DEPARTMENT OF MECHANICAL ENGINEERING
RICE UNIVERSITY

MECH 343: MODELING DYNAMIC SYSTEMS

Laboratory #1: Introduction to Hardware

Location: Ryon B14

Due: Midnight, *one week after lab session*

RESISTORS

Resistors are passive components commonly used in electrical circuits which resist the flow of current across their terminals when a voltage is applied. Resistors can be classified in two different ways: fixed or variable (as displayed below).

Figure 1: Fixed Resistor and Variable Resistor

Fixed resistors are available in carbon, thin film, and wire-wound varieties. The greater the physical size of the resistor, the greater the amount of electrical power it can handle without overheating. Variable resistors (or rheostats) are two-terminal resistors with a sliding contact that allow its resistance to be varied. These can also be used as potentiometers if all three terminals are used instead of two. The values of resistors in Ohms (Ω) are given by a code of colored stripes. The color bands are the only way to tell one resistance from another without having to physically measure the resistance of the resistor. Most resistors have four bands of various colors.

1^{st} Band	First digit of Ohmic value
2^{nd} Band	Second digit of Ohmic value
3^{rd} Band	Multiplier (power of 10) of the first two digits
4^{th} Band	Tolerance of the resistor (percentage)

The colors are to be read from the edge they are the nearest to (which is always opposite of the tolerance band). The tolerance of a resistor is the precision of the resistor (or maximum difference between its actual value and expected value) and is given as a ± percentage. Tolerance values are identified by the colors brown, red, gold, silver, or the absence of a tolerance band.

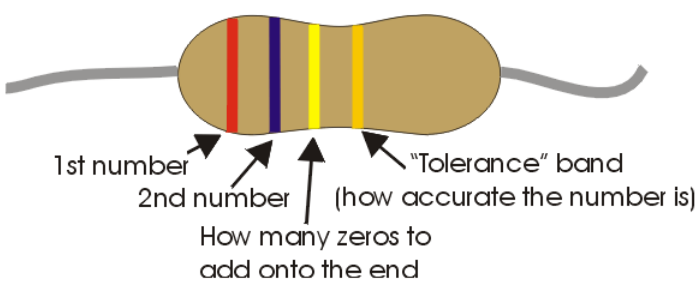


Figure 2: How to read a resistor

Color	Significant Digit	Multiplier	Tolerance
Black	0	10^0	-
Brown	1	10^1	±1%
Red	2	10^2	±2%
Orange	3	10^3	-
Yellow	4	10^4	-
Green	5	10^5	-
Blue	6	10^6	-
Violet	7	10^7	-
Gray	8	10^8	-
White	9	-	-
Gold	-	-	±5%
Silver	-	-	±10%
None	-	-	±20%

CAPACITORS

A capacitor is a two-terminal electrical component used to store energy in an electric field. Capacitors can range in value from pF (10^{-12} F) to µF (10^{-6} F). Below are symbolic representations of different capacitors:

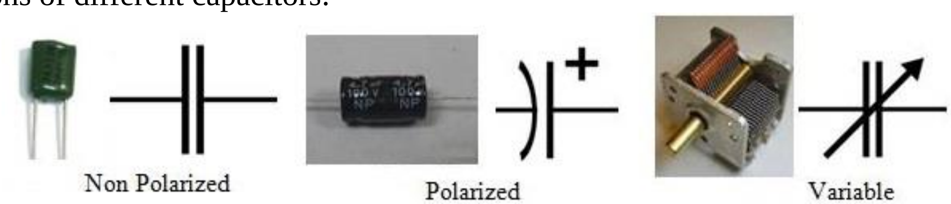


Figure 3: Sample Capacitors

Non-polarized capacitors are usually small disc capacitors that can be put into a circuit without regard to which terminal goes to + or -. Polarized capacitors have both + and – terminals and must be connected with + to + and – to -. Polarized capacitors are typically electrolytic capacitors, which resemble small cans with two terminals. The polarities of these capacitors will be marked on the sides of the "can" with either ± or P/N labels. Variable capacitors are capacitors with a capacitance value that can be changed. They have a series of parallel metal plates, one set of which can be rotated away from the other. An example of a variable capacitor is the trimmer capacitor, in which loosening or tightening a pressure screw changes the capacitance. Reading capacitor values is similar to reading those of a resistor. Large capacitors will usually have their capacitance value fully printed on them. Smaller disk type capacitors, however, often have 3 numbers and a letter to represent their capacitance value and tolerance percentage.

1^{st} Number	First significant digit
2^{nd} Number	Second significant digit of value
3^{rd} Number	Multiplier (power of 10) by which the first two digits are to be multiplied
Letter Symbol	Tolerance of the resistor

Below are two tables that (i) match the third digit to its corresponding multiplier value and (ii) match the letter symbols with their corresponding tolerance. ***NOTE that the resulting values are in units of pF (pico-Farads).***

Third Digit	Multiplier
0	1
1	10
2	100
3	1,000
4	10,000
5	100,000
6	-
7	-
8	.01
9	.1

Letter Symbol	Tolerance %
B	± 0.10%
C	±0.25%
D	±0.5%
E	±0.5%
F	±1%
G	±2%
H	±3%
J	±5%
K	±10%
M	±20%
N	±0.05%
P	+100%, -0%
Z	+80%, -20%

MULTIMETERS

A multimeter is an electronic measuring instrument that is capable of measuring voltage, current, resistance and capacitance. Analog multimeters typically use a galvanometer needle display but often have precision and reading accuracy limitations. Digital multimeters (DMM or DVOM) display the quantity measured as a number which eliminates parallax errors. To run a test to measure voltage, you connect the red lead to the positive side of the battery or component that you are testing and the black lead to the negative (ground) side and set the dial to the voltage range you are expecting. If you reverse which ends you measure the sign of the voltage will be reversed. When using a multimeter to measure current, you must break into the circuit so that the current passes through the meter as shown below.

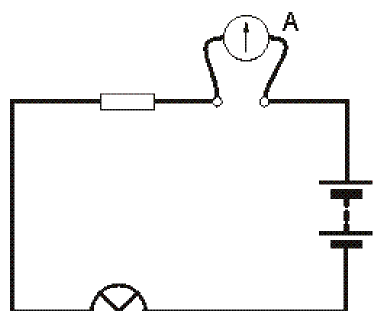


Figure 4: Sample multimeter and current measurement configuration

To measure current with a multimeter, first insert the leads to the circuit in which the current is being measured and then set the multimeter switch to the correct current range you are expecting. When selecting the range, it is important to make sure that the maximum range is above the expected reading anticipated because an improper selection may overload the meter. Although it is possible to read a resistor's resistance value by analyzing its color band, it is often easier to use a multimeter. To measure a resistor, make sure to clip the multimeter leads onto the resistor leads and dial the multimeter to the resistance range you believe the resistor fits in. If your multimeter reads 1 or 0, you have most likely guessed an incorrect resistance range and should move the dial to the next range up or down (respectively). If you happened to be on the lowest range of resistance on the multimeter and your read is still 0, your resistor has zero resistance.

<u>Please Note:</u> A common error when operating a multimeter is to set the meter to measure resistance or current and then connect it directly to a voltage source. Unfused, and even some fused, meters are ruined by such mistakes. It is important to always have the multimeter on the highest setting and disconnect it from the circuit before switching from one measurement to another.

Fig. 5: How to measure DC amperage (left) and DC voltage (right). Note in particular the connection of the leads (wires) and the dial setting.

BREADBOARDS

A breadboard is a construction base for prototyping of electronics specifically temporary circuit construction. It is formally considered to be a "solderless" breadboard because it does not require soldering to assemble and is reusable. The electrical connection between components is provided by an internal arrangement of electrical pathways. A breadboard, as shown below, can be divided into three parts: power buss strips, terminal strips, and dividing notch which is a channel that separates the two groups of holes and is designed to accommodate a dual inline package style chip.

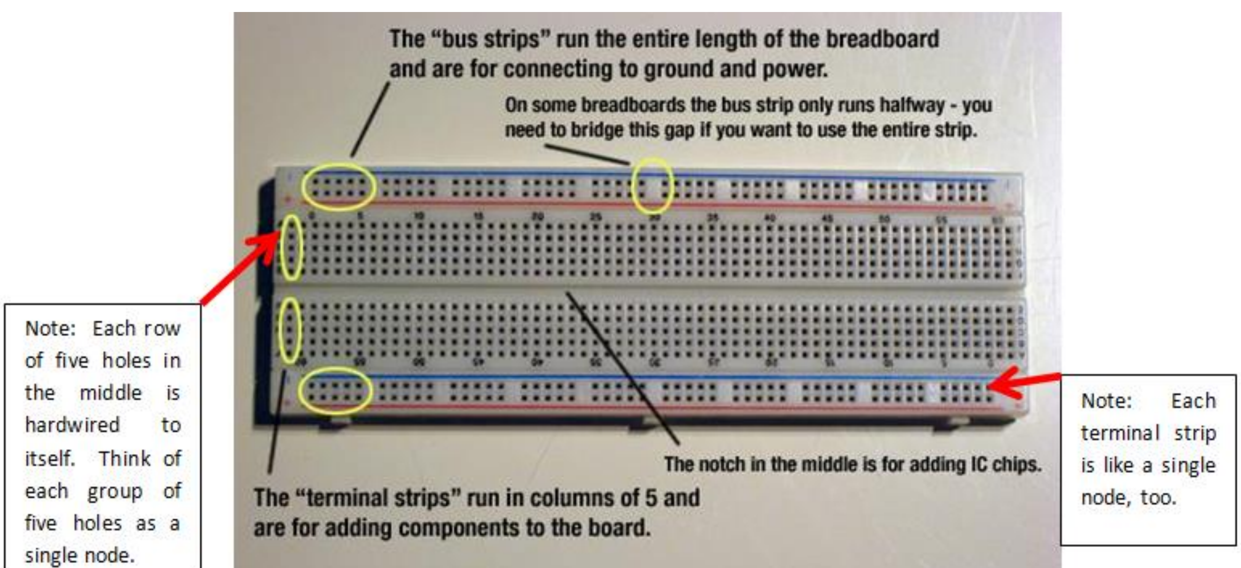


Figure 6: Breadboard basic operation

Power buss strips run the length of the breadboard and are electrically connected. These strips have red and blue lines on the sides of them and are typically used for power and ground connections. They are used to distribute a voltage or ground throughout the breadboard and are divided into two rows or holes (each row further divided into two groups of 25 holes). The 25 holes share an internal electrical connection. Any wire inserted into any of the 25 holes will share the same electrical connection.

The terminal strips consist of horizontal holes (5 columns) on each side of the breadboard. Anything plugged into any of the five holes in a single terminal strip will be electrically connected. It is important to note that one set of 5-column terminal strips on one side of the breadboard does not electrically connect to the terminal strips on the other side.

CIRCUITS

In this class you will be working with circuits, which are electrical networks that contain a closed loop giving a return path for the current. Finding voltages across components and currents running through them in an electrical circuit is considered to be circuit analysis. For our labs you will need to familiarize yourself with RC, RLC, and by association LC circuits.

Resistor-capacitor (RC) circuits consist of resistors and capacitors driven by either a voltage or current source. Resistor-inductor-capacitor (RLC) circuits consist of resistors, inductors, and capacitors. And as the name suggests LC circuits consist of solely inductors and capacitors. The circuits provide a good base for analyzing fundamental behaviors of analog electronics. Further explanation on how components of these circuits can be connected is explained below.

When components of a circuit are connected in series, the same current flows through all of the components since everything is in a single path. To connect components of a circuit in series on a breadboard make sure that only one leg of a component is in a terminal strip common to only one other component to ensure the current can only take a single path. An example is displayed below:

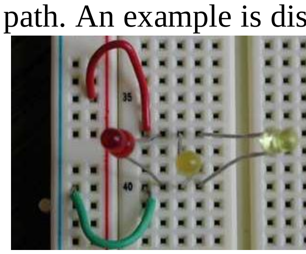


Figure 7: Two Resistors connected in series (left) and 3 LEDs connected in parallel (right)

When components of a circuit are connected in parallel, they will have the same potential difference (voltage) across them. This means that every component we want to be in parallel should have one leg in a specific terminal strip and the other leg in the other specific terminal strip. An example is shown above.

Circuit diagrams or electronic schematics are often used to provide a simplified conventional graphical representation of an electrical circuit. These diagrams are identifiable by their simplified standard symbols used for the components of the circuit. Below are two examples of a schematic diagram matched with its corresponding circuit on a breadboard:

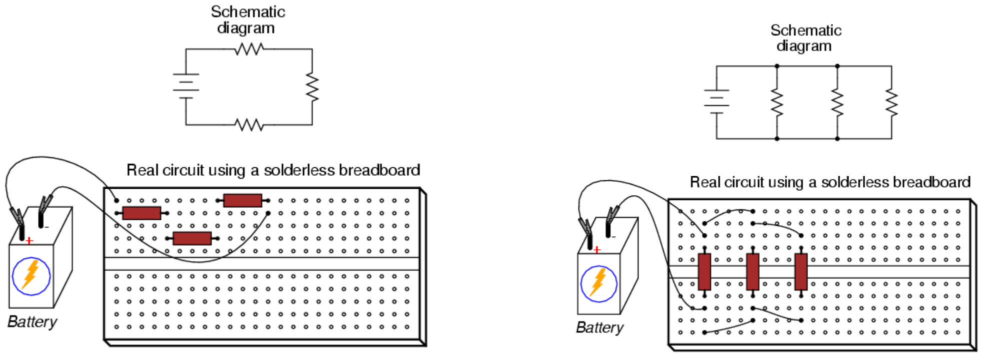


Figure 8: Three-Resistor Series Circuit (left) and 3-Resistor Parallel Circuit (right)

NI MYDAQ


Figure 9: NI myDAQ (left)

The NI myDAQ is a portable data acquisition (DAQ) device that uses LabVIEW software instruments, allowing students to analyze and process acquired signals and control simple processes. The myDAQ provides analog input (AI), analog output (AO), digital input and output (DIO), audio input and output, DC power supplies, and most importantly for this lab digital multimeter (DMM) functions in a compact USB device. DAQ range is usually ± 10 V, so any voltages in circuits outside this range will be saturated at ± 10 V. Using the analog input/output channels on the myDAQ follows the same procedure as that for the myRIO, and is discussed in the following section. To use the myDAQ as a DMM with a computer:

1. Connect the myDAQ to your computer using the USB cable that came with the device
2. A blue LED light should appear near the USB connection on the myDAQ when the connection is established, indicating the myDAQ has power.
3. Next you should start the NI ELVISmx Instrument Launcher by going to the Windows Start menu and selecting Programs → National Instruments → NI ELVISmx for NI ELVIS & NI myDAQ →NI ELVISmx Instrument Launcher (or, use the shortcut on the desktop).
4. The panel below should appear, showing the currently available instruments:

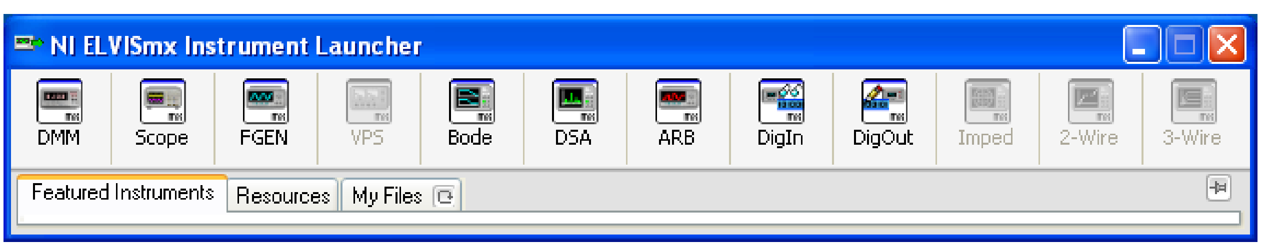


Figure 10: NI ELVISmx Instrument Launcher Panel

In this lab you will be using the NI myDAQ digital multimeter (DMM) to measure voltage, current, and resistance. Launch the DMM by clicking the DMM button from the Instrument Launcher Panel. A soft front panel for the DMM should appear:

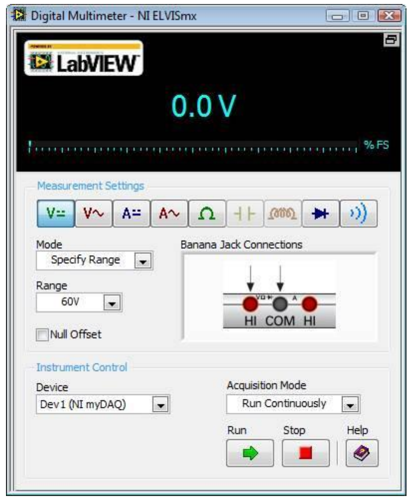


Figure 11: Panel for Digital Multimeter

Measuring Voltage with myDAQ

Measuring AC or DC voltage with the NI myDAQ DMM is available only through the banana jacks and can be done as follows:

1. For AC and DC voltage measurements, connect the VΩ (red) and COM (black) connectors on the bottom side of NI myDAQ to red banana jack and black banana jack, respectively.
2. The DMM is set in measuring DC Voltage mode when launched. Select the V-- or V~ button on the front panel of the DMM, depending on the signal to be measured, and the measurement type changes to show the value of the signal. Auto scaling should work best for most applications. If you want to specify the range, please start from the largest range and decrease the range according the measure result in order to protect the device from overdriven damage.
3. Use the probes to contact the corresponding signal leads. Remember that voltage is measured in PARALLEL to the device in question
4. 4. Now you have finished all the necessary setting and connections for voltage measurement. Press the Run or Stop button from the soft front panel. Selecting the Run button provides continuous measurements of voltage. Selecting the FStop button stops the measurement and displays the instantaneous value of the voltage just before stopping the measurement.
5. Measuring DC voltage gives you the actual DC voltage, while measuring AC voltage gives you the RMS (root mean square) value of the AC voltage you are measuring.

Measuring Current with myDAQ

Measuring AC or DC current with the NI myDAQ DMM is available only through the banana jacks and can be done as follows:

1. For AC and DC current measurements, connect the A (red) and COM (black) connectors on the bottom side of NI myDAQ to red banana jack and black banana jack, respectively.

2. The DMM is set in measuring DC Voltage mode when launched. Select the A-- or A~ button on the front panel of the DMM, depending on the signal to be measured, and the measurement type changes to show the value of the signal. Auto scaling should work best for most applications. If you want to specify the range, please start from the largest range and decrease the range according the measure result in order to protect the device from overdriven damage.
3. Use the probes to contact the corresponding signal leads. Remember that current is measured in SERIES with the device in question.
4. Now you have finished all the necessary setting and connections for current measurement. Press the Run or Stop button from the soft front panel. Selecting the Run button provides continuous measurements of current. Selecting the Stop button stops the measurement and displays the instantaneous value of the current just before stopping the measurement.
5. Measuring DC current gives you the actual DC current, while measuring AC current gives you the RMS value of the AC current you are measuring.

