz)	Period (s)	Vin (V) +/-.05	Vout (V) +/-.05	time delay +/-.005 (μ sec)	phase (degree) +/-.05	Gain +/- .005	Gain (dB)
1.7	5.88E-04	21.4	21.4	4.60E+00	-2.8	1.0	0.0
2.5	4.00E-04	21.0	21.4	5.60E+00	-5.0	1.0	0.2
10	1.00E-04	21.0	20.0	4.88E+00	-17.6	1.0	-0.4
25	4.00E-05	20.4	15.8	4.28E+00	-38.5	0.8	-2.2
50	2.00E-05	19.8	10.2	3.18E+00	-57.2	0.5	-5.8
100	1.00E-05	19.4	5.8	2.02E+00	-72.7	0.3	-10.5
150	6.67E-06	19.2	3.9	1.43E+00	-77.2	0.2	-13.8
240	4.17E-06	19.2	2.5	9.50E-01	-82.1	0.1	-17.8
300	3.33E-06	19.2	2.0	7.76E-01	-83.8	0.1	-19.6
500	2.00E-06	19.2	1.2	4.84E-01	-87.1	0.1	-24.0

Table 2: Data for Circuit A

The data collected in the table above is later used to calculate for the bode plots. The phase and gain is calculated from here to later be used in the bode plot.

The theoretical equations used for this RC circuit are:

- Theoretical Equation = 1/(1+jwRC)
  - ⇨ Gain = 1/(1+(wRC)^2)^.5
  - ⇨ Phase = -arctan(wRC)

By plotting the theoretical equations with the experimental points obtain from the experiment we can find the percent error as shown. By comparing the difference between the theoretical value and experimental value we can find the percent error. This will tell how close the value is actually from the true value.

Frequency (kHz)	2a (V) +/-.005	2b (V)+/-.005	2c (V) +/-.005	phase (deg)
1.7	1.00	21.4	21.4	2.7
2.5	1.60	21.4	21.0	4.3
10	6.00	20.0	21.0	17.5
25	8.80	15.8	20.4	33.8
50	8.40	10.2	19.8	55.4
100	5.40	5.8	19.4	69.6
150	3.75	3.9	19.2	73.1
240	2.25	2.5	19.2	65.1
300	1.90	2.0	19.2	71.8
500	1.20	1.2	19.2	82.6

Table 3: Lissajous data for circuit A (+/-.005V for the voltage measured)

Frequency (kHz)	$Phase_{measure}$ (degree)	$Phase_{the}$ (degree)	% error	$Gain_{measure}$ (dB)	$Gain_{the}$ (dB)	% error (%)
1.7	-2.8	-3.2	12.8	0.00E+00	0.0	N/A
2.5	-5.0	-4.7	6.2	1.64E-01	0.0	N/A
10	-17.6	-18.4	4.3	-4.24E-01	-0.5	6.7
25	-38.5	-39.7	3.0	-2.22E+00	-2.3	2.5
50	-57.2	-58.9	2.9	-5.76E+00	-5.7	0.3
100	-72.7	-73.2	0.7	-1.05E+01	-10.8	2.3
150	-77.2	-78.6	1.8	-1.38E+01	-14.1	2.2
240	-82.1	-82.8	0.9	-1.78E+01	-18.1	1.8
300	-83.8	-84.3	0.5	-1.96E+01	-20.0	1.8
500	-87.1	-86.6	0.7	-2.40E+01	-24.4	1.7

Table 4: Percent difference for phase and Gain.

The table above shows the error in our calculation.

Data Analysis

The graph resulting from the measured experimental values and theoretical value are display in the bode graph for both Gain and Phase. From the graph we can easily see that the theoretical and experimental graph are well aligned meaning this was a good experiment. The percent error was also extremely small. (Note: the error for division by zero cannot be done so should be ignored or it will result in large percent error.) To do this analysis the theoretical equation is needed. This theoretical equation is plot against the experimental to get the resulting graphs. With the equation the true (theoretical) dB can be calculated from any frequency.

