ME 104
Sensors and Actuators

Laboratory 5
Frequency Response

Department of Mechanical Engineering
University of California, Santa Barbara

(Rev. 2007)

Introduction

In this laboratory, you will use a *LabVIEW* VI that will enable you to obtain the frequency response (magnitude and phase) of an external system. You will use this VI to obtain (separately) the frequency response of an analog low-pass filter, an analog high-pass filter, an analog band-pass filter, and a DC motor.

Background Reading

Please read the following material prior to this lab:

1. Histand and Alciatore, **Introduction to Mechatronics**, Sections **4.4-4.5** and Section **4.10.2** (Up to and including Equation 4.73).
2. **DC Motor Control Module User Manual**, **Pages 3-7** and **14-16**, LJ Technical Systems Inc.

Pre-Lab

1. Given 10-kΩ resistors and 0.1-μF capacitors, determine how to build
   a. an RC low-pass filter with a cut-off frequency of 1000 rad/s (159 Hz)
   b. an RC high-pass filter with a cut-off frequency of 1000 rad/s (159 Hz)
   c. an RC bandpass filter with a pass-band of 159 to 339 Hz.

2. Please review the VI, **`lab5_ex1.vi`**, for this lab to ensure your understanding of them prior to this lab. The share drive for this course is accessible from the computers in the CAD lab and Rm. 2218. For Lab 5, go to **My Computer** >> **Network Drives** >> **melab** >> **ME 104** >> **Lab 5.**

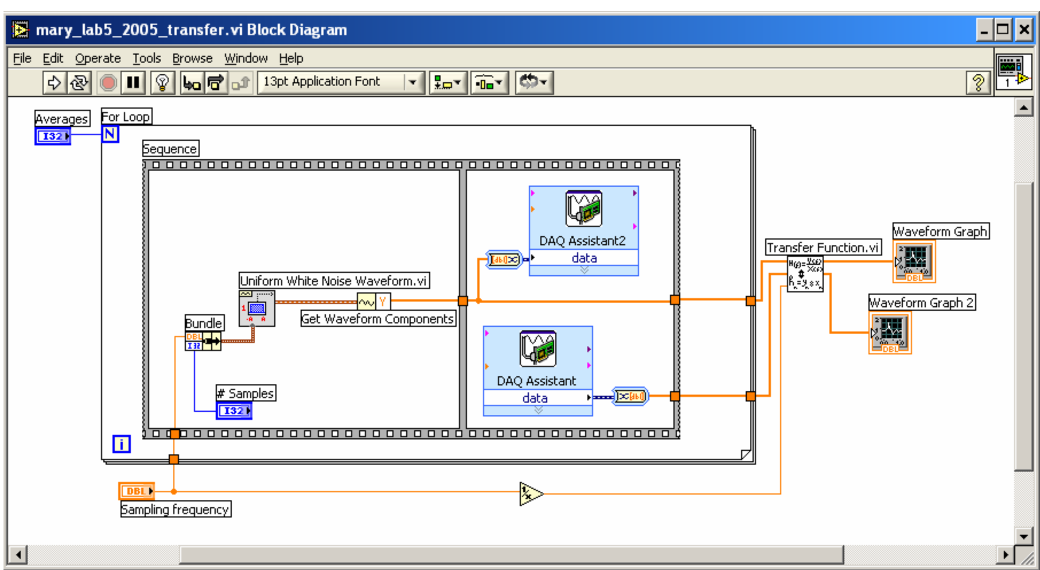

Figure 1. Block diagram of VI for Lab 5, **`lab5_ex1.vi`**

Experiment 1: Run a VI for Computing Frequency Response

In this experiment, you will use a *LabVIEW* VI to compute the frequency response of an external system.