Measuring Resistance with myDAQ

Measuring the resistance with the NI myDAQ DMM is available only through the banana jacks and can be done as follows:

1. For the resistance measurements, VΩ (red) and COM (black) connectors on the bottom side of NI myDAQ to red banana jack and black banana jack, respectively.
2. The DMM is set in measuring DC Voltage mode when launched. Select the Ω button on the front panel of the DMM to measure the resistance. Auto scaling should work best for most applications. If you want to specify the range, please start from the largest range and decrease the range according the measure result in order to protect the device from overdriven damage.
3. Use the probes to contact the resistor leads. Remember that the resistance is measured in Parallel with the device in question. The resistor in measurement should be disconnected from the circuit it is placed in, and otherwise the reading will not be correct.
4. Now you have finished all the necessary setting and connections for resistance measurement. Press the Run or Stop button from the soft front panel. Selecting the Run button provides continuous measurements of current. Selecting the Stop button stops the measurement and displays the instantaneous value of the resistance just before stopping the measurement

NI MYRIO

Figure 12: NI myRIO

The NI myRIO is a portable data acquisition (DAQ) device that includes computational hardware called a Field-Programmable Gate Array (FPGA) to perform real-time computation. The myRIO can deploy LabVIEW VI’s downloaded via USB or WiFi connection. The myRIO has analog input (AI), analog output (AO), digital input and output (DIO), audio input and output, DC power supplies, and unlike the myDAQ, has control loop rates in the kHz range. Voltage output from the myRIO, like the myDAQ, range is usually ± 10 V, so any voltages in circuits outside this range will be saturated at ± 10 V. Using the analog input/output channels on the myRIO follows the same procedure as that for the myDAQ, and is discussed in the following section.

<u>Measuring signals with the myRIO</u>
As with the myDAQ, the analog input/output channels are accessed via the Mini System Port (MSP) screw terminal connector, seen on the right side of the myRIO in Fig. 11. In order to read a signal using these terminals, secure both the + and – channels, since the myDAQ and myRIO measure the voltage difference between the terminals (just like a DMM measures the voltage between the red and black leads). Using the small screwdriver provided to you, securely fasten bare ends of the wire to the terminal.

POWERED BREADBOARD
There are a few ways of powering a normal breadboard. The breadboards at your lab station are similar to the one pictured in Fig. 13, in that they have a built in power supply, and can be powered using strategies similar to that shown in Fig. 14. However, if a breadboard does not have this same configuration, it could be valuable to use the NI myDAQ as a power supply. To do this, connect a jumper wire from +15, -15 or +5 MSP screw terminal on NI myDAQ to a bus strip on the breadboard, creating +15V, -15, or +5 (respectively) power rail in your breadboard, and then connect the wire from AGND (Analog Ground) screw terminal on NI myDAQ to another bus strip, creating the ground rail in your breadboard. Connect NI myDAQ to your computer through the USB cable to power it up. When the blue LED lights up, the power supply should be running.

Figure 13: Powered solderless breadboard

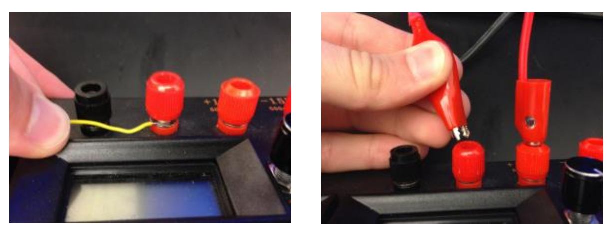
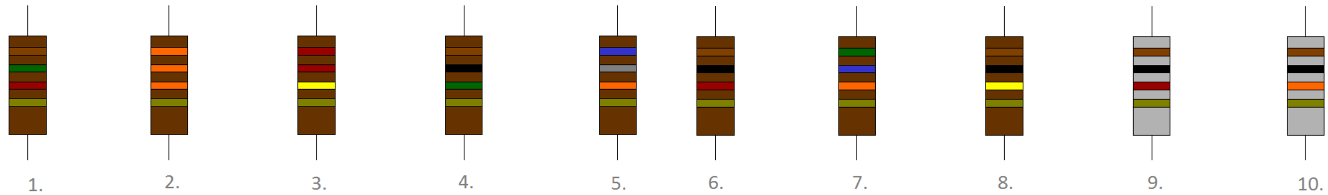


Figure 14: Common strategies to power bus strips

Figure 15: Jumper Wires

PRE-LAB ASSIGNMENT

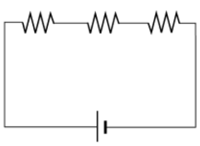
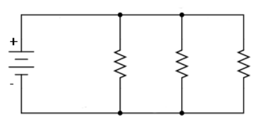
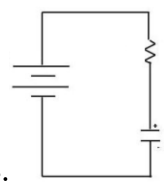
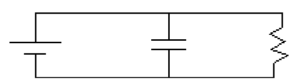
1. Identify the resistance values of the following resistors.
   Do not forget to include units and tolerance values.
   Also, if you would like to simplify, you are encouraged to do so (e.g. 100,000 Ω = 100 kΩ)

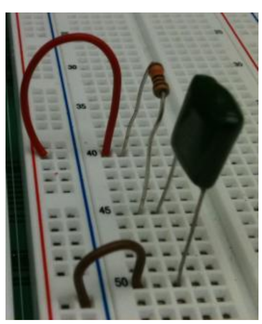
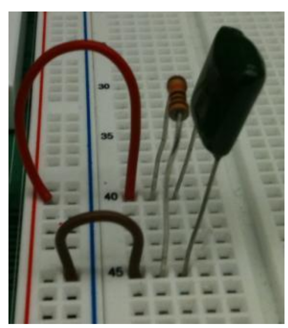
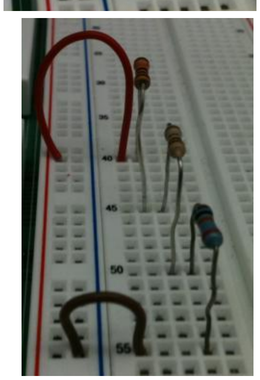
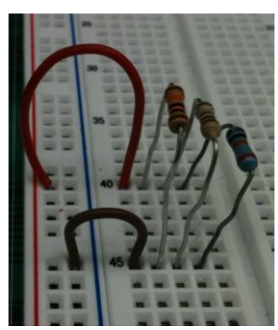


2. Identify the capacitance values of capacitors with the following labels:

a. 101	d. 104F
b. 104M	e. 225K
c. 472J	f. 154

3. Match the follow schematic diagrams and breadboard circuit pictures

1. 
2. 
3. 
4. 

A. 
B. 
C. 
D. 

Necessary Equipment for Lab

- 10 Ω Resistors (1)
- 100 Ω resistor (1)
- 150 Ω resistor (2)
- Green LED (4)

Note: Equipment can be found in the bins on the wall to the right of the entrance

Lab Procedure

Part 1: Reviewing Series vs. Parallel Circuits with LEDs

a. Turn the power supply on and set the +15 terminal to 4 V (± 0.1 V) then turn off the power supply.
b. Power the + terminal of the power supply to the + bus strip on your board and connect the ground terminal of the power supply to the – bus strip on your board. Do not turn on the power supply yet (be sure to use the +15V terminal, this is the one you just set to +4V).
c. Place one end of the 150 Ω resistor on the + power rail and then the other on any terminal strip. Do this for the second 150 Ω resistor but connect it to a different strip.
d. Connect two of the LEDs in series with the 150 Ω resistors, and the other two LEDs in parallel with the second resistor and connect the ends of the LEDs to ground through jumper cables (you should have two separate circuits, see Fig. 14). When placing the LEDs in the circuit take note that one pin is longer than the other, place the longer leg on the + side of the supply. If the LEDs don't turn on when you turn on the power in step f you may have the LED reversed.

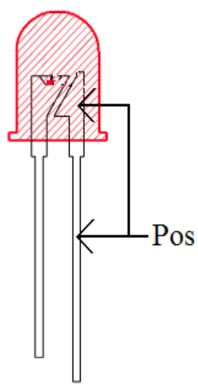


Figure 13: LED lead identification

e. Before turning on the power supply, check with a TA to see you have set up the circuits correctly.
f. Turn on the power supply and **take note of the brightness of the LEDs** in series compared to those in parallel.
g. OPTIONAL: If you're curious vary the power supply from 0 - 10 V and observe the changes in brightness of the LEDs. Don't leave the LEDs on 10 V for too long or they might burn up! When you are done change the power supply back to 4 V and turn it off.
h. Disconnect your LEDs and 150 Ω resistors from the circuit and place them back in the bin where you found them.

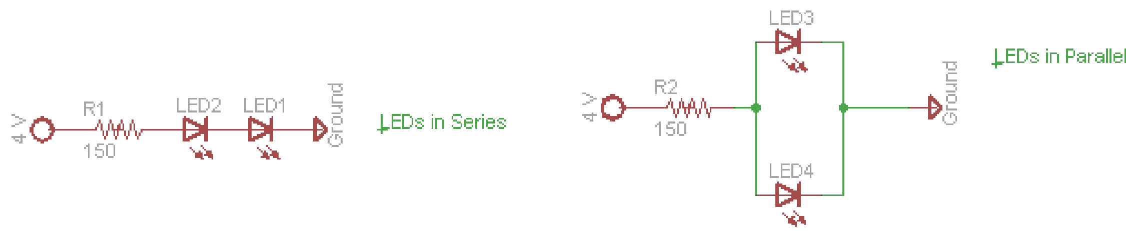


Figure 14: Series and Parallel LED circuits

Part 2: Comparing Observed Multimeter Values with Expected Values

a. Create a circuit with a10 Ω and 100 Ω resistor in series (make sure power supply is off but set at 4 V).
b. Make sure the power supply is off and measure the resistance of each resistor using the Fluke multimeter and record it.
c. Turn **on** the power supply and **Measure and record** the voltage drop across each resistor.
d. Now add the Fluke into the circuit by connecting it in series with the resistor .
e. **Measure and record** the current through the resistors (make sure to have the MM plugs in the right slots). Check with a TA first if you are unsure if you have the MM plugged in to the circuit correctly.
f. Repeat steps b, c, and e with the NI ElvisMX LabVIEW digital multimeter, described previously in this lab handout. Find NI ELVISmx Instrument Launcher by going to the Windows Start menu and selecting Programs → National Instruments → NI ELVISmx for NI ELVIS & NI myDAQ →NI ELVISmx Instrument Launcher or using the shortcut on your desktop. **Record your results.**

<u>Results to Report</u>

1. As seen in Part 1, explain the physics behind the change in brightness of the LEDs between those connected in series and those connected in parallel (this should be done with words based on mathematical reasoning).
2. What resistance did you measure for the 10 Ω and 100 Ω resistors using the Fluke and LabVIEW digital multimeters? Was it different than expected? Explain.
3. Calculate the theoretical voltage drop across the 10 Ω and 100 Ω resistors when in series with the 4 V power supply. Compare this to what you measured with the Fluke and LabVIEW digital multimeters.
4. Calculate the theoretical current through the circuit in Part 2 with the 4 V power supply. Compare this to what you measured with the Fluke and LabVIEW digital multimeters.

REFERENCES

1. mil.ufl.edu/3111/docs/myDAQ/Intro_myDAQ.pdf
2. http://www.ianjuby.org/readres.html
3. http://www.4crawler.com/Diesel/CheapTricks/Tachometer/Capacitor.html
4. www.wisc-online/objects/ViewObjects.aspx?ID=eng701

DEPARTMENT OF MECHANICAL ENGINEERING
RICE UNIVERSITY

MECH 343: MODELING DYNAMIC SYSTEMS

Laboratory #2 Parameter Identification: Inertia, Torque Constant, and Sensor Calibration

Location: Ryon B14

Due: Midnight, *one week after lab session*

Additional documentation available on course website:
Honeywell Hall-Effect Sensor Data Sheet
Pittman 9434 15.1V Specs
Pittman 9000 Series Motor Data Sheet

THE HAPTIC PADDLE

The Haptic Paddle is a low cost, single degree-of-freedom force feedback joystick capable of providing a peak force of about 6N at its handle. It is an ideal tool for the demonstration of electromechanical system properties and concepts covered in undergraduate engineering courses like MECH 343. In the next five lab exercises, you will investigate system components so that you can better understand your interaction with the complete system in the final exercise, in which you'll experience virtual environments and remote teleoperation with the haptic paddle.

WHY HAPTICS?

"Haptics" can be loosely defined as placing tactile (related to the sense of touch) feedback into a system. Some of you might be familiar with some haptic products, such as "force feedback" video game controllers, starting with the Rumble Pak [5] in the '97 release of *Star Fox*, or perhaps the da Vinci surgical robot [4]. So, even though the single degree-of-freedom paddle used in this lab is simpler than some of these devices, the technology is similar. Even some of Dr. O'Malley's research is in this field. If you have any questions, or want to find out more, your lab TA's will be happy to chat with you about their research; after all, it's why they're here.

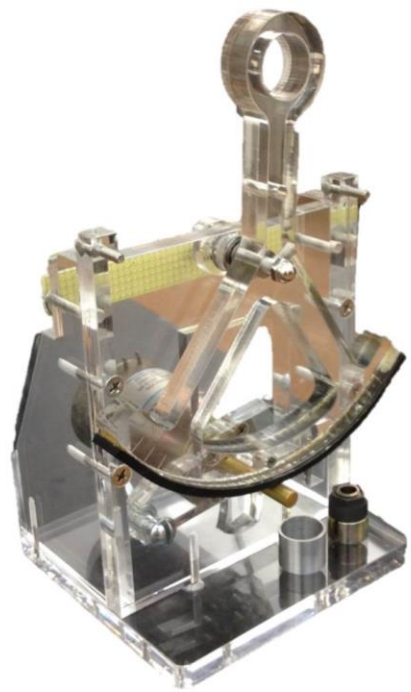


Figure 1: Haptic Paddle

INVESTIGATION OF THE HAPTIC PADDLE SYSTEM

In Part I of this lab exercise, you will characterize the rotational inertia of the paddle handle component through the use of a bifilar pendulum. In Part II of this lab exercise, you will learn how to calibrate the system's position sensor. An Honeywell ratiometric linear Hall-effect sensor, which outputs a voltage proportional to an applied magnetic field, and a permanent magnet are used to determine the paddle's angular position. You will notice during the exercise that the magnet has a cylindrical shape. Its poles go from North to South along the cylindrical axis. Why use the Hall-effect sensor, you ask? Well, in addition to being a cheaper alternative to an encoder, the Hall-effect sensor is widely used in applications ranging from commutation duties in many brushless DC motors [7], to the throttle "blipping" (rev matching for down-shifts) in the C-7 Corvette [3], and even in some of the research in Dr. O'Malley's Lab [6]!

A BIFILAR PENDULUM

A bifilar pendulum consists of a mass that is suspended by two vertical strings as seen in Fig. 1. The strings have equal length h and are attached to the hanging mass at a distance $D/2$ from the center of mass. The parameter r_{cm} is the distance from the center of mass to the pivot point of the Paddle component. For sufficiently small angular deflections about the axis through the center of mass, the system can be modeled as the second order system:

$$J_{cm}\ddot{\theta} + K_{BP}\theta = 0 \tag{1}$$

where J_{cm} is the inertia about the center of mass and K_{BP} is the equivalent spring constant due to the force of gravity and system parameters. The damping of the system is negligible and therefore ignored. By observing the natural frequency of the system, it is possible to determine J_{cm} for the suspended mass.

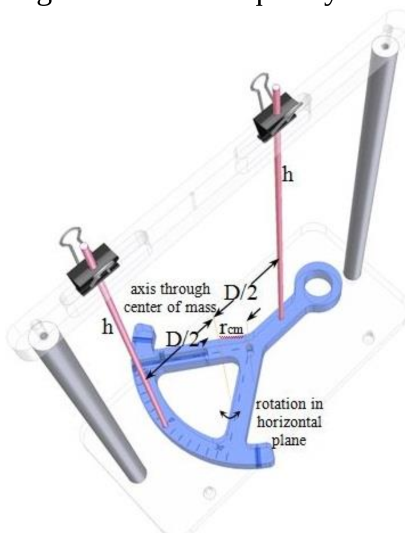


Figure 2. A bifilar pendulum with the Paddle component as the hanging mass.

WORKSPACE AND SENSOR CALIBRATION

In part II of this lab exercise, you will linearize a sensor output throughout the paddle's workspace in order to determine angular position. A robot's workspace is the space in which it is capable of moving its end effector. In order to move properly, the robot must know where it is within its workspace. Sensors send signals to the robot's control system, providing information related to the robot's position. As stated earlier, a Hall-effect sensor and magnet are used to sense the haptic paddle's position. This sensor outputs a voltage in the range of 0-5 volts which varies linearly with the strength of the magnetic field applied perpendicularly to the sensor by the magnet. In order to take full advantage of the analog to digital resolution of the DAQ, the sensor output is input to a signal conditioning circuit (SCC) that uses a series of op-amp stages to linearly amplify the 0-5 volt signal to a ±10 volt signal. This will be explained in more detail in Lab 3: Op-Amps in Electrical Systems. The linear relationship between the amplified signal and the strength of the perpendicularly applied magnetic field must be determined in order for the haptic paddle control software to properly know the angular position of the Paddle component.

THE HAPTIC PADDLE ACTUATOR: BASICS OF A DC MOTOR

In part III of this lab exercise, you will characterize parameters of the Haptic Paddle actuator. Specifically, you will characterize the actuator's torque constant. A Pittman LO-COG® 9434 15.1V DC motor provides actuation for the Haptic Paddle system. DC Motors are one of the most widely used actuators in industry. A DC motor is effectively a torque transducer that converts electric energy into mechanical energy. In electrical circuits, DC motors are often modeled as a voltage source and a resistance in series as shown in Fig 3. The electromechanical component of the motor that is modeled by this voltage source and resistance is known as the armature. Current that flows through the armature from the positive to negative lead will generate a torque on the motor rotor that acts in the positive direction of rotor spin, and vice versa for current that flows from the negative to positive lead. This torque is expressed as

$$T = K_t i_{arm} \tag{2}$$

where T is the motor torque (Nm), K_t is the torque constant of the motor (Nm/A), and i_{arm} is the armature current (amperes). K_t is sometimes listed as K_i in motor data sheets.

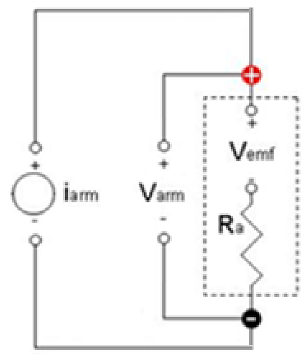


Figure 3: DC motor circuit schematic

TRANSMISSION OF MOTOR POWER TO END EFFECTOR

Robotic machines, such as haptic devices, often use transmissions to transmit power from their actuators to their end effectors. An end effector is a part of the robot that interacts with its surrounding environment or a user. The Haptic Paddle employs a friction drive to transmit the power of its actuator to affect a force at the paddle handle. The friction drive effectively acts as a gear transmission to impart a torque on the Paddle component about its pivot point. This torque is then levered about the pivot point to produce the output force at the handle.

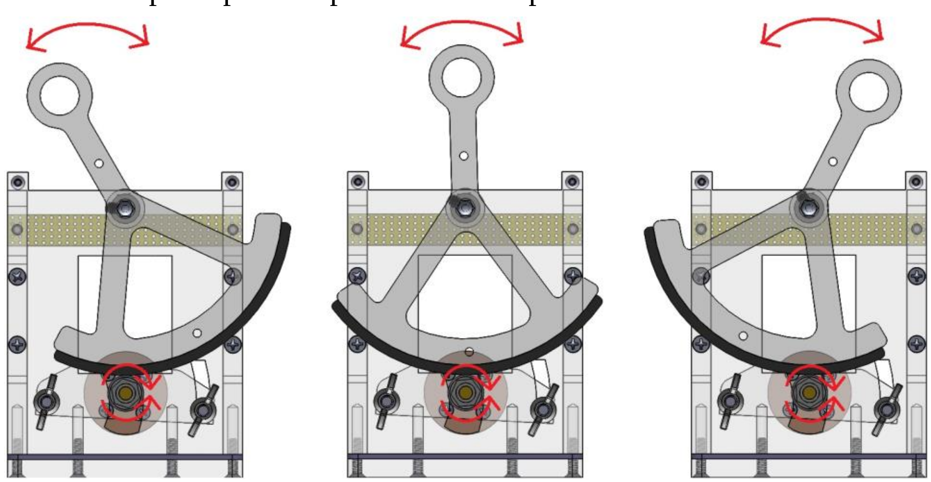


Figure 4: Haptic Paddle degree of freedom

Basic Implementation Hardware: Power Supplies and Amplifiers

The myDAQ is capable of outputting a voltage signal to be used as a control signal, but does not have the power to drive a motor. Remember, $Power = Flow \cdot Effort$, and the myDAQ's power limits of 500 mW are not enough to drive this particular motor. Therefore, we will be using a servo amplifier (sometimes referred to as simply the "amp"), shown below, and power supply to accomplish this task. Since the tasks for creating the motor signal and powering the motor are often accomplished with different hardware, it is convenient many times to consider each system belonging to either the "signal domain" (Hall effect sensor, myDAQ/myRIO, and LabVIEW) or the "power domain" (servoamplifier, power supply, and motor).