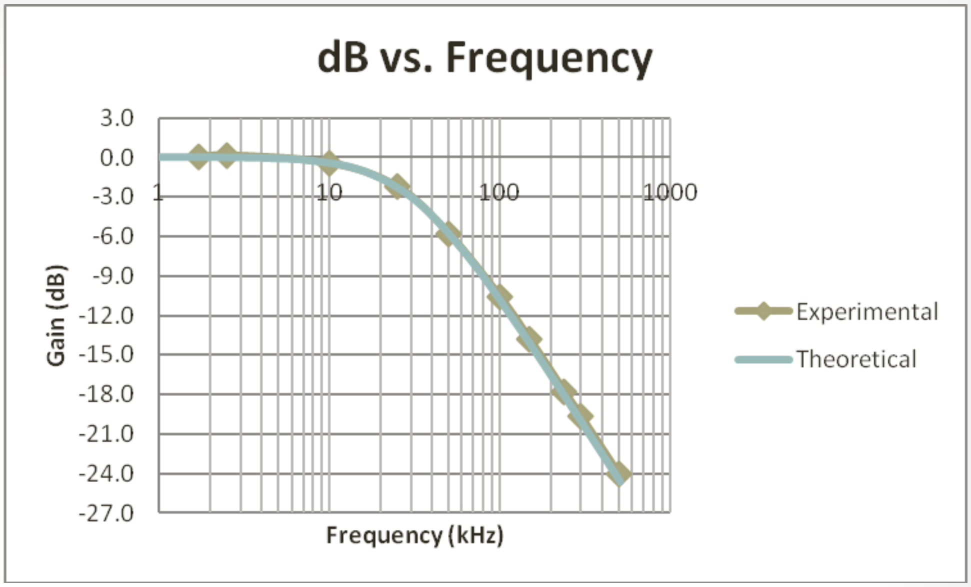

Figure 1: Circuit A Bode Plot for Gain

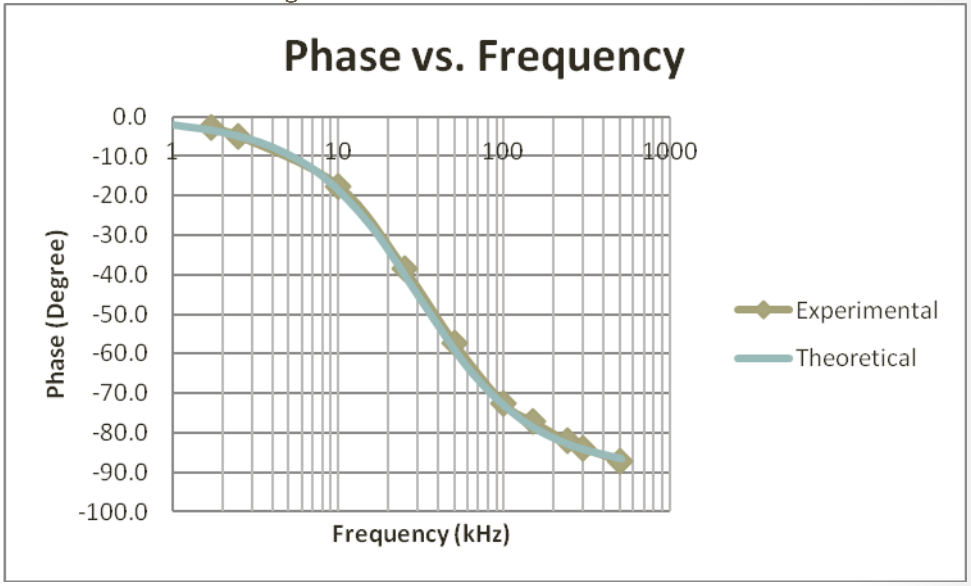

Figure 2: Circuit A Bode Plot for Phase

Discussion

From the graph we were able to pick out the -3dB value since it is pretty accurate. From the measurements though the closest value we measured is -2.22dB. At this location the frequency is 25kHz. At the 25kHz frequency the theoretical dB is -2.3. This give us a 2.5% error which is pretty small. As we move to higher frequency the range of % error remain around 2% as shown in table 4. So the expected -3dB would not be any different. Overall the good correlation between the experimental and theoretical graph verify that the experiment is a success. The experiment clear shows a low-pass filter type graph as we expected from the circuit with the 20dB/decade drop.

