PHYS 605 Lab 3 Analog 2 Progress Report

Name: Dan Albu[*]
Lab Partner: Ryan Coyne

March 1, 2024

1 Introduction

In this lab, we learned about impedance, RC, and RLC circuits. We also learned how to create Bode and Gain[1] plots. In addition to this, we became more familiar with the oscilloscope and function generator, as well as how different frequencies interact with different circuits, such as the high pass and low pass circuits.

1.1 Equipment Used

- **Mastech MS8268 Multi-Meter**

  ○ **NOTE:** Referenced as Multi-meter, Ohmmeter, Voltmeter, or Ammeter

- **PB-503 Proto-board**

  ○ **NOTE:** Referenced as board or breadboard

- **Analog Discovery 2 - USB Oscilloscope and Signal Generator**

  ○ **NOTE:** Referenced as AD, Analog Discovery, Oscilloscope, Scope, Wave-Gen, or wave generator[2]

---

[*]Each reference used in this report is a hyperlink.

[1]Gain plots will be interchangeably reffered to as Attenuation plots throughout the report

[2]The Analog Discovery can also act as an Ammeter or Voltmeter. If it is being mentioned, it will be noted that it is the AD rather than the Mastech MS8268. If both are being used, the AD instrument will have an * symbol after it to differentiate between the two.

- **Components** [3]

  ○ 100 nF Capacitor

  ○ 10 kΩ Resistor

  ○ 1 mH Inductor

Capacitor Value	Associated ID (Front/Back)
10 nF	103CSK/531RFO
100 nF	104ESM/335ACA
1 μF	BCI052[4]

Table 1: Capacitor Identification

1.2 Help

- Who we helped

  ○ Conor Bosworth's Group located in front of us

  ○ Ryan McClennan and Audrey Robison's group located behind us

- Who helped us

  ○ Dr. Holtrop and Gavin Riley

2 Measuring Capacitance

Before we started analyzing low and high pass circuits, we had to verify the capacitance of the capacitors we were using. To do this, we first built a low pass circuit (Figure 1). We made sure to connect channel 1 of the oscilloscope in parallel with the WaveGen to plot the 1 V square wave output of the WaveGen. After connecting a resistor in series with the WaveGen then adding a capacitor, we added
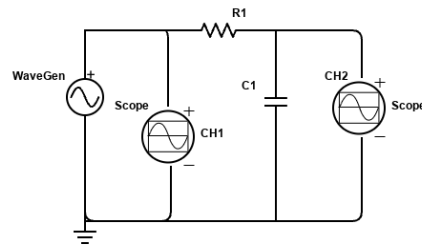

Figure 1: Low Pass Circuit Schematic

channel 2 of the oscilloscope in parallel with the capacitor to plot the voltage across the capacitor, which can also be modelled as the output voltage of the circuit. We gathered three different capacitors: 10 nF, 100 nF, and 1 μF.

---

[3]Not including the capacitors used for testing capacitance

[4]This may have been BC105Z but unfortunately my handwriting does not allow one to discern between the two.

We then had to choose three resistor values to use with the capacitors. We chose 100 kΩ, 10 kΩ, and 1 kΩ resistors, corresponding to the 10 nF, 100 nF, and 1 μF capacitors respectively. After circuit was built, we used a square wave with an amplitude of 0.5 V centered at 0 V and four different frequencies to measure the capacitance of the capacitors using the "Impedance" measurement on the AD. The frequencies used were 1 kHz, 500 Hz, 200 Hz, and 100 Hz. We then used the Mastech MS8268 Multi-meter to measure the capacitance of each capacitor and compared values.