Figure 5: Servoamplifier (left) and lab station servoamplifier + Power supply

The amplifier at your lab station, the AMC 12A8M Linear Servoamplifier converts a voltage command signal into a current output with a specified gain (the amps here are set to a gain of 1.4 A/V). If you have more questions about the servoamplifier, please ask your TA. The thick red and black wires leading from the +/- MOTOR outputs on the amp will be referred to as the motor amplifier leads. Also note the thinner wires leading to the +/- REF IN ports on the amp. These are the inputs that the amp uses to control its output.

Basic Implementation Software: LabVIEW

The above implementation hardware needs a control signal, and this can be generated in a multitude of ways. LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming language, like Mathworks' Simulink, that is useful for such tasks [8]. Further practice and assignments will be assigned in LabVIEW, but for now, it will suffice for you to believe us that LabVIEW is able to read sensor signals, perform some basic computations, and output a control command.

Experimental Systems and Equipment

- Bifilar Pendulum with paddle handle as hanging mass
- Hall-Effect Sensor with magnet
- Ruler
- NI myDAQ
- C-clamp
- Mass attachments

PRE LAB ASSIGNMENT

Part I

1. With the respect to the system depicted in Fig. 2, derive an expression for the equivalent spring constant K_{BP} in terms of the parameters m_p (the mass of the Paddle component), g, D, and h. Assume that the vertical motion of the Paddle component is negligible (assume that the paddle rotates in the plane pictured in Fig. 2). Hint: when you rotate the Paddle about the axis through its center of mass, you can draw a pair of right triangles relating the current positions of the string and the length $D/2$ to their respective equilibrium positions. Note that these two triangles have a common leg. **Result: $K_{BP} = m_p g D^2/(4h)$**
2. Use the previous result to derive an expression for J_{cm} in terms of the same parameters and the natural frequency ω_n.
3. Use the previous result to derive an expression for the moment of inertia J_p about the axis through the Paddle's pivot point.

Part II

4. Determine the limits of the small angle approximation. Create a table comparing the actual trigonometric values of small angles to the appropriate small angle approximation, along with the error associated with the approximation, from $0° - 45°$.

Part III

5. Draw the free body diagram of the Friction Drive-Paddle coupling shown in Fig. 10 (a different configuration than Part I) considering only moments about the pivot point and the following variables and parameters (variables and parameters not included are considered negligible):
   - F_w, the weight of the mass attached at the Paddle handle
   - T_m, the motor torque generated
   - r_{fd}, the radius of the friction drive drum (aluminum cover of trantorque)
   - r_{sp}, the radius of the Paddle sector pulley (sector pulley is the part of the transmission covered in neoprene; center of sector pulley is Paddle pivot point)
   - l_x, the distance from the Paddle pivot point to the center of hole in the handle
6. What is the relationship N describing the effective gear ratio of the transmitted motor torque via the friction drive to the paddle handle ($motor\ torque\ x\ N = handle\ torque$)? Assume no slipping between the paddle and the friction drive drum.
7. Under static conditions where the friction drive, Paddle pivot point, and handle are all at the same height (as shown in Fig. 10), derive the equation for T_m in terms of the other parameters and variables listed.

LAB PROCEDURES

Part I: Characterizing the Rotational Inertia of the Paddle Component

a) Place a piece of masking tape on the paddle handle such that it goes from the handle, over the pivot point, and to the bottom of the sector pulley. See Fig. 2 as a reference.
b) Balance the paddle handle on the bar of the bifilar pendulum to determine the approximate center of mass. Then mark two points, each at an equal distance (*D/2*) from the center of mass, at which you will hang the paddle handle. Record the distance *D*. Record the distance r_{cm} from the center of mass to the pivot point. The mass of the Paddle is **70 grams**.
c) Tape the string to the paddle handle at the marked points and use binder clips to adjust the length and position of the strings. The strings should be equal in length and hanging

vertically. The paddle handle should be flat in the horizontal plane. Measure the length *h* of the strings from the binder clips to the top of the paddle handle.

d) Deflect the paddle handle to an initial angular displacement about its center of mass (less than 30° so that the small angle approximation holds) and let it go to allow it to swing freely. Record the time it takes to make 20 oscillations. Repeat this twice more.

e) Remove your paddle handle from the string and discard the used tape. Disassemble and store away the bifilar pendulum experimental set up.

Part II: Position Sensor Calibration

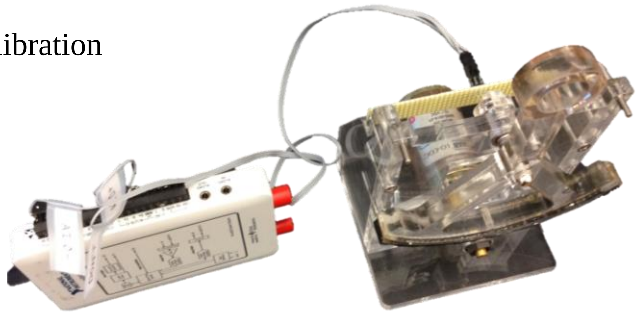
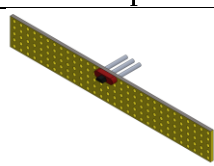
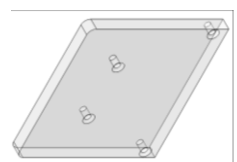
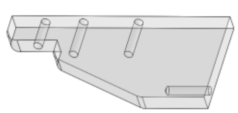
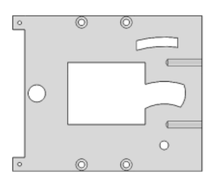
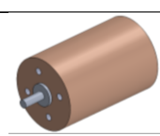
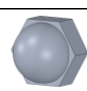
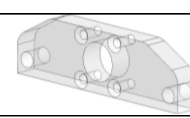
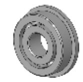
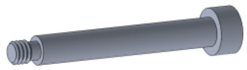
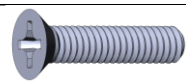
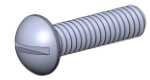
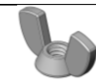


Figure 6: Experimental Set-up for Part II

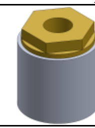
This part of the lab will require you to assemble the Haptic Paddle in order to complete your lab. For the first of many times, do not over-tighten screws. “Finger tight” will be acceptable.

a) Unpack the Haptic Paddle Kit at your lab station. You should have the components shown in the tables below in your kit and at your station. If for some reason you are missing components, please contact your TA.

Part Name	Picture/Description	Part Name	Picture/Description
Hall Effect Sensor		Base	
Side Support (x2)		Front Plate	
Pittman DC motor w/motor shaft		Paddle Handle w/ 8-32 set screw	
Acorn Nut		Motor Support	

Washer (x16)		Flanged Bearing (x2)	
Shoulder Screw		6-32 screw (x2) (for hard stops)	
Magnet cap + magnet		8-32 screw (x8)	
6-32 motor screw (x4)		¼-20 machine screw (x2)	
Motor Leads		Wingnut (x2)	

b) Each station will be equipped with the following equipment which is to REMAIN there:

Part Name	Picture/Description	Part Name	Picture/Description
Ribbon Cables for Hall Effect Sensor		Trantorque + slip cover	
Allen Wrench		Screwdriver	

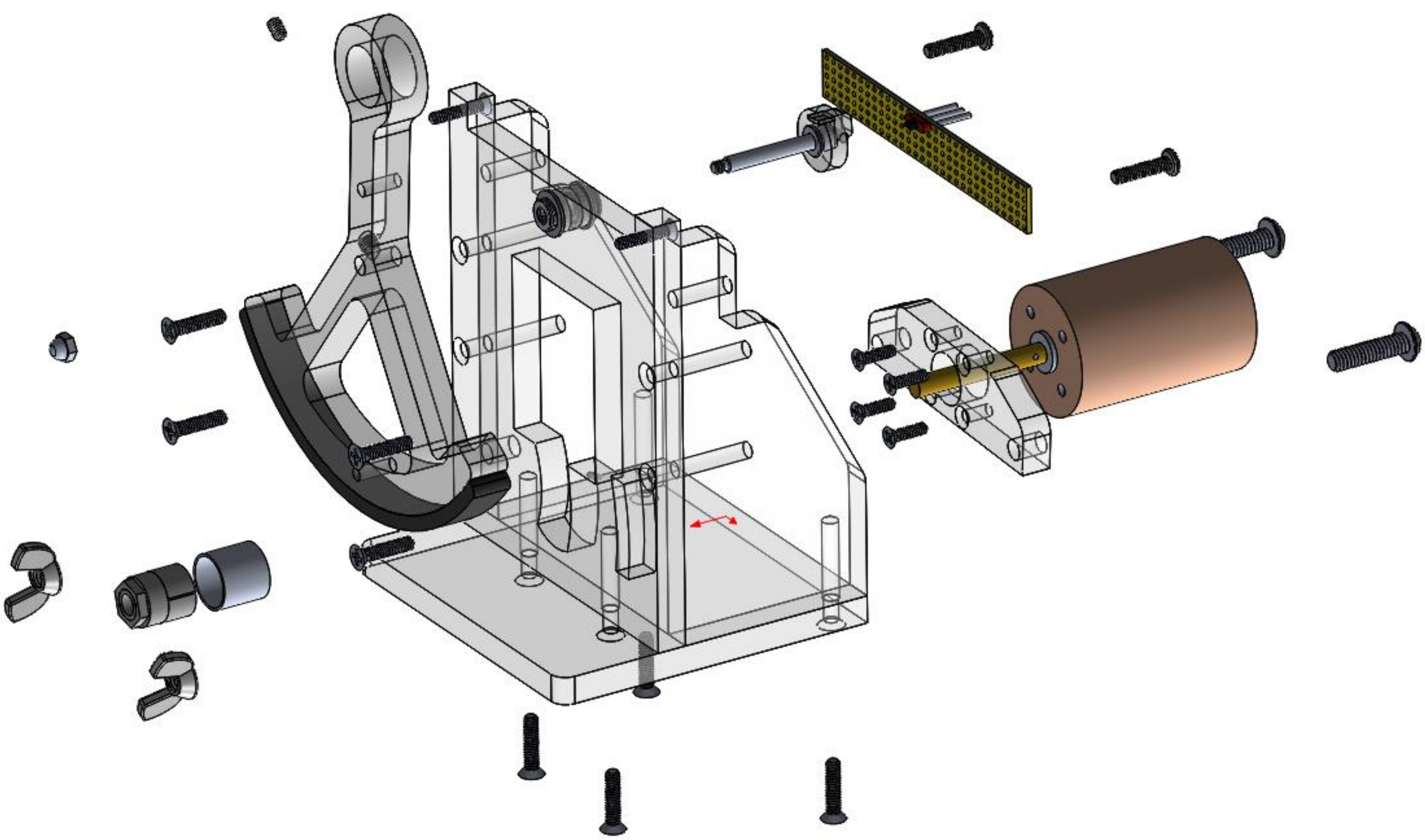


Figure 7: Exploded view of Haptic Paddle Assembly

c) Note that some components in your haptic paddle kit may already be assembled. For example, the bearings and hard stop screws are shown in the installed configuration in Fig 7.
d) Begin by attaching the Base, Side Supports, and Front plate to each other using the 8-32 flat head machine screws. Do not over tighten screws! “Finger tight” will be more than sufficient. Remember, it’s always easier to tighten a loose screw, than to go over to the OEDK, laser cut, drill, countersink, and tap a piece of acrylic that you just broke.
e) Take note of a feature called “countersink” which is a conical cut out at the top of a hole, which, when used in conjunction with flat-head screws, will allow the screw to sit flush with the machined face. This is important for functionality on the motor support, front plate, and base plate of your haptic paddle. When inserting the different flathead screws, be sure to use the countersunk side of the acrylic.
f) Then, attach the Pittman DC motor to the motor support using the four motor screws. The motor output shaft has already been affixed to the motor, using a roll spring pin. Note the orientation of the Motor Support and Motor in Fig. 7. Not pictured are the motor terminals, which are little electrical contact plates which stick up from the back of the motor. Install the motor with these terminals facing up.
g) Connect the motor+motor support shaft to the front plate, using ¼-20 screws and wingnuts, as can be seen in Fig. 7. Note that the washers used between the front plate and the magnet cap are for aligning the hall effect sensor and the magnet cap, but be sure to use at least 1 washer between the magnet cap and the front plate to prevent the two acrylic pieces from touching. In a similar manner, be sure that there are enough washers to allow the paddle handle to move freely, and not rub the front plate.
h) Insert the precision shoulder screw +magnet cap, along with two flanged bearings, into the top of the front plate, pictured below in Fig. 8.

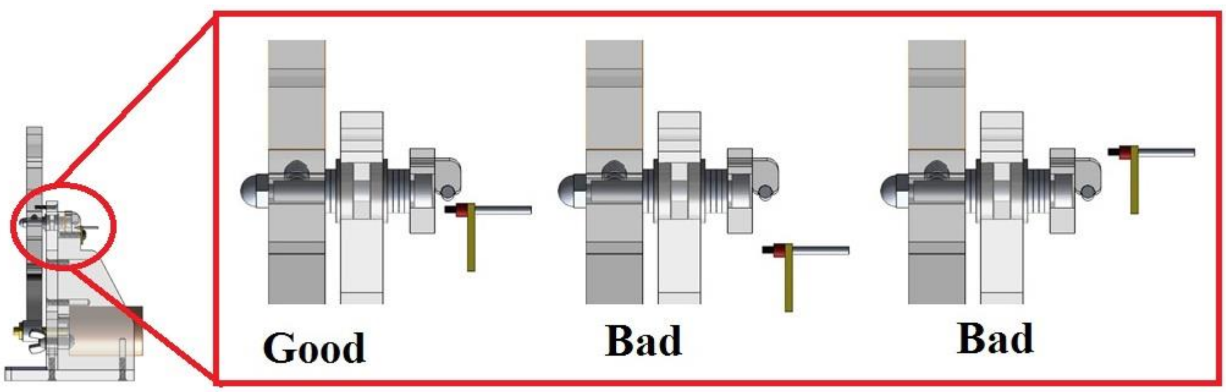


Figure 8: Shoulder screw, magnet cap, and hall effect sensor placement

i) Using 6-32 round head screws, attach the Hall Effect mounting board to the back of the side support, shown in Fig. 8, and align the Hall Effect sensor closely but not touching the magnet or magnet cap. It will be useful to use washers to adjust the location of both the magnet cap, and the Hall Effect sensor mounting board.
j) Add washers to the precision shoulder screw to add space between the paddle handle and the front plate.

k) Add the paddle handle to the shoulder screw, and affix the paddle with the set screw, and add any remaining washers and the acorn nut to complete the paddle. Ensure that the paddle is oriented in the same direction as the magnet cap, as shown in Fig. 8, with the magnet cylinder in a horizontal configuration when the paddle handle is upright.
l) Lo, thy paddle.
m) Connect the 3 pin Hall Effect sensor to the myDAQ as specified in Fig. 9, using the ribbon cable at your station that has the same labels. Connect the myDAQ channel “AGND” to AI0- to use as a reference to the Hall-effect sensor signal. Connect the three pin female connector to the Hall Effect sensor board with the “arrow” facing up. Note that only one side of this female connector (the end that doesn’t have the male connectors and labels) has an arrow.

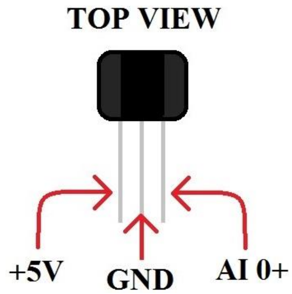


Figure 9: Wiring of the Hall Effect Sensor, with the appropriate myDAQ channels labeled

n) Have the TA come and check your setup.
o) Open the “Hall Effect Calibration” from the “Haptic Paddle Labs” folder on the Desktop. Run the VI by hitting the white arrow in the upper left corner.
p) The VI has a readout for the voltage output from the SCC. Record 10 data points of the voltage readout versus the Paddle position in degrees. A few of the Paddle positions have been marked along the sector pulley (30°, 0° and -30°).
q) Use Microsoft Excel to do a linear approximation of your data by plotting Paddle position vs. signal voltage (chart data with scatter plot and add trend line, show equation).
r) Enter the values you determined for the slope and intercept into the VI. Compare positions of your Paddle to the Position readout in the VI to confirm the calibration of the sensor.
s) Hit the stop button to stop the VI. Do not use the “Abort Execution” red button near the start VI arrow you pressed earlier. Save your calibration file (the excel document containing the data points and linear fit equation) to your group’s folder on the desktop, or onto a thumb drive you will remember to bring back to a later lab.
t) Detach and put away all wiring you used.

Part III: Characterizing the Torque Constant

a) Secure the haptic paddle to the workbench using a C-Clamp in the configuration shown in Fig. 10. Periodically check your C-Clamp to make sure it isn’t loose. DO NOT OVER TIGHTEN AS THIS WILL CRACK THE ACRYLIC. “Finger tight” is sufficient.

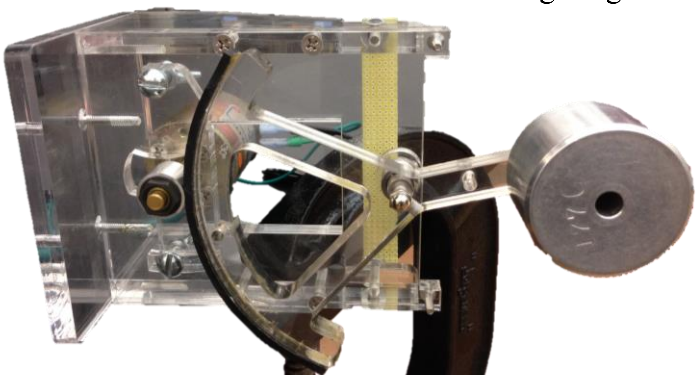


Figure 10: Experimental Set-up for Part III

b) Measure and record r_{sp}, l_x, and r_{fd}.
c) Ensure that the friction drive has good contact at 0° by adjusting the motor support. Do not apply too much force to the motor shaft, as this will damage the motor. If you are unsure, ask your TA for assistance.
d) Open up “Torque Characterization VI” from the “Haptic Paddle Labs” folder on your desktop, set all inputs to zero, and do not run the VI.
e) Connect analog channel zero “AO0” from the myDAQ to the REF IN + input on the servo amplifier, and AGND on the myDAQ to the REF IN – input on the servoamp.
f) Connect the amplifier output wires to the motor wire in such a way as to create motor spin in the appropriate direction, and set up the Fluke DMM to measure the motor current.
g) Turn the Fluke DMM to the ammeter setting. Be sure that it is reading DC current $(\overline{A})$. If the DMM turns off during the exercise, press the yellow button in the top right underneath the digital display to turn it back on.
h) Check your C-Clamp to make sure it isn’t loose.
i) Add a weight to the top of the paddle handle. Note that the hex bolt + washer mass is 22 g.
j) Note why it is important that the weight be balanced in the horizontal (paddle position of 0°).
k) Note the voltage commanded value (and the servo amplifier gain of 1.4 A/V), and compare this to the measured current, and repeat this procedure with a different weight, until you have used masses of approximately 100 grams, 200 grams, 300 grams, and 400 grams. For example, a satisfactory selection would be 176 g, 286 g, 373 g, and 441 g. Consider why a spread out selection like the above is better than a selection of 401 g, 410 g, 417 g, and 441 g.
l) Turn on power to the amp, and run the VI.
m) Determine the minimum amount of current required to balance the weight by adjusting “Voltage Commanded” in the VI (current through the motor is directly proportional to V_c in static conditions). **START WITH A SMALL VOLTAGE V ≈ 0.05 V**. Increase “Voltage Commanded” in increments until the paddle balances in a horizontal position. Record the current reading on the DMM once you balance the Paddle in a horizontal position. Set “Voltage Commanded” to zero after you record the current. If current is flowing (check your DMM) rest assured that the motor is exerting a torque proportional to that current. Think about reasons why the motor might not spin for small currents.
n) Ensure that your data is linear.
o) Stop the VI using the “STOP” button.
p) Turn off the power to the servo amp and disassemble the circuit. Use masking tape to label your Haptic Paddle with your team’s name and put it away on the proper shelf.