Circuit B

Data & Error Analysis

Frequency (kHz)	2a (V)	2b (V)+/- .005	2c (V) +/- .005	phase (deg)	Gain	Gain (dB)
1.7	1.24E+00	2.10E+01	1.15E+00	90	0.1	-25.2
2.5	1.50E+00	2.10E+01	1.72E+00	60.7	0.1	-21.7
10	5.90E+00	2.10E+01	6.28E+00	70	0.3	-10.5
25	9.60E+00	2.04E+01	1.24E+01	50.7	0.6	-4.3
50	8.80E+00	1.98E+01	1.66E+01	32	0.8	-1.5
100	5.40E+00	1.96E+01	1.86E+01	16.9	0.9	-0.5
150	4.00E+00	1.94E+01	1.90E+01	12.2	1	-0.2
240	2.50E+00	1.92E+01	1.94E+01	7.4	1	0.1
300	2.00E+00	1.94E+01	1.92E+01	6	1	-0.1
500	1.20E+00	1.96E+01	1.92E+01	3.6	1	-0.2

Table 5: Data for circuit B (+/-.005V for the voltage measured)

Frequency (kHz)	phase_mea (degree)	phase_the (degree)	% error	Gain_mea (dB)	Gain_the (dB)	% error
1.7	90.0	86.8	3.7	-25.2	-25.0	1.0
2.5	60.7	85.3	28.8	-21.7	-21.6	0.4
10	70.0	71.6	2.3	-10.5	-10.0	4.5
25	50.7	50.3	0.8	-4.3	-3.9	11.0
50	32.0	31.1	3.1	-1.5	-1.3	13.9
100	16.9	16.8	0.7	-0.5	-0.4	20.6
150	12.2	11.4	7.0	-0.2	-0.2	5.4
240	7.4	7.2	3.5	0.1	-0.1	232.6
300	6.0	5.7	4.3	-0.1	0.0	106.6
500	3.6	3.4	3.9	-0.2	0.0	1038.4

Table 6: Percent difference for phase and Gain.

The data collected in the table above is later used to calculate for the bode plots. The phase and gain is calculated from here to later be used in the bode plot.

The equations used for this RC circuit are:

- Theoretical Equation = R/[R+(1/jwC)]
  - ⇨ Gain = R/[R^2+(1/wC)^2]^.5
  - ⇨ Phase = -arctan(1/wCR)

By plotting the theoretical equations with the experimental points obtain from the experiment we can find the percent error as shown. By comparing the difference between the theoretical value and experimental value we can find the percent error. This will tell how close the value is actually from the true value.

