



LABORATORY GUIDE

2 DOF Helicopter Experiment for MATLAB®/Simulink® Users

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1 PRESENTATION

1.1 Description

The Quanser 2 DOF Helicopter experiment, shown in Figure 1.1, consists of a helicopter model mounted on a fixed base with two propellers that are driven by DC motors. The front propeller controls the elevation of the helicopter nose about the pitch axis and the back propeller controls the side to side motions of the helicopter about the yaw axis. The pitch and yaw angles are measured using high-resolution encoders. The pitch encoder and motor signals are transmitted via a slipring. This eliminates the possibility of wires tangling on the yaw axis and allows the yaw angle to rotate freely about 360 degrees.

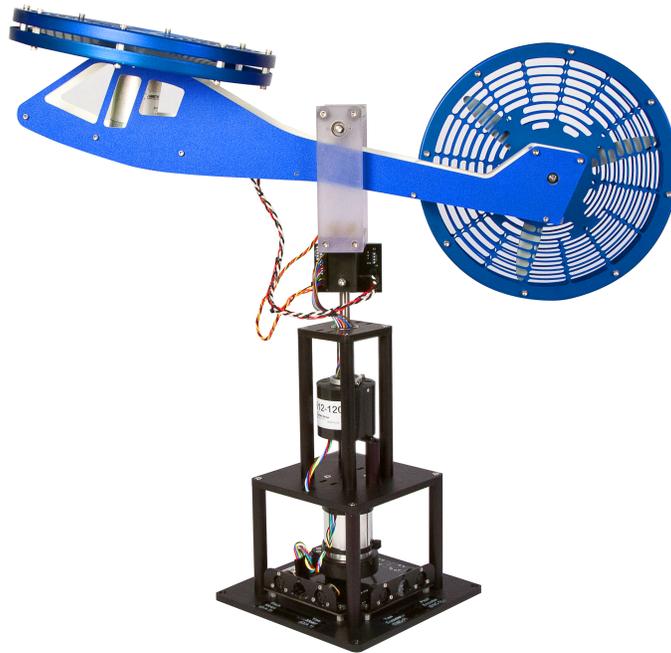


Figure 1.1: Quanser 2 DOF Helicopter

The modeling and position control design of the helicopter are summarized in section 3. In section 5, several procedures are outlined that show how to simulate the position controller and how to run this controller on the actual helicopter plant. Further, this section explains how to use the joystick to manually control the helicopter.

1.2 Prerequisites

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

- 2 DOF Helicopter main components (e.g. actuator, sensors), the data acquisition card (e.g., Q2-USB), and the power amplifier (e.g. VoltPaq), as described in [4], [2], and [3], respectively.
- Wiring the 2 DOF Helicopter plant with the amplifier and data-acquisition device, as discussed in the 2 DOF Helicopter User Manual ([4]).
- Designing a state-feedback control using Linear-Quadratic Regulator (LQR).
- Using **QUARC**[®] to control and monitor a plant in real-time and in designing a controller through **Simulink**[®].

2 EXPERIMENT FILES OVERVIEW

Table 2.1 below lists and describes the various files supplied with the 2 DOF Helicopter experiment.

File Name	Description
2 DOF Helicopter Reference Manual.pdf	This manual is both the user and laboratory guide for the Quanser 2-DOF Helicopter specialty aerospace plant. It contains information about the hardware components, specifications, information to setup and configure the hardware, system modeling, control design, as well as the experimental procedure to simulate and implement the controller.
2-DOF Heli Equations.mws	Maple worksheet used to analytically derive the state-space model involved in the experiment. Waterloo Maple 9, or a later release, is required to open, modify, and execute this file.
2-DOF Heli Equations.html	HTML presentation of the Maple Worksheet. It allows users to view the content of the Maple file without having Maple 9 installed. No modifications to the equations can be performed when in this format.
quanser.ind and quanser.lib	The <i>Quanser_Tools</i> module defines the generic procedures used in Lagrangian mechanics and resulting in the determination of a given system's equations of motion and state-space representation. It also contains data processing routines to save the obtained state-space matrices into a Matlab-readable file.
setup_lab_heli_2d.m	The main Matlab script that sets the model, control, and configuration parameters. Run this file only to setup the laboratory.
setup_heli2d_configuration.m	Returns the 2 DOF Helicopter model parameters and encoder calibration constants.
HELI2D_ABCD_eqns.m	Matlab script file generated using the Maple worksheet <i>2-DOF Heli Equations.mws</i> . It sets the A, B, C, and D matrices for the state-space representation of the 2 DOF Helicopter open-loop system.
d_heli2d_lqr.m	Matlab script that generates the position-velocity controller gain K using LQR.
d_heli2d_lqr_i.m	Matlab function that the position-integral-velocity controller gain K using LQR.
s_heli_2d_ff_lqr_i.mdl	Simulink file that simulates the open-loop or closed-loop 2 DOF Helicopter using a nonlinear model of the system.
q_heli_2d_ff_lqr_i.mdl	Simulink file that implements the real-time position controller for the 2 DOF Helicopter system.
q_heli_2d_open_loop.mdl	Simulink file that runs the 2 DOF Helicopter in open-loop, i.e. allows user to command voltage directly to motors.

Table 2.1: Files supplied with the 2 DOF Helicopter experiment

3 MODELING

3.1 Dynamics

The free-body diagram of the 2 DOF Helicopter is illustrated in Figure 3.1 and it accompanies the Maple worksheet named *2DOF Helicopter Equations.mws* or its HTML equivalent *2DOF Helicopter Equations.html*. The equations can be edited and re-calculated by executing the worksheet using Maple 9.

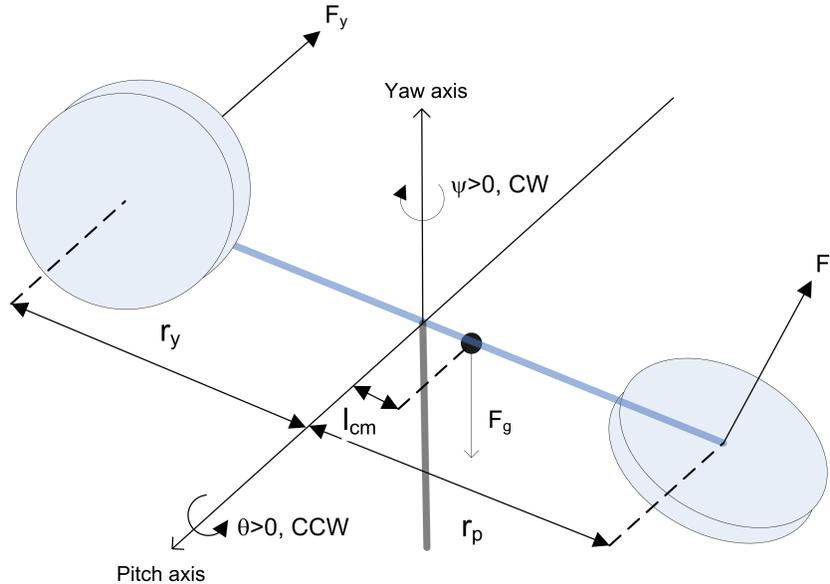


Figure 3.1: Simple free-body diagram of 2 DOF Helicopter

The 2 DOF Helicopter modeling conventions used are:

1. The helicopter is horizontal when the pitch angle equals $\theta = 0$.
2. The pitch angle increases positively, $\theta(t) > 0$, when the nose is moved upwards and the body rotates in the **counter-clockwise (CCW)** direction.
3. The yaw angle increases positively, $\psi(t) > 0$ when the body rotates in the **clockwise (CW)** direction.
4. Pitch increases, $\theta > 0$, when the pitch thrust force is positive $F_p > 0$.
5. Yaw increases, $\psi > 0$, when the yaw thrust force is positive, $F_y > 0$.

The Maple worksheet goes through the kinematics and dynamics of the system. The Cartesian coordinates of the center-of-mass are expressed relative to the base coordinate system, as shown in Figure 3.2. These resulting equations are used to find the potential energy and translational kinetic energy.

