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## Experiment A4 Electronics II Procedure

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**Deliverables:** Check lab notebook, Tech memo

**Recommended Reading:** Chapters 11, 13, and 23 of the textbook

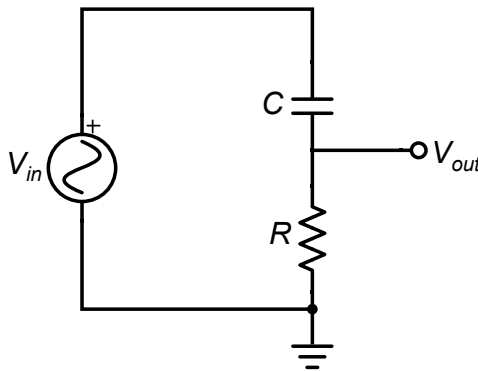
### Overview

In the previous two labs, you looked at simple DC (direct current) circuits, where the voltages and currents remained constant in time. In this lab, you will examine AC (alternating current) circuits, where current and voltage oscillates sinusoidally with time. In particular, you will build an electronic filter that blocks low frequency signals and passes high frequency signals. Such a circuit might be used in audio electronics, for example, to block bass notes, so you only hear treble.

Overall, you will learn to use the function generator and oscilloscope. You will also learn how “non-dimensionalize” data, such that it collapses onto a single curve. This is a particularly useful technique for experimental fluid mechanics and heat transfer.

### Part I: High-pass Filter

In this portion of the lab, you will construct the RC circuit shown in Figure 1. You will then measure the amplitude of the output voltage  $|V_{out}|$  as a function of the driving frequency  $f$ .



**Figure 1** - A high-pass filter circuit is constructed with a resistor and capacitor.

The *amplitude* of the AC output by the high-pass filter is given by the equation

$$|V_{out}| = \left( \frac{\omega RC}{\sqrt{1 + (\omega RC)^2}} \right) |V_{in}|, \quad (1)$$

where  $\omega$  is the frequency in rad/s,  $R$  is resistance,  $C$  is capacitance, and  $|V_{in}|$  is the amplitude of the input. Note that  $|V_{out}|$  goes to zero as the frequency  $\omega$  goes to zero, and it asymptotically approaches the input amplitude for high frequencies. Thus, the circuit *passes* high frequencies and blocks low frequencies. The “cutoff frequency” is defined as  $\omega_c = 1/RC$ , and frequency components below this value are significantly attenuated.

The *phase*  $\phi$  of the AC output relative to the input is given by the equation

$$\phi = \arctan\left(\frac{1}{\omega RC}\right). \quad (2)$$

The phase angle is directly proportional to time lag  $\Delta t$  between the two signals and can be calculated by multiplying by the frequency, i.e.  $\phi = \omega \Delta t$ .

Table 1a (R = 1 kΩ)		
$f$ (kHz)	Amplitude $ V_{out} $	Phase $\Delta t$ (s)
0.1		
1		
1.5		
2		
3		
5		
7		
10		

Table 1b (R = 2 kΩ)		
$f$ (kHz)	Amplitude $ V_{out} $	Phase $\Delta t$ (s)
0.1		
1		
1.5		
2		
3		
5		
7		
10		

1. Sketch the circuit in your lab notebook.
2. Construct the circuit in Fig. 1 using  $R = 1 \text{ k}\Omega$  and  $C = 0.047 \text{ }\mu\text{F}$ .
3. With the BNC-to-minigrabber cable, connect the ‘T’ on the “50Ω” output of the function generator to the circuit. Make sure the black minigrabber is connected to the grounded side of the resistor, and the red one is connected to the free lead of the capacitor.

**NOTE** – The black mini-grabbers should always be connected to ground.

4. Turn on the function generator. Press the “sine” button, then “output menu”, then “load impedance”, then “High Z”, then press “Top Menu” to exit to the main menu.
5. Connect the other side of ‘T’ on the function generator to CH1 on the oscilloscope (scope).
6. Set the output amplitude of the function generator to 10 V peak-to-peak and the frequency to 100 Hz. such that  $V_{in}(t) = (V_{pp}/2) \sin(2\pi ft)$ .
7. With a different BNC-to-minigrabber cable, connect  $V_{out}$  to CH2 of the oscilloscope. Make sure the black minigrabber is connected to the grounded side of the resistor, and the red one is connected to the resistor-capacitor junction.

