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STUDENT WORKBOOK

SRV02 Base Unit Experiment For LabVIEW™ Users

Standardized for ABET* Evaluation Criteria

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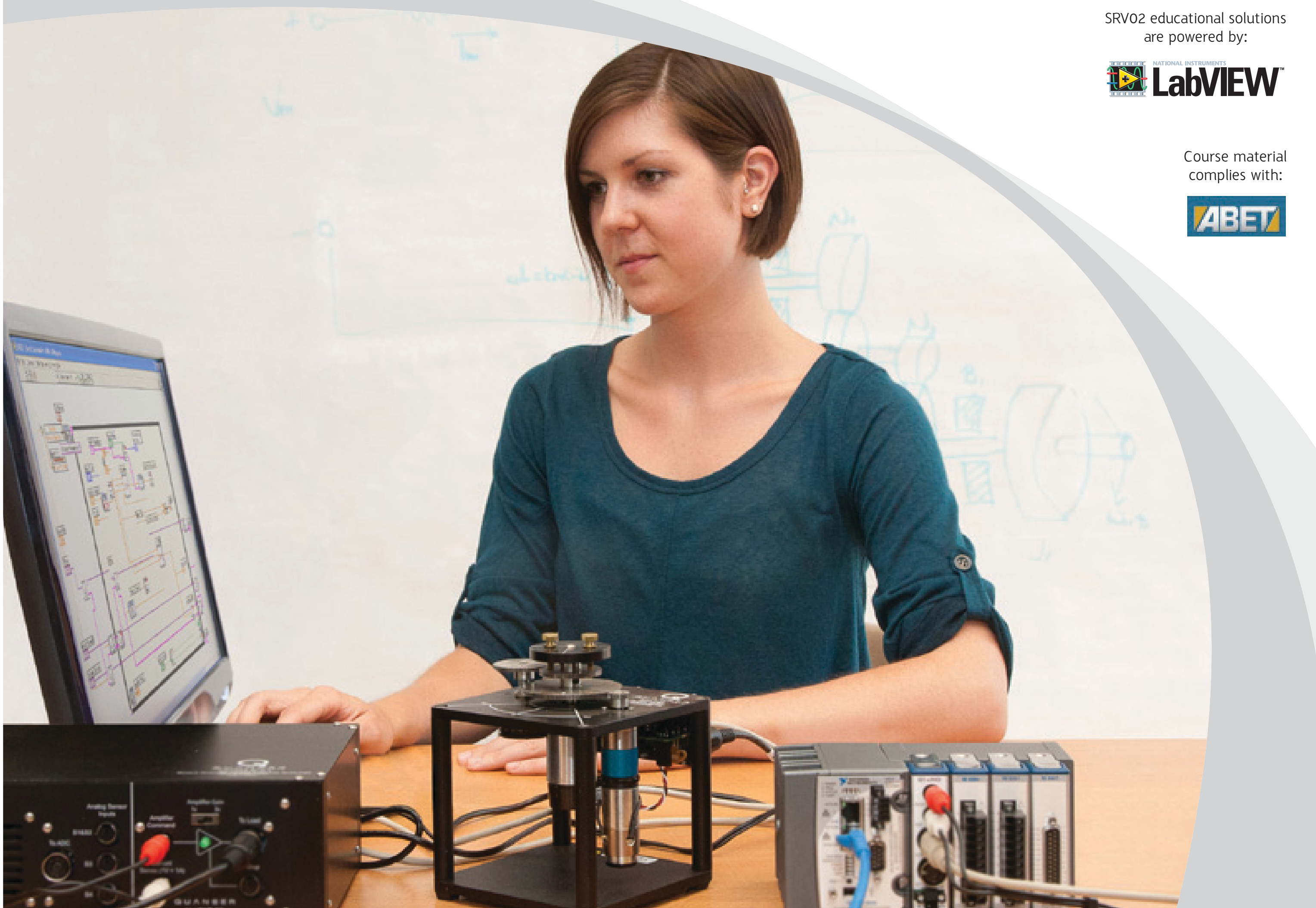

SRV02 educational solutions are powered by: LabVIEW

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CONTENTS

PREFACE

Every laboratory chapter in this manual is organized into four sections.

Background section provides all the necessary theoretical background for the experiments. You should read this section first to prepare for the Pre-Lab questions and for the actual lab experiments.

Pre-Lab Questions section provides targetted questions for preliminary calculations that need to be done prior to the lab experiments. You should go through these questions and try to answer them using the background materials and the references given at the end of the manual.

Lab Experiments section provides you with step-by-step instructions to conduct the lab experiments and to record the collected data.

System Requirements section describes all the details of how to configure the hardware and software to conduct the experiments. It is assumed that the hardware and software configuration have been completed by the instructor or the teaching assistant *prior* to the lab sessions. If not, you can configure the systems by following the instructions given in this section.

When you write your lab report, you should use the specific template for content given at the end of each laboratory chapter. A section on *Tips for Report Format* is also provided at the end of each laboratory chapter.

LABORATORY 1

SRV02 MODELING

The objective of this experiment is to find a transfer function that describes the rotary motion of the SRV02 load shaft. The dynamic model is derived analytically from classical mechanics principles and using experimental methods.

Topics Covered

- Deriving the dynamics equation and transfer function for the SRV02 servo plant using the first-principles.
- Obtaining the SRV02 transfer function using a frequency response experiment.
- Obtaining the SRV02 transfer function using a bump test.
- Tuning the obtained transfer function and validating it with the actual system response.

Prerequisites
In order to successfully carry out this laboratory, the user should be familiar with the following:

- Data acquisition device (e.g. Q2-USB), the power amplifier (e.g. VoltPAQ-X1), and the main components of the SRV02 (e.g. actuator, sensors), as described in References [1], [2], and [4], respectively.
- Wiring and operating procedure of the SRV02 plant with the amplifier and data-aquisition (DAQ) device, as discussed in Reference [4].
- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Laboratory described in Appendix A to get familiar with using LabVIEW™ with the SRV02.

1.1 Background

The angular speed of the SRV02 load shaft with respect to the input motor voltage can be described by the following first-order transfer function

$$\frac{\Omega_l(s)}{V_m(s)} = \frac{K}{(\tau s + 1)} \tag{1.1.1}$$

where $\Omega_l(s)$ is the Laplace transform of the load shaft speed $\omega_l(t)$, $V_m(s)$ is the Laplace transform of motor input voltage $v_m(t)$, K is the steady-state gain, τ is the time constant, and s is the Laplace operator.

The SRV02 transfer function model is derived analytically in Section 1.1.1 and its K and τ parameters are evaluated. These are known as the nominal model parameter values. The model parameters can also be found experimentally. Sections 1.1.2.1 and 1.1.2.2 describe how to use the frequency response and bump-test methods to find K and τ. These methods are useful when the dynamics of a system are not known, for example in a more complex system. After the lab experiments, the experimental model parameters are compared with the nominal values.

1.1.1 Modeling Using First-Principles

1.1.1.1 Electrical Equations

The DC motor armature circuit schematic and gear train is illustrated in Figure 1.1. As specified in [4], recall that R_m is the motor resistance, L_m is the inductance, and k_m is the back-emf constant.

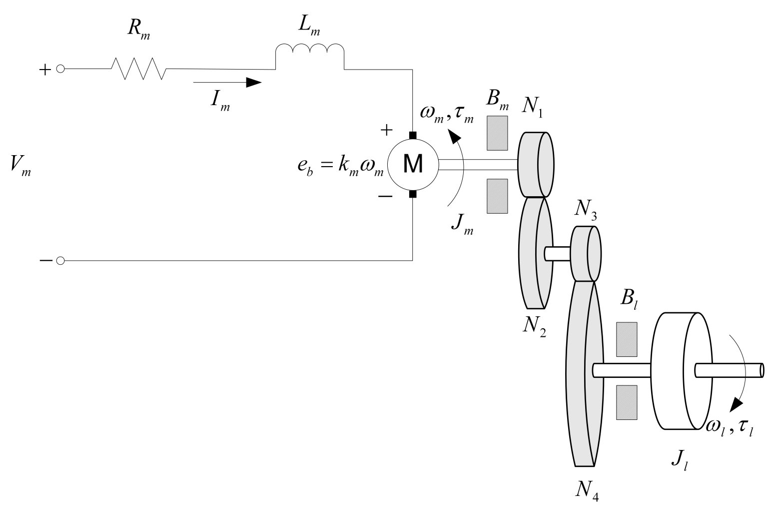


Figure 1.1: SRV02 DC motor armature circuit and gear train

The back-emf (electromotive) voltage $e_b(t)$ depends on the speed of the motor shaft, ω_m, and the back-emf constant of the motor, k_m. It opposes the current flow. The back emf voltage is given by:

$$e_b(t) = k_m\omega_m(t) \tag{1.1.2}$$

Using Kirchoff's Voltage Law, we can write the following equation:

$$V_m(t) - R_m I_m(t) - L_m\frac{dI_m(t)}{dt} - k_m\omega_m(t) = 0 \tag{1.1.3}$$

Since the motor inductance L_m is much less than its resistance, it can be ignored. Then, the equation becomes

$$V_m(t) - R_m I_m(t) - k_m\omega_m(t) = 0 \tag{1.1.4}$$

Solving for $I_m(t)$, the motor current can be found as:

$$I_m(t) = \frac{V_m(t) - k_m \omega_m(t)}{R_m} \quad (1.1.5)$$

1.1.1.2 Mechanical Equations

In this section the equation of motion describing the speed of the load shaft, ω_l, with respect to the applied motor torque, τ_m, is developed.

Since the SRV02 is a one degree-of-freedom rotary system, Newton's Second Law of Motion can be written as:

$$J \cdot \alpha = \tau \quad (1.1.6)$$

where J is the moment of inertia of the body (about its center of mass), α is the angular acceleration of the system, and τ is the sum of the torques being applied to the body. As illustrated in Figure 1.1, the SRV02 gear train along with the viscous friction acting on the motor shaft, B_m, and the load shaft B_l are considered. The load equation of motion is

$$J_l \frac{d\omega_l(t)}{dt} + B_l \omega_l(t) = \tau_l(t) \quad (1.1.7)$$

where J_l is the moment of inertia of the load and τ_l is the total torque applied on the load. The load inertia includes the inertia from the gear train and from any external loads attached, e.g. disc or bar. The motor shaft equation is expressed as:

$$J_m \frac{d\omega_m(t)}{dt} + B_m \omega_m(t) + \tau_{ml}(t) = \tau_m(t) \quad (1.1.8)$$

where J_m is the motor shaft moment of inertia and τ_{ml} is the resulting torque acting on the motor shaft from the load torque. The torque at the load shaft from an applied motor torque can be written as:

$$\tau_l(t) = \eta_g K_g \tau_{ml}(t) \quad (1.1.9)$$

where K_g is the gear ratio and η_g is the gearbox efficiency. The planetary gearbox that is directly mounted on the SRV02 motor (see [4] for more details) is represented by the N_1 and N_2 gears in Figure 1.1 and has a gear ratio of

$$K_{gi} = \frac{N_2}{N_1} \quad (1.1.10)$$

This is the *internal* gear box ratio. The motor gear N_3 and the load gear N_4 are directly meshed together and are visible from the outside. These gears comprise the *external* gear box which has an associated gear ratio of

$$K_{ge} = \frac{N_4}{N_3} \quad (1.1.11)$$

The gear ratio of the SRV02 gear train is then given by:

$$K_g = K_{ge} K_{gi} \quad (1.1.12)$$

Thus, the torque seen at the motor shaft through the gears can be expressed as:

$$\tau_{ml}(t) = \frac{\tau_l(t)}{\eta_g K_g} \quad (1.1.13)$$

Intuitively, the motor shaft must rotate K_g times for the output shaft to rotate one revolution.

$$\theta_m(t) = K_g \theta_l(t) \quad (1.1.14)$$

We can find the relationship between the angular speed of the motor shaft, ω_m, and the angular speed of the load shaft, ω_l by taking the time derivative:

$$\omega_m(t) = K_g \omega_l(t) \tag{1.1.15}$$

To find the differential equation that describes the motion of the load shaft with respect to an applied motor torque substitute (1.1.13), (1.1.15) and (1.1.7) into (1.1.8) to get the following:

$$J_m K_g \frac{d\omega_l(t)}{dt} + B_m K_g \omega_l(t) + \frac{J_l(\frac{d\omega_l(t)}{dt}) + B_l \omega_l(t)}{\eta_g K_g} = \tau_m(t) \tag{1.1.16}$$

Collecting the coefficients in terms of the load shaft velocity and acceleration gives

$$(\eta_g K_g^2 J_m + J_l) \frac{d\omega_l(t)}{dt} + (\eta_g K_g^2 B_m + B_l)\omega_l(t) = \eta_g K_g \tau_m(t) \tag{1.1.17}$$

Defining the following terms:

$$J_{eq} = \eta_g K_g^2 J_m + J_l \tag{1.1.18}$$

$$B_{eq} = \eta_g K_g^2 B_m + B_l \tag{1.1.19}$$

simplifies the equation as:

$$J_{eq} \frac{d\omega_l(t)}{dt} + B_{eq}\omega_l(t) = \eta_g K_g \tau_m(t) \tag{1.1.20}$$

1.1.1.3 Combining the Electrical and Mechanical Equations

In this section the electrical equation derived in Section 1.1.1.1 and the mechanical equation found in Section 1.1.1.2 are brought together to get an expression that represents the load shaft speed in terms of the applied motor voltage.

The motor torque is proportional to the voltage applied and is described as

$$\tau_m(t) = \eta_m k_t I_m(t) \tag{1.1.21}$$

where k_t is the current-torque constant $(N.m/A)$, η_m is the motor efficiency, and I_m is the armature current. See [4] for more details on the SRV02 motor specifications.

We can express the motor torque with respect to the input voltage $V_m(t)$ and load shaft speed $\omega_l(t)$ by substituting the motor armature current given by equation 1.1.5 in Section 1.1.1.1, into the current-torque relationship given in equation 1.1.21:

$$\tau_m(t) = \frac{\eta_m k_t \left(V_m(t) - k_m \omega_m(t)\right)}{R_m} \tag{1.1.22}$$

To express this in terms of V_m and ω_l, insert the motor-load shaft speed equation 1.1.15, into 1.1.21 to get:

$$\tau_m(t) = \frac{\eta_m k_t \left(V_m(t) - k_m K_g \omega_l(t)\right)}{R_m} \tag{1.1.23}$$

If we substitute (1.1.23) into (1.1.20), we get:

$$J_{eq}\left(\frac{d}{dt} w_l(t)\right) + B_{eq} w_l(t) = \frac{\eta_g K_g \eta_m k_t \left(V_m(t) - k_m K_g \omega_l(t)\right)}{R_m} \tag{1.1.24}$$

After collecting the terms, the equation becomes

$$\left(\frac{d}{dt} w_l(t)\right) J_{eq} + \left(\frac{k_m \eta_g K_g^2 \eta_m k_t}{R_m} + B_{eq}\right) \omega_l(t) = \frac{\eta_g K_g \eta_m k_t V_m(t)}{R_m} \tag{1.1.25}$$

This equation can be re-written as:

$$\left(\frac{d}{dt}w_l(t)\right) J_{eq} + B_{eq,v}\omega_l(t) = A_m\, V_m(t) \tag{1.1.26}$$

where the equivalent damping term is given by:

$$B_{eq,v} = \frac{\eta_g K_g^2 \eta_m k_t k_m + B_{eq} R_m}{R_m} \tag{1.1.27}$$

and the actuator gain equals

$$A_m = \frac{\eta_g K_g \eta_m k_t}{R_m} \tag{1.1.28}$$

1.1.2 Modeling Using Experiments

In Section 1.1.1 you learned how the system model can be derived from the first-principles. A linear model of a system can also be determined purely experimentally. The main idea is to experimentally observe how a system reacts to different inputs and change structure and parameters of a model until a reasonable fit is obtained. The inputs can be chosen in many different ways and there are a large variety of methods. In Sections 1.1.2.1 and 1.1.2.2, two methods of modeling the SRV02 are outlined: (1) frequency response and, (2) bump test.

1.1.2.1 Frequency Response

In Figure 1.2, the response of a typical first-order time-invariant system to a sine wave input is shown. As it can be seen from the figure, the input signal (u) is a sine wave with a fixed amplitude and frequency. The resulting output (y) is also a sinusoid with the *same* frequency but with a different amplitude. By varying the frequency of the input sine wave and observing the resulting outputs, a Bode plot of the system can be obtained as shown in Figure 1.3.

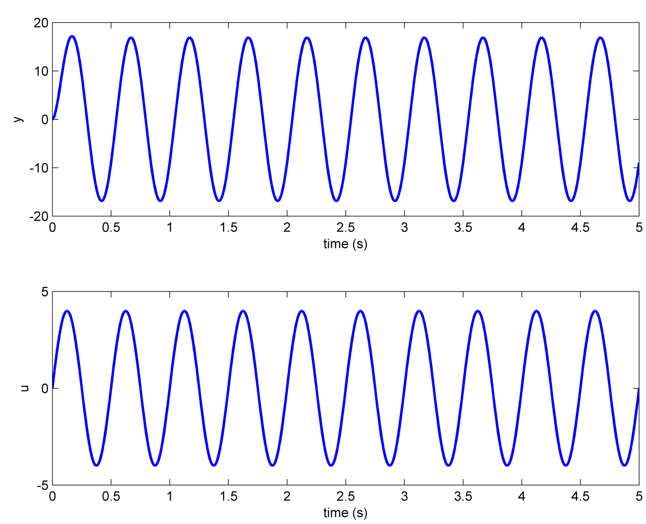


Figure 1.2: Typical frequency response

The Bode plot can then be used to find the steady-state gain, i.e. the DC gain, and the time constant of the system. The cuttoff frequency, ω_c, shown in Figure 1.3 is defined as the frequency where the gain is 3 dB less than the maximum gain (i.e. the DC gain). When working in the linear non-decibel range, the 3 dB frequency is defined as the frequency where the gain is $\frac{1}{\sqrt{2}}$, or about 0.707, of the maximum gain. The cutoff frequency is also known as the bandwidth of the system which represents how fast the system responds to a given input.

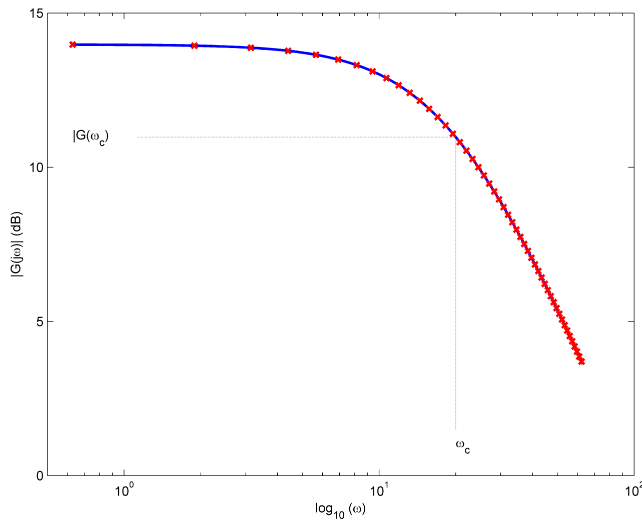


Figure 1.3: Magnitude Bode plot

The magnitude of the frequency response of the SRV02 plant transfer function given in equation 1.1.1 is defined as:

$$|G_{wl,v}(w)| = \left| \frac{\Omega_l(\omega\, j)}{V_m(\omega\, j)} \right| \tag{1.1.29}$$

where ω is the frequency of the motor input voltage signal V_m. We know that the transfer function of the system has the generic first-order system form given in Equation 1.1.1. By substituting $s = j\,w$ in this equation, we can find the frequency response of the system as:

$$\frac{\Omega_l(\omega\, j)}{V_m(\omega\, j)} = \frac{K}{\tau\omega\, j + 1} \tag{1.1.30}$$

Then, the magnitude of it equals

$$|G_{wl,v}(\omega)| = \frac{K}{\sqrt{1 + \tau^2\,\omega^2}} \tag{1.1.31}$$

Let's call the frequency response model parameters $K_{e,f}$ and $\tau_{e,f}$ to differentiate them from the nominal model parameters, K and τ, used previously. The steady-state gain or the DC gain (i.e. gain at zero frequency) of the model is:

$$K_{e,f} = |G_{wl,v}(0)| \tag{1.1.32}$$

1.1.2.2 Bump Test

The bump test is a simple test based on the step response of a stable system. A step input is given to the system and its response is recorded. As an example, consider a system given by the following transfer function:

$$\frac{Y(s)}{U(s)} = \frac{K}{\tau s + 1} \tag{1.1.33}$$

The step response shown in Figure 1.4 is generated using this transfer function with $K = 5$ rad/V.s and $\tau = 0.05$ s.

The step input begins at time t_0. The input signal has a minimum value of u_{min} and a maximum value of u_{max}. The resulting output signal is initially at y_0. Once the step is applied, the output tries to follow it and eventually settles at its steady-state value y_{ss}. From the output and input signals, the steady-state gain is

$$K = \frac{\Delta y}{\Delta u} \tag{1.1.34}$$

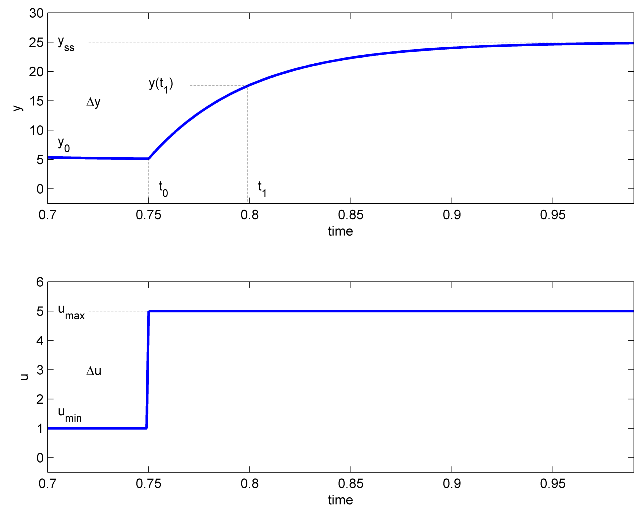


Figure 1.4: Input and output signal used in the bump test method

where $\Delta y = y_{ss} - y_0$ and $\Delta u = u_{max} - u_{min}$. In order to find the model time constant, τ, we can first calculate where the output is supposed to be at the time constant from:

$$y(t_1) = 0.632 y_{ss} + y_0 \tag{1.1.35}$$

Then, we can read the time t_1 that corresponds to $y(t_1)$ from the response data in Figure 1.4. From the figure we can see that the time t_1 is equal to:

$$t_1 = t_0 + \tau \tag{1.1.36}$$

From this, the model time constant can be found as:

$$\tau = t_1 - t_0 \tag{1.1.37}$$

Going back to the SRV02 system, a step input voltage with a time delay t_0 can be expressed as follows in the Laplace domain:

$$V_m(s) = \frac{A_v \, e^{(-s\,t_0)}}{s} \tag{1.1.38}$$

where A_v is the amplitude of the step and t_0 is the step time (i.e. the delay). If we substitute this input into the system transfer function given in Equation (1.1.1), we get:

$$\Omega_l(s) = \frac{K A_v \, e^{(-s\,t_0)}}{(\tau\,s + 1)\,s} \tag{1.1.39}$$

We can then find the SRV02 load speed step response, $w_l(t)$, by taking inverse Laplace of this equation. Here we need to be careful with the time delay t_0 and note that the initial condition is $\omega_l(0^-) = \omega_l(t_0)$.

$$\omega_l(t) = K\,A_v \left(1 - e^{\left(-\frac{t-t_0}{\tau}\right)}\right) + \omega_l\,(t_0) \tag{1.1.40}$$

1.2 Pre-Lab Questions

Before you start the lab experiments given in Section 1.3, you should study the background materials provided in Section 1.1 and work through the questions in this Section.

