Laboratory 2

Modern Data Acquisition and First-Order Systems

1 Objectives

- Use of the computer-based data acquisition software, *LabView*, as an instrumentation tool.
- Understand the time and frequency responses of first-order systems.
- Design passive filters.

2 Background

In Laboratory 1, traditional equipments such as the multimeter, function generator, and oscilloscope were utilized for instrumentation. With the advent of cheap, high-performance computer technologies, computer-aided instrumentation systems have found their way into laboratories. This laboratory introduces one such system, *LabView*, which will be exploited throughout most of the remaining experiments in this course.

First-order systems and particularly filters are an integral part of many measurement systems. As such, it is important to understand and predict their time and frequency behaviors when subjected to known input signals. In the following, some pertinent theoretical concepts of first-order systems and passive filters are briefly described.

More detailed information about the subjects covered in this laboratory can be found in references [1, 2, 3] and *LabView* manuals (the laboratory TA is responsible for having the manuals available if requested).

2.1 LabView

This section introduces the fundamentals of the computer-aided instrumentation system, *LabView*. The main computational platform is a 166 MHz Pentium-based computer with 64 MB of RAM, a $3\frac{1}{2}$ inch floppy drive, and a 2 GB hard disk. A color monitor with a 640×480 resolution (VGA) will be used for viewing the intermediate data. For hardcopies of your data, the computers have been interfaced to a laser printer. The computers are equipped with a 12–bit analog–to–digital (A/D) converter with 8 input channels. The signals that can be measured with this converter should be within ± 5 Volts. **Signals with amplitude higher than 5 Volts will damage the A/D converter; hence, precautions should be taken to avoid**

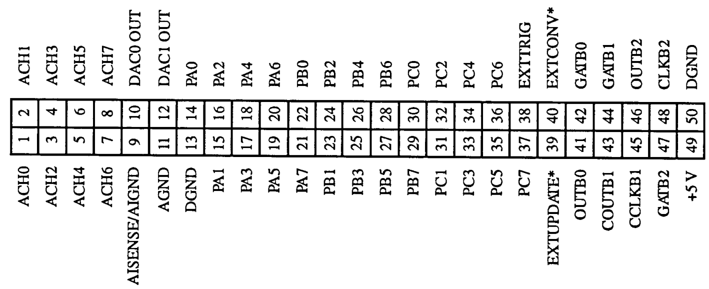

Figure 1: Pins of the Data Acquisition Connector

this situation. A digital–to–analog (D/A) converter with 2 channels and 12–bit resolution will be used as an output device. Moreover, 24 digital channels software configurable as input or output channels can be used for interfacing digital signals (0 or 5 Volts signals). A 50–pin connector (see Figure 1) attached to your computer will be used for interfacing the signals to your computer. Notice that the ground of this connector (pins 9 and 11) should be the same as the analog ground of your circuit. Throughout the experiments, we will be using pins 1 through 8 for A/D conversions (channels ACH0 through ACH7) and pins 10 and 12 for D/A conversions (channels DAC0 OUT and DAC1 OUT).

LabView is a software which uses a graphical programming language, *G*, to create programs in block diagram form. It contains libraries and subroutines for any programming task, including application–specific libraries for data acquisition, general purpose interface bus, data analysis, data presentation, and data storage. Within *LabView* you can either animate the program execution, or single–step through the program. *LabView* programs are called virtual instruments (VIs) because their appearance and operation imitate actual instruments. VIs have an interactive user interface and source code, and may accept parameters from a lower level VI. VIs can be built for acquiring data from plug–in boards and programmable instruments for further analysis and presentation. Each VI is comprised of:

- An interactive user interface called the front panel for simulating the panel of a physical instrument (*e.g.*, function generator, oscilloscope, *etc.*).
- The pictorial solution indicating the source code for the VI named the *block diagram*.
- Icons and connectors within the VI. Through the icons, VIs can pass/receive data to/from other VIs. Moreover, since the VIs are modular and hierarchical, a VI can be shrunk into an icon and used afterwards as a sub-VI within another VI.

Throughout the laboratories, you will be using for data acquisition VI files called *lab*.vi*, where the '*' stands for the particular laboratory number (*e.g.*, *lab2.vi*). These files will be located in the directory called *c:/windows/labview/lab**. The laboratory TA is responsible for assisting you in activating these VI files and making any necessary modifications to their setup.