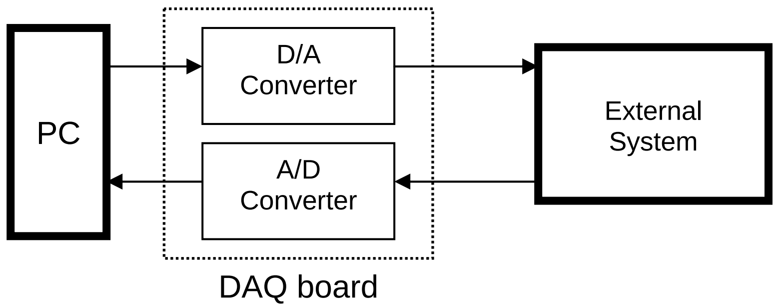

Figure 2. Measuring the frequency response of an external system

Specify Sampling Parameters

3. Open **`lab5_ex1.vi`** provided for Experiment 1. Go to **My Computer** >> **Network Drives** >> **melab** >> **ME 104** >> **Lab 5.**
4. Go to the front panel. Enter the values for the sampling parameters as indicated in Table 1.

Table 1. Sampling Parameters for Lab 5 VI

Parameter	Value
# Samples	2048
Sampling Frequency	1000
Averages	20

This specifies that you will generate and collect 2048 samples at a rate of 1000 samples per second (1 kS/s) and you will do this 20 times. Most digital signal processing algorithms (such as computation of frequency response) work fastest when the number of samples is a power of 2.

Run Your VI

5. Run your VI by clicking the **Run** button. The VI will run for just over 40 seconds before the frequency response is displayed.
6. Save this VI as **`yourname_lab5_ex1.vi.`**

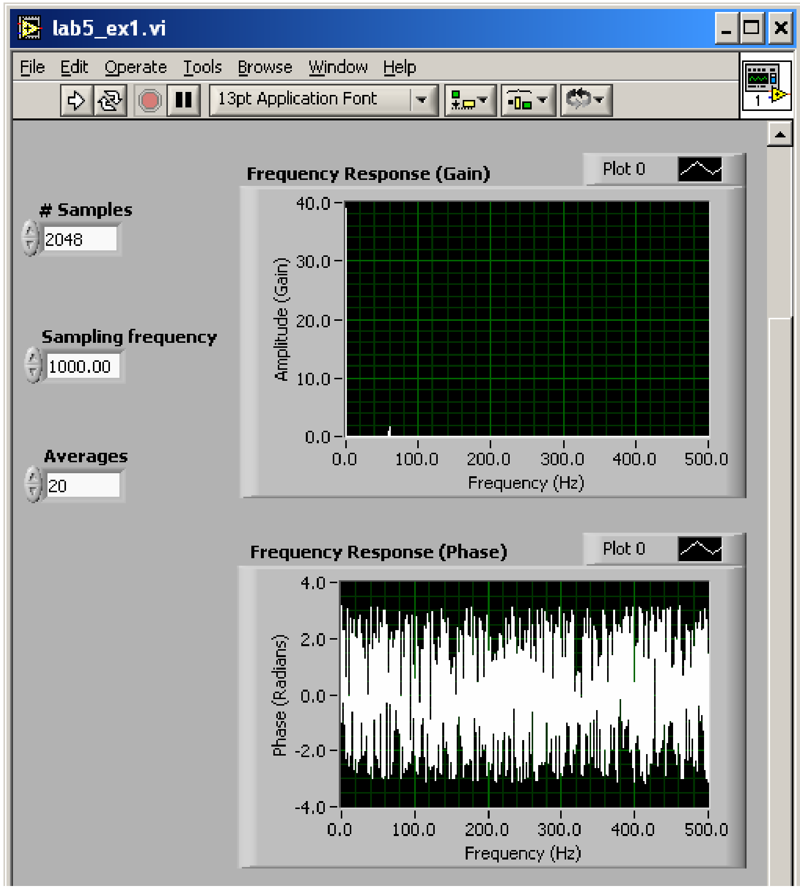

Figure 3. Display on **`yourname_lab5_ex1.vi`** after running it without any connections to the connector block.

Your frequency response indicates that there is no system![1] This should come as no surprise since you have not connected anything to your connector block. Notice that the maximum frequency displayed on your frequency response plots is 500 Hz, which is ½ of the sampling frequency of 1000 Hz.

Experiment 2: Obtain the Frequency Response of an Analog Low-Pass Filter

In this experiment, you will use a modified version of the VI from Experiment 1 to obtain the frequency response of an analog low-pass filter.

[1] Actually, a "system" does exist (the air in the laboratory), but this is of little practical interest.