1. In Section 1.1.1.3 we obtained an equation (1.1.26) that described the dynamic behavior of the load shaft speed as a function of the motor input voltage. Starting from this equation, find the transfer function $\frac{\Omega_l(s)}{V_m(s)}$.
2. Express the steady-state gain (K) and the time constant (τ) of the process model (Equation (1.1.1)) in terms of the J_{eq}, $B_{eq,v}$, and A_m parameters.
3. Calculate the $B_{eq,v}$ and A_m model parameters using the system specifications given in [4]. The parameters are to be calculated based on an SRV02-ET in the high-gear configuration.
4. Calculate the moment of inertia about the motor shaft. Note that $J_m = J_{tach} + J_{m,rotor}$ where J_{tach} and $J_{m,rotor}$ are the moment of inertia of the tachometer and the rotor of the SRV02 DC motor, respectively. Use the specifications given in [4].
5. The load attached to the motor shaft includes a 24-tooth gear, two 72-tooth gears, and a single 120-tooth gear along with any other external load that is attached to the load shaft. Thus, for the gear moment of inertia J_g and the external load moment of inertia $J_{l,ext}$, the load inertia is $J_l = J_g + J_{l,ext}$. Using the specifications given in [4] find the total moment of inertia J_g from the gears . **Hint:** Use the definition of moment of inertia for a disc $J_{disc} = \frac{mr^2}{2}$.
6. Assuming the disc load is attached to the load shaft, calculate the inertia of the disc load, $J_{ext,l}$, and the total load moment of inertia, J_l.
7. Evaluate the equivalent moment of inertia J_{eq}.
8. Calculate the steady-state model gain K and time constant τ. These are the *nominal model parameters* and will be used to compare with parameters that are later found experimentally.
9. Referring to Section 1.1.2.1, find the expression representing the time constant τ of the frequency response model given in Equation 1.1.31. Begin by evaluating the magnitude of the transfer function at the cutoff frequency ω_c.
10. Referring to Section 1.1.2.2, find the steady-state gain of the step response and compare it with Equation 1.1.34. **Hint:** The the steady-state value of the load shaft speed can be defined as $\omega_{l,ss} = \lim_{t \to \infty} \omega_l(t)$.
11. Evaluate the step response given in equation 1.1.40 at $t = t_0 + \tau$ and compare it with Equation 1.1.34.

1.3 Lab Experiments

The main goal of this laboratory is to find a transfer function (model) that describes the rotary motion of the SRV02 load shaft as a function of the input voltage. We can obtain this transfer function experimentally using one of the following two methods:

- Frequency response, or
- Bump test

In this laboratory, first you will conduct two experiments exploring how these methods can be applied to a real system. Then, you will conduct a third experiment to fine tune the parameters of the transfer functions you obtained and to validate them.

Experimental Setup

The SRV02 Modeling VI shown in Figure 1.5 will be used to conduct the experiments. The DC motor and sensors of the SRV02 system is interfaced using LabVIEW™ . Using the developed first-order transfer function, the SRV02 is also simulated. Thus, both the measured and simulated load shaft speed can be monitored simultaneously given an input voltage.

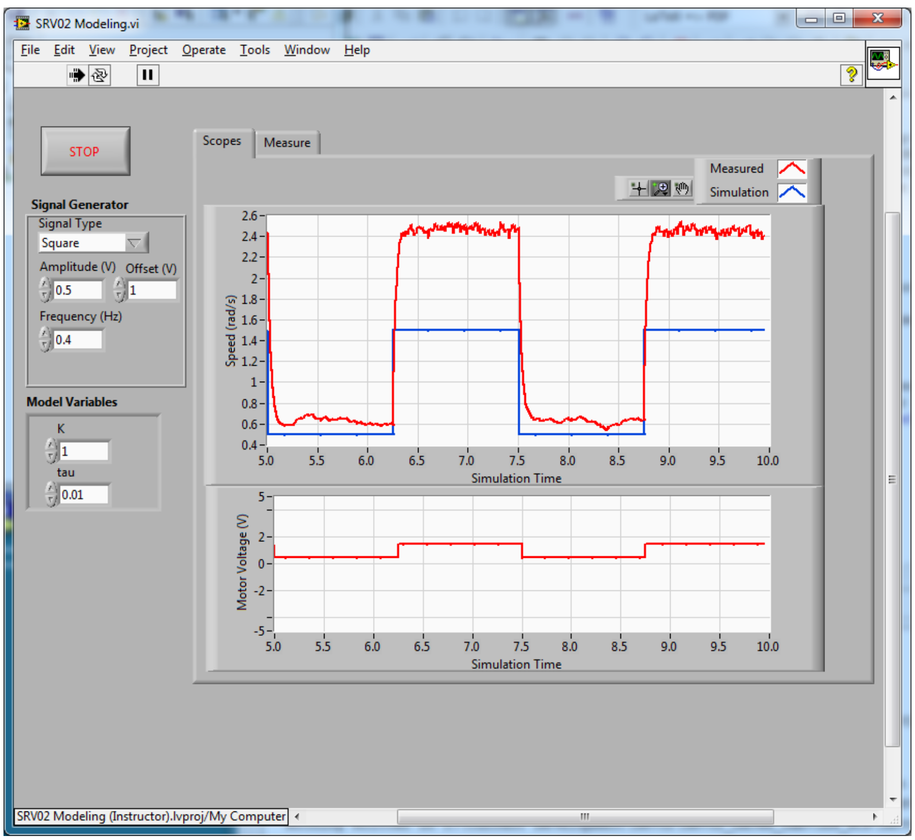


Figure 1.5: SRV02 Modeling VI used to model SRV02.

IMPORTANT: Before you can conduct these experiments, you need to make sure that the lab files are configured according to your SRV02 setup. If they have not been configured already, then you need to go to Section 1.4 to configure the lab files first.

1.3.1 Frequency Response Experiment

As explained in 1.1.2.1 earlier, the frequency response of a linear system can be obtained by providing a sine wave input signal to it and recording the resulting output sine wave from it. In this experiment, the input signal is the motor voltage and the output is the motor speed.

In this method, we keep the amplitude of the input sine wave constant but vary its frequency. At each frequency setting, we record the amplitude of the output sine wave. The ratio of the output and input amplitudes at a given frequency can then be used to create a Bode magnitude plot. Then, the transfer function for the system can be extracted from this Bode plot.

1.3.1.1 Steady-state gain

First, we need to find the steady-state gain of the system. This requires running the system with a constant input voltage. To create a 2*V* constant input voltage follow these steps:

1. Open the LabVIEW project called *Quanser SRV02 Project (Student).lvproj*, shown in Figure 1.11 in Section 1.4.
2. Open the *SRV02 Modeling.vi* shown in Figure 1.5. Make sure the VI is configured for your data acquisition device, as explained in Section 1.4.
3. Set the *Signal Generator* parameters to:
   - Signal Type: sine
   - Amplitude: 0 V
   - Offset: 2.0 V
   - Frequency: 0.4 Hz
4. Run the VI. The SRV02 unit should begin rotating in one direction and the VI should look something similar to Figure 1.6. Note that in the *Speed (rad/s)* scope, the red trace is the measured speed while the blue trace is the simulated speed (generated by the SRV02 Model).
5. Measure the speed of the load shaft and enter the measurement in Table 1.1 below under the *f = 0 Hz* row.

   Note: The measurement can be done directly from the LabVIEW™ chart. For a more precise measurement, stop the VI and go to the *Measure* tab. The graph saves the last 5 seconds of measured data. Use the cursors to take measurements. Cursor 0 and 1 are fixed to the plot traces, whereas Cursor 2 is free and can be positioned anywhere on the plot area.
6. Calculate the steady-state gain both in linear and decibel (dB) units as explained in 1.1.2.1. Enter the resulting numerical value in the *f = 0 Hz* row of Table 1.1. Also, enter its non-decibel value in Table 1.2 in Section 1.3.4.

1.3.1.2 Gain at varying frequencies

In this part of the experiment, we will send an input sine wave at a certain frequency to the system and record the amplitude of the output signal. We will then increment the frequency and repeat the same observation.

To create the input sine wave:

1. Run the VI.
2. To feed a 2V sine wave at 1 Hz set the *Signal Generator* parameters to:
   - Signal Type: sine
   - Amplitude: 2.0 V

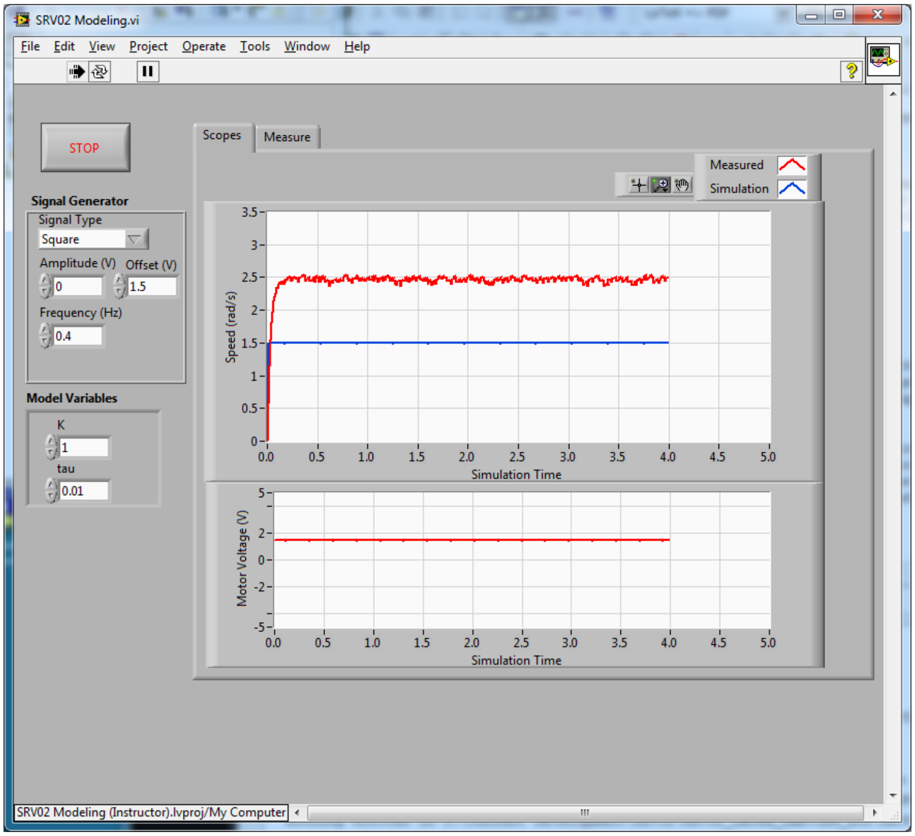


Figure 1.6: SRV02 Modeling VI when applying 2 V offset.

- Offset: 0 V
- Frequency: 1.0 Hz

3. The SRV02 unit should begin rotating smoothly back and forth and the scopes should be reading a response similar to Figure 1.8.

4. Measure the maximum positive speed of the load shaft at f = 1.0 Hz input and enter it in Table 1.1 below.

   Note: As before, this measurement can be done directly from the scope or, preferably, you can use *Measure* tab and use a cursor on the Graph to find the maximum load speed on the saved data (you will have to stop the VI).

5. Calculate the gain of the system (in both linear and dB units) and enter the results in Table 1.1.

6. Increase the frequency to f = 2.0 Hz by adjusting the *Frequency (Hz)* control box on the front panel. Measure the maximum load speed and calculate the gain. Repeat this step for each of the frequency settings in Table 1.1. Re-run the VI in case it was previously stopped (for example, to take cursor measurements).

7. Using the data collected in Table 1.1, generate a Bode magnitude plot. Make sure the amplitude and frequency scales are in decibels. When making the Bode plot, ignore the f = 0 Hz entry as the logarithm of 0 is not defined. Feel free to use any program to generate the Bode, e.g., LabVIEW™ or Microsoft Excel® . If using LabVIEW™ , you can complete the block diagram in the *Modeling Results (Student).vi* that is supplied.

8. Calculate the time constant $\tau_{e,f}$ using the obtained Bode plot by finding the cutoff frequency. Label the Bode plot with the -3 dB gain and the cutoff frequency. Enter the resulting time constant in Table 1.2.

9. Click the *Stop* button to stop the VI.

10. Turn off the power to the amplifier if no more experiments will be performed on the SRV02 in this session.

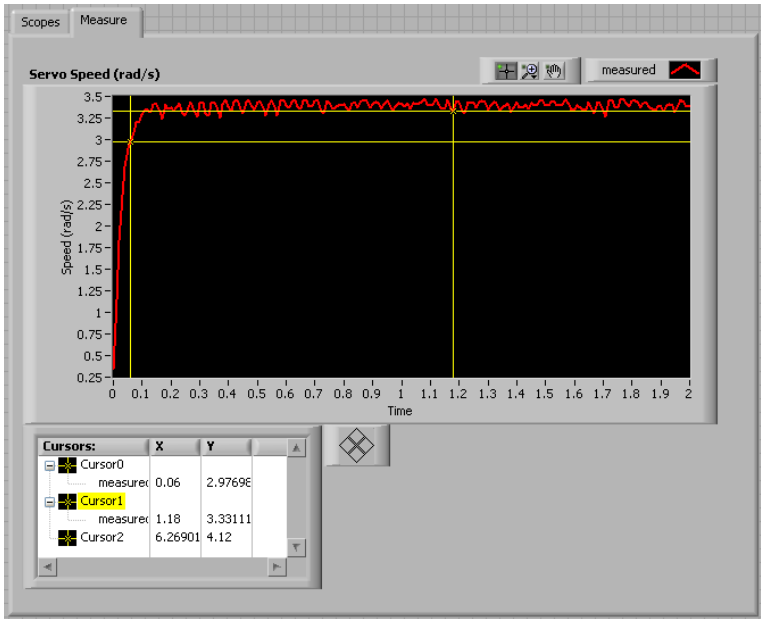


Figure 1.7: Using the Graph to take measurements.

f (Hz)	Amplitude (V)	Maximum Load Speed (rad/s)	Gain:|G(ω)| (rad/s/V)	Gain:|G(ω)| (rad/s/V, dB)
0.0	2.0			
1.0	2.0			
2.0	2.0			
3.0	2.0			
4.0	2.0			
5.0	2.0			
6.0	2.0			
7.0	2.0			
8.0	2.0			

Table 1.1: Collected frequency response data.

1.3.2 Bump Test Experiment

In this method, a step input is given to the SRV02 and the corresponding load shaft response is recorded. Using the saved response, the model parameters can then be found as discussed in Section 1.1.2.2.

To create the step input:

1. Open the LabVIEW project called *Quanser SRV02 Project (Student).lvproj*, shown in Figure 1.11 in Section 1.4.
2. Open the *SRV02 Modeling.vi* shown in Figure 1.5. Make sure the VI is configured for your data acquisition device, as explained in Section 1.4.
3. Set the *Signal Generator* parameters to the following:
    - Wave form: square
    - Amplitude: 1.5 V
    - Offset: 2.0 V

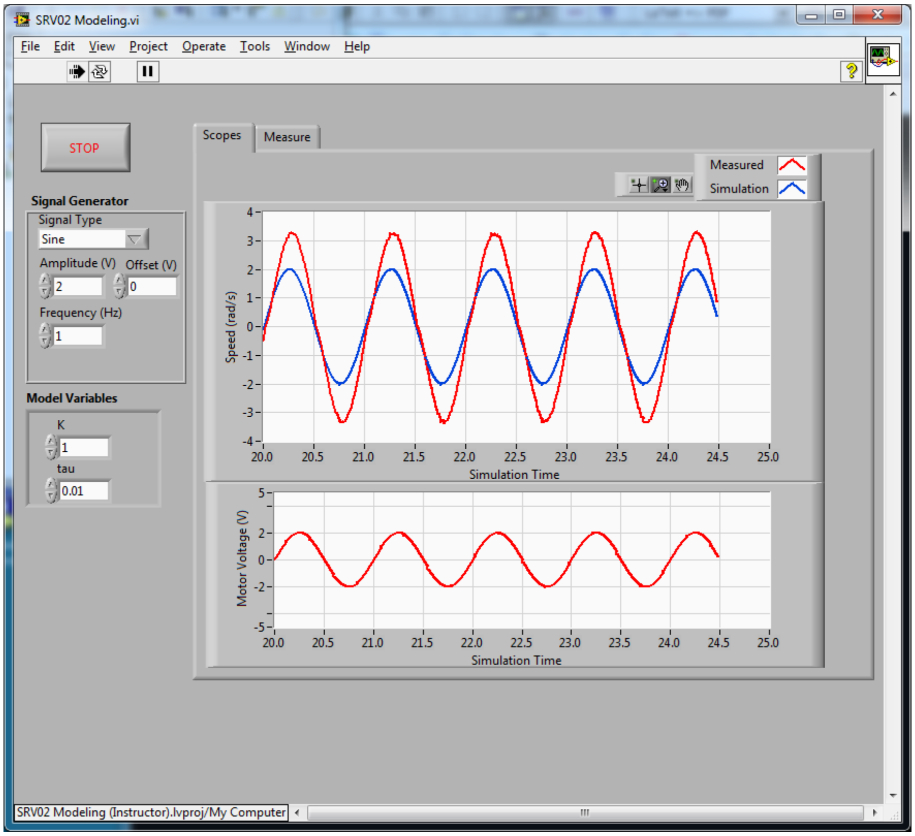


Figure 1.8: SRV02 Modeling VI when applying 2V sine wave at 1 Hz.

- Frequency: 0.4 Hz

4. Run the *SRV02 Modeling VI*. The gears on the SRV02 should be rotating in the same direction and alternating between low and high speeds. The response in the scopes should be similar to Figure 1.9.
5. Plot the response and attach it to your report.

   Note: As described in Section A.5, to export the image of the scope right-click on the LabVIEW Chart and go to *Export* | *Export Simplified Image*. Select the *Bitmap (*.bmp)* and *Export to clipboard* options to save the image to the clipboard and then save it using a graphics software. Alternatively, you can also export the data into an Excel® and generate the plot in the spreasheet.
6. Find the steady-state gain using the measured step response and enter it in Table 1.2. Use the cursors in the *Servo Speed (rad/s)* Graph in the *Measure* tab to measure points on the response.
7. Find the time constant from the obtained response and enter the result in Table 1.2.
8. Click the *Stop* button to stop the VI.
9. Turn off the power to the amplifier if no more experiments will be performed on the SRV02 in this session.

1.3.3 Model Validation Experiment

In this experiment, you will adjust the model parameters you found in the previous experiments to tune the transfer function. Our goal is to match the simulated system response with the parameters you found as closely as possible to the response of the actual system.

To create a step input:

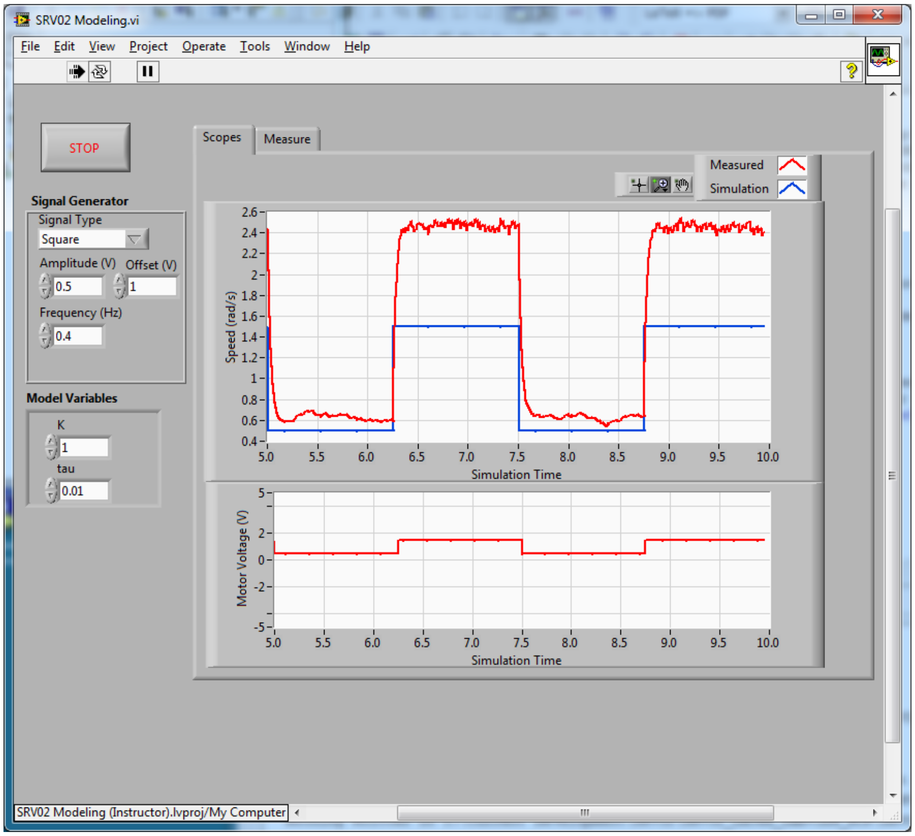


Figure 1.9: Square input motor voltage.

1. Open the LabVIEW project called *Quanser SRV02 Project (Student).lvproj*, shown in Figure 1.11 in Section 1.4.
2. Open the *SRV02 Modeling.vi* shown in Figure 1.5. Make sure the VI is configured for your data acquisition device, as explained in Section 1.4.
3. Set the *Signal Generator* parameters to the following:
   - Signal type: square
   - Amplitude: 1.0 V
   - Offset: 1.5 V
   - Frequency: 0.4 Hz
4. Run the VI. The gears on the SRV02 should be rotating in the same direction and alternating between low and high speeds and the scopes should be as shown in Figure 1.10. Recall that the red plot line is the measured load shaft rate and the blue line is the simulated speed from the model. By default, the steady-state gain and the time constant of the transfer function used in simulation are set to: *K* = 1 rad/s/V and *tau* = 0.1 s. *These model parameters do not accurately represent the system*.
5. In the *Model Variables* panel on the VI, set the model steady-state gain to *K* = 1.25 and observe how the simulation changes.
6. Change the model time constant to *tau* = 0.2 and observe how the simulation changes.
7. Vary the gain and time constant model parameters. How do the gain and the time constant affect the system response?
8. Enter the nominal values, K and τ, that were found in Section 1.2 in the *Model Variables* section on the VI front panel. Examine how well the simulated response matches the measured one.