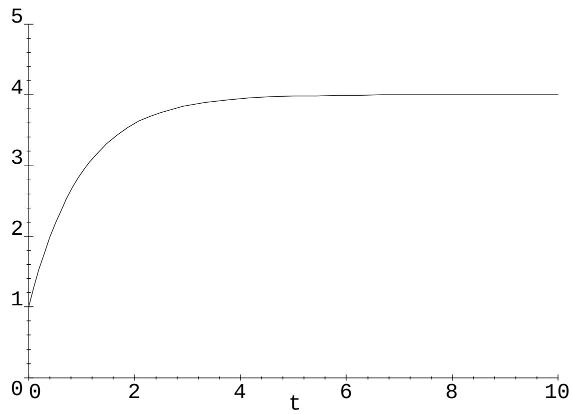

Figure 2: Typical Step Response of a First-Order System

2.2 First-Order Systems

Many components of measurement systems can be modeled as a linear differential equation with constant coefficients (*e.g.*, accelerometer, filter, *etc.*):

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_o y(t) = b_m \frac{d^m u(t)}{dt^m} + b_{m-1} \frac{d^{m-1} u(t)}{dt^{m-1}} + \cdots + b_0 u(t) \qquad (1)$$

where $y(t)$ is the system output variable, $u(t)$ is the input variable, the a_i's and b_i's are the constant coefficients, and n defines the order of the system. When $n = 1$ and $m = 0$ or 1, the system is referred to as a *first-order system*. For example, for the case where $m = 0$ and $b_0 = 1$, (1) reduces to

$$a_1 \frac{dy(t)}{dt} + a_o y(t) = u(t). \qquad (2)$$

Applying the Laplace transform to (2), the input-output transfer function of (2) can be obtained as[1]

$$\frac{Y(s)}{U(s)} = \frac{\frac{1}{a_0}}{\tau s + 1} \qquad (3)$$

where $\tau = \frac{a_1}{a_0}$ is called the *time constant* of the system. For the case where $u(t)$ is a step input of amplitude A, the response of (2) is given by

$$y(t) = \left(y(0) - y_\infty\right) e^{-\frac{t}{\tau}} + y_\infty \qquad (4)$$

where the constant $y_\infty = \frac{A}{a_0}$ is called the *steady-state* value of $y(t)$. Figure 2 shows the step response of (4) for the case where $y(0) = 1$, $y_\infty = 4$, and $\tau = 1$ sec.

For case where $u(t)$ is a harmonic signal, *i.e.*, $u(t) = A\sin(\omega t)$, the response of (2) is given by

$$y(t) = y(0)e^{-\frac{t}{\tau}} + \frac{A}{a_0\sqrt{1+\omega^2\tau^2}} \sin\left(\omega t + \phi\right), \qquad \phi = -\tan^{-1}\left(\omega\tau\right) \qquad (5)$$

[1] Recall that the transfer function is obtained by setting the initial conditions to zero. For (2), this means $y(0) = 0$.

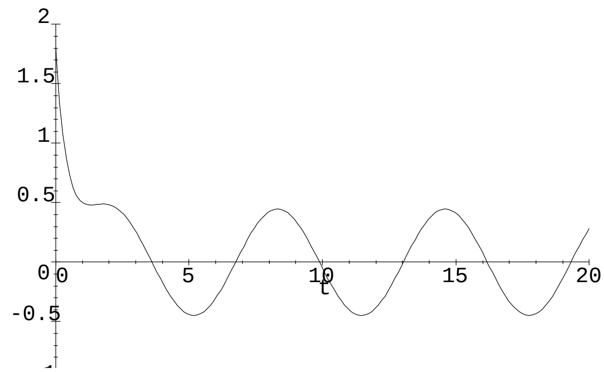

Figure 3: Typical Harmonic Response of a First-Order System

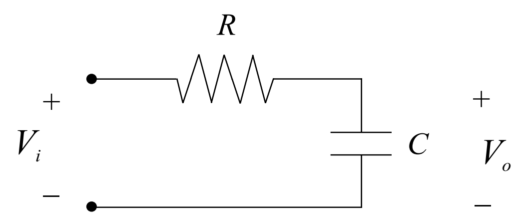

Figure 4: Passive, RC Low-Pass Filter

where ϕ denotes the phase shift in radians. Figure 3 shows the harmonic response of (5) for the case where $y(0) = 2$, $a_0 = 2$, $\tau = 0.5$ sec, $A = 1$, and $\omega = 1$ rad/sec.

2.3 Passive Filters

The term *filtering* is used to describe the process of removing certain frequency bands from an electric signal and allowing other frequencies to be transmitted. Filters are particularly useful in instrumentation since most sensors produce signals containing spurious noise which contaminate the measured quantity. Filters are then designed to extract the undesirable noise from the sensor signal. The term *passive* is used to denote filters which are constructed using only passive electric components such as resistors, capacitors, and inductors[2].

A typical example of the first-order system of (2) is a passive, RC *low-pass* filter. This filter is implemented by the simple circuit shown in Figure 4. To see how the mathematical model of the circuit in Figure 4 is given by (2), one must first know the voltage-current relationship of a capacitor.

