II. Lab 2: RC circuits

A. Introduction

In this lab you will build and make measurements on the following two circuits:

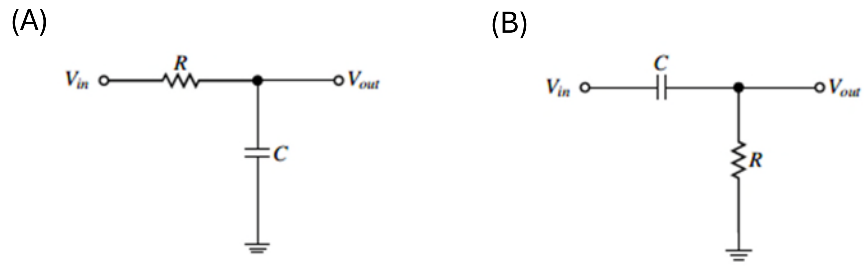

Figure II-1. *RC* circuits (A) and (B).

Note on including data from an oscilloscope in your report. From this point forward in the class, if you need to include a scope trace in your report, please don't use cell phone photos of the oscilloscope display. Instead, download your data from the oscilloscope to a USB drive and use that downloaded file in your report. USB drives are available for your use in the parts cabinets. Please don't take these from the lab.

The Tektronix TBS1052C oscilloscope can save either a screen image or the waveform (voltage *vs.* time data) to a file. In most cases you will want the screen image. Instructions for downloading the data can be found in the TBS1000C series oscilloscope manual, which is easily available online.

B. Procedure

1. Circuit A

a) <u>Rise and Fall Time</u>

Build circuit A with $R = 20\ \text{k}\Omega$ and $C = 0.005\ \mu\text{F}$. Drive it with an input voltage that is a square wave with no DC offset, and measure the output voltage with an oscilloscope with DC input coupling. Adjust the driving frequency *f* and the horizontal display until you can see the rise and fall times easily on the oscilloscope. Measure the time constant for both the rising and falling edges of the waveform. Note that the automated measuring functions on the scope do not measure time constants. They only measure the 10% to 90% rise and fall times.

Suggested method. Make sure that "Probe Setup" is at 1x. Press the "Cursor" button. You should see two vertical lines added to your display. "Time" should be highlighted. Switch to "Time" mode if it isn't. Each line will have a cursor where the waveform crosses the line, and the display will output the voltage at that point. Move one cursor so it is at the upper voltage in the flat part of the curve, and the other so it is at the lower voltage. To change cursors click on the multifunction knob. To move the cursor rotate the multifunction knob. Record the upper and lower voltage levels from the display. Then calculate what the voltage level would be one time constant past the start of the rise or fall of the waveform. Move one cursor so it is at the start of the rise or fall, and the other so that it is at the voltage you calculated. For the best accuracy, set the oscilloscope time scale so that the rise or fall is spread out over several divisions on the oscilloscope when you do this. Note that "Coarse" is displayed at the top of the screen. This is the resolution of your cursor movement. Press the multifunction knob in, hold it for a few seconds, and release. This should change the resolution to "Fine." Once you are in fine resolution, set the two cursors at the desired time/voltage level as accurately as you can. The time between the two vertical lines is reported on the display. If you have positioned the cursors correctly this is the measured time constant.

For your report: include a copy of the waveforms and your measured time constants. Are they the same? Measure the actual values of *R* and *C* with a DMM. Compare your observed time constants to the expected value *RC*.

b) <u>Integrator</u>

In the regime where $\omega \gg \dfrac{1}{RC}$, where $\omega = 2\pi f$, V_{out} is the *integral* of the input voltage:

$$V_{out}(t) = V_{out}(0) + \frac{1}{RC}\int_0^t V_{in}(t')dt' \tag{2.1}$$

Hence this circuit is sometimes referred to as an "integrator." Beginning with a low frequency *f* where the output waveform is approximately a square wave, increase the frequency in relatively small steps. Show how the output waveform gradually changes from a square wave to its integral (2.1). You may want to stop and think about what the integral of a square wave should look like. Adjust the frequency to a point where the approximation $\omega \gg \dfrac{1}{RC}$ is valid, and verify that the circuit does integrate the input signal at that frequency as given by Equation (2.1). For your report: include 4 or 5 waveforms to show how the output voltage changes from a square wave to its integral. Describe how you confirmed that the output voltage does indeed integrate the input voltage when $\omega \gg \dfrac{1}{RC}$.

c) <u>Low-pass filter</u>

With a sine wave input $V_{in} = V_{0,in}\sin(2\pi ft)$, the output voltage is $V_{out}(t) = V_{0,out}\sin(2\pi ft + \phi)$.