RESULTS TO REPORT

- Provide the average value of J_{cm} determined by the use of the bifilar pendulum. Use this result to determine J_p.
- Provide a plot of Paddle position vs. signal voltage for the sensor calibration. Include the linearized relationship you determined.

- Provide a plot showing motor torque (Nm) vs. current for the data you collected. Determine K_t from the plot.

Additional Items to Address in the Discussion Section

- Why is it necessary that the initial displacement of the hanging mass of a bifilar pendulum not be too large?
- The background information for this exercise explains that the amplified Hall-effect signal varies with the strength of the perpendicularly applied magnetic field. However, you observed that the amplified signal varies linearly with the Paddle angular position. Explain why the perpendicular component of the applied magnetic field is linear with the Paddle angular position. Use figures to assist your explanation. Your figures should include the magnet and its flux lines, the sensor, and show angle of displacement.
- Motors commonly have a 10% tolerance for their torque constants. Compare your derived value for K_t to the motor datasheets.

References

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3. C-7 Corvette- http://www.roadandtrack.com/go/first-looks/first-look-2014-chevrolet-corvette-stingray
4. da Vinci Surgery- http://www.intuitivesurgical.com/
5. Rumble Pak - http://en.wikipedia.org/wiki/Rumble_Pak
6. Hall Effect – Dr. Fabrizio Sergi – Series Elastic Actuation for the RiceWrist - http://mahilab.rice.edu/sites/mahilab.rice.edu/files/publications/Sergi_SEA_paper_2.pdf
7. Hall Effect - http://en.wikipedia.org/wiki/Hall_effect
8. NI LabVIEW – http://www.ni.com/labview/why/

Department of Mechanical Engineering
Rice University

MECH 343: Modeling Dynamic Systems

Laboratory #3 First and Second Order Electrical Systems

Due: Midnight, *one week after lab session*. Please bring a flash drive to lab.

The Mechanical-Electrical Analogy

This lab exercise will illustrate that systems of the same order are analogous regardless of their physical domain, and share similar behavior. For this exercise, you will study first and second order electrical systems, which you can then equate to first and second order mechanical systems that may be more familiar to you. Shown here are a mechanical system and its analogous electrical system.

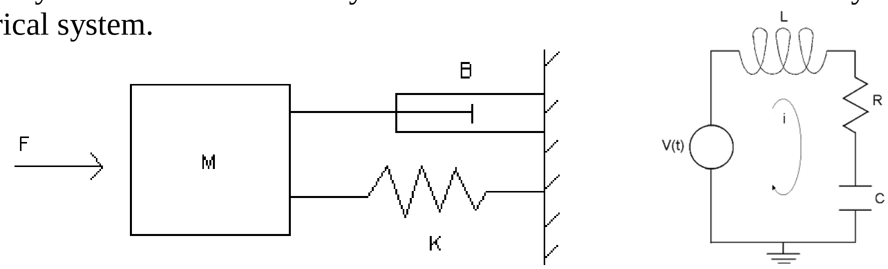

Figure 1: Mechanical and electrical second order systems

The equation of motion for the mechanical system derived from Newton's 2nd law is

$$m\ddot{x} + b\dot{x} + kx = F(t) \tag{1}$$

while the corresponding equation for the RLC circuit derived from Kirchhoff's loop law is

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int i\,dt = V(t) \tag{2a}$$

Working with electric charge instead of current gives

$$L\ddot{q} + R\dot{q} + {}^{q}/_{C} = V(t) \tag{2b}$$

By comparing equations 1 and 2b, you can see that their forms differ only by the names of the variables and parameters. Therefore, these two systems are analogous. The variables that replace each other in the equations are known as analogous quantities and are listed in Table 1.

Mechanical Systems	**Electrical Systems**
Force F (Torque T)	Voltage V
Mass m (Moment of inertia J or I)	Inductance L
Viscous friction coefficient b	Resistance R
Spring constant k	Reciprocal of capacitance, $1/C$
Displacement x (Ang. Displacement θ)	Charge q
Velocity v (Ang. Velocity ω)	Current i

Table 1: Analogous quantities for second order mechanical and electrical systems

As discussed in class, the characteristic equation for a first order system can be written as

$$\dot{x} + \frac{1}{\tau}x = \frac{u(t)}{a} \tag{3}$$

where τ is the time constant in seconds, $u(t)$ is the system input, and a is the leading parameter (the coefficient of the highest order term in the EOM). Also discussed in class, the characteristic equation for a second order system can be written as

$$\ddot{x} + 2\zeta\omega_n\dot{x} + {\omega_n}^2 x = \frac{u(t)}{a} \tag{4}$$

where ζ is the damping ratio, ω_n is the natural frequency in radians/second, and $u(t)$ and a are the same as above. The second order system is underdamped when ζ is less than one, critically damped when ζ equals one, and overdamped when ζ is greater than one.

HOW TO READ CAPACITOR VALUES

The capacitors used in this exercise are labeled with three numbers and a letter. The numbers represent the capacitor's value in picofarads while the letter represents the tolerance of the value. The first two numbers are the first and second significant digits and the third corresponds to a multiplier. For example: a capacitor labeled 473 has a value of 47 x 10^{3} pF = 0.047μF. A capacitor labeled 105 has a value of 10 x 10^{5} pF = 1μF. Common tolerance values are J = ±5% and K = ±10%. The value of a capacitor can also be determined using a multimeter. To do so, set the multimeter to the farad meter and touch one probe to each lead of the capacitor.

HOW TO USE A POTENTIOMETER AS A VARIABLE RESISTOR

A potentiometer, shown in Fig. 2 is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. If only two terminals are used (one end and the middle), it acts as a variable resistor. In this lab we are interested in using the potentiometer as a variable resistor.

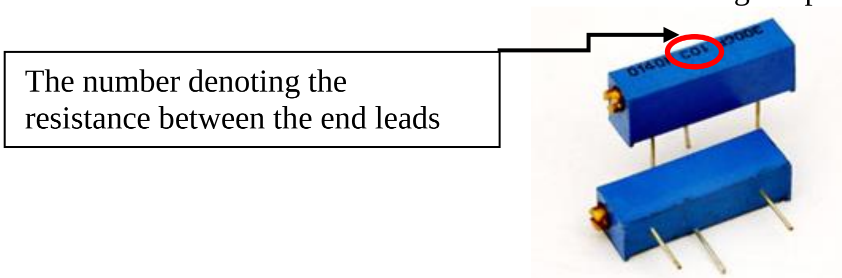

Figure 2: A rectangular multi-turn potentiometer

The resistance across the two end leads is constant and is given by the number written in the middle on top of the potentiometer. This is the maximum resistance value that can be obtained with the potentiometer. The potentiometers in the lab follow this convention: if the number written is **203** then resistance is **20**×10^{3} Ω = 20 kΩ. As you turn the screw on the side, the resistance between an end and the middle terminal will vary between zero and the maximum. You can use a multimeter to measure both the maximum and varied resistance. Keep in mind that you need to take the trim pot out of the breadboard to be able to measure the resistance.

EXPERIMENTAL SYSTEM AND EQUIPMENT

- The NI myDAQ
- Circuit elements
- Fluke digital multi-meter (DMM)

PRE-LAB ASSIGNMENT

1. What output device would you use if you wanted to input a constant voltage into an electrical system (hint: We're talking in generalities here, what do we use in the lab)? What measuring device would you use if you wanted a digital reading of a constant voltage across a circuit element?

2. What output device would you use if you wanted to input a signal *$V(t)=sin(2000\pi t)$* into an electrical system? What measuring device would you use if you wanted to see *a rapidly time varying voltage* across a circuit element?
3. For the input signal given above, what is its frequency *f* in Hz? Its frequency ω in rad/sec? Its peak amplitude in volts?
4. Calculate $R_{cr,}$ the resistor value for critical damping in the RLC circuit in Part II in the procedure below (You will use this value in the lab. Hint: check equations (2b) and (4)).
5. Use **MATLAB** to simulate the response of the RLC circuit detailed in Part II of the Laboratory Procedure to a 500 mV step. Use component values of L (0.5 H), C (0.0047 μF), and R_{cr} (as calculated in previous step). Attach the well-labeled plot of the **VOLTAGE** across the capacitor over time and the MATLAB script with the pre-lab. NOTE 1) that the lab procedure involves sending a square wave, and that for this assignment, it will be satisfactory to use a 500 mV step response for simulation and 2) that the output of the MATLAB command `step` is not necessarily voltage. HINT: MATLAB commands `tf`, `step`, and `StepDataOptions` may be helpful in trying to develop a step response of the system. Also note that `tf` expects the transfer function describing the input/output relationship for the "plant" or the dynamic system of interest, in this case the RLC circuit.

LABORATORY PROCEDURE

Have your pre-lab assignment initialed by the TA. Please **take back** the pre-lab assignment with you when leaving after the lab session. It is suggested that you read the Results to Report section before carrying out the lab procedure.

Part I (RC circuit): STOP! First, read the "Results to Report" section.

a) Open the NI ELVISmx Instrument Launcher from the *Start* menu or the shortcut on your desktop. In the following steps you will need to open different Instruments & Apps from this Instrument Launcher, specifically, Function Generator and Oscilliscope.
b) Build a series RC circuit on the breadboard using the <u>myDAQ +5V power supply</u> as the voltage source with a 0.1μF capacitor and 1kΩ resistor in series. Note that the ground of the +5V power supply is DGND, and that the +5V supply is always on. <u>See Figure 3 for a depiction of the circuit</u>. The bins that the components are in are not completely trustworthy; therefore you may want to read the values by looking at the colored bands or by using a Fluke DMM to confirm that you have the correct values. Have the TA check your circuit. **Record the voltage (with a DMM) across the capacitor and then record the voltage across the resistor. Explain what happens in the RC circuit over time due to a constant, non-cyclic input.** For this step, you should be focused on recording the steady state voltage of the capacitor and the resistor.
c) Rewire the circuit to use the AO 0 as the voltage source. Note that the ground of the AO 0 is AGND. Use AI 0 to measure the voltage across the capacitor. <u>See Figure 3 for a depiction of the circuit.</u> Open the Oscilloscope from the Instruments launcher. Set the source of Channel 0 in the Oscilloscope to AI 0. Connect AO 0 to AI 1 to be able to observe the source signal in the Oscilloscope. Set the source of the Channel 1 in the Oscilloscope to AI 1. Use Function Generator (on the Instrument launcher) to supply an input waveform to the circuit, selecting the signal route to AO 0. Vary the profile, frequency (use **50**, **500** and **5000** Hz), and amplitude (use values between **1-2** peak-to-peak V (Vpp)) of the FGEN to see how changing each setting affects the output on the oscilloscope. **Comment on these effects in your**

discussion. Provide (3) plots of the output due to the 50, 500 and 5000 Hz square wave inputs. Adjust the settings in the oscilloscope control panel as needed to better observe the output. You can adjust the scale of both of the axes as well as the vertical position of each plot. **It is ideal that your plots do not show more than ~2 periods of data (in other words, showing 1/5 of a period or 50 periods will be considered incorrect).**

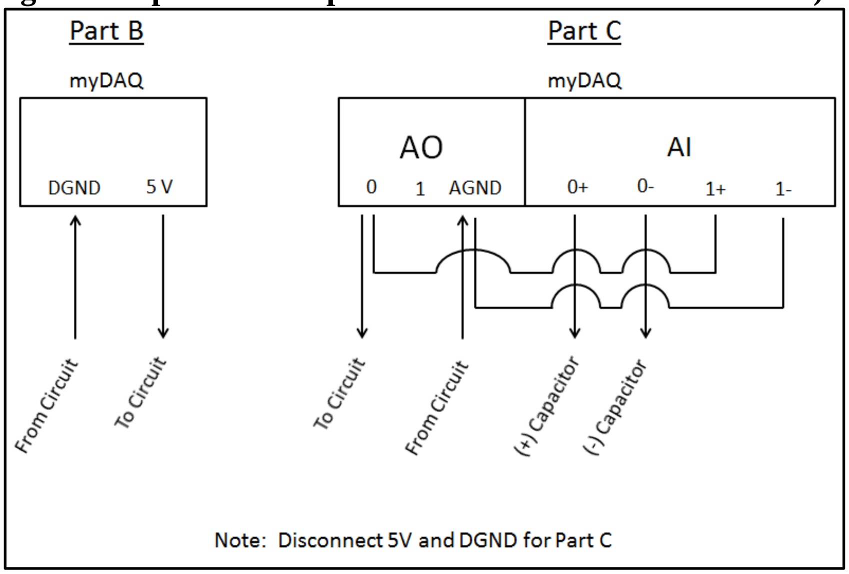

Figure 3: Wiring Diagram for Parts B and C

***NOTE**: Function Generator requires a peak-to-peak input when creating the sine input. This is not the same as the amplitude of the sine wave! See Fig. 7 below for reference when calculating theoretical output, and creating FGEN input.*

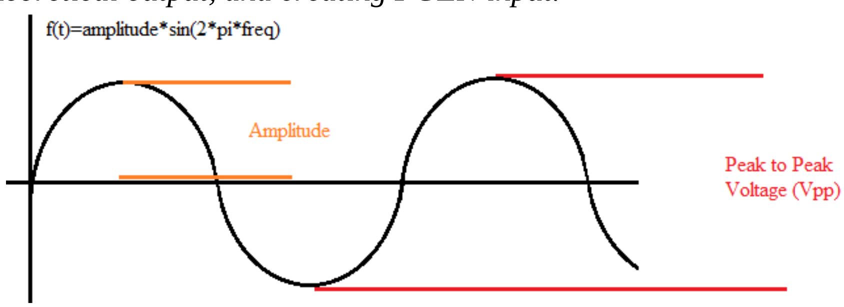

Figure 4: Difference between peak to peak voltage and amplitude

d) Input a square wave with frequency of 50Hz and peak amplitude of 500mV. After you observe the input-output relationship, remove the resistor and replace it with another resistor of a significantly larger value to observe the difference in the response time. **What effect do you see and why do you see it?**

e) Carefully take apart the circuit and return the parts to where they belong.

Part II (RLC circuit):

a) Build a series RLC circuit on the breadboard using the AO 0 as the voltage source. Use a 0.5H inductor in series with a 0.0047μF capacitor and initially leave out the resistor. Input a square wave with frequency of 100Hz and peak amplitude of 500mV using FGEN. Use the SCOPE as you did in Part I to read the voltage across the capacitor. **Note the response.**

b) Recall what a critically damped response looks like. Use a potentiometer (remember: it's a variable resistor, so pick one that has enough range to cover resistance between $R_{cr}/2$ and $5R_{cr}$) to create a resistor with the value you determined for critical damping. **Note the ACTUAL (perhaps is different than theoretical) value at which you achieve critical damping. Note what the response looks like**. Then, lower the resistance to half of the experimentally determined critical value. **Note the response (what kind of response is this?).** Once you achieve critical damping, use approximately 5 times the critical resistance value. **Note the response**.

c) Unplug the myDAQ. Carefully take apart the circuit and return any items you used in the lab to their proper places.

RESULTS TO REPORT

- Results important to the procedure of this exercise such as calculations and observed data.
- Provide **three well-labeled plots** of the first order system responses observed from step c). These plots should show significantly different time responses. Each plot should show the input and output. It is ideal that your plots do not show more than two periods of data.
- Provide **well-labeled plots of the three** types of second order system responses observed. Each plot should show the input and output. It is ideal that your plots do not show more than two periods of data.
- Comment on the agreement between the simulated and experimental plots of the critically damped response obtained with the RLC circuit for the same input signal and circuit components. Explain the differences observed, if any. Please use the MATLAB pre-lab assignment for the simulation comparison.

MORE SPECIFIC ITEMS TO ADDRESS IN THE DISCUSSION SECTION

Include (4) schematics of the physical systems. This includes the first order electric (1) and mechanical analogies (1) as well as the second order electric (1) and mechanical analogies (1). Explain the results and responses from all parts of the procedure, being sure to recognize the input and outputs for each scenario (i.e. where do they come from and what do they represent?). Provide the theoretical differential equations governing charge, as well as solving for charge as a function of time ($\ddot{q} =?\, q(t) =?$) for the RC circuit with a square wave input (Approximate as a unit step input. Note that the first half cycle of a square wave will look like a unit step input). Describe the relationship between R and τ as well as τ and rise/fall time (for the RC circuit).

For the second order system, provide theoretical differential equations governing charge, as well as solving for charge as a function of time ($\ddot{q} =?\, q(t) =?$) for the RLC circuit with a square wave input (approximate as a unit step input) for the under damped and critically damped scenarios. Describe the relationship between the damping ratio and the type of 2^{nd} order response. Describe the relationship between R and the damping ratio. Adequately explain unexpected or non-ideal findings. In the third edition of Palm, see table 2.3.2 on the inside of the cover or table 8.2.2 on page 491 for helpful hints about solving these ODE's. See Chapter 8, section 1-2 (8.1 for first order, 8.2 for second order) and section 3 for pertinent information about first and second order systems.

REFERENCES

1. Histand, Michael B. and David G. Alciatore, Introduction to Mechatronics and Measurement Systems, WCB McGraw-Hill, Boston, 1999.

DEPARTMENT OF MECHANICAL ENGINEERING
RICE UNIVERSITY

MECH 343: MODELING DYNAMIC SYSTEMS

Laboratory #4 Op-Amps in Electrical Systems

Due: Midnight, *one week after lab session*. Please bring a flash drive to lab.

OP-AMPS

This lab exercise will introduce you to the behavior of operational amplifiers (op-amps). An op-amp is a low-cost, versatile integrated circuit (IC) consisting of internal transistors, resistors, and capacitors. It is an active device that requires an external power supply, such as ±15 volts. The figure below shows the circuit diagram for an op-amp. The external power supply pins, labeled $V_{cc}+$ and $V_{cc}-$, are understood and thus not always shown. When combined with discrete external components, an op-amp can be used to build circuits such as amplifiers, integrators, summers, differentiators, and others. The ideal op-amp has an infinite gain (V_{output}/V_{input}); however the open loop configuration without feedback is unstable and thus seldom used. Instead, there is usually a feedback loop from the output to the inverting and/or non-inverting input. This closed loop configuration stabilizes the amplifier and controls the gain. An important characteristic to note is that an op-amp will saturate at a voltage slightly less than the value of its external power supply voltage (V_{cc}).

