Laboratory 4

Bandwidth, Filters, and Diodes

Required Components:
- 1 1kΩ resistor
- 1 0.1μF capacitor
- 1 1N914 small-signal diode
- 1 LED

4.1   Objectives

In the previous laboratory exercise you examined the effects of input and output impedances of instruments on signals and measurements. In this laboratory exercise you will study the bandwidth, which is another important signal, circuit, and instrument characteristic. You will build basic filter circuits and determine the range of frequencies that they affect.

You will also use semiconductor diodes and light emitting diodes (LED) and build basic circuits that require these components.

4.2   Introduction

Ideally an instrument with purely resistive input terminal characteristics should be able to faithfully reproduce any input of any frequency. However, real instruments also have capacitance and inductance which affect the quality of signal reproduction. With real instruments the range of frequencies over which the input is faithfully reproduced is limited, quite often severely, by such factors as reactance (capacitance or inductance) in electrical systems, and inertia and damping in mechanical systems.

In order to quantify the range of frequencies a system can reproduce, the term bandwidth is used. The bandwidth of a system is defined as: the range of frequencies for which the amplitude of the input of the system is attenuated not more than 3 dB. This is equivalent to 70.7% of its original value. The frequency at which the gain of the system drops below −3 dB is defined as a corner or cutoff frequency ω_c.

The bandwidth of a deterministic electrical system can be readily determined analytically by writing the transfer function and solving for the corner frequency as is done below for the example circuit shown in Figure 4.1.
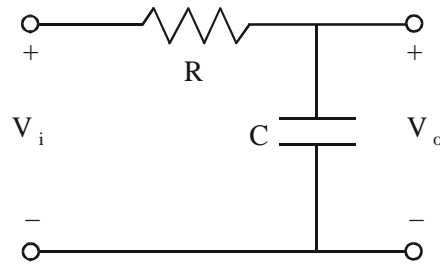
Figure 4.1 Low Pass Filter

Using the voltage divider relationship for AC circuit analysis, where the complex impedance of the resistor is R and the complex impedance of the capacitor is $\frac{1}{j\omega C}$, the output voltage for the network can be written in terms of frequency as

$$V_o = V_i \left[\frac{\dfrac{1}{j\omega C}}{\dfrac{1}{j\omega C} + R} \right] \tag{4.1}$$

and the transfer function (complex output amplitude divided by input amplitude) is

$$T(j\omega) = \frac{V_o}{V_i}(j\omega) = \frac{1}{j\omega RC + 1} \tag{4.2}$$

The amplitude ratio (V_o/V_i) is the magnitude of the transfer function:

$$\frac{V_o}{V_i}(\omega) = |T(j\omega)| = \frac{1}{\sqrt{1 + (RC\omega)^2}} = \frac{1}{\sqrt{1 + \left(\dfrac{\omega}{\omega_c}\right)^2}} \tag{4.3}$$

which is a real function of frequency ω where

$$\omega_c = \frac{1}{RC} \tag{4.4}$$

Note the following:

$$\text{as } \omega \to 0, \quad \frac{V_o}{V_i} \to 1 \tag{4.5}$$

$$\text{as } \omega \to \infty, \quad \frac{V_o}{V_i} \to 0 \tag{4.6}$$

$$\text{as } \omega \to \omega_c, \quad \frac{V_o}{V_i} \to \frac{1}{\sqrt{2}} = 0.707 = -3 \text{ dB} \tag{4.7}$$

Therefore, ω_c is the corner or cutoff frequency. This frequency, in Hertz, is

$$f_c = \frac{\omega_c}{2\pi} = \frac{1}{2\pi RC} \tag{4.8}$$

The bandwidth of this circuit is:

$$0 \leq \omega \leq \omega_c \tag{4.9}$$

which implies that this circuit passes low frequencies only which is why it is called a low-pass filter.

In order to experimentally determine the bandwidth of a circuit it is necessary to drive the circuit with signals having a range of frequencies. Measuring the output over the input as a function of frequency determines the frequency response of the system. The bandwidth is found by finding the −3 dB points of the frequency response curve. If there are two cutoff points, the bandwidth is written as:

$$\omega_{c_{low}} \leq \omega \leq \omega_{c_{high}} \tag{4.10}$$

To determine the bandwidth of the circuits used in this laboratory exercise you will be using the frequency sweep feature of a function generator, as described in the next section.