8. Press the “ON” button above the BNC T on the function generator. (Not the power button. This is a different “ON” button located in the lower-middle portion of the device panel.)
9. Press the “auto set” button on the top of the oscilloscope. You should see two sine waves on you screen.
10. Press the vertical position knobs for both CH1 and CH2. This should center both sine waves vertically on the scope.
11. Adjust the vertical and horizontal scale so one full period of the waveform fills the screen. **Make sure the peaks of waveform do not go off the top or bottom edge of the screen.**
  - a. Turn the horizontal scale knob to adjust the horizontal *time* scale.
  - b. Turn the vertical scale knob to adjust the vertical *voltage* scale.
12. Press the “Measure” button at the top of the scope. Then, press “Add Measurement” in the bottom left corner. Use the (a) and (b) multipurpose knobs to add an “Amplitude” measurement for both CH1 ( $V_{in}$ ) and CH2 ( $V_{out}$ ). Press the “Menu Off” button once to clear the screen.
13. Measure the amplitude of CH1 of the scope and record it in your lab notebook. Which signal CH1 is measuring:  $V_{out}$  or  $V_{in}$ ? Do you expect this amplitude to change with frequency?

**Pro-Tip:** The amplitude measurement will not work if the waveform goes off the top or bottom of the screen.

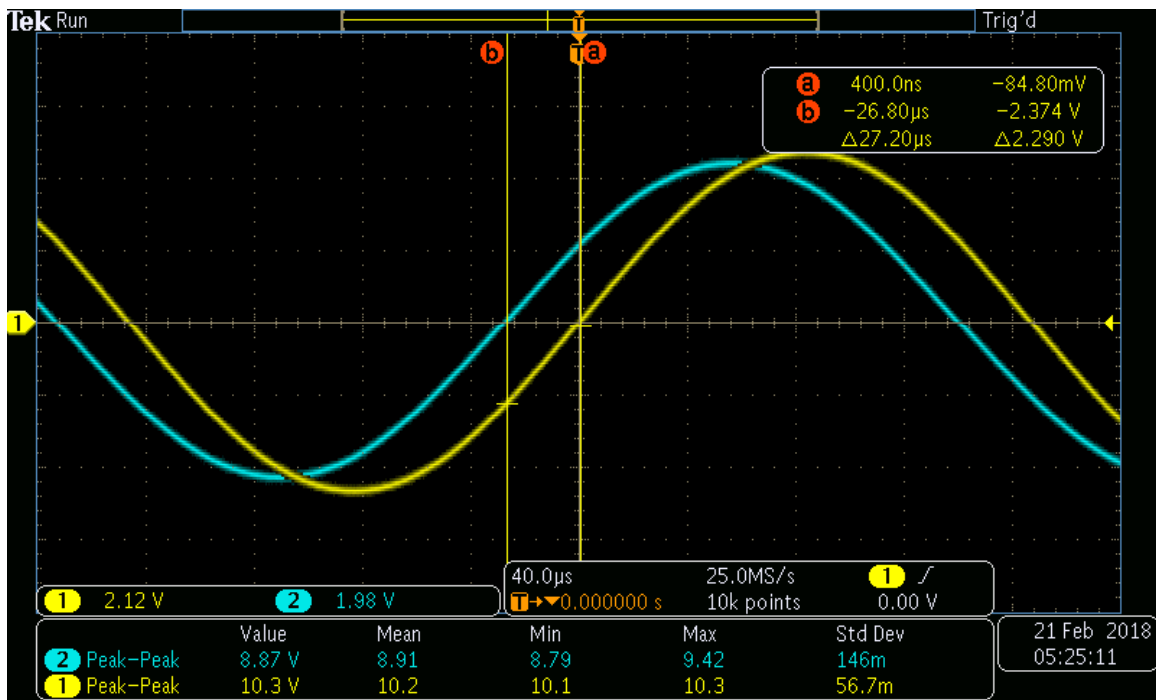
14. Press the “Cursor” button near the top of the scope. Two vertical lines should appear on the screen. You will use the (a) and (b) multipurpose knobs to adjust the cursor position and measure the phase  $\Delta t$  between the two waveforms.

**Pro-Tip:** Use the **zero-crossing method** to measure the phase: place cursor (a) at the point where the *rising edge* of CH1 intersects the midline and cursor (b) where the *rising edge* of CH2 intersects the midline. See Figure 2 for a sample screen shot.