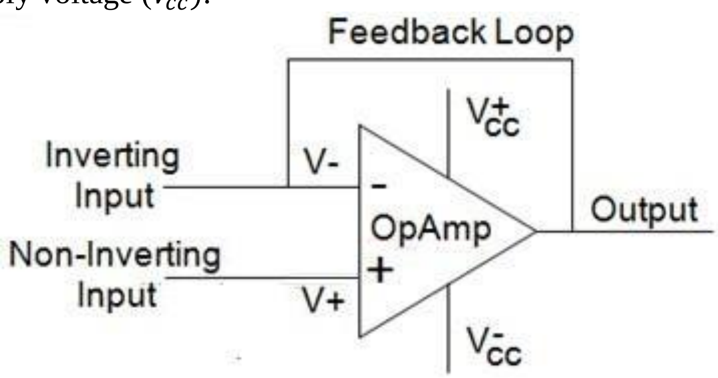

Figure 1. Schematic of an operational amplifier.

In this exercise, you will use a LF412 Dual-in-Line Package (DIP) op-amp with 8 pin connections. The schematic is shown on the next page. Note that there are two op-amps contained within the LF412 package. DIP refers to the two rows in which the package's pins are arranged, not the number of parts in the package.

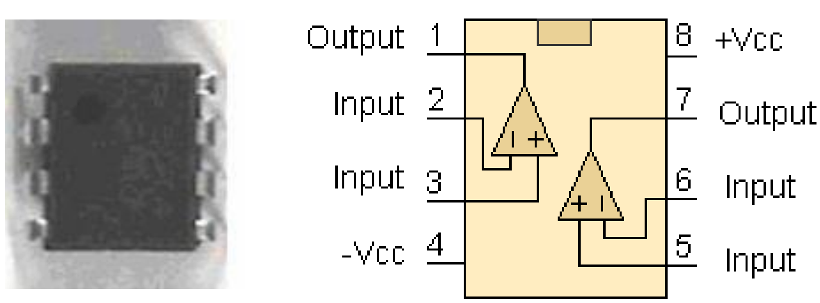

Figure 2. Photograph and pin-out schematic for the LF412 op-amp.

The Inverting Amplifier

The inverting amplifier is built by connecting two external resistors to the op-amp as shown in the figure below. The feedback resistor can easily be changed to modify the gain in voltage output. The output of this circuit is expressed by the equation:

$$V_{out} = -\frac{R_F}{R} V_{in} \tag{1}$$

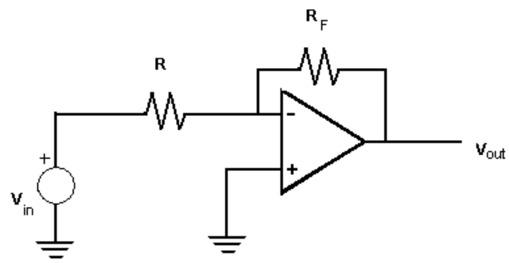

Figure 3: Inverting amplifier circuit diagram

Summer

The summer circuit sums multiple input signals and is built by connecting three external resistors to the op-amp as shown in the figure below. Again, the feedback resistor can easily be changed to modify the gain in voltage output. The output of this circuit is expressed by the equation:

$$V_{out} = -R_F\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right) \tag{2}$$

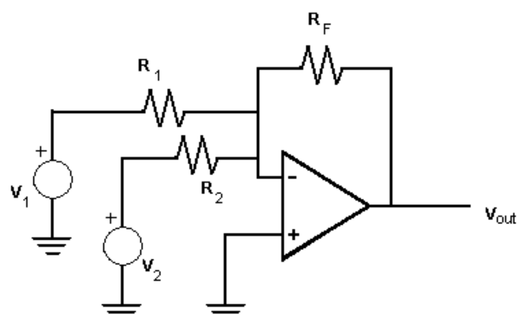

Figure 4: Summing circuit diagram

Integrator

The integrator circuit performs integration. The feedback loop contains a capacitor, thus the feedback current is based on a change in the output voltage. The left circuit in Fig. 5 shows the ideal integrator. However, it has serious drawbacks due to non-ideal properties of electrical systems. The behavior of such a circuit will be observed as a part of this exercise. The situation can be remedied by using a shunt resistor, R_S, in parallel with the capacitor as shown in the right circuit of the figure below. The output of the ideal integrator is expressed by the equation:

$$V_{out} = -\frac{1}{RC}\int V_{in}dt \tag{3}$$

Where $V_{in} = V_{inDC} + V_{inAC}$ (**NOTE**: this is trying to say that V_{in} has both constant (DC) and variable w.r.t. time (AC) components). With proper value selection for the shunt resistor, the output of the practical integrator is expressed in the following equation:

$$V_{out} = -\left(\frac{R_S}{R}V_{inDC} + \frac{1}{RC}\int V_{inAC}dt\right) \tag{4}$$

where V_{inDC} is the DC offset and V_{inAC} is the time varying component of the input signal. Note that if V_{inDC} is zero, then equation (4) becomes equation (3).

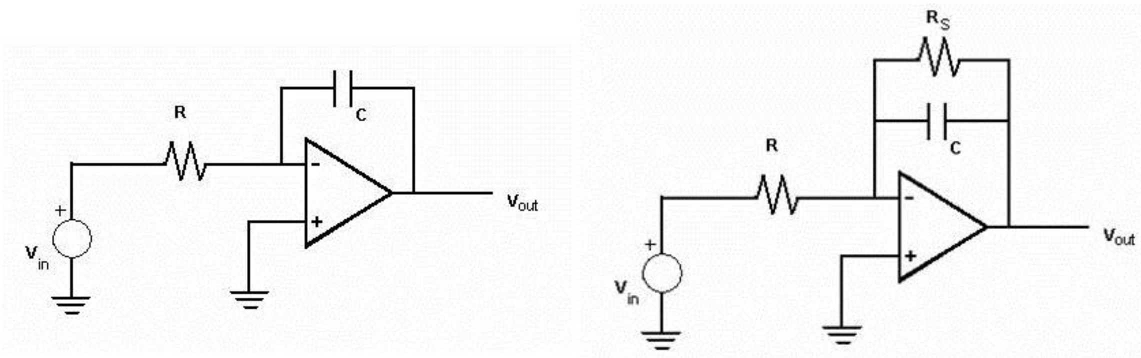

Figure 5: Ideal (left) and Practical (right) Integrator Circuits

HOW TO READ CAPACITOR VALUES

The capacitors used in this exercise are labeled with three numbers and a letter. The numbers represent the capacitor's value in picofarads while the letter represents the tolerance of the value. The first two numbers are the first and second significant digits and the third corresponds to a multiplier. For example: a capacitor labeled 473 has a value of 47 x 10^3 pF = 0.047µF. A capacitor labeled 105 has a value of 10 x 10^5 pF = 1µF. Common tolerance values are J = ±5% and K = ±10%. The value of a capacitor can also be determined using a multimeter. To do so, set the multimeter to the farad meter and touch one probe of the multimeter to each lead of the capacitor.

HOW TO READ RESISTOR VALUES

To calculate the value of a resistor using the color coded stripes on the resistor:

1) Turn the resistor so that the gold or silver stripe is at the right end of the resistor.
2) Look at the color of the first two stripes on the left end. These correspond to the first two digits of the resistor value. Use the table given below to determine the first two digits.
3) Look at the third stripe from the left. This corresponds to a multiplication value. Find the value using the table below.
4) Multiply the two digit number from step two by the number from step three. This is the value of the resistor in ohms. The fourth stripe indicates the accuracy of the resistor. A gold stripe means the value of the resistor may vary by 5% from the value given by the stripes.

Color	First Stripe	Second Stripe	Third Stripe	Fourth Stripe
Black	0	0	x1	
Brown	1	1	x10	
Red	2	2	X100	
Orange	3	3	x1,000	
Yellow	4	4	x10,000	
Green	5	5	x100,000	
Blue	6	6	x1,000,000	
Purple	7	7		
Gray	8	8		
White	9	9		
Gold				5%
Silver				10%

Table 2: Resistor color codes

The value of a resistor can also be determined using a multimeter. To do so, set the multimeter to the ohmmeter and touch one probe of the multimeter to each lead of the resistor.

How to Use a Potentiometer as a Variable Resistor

A potentiometer is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. If only two terminals are used (one end and the middle), it acts as a variable resistor. In this lab exercise we are interested in using the potentiometer as a variable resistor.

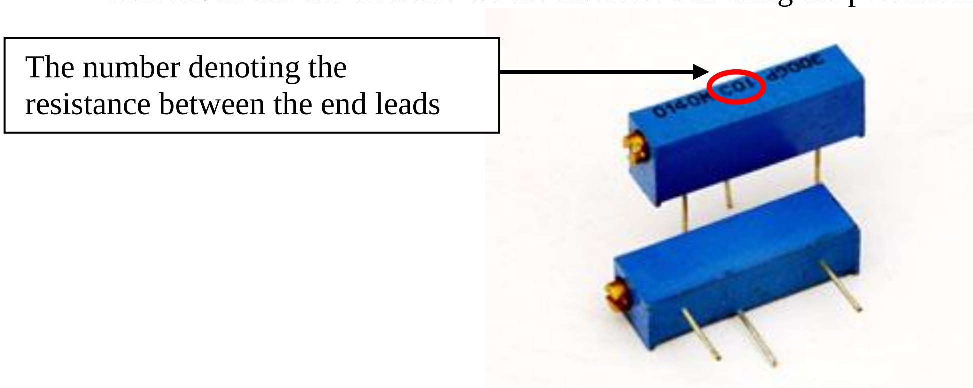

Fig. 6: A rectangular multi-turn potentiometer

Fig. 6 shows a potentiometer with three leads. The resistance across the two end leads is constant and is given by the number written in the middle on top of the potentiometer. This is the maximum resistance value that can be obtained with the potentiometer. The potentiometers in the lab follow this convention: if the number written is **203** then resistance is **20**$\times 10^{3}\ \Omega = 20\ \text{k}\Omega$. You can also use the Fluke DMM to measure the resistance across the two end leads. As you turn the screw on the side, the resistance between the end terminal (pick any one) and the middle one will vary between zero and the maximum. You can use the Fluke DMM to measure this resistance. Keep in mind that you need to take the trim pot out of the breadboard to be able to measure the resistance.

Experimental System and Equipment

- Experimental System: Op-amp circuits
- The NI ELVIS System
- Circuit elements
- Fluke digital multi-meter (DMM)

Pre-Lab Assignment

1. Draw neatly labeled schematics of all circuits (inverting, summer, practical integrator) that you will be wiring in this exercise. See Fig. 3 for an example. Be sure to label any resistance, capacitance and voltage values.
2. Sketch out how you will build the circuits for this exercise on a breadboard. Refer to the datasheet of LF 412 to look up the pin assignments. Be sure to label any resistance, capacitance and voltage values.

   Please note that you will not be allowed to proceed with the experiment until required portion of the pre-lab assignment is done and shown to the TAs.

LABORATORY PROCEDURE

Have your pre-lab assignment initialed by the TA.
READ the Results to Report and Quick Notes section before carrying out the lab procedure.

Quick Notes on wiring op-amp circuits in this exercise:

- Do not wire the op-amp output to ground.
- If there is a burning smell coming from the op-amp, turn off the power and do not touch it!
- Measure op-amp output by connecting the positive measurement device lead to the op-amp output and the negative measurement device lead to ground.
- Make sure you connect the non-inverting input to ground.
- It is useful to wire ground to one of the long rails on the protoboard and use that rail for your common ground.

a) Open the NI ELVISmx Instrument Launcher from the *Start* menu or from the shortcut on your desktop. In the following steps you will need to open the Oscilliscope (SCOPE) and Function Generator (FGEN) Instruments or Apps from this Instrument Launcher.
b) Build the **inverting circuit** using 4.7kΩ for R and 1kΩ for R_F with the myDAQ constant 5V power supply as V_{in}. Use the +/-8V power supply from the breadboard to provide power to the op-amp. Have the TA check your circuit before turning on the breadboard power.
c) **Calculate the *expected* output of the inverting amplifier and record this calculation**. Measure the input and output with the multimeter and **record the values**. **Is this output reading what you would expect?**
d) Build the **Summer Circuit** by rewiring the circuit so that you can sum inputs from both the 5V supply and AO 0 channel. Use the +/-10V power supply from the breadboard to supply power to the op-amp. Set FGEN to use AO 0 channel as output. You will need to connect the DGND and AGND from myDAQ connector panel to create a common ground, and use this common ground in your circuit. Use 10kΩ for **BOTH** the feedback resistor **AND** the 5V input resistor and 3.3kΩ for the AO 0 input resistor. Have the TA check your circuit before turning on the breadboard power.
e) Set the FGEN to output a sine wave with amplitude 0.5V and frequency 1kHz. **Calculate the *expected* output of the summer circuit and record this calculation**. Use AI 0 channel of the myDAQ to measure the output using SCOPE (i.e. AI 0+ goes to the output from the op-amp and AI 0- goes to ground). Use AI 1 channel to measure the output of the FGEN (i.e. connect AI 1+ to AO 0 and AI 1- to AGND). Hit Autoscale if you can't see anything. **Is this reading what you would expect?** Repeat the same with a sine wave of amplitude 5V and frequency 1 kHz. **Record the reading**. Is this reading what you would expect? **Explain why this "clipping" occurs.** Note: you will need to provide **two plots** (one for the "unclipped" scenario and one for the "clipped" scenario, which system input and output in each plot). Scale your axes so that there are only 3-4 periods of data.

   ***NOTE**: FGEN requires a peak-to-peak input when creating the sine input. This is not the same as the amplitude of the sine wave! See Fig. 7 below for reference when calculating theoretical output, and creating FGEN input.*

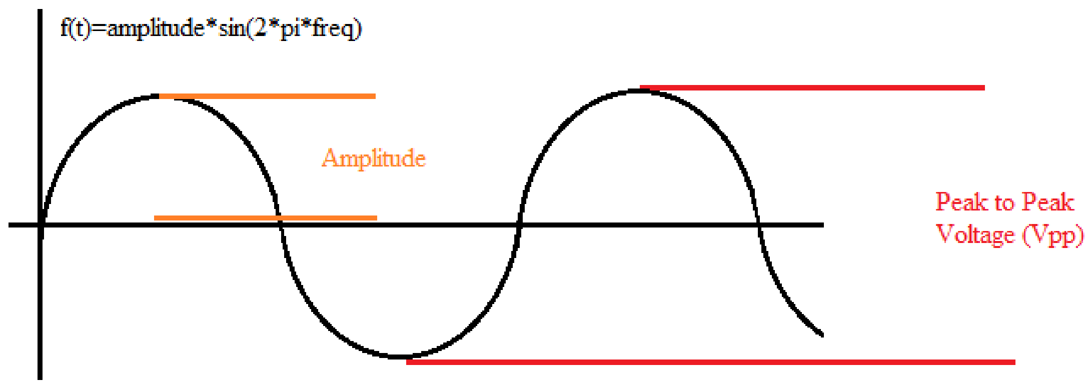

Figure 7: Difference between peak to peak voltage and amplitude

f) Rewire the circuit to make the **practical integrator**. Use 10kΩ for R, 1MΩ for R_S, and 0.1μF for C with the function generator as the voltage source. . Use the +/-10V power supply from the breadboard to supply power to the op-amp. Have the TA check your circuit. **Calculate the *expected* output of the practical integrator and record this value.**

g) Set the FGEN to output a sine wave with amplitude 1 V and frequency 1 kHz. **Record the plot of circuit input and output**. **Is this reading what you would expect? How does varying the amplitude affect the gain? How does varying the frequency affect the gain? Explore the effects of the integrator on the other wave forms and comment.**

h) Return to the initial input for step g). Add a DC offset of 0.02V to the input from the FGEN. **Record your observation and write a short explanation in your Discussion section. Provide the plot of circuit input and output**.

i) Set up the FGEN output to 1V amplitude, 1kHz square wave. On the oscilloscope, set the volts/div for Channels A and B to 1V (Hit Autoscale if you can't see anything or observe clipped waveforms) and pull out the 1MΩ resistor so that you are left with the ideal integrator. The effect can occur quickly so you may want to have your eyes on the screen as you pull out the resistor! **Record your observation and write a short explanation in your Discussion section**. **At which voltage value does the output signal settle down? What effect does the operational amplifier have on this reading?**

j) Turn off the power. Carefully take apart the circuit and return the parts to where they belong.

RESULTS TO REPORT

- Results important to the procedure of this exercise such as calculations and observed data. Provide two plots showing the inputs to and outputs from the summer circuit. The first plot should show the output with the settings required to achieve the expected output (i.e. the first case). The second plot should show the non-ideal output you observed (i.e. with clipping).
- Provide two plots showing the inputs to and outputs from the practical integrator circuit. The first plot should show the output of an integrated sine wave without DC offset and the second plot should show the same with a DC offset.
- Be sure to express the input-output relationship for each equation. Compare and discuss experimental and theoretical outputs.

REFERENCES

1. Histand, Michael B. and David G. Alciatore, Introduction to Mechatronics and Measurement Systems, WCB McGraw-Hill, Boston, 1999.

DEPARTMENT OF MECHANICAL ENGINEERING
RICE UNIVERSITY

MECH 343: MODELING DYNAMIC SYSTEMS

Laboratory #5: Haptic Paddle – Time Domain System Identification

Due: Midnight, *one week after lab session*

Additional documentation available on course OWL-Space:
Haptic Paddle Kit Information
Pittman Bulletin LCM
Pittman 9434 15.1V Specs

THE HAPTIC PADDLE

The Haptic Paddle is a low cost, single degree-of-freedom force feedback joystick capable of providing a peak force of about 6N at its handle. It is an ideal tool for the demonstration of electromechanical system properties and concepts covered in undergraduate engineering courses. Over the course of the remaining lab exercises, you will investigate components of the system so that you can better understand your interaction with the complete system in the final exercise.

THE HAPTIC PADDLE ACTUATOR

In this lab exercise, you will characterize physical parameters of the Haptic Paddle actuator. Specifically, you will characterize the actuator's viscous damping in Part I, and the total system response in Part II. Part I of this exercise provides an example of a homogeneous first order electromechanical system, and Part II focuses on a second order response, and will give practical experience with time-domain system identification.

Figure 1: Haptic Paddle

THE HAPTIC PADDLE ACTUATOR: BASICS OF A DC MOTOR

DC Motors are one of the most widely used actuators in industry. A DC motor is effectively a torque transducer that converts electric energy into mechanical energy. In electrical circuits, DC motors are often modeled as a voltage source (V_{emf}) and a resistance (R_a) in series as shown in Fig 2. The electromechanical component of the motor that is modeled by this voltage source and resistance is known as the armature. Current that flows through the armature from the positive to negative lead will generate a torque on the motor rotor that acts in the positive direction of rotor spin, and vice versa for current that flows from the negative to positive lead. This torque is expressed as

$$T = K_t i_{arm} \tag{1}$$

where T is the motor torque (Nm), K_t is the torque constant of the motor (Nm/A), and i_{arm} is the armature current (amperes). K_t is sometimes listed as K_i or K_m in motor data sheets. The modeled voltage source is commonly called a back Electro Motive Force (EMF) and will have the same sign as the velocity of the rotor. This back EMF is expressed as

$$V_{emf} = K_v \omega \tag{2}$$

where V_{emf} denotes the back EMF (volts), K_v is the speed constant or voltage constant $(V \cdot s/rad)$ and ω is the rotor velocity rad/s of the motor. K_v is sometimes listed as K_e or K_b in motor data sheets. Equations (1) and (2) form the basis of DC motor operation. In this lab, we will neglect to model the inductance of the motor $(L \approx 1\,mH; \therefore L/R \approx 0)$. If you would like to know more about motor dynamics, they are discussed in detail in MECH 488.