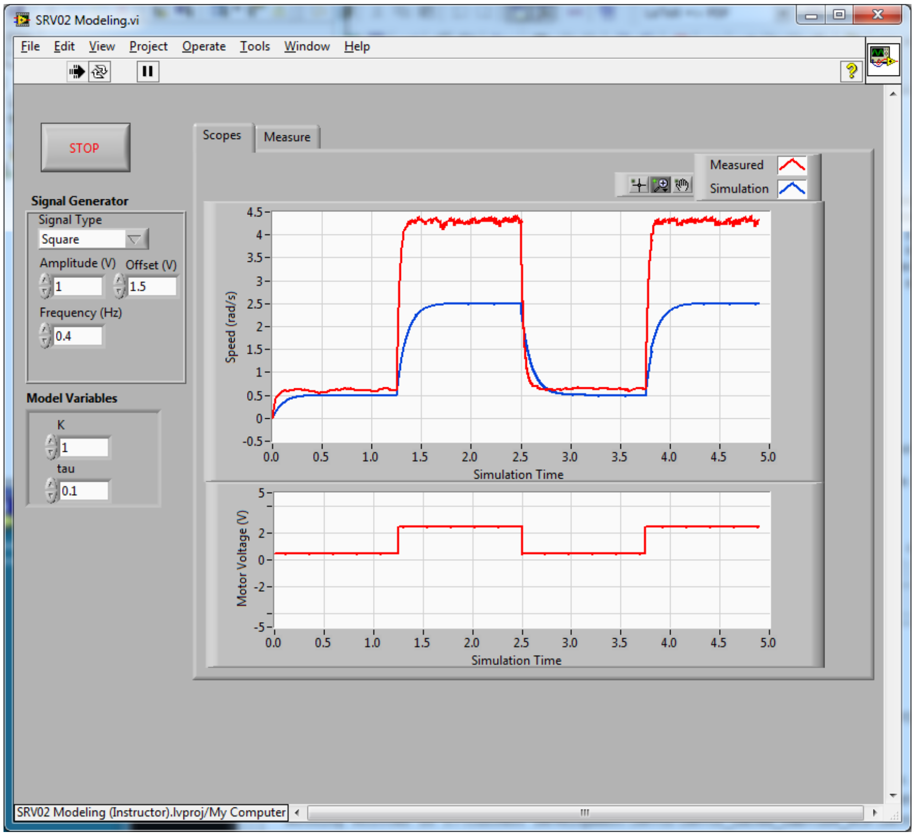


Figure 1.10: SRV02 Modeling VI used to perform model validation.

9. If the calculations were done properly, then the model should represent the actual system quite well. However, there are always some differences between each servo unit and, as a result, the model can always be tuned to match the system better. Try varying the model parameters until the simulated trace matches the measured response better. Enter these tuned values under the *Model Validation* section of Table 1.2.
10. Provide two reasons why the nominal model does not represent the SRV02 with better accuracy.
11. Show the measured and simulated response of each method (the nominal model, the frequency response model, and the bumptest model). Enter the nominal values, K and τ, in the *Model Variables*, run the VI, and examine the response. Repeat for the frequency response parameters $K_{e,f}$ and $\tau_{e,f}$ along with the bump test variables $K_{e,b}$ and $\tau_{e,b}$.
12. Explain how well the nominal model, the frequency response model, and the bumptest model represent the SRV02 system.
13. Click the *Stop* button to stop the VI.
14. Turn off the power to the amplifier if no more experiments will be performed on the SRV02 in this session.

1.3.4 Results

Fill out Table 1.2 below, with your results.

Section	Description	Symbol	Value	Unit
1.2	**Nominal Values**			
	Open-Loop Steady-State Gain	K		
	Open-Loop Time Constant	τ		
1.3.1	**Frequency Response Exp.**			
	Open-Loop Steady-State Gain	$K_{e,f}$		
	Open-Loop Time Constant	$\tau_{e,f}$		
1.3.2	**Bump Test Exp.**			
	Open-Loop Steady-State Gain	$K_{e,b}$		
	Open-Loop Time Constant	$\tau_{e,b}$		
1.3.3	**Model Validation**			
	Open-Loop Steady-State Gain	$K_{e,v}$		
	Open-Loop Time Constant	$\tau_{e,v}$		

Table 1.2: Summary of results for the SRV02 Modeling laboratory.

1.4 System Requirements

Required Hardware

- Data-aquisition (DAQ) device that is compatible with LabVIEW™ .
- Quanser SRV02-ET rotary servo. See Reference [4].
- Quanser VoltPAQ power amplifier, or equivalent (e.g. Reference [2] for VoltPAQ User Manual).

Required Software

- NI LabVIEW™
- NI LabVIEW Control Design and Simulation Module
- Quanser Rapid Control Prototyping Toolkit®
- For NI CompactRIO users:
  - NI LabVIEW Real-Time Module
  - NI LabVIEW FPGA Module 2010
  - RIO Drivers

1.4.1 Overview of Files

File Name	Description
SRV02 Manual (Student).pdf	This laboratory guide contains pre-lab questions and lab experiments demonstrating how to model the Quanser SRV02 rotary plant using various methods.
SRV02 Modeling (Student).lvproj SRV02 Modeling.vi	LabVIEW project containing the student-based VIs. VI used to model the SRV02.
Modeling Results (Student)	This VI can be used to generate a Bode plot. Some programming is required to complete it.

Table 1.3: Files supplied with the SRV02 Modeling laboratory.

1.4.2 Hardware Setup

Follow these steps to get the system hardware ready for this lab:

1. Connect the Quanser SRV02 to the amplifier (e.g. VoltPAQ) and DAQ device as described in [4].
2. Make sure the SRV02 is in the *high-gear configuration*.
3. Install the *disc load* on the top gear.

Note: If you are using the NI CompactRIO, then see the SRV02 cRIO User Manual ([3]).

1.4.3 Software Setup

Follow these steps to get the system ready for this lab:

1. Load the LabVIEW™ software.
2. Open the LabVIEW project called *Quanser Modeling (Student).lvproj* shown in Figure 1.11.

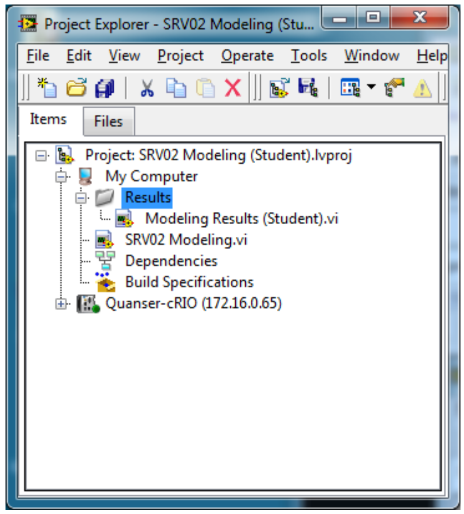


Figure 1.11: SRV02 Modeling Project.

3. To run the SRV02 Modeling Experiments, open the *SRV02 Modeling* VI.
4. **Choose data acquisition device:** Before running the VI, make sure you set the correct *Board type* in the HIL Initialize block (e.g., 'q1_cRIO', 'q2_usb', 'q8_usb', 'qpid', or 'qpid_e').
5. **Channel Configuration:** For any of these VIs, the analog input and ouput channels are set, by default, to match the wiring in the SRV02 User Manual ([4]). If the wiring is different on your system, make sure the VI uses the correct channels. For instance, if your tachometer is connected to Analog Input Channel #0 on your DAQ, then set the *tach* channel in the VI to 0 (instead of 1).
6. **Quanser CompactRIO Users:** Before running the VI, make sure you can connect to your CompactRIO through the Measurement & Automation software. See the SRV02 cRIO User Manual ([3]).

1.5 Lab Report

When you prepare your lab report, you can follow the outline given in Section 1.5.1 to build the *content* of your report. Also, in Section 1.5.2 you can find some basic tips for the *format* of your report.

1.5.1 Template for Content

I. PROCEDURE

I.1. Frequency Response Experiment

1. Briefly describe the main goal of this experiment and the procedure.
   - Briefly describe the experimental procedure (Section 1.3.1.1), *Steady-state gain*
   - Briefly describe the experimental procedure (Section 1.3.1.2), *Gain at varying frequencies*

I.2. Bump Test Experiment

1. Briefly describe the main goal of this experiment and the experimental procedure (Section 1.3.2).

I.3. Model Validation Experiment

1. Briefly describe the main goal of this experiment and the experimental procedure (Section 1.3.3).

II. RESULTS
Do not interpret or analyze the data in this section. Just provide the results.

1. Bode plot from step 7 in Section 1.3.1.2, *Gain at varying frequencies*.
2. Response plot from step 5 in Section 1.3.2, *Bump Test Experiment*.
3. Response plot from step 11 in Section 1.3.3, *Model Validation Experiment*.
4. Provide data collected in this laboratory (from Table 1.1).

III. ANALYSIS
Provide details of your calculations (methods used) for analysis for each of the following:

III.1. Frequency Response Experiment

1. Step 6 in Section 1.3.1.1, *Steady-state gain*.
2. Step 8 in Section 1.3.1.2, *Gain at varying frequencies*.

III.2. Bump Test Experiment

1. Steps 6 and 7 in Section 1.3.2.

IV. CONCLUSIONS
Interpret your results to arrive at logical conclusions.

1. Steps 7, 10, and 12 in Section 1.3.3.

1.5.2 Tips for Report Format

PROFESSIONAL APPEARANCE

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

LABORATORY 2

SRV02 POSITION CONTROL

The objective of this experiment is to develop a feedback system that controls the position of the rotary servo load shaft. Using the proportional-integral-derivative (PID) family, a compensator is designed to meet a set of specifications.

Topics Covered

- Design a proportional-derivative (PD) compensator that controls the position of the servo load shaft according to certain time-domain requirements.
- Simulate the PD controller using the developed model of the plant and ensure the specifications are met without any actuator saturation.
- Implement the controller on the Quanser SRV02 device and evaluate its performance.

Prerequisites

- Know the basics of LabVIEW™ .
- Understand transfer function fundamentals.
- The SRV02 model steady-state gain, K, and time constant, τ, are needed to compute the control gains. These parameters can either be given by the instructor or derived by doing the SRV02 Modeling (see Section 1) laboratory.

2.1 Background

2.1.1 Desired Position Control Response

The block diagram shown in Figure 2.1 is a general unity feedback system with compensator (controller) C(s) and a transfer function representing the plant, P(s). The measured output, Y(s), is supposed to track the reference signal R(s) and the tracking has to match to certain desired specifications.

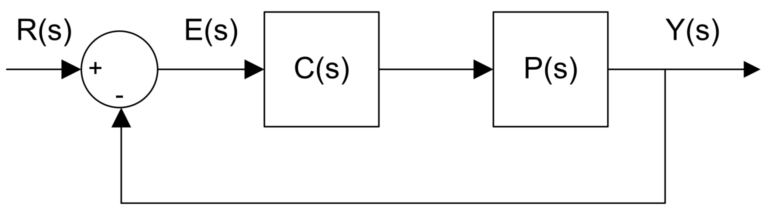


Figure 2.1: Unity feedback system.

The output of this system can be written as:

$$Y(s) = C(s)\,P(s)\,\left(R(s) - Y(s)\right) \tag{2.1.1}$$

By solving for $Y(s)$, we can find the closed-loop transfer function:

$$\frac{Y(s)}{R(s)} = \frac{C(s)\,P(s)}{1 + C(s)\,P(s)} \tag{2.1.2}$$

Recall in the SRV02 modelling laboratory, the SRV02 voltage-to-speed transfer function was derived. To find the voltage-to-position transfer function, we can put an integrator ($1/s$) in series with the speed transfer function (effectively integrating the speed output to get position). Then, the resulting open-loop voltage-to-load gear position transfer function becomes:

$$P(s) = \frac{K}{s\,(\tau s + 1)} \tag{2.1.3}$$

As you can see from this equation, the plant is a second order system. In fact, when a second order system is placed in series with a proportional compensator in the feedback loop as in Figure 2.1, the resulting closed-loop transfer function can be expressed as:

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\,\omega_n\,s + \omega_n^2} \tag{2.1.4}$$

where ω_n is the natural frequency and ζ is the damping ratio. This is called the *standard second-order* transfer function. Its response properties depend on the values of ω_n and ζ.

2.1.1.1 Settling Time and Overshoot

Consider a second-order system as shown in Equation 2.1.4 subjected to a step input given by

$$R(s) = \frac{R_0}{s} \tag{2.1.5}$$

with a step amplitude of $R_0 = 1.5$. The system response to this input is shown in Figure 2.2, where the red trace is the response (output), $y(t)$, and the blue trace is the step input $r(t)$. The maximum value of the response is denoted by the variable y_{max} and it occurs at a time t_{max}. For a response similar to Figure 2.2, the percent overshoot is found using

$$PO = \frac{100\,(y_{max} - R_0)}{R_0} \tag{2.1.6}$$

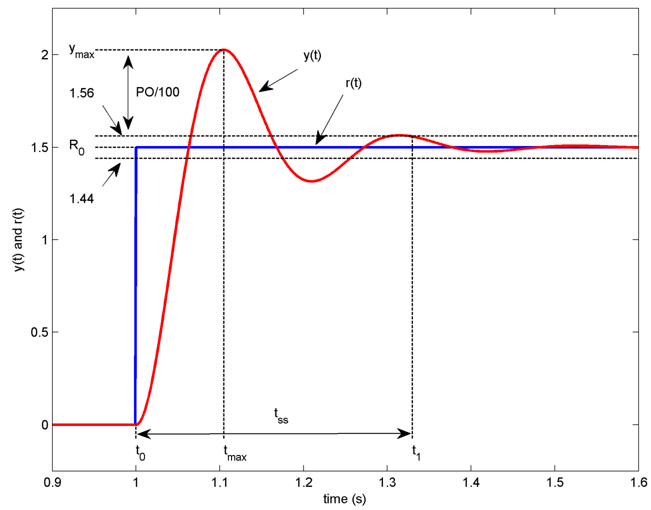


Figure 2.2: Standard second-order step response.

From the initial step time, t_0, the time it takes for the response to decay to 4% of its final value, t_1, is

$$t_s = t_1 - t_0 \tag{2.1.7}$$

This is called the *settling time* of the system.

In a second-order system, the amount of overshoot depends solely on the damping ratio parameter and it can be calculated using the equation

$$PO = 100\, e^{\left(-\frac{\pi\,\zeta}{\sqrt{1-\zeta^2}}\right)} \tag{2.1.8}$$

The settling time depends on both the damping ratio and natural frequency of the system and it can be derived as:

$$t_s = \frac{4}{\zeta\omega_n} \tag{2.1.9}$$

Generally speaking, the damping ratio affects the shape of the response while the natural frequency affects the speed of the response.

2.1.1.2 SRV02 Position Control Specifications

Frequency-Based Design (FBD)

Open-loop bode should satisfy the following phase margin and bandwidth specifications:

$$PM = 75.0 \text{ deg} \tag{2.1.10}$$

and

$$\omega_{bw} = 25.0 \text{ rad/s.} \tag{2.1.11}$$

Time-Domain Design (TDD)

The desired time-domain specifications for controlling the position of the SRV02 load shaft are:

$$e_{ss} \le 0.03 \text{ rad} \tag{2.1.12}$$

$$t_s \le 0.20 \text{ s} \tag{2.1.13}$$

and

$$PO \leq 2.0\ \% \tag{2.1.14}$$

Note: The specifications given above must be met while keeping the DC motor input voltage peak within ± 10V. This operating range is necessary to prevent any damage.

Thus when tracking the load shaft reference, the response should settle within 4% of its final value in 0.20 s or less and that final value should be within 0.03 rad of the reference signal. The overshoot should be less than or equal to 2 %. So if the step is 1.0 rad, then is the peak should not exceed 1.02 rad.

2.1.2 PD Controller Design

2.1.2.1 Closed Loop Transfer Function

The proportional-velocity (PD) compensator to control the position of the SRV02 has the following structure

$$V_m(t) = k_p\,(\theta_d(t) - \theta_l(t)) + k_d\left(\frac{d}{dt}\theta_d(t) - \frac{d}{dt}\theta_l(t)\right) \tag{2.1.15}$$

where k_p is the proportional control gain, k_d is the derivative control gain, $\theta_d(t)$ is the setpoint or reference load shaft angle, $\theta_l(t)$ is the measured load shaft angle, and $V_m(t)$ is the SRV02 motor input voltage. The block diagram of the PD control is given in Figure 2.3. We need to find the closed-loop transfer function $\Theta_l(s)/\Theta_d(s)$ for the closed-loop

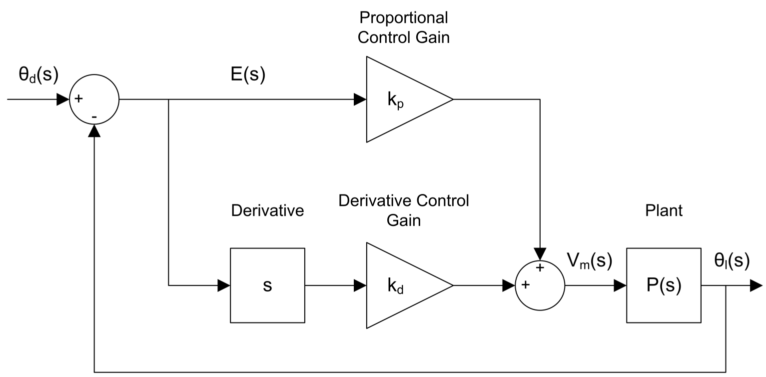


Figure 2.3: Block diagram of SRV02 PD position control.

position control of the SRV02. Taking the Laplace transform of equation 2.1.15 gives

$$V_m(s) = (k_p + k_d s)\,(\Theta_d(s) - \Theta_l(s)) \tag{2.1.16}$$

From the Plant block in Figure 2.3 and equation 2.1.3, we can write

$$\frac{\Theta_l(s)}{V_m(s)} = \frac{K}{s\,(\tau\,s + 1)} \tag{2.1.17}$$

Substituting equation 2.1.16 into 2.1.17 and solving for $\Theta_l(s)/\Theta_d(s)$ gives the SRV02 position closed-loop transfer function as:

$$\frac{\Theta_l(s)}{\Theta_d(s)} = \frac{K(k_p + k_d s)}{\tau\,s^2 + (1 + K\,k_d)\,s + K\,k_p} \tag{2.1.18}$$

2.2 Pre-Lab Questions

1. The SRV02 closed-loop transfer function was derived in equation 2.1.18 in Section 2.1.2.1. Find the control gains k_p and k_d in terms of ω_n and ζ. **Hint:** Recall the denominator of the standard second-order system in equation 2.1.4 .
2. Explain what approximation was made in order to find the PD gains above (assume $k_d > 0$). **Hint**: Look at the structure of the equations used.
3. Calculate the minimum damping ratio and natural frequency required to meet the specifications given in Section 2.1.1.2.
4. Based on the nominal SRV02 model parameters, K and τ, found in SRV02 Modeling Laboratory in Section 1, calculate the control gains needed to satisfy the time-domain response requirements given in Section 2.1.1.2.

2.3 Lab Experiments

The main goal of this laboratory is to explore position control of the SRV02 load shaft using the PD controller. You are asked to verify their control design and simulate the closed-loop PD response. Then, the PD controller is implemented on the actual SRV02.

Before getting starting... Read Section 2.4 for information about the files you will be using for the lab and how to configure your SRV02.

2.3.1 Frequency-Based Design (FBD)

2.3.1.1 Control Design

1. Open the LabVIEW project called *SRV02 Position Control (Student).lvproj*, shown in Figure 2.13 in Section 2.4.
2. Within the *SRV02 Control Design and Simulation* folder, open the *SRV02 Position Control Design.vi* shown in Figure 2.4.

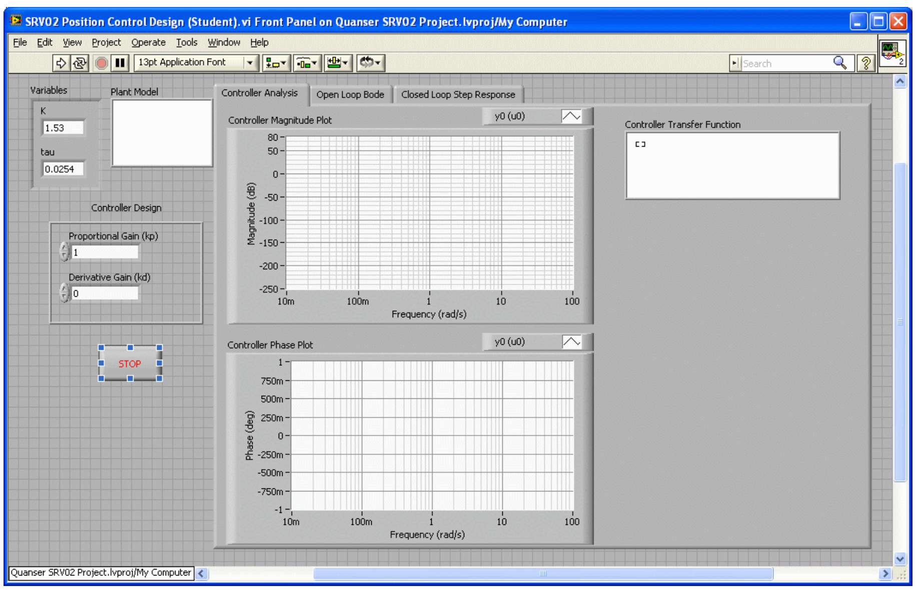


Figure 2.4: SRV02 Position Control.

3. Go to its block diagram and enter the SRV02 DC motor model plant in the MathScript node shown in Figure 2.5, below. Here's an example of how to use the *tf* function to generate the transfer function $G = \frac{s+1}{s+2s+3}$.

```
num = [1 2];
den = [1 2 3];
G = tf(num,den);
```

   For additional information about the *tf* function, look through the LabVIEW help or online.

4. Run the VI. It should look similarly as shown in Figure 2.6.
5. In the *Open-Loop Bode* tab, vary the proportional, k_p, and derivative gains, k_d, and examine its effect on the phase margin (PM) and bandwidth. The bandwidth is equivalent to the *PM Crossover* frequency on the plot, which is where the magnitude of the Bode plot hits 0 db (or 1). The larger the phase margin, the less overshoot

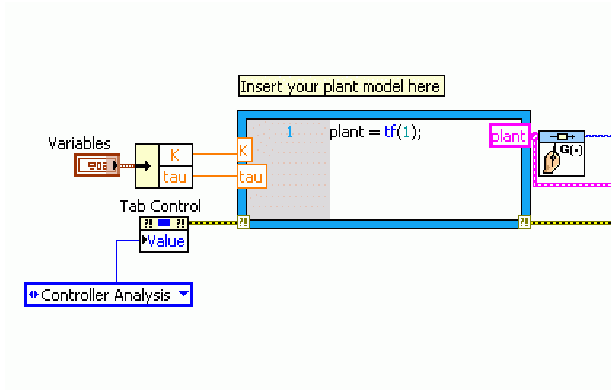


Figure 2.5: Enter dc motor transfer function

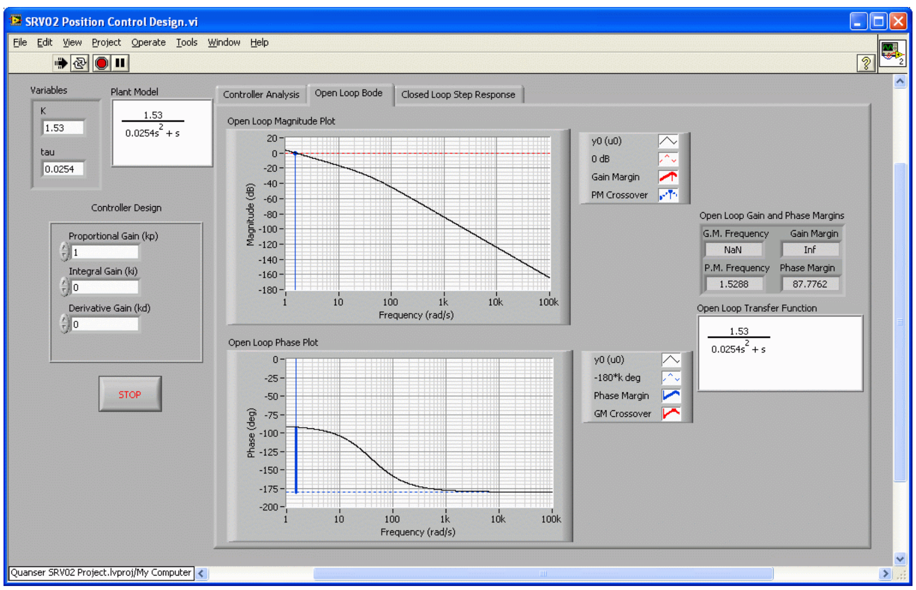


Figure 2.6: SRV02 Position Control Design - Controller Analysis

and more stable the system is. The higher the bandwidth, the more responsive the system is to an input. What is the effect of increasing k_p or k_d?