4.3   Using a Frequency Sweep Feature on a Function Genrator

This section outlines a procedure to generate a **frequency sweep**, which is a signal of a specific waveform (e.g., a sine or square wave) whose frequency increases in a step-wise fashion from a selected start frequency to another selected stop frequency as shown in Figure 4.2.   If a frequency sweep is used as an input to a circuit (e.g., a low pass filter circuit), the resulting output would will illustrate the frequency response of the circuit as shown in Figure 4.3. The cutoff frequency (f_c) can be found by estimating where the amplitude reaches 0.707 of the initial amplitude. Below are procedures for using frequency sweeps with both virtual instruments and typical desktop equipment.
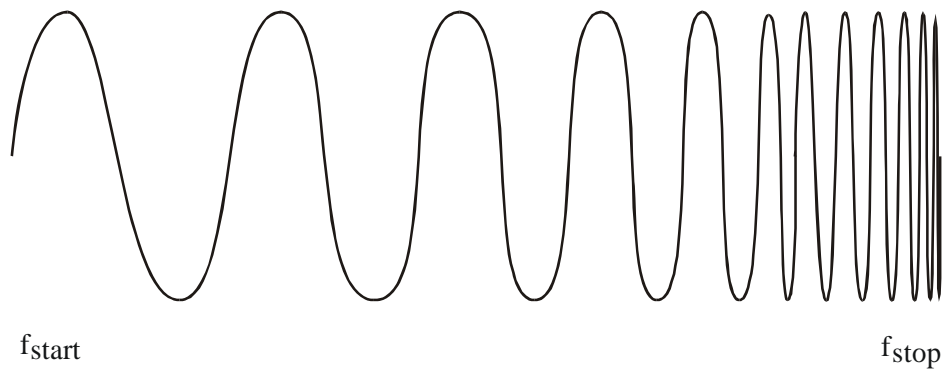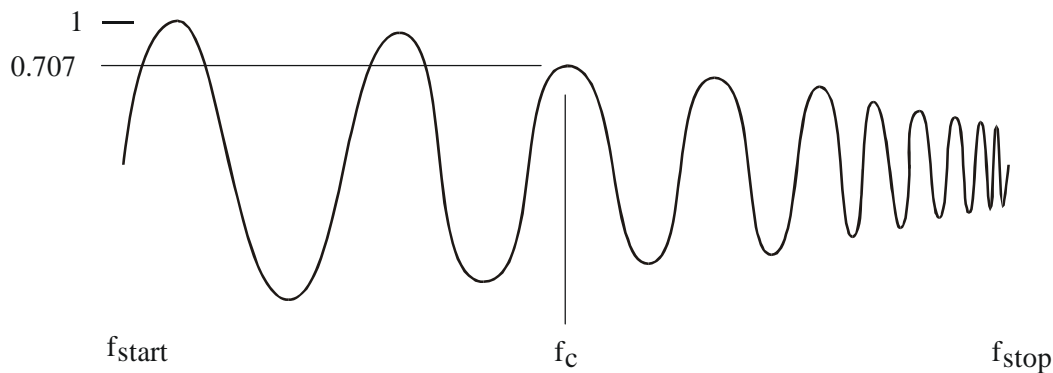

Figure 4.2 Frequency Sweep

Figure 4.3 Sweep Frequency Response

NI ELVIS Procedure:

One way to do a sweep is to just manually select individual input frequencies on the function generator without using the sweep function. Start with a low frequency (e.g., 1 Hz) and gradually increment the frequency (with the same amplitude) until the output amplitude on the oscilloscope reduces to 0.707 of the input value. **This is the recommended method in this Lab using the NI ELVIS.**

Alternatively, you can set up an automatic sweep and interupt the sweep manually when the output amplitude reaches the 0.707 level. To do it this way:

On the function generator:

(1)　Select "sine wave" for the waveform type.

(2)　Input a "start" frequency 1 Hz.

(3)　Input a "stop" frequency 4000 Hz.

(4)　Input the amplitude (1V) or peak-to-peak voltage (2Vpp).

(5)　Set the DC offset (Vdc) to 0.

(6)　Select the step interval to 20ms.

(7)　Select the step size to 10 Hz. This will result in a total sweep time of about 8 s (4000 Hz / 10 Hz * 0.02 s)

On the oscilloscope:

(1)　Attach the probe to the output and select "immediate."