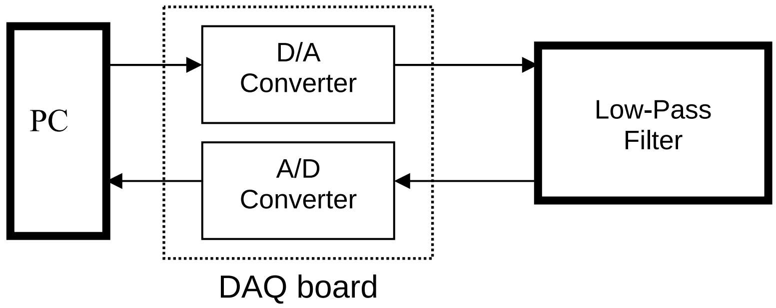

Figure 4. Obtaining the frequency response of an analog low-pass filter

1. Build the RC low-pass filter shown in Figure 5. Choose the resistor R_{LP} and the capacitor C_{LP} such that R_{LP} = 10 kΩ and C_{LP} = 0.1 μF.

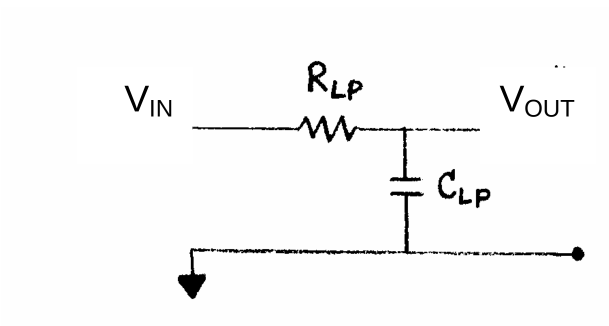

Figure 5. RC Low-pass filter.

Then, the cutoff frequency ω_0 of the filter is given by

$$\omega_0 = \frac{1}{RC} = 1000 \text{ rad/s} \quad \text{or} \quad f_0 = \frac{\omega_0}{2\pi} = 159 \text{ Hz}.$$

2. Provide ground (GND) to your circuit board using the black (-) terminal of the "5 V FIXED 3 A" output from your Tektronix PS280 DC Power Supply. You **do not** need to turn on the power supply.
3. Connect your circuit to the connector block such that the voltage input to your low-pass filter is provided from **Analog Output Channel 0** (AO0). Remember to provide **Analog Output Ground** (AOGND) to the connector block as in previous laboratories. Refer to the pin-out diagram for the connector block.
4. Connect your circuit to the connector block such that the voltage output from your low-pass filter is sent to **Analog Input Channel 0** (AI0). Remember to provide

Analog Input Ground (AIGND) to the CONNECTOR BLOCK as in previous Laboratories.

5. Open and run **`yourname_lab5_ex1.vi`**. The VI will run for just over 40 seconds before the frequency response is displayed.
6. Your axes should be linear. Obtain a printout of your front panel for your Lab Report.
7. Format the x-scale of both of your Frequency Response graphs such that the frequency axes are displayed on a *fine* **logarithmic** scale[2]. (The y-axes should remain linear.) You may have to change your axes colors for better viewing. Remember to obtain a printout of your front panel (frequency response) for your Lab Report.