6. Find proportional and derivative control gains that satisfy the bandwidth and phase margin specifications given in Section 2.1.1.2. These control gains are the *Frequency-Based Design*, or FBD, parameters.

7. In the *Closed Loop Step Response* tab, verify that the time-domain specifications given in Section 2.1.1.2 are satisfied. Enter the time-domain specifications values in Table 2.1.

8. Stop the VI.

2.3.1.2 FBD Control Simulation

1. Open *SRV02 Position Control* | *SRV02 Control Design and Simulation* | *SRV02 PD Control Simulation.vi* shown in Figure 2.7.

2. As shown in Figure 2.8, the block diagram is incomplete.

3. We want to simulate the position control of the SRV02 using a PD controller using the FBD gains you found in Section 2.3.1.1. First, enter the SRV02 plant in the MathScript node, as done in the previous procedure.

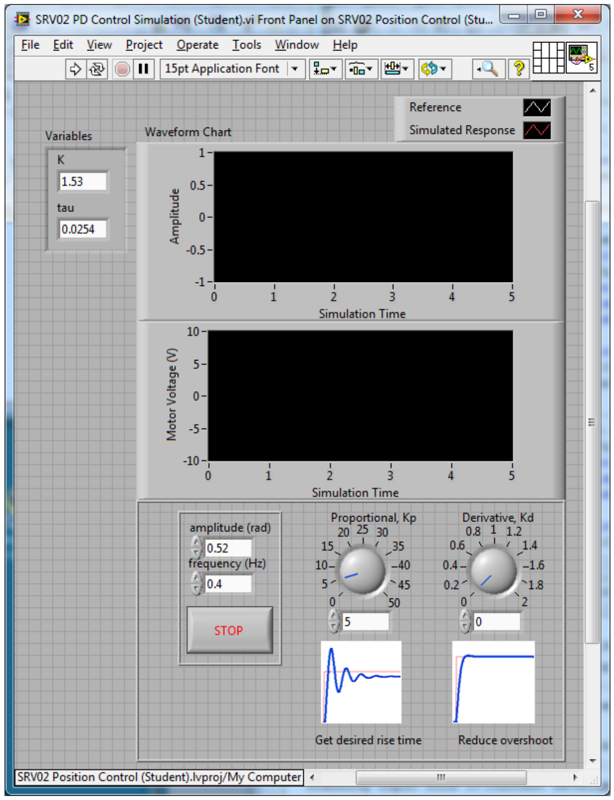


Figure 2.7: SRV02 PD Control Simulation VI

4. Using the Gain, Derivative, and Summation blocks from the *Control Design and Simulation* palette, build a PD controller as shown in Figure 2.3. Use the existing proportional and derivative gain controls already in the VI.
5. Run the VI with the following parameters:

$$k_p = 5$$
$$k_d = 0$$

   The response should be as shown in Figure 2.9. Both the output response, i.e. the servo angle, and the control input, i.e. the dc motor voltage, are being simulated.

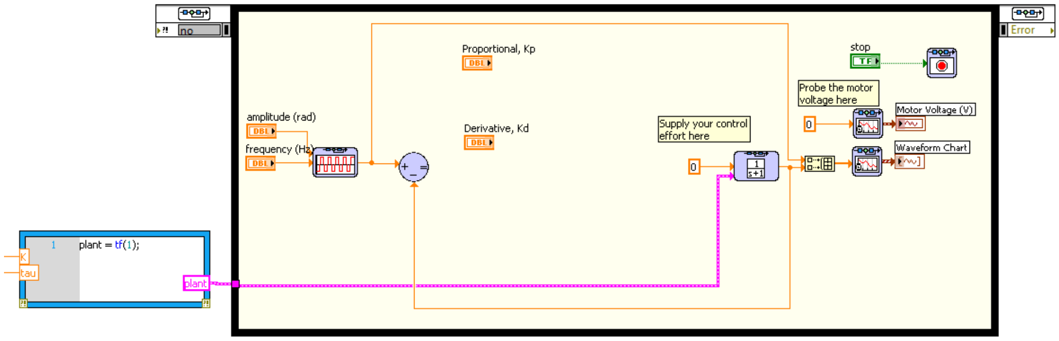


Figure 2.8: Incomplete block diagram in SRV02 PD Control VI

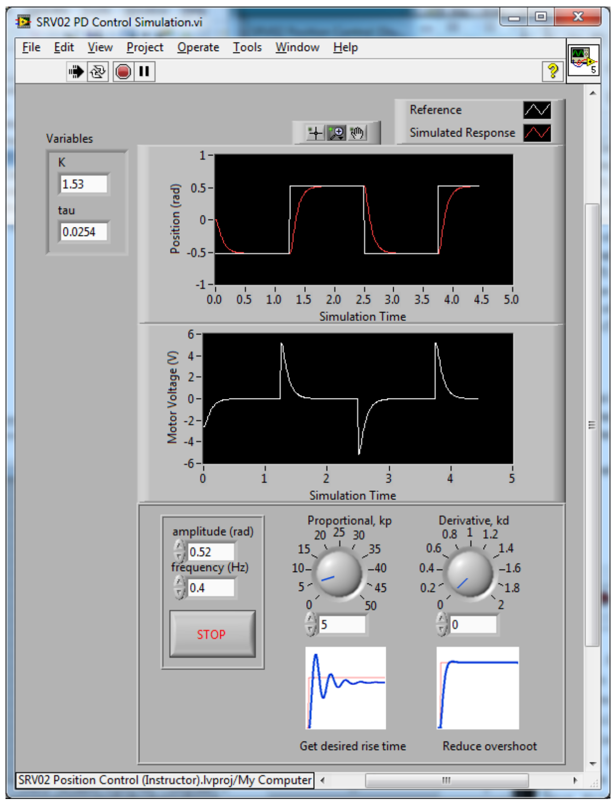


Figure 2.9: SRV02 PD Control Simulation VI shown when running with $k_p = 5$ and $k_d = 0$

6. Change the proportional gain, k_p, and examine its effect on the response. In particular, what happens to the overshoot and settling time as k_p is increased?

7. Change the derivative gain, k_d, and examine its effect on the response. What happens to the settling time and overshoot?

8. Enter the FBD gains, k_p and k_d, you found in Section 2.3.1.1. Attach the position and input voltage responses to your report. To export a response as an image right-click on the chart, go to *Export* | *Export Simplified Image*, and select the *BMP* and *Clipboard* options.

9. Are the settling time and overshoot specifications given in Section 2.1.1.2 satisfied using the FBD control?

   Hint: You can stop the VI and use the *Graph Palette* to zoom up on the overshoot and make sure the specifications are met. The *Graph Palette* located on the top of the chart is illustrated in Figure 2.10.

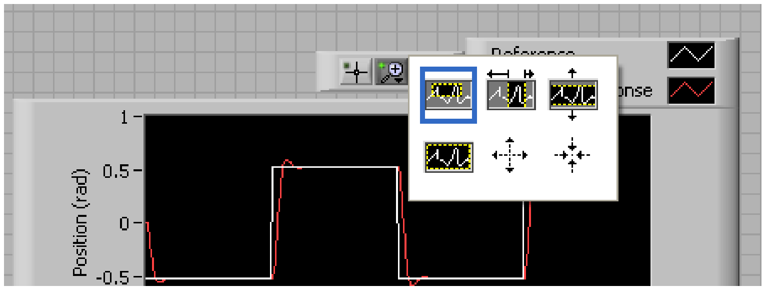


Figure 2.10: Using the Graph Palette to zoom up on a response

10. Examine the control input in the bottom scope. In regards to the input voltage, what is this simulation assuming? Should this controller be implemented on the actual hardware?
11. Based on your answer in 10, modify the simulation to make it more realistic. Looks through the Simulation Module palette for the appropriate block.
12. Run the VI.
13. Examine how the response changes with the saturation block. Attach the responses to your report (using the Export | Export Simplified Image command as descrbied previously).
14. Click on the *Stop* button to stop the VI.

2.3.2 Time-Domain Design (TDD)

2.3.2.1 Control Design

1. Run the *SRV02 Position Control.lvproj* | *SRV02 Position Control Design.vi* used in Section 2.3.1.1.
2. Run the VI.
3. Enter the PD gains you found in Section 2.2 in the VI.
4. Go to the *Closed Loop Step Response* tab.
5. Are the specifications in Section 2.1.1.2 satisfied?
6. List why the specifications based on the TDD PD control gains you calculated are not satisfied in simulation.
7. You may have to tune your gains slightly until the time-domain requirements are met. Once you have found a set of gains that satisfy the specifications, enter them below. These are known as the *Time-Domain Design* control gains, or TDD.
8. Based on the simulation, what is the expected settling time and percentage overshoot when using the TDD controller? Enter these in Table 2.1. Do they satisfy the specifications?
9. Go to the *Open-Loop Bode* tab. Enter the expected bandwidth and phase margin when using the TDD control gains. How does the bandwidth and phase margin compare with the FBD controller?
10. Stop the VI.

2.3.2.2 TDD Control Simulation

We will now simulate the closed-loop servo position control using a more realistic model (e.g. one that includes the saturation block).

1. Open *SRV02 Position Control | SRV02 Control Design and Simulation | SRV02 Manual Control PD.vi*.
2. Run the VI.
3. Enter the TDD control gains found in Section 2.3.2.1 in the VI. Show the position response and the resulting motor voltage, i.e., control effort.
4. Measure the overshoot, settling time, and steady-state error. Do they satisfy the TDD specifications listed in Section 2.1.1.2? Show your calculations and make sure the PD gains used and the resulting overshoot, settling time, and steady-state error values are given in your answer.

   Hint: You can stop the VI and use the *Graph Palette* to zoom up on the overshoot and make sure the specifications are met.
5. Stop the VI.

2.3.2.3 TDD Control Implementation

In this section the Time-Domain Design (TDD) controller is ran on the actual SRV02 system.

1. In the *SRV02 Position Control.lvproj* project, open the *SRV02 Position Control* VI. Make sure it is configured for your data acquisition device as explained in Section 2.4.

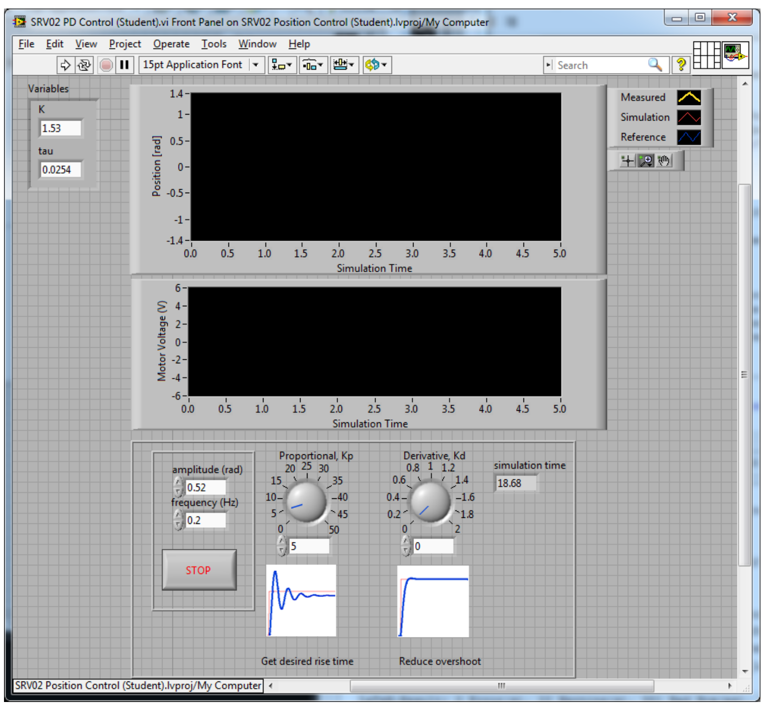


Figure 2.11: VI used to implement PD control on SRV02

2. As done previously in Section 2.3.1.1, enter the SRV02 plant in the MathScript node and build the PD control using the Gain, Summation, and Saturation VIs from the *Control Design and Simulation* palette. Use the existing proportional and derivative gain controls already in the VI.
3. Turn ON the power amplifier (e.g. Quanser VoltPAQ).
4. Run the VI. The top gears on the SRV02 should begin rotating back-and-forth and the VI should look similarly as shown in Figure 2.12. The top scope shown the measured response in yellow, the simulated response in red, and the desired or reference position in blue. The bottom scope is the input motor voltage.
5. Enter the TDD PD gains you found in Section 2.3.2.1 in the VI.

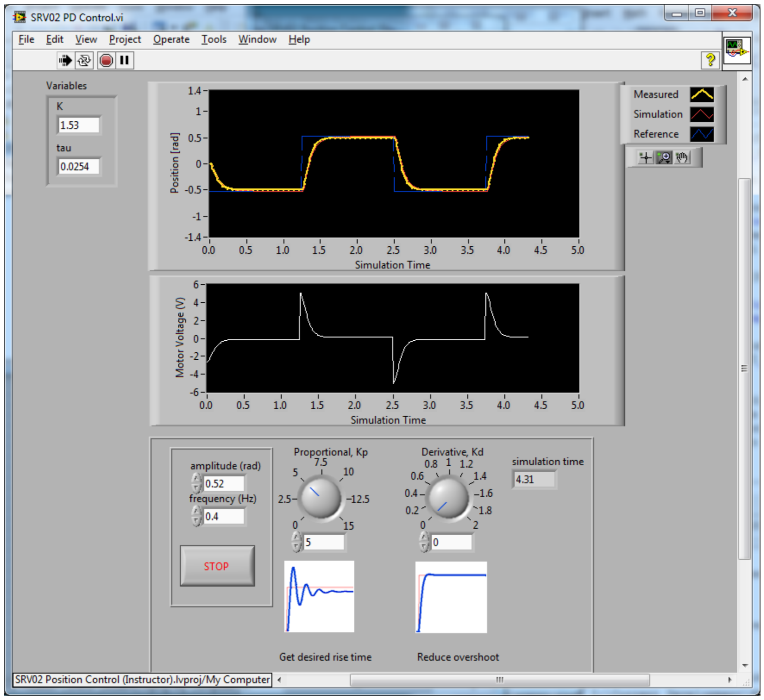


Figure 2.12: Running a sample PD control on the SRV02

6. Attach images of the position and voltage responses.

7. Do the simulated and measured responses match? Attach a closeup of the transient position response when the reference step goes up and give one reason why there is a discrepancy between the two.

8. Measure the overshoot, settling time, and steady-state of the measured response and enter them below. Are the specifications when controlling the actual servo satisfied? If the specifications have been met, enter the measured PO, t_s, and e_{ss} values in Table 2.1. If not, go to the next step.

9. If your measured response did not meet the specifications listed in 2.1.1.2, then try tuning the PD gains as the VI is ran until it does. Recall the strategy you used in Section 2.3.2.1 and document your approach. Attach the position and voltage response below. Show a close-up view of the response as the step goes up.

10. Measure the overshoot, settling time, and steady-state error. Enter your newly tuned TDD control gains and the measured specifications in Table 2.1.

11. Stop the VI.

12. Turn off the power amplifier.

2.3.3 Results

Fill out Table 2.1 with your answers from your TDD control lab results - both simulation and implementation.

From Section	Description	Symbol	Value	Unit
2.3.1	**Frequency-Based Design (FBD)**			
	Proportional gain	k_p		V/rad
	Derivative gain	k_d		V-s/rad
	Phase margin	PM		deg
	Bandwidth frequency	ω_{bw}		rad/s
	Settling time	t_s		s
	Percentage overshoot	PO		%
2.3.2.2	**Time-Domain Design (TDD) Simulation**			
	Proportional gain	k_p		V/rad
	Derivative gain	k_d		V-s/rad
	Phase margin	PM		deg
	Bandwidth frequency	ω_{bw}		rad/s
	Settling time	t_s		s
	Percentage overshoot	PO		%
	Steady-state error	e_{ss}		%
2.3.2.3	**Time-Domain Design (TDD) Implementation**			
	Proportional gain	k_p		V/rad
	Derivative gain	k_d		V-s/rad
	Settling time	t_s		s
	Percentage overshoot	PO		%
	Steady-state error	e_{ss}		%
2.3.2.3	**Time-Domain Design (TDD) Implementation - Tuned**			
	Proportional gain	k_p		V/rad
	Derivative gain	k_d		V-s/rad
	Settling time	t_s		s
	Percentage overshoot	PO		%
	Steady-state error	e_{ss}		%

Table 2.1: Summary of results for the SRV02 Position Control laboratory.

2.4 System Requirements

Required Hardware

- Data-aquisition (DAQ) device that is compatible with LabVIEW™ , e.g., NI USB or PCI DAQ, NI CompactRIO, or Quanser Hardware-in-the-loop (HIL).
- Quanser SRV02-ET rotary servo. See Reference [4].
- Quanser VoltPAQ power amplifier, or equivalent (e.g. Reference [2] for VoltPAQ User Manual).

Required Software

- NI LabVIEW™
- NI LabVIEW Control Design and Simulation Module
- Quanser Rapid Control Prototyping Toolkit®
- NI LabVIEW MathScript Module
- For NI CompactRIO users:
  – NI LabVIEW Real-Time Module
  – NI LabVIEW FPGA Module 2010
  – RIO Drivers

2.4.1 Overview of Files

File Name	Description
SRV02 Manual (Student).pdf	This laboratory guide contains pre-lab questions and lab experiments demonstrating how to design and implement a position controller on the Quanser SRV02 rotary plant using LabVIEW™ .
SRV02 Position Control (Student).lvproj	LabVIEW project containing the student-based VIs.
SRV02 Position Control Design (Student).vi	VI used to design the PD controller. The SRV02 model has not been enterred (e.g., to be completed by the student).
SRV02 PD Control Simulation (Student).vi	Simulates the PD closed-loop response of the SRV02. The model has not been enterred and the feedback loop is not completed.
SRV02 PD Control (Student).vi	Implement PD controller on the SRV02. Control loop not completed.

Table 2.2: Files supplied with the SRV02 Position Control laboratory.

2.4.2 Hardware Setup

Follow these steps to get the system hardware ready for this lab:

1. Connect the Quanser SRV02 to the amplifier (e.g. VoltPAQ) and DAQ device as described in [4].
2. Make sure the SRV02 is in the *high-gear configuration*.

3. Install the *disc load* on the top gear.

Note: If you are using the NI CompactRIO, then see the SRV02 cRIO User Manual ([3]).

2.4.3 Software Setup

Follow these steps to get the system ready for this lab:

1. Load the LabVIEW™ software.
2. Open the LabVIEW project called *SRV02 Position Control (Student).lvproj* shown in Figure 2.13.

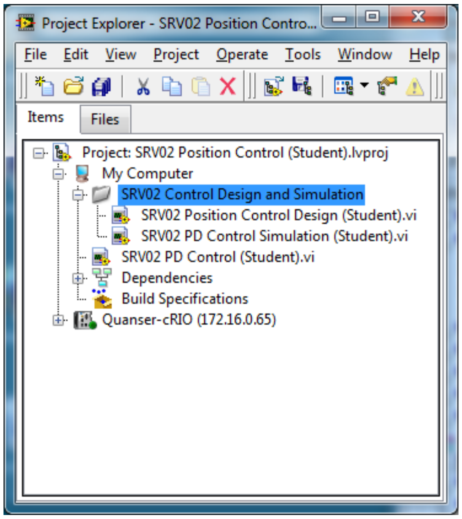


Figure 2.13: SRV02 Position Control.

3. The *SRV02 Control Design and Simulation* folder contains the simulation-based VIs that do not require any hardware.
4. **Choose data acquisition device:** Before running the VI, make sure you set the correct *Board type* in the HIL Initialize block (e.g., 'q1_cRIO', 'q2_usb', 'q8_usb', 'qpid', or 'qpid_e').
5. **Channel Configuration:** For any of these VIs, the encoder input and analog ouput channels are set, by default, to match the wiring in the SRV02 User Manual ([4]). If the wiring is different on your system, make sure the VI uses the correct channels.
6. **Quanser CompactRIO Users:** Before running the VI, make sure you can connect to your CompactRIO through the Measurement & Automation software. See the SRV02 cRIO User Manual ([3]).

2.5 Lab Report

This laboratory contains two experiments, namely,

1. Frequency-Based Design (FBD), and
2. Time-Domain Design (TDD).

When you are writing your lab report, follow the outline corresponding to the experiment you conducted to build the *content* of your report. Also, in Section 2.5.3 you can find some basic tips for the *format* of your report.

2.5.1 Template for Content (FBD Experiment)

I. PROCEDURE

I.1. FBD Control Design

- Briefly describe the main goal of the control design.
- Briefly describe the control design procedure (Section 2.3.1.1).

I.2. FBD Simulation

- Briefly describe the main goal of the simulation.
- Briefly describe the simulation procedure (Section 2.3.1.2).

II. RESULTS Do not interpret or analyze the data in this section. Just provide the results.

1. Step response plot from step 8 in Section 2.3.1.2, *Response without actuator saturation*.
2. Step response plot from step 13 in Section 2.3.1.2, *Response with actuator saturation*.
3. Provide applicable data collected in this laboratory (from Table 2.1).

III. ANALYSIS Provide details of your calculations (methods used) for analysis for each of the following:

III.1. FBD Control Design

1. Step 5 in Section 2.3.1.1, *Frequency-based control design*.

III.2. FBD Simulation

1. Step 6 in Section 2.3.1.2, *Effect of proportional gain on simulated step response (without actuator saturation)*.
2. Step 7 in Section 2.3.1.2, *Effect of derivative gain on simulated step response (without actuator saturation)*.

IV. CONCLUSIONS Interpret your results to arrive at logical conclusions for the following:

1. Step 9 in Section 2.3.1.2, *Step response simulation without actuator saturation*.
2. Step 10 in Section 2.3.1.2, *Assess whether the FBD controller can be implemented on hardware*.

2.5.2 Template for Content (TDD Experiment)

I. PROCEDURE

I.1 TDD Control Design

- Briefly describe the main goal of the control design.
- Briefly describe the control design procedure (Section 2.3.2.1).

I.2. TDD Simulation

- Briefly describe the main goal of the simulation.
- Briefly describe the simulation procedure (Section 2.3.2.2).

I.3. TDD Implementation

- Briefly describe the main goal of this experiment.
- Briefly describe the experimental procedure (Section 2.3.2.3).

II. RESULTS Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 3 in Section 2.3.2.2, *TDD controller simulation with step input*.
2. Response plot from step 6 in Section 2.3.2.3, *TDD controller implementation with step input*.
3. Response plot from step 9 in Section 2.3.2.3, *Tuned TDD controller with step input* (if applicable).
4. Provide applicable data collected in this laboratory (from Table 2.1).

III. ANALYSIS Provide details of your calculations (methods used) for analysis for each of the following:

III.1 TDD Control Design

1. Step 8 in Section 2.3.2.1, *Time-Domain Controller Design*.

III.2. TDD Simulation

1. Step 4 in Section 2.3.2.2, *TDD controller simulation with step input*.

III.3. TDD Implementation

1. Step 7 in Section 2.3.2.3, *Comparing simulated and implemented TDD controller*.
2. Step 8 in Section 2.3.2.3, *TDD controller implementation with step input*.

IV. CONCLUSIONS Interpret your results to arrive at logical conclusions for each of the following:

1. Step 8 in Section 2.3.2.1, *Time-domain controller design initial simulation*.
2. Step 4 in Section 2.3.2.2, *TDD controller simulation with step input*.
3. Step 8 in Section 2.3.2.3, *TDD controller implementation with step input*.
4. Step 10 in Section 2.3.2.3, *Tuned TDD controller implementation with step input*.

