Capacitors and Time-Dependent Signals

Concept

The purpose of this lab is to learn about time-dependent (AC – Alternating Current) analysis of RC circuits using a function generator and an oscilloscope. The transient response of an RC circuit will be studied in the time-domain using the combination of a square-wave from a function generator and an oscilloscope. Frequency-domain behavior will be measured as well, and the response function of RC circuits will be determined. Complex impedance will be introduced, and Fourier analysis of complicated waveforms will be presented.

Helpful hints and warnings

The "ground symbol" in a circuit implies that the grounds (outer conductors or shields) of the signal generator and the oscilloscope are connected to the circuit at this point. Unlike the DMM, the signal generator and oscilloscope grounds can be connected only to the circuit ground. Thus, in the low-pass RC circuit, the oscilloscope can be used to measure the potential across only the capacitor. Conversely, in the high-pass CR circuit, the scope can be used to measure the potential across only the resistor.

To read the capacitance on the brown plastic capacitors, look for three numbers such as 153. The first two digits are the first two digits of the capacitance. The third digit is the order of magnitude or power of ten. So, 153 means a capacitance of $15 \times 10^3 = 15{,}000$ something. To figure out what "something" is, the type and size of the capacitor needs to be considered. In this case, the unit is picoFarad or pF. So, 15,000 pF = 15 nF = 0.015 μF. As with resistors, do not rely on the code for an accurate value of C. Always measure the capacitance using the *LRC meter*, which can also measure the inductance L.

Three types of capacitors are used in this laboratory. *Ceramic* capacitors exhibit a low capacitance/volume value, a high maximum potential difference rating and low *inductance*, which makes them suitable for high frequency applications. *Polymer* or *plastic* capacitors have a higher C/volume value, a lower maximum potential difference rating and a higher inductance, making them suitable for medium frequency applications. *Electrolytic* capacitors have a large C/volume value, a low working maximum potential difference and slow time response. Furthermore, electrolytics are *polarized*, that is, one side must always be positive with respect to the other to avoid electrochemistry, heating and component failure.

Since the *return* or ground line of the oscilloscope is connected to earth ground, it is possible to observe the time-dependent potential difference $V(t)$ only between a point in the circuit and earth ground. You cannot measure $V(t)$ across an individual resistor or capacitor unless one side is connected to earth ground.

Experimental Instructions

1. Time-dependent analysis of RC circuits

In this experiment you will use a square wave signal from the function generator to measure the time constant of the RC circuit on the oscilloscope.

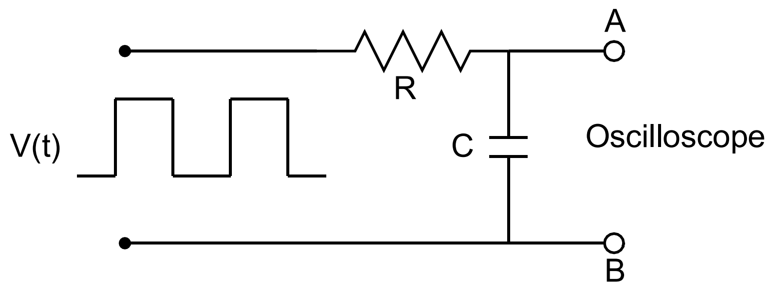

Figure 1: Use a square wave as input.

(i) Build the circuit shown in Fig. 1 with $R = 1\ k\Omega$ and $C = 100\ nF$.
(ii) Adjust the function generator and oscilloscope so that a square wave produces an output that clearly demonstrates the full time dependence of the capacitor charging or discharging.
(iii) Excel or another plotting program can be used to record the data after copying from LabVIEW.
(iv) Measure τ by determining the time for the output to drop to $1/e$ of the maximum and to rise to $1-1/e$ of the maximum. Are these two values of τ equal?