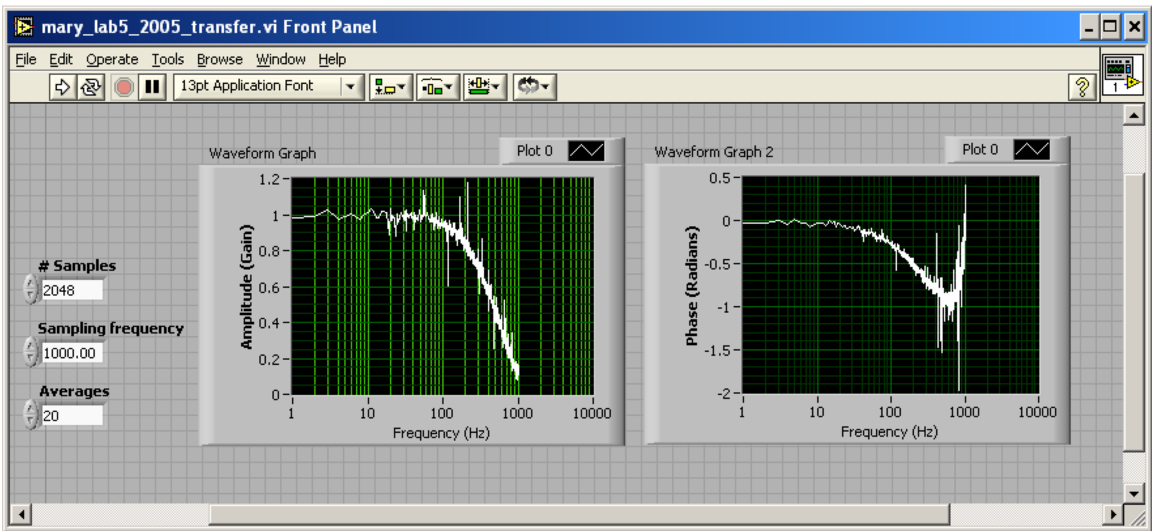

Figure 6. Frequency response of an analog low pass filter.

Add Smoothing Window

The frequency response of your low-pass filter appears distorted due to a phenomenon known as *spectral leakage*. To reduce the effects of spectral leakage, add a smoothing window[3] to your time-domain signal.

8. Add two Hanning Windows to the block diagram of **`yourname_lab5_ex1.vi`** as shown in Figure 7. Hanning Windows are useful for general-purpose windowing applications.
9. Save this as **`yourname_lab5_ex2.vi`**.
10. Run your VI by clicking the **Run** button. The VI will run for just over 40 seconds before the frequency response is displayed.

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[2] For instructions, refer to Lab 3, Experiment 5.

[3] See **Additional Reading** section to learn more about windowing.

11. The frequency response of your low-pass filter should be easily recognizable and not as choppy as the one you obtained in Step 5 above. Remember to obtain a printout of your front panel (frequency response) for your Lab Report.

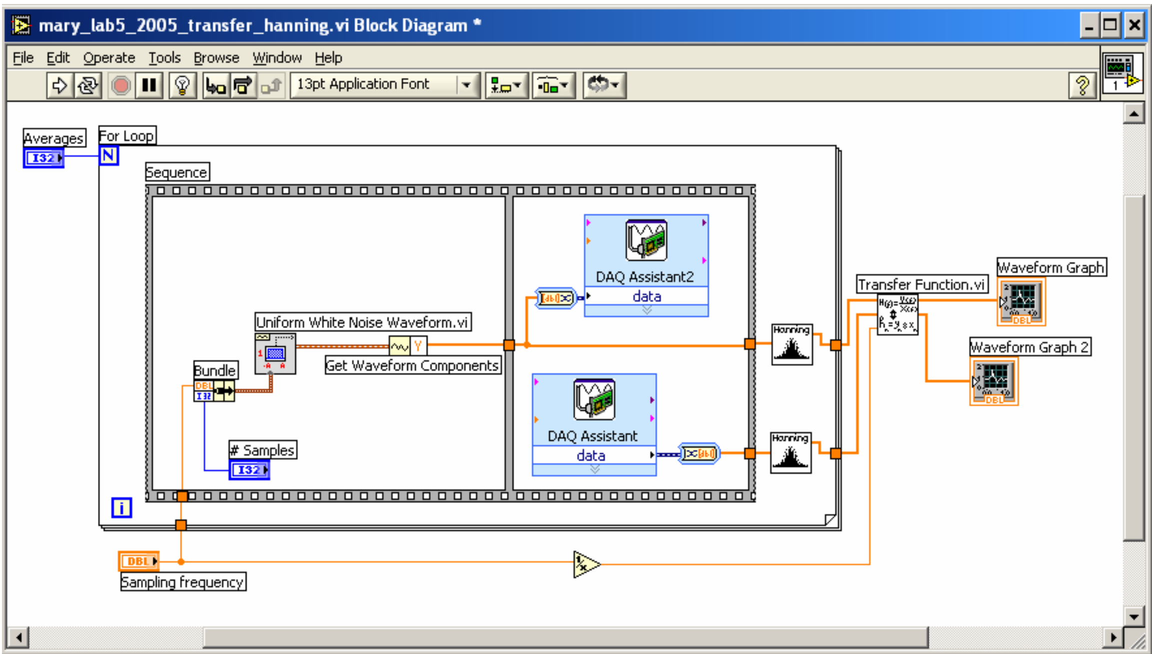

Figure 7. **Block diagram for** `yourname_lab5_ex2.vi`

You can check the validity of the gain (magnitude) portion of the frequency response you obtained (above) using a function generator and an oscilloscope.