2.1   Data

Frequency (Hz)	10 nF	100 nF	1 μF
1000	9.16 nF	89.2 nF	1.05 μF
500	9.21 nF	90.1 nF	1.08 μF
200	9.29 nF	91.3 nF	1.15 μF
100	9.34 nF	92.1 nF	1.19 μF

Table 2: Analog Discovery Expected Capacitance vs Measured Capacitance per Frequency

Expected Capacitance	Measured Capacitance
10 nF	9.2 nF
100 nF	90.6 nF
1 μF	1.13 μF

Table 3: Multi-meter Expected Capacitance vs Measured Capacitance

2.2   Conclusion

We determined that the AD was a much more trustworthy measurment device, as its measurements were much closer for almost every measurement. However we determined that the Multi-meter was still useful for a quick, less accurate measurement. An interesting thing we noted was that the capacitance had an inversely proportional dependence the frequency of the input signal. This is something we had already learned from the equations:

$$Z_C = \frac{1}{j\omega C} \Rightarrow C = \frac{1}{j\omega Z_C} \tag{1}$$

$$C \propto \frac{1}{\omega} \tag{2}$$

but it was interesting to see this relationship with data.

3   Low Pass Filter Circuit

NOTE

During this lab my lab partner and I were under the impression that Attenuation plots and Bode plots were the same thing due to misinterpretting the directions at the beginning of the lab and thus did not gather data for the Attenuation plots. We did, however, gather data for the Bode plots. Since we have the data for the Bode plots, we used that data to make the Attenuation plots. We used:

$$B = 20log(\frac{V_{out}}{V_{in}}) \tag{3}$$

and since we know that Attenuation, or Gain is just V_{out}/V_{in}, we can use the equation for B to get the equation for Gain, G:

$$\frac{B}{20} = log(\frac{V_{out}}{V_{in}}) \Rightarrow 10^{\frac{B}{20}} = \frac{V_{out}}{V_{in}} \tag{4}$$

thus we get:

$$G = 10^{\frac{B}{20}} \tag{5}$$

So in the plotting program I divided every value in the Bode plot data array by 20 and raised it to the exponent with 10 as the base to get the Gain plot data array.

3.1   Low Pass Filter

Now, after determining our capacitance and the accuracy of our measuring devices, we would start analyzing the low pass filter in earnest. Using the same circuit (Figure 1) as before, our resistor value was 10 kΩ and our capacitor value was 100 nF. Our input was a square wave at 100 Hz, with an amplitude of 1 V, centered at 0 V with a total ΔV of 2 V. Our time position was 0 s
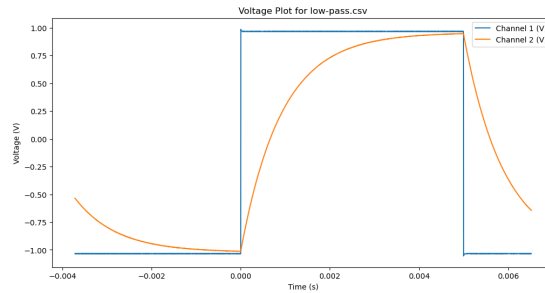

Figure 2: Low Pass Voltage Plot

and our base was 2 ms/div. Our range for both channel 1 & 2 was 500mV/div, with a 0 V offset. Our plot of the input voltage (Channel 1) and the output voltage (Channel 2) can be seen in Figure 2. After using the AD to get the measurements for rise (t_R) and fall (t_F) time, we used our cursor measurement to measure the time it took for the voltage to go from 1 V to e^{-1} V and e^{-2} V respectively (marked as t_1 and t_2 in equation 13 and 14). Once we had these measurements, we used each of these times to calculate the capacitance of the

capacitor. We then compared each of these values to the expected capacitance of the capacitor to determine which was the most accurate. To calculate the values seen in Table 5, we used the equation for the fall time:

$$V(t) = V_0 e^{\frac{-t}{RC}} \tag{6}$$

solving for C we get:

$$C = \frac{t}{R ln(\frac{V_0}{V(t)})} \tag{7}$$

and with the initial conditions:

$$V_0 = 1V, \ V(t_1) = e^{-1}V, \ V(t_2) = e^{-2}V \tag{8}$$

we get:

$$C_1 = \frac{t_1}{R}, \ C_2 = \frac{t_2}{2R} \tag{9}$$

Since the capacitance is the same regardless of whether we use the rise time or fall time equation, we used the fall time equation to calculate our capacitance using both t_R and t_F since it was more simple. When calculating these values in lab, I made a good amount of math errors, so in this report I am making sure to rectify those errors and present the corrected data and calculations (Table 5). To calculate the capacitance with t_R and t_F we used:

$$V(t_F) = V_0 e^{\frac{-t}{RC}} \tag{10}$$

In the case for rise and fall time, we know that regardless of which equation we use, our equation will simplify to the same point, so we will solve the equation for the case of fall time; that is, for when $V(t) = 0.9V_0$ and $V_0 = 1V$. This gives us:

$$V(t_F) = 0.9V_0 = V_0 e^{\frac{-t_F}{RC}} \Rightarrow 0.9 = e^{\frac{-t_F}{RC}} \Rightarrow ln(0.9) = \frac{-t_F}{RC} \tag{11}$$

$$C_F = \frac{t_F}{R ln(9)} \tag{12}$$

Where we can substitute t_R into C_F for C_R. We can then use Equation 12 and compute capacitance values. Of all the values we computed(Table 5), the value from the rise time seemed the most trustworthy[5] as it was the closest in value to the expected 100 nF capacitor we used as seen from the error row. After this we created a Bode plot with a Phase plot(Figure 3), plotting Gain (dB) vs Frequency (Hz) and Phase (degrees) vs Frequency (Hz) for the low pass filter. Using Equation 5 we also made an Attenuation plot(Figure 4), plotting Magnitude (x) vs Frequency (Hz) Our frequency range was 20 Hz to 200 kHz for all three plots. We also plotted the square wave input and circuit's output as shown in Figure 2. The Voltage plot is very clean and is exactly what we

---

[5]The fall time is a close second place.

saw on the WaveForms software. We can see that it starts at 0 degrees and falls down near -90. With the low pass filter, the voltage plot shows a visual representation for the capacitor charging up and discharging as voltage is applied by the square wave input. Our Bode plot was also quite good once I made the x-axis logarithmic, but has some noise in the higher frequencies. The Phase plot had the most notable noise of the three plots, but it was still quite accurate to what we saw on the WaveForms software. The Gain plot was the cleanest, even though I expected there to be some artifacting or noise due to the calculations I had to do to get the data for the plot.

3.2 Data and Calculations

$$\text{Time from 1 V to } e^{-1} \text{ V: } t_1 = 1.5 \text{ ms} \tag{13}$$

$$\text{Time from 1 V to } e^{-2} \text{ V: } t_2 = 2.3 \text{ ms} \tag{14}$$

Rise Time (t_R)	Fall Time (t_F)	t_1	t_2
1.97 ms	1.96 ms	1.5 ms	2.3 ms

Table 4: Low Pass Filter Rise and Fall Times

C_R	C_F	C_1	C_2
89.64 nF	89.18 nF	150 nF	115 nF
10.36%	10.82%	50%	15%

Table 5: Low Pass Filter Capacitance Calculations using Equations 9 and 12 with Error[6]
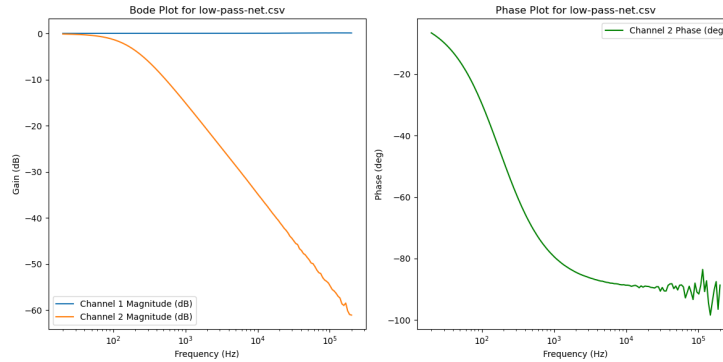