2. The RC Integrator (Low-Pass Filter)

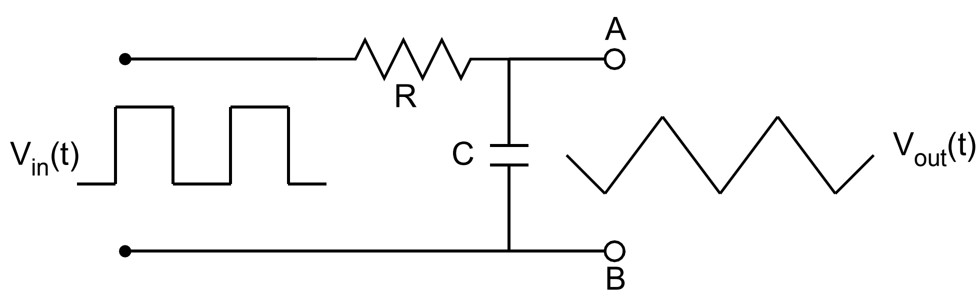

Figure 2: At a sufficiently high frequency, the RC circuit becomes an integrator.

a. Use the circuit of Part 1 and apply a 20 kHz square-wave signal.
b. Explain how the observed waveform is consistent with the concept of an RC circuit behaving as an integrator.
c. Over what frequency range does the circuit behave as an integrator, that is, is capable of producing a triangle-wave output from a square-wave input? Explain why this circuit is also known as a low-pass filter.
d. Apply a triangle wave input at 200 kHz and explain the observed waveform.

3. The CR Differentiator (High-Pass Filter)

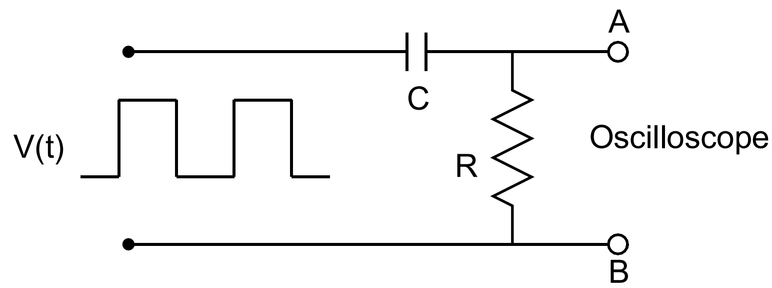

Figure 3: CR circuit with a square wave as input.

- **a.** Reverse the positions of R and C, as shown in Fig. 3.
- **b.** Vary the frequency of the square wave input from 1 Hz to 1 MHz and describe the behavior of this circuit. Does it ever appear to behave as an integrator or a differentiator? Explain why this circuit is also known as a high-pass filter.
- **c.** Apply a triangle-wave input at 200 Hz and explain the observed waveform.

4. Frequency response of both low-pass and high-pass filters

- **a.** The goal of this experiment is to measure the frequency dependence of each filter's response to a sine wave input. Measure both the amplitude and phase shift of the filter output relative to the input signal. Set the function generator to provide a sine wave with no offset. Manually vary the frequency from 1 Hz to 1 MHz and observe the variation in amplitude and phase of the output relative to the input. Make a series of at least 20 measurements over the full frequency range. Because you will be plotting your data on a logarithmic plot, make at least two measurements per decade of frequency. Determine the transmission function $A(\nu)$ by dividing the output amplitude by the input amplitude. Be sure to measure the input amplitude from the function generator at each frequency, because the combination of your circuit and the limitations of the generator may lead to a signal that changes in amplitude with frequency. Measure the phase difference $\phi(\nu)$ between the output and input signals. A good point on the waveform to use for such measurements is the point at which the trace crosses 0 Volts (i.e. ground). If the period of the input signal is T and the displacement of the output signal zero-crossing from the input signal zero-crossing is t, then the phase difference is $\phi = 2\pi t / T$. If the output signal zero-crossing occurs after the input signal zero-crossing, then that is a phase lag or a negative phase.
- **c.** For each filter, plot the data and theoretical curves together. For the amplitude plots, use the decibel (dB) scale $20 \log_{10} A(\nu)$ for the vertical axis and $\log \nu$ for the horizontal axis as in Fig. 4. For the phase plots, use a linear vertical axis for the phase and $\log \nu$ for the horizontal axis as in Fig. 5. Determine the *breakpoint* or *characteristic* frequency from the data plots by identifying the -3dB point on the amplitude plot (also known as a Bode plot) and the 45° point of the phase plot.

