ASEN 2003 LAB 6: ROTARY POSITION CONTROL EXPERIMENT

- Assigned: Wednesday, April 12, 2017
- Report Due: Monday, May 1, 2017

1 OBJECTIVES

- Design a controller for a second order system
- Observe and characterize the step response of a closed loop control system for a rotary positioner
- Compare the controller performance for a rigid and flexible arm structure
- Apply knowledge of second order systems, vibrations, and control to a real system

2 BACKGROUND

Control is a key component of aerospace systems on both large and small scales. For example, to successfully fly an inherently unstable fighter aircraft, complex control systems for coordination of thrust and control surface adjustments are required. In addition, the very motion of an actuator or control surface such as an aileron requires a smaller and simpler controller to ensure that the desired actuator position is achieved given varying aerodynamic loads. A similar situation occurs on a spacecraft where solar panels are positioned so as to maximize the incident radiation. Clearly the performance requirements for the two examples are quite different, both in terms of the required accuracy and response time of the system.

In this lab we will consider a simple control task that plays an important role in many dynamic systems relevant to aerospace, as well as other engineering disciplines. The objective is to position an arm mounted on a rotary shaft. We will consider two types of loads - a rigid arm rigidly mounted to the shaft and a flexible arm rigidly mounted to the shaft. The actuator is a DC motor that drives the shaft through a gearbox. The angular position of the shaft is sensed using a potentiometer. In addition, there is a wheatstone bridge of strain gauges to measure the deflection on the flexible arm. In order to effectively position the arm, we need to formulate a dynamic model of both the mechanical and electrical aspects of the system. A control strategy is then developed to achieve a desirable response - i.e. we want the arm to move to the desired position quickly, and accurately, without a lot of overshoot or vibration. These control requirements will be defined mathematically in the following sections.

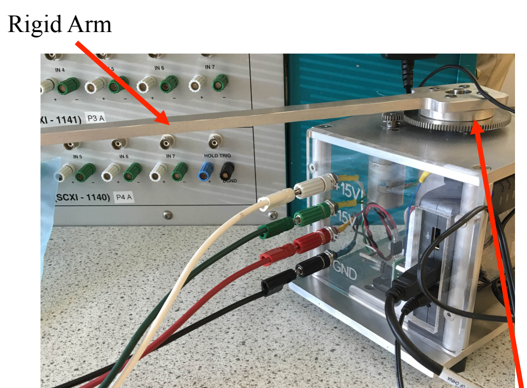

Figure 1: Rigid Arm Module

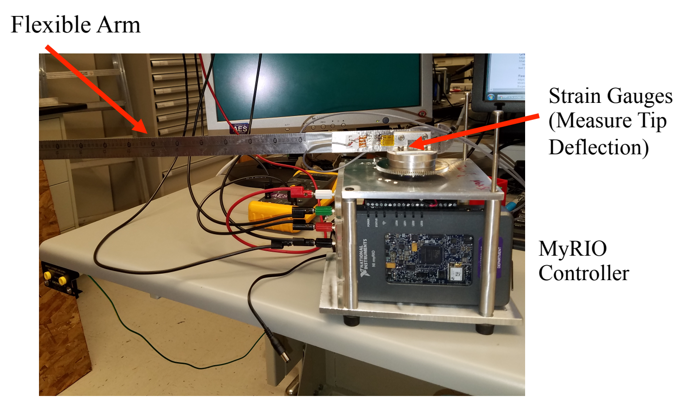

Figure 2: Flexible Arm Module

To be more specific, the goal of the experiment is to use a DC motor and gearbox to control the position of a rotary shaft as shown in the photographs in Figure 1. The equipment includes a motor and plant assembly designed in the CU Aerospace Instrumentation Lab, and the ITLL workstation with a LabVIEW ".vi". The LabVIEW program commands a myRIO microcontroller to output commanded voltages via a built in digital to analog converter (D/A). The voltage is applied to the input of the DC motor and determines the torque applied by the motor. The gearbox drives an output shaft to which we mount the rigid or flexible arm that is to be positioned. The rotary position of the arm is sensed by a potentiometer at the output shaft and this is fed back into the microcontroller. This provides the feedback data to the controller that is implemented in LabVIEW.