Figure 3: Low Pass Bode and Phase Plot

---

[6]The error is calculated using: Error $= |\frac{\text{Measured} - \text{Expected}}{\text{Expected}}| \times 100\%$
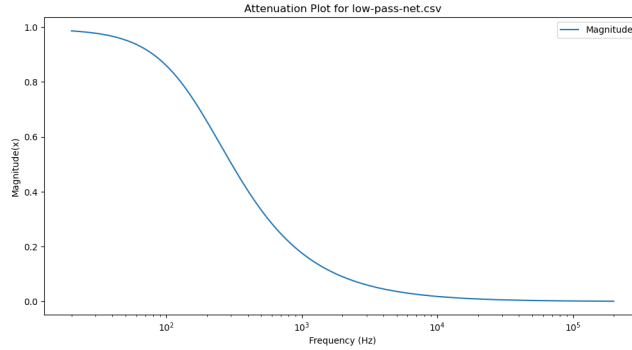
Figure 4: Low Pass Gain plot

3.3   Conclusion

We learned that the rise and fall time calculated by the AD were the most accurate, giving us a more accurate capacitance measurement. The Bode plot shows how the signal's strength behaves as a function of frequency. For the Low Pass Filter, the signal attenuates with higher frequencies. The Phase plot shows how the phase of the signal behaves as a function of frequency. For the Low Pass Filter, the phase of the signal is near 0 degrees at lower frequencies, and approaches -90 degrees as the frequency increases. Around the cutoff frequency, the Phase plot seems to slow down, that is, $\frac{d\phi}{d\omega}$ decreases after the cutoff frequency[7].A good reason to make such a circuit would be to limit specific frequencies, which in terms of applications, could be used for a multitude of things, such as audio filters, regulating voltage, and even in radio communications. The Attenuation plot shows very clearly, in terms of magnitude, the "strength" of the signal; giving the viewer an intuitive and useful way to see how the signal behaves as a function of frequency.

4   High Pass Filter Circuit

For the high pass filter we were instructed to repeat the same steps as with the low pass, so to make this section more compact, you can assume that everything that is not mentioned here was done and had the same result as the low pass circuit unless mentioned otherwise. Our high pass circuit was built
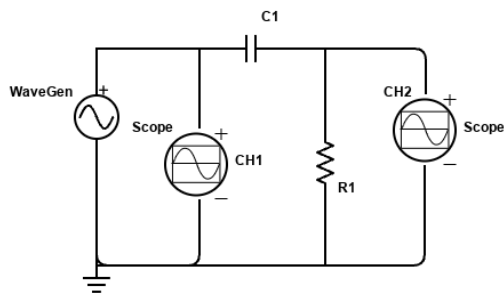

Figure 5: High Pass Circuit Schematic

---

[7]It looks like the cutoff frequency could also be described by where $\frac{d^2\phi}{d\omega^2} = 0$, as it looks like the cuttoff frequency is at the inflection point but this is just speculation.

through modifying our low pass circuit from the previous section by just switching the resistor and capacitor, as shown in Figure 5. All of our components are the same; therefore, we can do our calculations without much changing. We gathered our data by using the same square wave input as before at the same frequency, 100 Hz, and plotted the input and output voltages, marked as channels 1 and 2 on Figure 6.
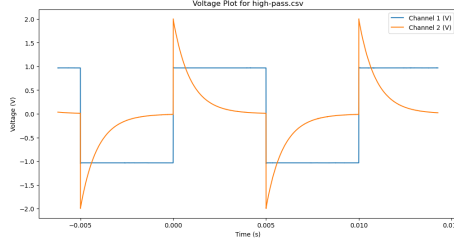

