<div align="center">

ECE343 Lab #1: Passive Filters

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1 Introduction

Welcome to ECE343! This class provides an opportunity to get hands-on circuit experience as an accompaniment to ECE342. Each lab will follow a "*Prove, Simulate, Verify*" methodology:

1. First we mathematically prove concepts. This provides intuition for what comes next.

2. Next, we introduce non-idealities by using `SPICE` models in simulation.

3. Finally, we validate all of the above by doing real measurements (using M2K kits and lab equipment).

Lab 1 serves as a quick review of key concepts from ECE210, as well as an introduction to the tools you'll be using for the rest of the lab. We will specifically be doing that in the context of a simple RC filter.

1.1 Learning Objectives:

- Review Fourier/LaPlace transforms and filter design

- Use LTspice to simulate circuit performance

- Use graphs to present simulation results

- Setup software/hardware needed in the experiments

- Take measurements using SCOPY and lab equipment

- Compare and analyze theoretical, simulated, and experimental results

- Explain the impact of R_{in} and R_{out} on the gain/frequency response of a system

2 Analysis - RC Filters

The work in this section involves only "paper work" and no bench setups. It requires you to use circuit analysis techniques learned in ECE 210 to compute the frequency response $\mathbf{H}(\omega)$ for circuits shown in Figs. 1 and 2. This exercise will also help set up the framework for Section 3.

2.1 First Order RC Filters

While we do not require you to memorize Fourier transform derivations for this lab, you should be able to do common time domain to/from frequency domain conversions. Consider the circuit shown below:
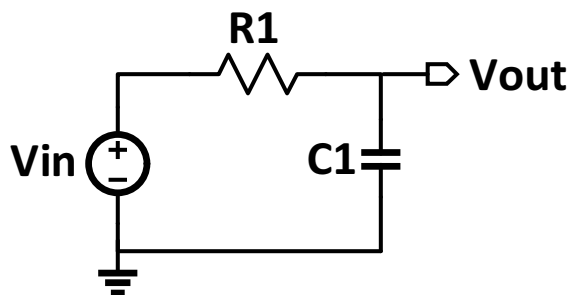

Figure 1: First Order RC Filter

1. Based on your intuition comment on the type of filter.
   (i.e: Low-pass, High-pass, ...)(Hint: Think about what the impedance of a capacitor is at $\omega=0$ and $\omega=\infty$.)

2. Compute the complex frequency response $\mathbf{H}(\omega)$.

3. Compute and sketch the magnitude response $|\mathbf{H}(\omega)|$. Compute the 3-dB cut-off frequency. Check the calculated result with your judgment in Question 1.

2.2   RC filter with load resistor

In this section we expand the analysis done in section 2.1 by attaching a load resistor at the output node.
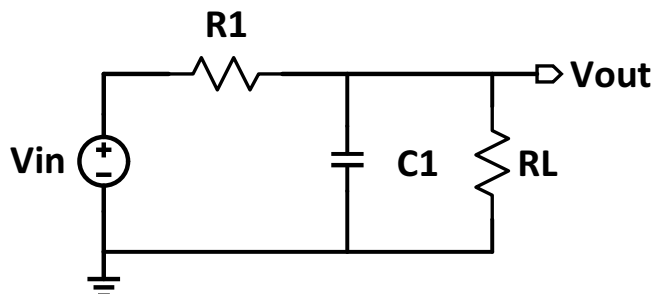

Figure 2: First order RC Filter with load resistor

For the circuit shown in Fig. 2 above:

1. Find the complex frequency response $\mathbf{H}(\omega)$

2. Compute and sketch the magnitude response. Compute the $\mathbf{3 - dB}$ cut-off frequency.

3. If we want the $\mathbf{3 - dB}$ cut-off frequency of the circuit in Fig.2 be the same as that of Fig. 1, how will you change the value of the load resistor in Fig.2

2.3   RC filter with opamp

In this section we expand the analysis done in section 2.2 by inserting an opamp between the filter and load resistor.
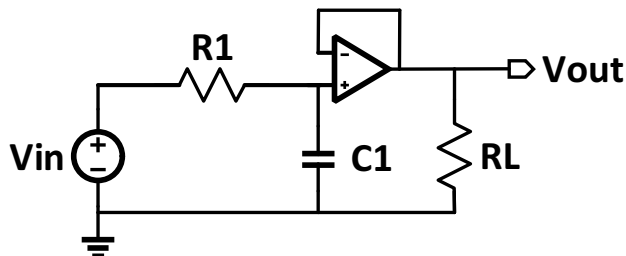

Figure 3: First order RC Filter with opamp

For the circuit shown in Fig. 3 above:

1. What is the input resistance looking into the (ideal) opamp?

2. Find the complex frequency response $\mathbf{H}(\omega)$ and compute the $\mathbf{3 - dB}$ cut-off frequency.

3. Compare the result of section 2.2 and 2.3, what is the advantage of the filter with opamp?

3   Simulation

In this section we will verify the analysis done in section 2 using a circuit simulation software called LTspice. Please refer to the tutorial on the course website to get started with LTspice.