Your primary task is to observe the nominal controller response and see how changes in the control gains affect performance. You will simulate both the rigid and flexible arms in order to predict the response of the systems for the control gains you choose. The following sections develop the dynamic models for both systems. Part of your assignment will be to use the attached documentation to determine the actual values for this model. Section 3 gives the specific requirements of the experiments you will perform.

2.1 Position Servo - DC Motor, Signal Conditioning, Gearbox, and Output Shaft

(References: Woods and Lawrence, Ch. 7.2; Apkarian, Section 2.1.)

The position servo consists of a DC servomotor with a built-in gearbox. The output of the gearbox is attached through a hub gear to a shaft for mounting the arm above, and to a potentiometer below that reads the angular position of the shaft. The input voltage to the motor ultimately controls the angular velocity of the arm, or *load* on the motor. Thus, we must relate V_{in} to the load angular velocity ω_L and angular position, θ_L.

The speed of the DC motor, ω_m, is determined by the input voltage, V_{in}, as follows,

$$\begin{aligned} V_m &= K_m \omega_m \\ V_{in} &= V_m + I_m R_m = K_m \omega_m + I_m R_m \end{aligned} \tag{1}$$

The total input voltage V_{in} is the sum of the ideal motor voltage, V_m, and the voltage drop due to the output resistance of the motor (R_m). This voltage is the product of the motor current I_m and the output motor resistance R_m. K_m is the proportional motor constant which relates the speed to the motor voltage. Note that the motor and arm speeds, ω_m and ω_L respectively, may be time varying.

The torque (or moment) generated by the motor is a function of the motor current, I_m and the motor constant K_m:

$$M_m = K_m I_m \tag{2}$$

It turns out that same proportionality constant, K_m appears in both relationships (Eq. 1 and 2). In Eq. 1 it appears to be in units of Volts/ (rad/s) = Volt-s and in Eq. 2 in units of N-m/Amp. These units can be related through the relationships for mechanical and electrical power: Watt = N-m/s = Volt-Amp. So, N-m/Amp = (Volt-Amp-s)/Amp = Volt-s. The values for the constants are exactly the same for an ideal motor.

The motor drives a gearbox connected to an output shaft. The effect of the gear train is to reduce the speed of the motor (ω_m) to the speed of the output shaft (ω_L) by the gear ratio, K_g:

$$\omega_m = K_g \, \omega_L \tag{3}$$

The torque of the motor (M_m) is then is related to the moment of the output shaft (M_o) thru the gear ratio:

$$M_m = M_o / K_g \tag{4}$$

The output shaft torque can now be expressed in terms of the motor parameters and the spin rate of the shaft using Equations 1-4, as shown here:

$$M_O = K_g K_m I_m = \frac{K_g K_m}{R_m}\left(V_{in} - K_g K_m \omega_L\right) \tag{5}$$

The mechanical and electrical parameters for the motor and gearbox are given in the equipment specification in the accompanying spreadsheet.

2.2 Rigid Arm Dynamics

The torque or moment produced by the output shaft is what drives the arm, governed by Newton's equations. The angle of the arm (or output shaft) is denoted by, θ_L. The first derivative of θ_L is the speed of the output shaft, ω_L. The second derivative of θ_L is the angular acceleration of the load. The equation of motion is determined by summing the moments about the (fixed) output shaft as follows,

$$J\ddot{\theta}_L + B\dot{\theta}_L + M_L = M_o \tag{6}$$

Or in terms of the angular rate of the load,

$$J\dot{\omega}_L + B\omega_L + M_L = M_o \tag{7}$$

Where J is the moment of inertia about the shaft, B is a damping coefficient, and M_L accounts for any disturbing moments applied to the shaft by the load. Note that the angle of the output shaft does not appear explicitly in Eq. (6) or (7). Only the speed and acceleration of the load are determined completely by the input voltage.