2.5.3 Tips for Report Format

PROFESSIONAL APPEARANCE

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

LABORATORY 3

SRV02 SPEED CONTROL

The objective of this laboratory is to develop feedback systems that control the speed of the rotary servo load shaft. A proportional-integral (PI) controller and a lead compensator are designed to regulate the shaft speed according to a set of specifications.

Topics Covered

- Design of a proportional-integral (PI) controller that regulates the angular speed of the servo load shaft.
- Design of a lead compensator.
- Simulation of the PI and lead controllers using the plant model to ensure the specifications are met without any actuator saturation.
- Implemention of the controllers on the Quanser SRV02 device to evaluate their performance.

Prerequisites

In order to successfully carry out this laboratory, the user should be familiar with the following:

- Data acquisition device (e.g. Q2-USB), the power amplifier (e.g. VoltPAQ-X1), and the main components of the SRV02 (e.g. actuator, sensors), as described in References [1], [2], and [4], respectively.
- Wiring and operating procedure of the SRV02 plant with the amplifier and data-aquisition (DAQ) device, as discussed in Reference [4].
- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Laboratory described in Appendix A to get familiar with using LabVIEW™ with the SRV02.

3.1 Background

3.1.1 Desired Response

3.1.1.1 SRV02 Speed Control Specifications

The time-domain requirements for controlling the speed of the SRV02 load shaft are:

$$e_{ss} = 0 \tag{3.1.1}$$

$$t_p \leq 0.05 \text{ s, and} \tag{3.1.2}$$

$$PO \leq 5 \text{ \%} \tag{3.1.3}$$

Thus, when tracking the load shaft reference, the transient response should have a peak time less than or equal to 0.05 seconds, an overshoot less than or equal to 5 %, and zero steady-state error.

In addition to the above time-based specifications, the following frequency-domain requirements are to be met when designing the *Lead Compensator*:

$$PM \geq 75.0 \text{ deg} \tag{3.1.4}$$

and

$$\omega_g = 75.0 \text{ rad/s} \tag{3.1.5}$$

The phase margin mainly affects the shape of the response. Having a higher phase margin implies that the system is more stable and the corresponding time response will have less overshoot. The overshoot will not go beyond 5% with a phase margin of at least 75.0 degrees.

The crossover frequency is the frequency where the gain of the Bode plot is 1 (or 0 dB). This parameter mainly affects the speed of the response, thus having a larger ω_g decreases the peak time. With a crossover frequency of 75.0 radians the resulting peak time will be less than or equal to 0.05 seconds.

3.1.1.2 Overshoot

In this laboratory we will use the following step setpoint (input):

$$\omega_d(t) = \begin{cases} 2.5 \text{ rad/s} & t \leq t_0 \\ 7.5 \text{ rad/s} & t > t_0 \end{cases} \tag{3.1.6}$$

where t_0 is the time the step is applied. Initially, the SRV02 should be running at 2.5 rad/s and after the step time it should jump up to 7.5 rad/s. From the standard definition of overshoot in step response, we can calculate the maximum overshoot of the response (in radians):

$$\omega(t_p) = \omega_d(t_0) + (\omega_d(t) - \omega_d(t_0))\left(1 + \frac{PO}{100}\right) \tag{3.1.7}$$

with the given values the maximum overshoot of the response is

$$\omega(t_p) = 7.75 \text{ rad/s} \quad (3.1.8)$$

The closed-loop speed response should therefore not exceed the value given in Equation 3.1.8.

3.1.1.3 Steady State Error

Consider the speed control system with unity feedback shown in Figure 3.1. Let the compensator be $C(s) = 1$.

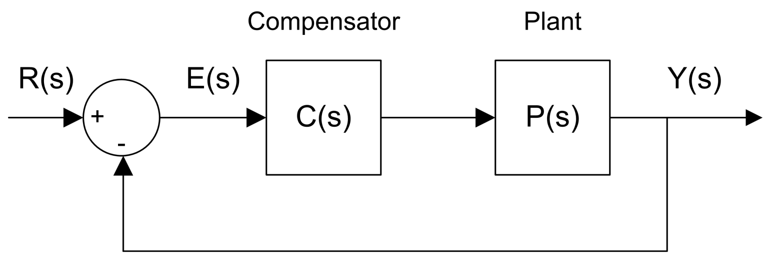


Figure 3.1: Unity feedback loop.

We can find the steady-state error using the final value theorem:

$$e_{ss} = \lim_{s \to 0} s\,E(s) \quad (3.1.9)$$

where

$$E(s) = \frac{R(s)}{1 + C(s)\,P(s)} \quad (3.1.10)$$

The voltage-to-speed transfer function for the SRV02 was found in Section 1 as:

$$P(s) = \frac{K}{\tau\,s + 1} \quad (3.1.11)$$

Substituting $R(s) = \frac{R_0}{s}$ and $C(s) = 1$ gives:

$$E(s) = \frac{R_0}{s\left(1 + \frac{K}{\tau\,s+1}\right)} \quad (3.1.12)$$

Applying the final-value theorem to the system gives

$$e_{ss} = R_0\left(\lim_{s \to 0} \frac{\tau\,s + 1}{\tau\,s + 1 + K}\right) \quad (3.1.13)$$

When evaluated, the resulting steady-state error due to a step response is

$$e_{ss} = \frac{R_0}{1 + K} \quad (3.1.14)$$

3.1.2 PI Control Design

3.1.2.1 Closed Loop Transfer Function

The proportional-integral (PI) compensator used to control the velocity of the SRV02 has the following structure:

$$V_m(t) = k_p\,(b_{sp}\,\omega_d(t) - \omega_l(t)) - k_i \int (\omega_d(t) - \omega_l(t))\,dt \quad (3.1.15)$$

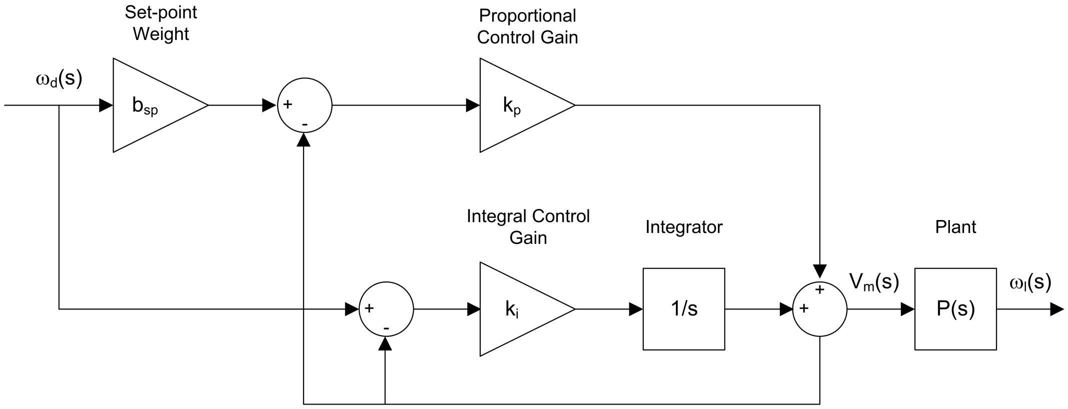


Figure 3.2: Block diagram of SRV02 PI speed control.

where k_p is the proportional control gain, k_i is the integral control gain, $\omega_d(t)$ is the setpoint or reference angular speed for the load shaft, $\omega_l(t)$ is the measured load shaft angular speed, b_{sp} is the setpoint weight, and $V_m(t)$ is the voltage applied to the SRV02 motor. The block diagram of the PI control is given in Figure 3.2.

We can take Laplace transform of the controller given in Equation 3.1.15:

$$V_m(s) = k_p\,(b_{sp}\,\Omega_d(s) - \Omega_l(s)) + \frac{k_i\,(\Omega_d(s) - \Omega_l(s))}{s} \tag{3.1.16}$$

To find the closed-loop speed transfer function, $\Omega_l(s)/\Omega_d(s)$, we can use the process transfer function from Equation 3.1.11 and solve for $\Omega_l(s)/\Omega_d(s)$ as:

$$\frac{\Omega_l(s)}{\Omega_d(s)} = \frac{K\,(k_p\,s\,b_{sp} + k_i)}{s^2\,\tau + (1 + K\,k_p)\,s + K\,k_i} \tag{3.1.17}$$

3.1.2.2 Finding PI Gains to Satisfy Specifications

In this section, we will first calculate the minimum damping ratio and natural frequency required to meet the specifications given in Section 3.1.1.1. Then, using these values we will calculate the necessary control gains k_p and k_i to achieve the desired performance with a PI controller.

The minimum damping ratio and natural frequency needed to satisfy a given percent overshoot and peak time are:

$$\zeta = -\ln\left(\frac{PO}{100}\right)\sqrt{\frac{1}{\ln\left(\frac{PO}{100}\right)^2 + \pi^2}} \tag{3.1.18}$$

and

$$\omega_n = \frac{\pi}{t_p\,\sqrt{1-\zeta^2}} \tag{3.1.19}$$

Substituting the percent overshoot specifications given in 3.1.3 into Equation 3.1.18 gives the required damping ratio

$$\zeta = 0.690 \tag{3.1.20}$$

Then, by substituting this damping ratio and the desired peak time, given in 3.1.2, into Equation 3.1.19, the minimum natural frequency is found as:

$$\omega_n = 86.7 \text{ rad/s} \tag{3.1.21}$$

Now, let's look at how we can calculate the gains. When the setpoint weight is zero, i.e. $b_{sp} = 0$, the closed-loop SRV02 speed transfer function has the structure of a *standard second-order system*. We can find expressions for the control gains k_p and k_i by equating the characteristic equation (denominator) of the SRV02 closed-loop transfer function to the *standard characteristic equation*: $s^2 + 2\,\zeta\,\omega_n\,s + \omega_n^2$.

The denominator of the transfer function can be re-structured into the following:

$$s^2 + \frac{(1 + K\,k_p)\;s}{\tau} + \frac{K\,k_i}{\tau} \tag{3.1.22}$$

equating the coefficients of this equation to the coefficients of the standard characteristic equation gives:

$$\frac{K\,k_i}{\tau} = \omega_n^2 \tag{3.1.23}$$

and

$$\frac{1 + K\,k_p}{\tau} = 2\,\zeta\,\omega_n \tag{3.1.24}$$

Then, the proportional gain k_p can be found as:

$$k_p = \frac{-1 + 2\,\zeta\,\omega_n\,\tau}{K} \tag{3.1.25}$$

and the integral gain k_i is

$$k_i = \frac{\omega_n^2\,\tau}{K} \tag{3.1.26}$$

3.1.3 Lead Control Design

Alternatively, a lead or lag compensator can be designed to control the speed of the servo. The lag compensator is actually an approximation of a PI control and this, at first, may seem like the more viable option. However, due to the saturation limits of the actuator the lag compensator cannot achieve the desired zero steady-state error specification. Instead, a lead compensator with an integrator, as shown in Figure 3.3, will be designed.

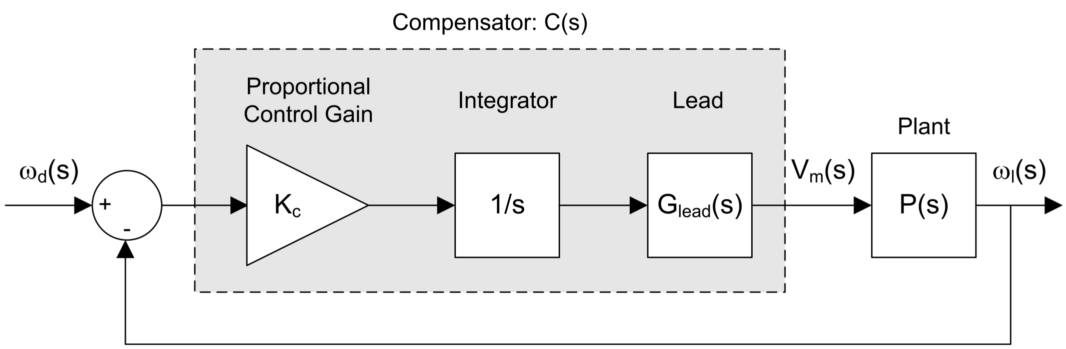


Figure 3.3: Closed-loop SRV02 speed control with lead compensator.

To obtain zero steady-state error, an integrator is placed in series with the plant. This system is denoted by the transfer function

$$P_i(s) = \frac{P(s)}{s} \tag{3.1.27}$$

where $P(s)$ is the plant transfer function in Equation 3.1.11.

The phase margin and crossover frequency specifications listed in equations 3.1.4 and 3.1.5 of Section 3.1.1.1 can then be satisfied using a proportional gain K_c and the lead transfer function

$$G_{lead}(s) = \frac{1 + a\,T\,s}{1 + T\,s} \tag{3.1.28}$$

The a and T parameters change the location of the pole and the zero of the lead compensator which changes the gain and phase margins of the system. The design process involves examining the stability margins of the *loop transfer function*, $L(s) = C(s) \cdot P(s)$, where the compensator is given by:

$$C(s) = \frac{K_c\;(1 + a\,T\,s)}{(1 + T\,s)\;s} \tag{3.1.29}$$

3.1.3.1 Finding Lead Compensator Parameters

The Lead compensator is an approximation of a proportional-derivative (PD) control. A PD controller can be used to add damping to reduce the overshoot in the transient of a step response and effectively making the system more stable. In other words, it increases the phase margin. In this particular case, the lead compensator is designed for the following system:

$$L_p(s) = \frac{K_c\, P(s)}{s} \tag{3.1.30}$$

The proportional gain Kc is designed to attain a certain crossover frequency. Increasing the gain crossover frequency essentially increases the bandwidth of the system which decreases the peak time in the transient response (i.e. makes the response faster). However, as will be shown, adding a gain $K_c > 1$ makes the system less stable. The phase margin of the $L_p(s)$ system is therefore lower than the phase margin of the $P_i(s)$ system and this translates to having a large overshoot in the response. The lead compensator is used to dampen the overshoot and increase the overall stability of the system, i.e increase its phase margin.

The frequency response of the lead compensator given in 3.1.28 is

$$G_{lead}\,(\omega\, j) = \frac{1 + a\, T\, \omega j}{1 + T\, \omega\, j} \tag{3.1.31}$$

and its corresponding magnitude and phase equations are

$$|G_{lead}(\omega\, j)| = \sqrt{\frac{T^2\, \omega^2\, a^2 + 1}{1 + T^2\, \omega^2}} \tag{3.1.32}$$

and

$$\phi_G = arctan(a\, T\omega) - arctan(T\, \omega) \tag{3.1.33}$$

The Bode plot of the lead compensator is shown in Figure 3.4.

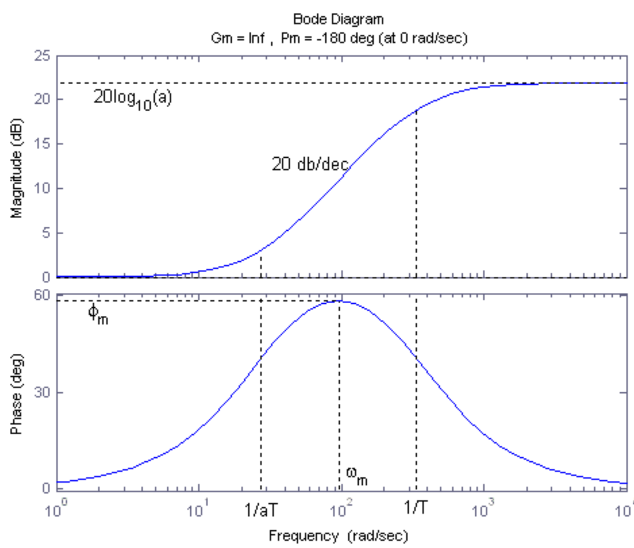


Figure 3.4: Bode of lead compensator.

3.1.3.2 Lead Compensator Design Steps

In this section, we will summarize the steps required to design a lead compensator that will satisfy the frequency-based specifications given in Section 3.1.1.1.

1. **Bode plot of the open-loop uncompensated system**, $P_i(s)$, must first be found. Use your software to generate a Bode plot of $P_i(s)$. For instance, in MathScript you could enter the following commands to construct the $P_i(s)$ transfer function.

```
% Plant transfer function
P = tf([K],[tau 1]);
% Integrator transfer function
I = tf([1],[1 0]);
% Plant with Integrator transfer function
Pi = series(P,I);
```

These parameters are used with the commands *tf* and *series* to create the $P_i(s)$ transfer function. You can then generate the Bode under your software requirement (e.g., Matlab®or LabVIEW™). The Bode of $P_i(s)$ is shown in Figure 3.5. It also lists the gain and phase stability margins as well as the phase and gain crossover frequencies.

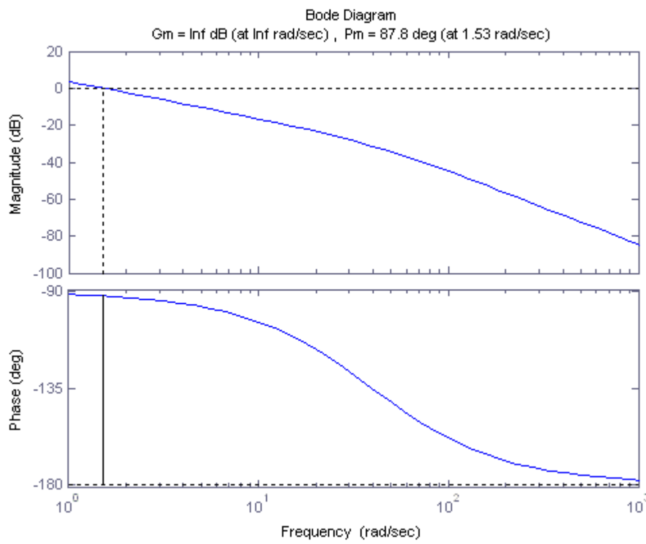


Figure 3.5: Bode of $P_i(s)$ system.

2. **Find how much more gain is required** such that the gain crossover frequency is 50.0 rad/s. As mentioned before, the lead compensator adds gain to the system and will increases the phase as well. Therefore, gain K_c is not to be designed to meet the specified 75.0 rad/s fully.

   As given in Figure 3.5, the crossover frequency of the uncompensated system is about 1.53 rad/s. The Bode plot after adding gain K_c, i.e., the loop transfer function $L_p(s)$ from Section 3.1.3, is given in Figure 3.6.

   This initial estimate of the gain can be found from the Bode plot and then adjusted according to the crossover frequency calculated in the generated Bode plot of the $L_p(s)$ system.

3. **Gain needed for specified phase margin** must be found next so that the lead compensator can achieve the specified phase margin of 75 degrees. Also, to ensure the desired specifications are reached, we'll add another 5 degrees to the maximum phase of the lead.

   To attain the necessary phase margin, the maximum phase of the lead can be calculated using

$$\phi_m = PM_{des} - PM_{meas} + 5 \tag{3.1.34}$$

   The lead compensator, as explained in Section 3.1.3.1, has two parameters: a and T. To attain the maximum phase ϕ_m shown in Figure 3.4, the Lead compensator has to add $20 \log_{10}(a)$ of gain. This is determined using the equation

$$a = -\frac{1 + \sin \phi_m}{-1 + \sin \phi_m} \tag{3.1.35}$$

4. **The frequency at which the lead maximum phase occurs** must be placed at the new gain crossover frequency $\omega_{g,new}$. This is the crossover frequency after the lead compensator is applied. As illustrated in Figure

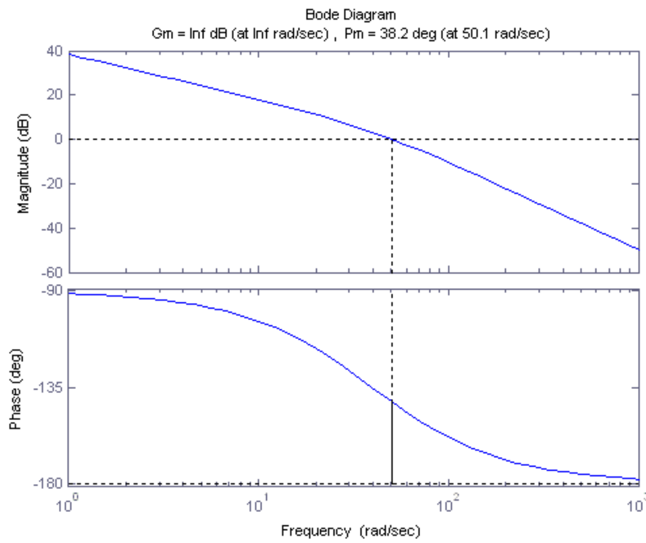


Figure 3.6: Bode of $L_p(s) = K_c P_i(s)$ system.

3.4, ω_m occurs halfway between 0 dB and $20\log_{10}(a)$, i.e. at $10\log_{10}(a)$. So, the new gain crossover frequency in the $L_p(s)$ system will be the frequency where the gain is $-10\log_{10}(a)$.

As illustrated earlier in Figure 3.4 in Section 3.1.3.1, the maximum phase occurs at the maximum phase frequency ω_m. Parameter T given by:

$$T = \frac{1}{\omega_m\sqrt{a}} \tag{3.1.36}$$

is used to attain a certain maximum phase frequency. This changes where the Lead compensator breakpoint frequencies $1/(a\,T)$ and $1/T$ shown in Figure 3.4 occur. The slope of the lead compensator gain changes at these frequencies.

5. **Bode plot of the lead compensator** $C_{lead}(s)$. By defining the Lead compensator transfer function given in Equation 3.1.28 in software, you can generate a Bode similarly as shown in Figure 3.7.

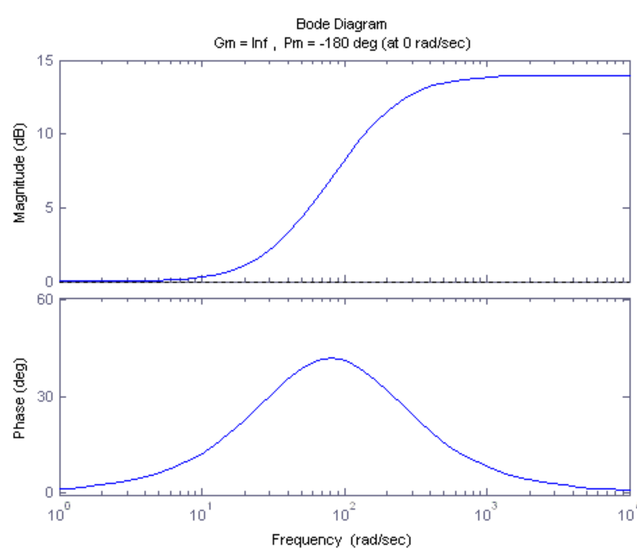


Figure 3.7: Bode of lead compensator $C_{lead}(s)$.

6. **Bode plot of the loop transfer function** $L(s)$, as described in 3.1.30, is shown in Figure 3.8. Measure the phase margin and crossover frequency on the Bode of $L(s)$ and determine whether or not the frequency-domain specifications given in Section 3.1.1 have been met.

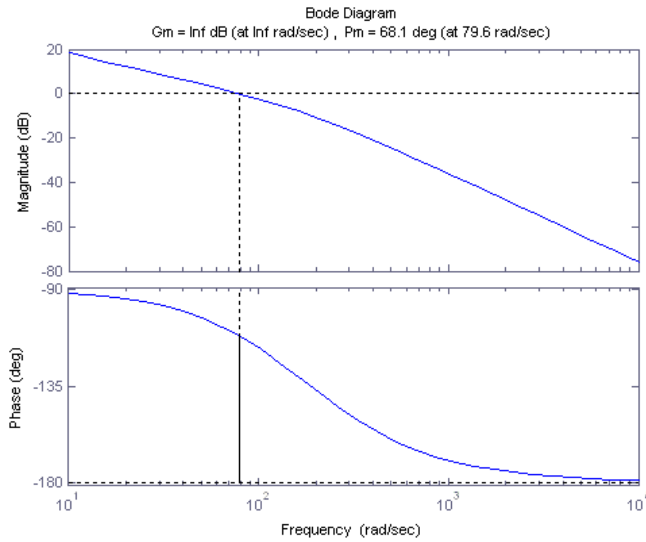


Figure 3.8: Bode of loop transfer function $L(s)$.