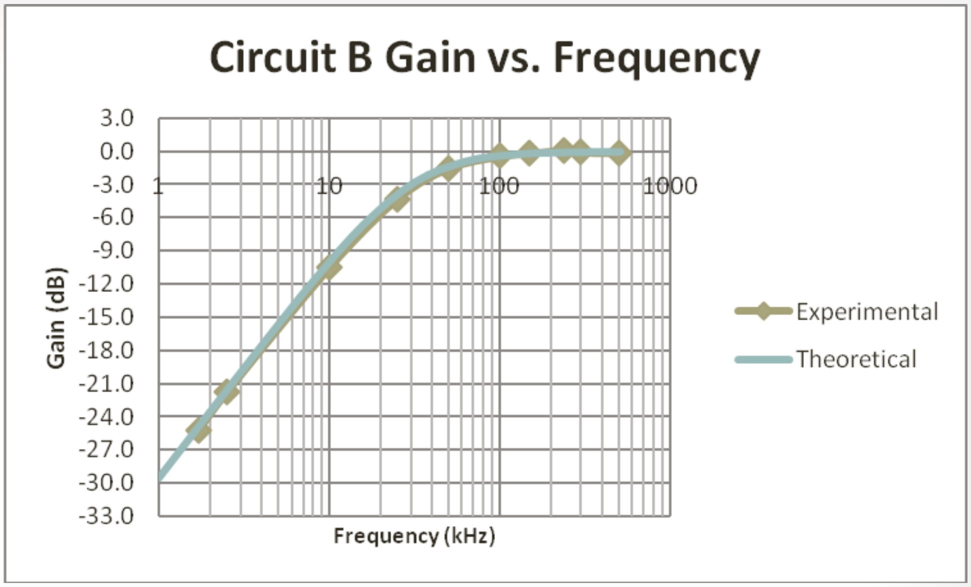

Figure 3: Circuit B Bode Plot for Gain

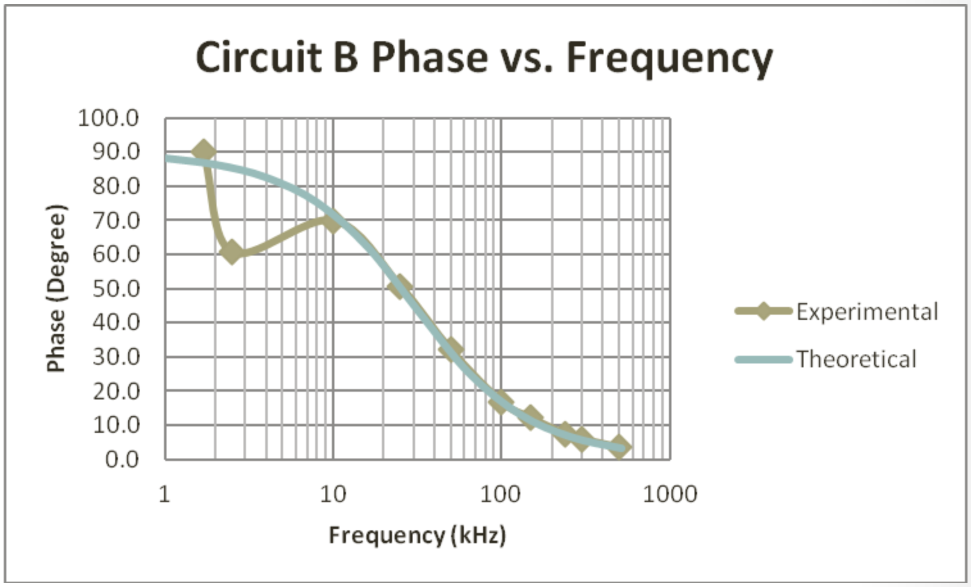

Figure 4: Circuit B Bode Plot for Phase

Data Analysis

In this circuit B calculating for the phase and gain we used the arctan and equation [10] respectively. The graph has a nice fit once we find the theoretical gain and plot it with the experimental gain. The theoretical and experimental values are close from looking at the graph. The most odd thing is in the phase. There is one point where it dropped significantly at about 2kHz. This is either due to poor measurements because we stopped our first half of the experiment and continue with it the next meeting. This mean that we have to setup the experiment again and could have recorded the wrong data when the setup was wrong. We realize the incorrect setup and corrected but could have forgot that we recorded one point.

Discussion

Overall the high-pass filter is clearly seen in this circuit B as we expected. There are some slight percent error as we expected but they do not create a large discrepancy for the graphs to not correlate. This is clear a high-pass filter and is another good setup. The closest we can get to the -3dB is at -4.3dB which results in a 25kHz frequency. At this 25kHz the theoretical dB is at -3.9. This mean there is a 11% error in this experiment. Though percent error seems high the overall high-pass filter is still shown in the graph. This is due to the log scale that minimize percent difference significance unless it is a few hundred percent error in magnitude. Again the theoretical and experimental graph correlates nicely with the 20db/decade positive slope with the high-pass filter characteristics.

Circuit C

Data & Error Analysis

Frequency (kHz)	Period (s)	Vin (V) +/- .05	Vout (V) +/-.05	time delay (usec) +/-.005	phase (degree)	Gain +/- .005	Gain (dB)
1.7	5.88E-04	19.4	1.92E+01	7.00E+00	-4.3	1.0	-0.1
2.5	4.00E-04	19.6	1.92E+01	6.88E+00	-6.2	1.0	-0.2
10	1.00E-04	19.6	1.80E+01	6.24E+00	-22.5	0.9	-0.7
25	4.00E-05	20.2	1.37E+01	5.08E+00	-45.7	0.7	-3.4
50	2.00E-05	21.0	8.88E+00	3.54E+00	-63.7	0.4	-7.5
100	1.00E-05	21.4	4.76E+00	2.12E+00	-76.3	0.2	-13.1
150	6.67E-06	21.4	3.18E+00	1.50E+00	-81.0	0.1	-16.6
240	4.17E-06	21.4	1.86E+00	9.80E-01	-84.7	0.1	-21.2
300	3.33E-06	21.4	1.35E+00	8.10E-01	-87.5	0.1	-24.0
500	2.00E-06	21.4	4.20E-01	4.96E-01	-89.3	0.0	-34.1