Now substituting for the torque exerted by the shaft from Eq. (5) we have,

$$\begin{aligned} J\dot{\omega}_L + B\omega_L + M_L &= \frac{K_g K_m}{R_m}\left(V_{in} - K_g K_m \omega_L\right) \\ \dot{\omega}_L + \left(\frac{B}{J} + \frac{K_g^2 K_m^2}{JR_m}\right)\omega_L &= \frac{K_g K_m}{JR_m}V_{in} - \frac{M_L}{J} \end{aligned} \tag{8}$$

For now we will ignore friction (B=0) and assume there are no disturbances (M_L=0), so Eq. (8) simplifies to,

$$\dot{\omega}_L + \left(\frac{K_g^2 K_m^2}{JR_m}\right)\omega_L = \frac{K_g K_m}{JR_m}V_{in} \tag{9}$$

Then, by using the very useful mathematical tool of Laplace Transforms, Eq. 9 becomes:

$$s\Omega_L + \left(\frac{K_g^2 K_m^2}{JR_m}\right)\Omega_L = \frac{K_g K_m}{JR_m}\mathbf{V}_{in} + \omega_L(0) \tag{10}$$

Where $\mathbf{V}_{in} = L\{V_{in}\}$ is used to represent the Laplace Transform of Vin and Ω_L is the Laplace of the speed ω_L.

The moment of inertia, J, is actually a combination of the hub inertia and the inertia due to the added load. This effective moment of inertia is given by,

$$J = J_{hub} + J_{load} \tag{11}$$

Then, the *open loop transfer function* of the system, relating the input voltage to the *load speed* is given by,

$$\frac{\Omega_L}{\mathrm{V}_{in}} = \frac{K_g K_m / JR_m}{s + K_g^2 K_m^2 / JR_m} \tag{12}$$

We represent Θ_L as the Laplace Transform of θ_L and by using the Laplace Transforms, therefore the

Open loop transfer function relating input voltage to the ***position*** of the load is given by:

$$\boxed{\frac{\Theta_L}{V_{in}} = \frac{K_g K_m / JR_m}{s\left(s + K_g^2 K_m^2 / JR_m\right)}} \tag{13}$$

We recognize Eq. (12) as the transfer function for a first order system with time constant,

$$\tau = \frac{JR_m}{K_g^2 K_m^2} \tag{14}$$

The output angle is just the integral of the output speed as shown by the extra 1/s term in Eq. 13.

This system model says that given the physical and electrical characteristics of the motor, gearbox, and load, the load speed is completely determined by the value of the input voltage. Thus, it appears that the load speed may be perfectly controlled in an open loop mode - no feedback control is required. However, the model also shows that it is not possible to set a particular output position in an open loop mode. This is because the transfer function has a pole at the origin. This integrator makes it impossible to set the actual value without modifying V_{in} to depend in some way on the output angle. This will be the task of the *closed loop controller*. In addition, our idealized simplifications in the system model have hidden inherent realities in open loop control of the speed, e.g. the effects of friction and any nonlinearities or deadband in the motor (where the motor does not begin to spin until a certain threshold voltage is applied).

2.3 Rigid Arm Control System Design

A feedback control scheme determines the time varying input voltage to apply based on measurements of the system. In the case of the rotary position servo, the measurement consists of the angle of the shaft measured by the potentiometer. In addition there might be a rate sensor or tachometer, or the angular rate might be derived from the angle measurements by calculating the derivative. A typical approach is to use a proportional plus derivative (PD) controller. The PD controller applies a voltage that is the sum of a term proportional to the angle error and a term proportional to the angle rate. Mathematically this is given by,

$$V_{in} = K_p\left(\theta_D - \theta_L\right) + K_d\left(\dot{\theta}_D - \dot{\theta}_L\right) \tag{15}$$

Where θ_D is the desired output angle. The particular selections of K_p and K_d, in conjunction with the natural characteristics of the system given in Eq.13 above, determine the response of the system.

For a constant desired angle the desired angle rate is zero and the Laplace Transform of Vin as given in Eq. (15) is,

$$V_{in} = V_{PD} = K_p\left(\Theta_D - \Theta_L\right) - sK_d\Theta_L \tag{16}$$

(Assuming that both the initial angle and angular rate are zero.)