3.2 State-Space Model

The thrust forces acting on the pitch and yaw axes from the front and back motors are then defined. Using the Euler-Lagrange formula, the nonlinear equations of motion of the 2 DOF Helicopter system are derived. These equations are linearized about zero and the linear state-space model (A,B,C,D) describing the voltage-to-angular joint position dynamics of the system is found. Given the state-space representation

$$\dot{x} = Ax + Bu$$

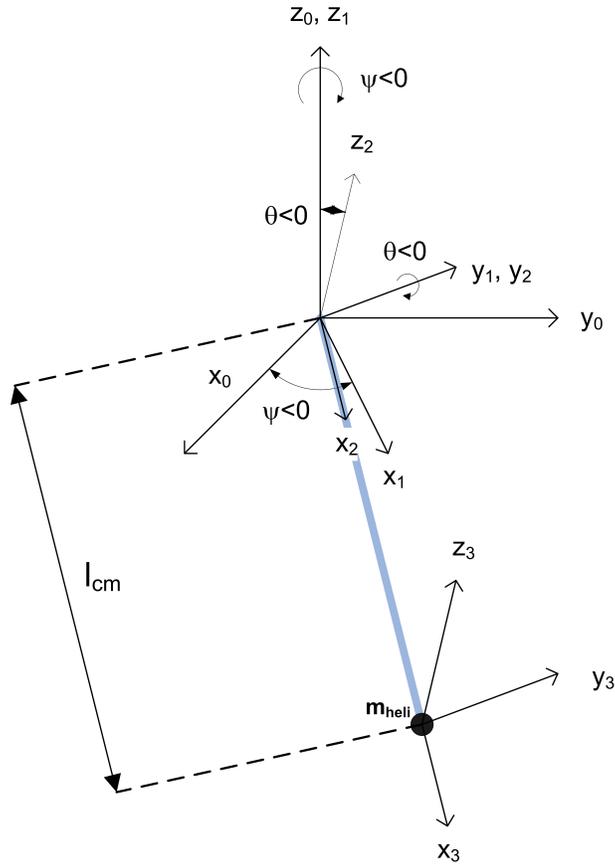


Figure 3.2: Kinematics of the 2 DOF Helicopter

and

$$y = Cx + Du$$

the state vector for the 2 DOF Helicopter is defined

$$x^T = [\theta(t), \psi(t), \dot{\theta}(t), \dot{\psi}(t)] \quad (3.1)$$

and the output vector is

$$y^T = [\theta(t), \psi(t)]$$

where θ and ψ are the pitch and yaw angles, respectively. The corresponding helicopter state-space matrices (as derived in the Maple worksheet) are

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\frac{B_p}{J_{Tp}} & 0 \\ 0 & 0 & 0 & -\frac{B_y}{J_{Ty}} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{K_{pp}}{J_{Tp}} & \frac{K_{py}}{J_{Tp}} \\ \frac{K_{yp}}{J_{Ty}} & \frac{K_{yy}}{J_{Ty}} \end{bmatrix}$$

where

$$J_{Tp} = J_{eq_p} + m_{heli} l_{cm}^2$$

$$J_{Ty} = J_{eq_y} + m_{heli} l_{cm}^2$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The model parameters used in the (A,B) matrices are defined in the 2 DOF Helicopter User Manual.

4 CONTROL DESIGN

4.1 State-Feedback

In this section a state-feedback controller is designed to regulate the elevation and travel angles of the 2 DOF Helicopter to desired positions. However, as will be shown, the control structure is basically linear proportional-integral-derivative, i.e. PID, controller. The control gains are computed using the Linear-Quadratic Regulator algorithm in Section 4.2.

The state-feedback controller entering the front motor, u_f , and the back motor, u_b , is defined

$$\begin{bmatrix} u_p \\ u_y \end{bmatrix} = K_{PD}(x_d - x) + V_i + \begin{bmatrix} u_{ff} \\ 0 \end{bmatrix},$$

with the proportional-derivative gain

$$K_{PD} = \begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & k_{1,4} \\ k_{2,1} & k_{2,2} & k_{2,3} & k_{2,4} \end{bmatrix},$$

the desired state

$$x_d^T = [\theta_d \quad \psi_d \quad 0 \quad 0],$$

the integral control

$$V_i = \begin{bmatrix} k_{1,5} \int (x_{d,1} - x_1) dt + k_{1,6} \int (x_{d,2} - x_2) dt \\ k_{2,5} \int (x_{d,1} - x_1) dt + k_{2,6} \int (x_{d,2} - x_2) dt \end{bmatrix},$$

and the nonlinear feed-forward control

$$u_{ff} = \frac{K_{ff} m_{helicopter} g l_{cm} \cos x_{d,1}}{K_{pp}}.$$

The feed-forward control compensates for the gravitational torque that forces the pitch angle down. The system state, x , is defined in Equation 3.1. The variables θ_d and λ_d , are the pitch and yaw setpoints, i.e. the desired angles of the helicopter. In state-space, the desired pitch is angle $x_{d,1}$ and the desired yaw is $x_{d,2}$. The gains $k_{1,1}$ and $k_{1,2}$ are the front motor control proportional gains and the gains $k_{2,1}$ and $k_{2,2}$ are the back motor control proportional gains. Next, $k_{1,3}$ and $k_{1,4}$ are the front motor control derivative gains and $k_{2,3}$ and $k_{2,4}$ are the back motor control derivative gains. The integral control gains used in the front motor control are $k_{1,5}$ and $k_{1,6}$ and the integral gains $k_{2,5}$ and $k_{2,6}$ are used in the back motor regulator.

4.2 Linear Quadratic Regulator

The control gains are computed using the Linear-Quadratic Regulator scheme. The system state is first augmented to include the integrals of the pitch and yaw states,

$$x_i^T = [\theta \quad \psi \quad \dot{\theta} \quad \dot{\psi} \quad \int \theta dt \quad \int \lambda dt]$$

Using the feedback law

$$u = -K x_i$$

the weighting matrices

$$Q = \begin{bmatrix} 200 & 0 & 0 & 0 & 0 & 0 \\ 0 & 150 & 0 & 0 & 0 & 0 \\ 0 & 0 & 100 & 0 & 0 & 0 \\ 0 & 0 & 0 & 200 & 0 & 0 \\ 0 & 0 & 0 & 0 & 50 & 0 \\ 0 & 0 & 0 & 0 & 0 & 50 \end{bmatrix}$$

and

$$R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

and the state-space matrices (A,B) found previously, the control gain

$$K = \begin{bmatrix} 18.9 & 1.98 & 7.48 & 1.53 & 7.03 & 0.770 \\ -2.22 & 19.4 & -0.45 & 11.9 & -0.770 & 7.03 \end{bmatrix}$$

is calculated by minimizing the cost function

$$J = \int_0^{\infty} x_i^T Q x_i + u^T R u dt.$$

$$K = \begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & k_{1,4} & k_{1,5} & k_{1,6} \\ k_{2,1} & k_{2,2} & k_{2,3} & k_{2,4} & k_{2,5} & k_{2,6} \end{bmatrix}$$

4.3 Anti-Windup

The helicopter system runs the risk of integrator windup. That is, given a large error in the between the measured and desired pitch angle, $\theta - \theta_d$, or between the measured and desired yaw angle, $\psi - \psi_d$, the integrator outputs a large voltage that can saturate the amplifier. By the time the measured angle reaches the desired angle the integrator built-up so much energy that it remains saturated. This can cause large overshoots and oscillations in the response. To fix this, an integral windup protection algorithm is used. Figure 4.1 illustrates the anti-windup scheme implemented to control the pitch.

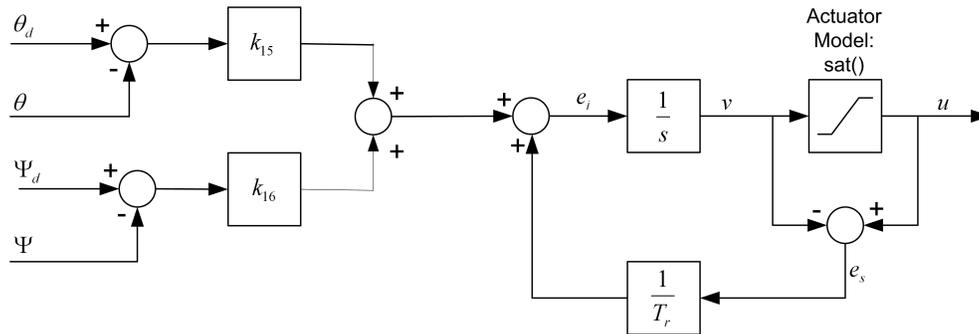


Figure 4.1: Anti-windup loop

The integrator input shown in the windup loop is

$$e_i = k_{1,5} (\theta_d - \theta) + k_{1,6} (\psi_d - \psi) + \frac{u - v}{T_r}$$

When the integrator output voltage, v , is larger than the imposed integral saturation then the saturation error becomes negative, $e_s < 0$. The saturation error gets divided by the reset time, T_r , and its result is added to the integrator input. This effectively decreases the integrator input and winds-down the integrator. In the simulation and experimental results the saturation limit of the integrator is set to 5 V and the reset time to 1 sec for maximum wind-down speed.