A capacitor is a passive element that stores energy in the form of an electric field. A capacitor is constructed by introducing a nonconducting medium within the gap between two

[2] *Active* filters (those which also involve the use of operational amplifiers) will be the topic of Laboratory 3.

conductors. The voltage-current relationship of a capacitor is given by

$$V = \frac{1}{C}\int I(t)dt \tag{6}$$

where V is the voltage across the capacitor, I is the current arriving at the capacitor terminal, and C is the capacitance of the capacitor in *Farads* (F). Note that by differentiating (6) with respect to time, the voltage-current relationship of a capacitor can also be written as

$$I = C\frac{dV}{dt}. \tag{7}$$

Capacitors are manufactured in a wide variety of shapes and materials. Electrolytic types are usually cylindrical with axial leads. Electrolytic capacitors require the same voltage polarity, and they typically carry large capacitance values (μF and in some cases mF). Tantalum capacitors denoted by their light blue coating color exhibit the highest capacitances per volume. Ceramic capacitors (to be used in this laboratory) are round or rectangular in shape.

Now, to show that the mathematical model for the low-pass filter is given by (2), one has to simply apply Kirchhoff's voltage law to the circuit of Figure 4 along with the relationship of (7). As a result, the following transfer function is obtained

$$\frac{V_o(s)}{V_i(s)} = \frac{1}{RCs+1} \tag{8}$$

where the time constant $\tau = RC$. Figure 5 shows the frequency response of a first-order, low-pass filter (*i.e.*, Bode plot of (8)) for the case where $\tau = 10^{-2}$ sec. Note the magnitude attenuation for frequencies higher than the *cutoff* frequency $\omega_c = \frac{1}{\tau} = 100$ rad/sec.

A first-order, *high-pass* filter is obtained if the output voltage V_o in the circuit of Figure 4 is now taken to be the voltage across the resistor. In this case, the transfer function will be

$$\frac{V_o(s)}{V_i(s)} = \frac{RCs}{RCs+1}. \tag{9}$$

Note that this transfer function is representative of a first-order system where $m = 1$ in (1). Figure 6 shows the frequency response of a first-order, high-pass filter (*i.e.*, Bode plot of (9)) for the case where $RC = 10^{-2}$ sec.

3 Laboratory Procedure

3.1 Equipment List

- A Pentium-based computer containing Windows, LabView, and a data acquisition board manufactured by National Instruments Corp.
- Set of known resistors and capacitors.
- An unknown capacitor C_u.
- Breadboard and a set of leads.
- Set of connectors.