7. **Check response** by simulating the system to make sure that the time-domain specifications are met. Keep in mind that the goal of the lead design is the same as the PI control, the response should meet the desired steady-state error, peak time, and percentage overshoot specifications given in Section 3.1.1. Thus, if the crossover frequency and/or phase margin specifications are not quite satisfied, the response should be simulated to verify if the time-domain requirements are satisfied. If so, then the design is complete. If not, then the lead design needs to be re-visited.

   You will work on this later in the laboratory as described in Section 3.3.2.1.

3.1.4 Sensor Noise

When using analog sensors, such as a tachometer, there is often some inherent noise in the measured signal.

The peak-to-peak noise of the measured SRV02 load gear signal can be calculated using

$$e_\omega = \frac{1}{100} K_n \, \omega_l \tag{3.1.37}$$

where K_n is the peak-to-peak ripple rating of the sensor and ω_l is the speed of SRV02 load gear. The rated peak-to-peak noise of the SRV02 tachometer is given in Appendix B of Reference [4] as:

$$K_n = 7 \text{ \%} \tag{3.1.38}$$

Based on this specification, the peak-to-peak noise, when the load shaft runs at 7.5 rad/s, will be

$$e_\omega = 0.525 \text{ rad/s} \tag{3.1.39}$$

Thus, the signal will oscillate ± 0.2625 rad/s about the 7.5 rad/s setpoint, or approximately between 7.24 rad/s and 7.76 rad/s. Then, taking the noise into account, what would be the maximum peak in the speed response that is to be expected?

Equation 3.1.7 was used to find the peak value of the load gear response for a given percent overshoot. To take into account the noise in the signal, this formula is modified as follows:

$$\omega(t_p) = \omega_d(t_0) + (\omega_d(t) - \omega_d(t_0)) \left(1 + \frac{PO}{100}\right) + \frac{1}{2} e_\omega \tag{3.1.40}$$

Given a reference signal that goes between 2.5 rad/s to 7.5 rad/s, as described in Section 3.1.1.1, and the peak-to-peak ripple estimate in Equation 3.1.39, the peak speed of the load gear, including the noise, can be found as:

$$\omega(t_p) = 8.01 \text{ rad/s} \tag{3.1.41}$$

Using

$$PO = \frac{100\ (\omega(t_p) - \omega_d(t))}{\omega_d(t) - \omega_d(t_0)} \tag{3.1.42}$$

the new maximum percent overshoot for a 5.0 rad/s step is

$$PO \leq 10.2 \text{ \%} \tag{3.1.43}$$

3.2 Pre-Lab Questions

1. Based on the steady-state error result of a step response from Equation ,what *type* of system is the SRV02 when performing speed control (Type 0, 1, or 2) and why?
2. The nominal SRV02 model parameters, K and τ, found in SRV02 Modeling Laboratory (Section 1) should be about 1.53 (rad/s-V) and 0.0254 sec, respectively. Calculate the PI control gains needed to satisfy the time-domain response requirements.
3. Find the frequency response magnitude, $|P_i(\omega)|$, of the transfer function $P_i(s)$ given in Equation 3.1.27.
4. Calculate the DC gain of $P_i(s)$ given in Equation $3.1.27$. **Hint:** The DC gain is the gain when the frequency is zero, i.e. $\omega = 0\, rad/s$. However, because of its integrator, $P_i(s)$ has a singularity at zero frequency. Therefore, the DC gain is not technically defined for this system. Instead, approximate the DC gain by using $\omega = 1\, rad/s$. Make sure the DC gain estimate is evaluated numerically in dB using the nominal model parameters, $K = 1.53$ and $\tau = 0.0254$, (or use what you found for K and τ in Section 1).
5. The gain crossover frequency, ω_g, is the frequency at which the gain of the system is 1 or 0 dB. Express the crossover frequency symbolically in terms of the SRV02 model parameters K and τ. Then, evaluate the expression using the nominal SRV02 model parameters $K = 1.53$ and $\tau = 0.0254$, (or use what you found for K and τ in Section 1).

3.3 Lab Experiments

The main goal of this laboratory is to explore closed-loop speed control of the SRV02 load shaft.

In this laboratory you will conduct two experiments:

1. Step response with PI control, and
2. Step response with Lead control

In each of the experiments, you will first simulate the closed-loop response of the system. Then, you will implement the controller using the SRV02 hardware and software to compare the real response to the simulated one.

IMPORTANT: Before you conduct these experiments, you need to make sure that the correct LabVIEW™ VI is used and configured according to your SRV02 setup. If it has not been configured already, then you need to go to Section 3.4 to configure the VI first.

3.3.1 Step Response with PI Control

3.3.1.1 Simulation

First you will simulate the closed-loop speed response of the SRV02 with a PI controller and a step input. Our goals are to confirm that the desired reponse specifications in an ideal situation are satisfied and to verify that the motor is not saturated.

Experimental Setup
The SRV02 Speed Control Simulation VI shown in Figure 3.9 is used to simulate the closed-loop speed response of the SRV02 when using either the PI or Lead controls. The SRV02 is simulated using a Transfer Function model. The PI compensator subsystem contains the PI control detailed in Section 3.1.2 and the *Lead Compensator* block has the compensator described in Section 3.1.3.

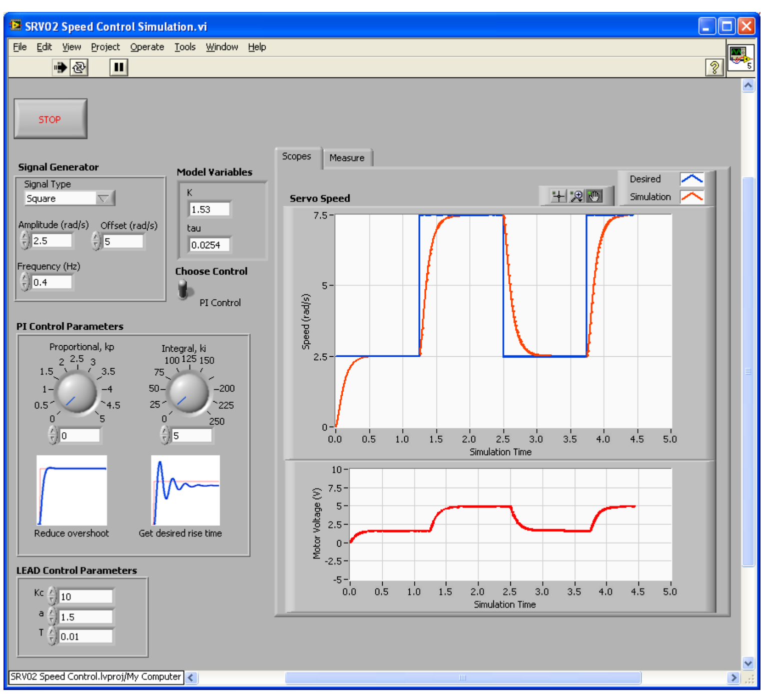


Figure 3.9: LabVIEW VI used to simulate the closed-loop SRV02 speed response.

IMPORTANT: Before you can conduct these experiments, you need to make sure that the lab files are configured according to your SRV02 setup. If they have not been configured already, then you need to go to Section 3.4.2 to configure the lab files first.

1. Open the LabVIEW project called *SRV02 Speed Control.lvproj*, shown in Figure 3.12 in Section 3.4.
2. In the *Simulation and Control Design* folder, open the *SRV02 Speed Control Simulation.vi*.
3. Run the VI.
4. The speed reference signal is to be a 0.4 Hz square wave that goes between 2.5 rad/s and 7.5 rad/s (i.e. between 23.9 rpm and 71.6 rpm). Set the *Signal Generator* parameters to:
    - Signal Type: Square
    - Amplitude: 2.5
    - Offset: 5.0
    - Frequency: 0.4
5. Ensure the *Manual Switch* is set to the upward position to activate the PI control.
6. The scopes should be displaying responses similar as shown in Figure 3.9. Note that in the *Servo Speed* scope, the blue trace is the setpoint speed while the red trace is the simulated speed.
7. Enter the proportional and integral control gains found in Section 3.1.2.2 as *kp* and *ki* in the VI front panel.
8. Show the simulated PI speed response and its input voltage in two separate figures. To do this, stop the VI, right-click on the chart, and select *Export | Export Simplified Image* from the menu. Save it as a bitmap on the clipboard and append it your report. See Section A.5 for more details on saving data.
9. Measure the steady-state error, the percent overshoot, and the peak time of the simulated response. Does the response satisfy the specifications given in Section 3.1.1.1? Use the cursors in the *Servo Speed (rad/s)* Graph in the *Measure* tab to measure points off the response.

3.3.1.2 Implementing PI Speed Control

Experimental Setup
The *SRV02 Speed Control* VI in Figure 3.10 is used to perform the speed control exercises in this laboratory. The VI interfaces with the DC motor and sensors of the SRV02 system. The PI control subsystem implements the PI control detailed in Section 3.1.2 and the Lead Compensator block implements the lead control described in Section 3.1.3.

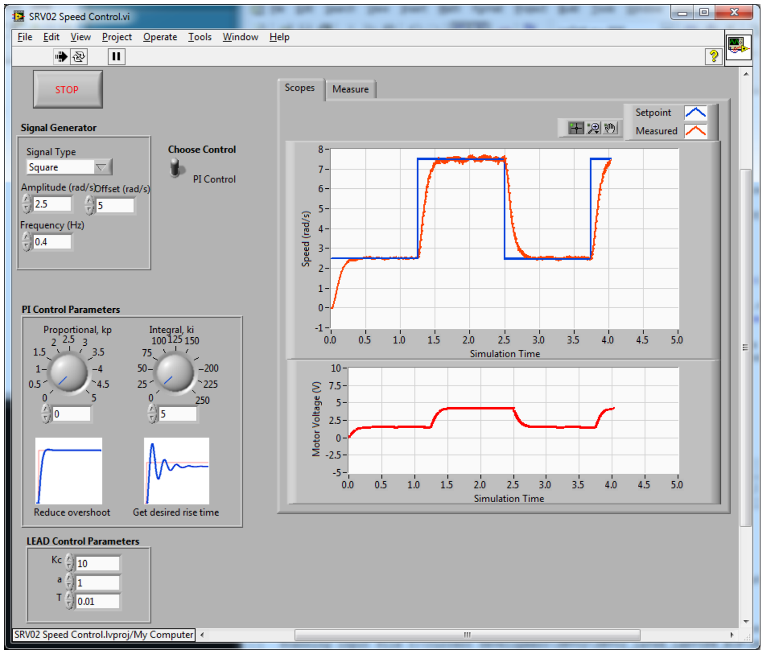


Figure 3.10: LabVIEW VI used to run the PI and Lead speed controllers on the SRV02.

1. Open the LabVIEW project called *SRV02 Speed Control.lvproj*, shown in Figure 3.12 in Section 3.4.
2. Open the *SRV02 Speed Control.vi* and make sure it is configured for your data acquisition device, as detailed in Section 3.4.
3. Run the VI.
4. The speed reference signal is to be a 0.4 Hz square wave that goes between 2.5 rad/s and 7.5 rad/s (i.e. between 23.9 rpm and 71.6 rpm). Set the *Signal Generator* parameters to:
   - Signal Type: Square
   - Amplitude: 2.5 rad/s
   - Offset: 5.0 rad/s
   - Frequency: 0.4 Hz
5. Ensure the *Manual Switch* is set to the upward position to activate the PI control.
6. The scopes should be displaying responses similar as shown in Figure 3.10. Note that in the *Servo Speed* scope, the blue trace is the setpoint speed while the red trace is the simulated speed.
7. Enter the proportional and integral control gains found in Section 3.1.2.2 as *kp* and *ki* in the VI front panel.
8. When a suitable response is obtained, click on the *Stop* button to stop running the VI. Generate a figure showing the PI speed response and its input voltage (as in the simulation lab in Section 3.3.1.1).
9. Due to the noise in the measured speed signal, it is difficult to obtain an accurate measurement of the specifications. In the *Signal Generator* section of the VI, set the *Amplitude (rad/s)* to 0 rad/s and the *Offset (rad/s)* to 7.5 rad/s in order to generate a constant speed reference of 7.5 rad/s. Show the response of the noise in the signal.
10. Measure the peak-to-peak ripple found in the speed signal, $e_{\omega,meas}$, and compare it with the estimate in Section 3.1.4. Then, find the steady-state error by comparing the average of the measured signal with the desired speed. Is the steady-state error specification satisfied?
11. Measure the percent overshoot and the peak time of the SRV02 load gear step response. Taking into account the noise in the signal, does the response satisfy the specifications given in Section 3.1.1.1?

12. Click the Stop button to stop the VI.

13. Turn off the power to the amplifier if no more experiments will be performed on the SRV02 in this session.

3.3.2 Step Response with LEAD Control

3.3.2.1 Control Design

In this section, the lead compensator for SRV02 speed control is designed. Our goal is to confirm that the desired frequency-based specifications in an ideal situation are satisfied. There is a step response simulation at the end to verify, at least preliminary, that the time-domain specifications are also satisfied. The full closed-loop lead simulation will be performed in the next section.

Experimental Setup
The SRV02 Lead Control Design LabVIEW™ VI shown in Figure 3.11 is used to design the lead controller of the SRV02. The various systems described in Section 3.1.3 (e.g., compensated system, lead compensator) are defined in the VI and their corresponding Bode plots are generated using the LabVIEW™ *Control Design Module* tools.

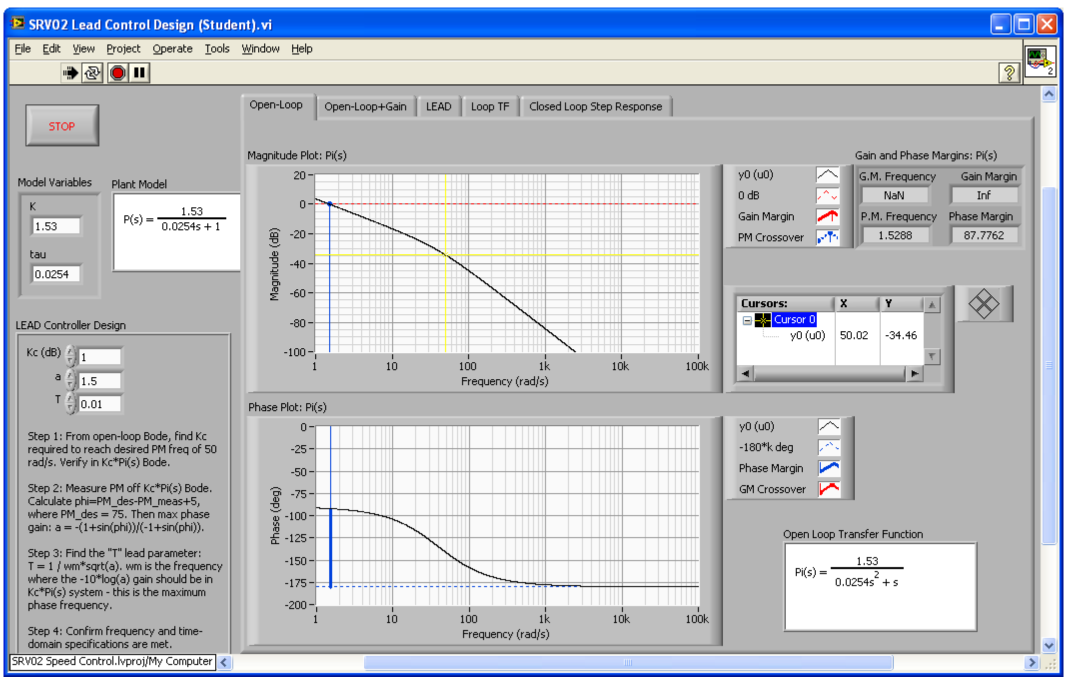


Figure 3.11: LabVIEW VI used to design the lead compensator for SRV02 speed control.

1. Open the LabVIEW project called *SRV02 Speed Control.lvproj*, shown in Figure 3.12 in Section 3.4.

2. Open the *SRV02 Lead Control Design.vi*.

3. Enter the model parameters *K* and *tau* of your system in the VI front panel control boxes (or use the default nominal values).

4. Run the VI. The steps below correspond to the design steps outlined in Section 3.1.3.2 to find K_c, a, and T lead parameters.

5. **Step 1: Bode plot of open-loop uncompensated system**. The *Open-Loop* tab in the VI displays the magnitude and phase Bode plots of the plant + integrator transfer function: $P_i(s) = P(s)/s$. Similarly as described in Step 1 of Section 3.1.3.2, the phase margin crossover frequency is about 1.52 rad/s (i.e., the frequency where the magnitude of the system is 0 dB). This however depends on the SRV02 model parameters, K and τ, you entered.

6. **Step 2: Find how much more gain is required.** Find gain K_c that is needed to bring the $P_i(s)$ PM crossover frequency to 50.0 rad/s. For your initial estimate, use the cursor on the *Magnitude Plot: Pi (s)* to find the appropriate gain. Enter the gain in the *Kc (dB)* input on the VI (in decibels). To confirm that the phase margin frequency is at around 50 rad/s, go to the *Open-Loop+Gain* tab. This shows the Bode of $P_i(s)$ with the gain you just added, i.e., system $L_p(s) = K_c P_i(s)$, and displays the crossover frequency in the *P.M. Frequency* indicator. Tune your *Kc* gain if necessary. Show the magnitude Bode of $K_c P_i(s)$ (when exporting, make sure to select the *Hide Grid* option).
7. **Step 3: Gain needed for specified phase margin**. Measure the phase margin (PM) on the Bode magnitude plot of $K_c P_i(s)$. Calculate ϕ_m, given in Equation 3.1.34, for a desired phase margin of 75.0 degrees. Then compute parameter a using Equation 3.1.35.
8. Enter parameter a in the *a* input box on the VI. Go to the *LEAD* tab and examine the magnitude plot of the lead compensator and how it adds $20 \log_{10}(a)$ of gain.
9. **Step 4: The frequency at which the lead maximum phase occurs**. Find parameter T using Equation 3.1.36, where ω_m is the frequency where $-10 \log a$ gain should be in the $K_c P_i(s)$ system. To do this, go back to the *Open-Loop Gain* tab. Compute $-10 \log a$, find this on the $K_c P_i(s)$ magnitude Bode plot (using the cursor on the graph), and record the frequency. You can then find parameter T.
10. **Step 5: Bode plot of the lead compensator**. Enter the parameter T you found in the *T* input box on the VI. The updated lead Bode plot, in the *LEAD* tab, shows the breakpoint frequencies occursing at $1/(aT)$ and $1/T$.
11. **Step 6: Bode plot of the loop transfer function**. Go to the *Loop TF* tab. This shows the Bode plot of full loop transfer function $L(s) = K_c C(s) P(s)/s$. Record the frequency-domain specifications and attach the magnitude and phase Bode plots of $L(s)$.
12. **Step 7: Check response**. Go the *Closed Loop Step Response* and record the time-domain specifications.
13. Are the frequency-based and time-domain specifications given in Section 3.1.1.1 satisfied?
14. Click on the *Stop* button to stop the VI.

3.3.2.2 Simulation

You will simulate the closed-loop speed response of the SRV02 with a lead controller to step input. Our goals are to confirm that the desired reponse specifications in an ideal situation are satisfied and to verify that the motor is not saturated.

As in the step response with PI control experiment in Section 3.3.1.1, in this experiment you need to use the SRV02 Speed Control Simulation LabVIEW™ VI shown in Figure 3.9 again.

1. Open the LabVIEW project called *SRV02 Speed Control.lvproj*, shown in Figure 3.12 in Section 3.4.
2. Open the *SRV02 Speed Control Simulation.vi*.
3. Enter the lead control parameters found in Section 3.1.3.2. These are denoted as *Kc*, *a*, and *T* in the VI front panel.

   IMPORTANT: Make sure you enter the linear value of K_c, i.e., not the value in decibels. Recall that $x_{dB} = 20 \log_{10} x$.
4. Set the *Signal Generator* block parameters to the following:
   - Signal Type: Square
   - Amplitude: 2.5 rad/s
   - Offset: 5.0 rad/s
   - Frequency: 0.4 Hz

5. To engage the lead control, set the *Manual Switch* to the downward position.
6. Run the VI.
7. Verify if the time-domain specifications in Section 3.1.1.1 are satisfied and that the motor is not being saturated. To calculate the steady-state error, peak time, and percent overshoot, use the cursor in the *Servo Speed (rad/s)* Graph found in the *Measure* tab (after the VI is stopped).
8. If the specifications are not satisfied, go back in the lead compensator design. You may have to, for example, add more maximum phase in order to increase the phase margin. If the specifications are met, move on to the next step.
9. Show the *Simulated Lead* speed response and its input voltage.

3.3.2.3 Implementing LEAD Speed Control

In this section the speed of the SRV02 is controlled using the lead compensator. Measurements will be taken to see if the specifications are satisfied.

1. Open the LabVIEW project called *SRV02 Speed Control.lvproj*, shown in Figure 3.12 in Section 3.4.
2. Open the *SRV02 Speed Control.vi* and make sure it is configured for you data acquisition device. See Section 3.4 for details.
3. Enter the lead control parameters found in Section 3.1.3.2. These are denoted as *Kc*, *a*, and *T* in the VI front panel.

   IMPORTANT: Make sure you enter the linear value of K_c, i.e., not the value in decibels. Recall that $x_{dB} = 20\log_{10} x$.
4. Set the *Signal Generator* block parameters to the following:
   - Signal Type: Square
   - Amplitude: 2.5 rad/s
   - Offset: 5.0 rad/s
   - Frequency: 0.4 Hz
5. To engage the lead control, set the *Manual Switch* to the downward position.
6. Run the VI. The scopes should be displaying responses similar to Figure 3.10.
7. When a suitable response is obtained, click on the *Stop* button to stop the VI. Show the lead speed response and its input voltage.
8. Measure the steady-state error, the percent overshoot, and the peak time of the SRV02 load gear. For the steady-state error, it may be beneficial to give a constant reference and take its average as done in Section 3.3.1.2. Does the response satisfy the specifications given in Section 3.1.1.1?
9. Using both your simulation and implementation results, comment on any differences between the PI and lead controls.
10. Click the *Stop* button to stop the VI.
11. Turn off the power to the amplifier if no more experiments will be performed on the SRV02 in this session.

3.3.3 Results

Fill out Table 3.1 below with your answers to the Pre-Lab questions and your results from the lab experiments.

Section / Question	Description	Symbol	Value	Unit
Question 2	**Pre-Lab: PI Gains**			
	Proportional Gain	k_p		
	Integral Gain	k_i		
	Open-Loop Time Constant	τ		
	Open-Loop Steady-state Gain	K		
Question 4	**Pre-Lab: DC Gain Estimate**			
	DC Gain Estimate of $P_i(s)$	$\|P_i(1)\|$		
Question 5	**Pre-Lab: Gain Crossover Frequency**			
	Gain crossover frequency	ω_g		
Section 3.3.1.1	**In-Lab: PI Step Response Simulation**			
	Peak time	t_p		
	Percent overshoot	PO		
	Steady-state error	e_{ss}		
Section 3.3.1.2	**In-Lab: PI Speed Control Implementation**			
	Measured peak-to-peak ripple	$e_{\omega,meas}$		
	Steady-state error	e_{ss}		
	Peak time	t_p		
	Percent overshoot	PO		
Section 3.3.2.2	**In-Lab: Step Response Simulation with Lead Control**			
	Peak time	t_p		
	Percent overshoot	PO		
	Steady-state error	e_{ss}		
Section 3.3.2.3	**In-Lab: Lead Speed Control Implementation**			
	Peak time	t_p		
	Percentage overshoot	PO		
	Steady-state error	e_{ss}		

Table 3.1: Summary of results for the Speed Control laboratory.