5 IN-LAB PROCEDURE

5.1 2 DOF Helicopter Simulink Models

The Simulink models supplied with the 2 DOF Helicopter contain various subsystems that implement the model and controllers presented previously. The *2DOF HELI: FF+LQR+I Controller* subsystem implements the feed-forward control and the LQR PID position controller discussed in section 4. The *2DOF HELI: FF+LQR Controller* is a feed-forward and proportional-derivative control. Thus it is the same as the FF+LQR+I algorithm developed except there is no integral action. The nonlinear feed-forward control is constructed in the *Pitch feed-forward controller* block. The *2DOF HELI: Nonlinear Model* contains the nonlinear model summarized in section 3.

The interior of the *2DOF HELI: FF+LQR+I Controller* subsystem is displayed in Figure 5.1. As discussed in Section 4, the position and velocity states are multiplied by the corresponding elements of control gain K . The state includes the integral of the pitch and yaw angles and those are multiplied by the integral gains in K . Further the anti-windup scheme shown in Figure 4.1 is implemented in the *Pitch Integral Antiwindup* and *Yaw Integral Antiwindup* blocks. The *Pitch feed-forward controller* and *2DOF HELI: FF+LQR Controller* subsystems blocks are linked to 2 DOF Helicopter Simulink library.

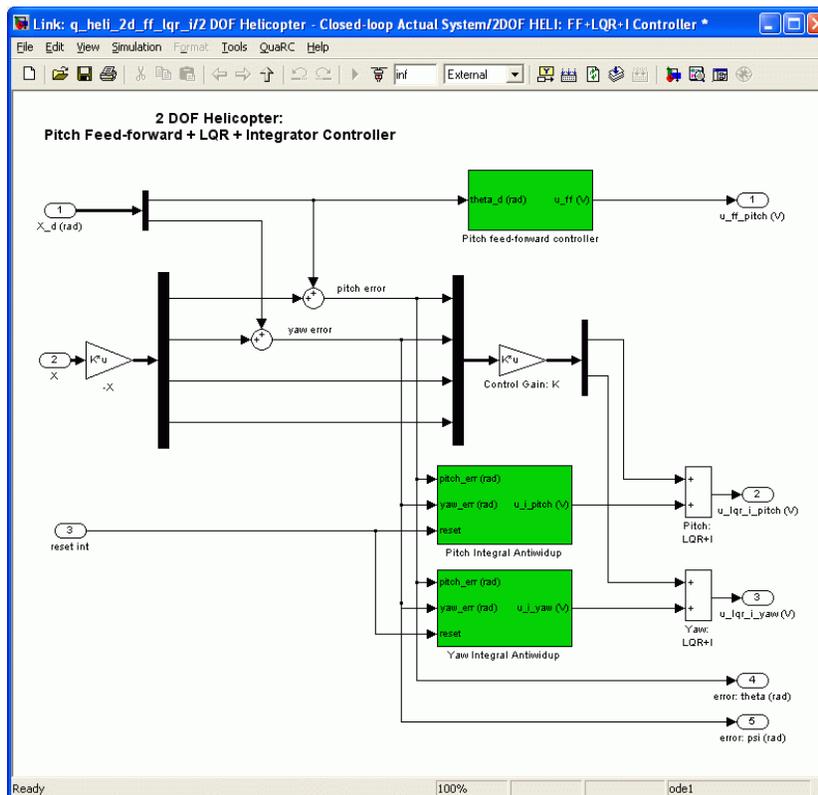


Figure 5.1: Subsystem that implements the FF+LQR+I controller

5.2 Controller Simulation

5.2.1 Objectives

- Investigate the closed-loop position control performance of the FF+LQR and FF+LQR+I using a nonlinear model of the 2 DOF Helicopter system.

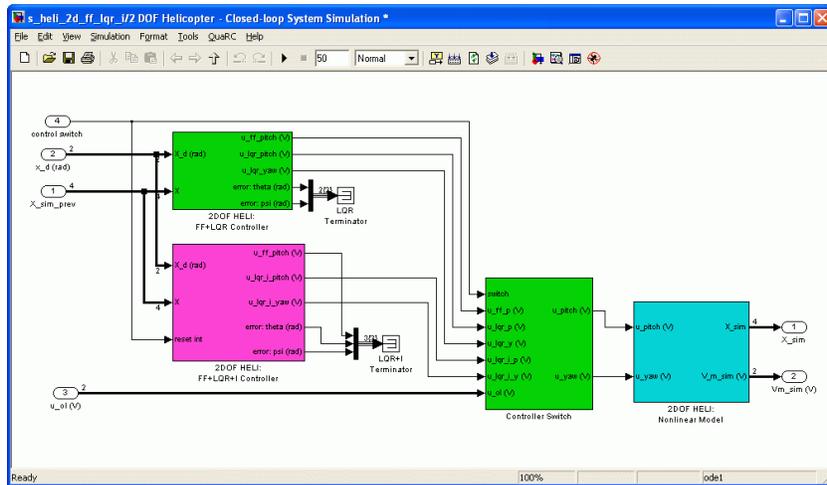


Figure 5.3: Closed-loop simulation of 2 DOF Helicopter

5. Open the Matlab script called `setup_lab_heli_2d.m`. This script sets the model parameters, control gains, amplifier limits, and so on that are used in the 2 DOF Helicopter Simulink models supplied, such as `s_heli_2d_lqr_i.mdl`. By default, `VMAX_AMP_P`, `VMAX_AMP_Y`, `K_AMP`, `K_EC_P`, and `K_EC_Y` is set to match the configuration in the actual implementation section.
6. The saturation limit of the integrators that are used in the FF+LQR+I controller are set using the variables `SAT_INT_ERR_PITCH` and `SAT_INT_ERR_YAW`. The reset time of the anti-windup loop can be changed using `Tr_p` and `Tr_y`. For more information on the anti-windup algorithm see section 4.
7. Ensure the CONTROLLER TYPE is set to 'LQR AUTO' to generate the controller automatically. Set the feed-forward gain $K_{ff} = 1 V/V$ and the LQR and LQR+I Q and R weighting matrices as already given in the script.
8. Run the Matlab script `setup_lab_heli_2d.m` to load the state-space model matrices, control gains, and various other parameters into the Matlab workspace. The LQR and LQR+I controls gains should be displayed in the Matlab Command Window.
9. Open the subsystem labeled *Desired Angle from Program*, shown in Figure 5.4, below

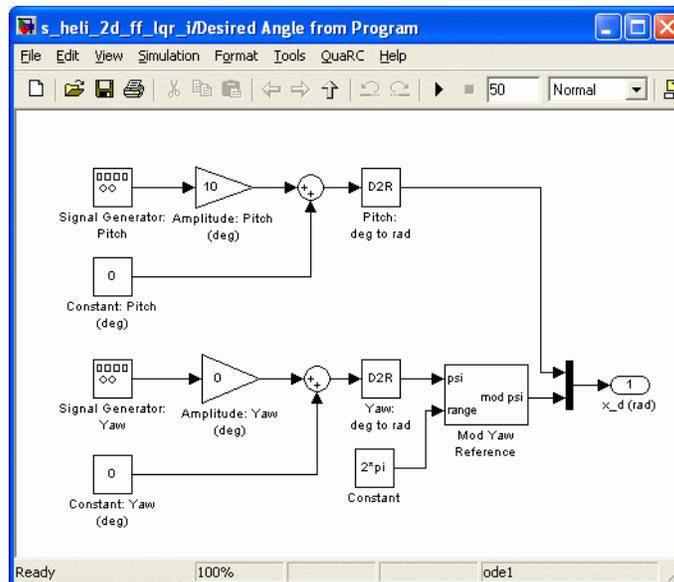


Figure 5.4: Desired Angle from Program subsystem

10. Ensure the pitch scope, θ (deg), the yaw scope, ψ (deg), and the motor input voltage scope, V_{m_sim} (V), are open. If not, go into the *Scopes* subsystem and double-click on those sinks.
11. To generate a desired pitch step of 20.0 degrees at 0.05 Hz frequency, set the *Amplitude: Pitch (deg)* gain block to 10.0 degrees and *Frequency* input box in the *Signal Generator: Elevation* block to 0.05 Hz.
12. Click on the *Start* simulation button, or on the *Start* item in the *Simulation* menu, to run the closed-loop system using LQR+I and the scopes should read as shown in Figure 5.5, Figure 5.6, and Figure 5.7. In each scope, the simulated pitch and yaw angles (purple trace) should track the corresponding desired position signals (yellow trace). Also, examine the voltage in the V_{m_sim} (V) scope and ensure the front (yellow plot) and back motor (purple plot) are not saturated. Recall that the maximum peak voltage that can be delivered to the front motor by the VoltPaq amplifier is ± 24 V.