Table 7: Data for circuit C (+/-.005V for the voltage measured)

Frequency (kHz)	phase_mea (degree)	phase_the (degree)	% error	Gain_mea (dB)	Gain_the (dB)	% error
1.7	-4.3	-2.9	47.0	-25.2	-0.1	27930.7
2.5	-6.2	-4.3	44.6	-21.7	-0.2	12035.2
10	-22.5	-16.7	34.8	-10.5	-0.7	1317.5
25	-45.7	-36.8	24.2	-4.3	-3.4	28.2
50	-63.7	-56.3	13.3	-1.5	-7.5	79.5
100	-76.3	-71.5	6.7	-0.5	-13.1	96.5
150	-81.0	-77.4	4.6	-0.2	-16.6	98.9
240	-84.7	-82.1	3.2	0.1	-21.2	100.4
300	-87.5	-83.6	4.6	-0.1	-24.0	99.6
500	-89.3	-86.2	3.6	-0.2	-34.1	99.5

Table 8: Percent difference for phase and Gain.

The data collected in the table above is later used to calculate for the bode plots. The phase and gain is calculated from here to later be used in the bode plot.

The equations used for this RC circuit are:

- Theoretical Equation = R/(R+jwL)
  - ⇨ Gain = R/(R^2+(wL)^2)^.5
  - ⇨ Phase = -arctan(wL/R)

By plotting the theoretical equations with the experimental points obtain from the experiment we can find the percent error as shown. By comparing the difference between the theoretical value and experimental value we can find the percent error. This will tell how close the value is actually from the true value.

In this experiment the percent error is calculate like the previous step by finding the theoretical value with the theoretical equation and taking the difference. Finding the rest of the data is the same as the previous circuit A and B.