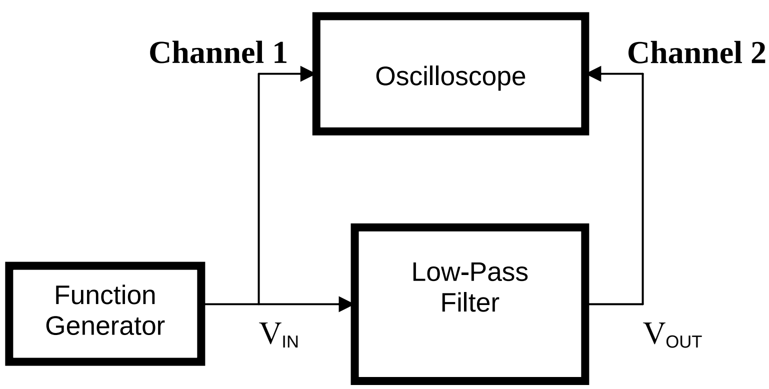

Figure 8. Verifying the frequency response of an analog low-pass filter.

12. Disconnect the connector block from your low-pass circuit.

13. Connect the output (**MAIN OUT**) from your function generator to Channel 1 of your oscilloscope.
14. Generate a sine wave with an amplitude of 1 V (2V peak-to-peak) and a frequency of 10 Hz. Verify the properties of your sine wave using your oscilloscope.
15. Connect your function generator to your low-pass filter such that the output from the function generator is the input (V_{IN}) to your low-pass filter.
16. Connect the output (V_{OUT}) from your low-pass filter to Channel 2 of your oscilloscope.
17. Observe the voltage signals on Channels 1 and 2 of the oscilloscope and write down the amplitude of V_{IN} and V_{OUT}.
18. Compute the gain and compare it with the frequency response you obtained in Step 9 above.
19. Check the validity of your frequency response at enough frequencies[4] that you are convinced of the accuracy of your frequency response graph.

Experiment 3: Obtain the Frequency Response of an Analog High-Pass Filter

In this experiment, you will obtain the frequency response of an analog high-pass filter.

1. Build an RC high-pass filter with a cutoff frequency of 1000 rad/s.[5]
2. Obtain the frequency response of your high-pass filter using `yourname_lab5_ex2.vi.` Remember to obtain a printout of your front panel (frequency response) for your Lab Report.
3. Using a procedure similar to steps 10-19 of Experiment 2, verify the frequency gain response using a function generator and oscilloscope.

Experiment 4: Obtain the Frequency Response of an Analog Band-Pass Filter

In this experiment, you will obtain the frequency response of an analog band-pass filter.

1. Combine an analog RC low-pass filter and an analog RC high-pass filter such that the resulting circuit is a band-pass filter[6] with a pass-band of 159 to 339 Hz.
2. Obtain the frequency response of your band-pass filter using `yourname_lab5_ex2.vi.` Remember to obtain a printout of your front panel (frequency response) for your Lab Report.

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[4] For example, f = 10, 20, 30,..., 90, 100, 200,..., 500 Hz.
[5] See Mechatronics textbook.

[6] A superior band-pass filter design would also incorporate an inductor, but we will not build such a filter in this Lab.

3. Using a procedure similar to steps 10-19 of Experiment 2, verify the frequency gain response using a function generator and oscilloscope.

Experiment 5: Obtain the Frequency Response of a DC Motor

In this experiment, you will obtain the frequency response of a DC Motor.