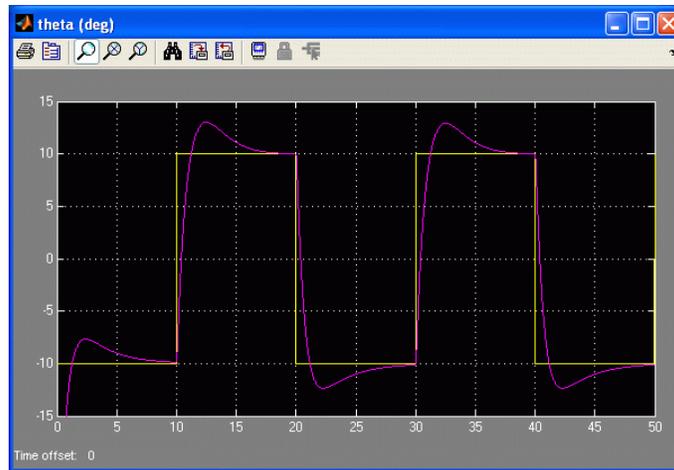


Figure 5.5: Simulated pitch response under pitch reference step using LQR+I

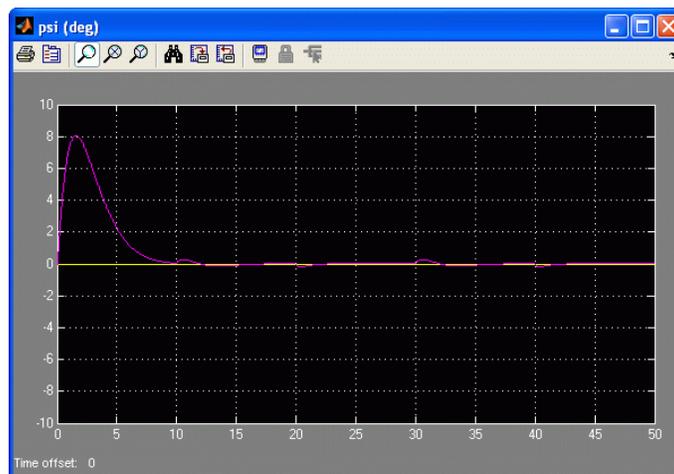


Figure 5.6: Simulated yaw response under pitch reference step using LQR+I

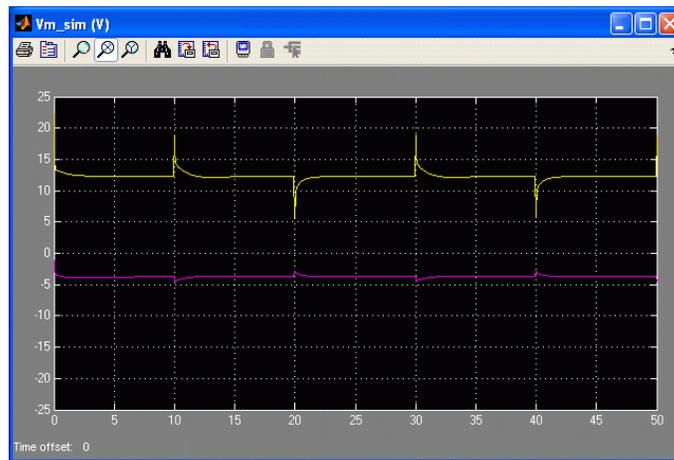


Figure 5.7: Simulated front and back motor voltage under pitch reference step using LQR+I

13. To generate a desired yaw step of 100 degrees at 0.05 Hz frequency set the *Amplitude: Yaw (deg)* block to 50.0 degrees and the *Frequency* input box in the *Signal Generator: Yaw* block to 0.05 Hz.
14. Run the simulation and the responses shown in Figure 5.8, Figure 5.9, and Figure 5.10 should be obtained. The yaw voltage saturates the back amplifier at -15 V

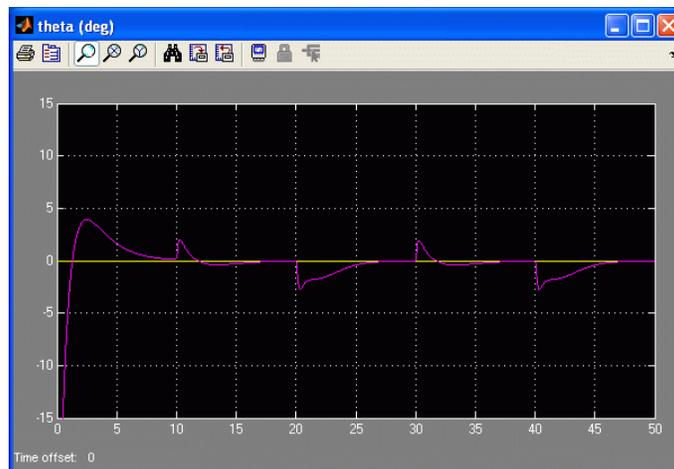


Figure 5.8: Simulated pitch response under a desired yaw reference step using LQR+I

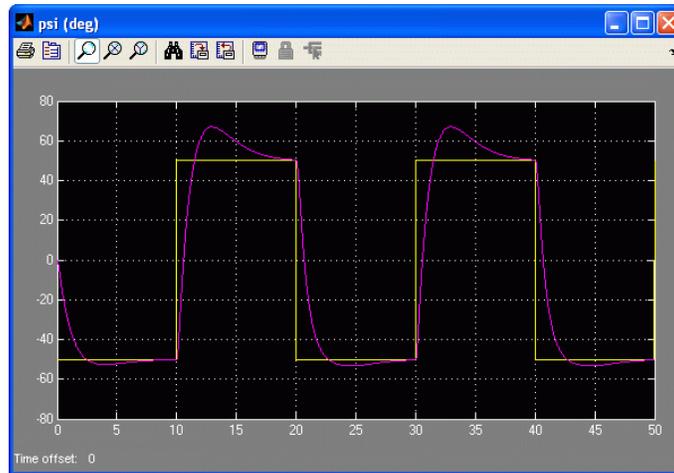


Figure 5.9: Simulated yaw response under a desired yaw step using LQR+I

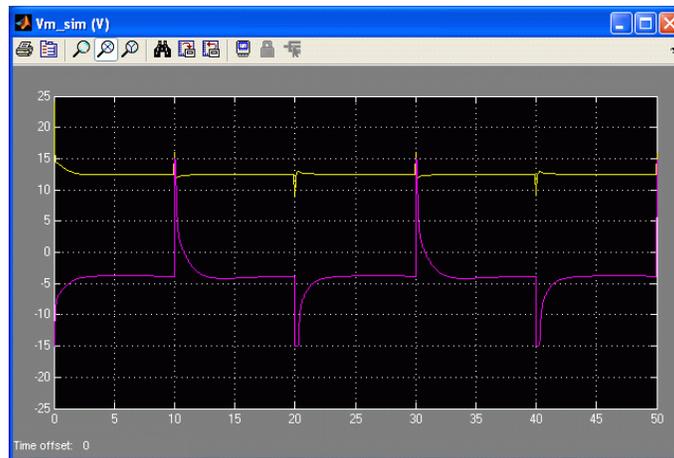


Figure 5.10: Simulated front and back motor voltage under yaw reference step using LQR+I

15. Try changing the desired elevation and travel angles to familiarize yourself with the controller. Observe that rate limiters are placed in the desired position signals to eliminate any high-frequency changes. This makes the control signal smoother which places less strain on the actuator.