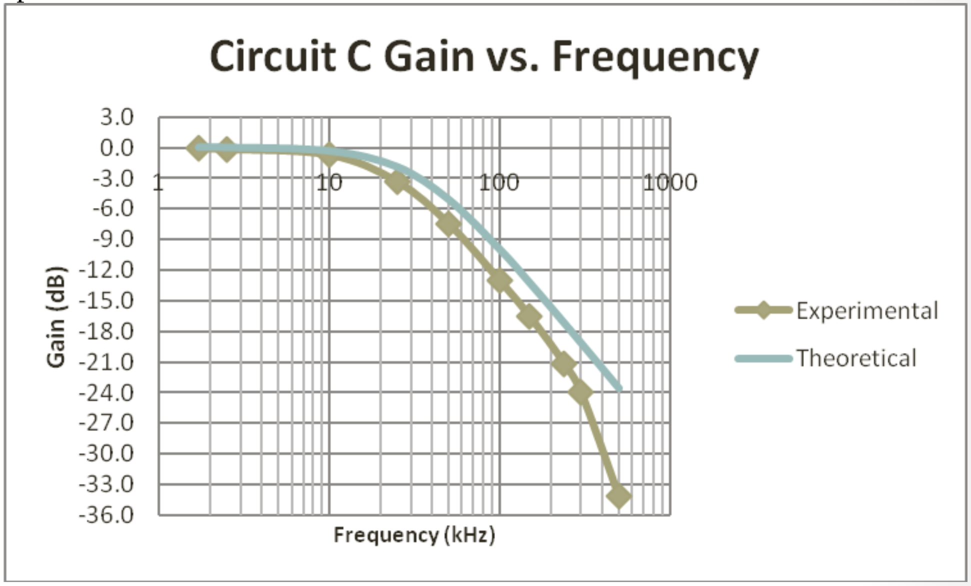

Figure 5: Circuit C Bode Plot for Gain

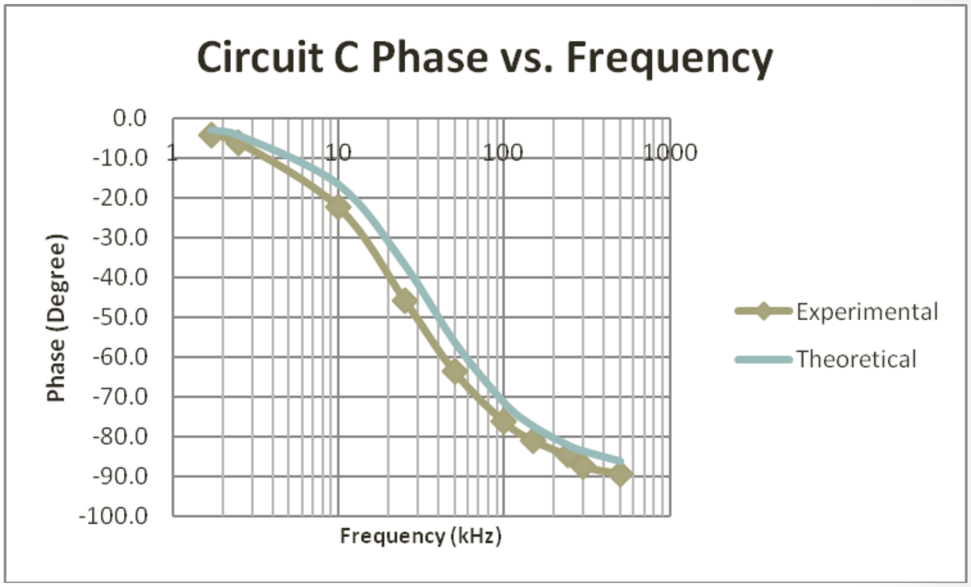

Figure 6: Circuit C Bode Plot for Phase

Data Analysis

In this circuit C calculating for the phase and gain we used the arctan and equation [10] respectively. The graph has a nice fit once we find the theoretical gain and plot it with the experimental gain. The theoretical and experimental values are close from looking at the graph. The data analysis is done the same is the previous circuits using the theoretical equation at the beginning of this section.

Discussion

Overall the low-pass filter is clearly seen in this circuit C as we expected. There are some slight percent errors as we expected but they do not create a large discrepancy for the graphs to not correlate. This is clear a low-pass filter and is another good setup. The closest we can get to the -3dB is at -4.3dB which results in a 25kHz frequency. At this 25kHz the theoretical dB is at -3.4. This mean there is a 28.2% error in this experiment. Though percent error seems high the overall low-pass filter is still shown in the graph. This is due to the log scale that minimizes percent difference significance unless it is a few hundred percent error in magnitude. Again the theoretical and experimental graph correlates nicely with the -20db/decade slope and the low-pass filter characteristics.

Circuit D

Data & Error Analysis

Frequency (kHz)	2a (V) +/-.005	2b (V)+/- .005	2c (V) +/- .005	phase (deg)	Gain	Gain (dB)
1.7	1.36E+00	1.96E+01	1.38E+00	80.2	0.1	-23.0
2.5	1.90E+00	1.96E+01	2.00E+00	71.8	0.1	-19.8
10	6.50E+00	2.00E+01	7.20E+00	64.5	0.4	-8.9
25	9.60E+00	2.02E+01	1.40E+01	43.3	0.7	-3.2
50	7.90E+00	2.10E+01	1.86E+01	25.1	0.9	-1.1
100	4.60E+00	2.12E+01	2.04E+01	13.0	1.0	-0.3
150	3.00E+00	2.12E+01	2.08E+01	8.3	1.0	-0.2
240	1.50E+00	2.12E+01	2.12E+01	4.1	1.0	0.0
300	1.00E+00	2.12E+01	2.12E+01	2.7	1.0	0.0
500	3.00E-01	2.14E+01	2.12E+01	0.8	1.0	-0.1

Table 9: Lissajous data for circuit D (+/-.005V for the voltage measured)

Frequency (kHz)	phase_mea (degree)	phase_the (degree)	% error	Gain_mea (dB)	Gain_the (dB)	% error
1.7	80.2	87.1	7.9	-25.2	-25.9	2.5
2.5	71.8	85.7	16.2	-21.7	-22.5	3.6
10	64.5	73.3	12.0	-10.5	-10.8	3.3
25	43.3	53.2	18.6	-4.3	-4.4	2.8
50	25.1	33.7	25.5	-1.5	-1.6	4.4
100	13.0	18.5	29.4	-0.5	-0.5	0.9
150	8.3	12.6	33.9	-0.2	-0.2	13.9
240	4.1	7.9	48.8	0.1	-0.1	208.1
300	2.7	6.4	57.4	-0.1	-0.1	68.3

500	0.8	3.8	78.8	-0.2	0.0	826.4

Table 10: Percent difference for phase and Gain.