Figure 6: High Pass Voltage Plot

We can see that instead of the output being smaller that the input, we can see the capacitor charging at the beginning of the square wave and discharging as the wave continues. Our measurements for our rise and fall time are different(Table 6) but the equations we used to calculate the capacitance are the same(Equations 11 and 12). During the lab, we didn't actually get the times for the voltage to fall from 1 V to e^{-1} V and e^{-2} V, so I relied on the workspace that my partner Ryan sent me. Unfortunately, my WaveForms software doesn't recognize the file as a workspace, so I do not have data for those times. I will still do the calculations for the rise and fall time(Table 7), but unfortunately I will not be able to compare the calculated capacitance from the rise and fall time to the data from the high pass circuit's t_1 and t_2. Using the results from Table 7, we find that rise time is the most accurate for calculating capacitance as it is closer to the expected value, 100 nF. Even though I don't have t_1 or t_2, the method of data acquisition for those values is less accurate than the AD's rise and fall time values as it relies on getting the approximate value of e^{-1} and e^{-2} with the cursor. Interestingly, the Bode and Phase plot (Figure 7) as well as the Gain plot (Figure 8) for the high pass circuit were much better than the plots for the low pass circuit.

4.1 Data and Calculations

Rise Time (t_R)	Fall Time (t_F)
2.86 ms	3.01 ms

Table 6: High Pass Filter Rise and Fall Times

t_R	t_F
130.16 nF	139.99 nF
30.16%	39.99%

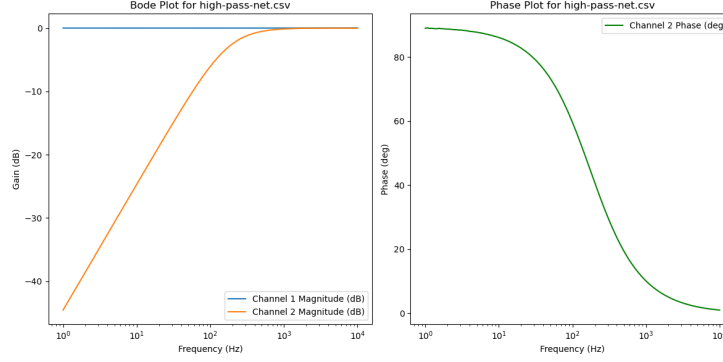Table 7: High Pass Filter Capacitance Calculations using Equation 12 with Error

8

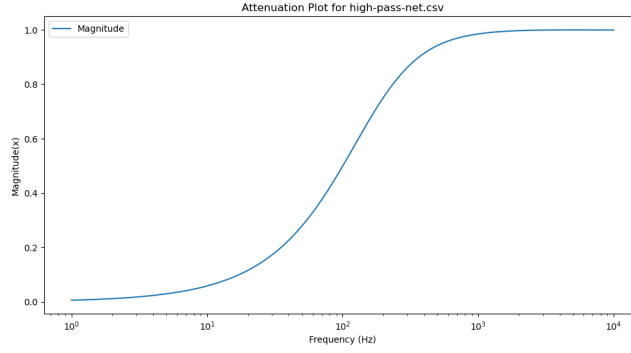Figure 7: High Pass Bode and Phase Plot

Figure 8: High Pass Gain Plot

4.2 Conclusion

For the high pass filter, it seems like the rise and fall times we recorded resulted in a calculation that was greater than the expected capacitance rather than less than like the low pass filter. As seen from the error row in Table 7, t_R is more accurate than t_F. We can see that for the high pass filter, the Bode plot starts at a much lower value than the low pass filter, and and rises in the same fashion as the low pass filter's Bode plot. The Phase plot for the high pass filter is very similar to the low pass filter's but instead of starting at 0 degrees and ending to -90, it starts at 90 degrees and falls to 0 degrees. The Gain plot is very similar to the low pass filter's, but it is inverted across the y-axis. A high pass filter would definitely be useful in the same way as a low pass filter, though naturally used for different applications. For example, a high pass filter could be used to remove low frequency noise from a signal, or to remove DC offset from a signal.