5.3 Open-loop Implementation

5.3.1 Objectives

The objectives of running the 2 DOF Helicopter in open-loop are to:

- Gain an intuition on the dynamics of the system, in particular the coupling effect that exists between the pitch and yaw actuators.
- Obtain an idea on how difficult it is to control the apparatus in order to compare human operator performance with computer control.

5.3.2 Procedure

1. Load the **Matlab®** software.
2. Open Simulink model *q_heli_2d_open_loop.mdl* shown in Figure 16. The model runs your actual 2 DOF Helicopter plant by directly interfacing with your hardware through the QUARC blocks, described in [1].

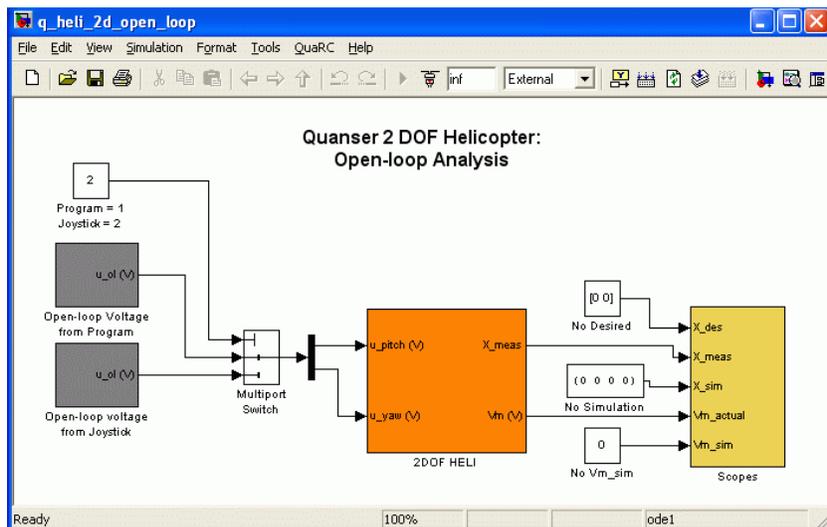


Figure 5.11: Simulink diagram to run 2 DOF Helicopter in open-loop with QUARC

3. **Configure setup script:** Open the design file *setup_lab_heli_2d.m* and ensure everything is configured properly. The `K_JOYSTICK_V_X` and `K_JOYSTICK_V_Y` parameters control the rate that a voltage command is generated. The `JOYSTICK_X_DZ` and `JOYSTICK_Y_DZ` specify the deadzone of the joystick. The deadzone is used to remove negligible joystick outputs due to noise or from small motions in the joystick handle.
4. Execute the *setup_lab_heli_2d.m* Matlab script to setup the workspace before compiling the diagram and running it in real-time with **QUARC®**.
5. Open the *2DOF HELI* subsystem. Its contents are shown in Figure 5.12. This subsystem contains the QUARC blocks that interface with the hardware of the actual plant. The Analog Output block sends the voltage computed by the controller to the DAQ device which drives the actuators and the Encoder Input block reads the encoder measurements.
6. **Configure DAQ:** Double-click on the HIL Initialize block in the Simulink diagram and ensure it is configured for the DAQ device that is installed in your system. By default the block shown in Figure 5.12 is setup for the Quanser Q8 hardware-in-the-loop board.

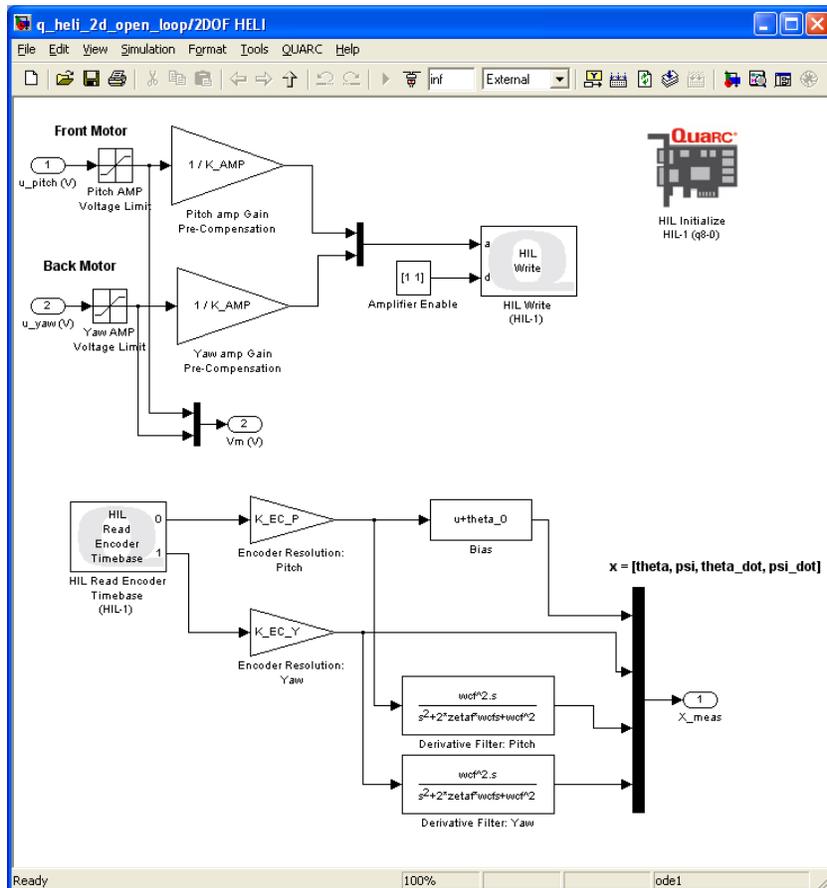


Figure 5.12: 2DOF HELI subsystem contains QUARC blocks that interface with hardware

7. The voltage sent to the Analog Output block is amplified by the amplifiers and applied to the power amplifier's attached motor. Note that the control input is divided by the amplifier gain, K_AMP , before being sent to the DAQ board. This way, the amplifier gain does not have to be included in the mathematical model as the voltage output from the controller is the voltage being applied to the motor. The amplifier and DAQ saturation blocks limit the amount of voltage that can be fed to the motor.
 8. Open the θ (deg), ψ (deg), and V_m (V) scopes in the *Scopes* folder. These scopes display both the desired and measured angles of the Helicopter as well as the voltages being applied to the front and back motors.
 9. Ensure the helicopter has been setup and all the connections have been made as instructed in the 2 DOF Helicopter User Manual.
 10. Turn ON the amplifier. For the VoltPAQ-X2, the green LED on the amplifier should be lit.
 11. In the $q_heli_2d_open_loop$ Simulink diagram, make sure the *Program/Joystick* block shown in Figure 5.11 is set to 2 in order to generate the desired voltage from the joystick.
 12. Click on QUARC | Build to compile the code from the Simulink diagram.
 13. Select QUARC | Start to begin running the controller.
- IMPORTANT:** Be ready to click on the STOP button in the Simulink tool bar at any time to stop running the controller. If using the VoltPAQ-X2, you can also press down on the E-Stop switch to disable the amplifier.
14. Try to bring the helicopter body to a horizontal by pulling the joystick handle toward you. This supplies a positive voltage to the pitch motor and causes the pitch angle to increase

15. As depicted in Figure 5.13, you will notice that the yaw angle moves clockwise in the positive direction as the voltage in the pitch motor increases. Compensate for this coupling effect by moving the joystick arm to the left and apply a negative voltage to the yaw motor. As illustrated, the pitch is eventually stabilized at about 0 degrees when the pitch motor voltage is approximately 12.5 V and the yaw begins to stabilize when feeding a voltage of about -6.0 V to the yaw motor.