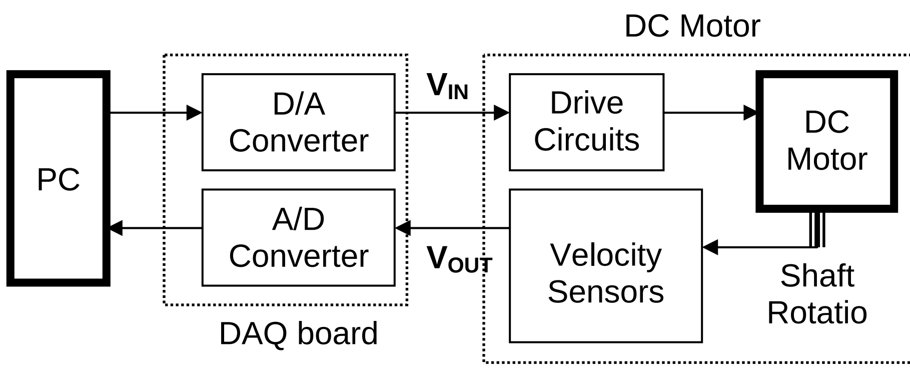

Figure 9. Obtaining the frequency response of a DC Motor

Set Up DC Motor Control Module

1. Find the **MOTOR DRIVE** switch on your MS15 DC Motor Control Module. To specify that you are using analog drive input, select the $\mathbf{V_{IN}}$ position.
2. Find the **TACHO GENERATOR** switch on your motor control module. To specify that you do not want to apply a variable load to the DC motor, select the $\mathbf{V_{OUT}}$ setting.
3. Find the **MOTOR DRIVE INPUT** panel on your motor control module. To enable the selected input ($\mathbf{V_{IN}}$) to drive the motor, use a banana connector to connect the $\overline{\mathbf{E}}$ (**Enable Input)** socket to the **0V** socket.
4. Make sure the **Eddy Current Brake** is disengaged. That is, make sure it is in the 0 position.
5. To drive the motor using the analog voltage output ("system input") from the DAQ board, connect your motor control module to the connector block according to Table 2.

Table 2. Connector block pin assignment for driving DC motor using a voltage signal from Analog Output Channel 0.

MOTOR DRIVE INPUT Panel on DC Motor Control Module	Connect to:
$\mathbf{V_{IN}}$ socket (Analog voltage)	Pin 22 (AO0)

OV socket (Analog ground)	Pin 55 (AOGND)

6. To acquire the analog velocity feedback signal ("system output"), connect the Tacho Generator Output from your motor control module to the connector block according to Table 3.

Table 3. Connector block pin assignment for acquiring a voltage signal using Analog Input Channel 0.

TACHO GENERATOR OUTPUT Panel on Motor Control Module	Connect to:
V_{OUT} socket (Analog feedback)	Pin 68 (AI0)
OV socket (Analog ground)[7]	Pin 67 (AIGND)

Obtain Frequency Response of DC Motor

7. Make sure that no wires or cables interfere with the moving parts of your motor.
8. Turn ON your Tektronix PS280 DC Power Supply. This will provide power to the motor control module.
9. Obtain the frequency response of your DC Motor using **`yourname_lab5_ex2.vi.`**
10. Remember to obtain a printout of your front panel (frequency response) and block diagram for your Lab Report.
11. Modify your VI such that you can obtain and display the frequency response up to 1 kHz. Obtain the frequency response by running your VI. Remember to obtain a printout.
12. Use the *Wiring* tool to add a constant to allow user specification of the **amplitude** of the **Uniform White Noise VI.**
13. Change the amplitude of the white noise from 1 (default) to `2.00`. Obtain the frequency response by running your VI. Remember to obtain a printout of the front panel.
14. Save this VI as **`yourname_lab5_ex3.vi`**.
15. Repeat Step 13 for white noise amplitude of `3.00`.

Experiment 6: Obtain the Frequency Response of a DC Motor under an Applied Load

In this experiment, you will obtain the frequency response of a DC Motor under an external load applied by the **Eddy Current Brake**.

[7] You can establish this ground connection by connecting Pin 67 (AIGND) to Pin 55 (AOGND).

1. Using a procedure similar to Experiment 5, obtain the frequency response of the DC motor with the **Eddy Current Brake** in the `1` setting. Set the white noise amplitude to 3 V.