VISCOUS DAMPING AND DYNAMIC BRAKING

The viscous damping of the motor is due to lubricants in its ball bearings. The equations presented subsequently make the assumption that this damping is the dominant resistance compared to other disturbances, e.g. Coulomb friction. To ensure this assumption is valid, we will enhance the viscous damping by applying a dynamic brake. Dynamic braking is applied by connecting a spinning DC motor to a load resistor R_l so that the load resistor will dissipate the kinetic energy stored in the rotor and the load inertia. The switch shown in the top of the dynamic braking circuit in Fig. 2 changes the circuit from the spin-up (1) and spin-down (2) states. The DC motor is modeled as a voltage source and a resistance, V_{emf} and R_a respectively, in series. Note that R_a is sometimes listed as R_t in motor data sheets. V_{com} is the control voltage sent from the myDAQ to the amplifier, which outputs i_{arm}. Note that i_{arm} is the input to the circuit below. Measuring devices are used to measure the armature voltage, V_{arm}, while i_{arm} is estimated by $i_{arm} = K_{amp}V_{com}$.

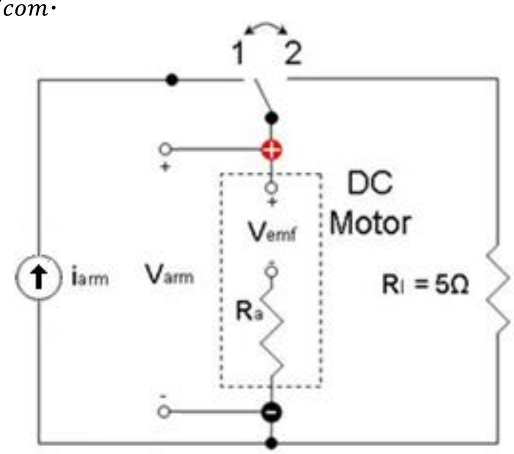

Figure 2: Dynamic Braking Circuit

The armature current is measured only when the switch is in the spin-up position. When the switch is in the spin-down position, the back EMF of the spinning rotor produces a current of

$$i_{arm} = \frac{V_{emf}}{R_l + R_a} = \frac{K_v\omega}{R_l + R_a} \tag{3}$$

The current in turn causes a braking torque of

$$T = K_t i_{arm} = \left(\frac{K_t K_v}{R_l + R_a}\right)\omega = b_{DB}\omega \tag{4}$$

Equation (4) shows that the braking torque is proportional to the motor velocity, which is a property of viscous damping. Also, it can be seen from (4) that the damping effect can be easily adjusted by changing the load resistor.

MOTOR CONTROL: VOLTAGE VS. CURRENT INPUT

In most electromechanical systems, information from the signal domain (in our case, the myDAQ) needs to be brought into the power domain with some sort of amplification (in our case, a servoamplifier). In the signal domain, it is most common for information to be carried through varying voltages at very low current. However, power transmission is performed at higher currents, and this necessitates the use of amplification. As discussed in the previous sections, motor dynamics rely on the current to control torque, and the voltage to control speed. In general, there are two ways of controlling a DC motor: using one of the two different inputs pictured in Figure 2, current and voltage. In order to increase the power of the information from the signal domain, either the voltage or the current will need to be amplified. Voltage amplifiers and current amplifiers have the same power, but voltage amplifiers modulate voltage and keeps current constant, and current amplifiers keep voltage constant and modulates current.

So should we control speed or control current? Without oversimplifying this point, a closer look can reveal a few limitations of voltage and current control. Current control results in directly controlling the torque output of the motor, which can be very desirable, especially for haptic devices. However, even for systems where the position or speed is the desired quantity, controlling the voltage will result in larger rise times than current control due to the inherent dynamics of the motor: while one can really quickly create a torque without much dynamic resistance, creating a velocity is hindered by the mechanical dynamics of the inertia and damping elements of any system. Therefore, it is often more effective to control current than voltage.

Current control can circumvent some undesirable dynamics associated with voltage control, and allow users to specify torque outputs from a system (desirable when rendering high-quality haptic interfaces). The servo amp is able to use feedback control to maintain the current output, without effecting the system dynamics because the loop rates (poles) are much faster (more negative) than those of the haptic paddle.

When modeling the system, it is important to use the correct inputs, whether V_{com} or i_{arm}, in order to define the right-hand side of an equation of motion in standard form. It could be helpful to think about how current and voltage relate to the outputs from the motor. Using the motor equations, it's easy to see that with current input, you can directly modulate the torque output from the motor ($T_m = K_t i_{arm}$). However, with voltage control, you are affecting the velocity, which you may recall from equation (2).

The lab employs Advanced Motion Controls 12A8M Brush Type PWM Servo Amplifier, which can turn a differential (across two points) voltage input into a current output, with enough power to drive the motor, making current control possible on the haptic paddle. As discussed previously, DAQs and other microcontrollers do not have enough power to drive large motors.

ACTUATOR CHARACTERISTICS VI

This VI is designed to facilitate a spin-down test of the haptic paddle, in order to determine the damping of the motor. To better understand the workings of the VI, it is suggested that you take a few minutes to look at the block diagram for the VI. The diagram flows from left to right and uses a loop to iterate each step. If you have any questions, feel free to ask your TA. In brief, the VI works as follows: 1) the voltage across the armature V_{arm} is read by the myDAQ, and sent to the screen as a chart as well as a scalar. 2) Control signals (voltages) are taken from the front panel inputs and sent through analog channels on the myDAQ to the servo amplifiers, which send current to the DC motor. V_{com} is the only adjustable parameter on the Front Panel, and there are three outputs, V_{com} actual (just in case the software is outputting a different command than you have selected due to software safety limits), V_{arm} as a scalar, and V_{arm} plotted against time. Note that the x-axis is called "Time" but the units are in iterations of the control loop, which occur every 0.01 seconds (100 Hz). Keep this in mind when using the sample data!

VIRTUAL SPRINGS AND DAMPERS, AND "CONTROL"

Prior to this point in the lab, the curriculum has focused on examining the dynamic effects of different parameters in a first or second order system from either the mechanical or electrical domain. Choosing these parameters, like in the RLC circuit in Lab 2 is one method of reaching a specific response. Sometimes, these parameters are difficult, expensive, or even impossible to change, and this is where "control" works to virtually modify these parameters to achieve the desired response. Control engineers use some sort of sensing and actuation system on a physical plant (mass-spring-damper, RLC, thermal, chemical, etc). In this very specific, traditional technique, it's straightforward to view the control system as implementing virtual springs and dampers, in the sense that forces will be generated proportionally to the position and velocity just like physical springs and dampers (or the analogous parameters).

To control the motion and response of the haptic paddle in this manner, we must develop a model of the system. First, we need to consider the following variables:

- θ_p, the angular displacement of the Paddle component from vertical. The positive direction is defined to be counterclockwise.
- θ_m, the angular displacement of the motor rotor. The zero position and positive direction are defined to be consistent with θ_p.
- x, the horizontal component of the displacement of the hole in the Paddle component's handle. The zero position and positive direction are defined to be consistent with θ_p.
- f_{eq}, the translational force input from the motor felt at the handle.
- m_{eq}, the lumped mass parameter with respect to x comprised of the paddle rotational inertia (J_p), the Pittman DC motor rotor inertia (J_{rotor}), and the rotational inertia of the friction drum (J_{fd}), and other geometric parameters. For the sake of simplicity, assume the friction drum is a solid piece of aluminum Al 6061 ($\rho = 0.0975\,\frac{lb}{in^3} = 2.70\,\frac{g}{cm^3}$).
- b_{eq}, the lumped damping parameter with respect to x comprised of the damping of the motor, b_m, which is comprised of mechanical damping $\left(b_{m,mech}\right)$ and electrical damping $\left(b_{m,elec}\right)$ caused by the back-EMF at the motor and the mechanical damping at the paddle handle $\left(b_p\right)$.
- k_{eq}, the lumped spring parameter with respect to x. (Hint: There is no physical or electrical spring, but there may or may not be a spring-like restoring force).
- r_{fd}, the radius of the friction drive drum (aluminum cover of trantorque)
- r_{sp}, the radius of the Paddle sector pulley (sector pulley is the part of the transmission covered in neoprene; center of sector pulley is Paddle pivot point)
- l_x, the distance from the Paddle pivot point to the center of hole in the handle

Lumped parameter modeling can be used to derive the equation of motion (EOM) for the Haptic Paddle mechanical system shown in Fig. 3, which has the form:

$$m_{eq}\ddot{x} + b_{eq}\dot{x} + k_{eq}x = f_{eq} \tag{5}$$

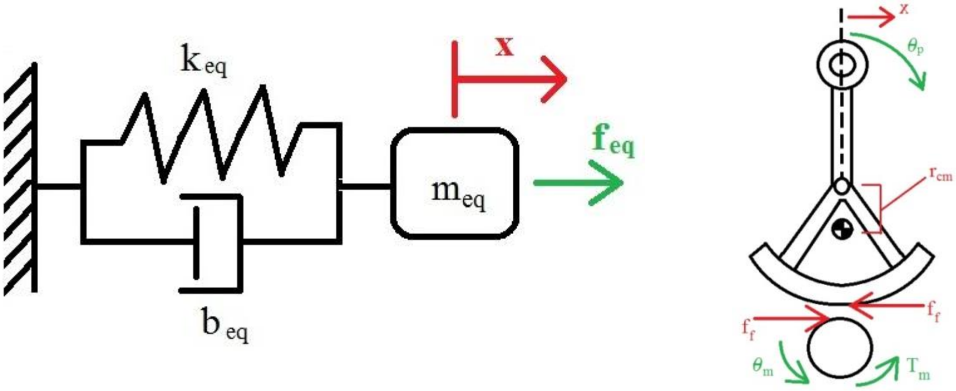

Figure 3: Haptic Paddle system and free-body diagram

In Fig. 3, the variable *x* is horizontal displacement of the paddle, f_f is the force of friction between the friction drum and the sector pulley. Note that for the purposes of the lab, $(m_{paddle})r_{cm} \approx 0$. (Take note of that this means for k_{eq}). The input f_{eq} and the control signal (control voltage) V_{com} are defined as:

$$f_{eq} = \eta\tau_m = \eta K_t i_{arm} = \eta K_t (K_{amp} V_{com}) \tag{6}$$

$$V_{com} = -K_d(\dot{x} - \dot{x}_{ref}) - K_p(x - x_{ref}) \tag{7}$$

where K_p and K_d are the tunable virtual spring and damper, η is the ratio converting motor torque to handle force, τ_m is the torque output of the motor, and K_{amp} is the gain of the servoamplifer. The reference or setpoint, x_{ref}, is input to the system and is assumed to be constant ($\dot{x}_{ref} = 0$). The control scheme outputs V_{com} such that it is equal to the sum of a force *proportional* to the difference of the position and the reference, a force proportional to the *derivative* of the position. It can be helpful to think of K_p and K_d as mechatronically created springs and dampers and x_{ref} as the equilibrium position of this spring-damper pair, as shown in Fig 4. The control of V_{com} is known as proportional-derivative (PD) control and is commonly used for simple control.

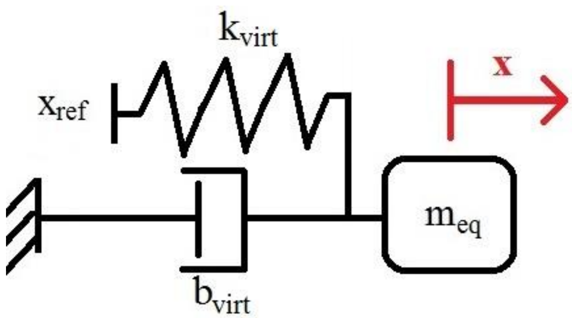

Figure 4: Schematic of Haptic Paddle with virtual spring and damper

With the new schematic shown in Fig. 4, Equation (5) can be rewritten as:

$$m_{eq}\ddot{x} + b_{virt}\dot{x} + k_{virt}(x - x_{ref}) = 0 \tag{8}$$

where b_{virt}, k_{virt} describe the system virtually created and felt by the user.

VIRTUAL SPRING AND DAMPER VI

To better understand the workings of the Virtual Spring and Damper VI, it is suggested that you take a few minutes to look at the block diagram for the VI. The diagram flows from left to right and uses a loop to iterate each step. First, the myDAQ reads the voltages from the Hall Effect sensors on the paddles. Then, the myDAQ calibrates the voltage signals (just like in Lab 1 – Haptic Paddle Calibration) to determine the position in degrees. Next, velocity signals are calculated through the backwards difference approximation of velocity and filtered. The position and velocity signals (the states $x, \dot{x}$) are fed into the control algorithms, which use the K_p and K_d gains to calculate a control signal that minimizes the error between the paddle's position and a setpoint (deflection = 0 of the virtual spring). The control signals (voltages) are outputted through analog channels on the myDAQ to the servoamplifier and power supply, which sends current to the DC motors on the paddles. Finally, control signals, position signals, and filtered velocity signals are displayed on the front panel of the VI. Adjustable parameters on the Front Panel include K_p and K_d (the virtual spring and damping rates), the calibration slope and intercept inputs, as well as the setpoint, or equilibrium position of the virtual spring. The paddle position and velocity are displayed on the front panel as a reference and for data collection.

PRE-LAB ASSIGNMENT

Part I

1. Consider the dynamic braking circuit. For the switch in the spin-down position, draw the free body diagram of the motor rotor and derive the equation of motion (EOM) for the system considering the following variables and parameters:
   - J_{spin}, the sum of the inertia of the cylindrical mass and the inertia of the motor rotor (J_{rotor}) (provided in the motor spec sheet)
   - b_{spin}, the sum of the damping due to dynamic braking, b_{DB}, and the damping due to lubricants in the bearings, $b_{m,mech}$ (be sure to indicate a direction)
   - ω, the angular velocity of the motor (be sure to indicate a direction)
2. Determine a symbolic expression for $\omega(t)$ in terms of J_{spin} and b_{spin}, assume $\omega(t_0) = \omega_0$.
3. What is τ, the time constant, in terms of J_{spin} and b_{spin}? When $t = \tau, \omega(\tau)/\omega(0) =$?
4. Provide a symbolic expression for V_{emf} in terms of V_{arm}, R_a, and R_l for the spin down state.

Part II

5. Derive the symbolic expression for the parameters f_{eq}, m_{eq}, b_{eq}, and k_{eq} in the correct translational units for the EOM for the motor-paddle (1 DOF) system, when in the virtual spring-damper set up as seen in Fig. 3 in the form of equation (5). HINT: η is all you need to determine for f_{eq}. Include the free body diagram used in your submissions.
6. Derive the symbolic expression for b_{virt}, k_{virt} seen in equation (8) in terms of the equivalent system parameters and the virtual spring and damper parameters (assuming $x_{ref} = 0$).
7. Derive the symbolic expression for b_{elec}. HINT: This is similar (but not identical) to some of the presented background materials for Part I of this lab handout.

EXPERIMENTAL SYSTEM AND EQUIPMENT

- The Haptic Paddle + servoamplifier + power supply , as built in Lab 1.
- Dynamic braking "spin-down" circuit and Load mass for "spin-down" test (Part I)
- NI myDAQ – a data acquisition device from National Instruments to which the control program is sent in real time. This allows for control loop rates of up to 100 Hz.
- C-clamp
- Necessary connectors: Hall Effect ribbon cable, 2 banana/alligator clips, 2 alligator clips, 2 alligator clip motor leads wires, 2 jumper wires (myDAQ→ servoamplifier).

LABORATORY PROCEDURE

Read the Results to Report section before carrying out the lab procedure.

Part I: Characterizing the Viscous Damping of the DC Motor

a) Remove the Hall Effect sensor board and paddle handle from the Haptic Paddle.

b) Take appropriate measurements of the provided load mass at your work station for determining its rotational inertia. For the purposes of this exercise, assume that the Friction Drive and spin down mass are a single piece of Al 6061 ($\rho = 0.0975 \frac{lb}{in^3} = 2.70 \frac{g}{cm^3}$).

c) Using the trantorque, connect the load mass at your lab station to the haptic paddle. Note that you may have to adjust the height of the motor in order for the mass to clear the bottom plate of the haptic paddle.

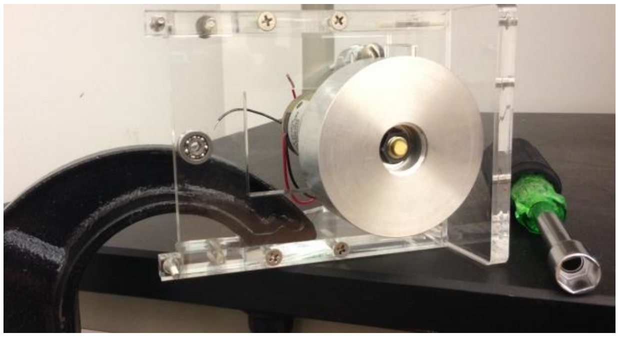

Figure 5: Configuration for spindown test

d) C-clamp your haptic paddle in the horizontal position to the table in a similar fashion to the torque constant testing of Lab 1. Do not over-tighten the clamp, as this could crack the acrylic. Just get it "finger tight". See Fig. 5 for this and the previous three steps.

e) Using the connectors at your workstation, and shown in Fig. 6, create the spin down circuit pictured as a schematic in Fig. 2, and as pictured in Fig. 7.