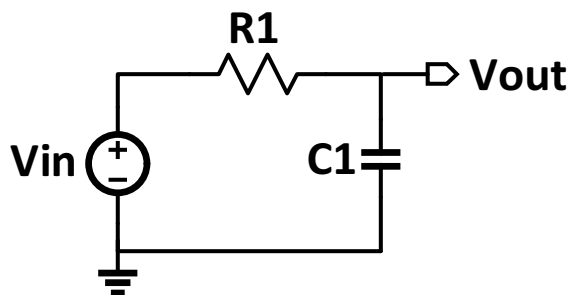## 3.1   Simulation - First Order RC Filter with opamp

Figure 4: First Order RC Filter

Component Values: $V_{in} = 1\sin(\omega t)V, R_1 = 1k\Omega$

1. Consider the first order RC circuit shown in Fig. 4. Compute the value of **C** so that the $\mathbf{3 - dB}$ cut-off frequency is at **160Hz**.

2. Draw the circuit shown in Fig. 4 in LTspice. Use the capacitor value that you calculated above.

3. Plot and **save** the magnitude and phase response of the RC filter in LTspice using the following parameters.

   - Type of Sweep: Decade
   - Number of points per decade: 100
   - Start Frequency: 1 Hz
   - Stop frequency: 100 kHz

   NOTE: If you are using the MATLAB sample code from course website, please make sure the exported data is saved in **Cartesian** format under "*Select Traces to Export*".

4. Export the data from LTspice to MATLAB using the instructions given in the LTspice tutorial on the website. Then plot and **save** each of the graphs specified below (in MATLAB):

- Magnitude (dB) vs log Freq

- Magnitude (dB) vs linear frequency

- Phase (deg) vs log Freq

- Magnitude (V/V) vs log frequency

5. Fill out Table 1. Note: you can either do this in LTspice (by changing the axes from linear to logarithm) or do it in MATLAB.

Frequency	$|\mathbf{H}(\omega)|$ [V/V]	$|\mathbf{H}(\omega)|$ [dB]	$\angle\mathbf{H}(\omega)$ [deg]
40 Hz			
60 Hz			
80 Hz			
100 Hz			
120 Hz			
140 Hz			
160 Hz			
180 Hz			
200 Hz			

Table 1: Simulation Results - First Order RC filter

6. After looking at your plots, why do we plot magnitude vs log frequency most of the time?

7. In the plot of magnitude (dB) vs log Freq, mark the gains at **1kHz** and **10kHz** with the 'Data Cursors' in MATLAB. **Save** this plot with both markers included. Finally, compute the slope of the line segment between the two frequencies (in units of **dB/decade**)
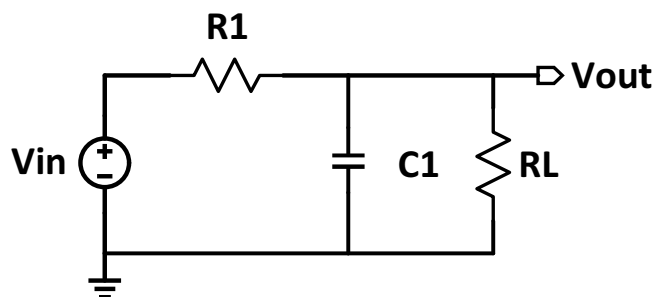
3.2   RC filter with load resistor

Figure 5: RC filter with load resistor

Component Values: $V_{in} = 1\sin(\omega t)V, R_1 = 1k\Omega, R_L = 330\Omega, 1k\Omega, 5k\Omega, C_1 = 1uF$

1. Draw the circuit shown in Fig. 6 in LTspice.
   (Note: It's always a good idea to draw different circuits in a new LTspice schematic in case the TA asks you to see your circuit. You can always copy and paste from an existing schematic so you don't have to draw from scratch.)