Substituting Eq. (16) into Eq. (13) above, and solving for the ***closed loop transfer function*** from Θ_D to Θ_L gives,

$$\boxed{\frac{\Theta_L}{\Theta_D} = \frac{K_p K_g K_m / JR_m}{s^2 + \left(K_g^2 K_m^2 / JR_m + K_d K_g K_m / JR_m\right)s + K_p K_g K_m / JR_m}} \tag{17}$$

The denominator is seen to be the characteristic polynomial for a 2nd order linear system. Note that there is a non-zero damping term even without the derivative control term; thus, using only proportional control the system can be brought to a desired angle. The performance of the system may not be good in that it might take too long to achieve the desired result or there might be too much overshoot.

The dynamic characteristics of this second order system are:

$$\begin{aligned} \omega_n^2 &= \frac{K_p K_g K_m}{J R_m} \\ \zeta &= \frac{K_g^2 K_m^2 + K_d K_g K_m}{2\sqrt{K_p K_g K_m J R_m}} \end{aligned} \tag{18}$$

If there is friction in the shaft or a dead-band in the motor, there will a steady-state offset between the actual and desired output positions. This may be corrected through the use of an additional gain on the integral of the angle error, so that

$$V_{in} = V_{PD} = K_p\left(\Theta_D - \Theta_L\right) + \frac{K_i}{s}\left(\Theta_D - \Theta_L\right) - sK_D\Theta_L \tag{19}$$

The integrator gain, Ki, must be kept small to prevent instability in the system. The computation of the closed loop transfer function with the full PID controller is left as an exercise for the interested student.

2.4 Flexible Arm Dynamics

Recall from the posted course notes that we can model a cantilever beam as a spring-mass-damper system. Thus, the flexible arm dynamics can be modeled as the rigid arm (a spring-mass-damper system) plus an additional spring-mass-damper. See Figure 2.

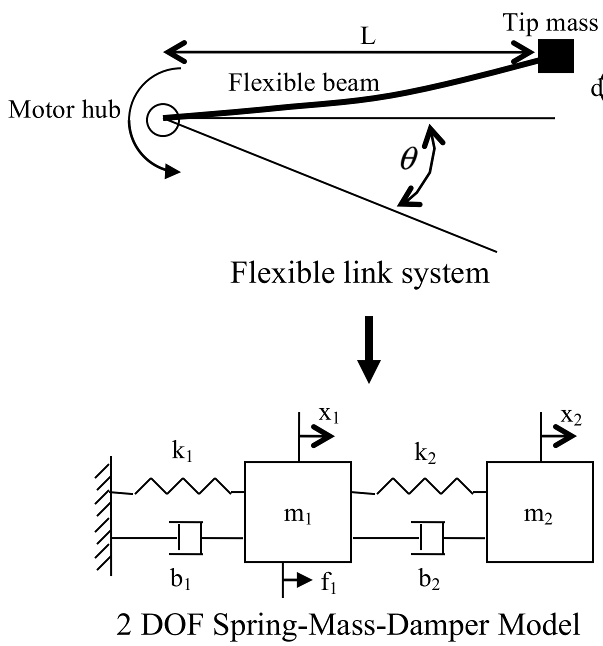

Figure 2. Modeling the flexible arm as a two DOF spring-mass-damper system

In order to apply the two DOF spring-mass-damper model to our system, we observer the following equivalence:

Parameter	Generic model	Flexible arm
mass 1	m_1	J_{hub}
mass 2	m_2	$J_L = J_{hub} + J_{arm}$
Spring 1	k_1	0 (rigid)
Spring 2	k_2	K_{arm}
Damper 1	b_1	0 (assumed)
Damper 2	b_2	0 (assumed)
Displacement 1	x_1	θ
Displacement 2	x_2	θ+d/L
Relative displacement	x_2-x_1	d/L
Force 1	f_1	M