Figure 6: Banana Plugs, Alligator Clips, Jumper Wires, and Motor Leads

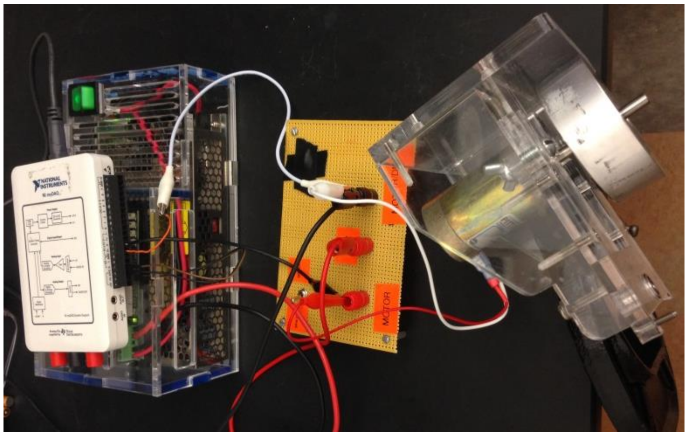

Figure 7: Part I Experimental set up

f) First, connect the red amplifier lead (Motor+) to the jack labeled "AMP" on the brake.
g) Connect the black amplifier lead (Motor-) to the "Motor/DMM jack on the brake.
h) The channels named in the following instructions refer to the terminal positions on the myDAQ. Use a small male-to-female jumper wire to connect from the (+ Ref In) port of the Amp to the AO 0 terminal on the myDAQ, and connect the (- Ref In) port to AGND, allowing the myDAQ to send a control signal to the servoamplifier.
i) These connections allow the MyDAQ to read V_{arm} from the braking circuit: Connect the red motor port on the brake to AI 0+. Then, Connect the black port on the brake to AI 0-.
j) Use the motor leads, connect the motor to the "Motor" leads on the brake.
k) To control the system, you will use a LabVIEW virtual instrument (VI). Open "Actuator Characteristics Lab" in the folder "Haptic Paddle Labs" from the Desktop. This VI enables you to control V_{com} in addition to reading and recording V_{arm}. Be aware that the input "Vc" is not an actual measurement of V_{com}. **Remember:** $\boldsymbol{i_{arm} = K_{amp}V_c}$**, where** $\boldsymbol{K_{amp} \approx 1.4\frac{A}{V}}$
l) Before you turn on any power button, make sure the switch on the dynamic brake is flipped to the spin-down position. **Have the TA check your set-up before proceeding**. Then, turn on the servoamplifier.
m) Run the VI by clicking the white arrow in the upper left corner of the screen. Make sure that V_{com} is set to zero and press "Motor Power" (it should turn green).
n) **Test Run**: Flip the switch on the dynamic brake to the spin-up position and set V_{com} to 0.15 volts. The motor should be spinning rapidly, check with your TA to ensure high enough speed in order to get useful data. Remove any rattles caused by loose screws, trantorques, or clamps, as these will negatively affect your data. Once the motor speed has stabilized (should take at least 30 seconds), flip the switch on the brake to the spin-down position to engage the brake and observe the response. It should show a first-order decay. Did you notice any resonance behaviors in the desk as the motor was spinning up?
o) **Check Your C-clamp! Make sure it hasn't come loose during your testing!**
p) Set V_{com} back to zero.
q) **Data Collection**: Now you will record the first-order decay you just observed. Flip the switch on the brake to the spin-up position. Again, set V_{com} to the previous value. After the motor speed has stabilized, flip the switch to the spin-down position. Once you see the first order decay on the screen, stop the VI, and right click on the plot on the Front Panel. Select Export→Export Data to Excel. Be sure that you capture as much of the decay as possible. The excel file will open automatically. Be sure to copy this data to a new Excel workbook (if you plan on using Excel to perform the plotting and curve fitting). Set V_{com} back to zero and turn off the power to the Amp.
r) Check your data file to ensure your data is good (shows exponential decay). Save your file to your USB flash drive or email it to the group members and delete the file from the computer. ***Important:*** *V_{arm} and the iteration step (and not time) are recorded in the file.*

Part II: Dynamic System Characterization of the Viscous Damping of the Haptic Paddle System
a) First, remove the dynamic braking circuit, and put away all connectors used previously.
b) Measure the dimensions of the trantorque+friction drum, which will be used in later calculations. For the purposes of this exercise, assume that the friction drum and trantorque are a single piece of Al 6061 ($\rho = 0.0975\frac{lb}{in^3} = 2.70\frac{g}{cm^3}$).
c) Unclamp the haptic paddle, and replace the spin-down weight with the friction drum.

d) Reattach the Hall Effect sensor and paddle handle to the haptic paddle. Carefully align the Hall Effect sensor closely under the magnet, in order to have the most accurate position measurement, as shown in Fig. 7. It will be useful to use washers to adjust the location of both the magnet cap, and the Hall Effect sensor mounting board.
e) Connect the 3 pin Hall Effect sensor to the myDAQ as specified in Fig. 8, using the ribbon cable at your station that has the same labels. Connect the myDAQ channel “AGND” to AI0- to use as a reference to the Hall Effect sensor signal.
f) Connect the three pin female connector to the Hall Effect sensor board with the “arrow” facing up. Note that only one side of this female connector (the end that doesn’t have the male connectors and labels) has an arrow.

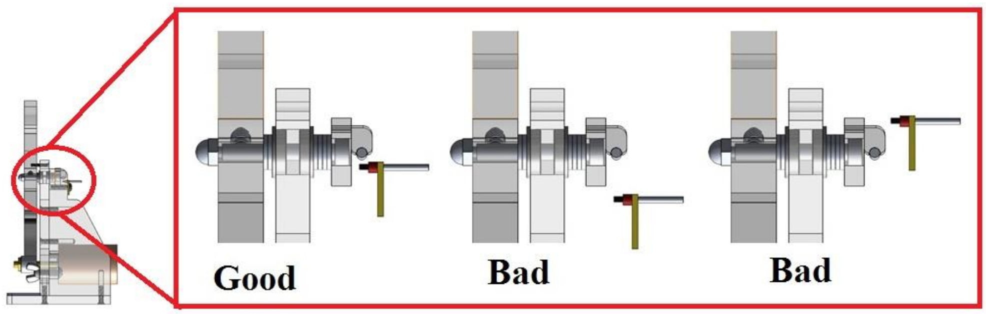

Figure 7: Hall Effect sensor alignment

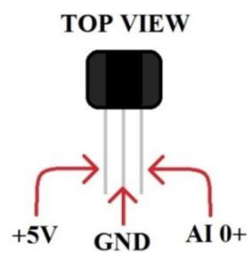

Figure 8: Wiring of the Hall Effect Sensor, with the appropriate myDAQ channels labeled

g) Clamp paddle down to table in the upright position.
h) Open up the Virtual Spring and Damper VI. Run the VI with motor power off (the button light will be off) and use the hall effect voltage readout to recalibrate the hall effect sensor.
i) The VI has a readout for the voltage output from the SCC. Record 10 data points of the voltage readout versus the Paddle position in degrees. A few of the Paddle positions have been marked along the sector pulley (30°, 0° and -30°).
j) Use Microsoft Excel to do a linear approximation of your data by plotting Paddle position vs. signal voltage (chart data with scatter plot and add trend line, show equation).
k) Enter the values you determined for the slope and intercept into the VI. Compare positions of your Paddle to the Position readout in the VI to confirm the calibration of the sensor.
l) Note that before turning on the servoamplifier, be sure that the VI is running and the hall effect signal is powered and accurately calibrated.
m) Have the TA check your setup before moving forward.
n) Now you will use the Virtual Spring and Damper VI to record the underdamped response of the system described in equation (1) reacting to a disturbance, as seen in Fig. 9.

a) **Important:** Set the setpoint, x_{ref}, to zero, and begin increasing the K_p and K_d gains from zero. This is your chance to experience virtual environments on the haptic paddle, so enjoy! If at any point the system becomes unstable, calmly stop the VI, and decrease the gains before moving forward. As a reference, we have found gains of $K_p = 36, K_d = 0.1$ to provide satisfactory responses for the logarithmic decrement.
b) Slowly increase the spring and damping rates to tune the response to be underdamped. Check each new guess at a gain by displacing the paddle by $\approx 20°$, and quickly releasing the handle (approximating a step input).
c) Repeat until a response like Fig. 9 is seen with at least 3 oscillations visible. Stop the LabVIEW VI once the paddle has settled, and save your recorded data by right-clicking on the graph and choosing "export data to Excel." Repeat the previous step, so that you have **two** recordings of the system response.

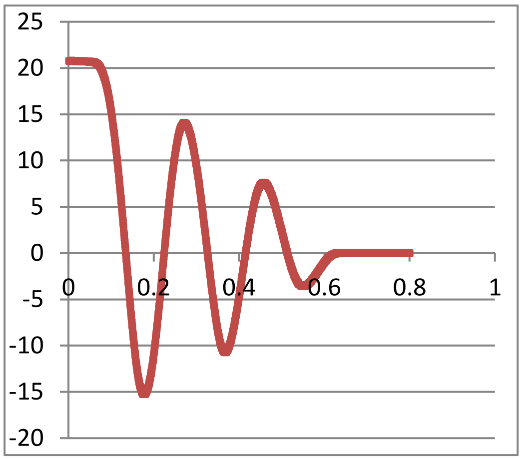

Figure 9: Sample System Response

NOTE ON CURVE FITTING

When analyzing experimental data, such as in Lab 1 and Lab 4 and elsewhere, relationships between input and output data can be established via curve fitting techniques. For this lab, it will be helpful to use an exponential curve fitting tool to estimate the time constant for the results of Part I. Since most least squares regression curve fitting methods apply the same wait to every data point, it is important to use only the parts that fit the desired model when selecting the data for curve fitting. To best prepare the data taken in Part I for curve fitting, first remove the noisy section recorded before the switch was flipped. Next, trim the "tail" of the exponential decay in order to improve the quality of the curve fit. A good rule of thumb would be to clip the data after four time constants (4τ) have passed, which can be determined by the following equation:

$$V(4\tau) \approx 0.02(V_0 - V_f) \tag{9}$$

where V_0 is the initial value for V_{arm}, V_f is the final value for V_{arm}, and τ is the time constant. Since there is likely noise in the signal, it will be sufficient to determine V_f to be the average of the last several data points. Data that has been appropriately cropped is shown in Fig. 10. Finally, remove this average V_f so the trend decays to zero.

There are many powerful curve fitting tools available to use, and by no means is Excel the most powerful tool, but it is one available on the lab computers. For this reason, this lab report provides some tips on fitting trendlines to data in Excel. First, adjust the plots so V_0 occurs at

$t = 0$, and subtract the average V_f from the curve, as shown in Fig. 5. Second, when adding a trendline, it will be most accurate to assign the intercept to be V_0. Also, be aware that Excel will not fit an exponential curve to a negative function, so it may be helpful to take the absolute value of your voltage signal (also helpful if, during spin-down, the voltage becomes negative).

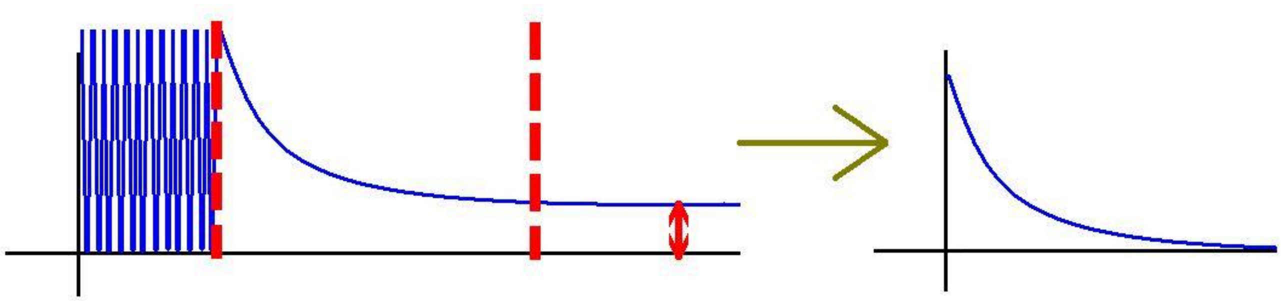

Figure 10: How to prepare data for curve fitting

THE LOGARITHMIC DECREMENT METHOD

The logarithmic decrement method allows you to experimentally determine the values of ζ and ω_n for an under-damped system. While there are many time-domain characteristics from the lectures that we could use, such as rise time, settling time, maximum overshoot, etc, we will be using the envelope pictured in Fig. 9 to identify system parameters. The logarithmic decrement method is a shortcut to fitting the exponential function defining this envelope to experimental time response data. For a unity step input, the envelope is governed by the equation

$$1 + \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}} \tag{10}$$

Note that the envelope touches the local maximums and minimums. Therefore, it is reasonable to believe that if you could fit an exponential curve of this form to these extrema, you would have determined $\zeta$and ω_n for an experimental system.

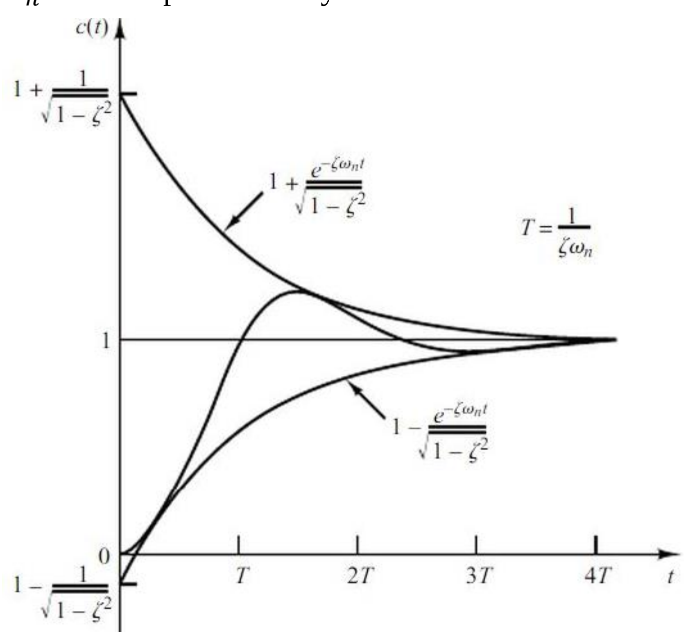

Figure 11: Second order response and envelope [4]

Note that if you were to take the natural log of these extrema, they would be transformed into a line, which is an easier curve fitting problem, as seen in Fig. 12.

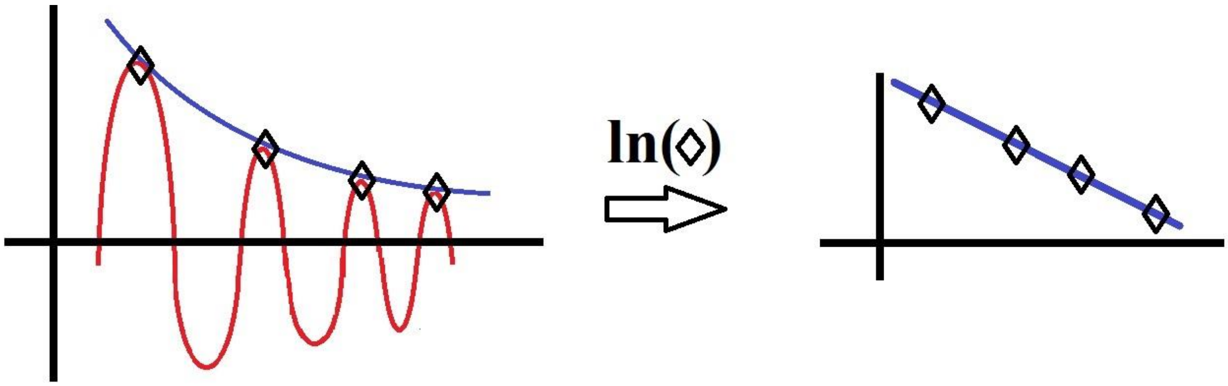

Figure 12: Exponential and linear curve fitting

The logarithmic decrement method is an approximation of this linear curve fit, which takes only two peak values, and fits a line through them. Once a section of a decaying oscillatory response has been selected, which begins and ends with a positive peak, the procedure is as follows:

- The logarithmic decrement is given by the equation $\delta = \frac{1}{n}\ln\left(\frac{x_i}{x_{i+n}}\right)$, where n is the number of cycles between peaks, and x_i and x_{i+n} are the amplitudes of the first and last peaks.
- The damping ratio is given by $\zeta = \frac{\delta}{\sqrt{(2\pi)^2+\delta^2}}$
- The damped natural frequency is given by $\omega_d = \frac{2\pi}{p}$, where p is the period (time/n cycles)
- Then use $\omega_d = \omega_n\sqrt{1-\zeta^2}$ to find ω_n.

RESULTS TO REPORT

Part I:

- Provide a plot of your spin-down test with time on the x-axis and rotor velocity (rad/s) on the y-axis. Be judicious in your choice of $\omega(0)$ so that it is a good representation of the initial velocity. After you select your initial data point, time shift your data so that $t_0 = 0$. There are a significant number of data points for this plot, thus it is only necessary to show a sample calculation as to how you achieved your plotted values.
- Use either the ratio $\omega(t)/\omega(0)$ calculated as a part of the pre-lab assignment, or an exponential curve fitting tool to determine a numerical value for τ, and mark the point $t = \tau$ on the plot of of ω vs. t.
- Determine a numerical value for b_{spin}. Also determine a numerical value for $b_{m,mech}$, the constant for the mechanical damping of the motor and $b_{m,elec}$, the constant for the electrical damping of the motor (Hint, it will be similar in nature to equation 4, which describes b_{DB}.
- From Pittman DC motor data sheet, determine a theoretical value for the damping of the motor, b_m by using the motor time constant and the rotor intertia (similar to the experimental procedure). Compare this theoretical value to the experimentally determined value
- Provide a theoretical plot of $\omega(t)$ vs. t, where t varies from 0 to 3τ, incremented at 0.03 seconds. Use the numerical values you determined for b_{spin} and J_{spin} to generate this plot.

Provide a second plot with your new $\omega(t)$over your original data. Also give a sample calculation for a single point ($\omega(t)$evaluated at a particular time instant).

- Justify the relationship between K_v and K_t by first converting K_v provided in the datasheet to have the same units as K_t. Hint: consider power.

Part II

- Produce a graph of the underdamped system response generated during the setpoint control.
- A table recording the extrema used for log-decrement calculations, or clearly marked extrema using Data Labels in Excel will be acceptable.
- Calculate ζ and ω_n from the extrema using the log-decrement method.
  Use the ζ and ω_n to determine experimental values for b_{virt}, k_{virt}. What then is b_p? Note: for this calculation, you should use the mass moment of inertia for the haptic paddle handle determined in Lab 1. However, for the sake of simplicity (and since many students do not keep accurate records) you may use $J_p = 1.8 \cdot 10^{-4}\ kg \cdot m^2$.
- Produce a theoretical step response of the system using the values determined for $m_{eq}, b_{virt}, k_{virt}$using MATLAB or Simulink. Hint: The pre-lab assignment for Lab 2. MATLAB commands `tf`, `step`, and `StepDataOptions` may be helpful in trying to develop a step response of the system. Also note that `tf` expects the transfer function describing the input/output relationship for the "plant" or the dynamic system of interest, in this case the controlled haptic paddle system in equation 8.

ITEMS TO ADDRESS IN THE DISCUSSION SECTION

- In what ways are the first-order dynamic system and its time response observed in this exercise analogous/dissimilar to the first-order dynamic system and its time response of the RC circuit observed in Lab #2? In what ways is the time constant observed in this exercise analogous/dissimilar to the time constant of the RC circuit observed in Lab #2? Be sure to:
    a. Provide first order EOM
    b. Provide equations for $V_{arm}(t)$ and $\omega(t)$
    c. Explain differences between theoretical and experimental plots for $\omega(t)$
    d. Address similarity/dissimilarity of dynamic systems
    e. Address similarity/dissimilarity of solutions to the 1st order differential equations
- For Part I, hypothesize the relationship you observed during the unit conversion between K_v and K_t. Hint: consider the mechanical design of a DC motor.
- For Part II, compare theoretical (from the model proposed in the pre-lab) and experimental values (determined via the log-decrement method) for k_{virt}. What role does k_{eq} play in this value? Explain any discrepancies.
- For Part II, discuss the accuracy of your model, and consider the presence of steady state error (why doesn't the position go to the setpoint?), and what might cause the error. What is the model neglecting?
- For Part II, hypothesize why the setpoint, x_{ref} was chosen to be zero.
- Examine the role of b_p, determined in Part II in b_{virt}, and how experimentally determining $b_{m,mech}$, (Part I), affects this estimation. Are these experimentally determined parameters compatible? How does the theoretical value for $b_{m,elec}$ affect these estimations? What are the likely sources of error in these measurements? Be specific and thorough! HINT: If by chance, one of the experimentally determined values comes out negative, is this physically

possible? Regardless of the outcome for each of your experimental values, consider each step of the experimental procedure for this lab. What values were estimated or neglected, and how would errors in those estimates affect the results of the experiment? “Errors propagate” is not sufficient discussion.

BONUS DISCUSSION

- Explain the sudden drop in V_{arm} when you flipped the switch on the dynamic brake.
- With the switch in the spin-up position, explain the rapid, high frequency fluctuation in V_{arm}.
- With the switch in the spin-up position, how could you experimentally characterize the voltage constant (assuming the rapid, high frequency fluctuation in V_{arm} could be removed)? Present the necessary equations and measurements to accomplish this.
- What would you do to improve the experiment in Part II?

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1. Kuo, Benjamin C., Automatic Control Systems, 5th edition, 1987, Prentice Hall, Inc, Englewood Cliffs, N.J.
2. http://www-cdr.stanford.edu/Touch/previous_projects/paddle/
3. Bowen, K. and M. K. O’Malley, “Adaptation of Haptic Interfaces for a LabVIEW-based System Dynamics Course,” Proceedings of the 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS), 25-26 March 2006.
4. Ogata, Katsuhiko. Modern Control Engineering, 5th edition, 2010, Prentice Hall Inc, Englewood Cliffs, N.J.