15. Complete Table 1a in your lab notebook by varying the driving frequency  $f$  and recording the *amplitude* of the output  $V_{out}$  of CH2 on the oscilloscope and the *phase*,  $\Delta t$  of CH1 relative to CH2. (Use the “measure” feature to determine the *amplitude* and use the “cursors” to determine  $\Delta t$  of Channel 1 relative to Channel 2.)

**Pro-Tip:** When measuring amplitude and phase, adjusting the **vertical scale** and **horizontal scale** will give you a more accurate measurement of amplitude and phase.

16. Change the resistor to  $R = 2 \text{ k}\Omega$  and repeat the procedure to fill out Table 1b in your lab notebook. We recommend that you also switch with your lab partner on the oscilloscope, so that you each get a turn using it.



**Figure 2** – A screen shot of the oscilloscope with the cursors being used to measure phase, which is displayed in the upper right corner as “ $\Delta 27.20\mu s$ ”.

## Part II: Design a Filter

Design a filter that attenuates (weakens) signals with a frequency below 7 kHz and passes signals with a frequency above 7 kHz using circuit elements from the lab.

- Sketch a schematic of the circuit with the values you chose for the various circuit elements in your lab notebook.
- You must get within 10% of the specified cut-off frequency.
- You may only use at most two resistors and two capacitors.
- Set the frequency of  $V_{in}$  to be the cutoff frequency, and measure the amplitude  $|V_{out}|$ . Based on Eq. (1), is it close to what you expect it to be?
- Measure the output amplitude  $|V_{out}|$  as a function of frequency  $f$ . Use at least 10 different frequencies between 0 and 20 kHz. Be sure to record the input amplitude  $|V_{in}|$ , as well.
- You do not need to measure phase.

**Finishing Move:** When you are all finished return the set-up to its initial configuration.

1. Disconnect all the cables and remove the circuit from the breadboard.
2. Press the “Default Setup” button at the bottom of the oscilloscope.

## Data Analysis and Deliverables

Create plots and other deliverables listed below. Save the plots as PDFs, import them into either Microsoft Word or LaTeX, and add an intelligent, concise caption. Make sure the axes are clearly labeled with units. Plots with multiple data sets on them should have a legend. **Additionally, write 1 – 3 paragraphs describing the items below. Any theoretical formula you used in your analysis should be included as a numbered equation within these paragraphs.**