Experiment 7. Verify Amplitude of Frequency Response

You can check the validity of the gain (amplitude) portion of the frequency response you obtained (above) using a function generator and an oscilloscope.

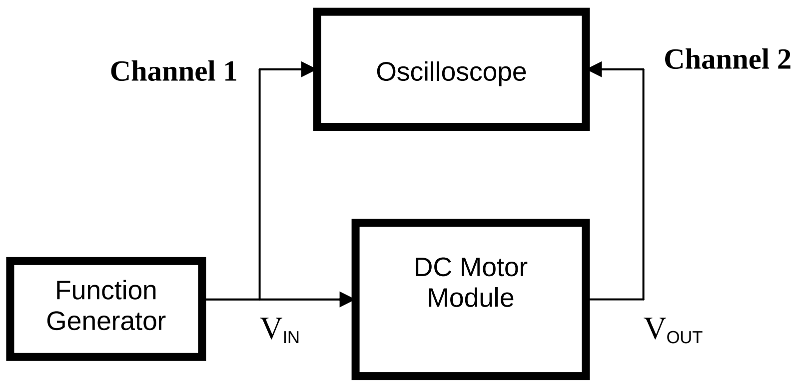

Figure 10. Verifying the frequency response of a DC Motor.

Set Up Function Generator

1. Disconnect the connector block from your DC Motor Module.
2. Find the **MOTOR DRIVE INPUT** panel on your motor control module. To prevent the selected input (**V_{IN}**) from driving the motor, disconnect the $\overline{\mathbf{E}}$ (**Enable Input)** socket from the **0V** socket.
3. Using a BNC cable, connect the **MAIN OUT** terminal on the function generator to Channel 1 of your oscilloscope.
4. Turn on the oscilloscope and set its vertical scale to 500 millivolts/division.
5. On your function generator, select the "MAIN **0-2Vp-p**" setting by pressing down that button. This will limit your voltage output to 2 volts, peak-to-peak[8].
6. Find the **FUNCTION** selection buttons on your function generator. Select (press down) the sine wave function (⌒◡) button. Make sure that none of the other buttons on that row are pressed down.
7. Turn ON the function generator.

[8] Therefore, the maximum amplitude will be 1 V.

8. Press down the **MULTIPLIER** (∇) button until the MULTIPLIER indicator (red light) shows 1 and the PERIOD indictor shows SEC. In this setting, the digital display shows the output period in seconds.
9. Turn the **FREQUENCY** dial on the function generator until the digital display shows approximately 1.000. This indicates that the function generator is generating a signal with a period of approximately 1 second (and therefore, a frequency of approximately 1 Hz).
10. Find the **AMPLITUDE** knob on the function generator. Turn it clockwise as far as you can to select the maximum (MAX) amplitude of 2V peak-to-peak.
11. Verify on your oscilloscope that the output from your function generator is, in fact, a sine wave with an amplitude of 1 volt and a period of 1 second (frequency of 1 Hz). **For safety purposes, please show your output signal to a TA before proceeding to the next step.**

Set Up DC Motor Control Module

12. Connect your function generator to your **MOTOR DRIVE INPUT** panel such that the output from the function generator is the input (V_{IN}) to your motor. Don't forget to connect ground (GND) and **0 V**.
13. Connect the output (V_{OUT}) from the **TACHO GENERATOR OUTPUT** panel of your motor module to Channel 2 of your oscilloscope. Don't forget to connect ground (GND) and **0 V**.
14. Find the **MOTOR DRIVE INPUT** panel on your motor control module. To enable the selected input (V_{IN}) to drive the motor, connect the $\overline{E}$ (**Enable Input)** socket to the **0V** socket.