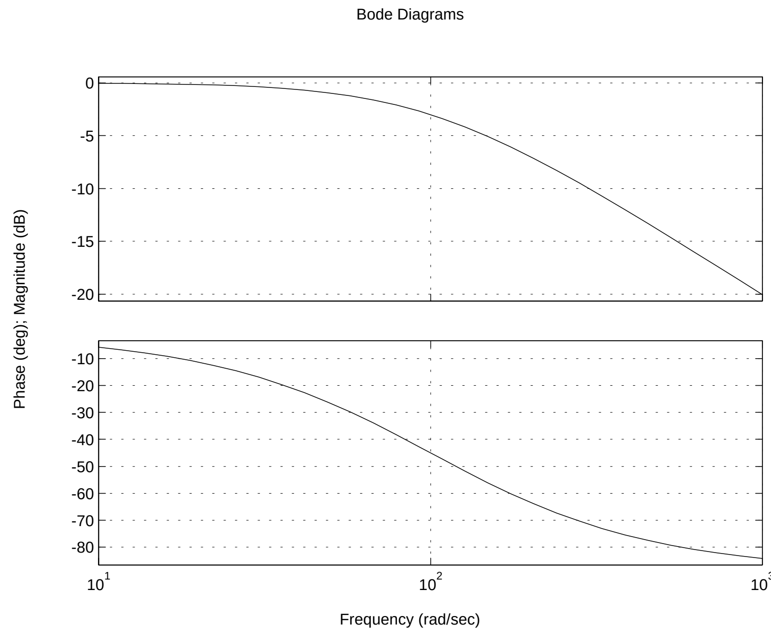

Figure 5: Typical Frequency Response of a First-Order, Low-Pass Filter

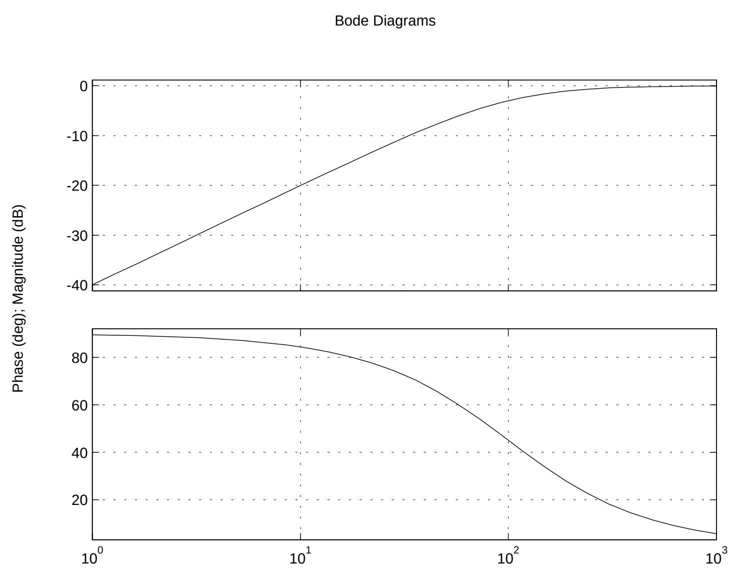

Figure 6: Typical Frequency Response of a First-Order, High-Pass Filter

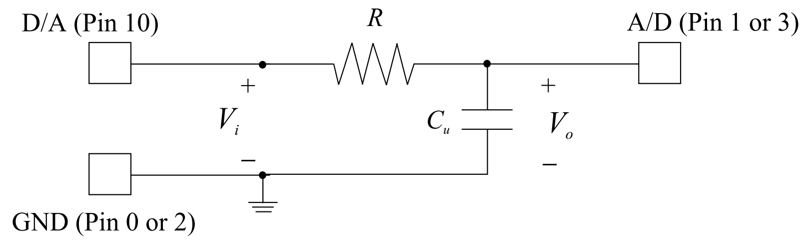

Figure 7: Connections for Interfacing Circuit with LabView

3.2 Time Response of First-Order Systems

1. Assemble the circuit of Figure 7 on the breadboard using a known resistor and the unknown capacitor C_u. To interface the circuit with LabView, connect the input of the circuit to the D/A converter (Pin 10 of the connector) and the output to the A/D converter (Pins 1 or 3). Also, connect the ground of the circuit to either Pins 0 or 2 of the connector. **Before proceeding, you must request the laboratory TA to approve your electrical connections**. Start LabView and open the VI file *lab2.vi*. This file, which will also be used in all the subsequent experiments of this laboratory, will allow you to select and apply an input voltage to the circuit, and view the output voltage response as a function of time.[3] Apply a *unit* step input voltage to the circuit and record its output response. Based on this response, devise a way of identifying the unknown capacitance C_u (Hint: use equation (4) and the definitions of τ and y_∞). Compare the calculated value of C_u with its nominal value (use the capacitance meter on a multimeter to provide the nominal value).

2. Apply a sinusoidal input voltage with zero DC-offset and **appropriate** amplitude to the circuit of Figure 7, and record its output response. Compare the input and output waveforms in terms of the amplitude, frequency, and phase shift (time delay). Compare the measured values of the output voltage's amplitude and phase shift with their theoretical values.

3.3 Frequency Response of Passive Filters

1. Build a first-order, passive, low-pass filter that provides "good" attenuation of signals with frequencies $f \geq 5$ KHz (note that this frequency is given in Hz, not rad/sec). **Before proceeding, you must request the laboratory TA to approve your electrical connections**. Devise a way of experimentally determining the magnitude and phase frequency response of the filter. Plot your experimental results in a semi-log paper with the magnitude in decibels, phase in degrees, and frequency in rad/sec. What is the transfer function of the filter you built? Plot the theoretical frequency response using Matlab and compare it to the experimental one.

[3] If necessary, you may use a traditional instrument (*e.g.*, oscilloscope, multimeter) for verification purposes only of the measurements made in LabView.

2. Build a first-order, passive, high-pass filter that provides "good" attenuation of signals with frequencies $f \leq 2$ KHz. Repeat the same procedure as above.

3. **Extra Credit:** Build a circuit that implements the following transfer function

$$\frac{V_o(s)}{V_i(s)} = \frac{1}{(5 \times 10^{-4}s + 1)^2}.$$

Experimentally determine its magnitude frequency response, and compare it to the theoretical, magnitude frequency response of the following transfer function

$$\frac{V_o(s)}{V_i(s)} = \frac{1}{5 \times 10^{-4}s + 1}.$$

Comment on the differences.

References

[1] W. Bolton, *Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering*, Addison Wesley, New York, NY, 1999.

[2] M.B. Histand and D.G. Alciatore, *Introduction to Mechatronics and Measurement Systems*, WCB/McGraw-Hill, Boston, MA, 1999.

[3] J.W. Nilsson, *Electric Circuits*, Addison Wesley, Reading, MA, 1996.