The equations of motion of the two DOF spring-mass-damper system can be derived by applying Newton's 2nd Law to each mass. We will not go through the full derivation here, however, the resulting system has the two coupled differential equations given below:

$$\ddot{\theta} = -\frac{K_g^2 K_m^2}{J_{hub} R_m}\dot{\theta} + \frac{K_{arm}}{J_{hub}}\frac{d}{L} + \frac{K_g K_m}{J_{hub} R_m} V_{in} = p_1\dot{\theta} + q_1 d + r_1 V_{in} \tag{20}$$

$$\ddot{d} = \frac{K_g^2 K_m^2}{J_{hub} R_m} L\dot{\theta} - \frac{K_{arm}\left(J_{hub} + J_L\right)}{J_{hub} J_L} d - \frac{K_g K_m L}{J_{hub} R_m} V_{in} = p_2\dot{\theta} + q_2 d + r_2 V_{in} \tag{21}$$

where the constants $p_1, q_1, r_1, p_2, q_2, r_2$ are used to simplify notation so:

$$\begin{gathered} p_1 = -\frac{K_g^2 K_m^2}{J_{hub} R_m} \quad q_1 = \frac{K_{arm}}{L \cdot J_{hub}} \quad r_1 = \frac{K_g K_m}{J_{hub} R_m} \\ p_2 = \frac{K_g^2 K_m^2 L}{J_{hub} R_m} \quad q_2 = -\frac{K_{arm}\left(J_{hub} + J_L\right)}{J_L \cdot J_{hub}} \quad r_2 = -\frac{K_g K_m L}{J_{hub} R_m} \end{gathered} \tag{22}$$

Notice that Equation 20 is equivalent to Equation 9 plus a coupling term that is a function of the displacement *d*. The ***open loop transfer functions*** from input voltage to load angle and arm displacement are:

$$\boxed{\begin{aligned} \frac{\Theta_L}{V} &= \frac{r_1 s^2 + \left(r_2 q_1 - r_1 q_2\right)}{s^4 - p_1 s^3 - q_2 s^2 + \left(p_1 q_2 - q_1 p_2\right)s} \\ \frac{D}{V} &= \frac{r_2 s^2 - \left(p_1 r_2 - p_2 r_1\right)s}{s^4 - p_1 s^3 - q_2 s^2 + \left(p_1 q_2 - q_1 p_2\right)s} \end{aligned}} \tag{23}$$

2.5 Flexible Arm Control Design

Control of the flexible arm is complicated by the presence of the flexible link (and what we call a second *dynamic mode*). In order to see the difficulty posed by the added dynamics, apply the same gains you select for the rigid arm to the flexible arm and compare the responses. One approach to address the complex dynamics of the two DOF system is to add more sensors. This is exactly what we have done.

In order to measure the deflection of the arm tip *d*, a strain gauge is attached to the arm to measure the flexion of the arm and thus the deflection of the tip. Given this measurement and the hub angle measurement we also have for the rigid arm, we can express a new proportional-derivative control law that uses both sensors:

$$V_{in} = K_{P\theta}\left(\theta_D - \theta_L\right) + K_{D\theta}\left(\dot{\theta}_D - \dot{\theta}_L\right) + K_{Pd}\left(d_D - d\right) + K_{Dd}\left(\dot{d}_D - \dot{d}\right) \tag{24}$$

where d_D is the desired displacement.

Typically we want the desired tip displacement to be zero so that the beam is straight. We also want the system to come to rest ($\dot{\theta}_D = 0, \dot{d}_D = 0$), yielding the following equation for the control input

$$V_{in} = K_{P\theta}(\theta_D - \theta_L) - K_{D\theta}\dot{\theta}_L - K_{Pd}d - K_{Dd}\dot{d} \tag{25}$$

An equation for the closed loop behavior of this system can be calculated by taking the Laplace Transform of Equation 25 and substituting in the transfer functions derived from Equation 20 and Equation 21. The derivation for this step is not given here. Using the constants defined above the ***closed loop transfer functions*** are

$$\boxed{\begin{aligned} \frac{\Theta_L}{\Theta_D} &= \frac{K_1\left[r_1 s^2 + (q_1 r_2 - r_1 q_2)\right]}{s^4 + \lambda_3 s^3 + \lambda_2 s^2 + \lambda_1 s + \lambda_0} \\ \frac{D}{\Theta_D} &= \frac{K_1\left[r_2 s^2 + (p_2 r_1 - r_2 p_1)s\right]}{s^4 + \lambda_3 s^3 + \lambda_2 s^2 + \lambda_1 s + \lambda_0} \end{aligned}} \tag{26}$$

where

$$\begin{aligned} \lambda_3 &= -p_1 + K_3 r_1 + K_4 r_2 \\ \lambda_2 &= -q_2 + K_1 r_1 + K_2 r_2 + K_4(p_2 r_1 - r_2 p_1) \\ \lambda_1 &= p_1 q_2 - q_1 p_2 + K_3(q_1 r_2 - r_1 q_2) + K_2(p_2 r_1 - r_2 p_1) \\ \lambda_0 &= K_1(q_1 r_2 - r_1 q_2) \end{aligned} \tag{27}$$

and

$$\begin{aligned} K_1 &= K_{p\theta} \\ K_2 &= K_{pd} \\ K_3 &= K_{D\theta} \\ K_4 &= K_{Dd} \end{aligned}$$