Compare these to the expected theoretical value. Draw conclusions about the behavior of both circuits.

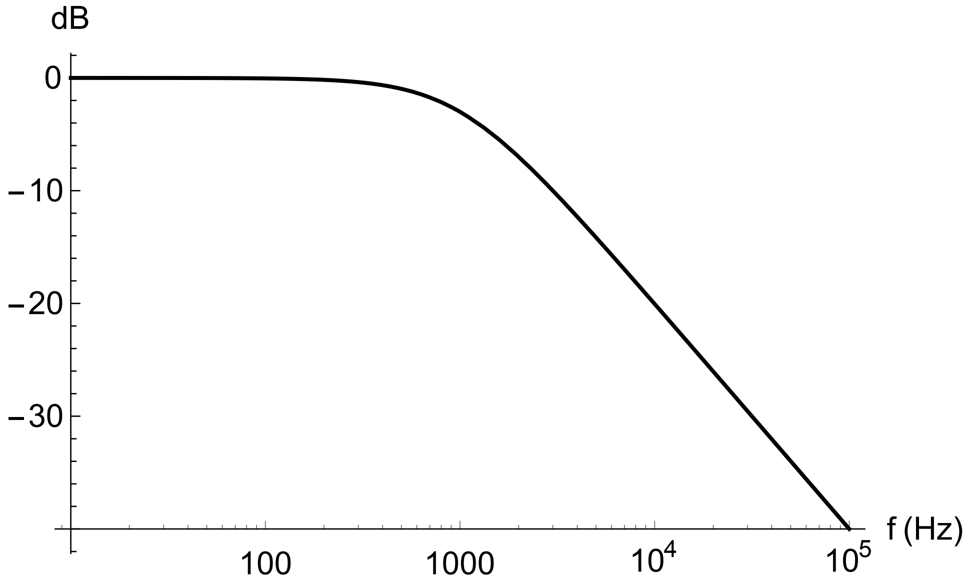

Figure 4: Bode amplitude plot for a low-pass RC filter.

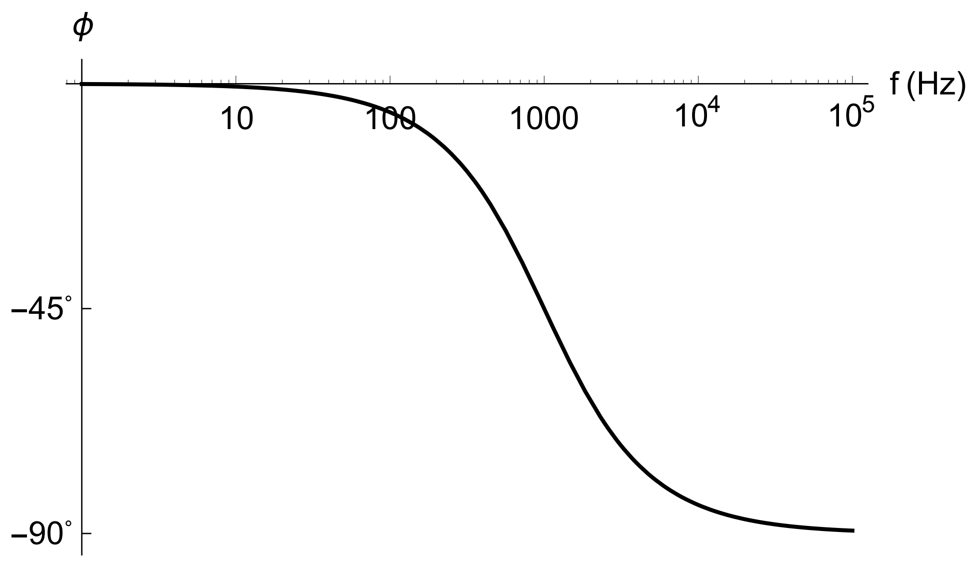

Figure 5: Bode phase plot for a low-pass RC filter.