(2)　Click "run" on the oscilloscope and then "sweep" (not "run") on the function generator, and wait for the Vpp to be about 1.414 V, then click "stop."

(3)　Read and record the corresponding frequency. (If the frequency did not appear, try again after setting more appropriate values for volts/div and time/div.)

Philips PM5193 Programmable Function Generator Procedure:

The frequency is controlled by a voltage-controlled oscillator in the instrument. The voltage that corresponds to the frequency is available at the SWEEP output on the back of the instrument.

(1)　Choose the type of waveform you desire
　　　Push the "sine wave" button on the keypad labeled "Wave Form."

(2)　Select the "start" frequency
　　　Press the "start" button on the keypad labeled "Frequency." Then type in the numerical value of 1. If Hz is not indicated, press the Hz/kHz button to indicate Hz. **Do not press ENTER until step 7!**

(3)　Select the "stop" frequency
　　　Press the "stop" button to the right of the "start" button. Now type in the value of 4000, again making sure that Hz is indicated.

(4) Select the amplitude or peak-to-peak voltage
Press the "V$_{pp}$" button on the "Level" keypad. Then enter a value of 2 to result in an amplitude of 1.

(5) Set the DC offset
Press the "V$_{dc}$" button and enter 0.

(6) Select the sweep time
Press the "Time(s)" button under "Modulation" and enter 10 milliseconds (0.01 s).

(7) Activate the parameters
Press the orange "enter" button at the far right of the function generator.

(8) Activate the line sweep
Press the "lin sweep" button on the "Modulation" keypad. Within 4 seconds of pressing the button, enter 1 on the keypad to select the appropriate mode. Then press the "cont" button to continuously repeat the sweep defined by the parameters above. In order to change any of the parameters, press the "single" button, change the parameter as indicated above, and press the "cont" button to resume the continuously repeating sweep.

Use the following steps to generate a frequency response display on the oscilloscope:

(1) Set the time and voltage scales to appropriate values
Set the time base of the scope to match the sweep time, in this case 2 ms/div. Then select an amplitude/division value (e.g., 5 V/div) that will fit the entire waveform on the display.

(2) Use the sweep signal as the trigger
Connect the **SWEEP output on the back of the PM5193** (not the TTL or regular outputs on the front) to CH2 of the oscilloscope with its vertical scale set at 5 V/div. This is a stepped triangular waveform that controls the frequency sweep (see Figure 4.4). Select Norm Trigger, CH2, -slope, and internal source to trigger off the falling edge of the triangle waveform. To better view the full frequency response, place the first step of the triangle on the 2nd division on the scope and the last step on the 7th division (see Figure 4.4). With the parameters defined above, 5 horizontal divisions (2 ms/div) correspond to the sweep time of the signal.
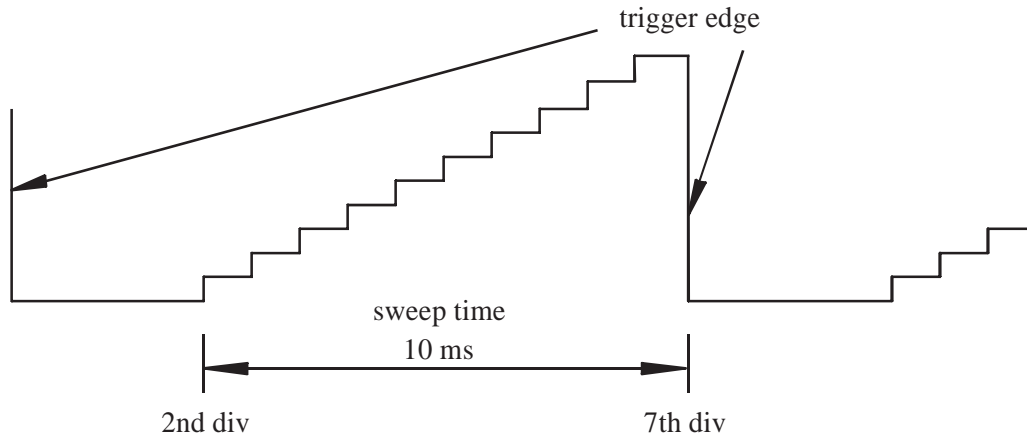
Figure 4.4 Function Generator Sweep Signal

(3)   View the swept frequency signal
Connect the output of the PM5193 to CH1 of the scope. Be careful not to change the triggering from the SWEEP on CH2. You should see a waveform similar to that shown in Figure 4.2.