5 RLC Band-Pass Flter Circuit[8]

The last part of the lab was to analyze a low pass circuit with an inductor in parallel with the capacitor, as shown in Figure 9. For our RLC band-pass filter, we used the same resistor and capacitor as the low pass and high pass filters, but we used a 1 mH inductor. The components we used worked well allowing us to observe resonance in the
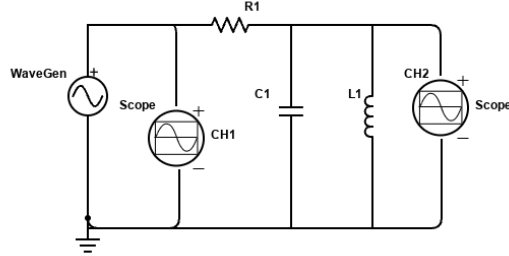
Figure 9: RLC Band-Pass Circuit Schematic

form of the ringing signal. We used the same square wave input as before at the same frequency, 100 Hz, and measured the ringing frequency (f_r) and its corresponding Δt(Table 8). After this we made a Bode plot with a Phase plot(Figure 10) and a Gain plot(Figure 11) using the data from the circuit. These plots were radically different from the low and high pass filters. As the name "Band-Pass" suggests, there is a band of frequencies that isn't attenuated. This is most easily observed in the Gain plot, since it's y-axis isn't logarithmic it can be much easier to visualize where the band is. The Bode plot had some noise around the lower and higher frequencies, which was only accentuated in the the Phase plot, which has a much different shape than the previous ones, ranging from 90 to -90, with a steep drop around 16 kHz. Each plot clearly has an interesting point at the ringing frequency, with the Phase plot having a steep drop and the Gain and Bode plot having peaks at that point.
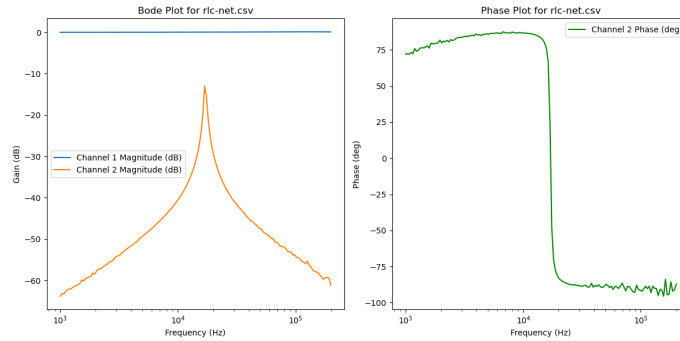
5.1 Data

Figure 10: RLC Band-Pass Bode and Phase Plot

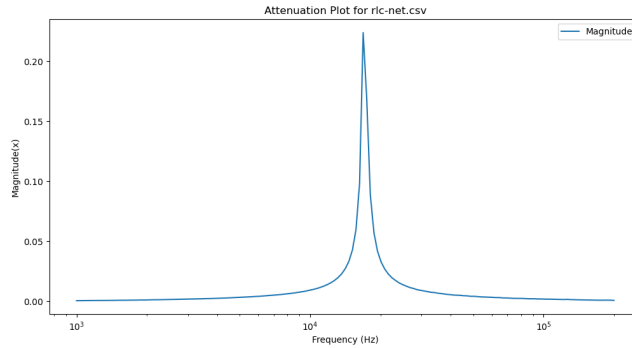[8]We skipped the inductor part as we were running low on time and were more interested in the RLC band-pass filter.

Figure 11: RLC Band-Pass Gain Plot

f_r	Δt
16.57 kHz	60.35 μs

Table 8: RLC Band-Pass Filter Ringing Frequency and Δt

5.2 Conclusion

The RLC band-pass filter is a very interesting circuit. It has a very different behavior than the low and high pass filters. The ringing frequency is very interesting, and it's interesting to graphically see the band of frequencies that are able to pass through the filter. Needless to say this is very applicable in the real world, as it can be used to filter out specific frequencies from a signal, making it very versatile. This could be used in a multitude of applications, such as in radio communications, audio filters, and even in the medical field[9].

6 What I learned

- The difference between a Bode plot and an Attenuation plot and how to translate between the two

- How to calculate the capacitance of a capacitor using the rise and fall time of a square wave

- How to build and analyze low, high, and band-pass filters as well as how to plot their Bode and Gain plots

- Gained a greated conceptual understanding of how each filter works and how voltage dividers work in general

---

[9]My girlfriend actually has a hearing defect and her chochlear implant (when working) uses either a band-pass filter or a high pass filter!