Using a sine wave input, measure the "gain" $\dfrac{V_{0,out}}{V_{0,in}}$ and phase shift ϕ as a function of the input frequency.

Suggestions. You can use a BNC tee to hook up your function generator to the circuit input and the oscilloscope CH1 input simultaneously. You can then hook up to the output of your circuit to channel 2 of your oscilloscope and view the input and output waveforms simultaneously. Don't forget to make sure "Probe setup" is set to 1x for both channels. You'll want to change the scope resolution back to "Coarse", since otherwise the vertical sensitivity can be changed only in very small increments. To make measurements, set the scope to measure Frequency and Amplitude on channel 1, and Amplitude and Phase CH2-CH1 on channel 2. The scope should then display the input waveform, output waveform, and the quantities that you need to calculate the gain and phase shift.

Take these measurements for 10 to 12 different frequencies. Your frequencies should span the range from well below $1/RC$ to well above $1/RC$.

For your report: include representative scope displays for several different frequencies. Include plots of the gain and phase shift as a function of frequency. You should find that your circuit functions as a low-pass filter. Determine the 3 dB point of this filter from your gain plot.

2. Circuit B

a) Time constants

Build circuit B with the same *R* and *C* as before. Drive it with a square wave with no DC offset. Adjust the driving frequency and the horizontal display until you see an output waveform in which the output voltage decays exponentially towards zero two times in each cycle. Measure the time constants for both decays. For your report: Include your measured time constants and a copy of the observed output waveform. Are the two time constants the same? Compare them to the value of *RC*.

b) Differentiator

In the frequency range where $\omega \ll \frac{1}{RC}$, V_{out} is the *derivative* of the input voltage:

$$V_{out} = RC\frac{dV_{in}}{dt} \tag{2.2}$$

Hence the circuit is sometimes referred to as a "differentiator."

Set your function generator to produce a triangle wave output and set the frequency to a value that is high enough that the output waveform is also a triangle wave. Decrease the frequency in small steps and show how the output voltage changes from a triangle wave to its derivative. Choose one frequency such that $\omega \ll \frac{1}{RC}$, and confirm for that frequency that the output voltage is approximately equal to the derivative of the input voltage as given by Equation (2.2).

For your report: include about 4 representative waveforms that show how the output waveform changes from a triangle wave to its derivative. Also, described how you confirmed that the output does follow Equation (2.2) for $\omega \ll \frac{1}{RC}$.

c) <u>High-pass filter</u>

Using a sine wave input, measure the gain $\left(V_{0,out} / V_{0,in}\right)$ and phase shift ϕ of circuit (B) as a function of drive frequency. The suggestions for part (c) above apply here too. For your report: include representative scope displays for several different frequencies. Includes plots of the gain and phase shift as a function of frequency. You should find that your circuit functions as a high-pass filter. Determine the 3 dB point of this filter from your gain plot.

3. Comparison with theory

a) <u>Circuit A</u>

Using the complex variable methods outlined in your Textbook section 2.27, derive the ratio $\left(V_{0,out} / V_{0,in}\right)$ as a function of frequency for circuit A. Do the same for the phase shift ϕ. (There is a similar example of this for an *RL* circuit on p. 174.) For your report: show your derivation and the resulting formulas. Make plots of the theoretical $\left(V_{0,out} / V_{0,in}\right)$ and ϕ *vs.* drive frequency for the values of *R* and *C* that you used in the above experiments. Comment on whether the theory seems to agree with your measurement. In lecture, we discussed the fact that real capacitors depart from an ideal capacitor at high frequencies. Do you see any evidence of such a departure in your data?

b) <u>Circuit B</u>

Do the same for circuit B.