(4)   View the frequency response of a circuit
Connect the function generator output to the circuit input and connect the circuit output to CH1 of the scope. The cutoff frequency (f_c) can be found by estimating where the amplitude reaches 0.707, and by determining the frequency value that corresponds to that point in the sweep. For example, if cutoff point is at 1/5th of the distance from the start of the sweep to the end, f_c would be 800 Hz   (4000 Hz / 5).
You can count the number of steps in the function-generator sweep output to help estimate the fraction (e.g., 2 steps out of 10 would be 1/5). You can also use the oscilloscope cursors to help in estimating the cutoff frequency.

4.4   Laboratory Procedure / Summary Sheet

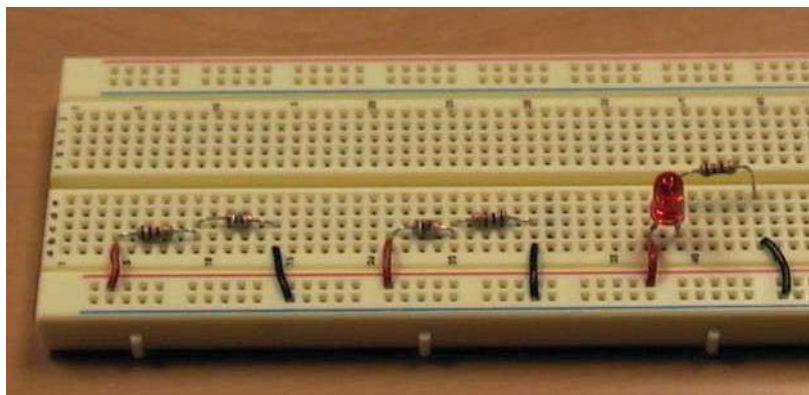Group: _____   Names: _____   _____

_____   _____

Figure 4.5 Circuits for Steps 1 and 3

(1)   Build each filter circuit shown below. For each, use the procedures outlined in the previous section to generate the frequency sweep response and to estimate the cutoff frequency. Also, make a rough sketch of the response.
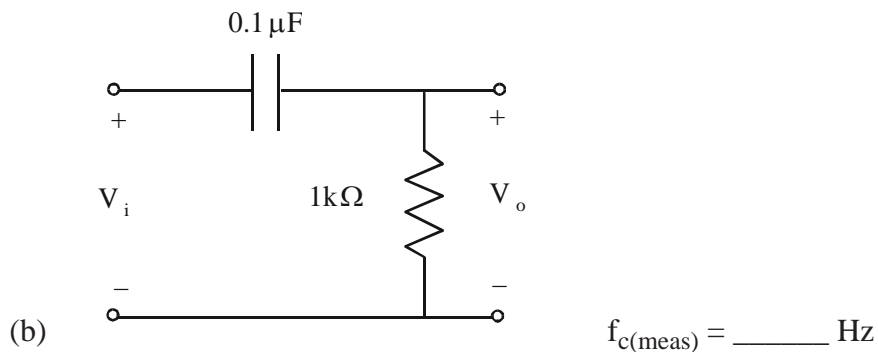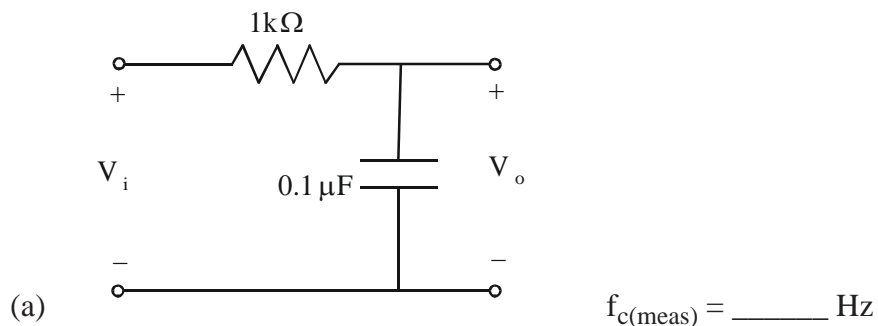

(a) $f_{c(meas)} =$ _____ Hz

(b) $f_{c(meas)} =$ _____ Hz

Figure 4.6 Filter Circuits

(2)   Examine the silicon diode and LED. Decide which lead is the anode and which is the cathode. As shown in the Figure 4.7, the anode lead on an LED is longer. If using the HP 34401A DMM, select the diode test function (—▷⊢) and determine if the leads are identified properly. You will notice that the diode test does not work properly for the LED. This is because the LED voltage drop is larger than the expected range for a silicon diode (0.3 V to 0.8 V). However, you should see the LED light up when properly biased by the DMM. Write down the measured voltage drop across the silicon diode.