2.6 Loads: Rigid Arm - Rigid Joint, Rigid Arm - Flexible Joint, Flexible Arm

Two loads may be attached to the rotary positioner – a rigid arm with a rigid mount and a flexible arm. For both the rigid and flexible arm systems, angle measurements of the shaft position (and therefore the arm) with respect to the shaft θ_L are read by a LabVIEW VI. For the flexible arm system, there are additional strain gauges that provide a measurement of the tip deflection (d) from the centerline of the motor base.

A PD (proportional, derivative) controller may be implemented using the LabVIEW VI. The control objective for a system like this might be to find the best control parameters to bring the tip of the arm to rest at some distance from the initial position. You will compare the step responses of the different systems for various proportional and derivative feedback gains.

2.7 LABVIEW .vi

The LabVIEW .vi, written by Bobby Hodgkinson reads the measurement data from the A/D converter, displays and records the angle and rate data as a function of time, and implements four feedback gains that may be adjusted by the user.

The measurements read by the .vi are the voltages from the output shaft potentiometer and the strain gauge system developed by Trudy Schwartz. These values are converted to angle and tip deflection measurements that are recorded and used for computation of the control output. The derivatives of the measurements (i.e. the rotation rates) are computed numerically.

The gains that can be set by the user are as follows:

K1 – Proportional gain applied to the hub angle measurement
K2 – Proportional gain applied to the tip sensor measurement
K3 – Derivative gain applied to the hub angle rate
K4 – Derivative gain applied to the tip sensor rate

The user may command a step input to the controller or command it to rotate at a given rate through an angle of up to +/- 25 degrees, or about 0.45 radians. This is limited by your gain selection combination and the maximum output voltage to the motor from the myRIO. Smaller commanded step angles can also be used to improve performance.

3 Theory and Simulation

1. Derive Equation 17 and Equation 18 beginning with Equation 13. (Hint: First, solve Equation 13 for V_{in}.) Substitute the resulting expression into Equation 16. Finally, arrange like terms and divide through to get the closed loop transfer function.)

2. Develop a MATLAB simulation of the closed loop behavior of the rigid arm (Equation 17). Use the physical and electrical parameters given in the spreadsheet to determine the parameters for the equations of motion derived above. The following sample code can be used (you provide the values for the coefficients:

```
%%% Closed loop system
num = n1;
den = [d2 d1 d0];
sysTF = tf(num,den);

%%% Step response
% thetad = desired arm angle (scalar)
[x,t] = step(sysTF);
theta = 2*thetad*x;
figure(1);clf;
plot(t,theta);
```

   Note 1: The hardware travels up to about +/- 0.45 radians for desired angle θ_D, and you will need to shift the data to model this as a step function from 0 to 0.9 radians or **whatever desired θ_D** you chose to test.
   Note 2: You will want to scale the unity step function in Matlab by the total desired angle range traveled to compare the model with the experimental data.
   Note 3: You can also use the `lsim` command in MATLAB to find the theoretical response of your system to a specified input u(t). This is useful in comparisons with the experimental data where the reference or commanded hub angle values and time are also recorded on the data file.

3. Use the simulation developed for Part 2 in order to investigate the behavior of the step response of the Rigid Arm system for different values of proportional and derivative gain. Select several sets of values that give "reasonable" behavior. (Use your engineering judgment to define "reasonable").
   Keep in mind that the input voltage to the motor is limited by $|V_{in}| < 5 volts$, which directly relates to the θ_D that you can achieve and varies for each Unit # based on friction, gear alignment, bearings, etc.
   Rigid Arm Design Requirements: Using your knowledge of 2nd order systems and the transfer function for this system to compute gain values for the rigid arm that will have no overshoot and achieve 5% settling in less than 0.5 seconds without exceeding the 5V limit on Vin.