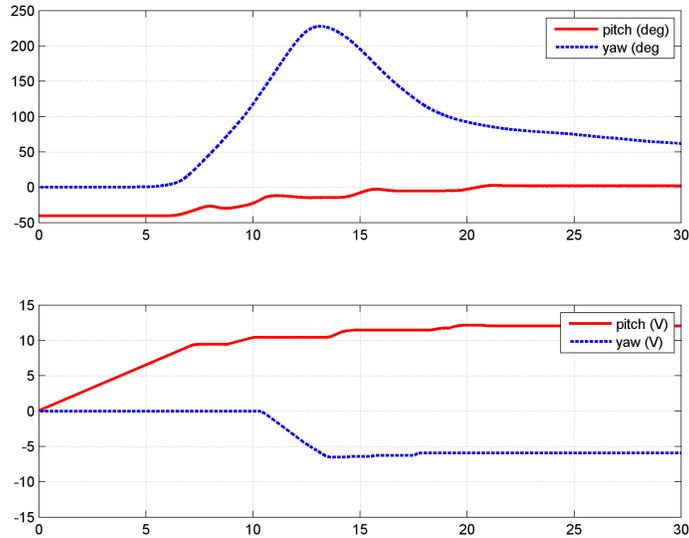


Figure 5.13: Effect of pitch on yaw

16. From this point, now try decreasing the yaw voltage and observe its effect on the pitch angle.

17. As depicted in Figure 5.14, applying a negative voltage to the yaw motor causes the pitch angle to decrease, i.e. the helicopter nose goes down. Similarly to the effect the pitch motor has on the yaw motion, the voltage applied to the yaw motor generates a torque on the pitch axis

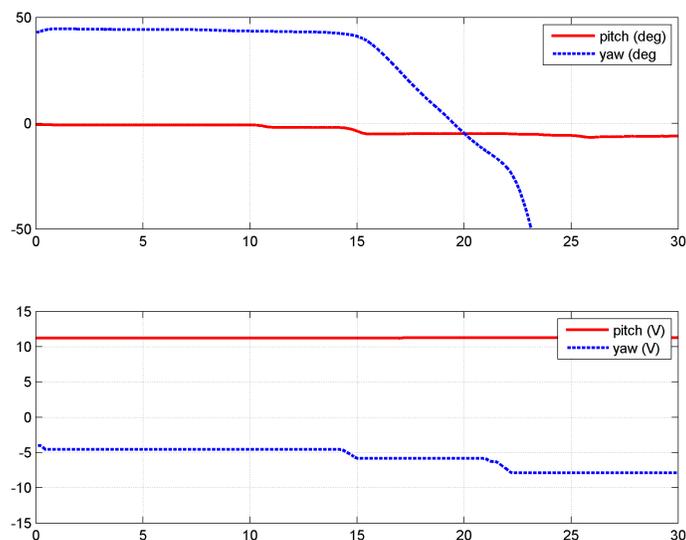


Figure 5.14: Effect of yaw on pitch

18. Gradually bring the helicopter back to starting position.
19. Click on the *Stop* button on the Simulink diagram tool bar (or select QUARC | Stop from the menu) to stop running the controller.
20. If the laboratory session is complete, power off the amplifier.

5.4 Closed-loop Position Control Implementation

5.4.1 Objectives

The objectives of running the 2 DOF Helicopter in closed-loop are to:

- Investigate the closed-loop performance between the FF+LQR and the FF+LQR+I controllers running on the actual 2 DOF Helicopter plant.
- Compare the measured closed-loop response with the simulated response.

5.4.2 Procedure: 2 DOF Helicopter

Follow this procedure to run the FF+LQR and the FF+LQR+I controllers on the actual helicopter plant:

1. Load **Matlab®**.
2. Open Simulink model *q_heli_2d_ff_lqr_i.mdl* shown in Figure 5.15 that implements the closed-loop LQR and LQR+I position controllers.

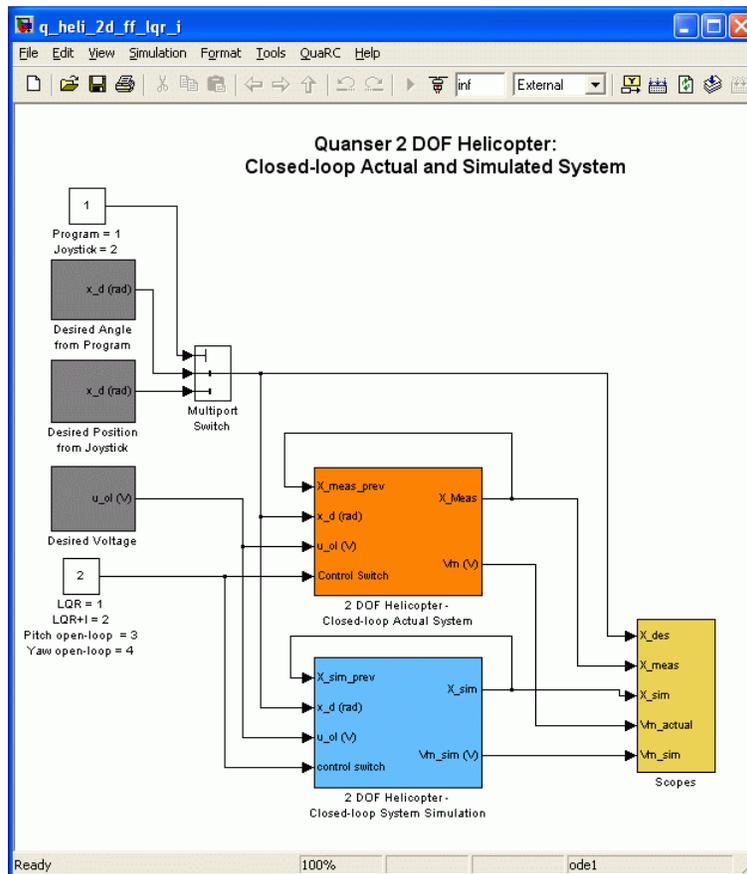


Figure 5.15: Simulink model used with QUARC to run the closed-loop controller on the 2 DOF Helicopter

3. **Configure setup script:** Open the design file *setup_lab_heli_2d.m* and ensure everything is configured properly.
4. Execute the *setup_lab_heli_2d.m* Matlab script to setup the workspace before compiling the diagram and running it in real-time with QUARC. This file loads the model parameters of the 2 DOF Helicopter system, calculates the LQR and LQR+I feedback gains, and sets various other parameters that are used such as the filter cutoff frequencies, amplifier gain, encoder sensitivities, and the amplifier and DAQ board limits.
5. Open the *2-DOF HELI* subsystem shown in Figure 5.15. It contains the QUARC blocks that interface with the hardware of the actual plant. The Analog Output block outputs the voltage computed by the controller to the DAQ board and the Encoder Input block reads the encoder measurements.
6. **Configure DAQ:** Double-click on the HIL Initialize block located in the *2-DOF Helicopter - Closed-loop Actual System 2-DOF HELI* subsystem (contents are as shown in Figure 5.12, above) and ensure it is configured for the DAQ device that is installed in your system. By default the block is setup for the Quanser Q8 hardware-in-the-loop board.
7. Ensure the helicopter has been setup and all the connections have been made as instructed in the 2 DOF Helicopter user manual.
8. Turn ON the amplifier. For the VoltPAQ-X2, the green LED on the amplifier should be lit.
9. In the *q_heli_2d_ff_lqr_i* Simulink diagram, make sure the *Program/Joystick* block shown in Figure 5.15 is set to 1 in order to generate the desired angle from Simulink.
10. Click on QUARC | Build to compile the code from the Simulink diagram.
11. Select QUARC | Start to begin running the controller. The pitch propeller should start turning lightly.

IMPORTANT: Be ready to click on the STOP button in the Simulink tool bar at any time to stop running the controller. If using the VoltPAQ-X2, you can also press down on the E-Stop switch to disable the amplifier.

12. By default, the helicopter pitch angle command is initially set to -30.0 degrees. In the *Desired Angle from Program* subsystem, set the *Amplitude: Pitch (deg)* to 10 and the *Pitch: Constant (deg)* to 0. Gradually increase the pitch constant, i.e., increment by steps of 10 degrees. The helicopter should be tracking this reference position about its horizontal.
13. Open the *theta (deg)*, *psi (deg)*, and *Vm_actual (V)* scopes in the *Scopes* folder. In the *theta (deg)* scope, the desired pitch position is the yellow line, the measured pitch position is the purple plot, and the simulated pitch position is light blue trace. Similarly in the yaw scope, *psi (deg)*, yellow is the desired yaw, purple is the measured yaw, and light blue is the simulated yaw. The *Vm_actual (V)* scope plots the voltage being applied to the pitch motor in yellow and yaw motor in purple.
14. Figure 5.16 depicts the typical measured and simulated pitch and yaw response under a desired step pitch angle. The measured response is the solid red line, the simulation is the dashed blue line, and the reference is the solid green line. Notice in both the measured and simulated responses the pitch angle has a steady-state error.