The data collected in the table above is later used to calculate for the bode plots. The phase and gain is calculated from here to later be used in the bode plot.

The equations used for this RC circuit are:

- Theoretical Equation = jwL/(R+jwL)
  - ⇨ Gain = wL/(R^2+(wL)^2)^.5
  - ⇨ Phase = -arctan(R/wL)

By plotting the theoretical equations with the experimental points obtain from the experiment we can find the percent error as shown. By comparing the difference between the theoretical value and experimental value we can find the percent error. This will tell how close the value is actually from the true value.

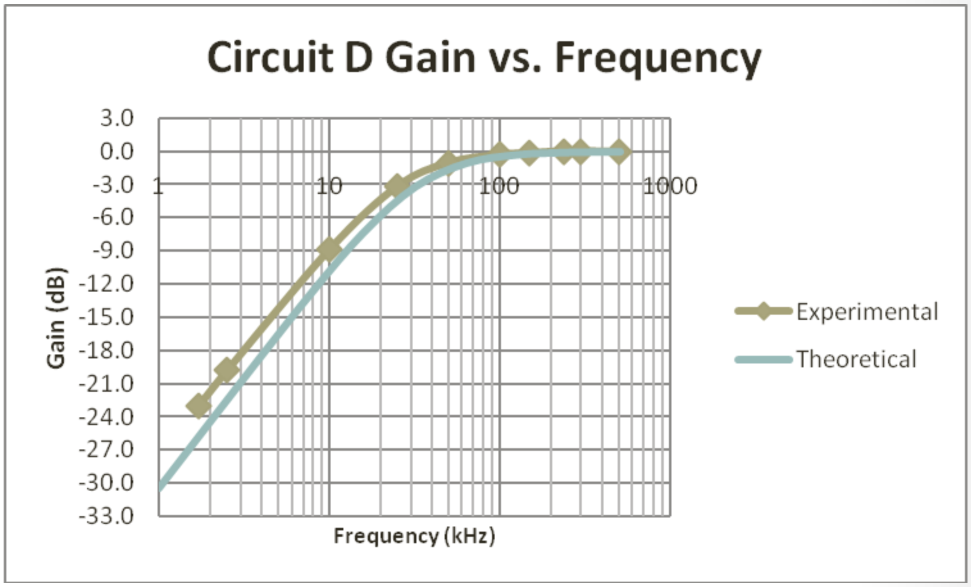

Figure 7: Circuit D Bode Plot for Gain

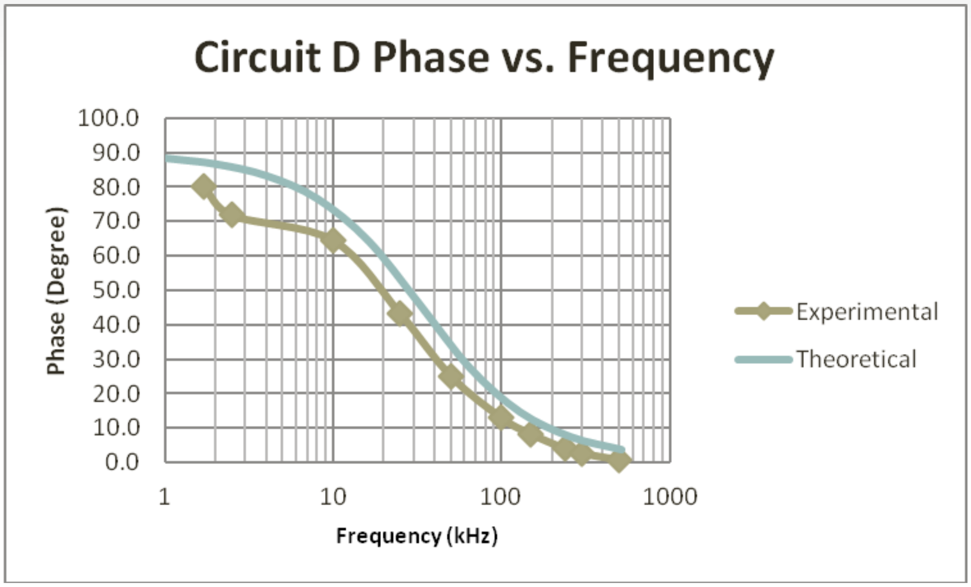

Figure 8: Circuit D Bode Plot for Phase

Data Analysis

In this circuit D calculating for the phase and gain we used the arctan and equation [10] respectively. The graph has a nice fit once we find the theoretical gain and plot it with the experimental gain. The theoretical and experimental values are close from looking at the graph. The data analysis is done the same is the previous circuits using the theoretical equation at the beginning of this section.

Discussion

Overall the high-pass filter is clearly seen in this circuit D as we expected. There are some slight percent error as we expected but they do not create a large discrepancy for the graphs to not correlate. This is clear a high-pass filter and is another good setup. The closest we can get to the -3dB is at -4.3dB which results in a 25kHz frequency. At this 25kHz the theoretical dB is at -4.4dB. This mean there is a 2.8% error in this experiment. Again the theoretical and experimental graph correlates nicely with the 20db/decade positive slope and the high-pass filter characteristics.

Lab experiment 2:

Data & Error Analysis

The value we chose for the capacitor and resistors are:
R = 1611+/-10 Ohms (tuned with the device) || C = 10.26+/-.005 nF
Note: the resistor sometime change by +/-10 ohms when re-measuring it.

	Frequency (kHz)	Vin (V) +/- .05	Vout (V) +/- .05
Experimental	9.3	21.20	14.80
Theoretical	9.3	21.20	14.98
% error	0% chosen	0% chosen	1.20%

Table 11: Birthday frequency data

In this experiment to calculate for the theoretical value we use the experimental value frequency and V_{in}. This would make the most logical sense as it is the value we are using.