3.4 System Requirements

Required Hardware

- Data-aquisition (DAQ) device that is compatible with LabVIEW™ , e.g., NI USB or PCI DAQ, NI CompactRIO, or Quanser Hardware-in-the-loop (HIL).
- Quanser SRV02-ET rotary servo. See Reference [4].
- Quanser VoltPAQ power amplifier, or equivalent (e.g. Reference [2] for VoltPAQ User Manual).

Required Software

- NI LabVIEW™
- NI LabVIEW Control Design and Simulation Module
- Quanser Rapid Control Prototyping Toolkit®
- NI LabVIEW MathScript Module
- For NI CompactRIO users:
  - NI LabVIEW Real-Time Module
  - NI LabVIEW FPGA Module 2010
  - RIO Drivers

3.4.1 Overview of Files

File Name	Description
SRV02 Manual (Student).pdf	This laboratory guide which contains pre-lab questions and lab experiments demonstrating how to design and implement a speed controller on the Quanser SRV02 rotary plant using LabVIEW™ .
Quanser SRV02 Speed Control.lvproj	LabVIEW project containing the SRV02 speed control VIs.
SRV02 Lead Control Design.vi	VI used to design the Lead compensator.
SRV02 Speed Control Simulation.vi	Simulates both the PI and LEAD closed-loop response of the SRV02.
SRV02 Speed Control.vi	Implements PI and LEAD controllers on the SRV02.

Table 3.2: Files supplied with the SRV02 Speed Control laboratory.

3.4.2 Software Setup

Follow these steps to get the system ready for this lab:

1. Load the LabVIEW™ software.
2. Open the LabVIEW project called *Quanser Speed Control.lvproj* shown in Figure 3.12.
3. **Choose data acquisition device:** Before running the VI, make sure you set the correct *Board type* in the HIL Initialize block (e.g., 'q1_cRIO', 'q2_usb', 'q8_usb', 'qpid', or 'qpid_e').

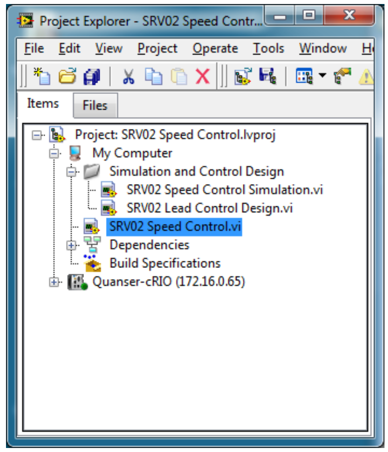


Figure 3.12: SRV02 Speed Project.

4. **Channel Configuration:** For any of these VIs, the analog input and ouput channels are set, by default, to match the wiring in the SRV02 User Manual ([4]). If the wiring is different on your system, make sure the VI uses the correct channels. For instance, if your tachometer is connected to Analog Input Channel #0 on your DAQ, then set the *tach* channel in the VI to 0 (instead of 1).

5. **Quanser CompactRIO Users:** Before running the VI, make sure you can connect to your CompactRIO through the Measurement & Automation software. See the SRV02 cRIO User Manual ([3]).

3.5 Lab Report

This laboratory contains two experiments, namely,

1. Step response with PI control, and
2. Step response with lead control.

When you are writing your report, follow the outline corresponding to the experiment you conducted to build the *content* of your report. Also, in Section 3.5.3 you can find some basic tips for the *format* of your report.

3.5.1 Template for Content (PI Control Experiments)

I. PROCEDURE

I.1. Step Response with PI Control

1. *Simulation*
   - Briefly describe the main goal of this simulation.
   - Briefly describe the procedure (Section 3.3.1.1)
2. *Implementation*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure (Section 3.3.1.2)

II. RESULTS
Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 8 in Section 3.3.1.1, *Step response simulation with PI Control*
2. Response plot from step 8 in Section 3.3.1.2, *Step response implementation with PI Control*
3. Signal noise plot from step 9 in Section 3.3.1.2, *Step response implementation with PI Control*
4. Provide data collected in this laboratory (from Table 3.1).

III. ANALYSIS
Provide details of your calculations (methods used) for analysis for each of the following:

III.1. Step Response with PI Control

1. Step 9 in Section 3.3.1.1, *Step response simulation with PI Control*
2. Step 10 in Section 3.3.1.2, *Step response implementation with PI Control*
3. Step 11 in Section 3.3.1.2, *Step response implementation with PI Control*

IV. CONCLUSIONS
Interpret your results to arrive at logical conclusions for the following:

1. Step 9 in Section 3.3.1.1, *Step response simulation with PI Control*
2. Step 10 in Section 3.3.1.2, *Step response implementation with PI Control*
3. Step 11 in Section 3.3.1.2, *Step response implementation with PI Control*

3.5.2 Template for Content (Lead Control Experiments)

I. PROCEDURE

I.1. Step Reponse with Lead Control

1. *Control Design*
   - Briefly describe the main goal of the control design.
   - Briefly describe the procedure (Section 3.3.2.1).
2. *Simulation*
   - Briefly describe the main goal of this simulation.
   - Briefly describe the procedure (Section 3.3.2.2)
3. *Implementation*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure (Section 3.3.2.3)

II. RESULTS
Do not interpret or analyze the data in this section. Just provide the results.

1. Bode plot from step 6 in Section 3.3.2.1, *Bode plot of* $L_p(s) = K_c P_i(s)$ *system*.
2. Bode plot from step 11 in Section 3.3.2.1, *Bode plot of loop transfer function*, $L(s)$.
3. Response plot from step 9 in Section 3.3.2.2, *Step response simulation with Lead Control*.
4. Response plot from step 7 in Section 3.3.2.3, *Step response implementation with Lead Control*.
5. Provide data collected in this laboratory (from Table 3.1).

III. ANALYSIS
Provide details of your calculations (methods used) for analysis for each of the following:

III.1. Lead Control Design

1. Step 6 in Section 3.3.2.1, *Finding necessary gain* K_c *needed to reach desired crossover frequency*.
2. Step 7 in Section 3.3.2.1, *Finding lead gain* a *needed for specified phase margin*.
3. Step 9 in Section 3.3.2.1, *Finding frequency at which the lead maximum phase occurs and obtaining lead parameter* T.

III.2. Step Response with Lead Control

1. Step 7 in Section 3.3.2.2, *Step response simulation with Lead Control*.
2. Step 8 in Section 3.3.2.3, *Step response implementation with Lead Control*.

IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Step 13 in Section 3.3.2.1, *Bode and preliminary step response simulation with Lead Control*.
2. Step 7 in Section 3.3.2.2, *Step response simulation with Lead Control*
3. Step 8 in Section 3.3.2.3, *Step response implementation with Lead Control*
4. Step 9 in Section 3.3.2.3, *Step response implementation with Lead Control*

3.5.3 Tips for Report Format

PROFESSIONAL APPEARANCE

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

Appendix A

SRV02 LABVIEW INTEGRATION

In this section, we explain how to command voltages to the Quanser® SRV02 and measure the position and speed of its load shaft using LabVIEW™ .

Required Hardware

- Data acquisition (DAQ) device that is compatible with LabVIEW™ and the Quanser Rapid Control Prototyping Toolkit® (RCP TK).
- Quanser SRV02-ET rotary servo. See Reference [4].
- Quanser VoltPAQ power amplifier, or equivalent (e.g. Reference [2] for VoltPAQ User Manual).

Required Software
Follow the instructions given in the RCP Toolkit Quick Start Guide - for either Windows or NI-CompactRIO - to install LabVIEW™ , its necessary add-on modules, and RCP on your PC/laptop and on the NI CompactRIO (if used).

Prerequisites
The user should be familiar with the following:

- Main components of the SRV02, e.g., DC motor and sensors such as the potentiometer [4].
- Basics of LabVIEW™ .

A.1 Applying Voltage to SRV02 Motor

Topics Covered

- Adding Simulation Loop and configuring the simulation parameters.
- Add and configure Quanser Rapid Control Prototyping Toolkit® drivers to output voltage to the motor.
- Using the *Sine Signal* Simulation Module block.

Note: Quanser Q1-cRIO users: If you are using a Q1-cRIO with the NI CompactRIO, make sure you add your NI cRIO to your LabVIEW project before proceeding, as shown the Quanser Rapid Control Prototyping Toolkit® Getting Started page.

A.1.1 Configuring the Simulation Loop

In this section, we will design a new LabVIEW™ Virtual Instrument (VI) to apply a sinusoidal voltage to the SRV02 DC motor. The completed block diagram of the VI is shown in , as shown in Figure A.1. The Quanser Rapid Control Prototyping Toolkit® drivers are used to interact with a data-acquisition board, e.g., NI PCIe-6251 device.

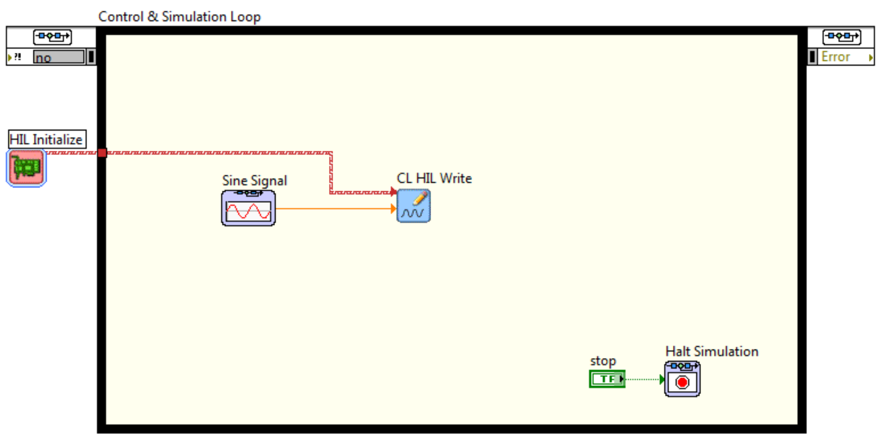


Figure A.1: Block diagram used to apply voltage to SRV02

Follow these steps to make the LabVIEW block diagram:

1. Load the LabVIEW™ software.
2. Create a new, blank Virtual Instrument (VI).
3. Go to the block diagram and create a Simulation loop, as depicted in Figure A.2. It is found in the *Control Design & Simulation* | *Simulation* palette.
4. Double-click on the Simulation loop input node (or right-click on the border and select *Configure Simulation Parameters*) to access the *Simulation Parameters* box shown in Figure A.3.
5. As shown in Figure A.3, in the *Simulation Parameters* tab set the following:
    - Final time (s): Inf

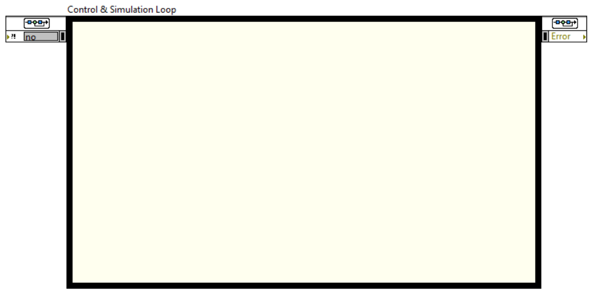


Figure A.2: Create a Simulation Loop in the block diagram

- ODE Solver: Runge-Kutta 1 (Euler)
- Step Size (s): 0.01

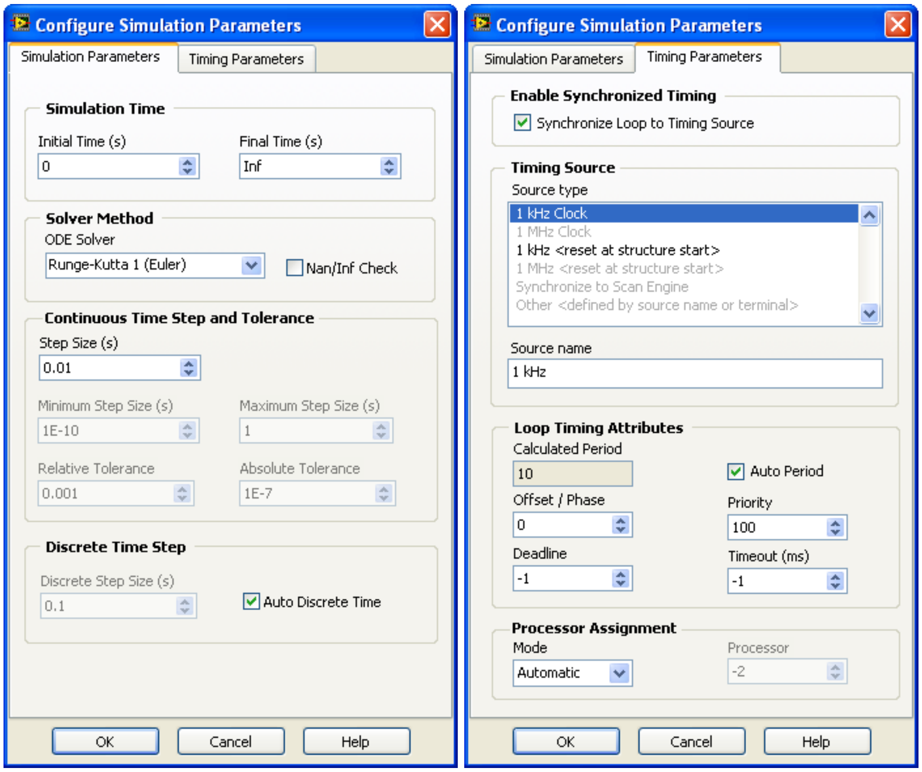
This configures the simulation to run until it is stopped by the user at a sampling rate of 100 Hz. When performing control, any of the fixed solvers can be used but Runge-Kutta 1 is typically the default.

6. As shown in Figure A.3, in the *Timing Parameters* tab set the following:
   - Select *Synchronize Loop to Timing Source*
   - Timing Source: 1 kHz Clock
   - Select *Auto Period*

   This synchronizes the simulation to the PC clock. Otherwise, the simulation would run as fast as possible (which is fine when doing pure simulation, but not when interfacing to hardware).
7. Click on the OK button to apply the changes.

A.1.2 Interfacing to the DC Motor

1. Add the *HIL Initialize* VI from the *Quanser Rapid Control Prototyping Toolkit* palette.
2. When added a prompt will appear. Under *Board type*, select the data acquisition device that you will be using.
3. Click on OK.
4. Add the following VIs:
   - *HIL Write* VI from *Quanser Rapid Control Prototyping Toolkit*.
   - *Sine Signal* block from the *Control Design & Simulation* | *Simulation* | *Signal Generation* palette.
5. As shown in Figure A.1, connect *Sine Signal* block to the *analog voltages* terminal of *HIL Write* VI.
6. Add the
7. *Halt Simulation* block from the *Control Design & Simulation* | *Simulation* | *Utilities* palette.
8. To add a *Stop* button, go the front panel of the VI and look through the *Modern* | *Boolean* palette.
9. In the block diagram, connect the *Stop* button and *Halt Simulation* VI as shown in Figure A.1.



(a) Simulation Parameters (b) Timing Parameters

Figure A.3: Simulation Loop Parameters Dialog

A.1.3 Running the VI

Here are the steps to run the VI designed in the previous section:

1. Make sure the SRV02, DAQ, and amplifier are connected as described in *SRV02 User Manual* (see [4]).
2. Power ON your power amplifier (e.g., Quanser VoltPAQ-X1).
3. By default, the HIL Write VI is set write to Analog Output Channel #0. If the motor is not connected to Analog Output Channel #0, then select the appropriate channel in HIL Write.
4. Run the VI by clicking on the white arrow in the top-left corner. This should apply a sine wave voltage to the DC motor and cause the SRV02 gears to rotate back-and-forth.
5. Click on the *Stop* button to stop the VI.
6. Power OFF the amplifier if no more experiments will be run in this session.

A.2 Reading Position using Potentiometer

In this section, the LabVIEW VI previously designed in Section A.1 is modified to obtain readings from the potentiometer sensor.

Topics Covered

- Add and configure Quanser Rapid Control Prototyping Toolkit® drivers to read potentiometer sensor.
- Use SimTime Waveform Simulation blocks to plot potentiometer reading.
- Calibrate sensor to read degrees using Gain block.

A.2.1 Interfacing to the Potentiometer

In this section, the VI shown in Figure A.4 is built to read the potentiometer voltage.

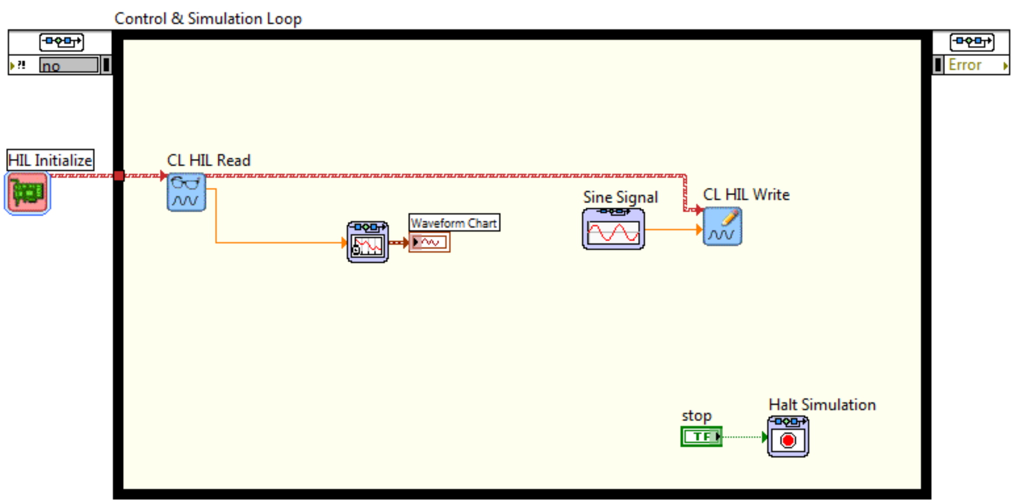


Figure A.4: VI used to read potentiometer

1. Add the *HIL Read* VI from the *Quanser Rapid Control Prototyping* palette and connect it as shown in Figure A.4.
2. **If you followed the SRV02 Quick Start Guide or the typical connections in the User Manual, then your potentiometer is NOT connected**. Make sure you connect the potentiometer to Analog Input #0 on your data acquisition (DAQ) device before proceeding. Follow the instructions given the SRV02 User Manual [4] for a Two-Channel DAQ. **Note**: If you are using a Q1-cRIO, omit the connection to Analog Input #1.
3. The potentiometer is connected to Analog Input #0 on the DAQ board. Since the HIL Read is already configured to read from this channel, no changes are necessary.
4. Add the *SimTime WaveForm* block from the *Control Design & Simulation* | *Simulation* | *Graph Utilities* palette. Connect the *analog voltages* output from the *HIL Read* VI to the graph as shown in Figure A.4.
5. Power ON the power amplifier.

6. Run the VI. As the SRV02 rotates back-and-forth, the chart should display the potentiometer readings similar as shown in Figure A.5. Notice that the readings are the voltage output of the potentiometer and not an angular measurement in degrees or radians.

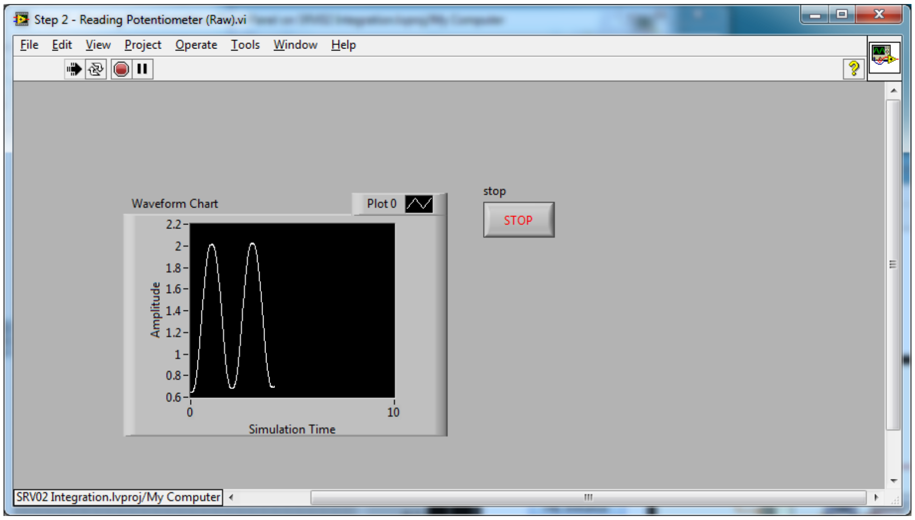


Figure A.5: Reading raw voltage from the SRV02 potentiometer

Note: The potentiometer has an electrical range of 352 degrees across $\pm$ 5 V (see [4] for further details). As a result, the potentiometer outputs a discontinuous voltage signal as seen in Figure A.6. The disadvantage is that you cannot surpass the $\pm$ 180 degree range when controlling the position or take the derivative of this sensor to control velocity.

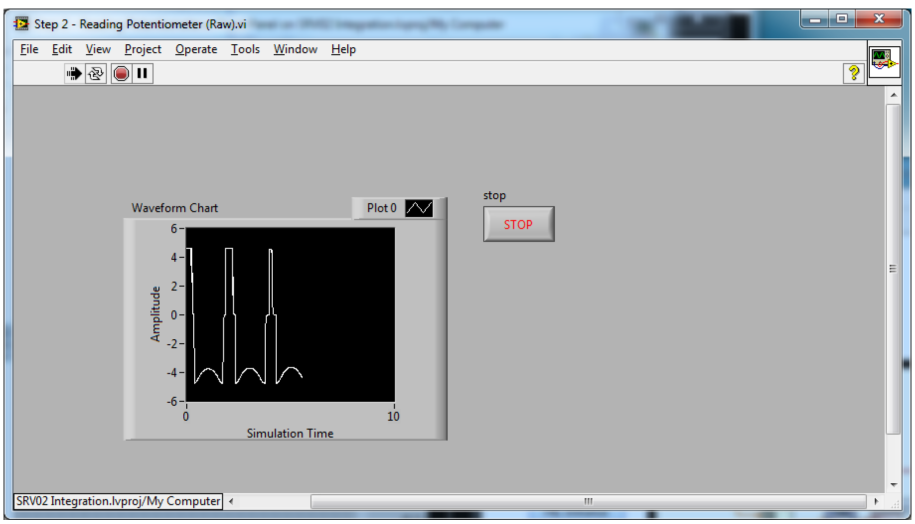


Figure A.6: Potentiometer reading when encountering its discontinuity

7. Click on the *Stop* button to stop the VI.

A.2.2 Measuring Position

The VI will now be modified to measure the servo load angle from the potentiometer as shown in Figure A.7.