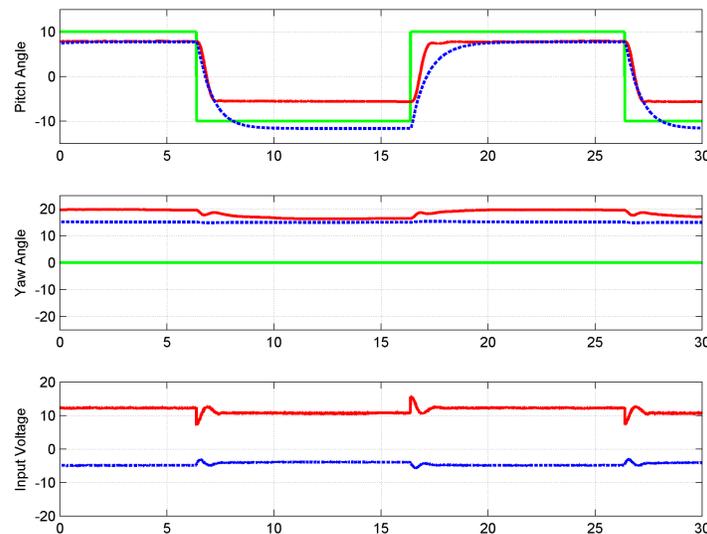


Figure 5.16: Closed-loop LQR response under pitch reference step

15. Inside the *Desired Angle from Program* set the *Amplitude: Pitch (deg)* to 0 and the *Amplitude: Yaw (deg)* to 50. The helicopter should tracking the commanded yaw angle.
16. Figure 5.17 depicts the typical measured and simulated pitch and yaw response given a desired step yaw angle. There is a steady-state error in the yaw angle.

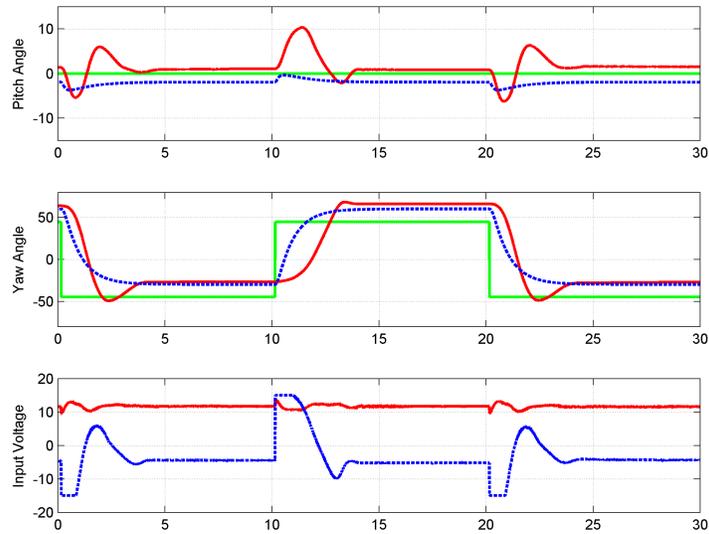


Figure 5.17: Closed-loop LQR response under yaw reference step

17. Set *Amplitude: Yaw (deg)* to 0. Both the pitch and yaw setpoints should now be zero.
18. The steady-state error can be removed using integral action. Switch to the FF+LQR+I control by setting the control switch source block to 2. The pitch and yaw angle should both, eventually, converge to 0 degree.
19. Set the *Amplitude: Pitch (deg)* to 10 and the *Pitch: Constant (deg)* to 0 to observe the LQR+I response under a step pitch reference. The result should be similar to the response shown in Figure 5.18. Note that the steady-state error is removed.

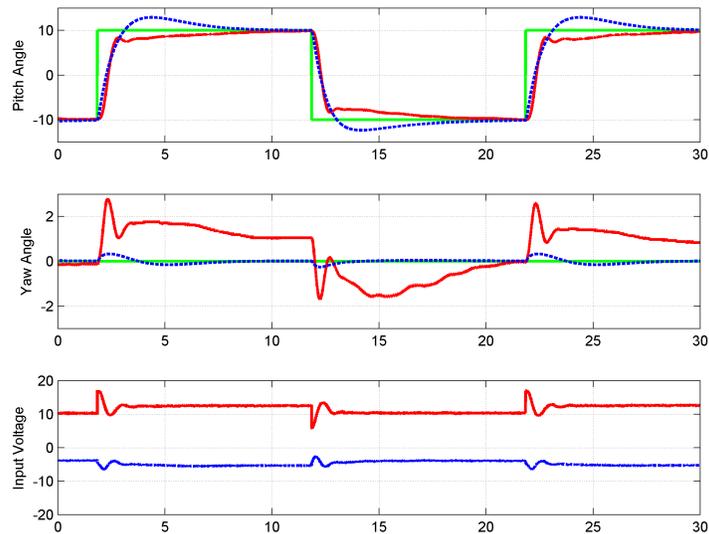


Figure 5.18: Closed-loop LQR+I response under pitch reference step

20. Set the *Amplitude: Pitch (deg)* to 0 and *Amplitude: Yaw (deg)* to 30.0 observe the LQR+I response under a desired yaw step. The obtained response should be similar to Figure 5.19. There is no steady-state error but the controller saturates the yaw amplifier due to the large step reference.

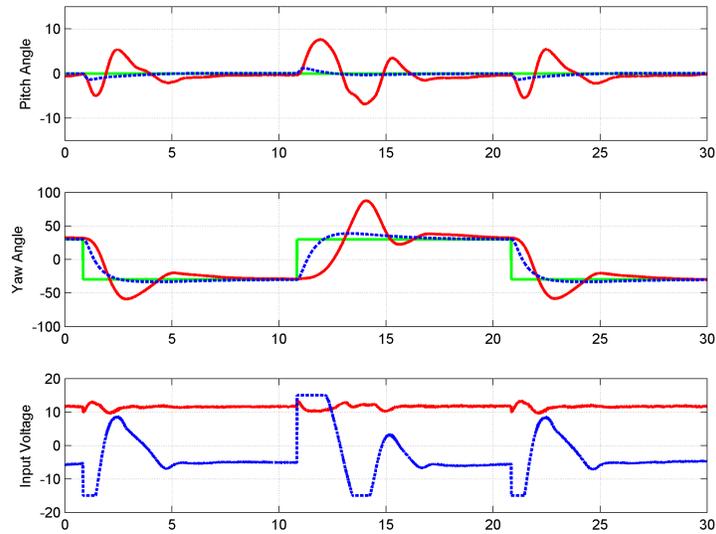


Figure 5.19: Closed-loop LQR+I response under yaw reference step

21. Alternatively, the desired angle can be generated using the joystick. To use the joystick, set the *Program/Joystick* switch shown in Figure 5.15 to 2. The rate at which the desired angle increases or decreases given a joystick position can be changed using the $K_JOYSTICK_X$ and $K_JOYSTICK_Y$ variables that are set in the *setup_lab_heli_2d.m* script file and the using the *Rate Command* knob. When starting, set the *Rate Command* knob on the joystick to the midpoint position.

■ **Caution:** Do not switch from the Program to the Joystick (from 1 to 2) when the controller is running. Set the program/joystick switch to 2 before starting QUARC if the joystick is to be used.

22. Gradually bring the helicopter back to starting position.
23. Click on the *Stop* button on the Simulink diagram tool bar (or select QUARC | Stop from the menu) to stop running the code.
24. Power off the amplifier.

5.5 Model Validation Implementation

5.5.1 Objectives

The objectives of running the model validation controller on the 2 DOF Helicopter are to:

- Verify that the nonlinear model, which is summarized in Section 5.1, represents the actual device with reasonable accuracy.
- Roughly identify the rotary viscous friction parameter about pitch and yaw axis.