DEPARTMENT OF MECHANICAL ENGINEERING
RICE UNIVERSITY

MECH 343: MODELING DYNAMIC SYSTEMS

Laboratory #6: Haptic Paddle - Virtual Environments and Teleoperation

Due: Midnight *one week after lab session*

THE COMPLETE HAPTIC PADDLE ELECTROMECHANICAL SYSTEM

In the previous labs, the experiments have focused on either developing fundamental understanding of some of the electromechanical elements at work, such as Lab 2: First and Second Order Electrical Systems and Lab 3: Op-Amps, or developing experimentally determined values for the second order paddle model. With both of these goals accomplished, the Haptic Paddle can be fully implemented as a haptic device. As the culmination of the MECH 343 lab curriculum, during this lab exercise, you will explore more virtual systems displayed on the Haptic Paddle. Similarly to Lab 4, the virtual systems are implemented through the use of proportional-derivative (PD) control, including several virtual environments and teleoperation.

BRIEF REVIEW OF CONTROL

As detailed in Lab 4, control utilizes some sort of sensing and actuation system on a physical plant (mass-spring-damper, RLC, thermal, chemical, etc) to extract some desirable performance. In this very specific, traditional technique of proportional-derivative (PD) control, it's straightforward to view the control system as implementing virtual springs and dampers, in the sense that forces will be generated proportionally to the position and velocity just like physical springs and dampers (or the analogous parameters). Equation 1 shows the typical second order model for a typical translational mechanical system, and equations 2 and 3 show that, cleverly designing the input to the system can render the mechanical system's performance to be similar to a different mechanical system represented by equation 4 ($b_{eq}, k_{eq} \neq b_{virt}, k_{virt}$).

$$m_{eq}\ddot{x} + b_{eq}\dot{x} + k_{eq}x = f_{eq} \tag{1}$$

$$f_{eq} = \eta\tau_m = \eta K_t i_{arm} = \eta K_t\left(K_{amp}V_{com}\right) \tag{2}$$

$$V_{com} = -K_d\left(\dot{x} - \dot{x}_{ref}\right) - K_p\left(x - x_{ref}\right) \tag{3}$$

$$m_{eq}\ddot{x} + b_{virt}\dot{x} + k_{virt}\left(x - x_{ref}\right) = 0 \tag{4}$$

In these equations, K_p and K_d are virtual parameters entered into the LabVIEW VI which govern k_{virt} and b_{virt}, respectively. The states $x, \dot{x},$ are measured and calculated by the myRIO and the LabVIEW RT VI. The reference value or set point value, x_{ref}, is input to the system and the control scheme outputs V_{com} such that it is equal to the sum of a force *proportional* to the difference of the position and the reference, a force proportional to the *derivative* of the position (hence the control is referred to as PD).

VIRTUAL ENVIRONMENTS

Every virtual environment in this lab is built using the PD architecture, which is modified to render several different environments. Changing the values of $K_d, K_p,$ and x_{ref} cleverly can yield very different results, and in the lab you will experience several of them. Just like in the previous lab, you will have a chance to experience virtual springs and dampers, but also virtual walls, where control is only implemented on half of the workspace, bumps, and dips, where control is only implemented on a portion of the workspace. Note that Fig. 1 no longer shows the system depicted where $x_{ref} = 0, \dot{x}_{ref} = 0$, and it is precisely the clever selection of these reference positions and velocities (the "setpoint" of the control, or the free length of the virtual spring) that creates the virtual environments.

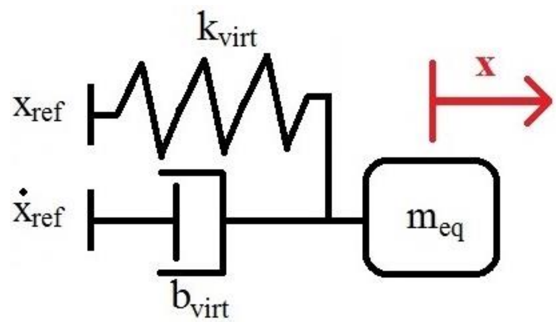

Figure 1: Schematic of Haptic Paddle with virtual spring and damper

TELEOPERATION

Teleoperation is the control of a machine from a remote location, which was pioneered by the likes of Tesla, creating the designs for radio-controlled devices, and scientists looking for ways to work with radioactive materials during the second world war [1]. Often, the machine being teleoperated is a robot. In cases where the teleoperator, or input device, is also a robot, the teleoperator is known as the “master” robot and the teleoperated robot is known as the “slave” robot. The teleoperation scheme implemented in this exercise is depicted in the following figure. The master is the ground reference for the slave, meaning that for the slave device $x_{ref} = x_{master}$. In this way, instead of the haptic paddle being commanded to go to a single point (set point) the paddle is commanded to match the position of the master paddle. The virtual spring connecting the slave to the master is at its "free length" (zero force output) when $x_{master} = x_{slave}$, and the virtual damper between the master and slave exerts no force when $\dot{x}_{master} = \dot{x}_{slave}$. If the master is a force feedback manipulator, such as the Haptic Paddle, then the user can feel the remote environment of the slave via the master, meaning that for the master device, $x_{ref} = x_{slave}$. Note that in this case, the reference for each device is the other device's current position and velocity. Haptics enables this unique bilateral (i.e. two-way) communication and both robots are in effect a master and a slave grounded through their environment or user. The haptic teleoperation scheme implemented in this exercise is depicted in Fig. 2.

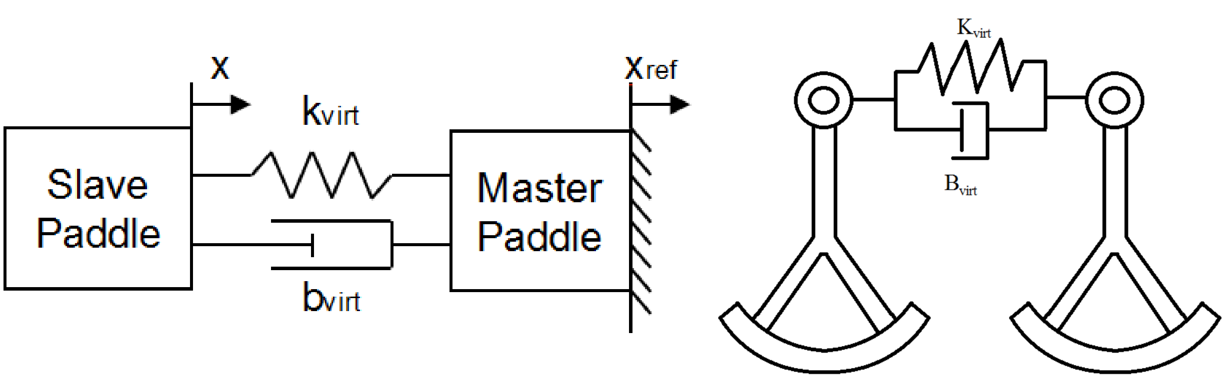

Figure 2: Bilateral teleoperation represented by virtual springs and dampers between paddles

TELEOPERATION – THE HARDWARE

Figure 3: NI myRIO

The NI myRIO is a data acquisition (DAQ) device (similar to the myDAQ) that includes computational hardware called a Field-Programmable Gate Array (FPGA) to perform real-time computation. Unlike on the myDAQ, the control program is downloaded to the myRIO. This allows for faster control loop rates (up to 4,000 Hz for this particular control program, unlike the 100 Hz on the myDAQ), because the controller does not need to communicate continuously with the computer via a USB connection. Once the VI is downloaded to the myRIO via USB or WiFi connection, the program will run autonomously. The myRIO has analog input (AI), analog output (AO), digital input and output (DIO), audio input and output, DC power supplies, and unlike the myDAQ, has control loop rates in the kHz range. Voltage output from the myRIO, like the myDAQ, range is usually ± 10 V, so any voltages in circuits outside this range will be saturated at ± 10 V. As with the myDAQ, the analog input/output channels are accessed via the Mini System Port (MSP) screw terminal connector, seen on the right side of the myRIO in Fig. 11. In order to read a signal using these terminals, secure both the + and – channels, since the myDAQ and myRIO measure the voltage difference between the terminals (just like a DMM measures the voltage between the red and black leads). Using the small screwdriver provided to you, securely fasten bare ends of the wire to the terminal.

The myRIO is capable of outputting a voltage signal to be used as a control signal, but does not have the power to drive a motor. Remember, $Power = Flow \cdot Effort$, and the myDAQ power limits of 500 mW are not enough to drive this particular motor. Therefore, we will be using a servo amplifier (sometimes referred to as simply the "amp"), shown below, and power supply to accomplish this task. Since the tasks for creating the motor signal and powering the motor are often accomplished with different hardware, it is convenient many times to consider each system belonging to either the "signal domain" (Hall Effect sensor, myDAQ/myRIO, and LabVIEW) or the "power domain" (servoamplifier, power supply, and motor).

Figure 4: Servoamplifier (left) and lab station servoamplifier + Power supply

The amplifier at your lab station, the AMC 12A8M Linear Servoamplifier converts a voltage command signal into a current output with a specified gain (the amps here are set to a gain of 1.4 A/V). If you have more questions about the servoamplifier, please ask your TA. The thick red and black wires leading from the +/- MOTOR outputs on the amp will be referred to as the motor amplifier leads. Also note the thinner wires leading to the +/- REF IN ports on the amp. These are the inputs that the amp uses to control its output.

TELEOPERATION – THE SOFTWARE

The control signal for rendering the virtual environments is generated through LabVIEW (Laboratory Virtual Instrument Engineering Workbench), a graphical programming language, like Mathworks' Simulink. For this lab, the virtual environments are managed via a LabVIEW virtual instrument (VI) with variations on a PD control scheme. To better understand the VI, it is suggested that you look qualitatively at the block diagram. The diagram flows from left to right and uses structures (that look like film strips) to clarify the order in which the actions take place:

1. Data acquisition board reads the voltages from the Hall Effect sensors on the paddles
2. Calibration is performed on the voltage signals (just like in Lab 1) to get position in degrees
3. Position signals are differentiated to get velocity signals using a backwards difference calculation, $\frac{Current\ Position - Last\ Position}{Time\ Step}$ and filtered using a Butterworth filter.
4. Position and velocity signals are fed into the control algorithms, which use K_p and K_d gains to calculate a control signal to minimize the error between the paddles' positions.
5. Control signals (voltages) are outputted through analog channels on the myRIO to the servo amplifiers, which send current to the DC motors on the paddles
6. Control, position, and filtered velocity signals are displayed on the front panel.

<u>Adjustable Parameters on the Front Panel Include:</u>

- Hall effect calibration coefficients for "left" and "right" paddles (slope and intercept)
- Sample period (default 500 μs, corresponding to 2,000 Hz loop rate)
- Proportional gain, K_p $\left(default\ value\ of\ 50\frac{V}{m}\right)$
- Derivative gain, K_d $\left(default\ value\ of\ 0.35\ \frac{V \cdot s}{m}\right)$
- Drop-down menu, where the virtual environment is selected. Options include: Virtual Wall, Ridges, Bump, Notch, Tunnel, Unilateral Teleoperation, and Bilateral Teleoperation.

<u>Other Information Displayed on the Front Panel:</u>

- Left and Right Hall sensor voltages, paddle position numeric readouts (degrees)
- Control signal graphs (the output voltages from the myRIO to the servo amplifiers)
- Left and Right paddle position graphs filtered velocity graphs

LABORATORY PROCEDURE

In order to complete this lab procedure, pair up with the group next to your lab station, and combine your paddles into the virtual environment configuration using the following steps.

a) Completely assemble the haptic paddle: Hall Effect sensor mounted, paddle handle rigidly attached to shoulder screw via set screw, and the trantorque and friction drum attached to the motor shaft, and in contact (but not too firm) with the neoprene tape on the paddle handle. If you are not sure, be sure to look at the Lab 1 handout for a reference. The paddle handle should not be difficult to move with just a finger. Most importantly, be sure that the Hall Effect magnet is optimally located under the magnet as shown in Fig. 5.

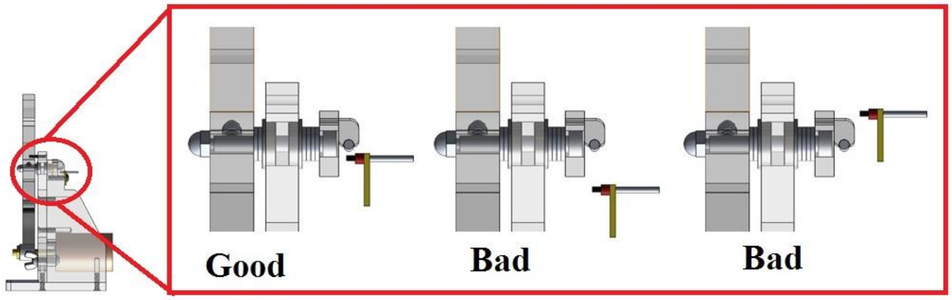

Figure 5: Hall Effect sensor alignment

b) As an arbitrary way to organize this teleoperation, your two paddles will be considered to either be "left" or "right", since the distinctions between master and slave can be obfuscated by bilateral teleoperation of identical devices in close proximity. Using Fig. 6 as the pin out guide for the myRIO, connect the haptic paddle systems in the manner guided by the following steps.

c) Connect the left paddle's Hall Effect sensor to 5V, AGND (located to the immediate left of the Analog Input ports), and AI0+ using the appropriately labeled ribbon cable. Connect the three pin female connector to the Hall Effect sensor with the “arrow” facing up, which will have the same configuration as Fig 7. Note that only one side of this female connector (the end that doesn’t have the male connectors and labels) has an arrow. Connect AI0- to the same AGND using a jumper wire. In a similar fashion, connect the right paddle's hall effect sensors to 5V, AGND, and AI1+. Connect the three pin female connector to the Hall Effect sensor board with the “arrow” facing up. Note that only one side of this female connector (the end that doesn’t have the male connectors and labels) has an arrow. Connect AI1- to the same AGND using a jumper wire. Note that there will be four connections made at this AGND, two Hall Effect ground wires, and two jumper wires connecting to the minus channels of each Analog Input.

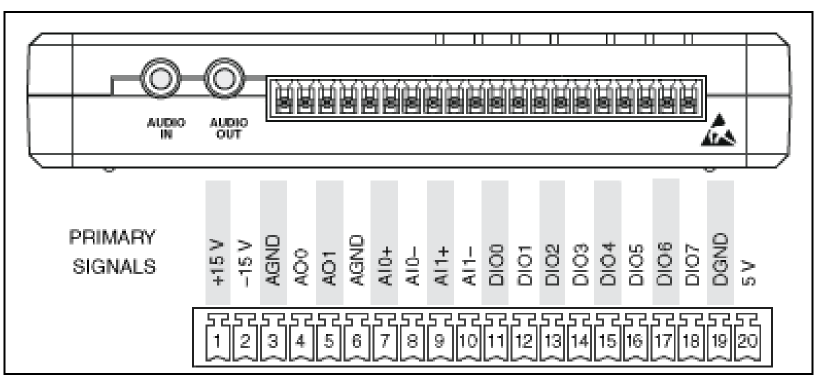

Figure 6: Pinout for NI myRIO

d) Connect AO0 and AGND (located to the left of the Analog Output "AO" ports) to the Ref In + and Ref In - ports on the left paddle servoamp. Similarly, connect AO1 and AGND (located to the left of the Analog Output "AO" ports) to the Ref In + and Ref In - ports on the right paddle servoamp. Now there will be two pins connected to this particular AGND port.

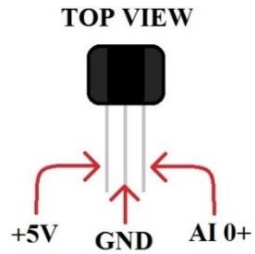

Figure 7: Wiring of the Hall Effect Sensor, with the appropriate myDAQ channels labeled

e) Making sure that the servoamp+power supply is turned off, connect the red Motor + lead to the + terminal of the Pittman DC motor, and connected the black Motor- lead to the - terminal of the Pittman DC motor for each paddle and their respective servoamp+power supply.
f) Clamp both paddles down to table in the upright position, with the paddle handle facing you.
g) Open up the Teleoperation Project from the Haptic Paddle Labs folder on the desktop. Note that the project, not the VI needs to be opened first. Note that the file type of Teleoperation Lab will be "LabVIEW Project". After opening the project, right click the myRIO on the project menu, and see if "Disconnect" is an option. If instead "Connect" is an option, choose "Connect". If the connection attempt fails, repeat, and try resetting the myRIO by unplugging the power cord.
h) Expand the folder on the project labeled with the myRIO, and double click Lab 5 - Virtual Environments and Teleoperation VI, and run the VI with the motor power off (the button light will be off) and use the hall effect voltage readout to recalibrate the hall effect sensor. Note that since the code is downloaded to the myRIO, it will not run instantly as it did with the myDAQ.
i) The VI has a readout for the voltage output from the hall effect sensor. Record 7-10 data points of the voltage readout versus the Paddle position in degrees. A few of the Paddle positions have been marked along the sector pulley (30°, 0° and -30°). Be sure to use the same sign convention for each of the paddles (one direction will be considered positive angular displacement, and the other negative).
j) Use Microsoft Excel to do a linear approximation of your data by plotting Paddle position vs. signal voltage (chart data with scatter plot and add trend line, show equation). Be sure that you plot voltage on x-axis (since we're looking for a relationship with voltage as the input, and position in degrees as the output).
k) Enter the values you determined for the slope and intercept for each paddle into the VI, keeping the left and right paddle nomenclature. Compare positions of your Paddle to the position readout in the VI to confirm the calibration of the sensor.
l) Note that before turning on the servoamplifier, be sure that the VI is running and the hall effect signal is powered and accurately calibrated.
m) If at any time the system becomes unstable, press the stop button on the VI.
n) Have the TA check your setup before moving forward.
o) Turn on motor power and the power to the servoamplifiers.
p) Note that there are nominal control gains for each of the virtual environments. Use these as a starting point for every environment.
q) Begin by selecting the virtual wall button, and choosing the following gains: $K_p = 500, K_d = 1$
r) Now decrease the gains by a factor of 2. Note the difference.
s) Select Ridges. How do you think this virtual environment was implemented?
t) Then select Notch, and use the suggested gains from the VI. Repeat the previous step.
u) Continue on with Bump, and repeat the process.

v) After each of you have investigate the various virtual environments, select unilateral teleoperation. Now your paddles are engaged in a master-slave teleoperation configuration (called unilateral because position/force information only travels one direction). Which paddle is the master? Now reduce the default gains by half and note the difference. What changes?
w) Now select Bilateral teleoperation. As you can tell, force information travels between the paddles, hence "bilateral teleoperation".
x) After you are satisfied that you have experienced all of the virtual environments, understand the effects of changing gains, and have gone back to re-examine any of the environments, disassemble your paddle completely and place it back in the box in which you received it.
y) Plot a course for MECH 420. Engage.

SPECIFIC ITEMS TO ADDRESS IN THE DISCUSSION SECTION

In the discussion section of your report, discuss:

- Haptic Systems
- Haptic Environments explored in this lab. Specifically, what effects gains had on each virtual environment.
- Any discrepancies between theoretical and experimentally determined systems (what did our model neglect that affected performance). Hint: limits of stability and haptic paddle force output could be an interesting discussion point.
- A “scavenger hunt” detailing why each lab (#0-4) support this ultimate lab exercise
- Feedback for next year’s MECH 343

REFERENCES

1. Peter F. Hokayem, Mark W. Spong, Bilateral teleoperation: An historical survey, Automatica, Volume 42, Issue 12, December 2006, Pages 2035-2057, ISSN 0005-1098.