Choosing the pre-lab value would not make sense as resistors or capacitors of desired value might not exist so we are technically basing our error on something we know is not used in the experiment. After obtaining the percent error it is only at 1.2% which is a nice low value.

Data Analysis

To calculate for the theoretical we used the theoretical gain equation listed in the experiment 1. Calculate for the expected V_{out} when we know what the V_{in}, R, and C is at -3dB. This give us a nice -3dB location.

Discussion

In this section the -3dB is easily found with the theoretical equation. There is not much steps to help improve on this process with current equipment. The percent error is as small as it is.

Lab experiment 3:

	Frequency (kHz)
Experimental	60.24+/-.05 Hz
Theoretical	60 Hz
% error	0.4%

Table 12: Frequency of human body close to outlet.

In this experiment we measure the frequency across our body. It turns out that from this experiment our body frequency is close to that of the current of the outlet. This is probably due to the saltwater in our body that acts like an antenna that picks up the frequency of the electrons resulting in us having a 60Hz frequency as well.

Conclusions

In this lab our experiments were very successful and we were able to demonstrate and verify the low-pass and high-pass filter for each circuits. The -3dB though were not exactly found but there were values that were quite near it that was obtained. The -3dB can be easily seen in all of the graphs and locate if by drawing a horizontal line from the -3dB until it intersect the graph. Then when comparing the point of the -3dB for the theoretical and experimental values they are extremely close on the graph. As most of our experimental values have small percent error. The body frequency phenomenon is also an interesting concept in this experiment and we were able to relate it to that possible effect of the outlet that we were close to.

The only main issues that we encounter were the many large percent error that occurs at small value in dB. This is because log of values close to 1 is 0 so when we take the percent error of a value over an extremely small value (or 0) we obtain a huge percent error. This does not affect the result of high and low pass filters since they were on the log scale. This just goes to show that percent error is not very useful in this case. Overall the experiment is a success and not much improvement is needed as all results just verify the theoretical values.