Modify the VI built in the previous section following these steps:

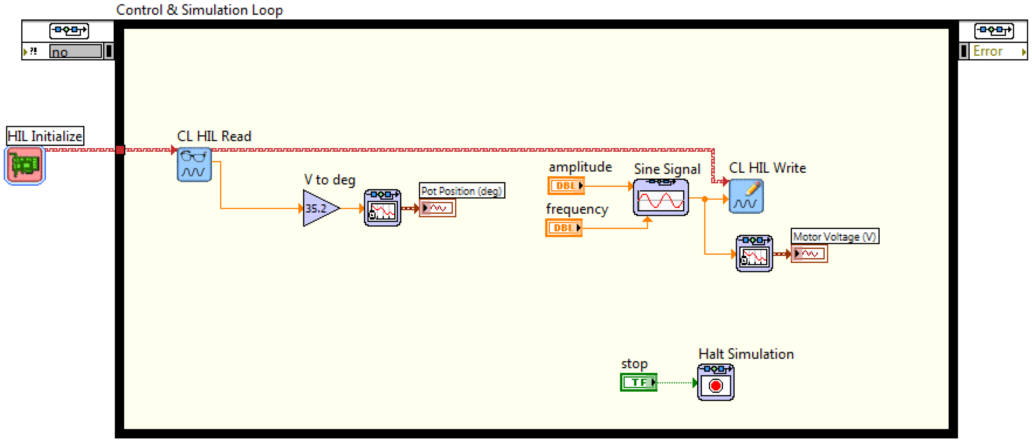


Figure A.7: VI used to send voltage to the SRV02 and read its load shaft angle using potentiometer.

1. In the block diagram, name the *SimTime Waveform* block as *Pot Position (deg)*. This scope will display the angular measurement of the load gear in degrees.
2. Add another *SimTime WaveForm* block and connect it to the voltage outputted by the *Signal Generator*, as depicted in Figure A.7. Label this as *Motor Voltage (V)*.
3. To adjust the amplitude and frequency of the *Signal Generator* from the front panel, double-click on the *Signal Generator* block and configure it as follows:
   - amplitude Parameter Source: terminal
   - frequency Parameter Source: terminal
4. Add the *amplitude* and *frequency* control, as illustrated in Figure A.7. Do this by right-clicking on the *amplitude* terminal and selecting *Create* | *Control*. Similarly create a control for *frequency*.
5. From *Control Design & Simulation* | *Simulation* | Signal Arithmetic palette, add a *Gain* block to the VI and connect it between the Index Array and scope blocks as shown in Figure A.7.
6. As described in [4], the potentiometer outputs between $\pm$ 5 V when it rotated 352 degrees. Enter the value 352/10=35.2 in the Gain block.
7. Make sure your amplifier is powered ON.
8. On the front panel, set the *amplitude* to 0.
9. Run the VI.
10. Manually rotate the load gear and examine the corresponding response in the *Pot Position (deg)* chart. Confirm that, indeed, the correct measurement is being taken.
11. Position the load gear such that 0 is read in the scope.
12. Set the *amplitude* to 1. Examine the relationship between the input voltage and load position. When the input voltage increases in the positive direction, the potentiometer angle increases. This is an important convention used in controls. You want to make sure a positive control effort results in a positive measurement.
13. Click on the *Stop* button to stop the VI.
14. Power OFF the amplifier if no more experiments will be run in this session.

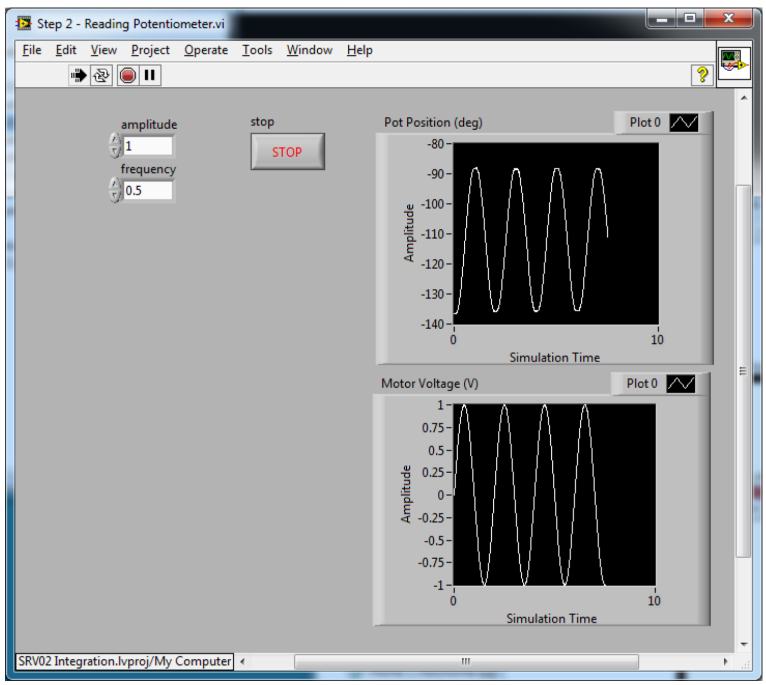
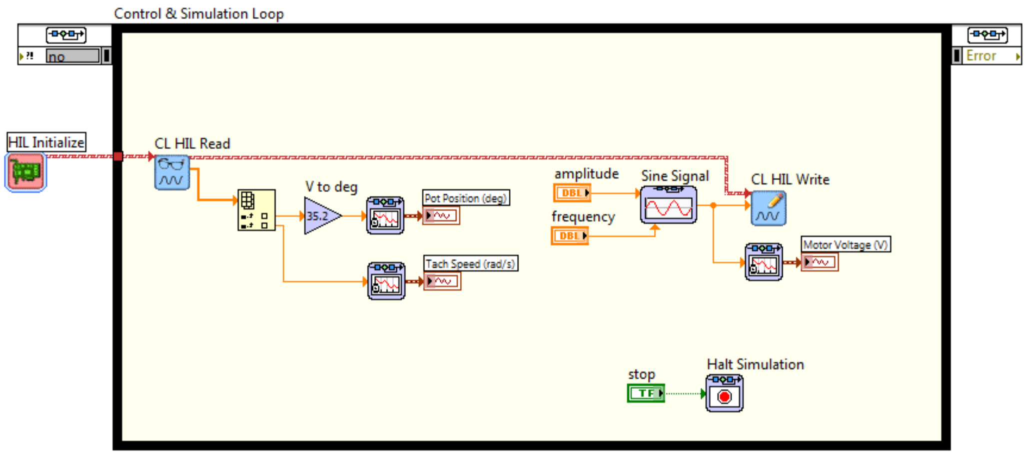


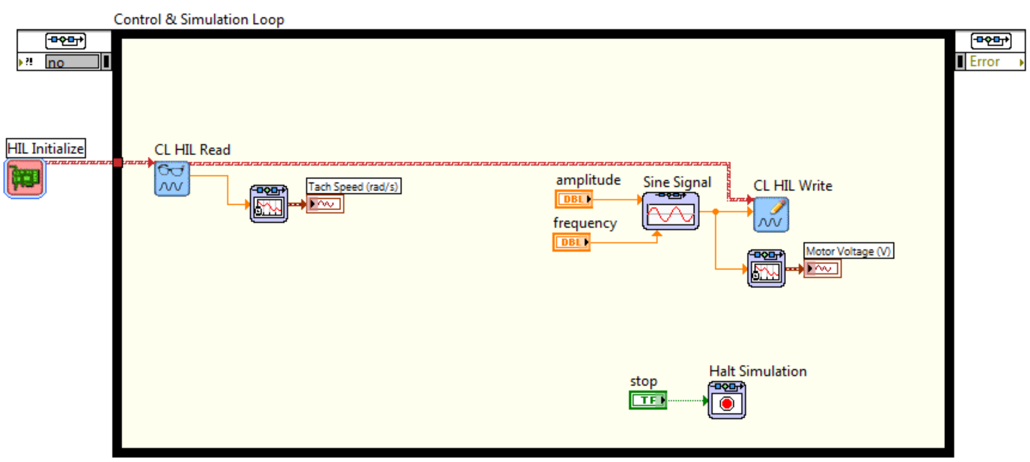
Figure A.8: Reading the SRV02 load angle using the potentiometer.

A.3 Measuring Speed using Tachometer

In this section, we will modify the VI designed in Section A.2 to include the reading from the tachometer. The completed block diagram of the VI is depicted in Figure A.9.



(a) Reading both the potentiometer and tachometer



(b) Reading the tachometer

Figure A.9: Measuring speed with the tachometer.

Using the VI built in Section A.2, go through this procedure to add the tachometer functionality:

1. **Two-Channel DAQ Users**: If your DAQ has 2 or more analog input channels (e.g., Quanser Q2-USB), then make sure you follow the connections given in the *SRV02 User Manual* [4] for a two-channel DAQ. This way you can measure both the potentiometer and the tachometer.

   Q1-cRIO Users: If you are using a single Q1-cRIO module in your NI CompactRIO, then connect the tachometer from the SRV02 to Analog Input #0 on the Q1-cRIO, as shown in the SRV02 Quick Start Guide (and the *SRV02 User Manual* [4] for a single-channel DAQ and amplifier).

2. **Two-Channel DAQ Users**: If you connected your tachometer to Analog Input #1 (as well as the potentiometer

on #0), then do the following:

(a) Double-click on the HIL Read VI.

(b) Under *Polymorphic instances*, select *Analog (vector)* and set the second array element to 1 as shown in Figure A.10. This will allow you to read from channel #0 and #1.

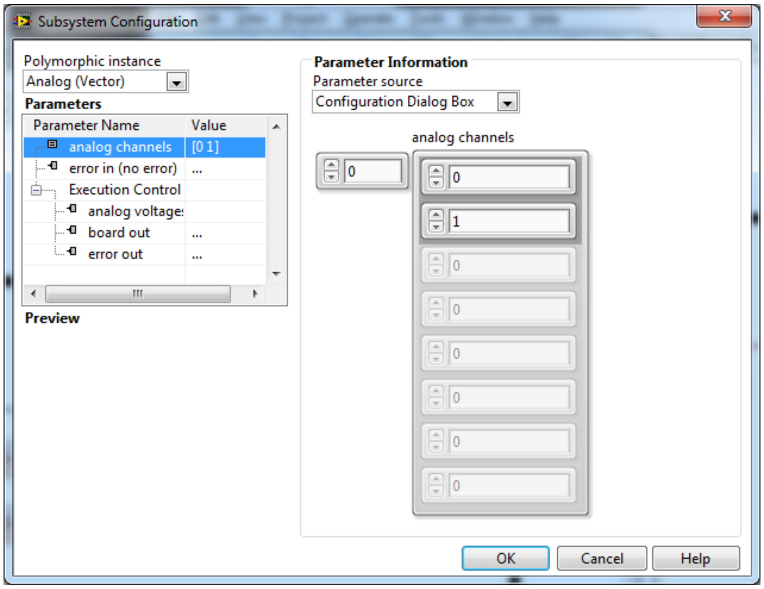


Figure A.10: Configuring HIL Read to read from analog channel 0 and 1.

(c) Add an *Index Array* block from the *Programming* | *Array* palette and expand it to output two array elements.

(d) Add a *SimTime Waveform* called *Tach Speed (rad/s)* into the VI.

(e) Connect the *Index Array* and *SimTime Waveform* blocks as shown in Figure A.9a. This is how you access multiple analog channels in LabVIEW™ with RCP.

3. **Q1-cRIO Users**: The VI is already set up to read from AI #0. To read the correct value, change the gain that was added to read the position from the potentiometer in Section A.2 to 1 (instead of 35.2). See the VI shown in Figure A.9b.

4. Power ON the amplifier.

5. Run the VI. As the SRV02 rotates back-and-forth, the *Tach Speed (rad/s)* chart should be plotting the tachometer readings in rad/s.

   Note: Similarly as in Section A.2, you can add a gain between the output of channel #1 in the *HIL Read* VI to obtain a measurement in certain units (e.g., rpm). In this case, the calibration gain is approximately 1 rad/s/V, so there is no calibration gain required to read in radians per second.

   Finding Calibration Gain: The back-emf constant of the tachometer sensor is 1.5 mV/rpm. However, the measurement is taken directly from the motor itself (see [4]). Thus, to read the velocity of the gear the tachometer calibration gain must be divided by the gear ratio, i.e., 1000 / 1.5 / 70 to read the rate in RPM when using the SRV02 in the high-gear configuration (or 1 / 1.5 / 14 if using the low-gear configuration). To obtain in radians per second, multiply the gain by $2\pi/60$, which results in $\frac{1000(2\pi)}{1.5(70)(60)} = 0.997 \approx 1$ rad/s/V.

6. Examine the relationship between the input voltage and load speed. When the input voltage increases in the positive direction, the tachometer velocity increases. Similar to the potentiometer, the speed of the load shaft should go positive when the input voltage is positive. Otherwise we could add a -1 gain to the tach output to follow the conventions.

7. Click on the *Stop* button to stop running the VI.

8. Power OFF the amplifier if no more experiments will be run in this session.

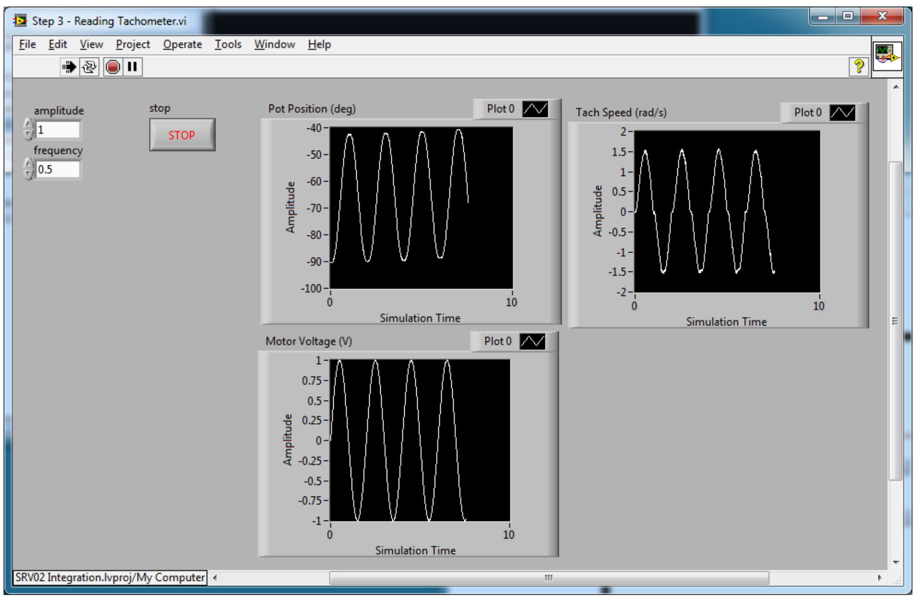


Figure A.11: Velocity reading using tachometer.

A.4 Measuring Position using Encoder

The VI designed previously is modified to include an encoder measurement, as illustrated in Figure A.12 below.

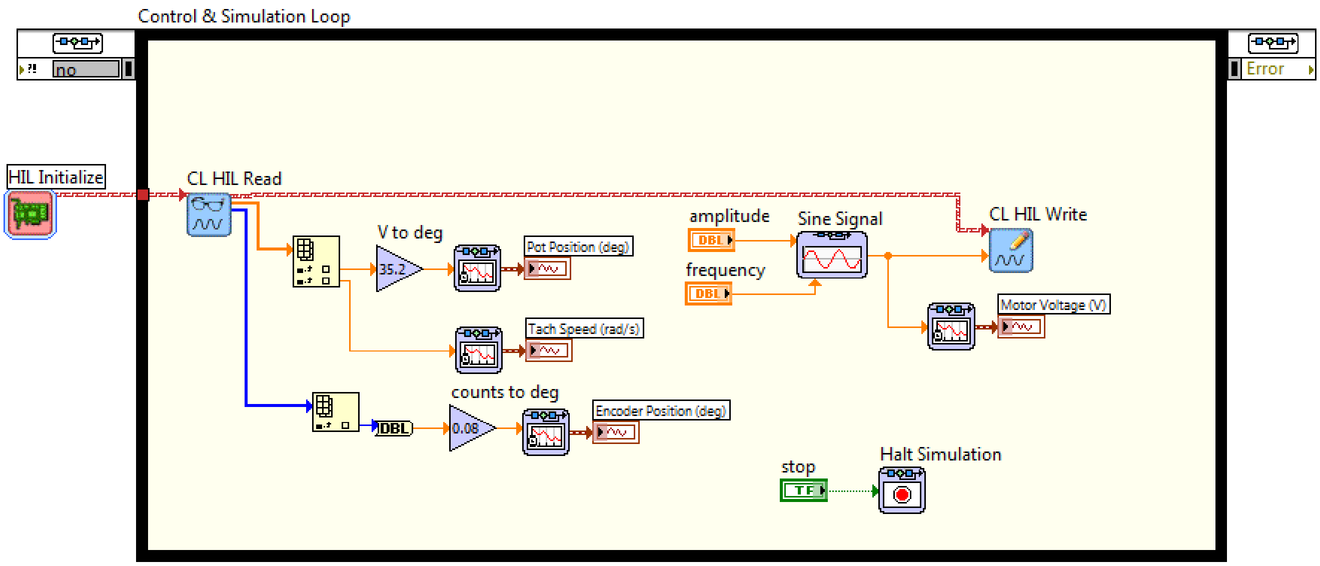


Figure A.12: VI used to send voltage to SRV02 and read the potentiometer, tachometer, and encoder sensors.

Using the VI designed in either Section A.2 or A.3, follow this procedure to add encoder functionality:

1. Recall that, as instructed in [4], the encoder is connected to Encoder Input #0 on the data acquisition board.
2. To add the encoder read channel, double-click on the *HIL Read* VI.
3. Under *Polymorphic instances*, select *Mixed*.
4. Set the *analog channels* array to read [0,1] and the first element in the *encoder channels* array to [0].
5. Similarly as done in Section A.3 for the HIL Read, add an Index Array to access the Encoder Channel #0 measurement as a scalar value (instead of an array).
6. The *HIL Read* VI outputs counts. The SRV02 encoder has (in quadrature mode) outputs 4096 counts per revolution. To convert this into an angle in degrees, add a DBL Conversion and a Gain block with the value $360/4096 = 0.08789$ deg/count. Connect blocks as shown in Figure A.12.
7. Put in another *SimTime Waveform*, label it *Encoder Position (deg)*, and connect it to the *enc (deg)* output terminal on the *encoder_count* sub-VI. This will display the encoder measurement in degrees.
8. Power ON the power amplifier.
9. Run the VI. As the SRV02 rotates back-and-forth, the *Encoder Position (deg)* should display the encoder readings. The input voltage and position scopes should appear similarly as shown in Figure A.13. Note that no further calibration is needed since the encoder position increases when the input voltage goes positive.
10. Click on the *Stop* button to stop running the VI.
11. Power OFF the amplifier if no more experiments will be run in this session.

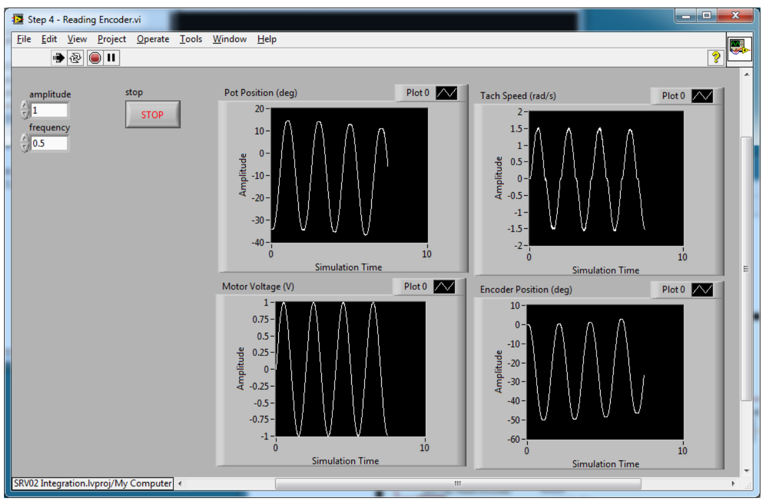


Figure A.13: SRV02 load gear measurement using encoder.

A.5 Saving Data

Data plotted in the Charts and Graphs in LabVIEW can be exported to various formats for offline analysis or to add to reports.

Consider the encoder position response obtained in Figure A.14. The procedure below will show you how to save this response as a bitmap.

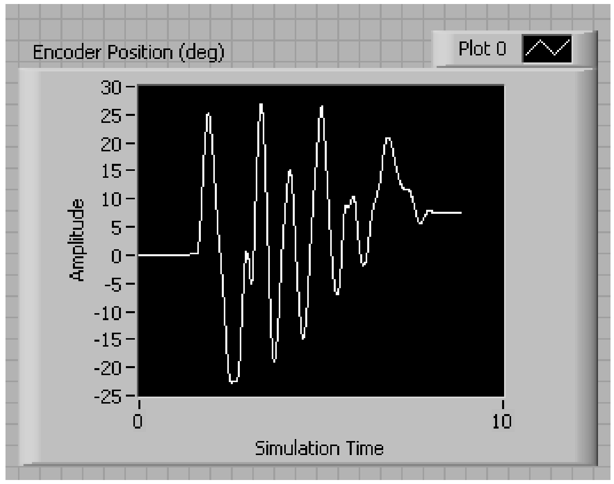


Figure A.14: Sample encoder data

1. When the VI is stopped, right-click on the Chart or Graph and select *Export* | *Export Simplified Image* to load the window shown in Figure A.15.

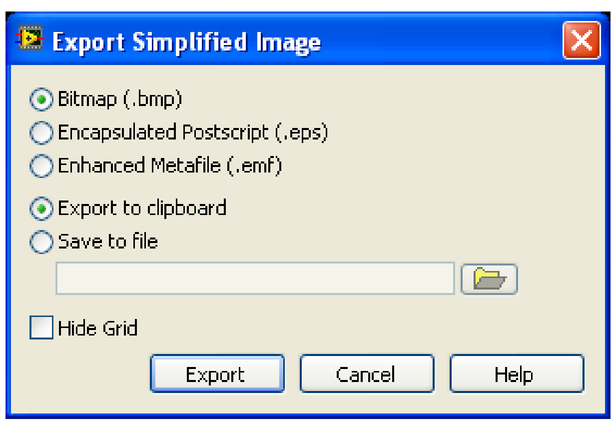


Figure A.15: Export Simplified Image Dialog

2. Select the *Bitmap (*.bmp)* and *Export to clipboard* options and click on *Export*.

   Note: When the Chart or Graph includes a grid, it may be better to set the *Hide Grid* option to see the response better in the image.

3. Paste the image into your favorite image program (e.g., Microsoft Paint, IrfanView) to save it to some location (or paste the image directly into a document). The exported bitmap of Figure A.14 is shown in Figure A.16.

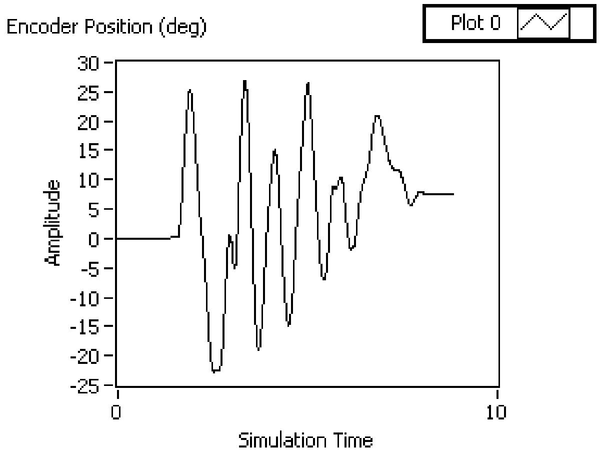


Figure A.16: Plotting saved data

You can also export the data into Excel® by selecting *Export* | *Export to Excel* when right-clicking on the Chart or Graph. You can then generate a plot in Excel® from the saved data points.

BIBLIOGRAPHY

[1] Quanser Inc. *Q2-USB User's Manual*, 2010.

[2] Quanser Inc. *VoltPAQ User's Manual*, 2010.

[3] Quanser Inc. *SRV02 cRIO User Manual*, 2011.

[4] Quanser Inc. *SRV02 User Manual*, 2011.

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