V_{diode} = _____ V

colored plastic lens
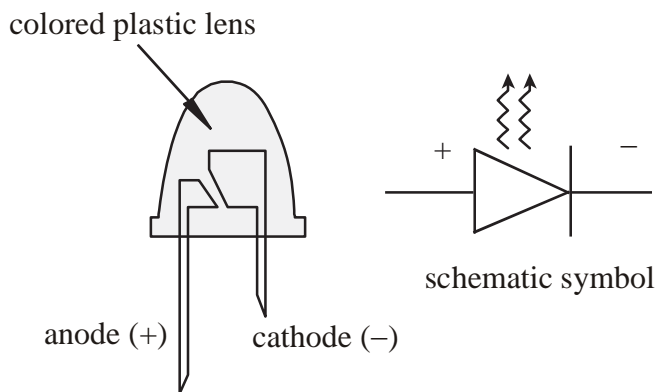
schematic symbol

anode (+)   cathode (−)

Figure 4.7 LED

(3) Construct the circuit in Figure 4.8 for both the diode and the LED and record the indicated voltages. Make a sketch for each output voltage superimposed on the input for the signals labeled with an asterisk below.

V_i	V_D (diode)	V_o(diode)	V_D (LED)	V_o(LED)
+5 V				
-5 V				
2 sin (6πt)	*	*	*	*

*: Sketch one cycle of the input voltage and the measured voltages (V_D and V_o) versus time. Use the axes provided below and provide appropriate scales and label each curve.
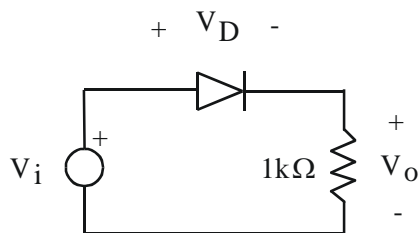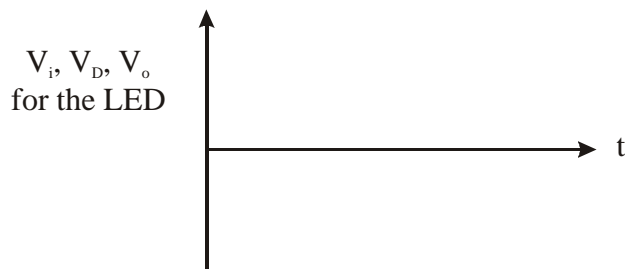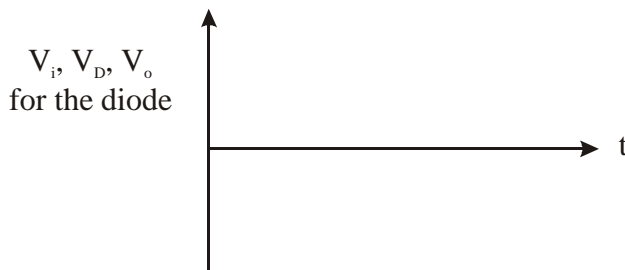

Figure 4.8 Diode/LED Circuit

LAB 4 QUESTIONS

Group: _____   Names: _____   _____

_____   _____

(1)   For the circuit in Step 1a:

what type of filter is this? _____

Also, calculate the theoretical cutoff frequency and the percent error in your measured value:

$\omega_{c(meas)} =$ _____ $\omega_{c(theor)} =$ _____   % error = _____

Remember that $\omega = 2\pi f$.

(2)   For the circuit in Step 1b, derive expressions for the magnitude ratio of the frequency response and for the cutoff frequency (ω_c).

$\left| \dfrac{V_o}{V_i} \right| =$ $\omega_c =$

what type of filter is this? _____

Also, calculate the theoretical cutoff frequency and the percent error in your measured value:

$\omega_{c(meas)} =$ ————— $\omega_{c(theor)} =$ ————— % error = —————

(3) In step 3, if the diode where removed and replaced in the opposite direction in the circuit, what effect would this have on the outputs for the sine wave input?