2. Fill out Table 3.

RL	$3 - \mathbf{dB}$ cut-off frequency
330Ω	
1000Ω	
5000Ω	

Table 2: Simulation Results - RC filter with load resistor

3. Based on the simulation result(or your intuition), how will the $3 - \mathbf{dB}$ cut-off frequency change if the load resistance is very large.(Give an approximate frequency)

4. In the plot of magnitude (dB) vs log Freq, mark the gains at **1kHz** and **10kHz**. **Save** this plot with both markers included. Finally, compute the slope of the line segment between the two frequencies (in units of **dB/decade**)(You only need to do this with one load resistance.)
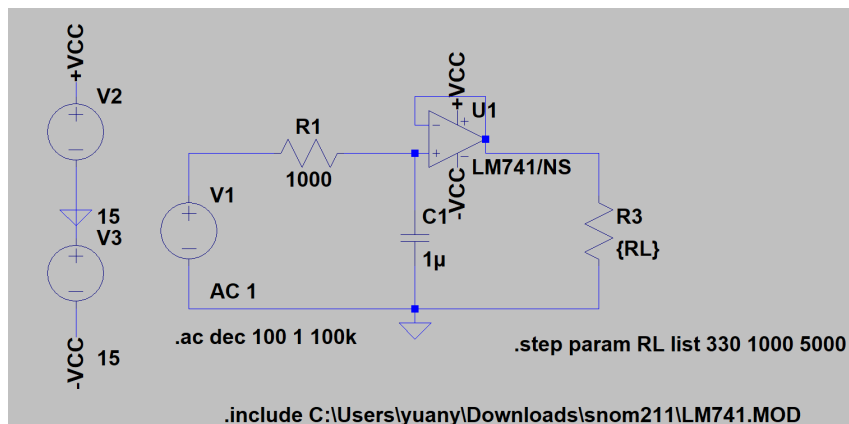
3.3 RC filter with opamp

Figure 6: RC filter with opamp

Component Values: $V_{in} = 1\sin(\omega t)V, R_1 = 1k\Omega, R_L = 330\Omega, 1k\Omega, 5k\Omega, C_1 = 1uF$

1. Draw the circuit shown in Fig. 6 in LTspice.
   (Note: Use the opamp2 LTspice component symbol and include the .MOD file of the opamp. Change the value of component to "LM741/NS")

2. Fill out Table 3.

RL	$3 - dB$ cut-off frequency
330Ω	
1000Ω	
5000Ω	

Table 3: Simulation Results - RC filter with load resistor

3. Check the voltage at the two input nodes of the opamp. Why we can assume that the voltage at two input pins of the opamp are equal to each other?

4. What is the functionality of the opamp in the circuit?

4   Measurement Data

In this section you will build the circuits from the previous sections on a breadboard and take measurements in SCOPY using your own ADALM1000 module. Once again, refer to the tutorials given on the website to become more familiar with setting up and using SCOPY.

4.1   Measurements - First Order RC Filter

1. Build the first-order RC circuit shown in Fig. 7 on the breadboard. Use the same values of resistors and capacitors computed in section 3.1.
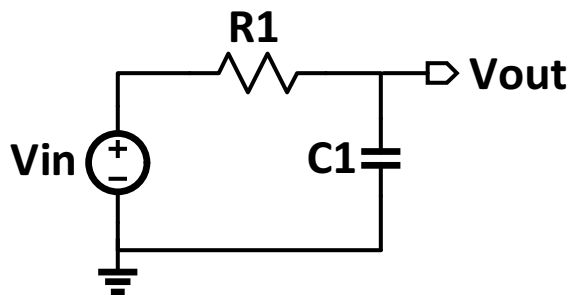
Figure 7: First Order RC Filter

2. Connect your circuit to the ADALM1000 board with **CH A** as the input, **CH B** as the output, and **GND** to ground.

3. Open up SCOPY and change the device measurement settings in the small AWG window.

   - Set the **mode** of CHA to **SVMI** (Source-Voltage Measure Current). Set **max**=1, **min**=0, **freq**=40, and **shape** to 'sine'.
   - Set the **mode** of CHB to **Hi-Z** mode.

4. Change the settings in the oscilloscope to display the results properly.

   - Select **CA-V** and **CB-V** in the **curves** menu.
   - Open up the **CB** menu in the top right. Select **P-P** under **-CB-V-**.
   - Open up the **CA** menu. Select **A-B phase** to display the phase.
   - Set **Time mS/Div = 2.0**.
   - Set **Hold Off = 50.0**.
   - Set **CA V Pos = 0** and **CB V Pos = 0**.

5. Run the time-domain measurement by selecting **RUN**. Make sure to **save** a screenshot (only one screenshot is needed in total. No need to save it for each of the frequencies)

6. Fill out (mag [V/V] and phase [deg]) of the following table by changing the frequencies in the AWG window and reading the measurements from the oscilloscope.