**NOTE: In the lab all frequencies,  $f$  are in units of Hz and plotted on a linear scale.**

**Theoretical equations should always be plotted as smooth, continuous curves.**

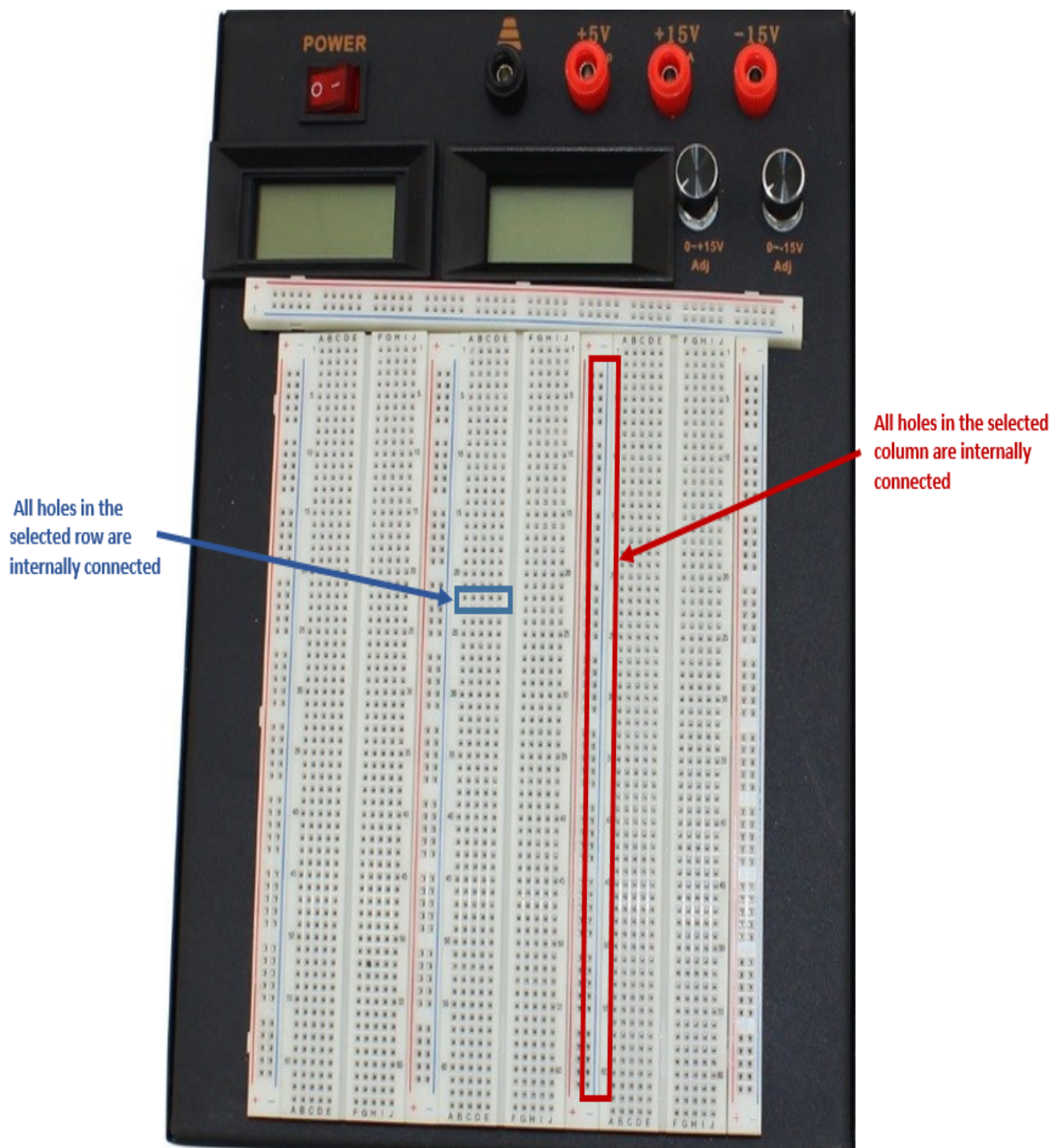
1. A plot the measured output amplitude for the high-pass filter  $|V_{out}|$  as a function of  $f$  with the theoretical equation plotted on top. Be sure to include a legend to distinguish between the data for  $R = 1\text{ k}\Omega$  and  $2\text{ k}\Omega$ .
2. A plot of the measured phase angle  $\phi$  as a function of  $f$  with the theoretical equation plotted on top. Be sure to include a legend to distinguish between the data for  $R = 1\text{ k}\Omega$  and  $2\text{ k}\Omega$ . Be sure to convert the phase,  $\Delta t$ , into units of degrees by multiplying by the frequency  $f$  in Hz (i.e.  $\phi = 360f\Delta t$ ). Note that  $-180 < \phi < 180$ .
3. A plot of the *amplitude* data from the high-pass filter, but this time *non-dimensionalize* your data to be  $V_{out}/V_{in}$  as a function of  $2\pi fRC$ . This should *collapse* your data to a single curve. Plot the theoretical high-pass filter equation as a function of the non-dimensional parameter  $2\pi fRC$  on top of the data. Be sure to include a legend to distinguish between the data for  $R = 1\text{ k}\Omega$  and  $2\text{ k}\Omega$ .
4. A plot of the *phase* data from the high-pass filter, but this time *non-dimensionalize* your data by plotting phase  $\phi$  in *radians* as a function of  $2\pi fRC$ . This should *collapse* your data to a single curve. Plot the theoretical high-pass filter equation as a function of the non-dimensional parameter  $2\pi fRC$  on top of the data. Be sure to include a legend to distinguish between the data for  $R = 1\text{ k}\Omega$  and  $2\text{ k}\Omega$ .
5. A plot of magnitude ratio  $V_{out}/V_{in}$  as a function of frequency  $f$  for the filter you designed in Part II. Include a vertical line at the cutoff frequency  $f_c = 7\text{ kHz}$ .

## Appendix A

### Equipment

- Tektronix AFG3021C Function Generator
- Tektronix MDO3012 Digital Oscilloscope
- Powered Breadboard
- Breadboard Solder-less Connectors
- 2 BNC connector to red/black grabbers
- 3 BNC Cables 3' – 4' in length
- BNC – “T” connector
- Resistors
- $C = 47 \text{ nF}$  Capacitor

## Appendix B



**Figure 3** – Shown in blue, any 5 holes in a horizontal row are electrically connected, but they are NOT connected to the adjacent row of 5. Shown in red, all 50 holes in any vertical column or “bus bar” are electrically connected.