5.5.2 Procedure

Follow this procedure to identify the viscous rotary friction on the yaw axis and do model validation of the pitch:

1. Follow the steps 1 to 11 given in 5.4 to run the *q_heli_2d_ff_lqr_i* QUARC controller. The helicopter should be at the starting point, i.e. pitch of -30 degrees and yaw of 0 degrees.
2. Run the LQR+I controller by setting the control switch source block to 2.
3. Inside the *Desired Angle from Program* set the *Amplitude: Pitch (deg)* to 0 and the *Pitch: Constant (deg)* to 0. The helicopter should be stabilized about a pitch and yaw angle of zero.
4. In the *Scopes* subsystem, double-click on the *theta (deg)*, *psi (deg)*, and *Vm_Actual (V)* sinks. In the *theta (deg)* scope, the desired pitch position is the yellow line, the measured pitch position is the purple plot, and the simulated pitch position is light blue trace. Similarly for the yaw *psi (deg)* scope. The *Vm_actual (V)* scope plots the voltage being applied to the pitch motor in yellow and yaw motor in purple.
5. To identify the viscous rotary friction parameter in the yaw axis a voltage step command must be applied to the yaw motor. In the *Desired Voltage* subsystem, set the *Signal Generator: Yaw (V)* block to 2.5.
6. Change the control switch to 4. The yaw input motor voltage is now the control voltage used to stabilize the yaw angle, $u_{lqr,y}^*$, added to the commanded open-loop voltage, i.e. $V_{m,p} = u_{lqr,y}^* + 2.5$. The plot should resemble Figure 5.20.

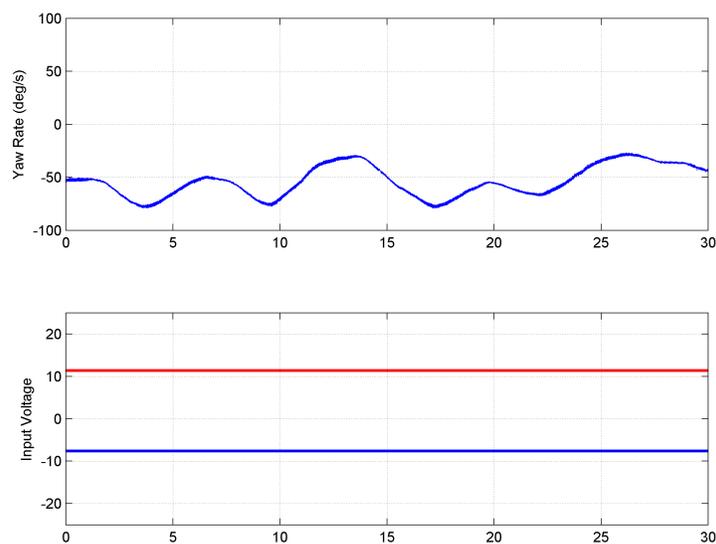


Figure 5.20: Identifying the viscous damping about the yaw axis

- For calculating the viscous damping parameter B_y , consider the linear equation describing the yaw motion in the 2 DOF Helicopter Maple worksheet (or its HTML equivalent). Given that the helicopter is rotating more or less at a constant speed, it can be assumed that the acceleration is zero, thus $\ddot{\psi}(t) = 0$. Setting the acceleration to zero as well as the pitch angle to zero and then solving for the viscous damping term gives the expression

$$B_y = \frac{K_{yy}V_{m,y} + K_{yp}V_{m,p}}{\dot{\psi}(t)_{avg}} \quad (5.1)$$

where the bottom term is the average velocity of the yaw angle. From Figure 25, the voltage and average velocity found are:

$$\begin{aligned} V_{m,y} &= -7.65 \text{ V} \\ V_{m,p} &= 11.36 \text{ V} \\ \dot{\psi}(t)_{avg} &= -0.9481 \text{ rad/s} \end{aligned}$$

Substituting these values into Equation 5.1 gives the equivalent viscous damping acting about the yaw axis

$$B_y = 0.319 \text{ N m s/rad}$$

- Bring the helicopter back to $(\theta = 0, \psi = 0)$ by setting the control switch block to 2 to run the LQR+I controller.
- To apply a voltage directly to the pitch motor set the control switch source block to 3.
- In the *Desired Voltage* subsystem, set the frequency of the *Signal Generator: Pitch (V)* block to 0.4 Hertz, the *Amplitude: Pitch (V)* gain block to 0.2, and the *Constant Pitch (V)* to 0.
- As shown in Figure 5.21, the measured and simulated pitch angles are quite close. The pitch viscous damping term B_p was estimated by tuning its value online as the controller is running. To do this enter a value for B_p in the Matlab command window, for example $B_p = 0.8$. Because the parameter change is made in Matlab (and not directly in the Simulink model), the controller that is running must be updated for the changes of this parameter to take effect. The change can be applied by clicking on the *Edit* menu in the Simulink model and selecting the *Update Diagram* item. Alternatively, controller parameters can be updated by use the keystroke CTRL-D whenever the Simulink model is active.

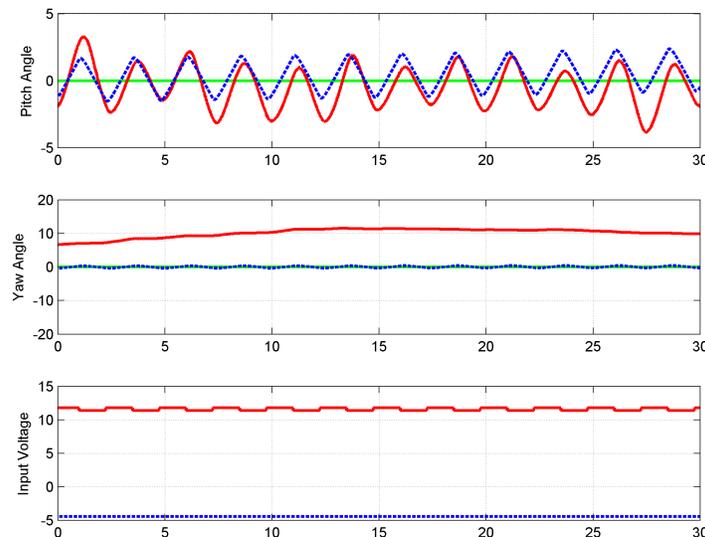


Figure 5.21: Open-loop pitch step

- Gradually bring the helicopter back to starting position.

13. Click on the *Stop* button on the Simulink diagram tool bar (or select QUARC | Stop from the menu) to stop running the code.
14. Make sure the amplifier is turned off if the session is complete.

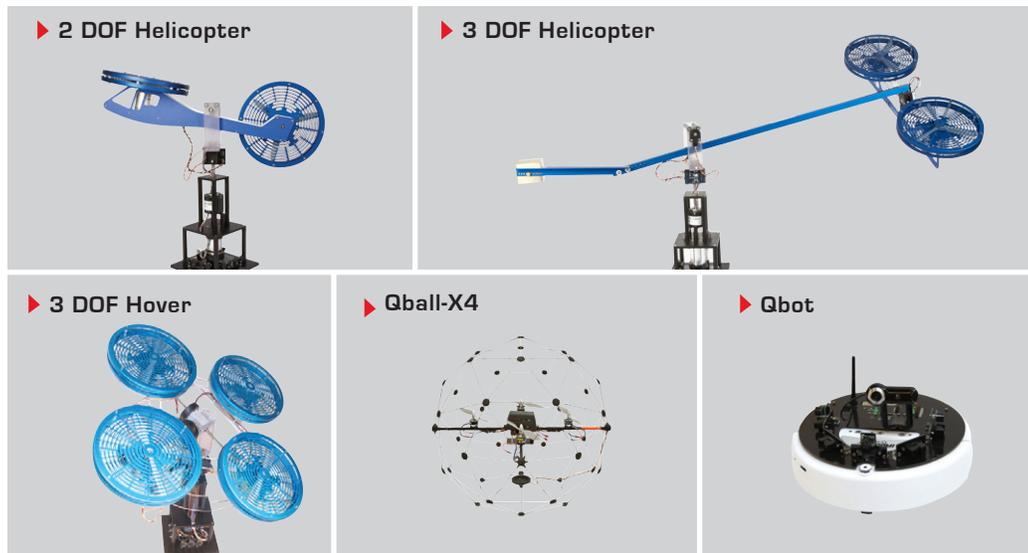
6 TECHNICAL SUPPORT

To obtain support from Quanser, go to <http://www.quanser.com/> and click on the Tech Support link. Fill in the form with all the requested software and hardware information as well as a description of the problem encountered. Also, make sure your e-mail address and telephone number are included. Submit the form and a technical support representative will contact you.

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- [1] Quanser Inc. *QUARC User Manual*.
- [2] Quanser Inc. *Q2-USB Data-Acquisition System User's Guide*, 2010.
- [3] Quanser Inc. *VoltPAQ User Guide*, 2010.
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