Frequency	$\lvert\mathbf{H}(\omega)\rvert$ [V/V]	$\lvert\mathbf{H}(\omega)\rvert$ [dB]	$\angle\mathbf{H}(\omega)$ [deg]
40 Hz			
60 Hz			
80 Hz			
100 Hz			
120 Hz			
140 Hz			
160 Hz			
180 Hz			
200 Hz			

Table 4: Measurement Results - First Order RC filter

NOTE: The phase given by A-B Phase may not match the phase given in the simulations. For these phases, you should use cursors to measure the time delay t_d between the output and input signal to calculate $\angle\mathbf{H}(\omega)$ as shown below:

$$\frac{\angle\mathbf{H}(\omega)}{360} = \frac{t_d}{T_p} \tag{1}$$

7. Plot and **save** the frequency response by following the steps below:

   - Click on **Bode Plot** on the right panel of the oscilloscope.
   - In **Curves**, choose **CB-dB - CA-dB**.
   - Choose **Log F**.
   - Under **-Sweep Gen-**, set **Startfreq = 10**, **Stopfreq = 1000** and choose **CH-A** as the channel to sweep the frequency.
   - Press **Run** and wait for the measurement to complete.
   - Change the scale by clicking on -dB/div
   - Place markers on the curve by left-clicking, and fill out the mag [dB] column. (**Warning:** Right clicking will delete all the markers)

8. Comment on the results obtained from measurements and simulations for the 1st-order RC filter.

4.2   RC filter with load resistor

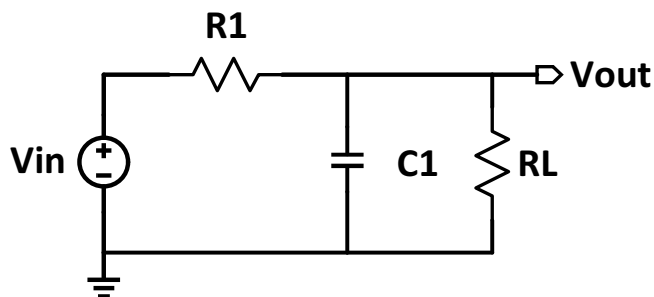Build the second order RC circuit in Fig. 8 on the breadboard.

Figure 8: RC filter with load resistor

Component Values: $V_{in} = 1\sin(\omega t)V, R_1 = 1k\Omega, R_L = 330\Omega, 1k\Omega, 5k\Omega, C_1 = 1uF$

1. Follow the same procedure given in section 4.1 and fill out the following table.

RL	$\mathbf{3-dB}$ cut-off frequency
330Ω	
1000Ω	
5000Ω	

Table 5: Measurement Results - RC filter with load resistor

2. Make sure to **save** the screenshots of the results in both the time-domain and frequency-domain as before.

3. How does the load resistor change the $\mathbf{3-dB}$ cut-off frequency? How does it change your gain at DC?

4.3   RC filter with opamp

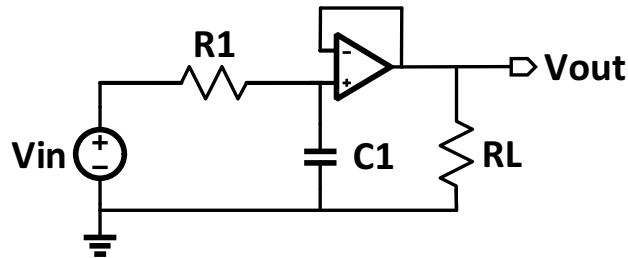Build the second order RC circuit in Fig. 9 on the breadboard. **Keep this circuit for your demo in lab.**

Figure 9: RC filter with opamp

Component Values: $V_{in} = 3 + 1\sin(\omega t)V, R_1 = 1k\Omega, R_L = 330\Omega, 1k\Omega, 5k\Omega, C_1 = 1uF$

1. Using your ADALM1000, what can you connect the supplies of the op-amp to ? (Hint: Vcc+ is the upper rail and Vcc- is the lower rail of the op-amp)

2. Follow the same procedure given in section 4.1 and fill out the following table.

RL	$3 - dB$ cut-off frequency
330Ω	
1000Ω	
5000Ω	

Table 6: Measurement Results - RC filter with opamp

Warning: You may not get the correct output for 330Ω. Why might this be the case?

3. Make sure to **save** the screenshots of the results in both the time-domain and frequency-domain as before.

4. Comment on the results obtained from measurements and simulations for the RC filter.