4. Simulate Equations 26 in MATLAB to investigate the behavior of the step response of the closed loop flexible arm system for different values of proportional and derivative gain. Investigate several sets of values that give "reasonable" behavior. Note, there are many possible solutions to this more complex system. Use an iterative approach to vary the gains and plot the performance in order to design your gains.
   Flexible Arm Design Requirements: Choose one set of gains that does not overshoot, achieves 5% settling time in less than 1 second, and reduces tip deflection to less than 0.5 cm of residual vibrations.

The following MATLAB commands may be helpful in developing your simulations: tf, step, lsim. Type help function_name to learn more about the functions.

4 Experiment

1. Sketch a functional block diagram of one of the systems. Identify the input and output of each block and the function of each block. Also, show a control block diagram for the system showing the Transfer Functions, etc. Make sure you understand what is being done by the arm, the sensors, the myRIO, the actuator and the LabVIEW VI.
2. Explore the behavior of the rigid arm with only proportional feedback on the hub angle. Record the step response with several K1 values. Add derivative control (K3) and redo the experiment with the same proportional gain values. How does the behavior change?
3. Explore the behavior of the flexible arm with only proportional feedback. In your lab notebook, sketch the types of motion seen and describe in words what you observed. First try using only proportional gain on the hub measurement. Add in the tip deflection feedback and record the step response with several K1 & K2 values. Add derivative control and redo the experiment with the same proportional gain values. How does the behavior change?
4. In what ways are the two systems the same? How are they different? Which can be controlled more precisely?
5. Implement the gain values you chose in (3.3) to achieve the desired requirements for the rigid arm in the system and record the results. Start with modeled gains and then experimentally tune them as needed.
6. Implement your selected flexible arm gains from (3.4) that meet the desired requirements. Implement these gains in the system and record the results. Start with modeled gains and then experimentally tune them as needed.

5 Results and Analysis

1. For the rigid arm, plot and compare the experimental results with the model results for the no overshoot gains you chose in (3.3) and for one other case that you performed. Describe your results qualitatively. Label on your plots, the overshoot and 5% settling time observed.
2. For the flexible arm, plot and compare the experimental results with the model results for the gains you chose in (3.4) and for one other case that you performed. Describe your results for the hub angle and the tip deflection. Label on your plots, the overshoot and 5% settling time observed for the hub angle.
3. For each case, discuss the results and explain how and why you think the experimental results differ from theory.
4. Discuss the results and explain how and why you think the flexible arm results differ from the rigid arm. What are the implications of this for controlling a flexible structure?

6 REPORT CONTENTS

Title Page - Lab# and Title, Course Number, Student Names, Date Submitted

Abstract - Briefly summarize the rest of the report including the objectives of the lab, what was actually done, the most important qualitative and quantitative results, and your conclusions.

Theory

- Present the derivation of the closed loop transfer function for the rigid arm from (3.1).
- Explain how you selected the gains for the rigid and flexible arms.
- Show control block diagram with derived Transfer Functions, etc.

Experiment

- Describe the experimental setup using your functional block diagram and a photo or sketch of the equipment.
- Describe the data collection procedure and give a summary of the trials you performed.
- Note any events or glitches that may affect specific experimental data items.

Results and Analysis

- Describe, tabulate & plot results, as described in Section 5.
- Answer the analysis questions in Section 5.

Conclusions and Recommendations – Summarize your lab experience and what was learned. Suggest possible improvements to the experimental setup or procedures.

Acknowledgements - Describe assistance or contributions provided by classmates or others (not including group members who authored the report).

References - List reference material used in professional format. Each reference must be cited in the text.

Appendix A – List the contributions of each member of the group and have each group member initial this page.

Appendix B, C, etc - Include any computer code you used to compute values or generate plots.

6.1 REPORT GRADING

	Title Page
5	Abstract
15	Theory
25	Experiment
35	Results & Analysis
5	Conclusions and Recommendations
15	(Style and Clarity - includes title page, toc, organization, references, appendices, grammar, spelling)
100	