Record Amplitude of Frequency Response

15. Observe the voltage signals on Channels 1 and 2 of the oscilloscope and write down the amplitude of V_{IN} and V_{OUT}.
16. Press the up **MULTIPLIER** (Δ) button **twice**. The MULTIPLIER indicator (red light) should show 10-1M and the FREQUENCY indicator should show kHz. In this setting, the digital display shows the output frequency in kilohertz.
17. Make sure that by turning the **FREQUENCY** dial (and nothing else) on your function generator, you are able to vary the frequency of V_{IN} from a few Hertz to over 500 Hz. (**The amplitude of your sine wave should remain at 1!**).
18. **To avoid causing damage to the motor bearings, please do not set the frequency at f_{res} for longer than a few seconds**! Using the **FREQUENCY** dial, slowly increase the frequency of V_{IN} from a few Hertz to just over the motor resonant frequency, f_{res}.[9] Pay attention to the oscilloscope display. At frequencies very near f_{res}, your motor will vibrate, placing excessive stress on the motor bearings.
19. Repeat Step 18 above, but this time, observe and write down the amplitude of V_{IN} and V_{OUT} for your Lab Report. Record your observations at enough frequencies that you have enough data to check the accuracy of your frequency response graph.

[9] Typically, this should occur between 200-300 Hz.

20. Turn off your function generator.

Saving Files

Before you leave, remember to save all of your files to **your ECI account** (for later use and backup purposes). For this laboratory, you should save the following files:

`yourname_lab5_ex1.vi`
`yourname_lab5_ex2.vi`
`yourname_lab5_ex3.vi`.

Laboratory Report

1. Provide a printout that shows the front panel and block diagram for **`yourname_lab5_ex2.vi`** and **`yourname_lab5_ex3.vi`**. You may have to print them separately for clarity.
2. For each of the following systems, display the frequency response (front panel) and clearly label and list the low frequency (DC) gain and the high frequency gain. Also label and list cutoff frequencies, if they exist. (a) Low-pass filter, (b) High-pass filter, (c) Band-pass filter (d) DC Motor with 1V white noise stimulus, (e) DC Motor with 2V white noise stimulus, (f) DC Motor with 3V white noise stimulus.
3. Provide circuit diagrams for each analog filter you built during this Lab. Clearly label your resistor and capacitor values. For each of those filters, what are the theoretical cutoff frequencies? (Make sure to list the theoretical nominal cutoff frequency, a theoretical lowerbound and a theoretical upperbound. Hint: How accurate are your resistor values? Explain). What are the measured cutoff frequencies shown by your frequency response graphs (front panel)? Do the measured cutoff frequencies fit within your theoretical bounds?
4. For system (a)-(f) in Question 2, you obtained (measured) values for V_{IN} and V_{OUT}. For each of these systems, provide a separate table that lists V_{IN}, V_{OUT}, and the calculated gain. Plot your measured frequency (gain) responses (on a logarithmic frequency scale and a linear amplitude scale) and compare with your frequency response graphs from Question 2 above.
5. Compare the DC Motor frequency responses you displayed in parts (d)-(f) in Question 4 above. Are they qualitatively similar? Explain. Why are the DC gains differ for different values of the white noise amplitude? (Hint: What is the effect of a dead zone?)
6. What are the maximum and minimum phase values of your frequency response graphs? Explain why those particular values occur. (For example, why can the maximum phase not be, say, 5?).
7. Display the frequency response you obtained in Experiment 2, Step 6. Explain why the phase exhibits discontinuities. Based on your frequency (phase) response, list all

the frequencies at which you could drive your circuit and observe no (zero) phase lag. Does your low-pass filter exhibit "phase linearity"?[10]

8. For Experiment 6, display the frequency response (front panel) and clearly label and list the low frequency (DC) gain and the high frequency (Nyquist) gain. Also label and list all cutoff frequencies and resonant frequencies, if they exist. Compare this frequency response with the frequency response you displayed in part (f) of Question 2. Explain why the two frequency responses are different.

Your Lab Report should clearly state your name, Lab Report number, Lab date, and your laboratory partner's name (if any). Your lab report should be thorough, but concise. You will be graded on quality, not quantity. **Lab Report 5 is due at the beginning of Laboratory 6.**

Additional Reading and Practice

1. ***LabVIEW* User Manual**, **Chapters 14** and **15**, January 1998 Edition. Browse through these chapters to learn more about Smoothing Windows and Spectrum Analysis and Measurement. Available online at www.ni.com/pdf/manuals/320999b.pdf.

[10] Assume equal time displacement of frequency components. See Mechatronics textbook.