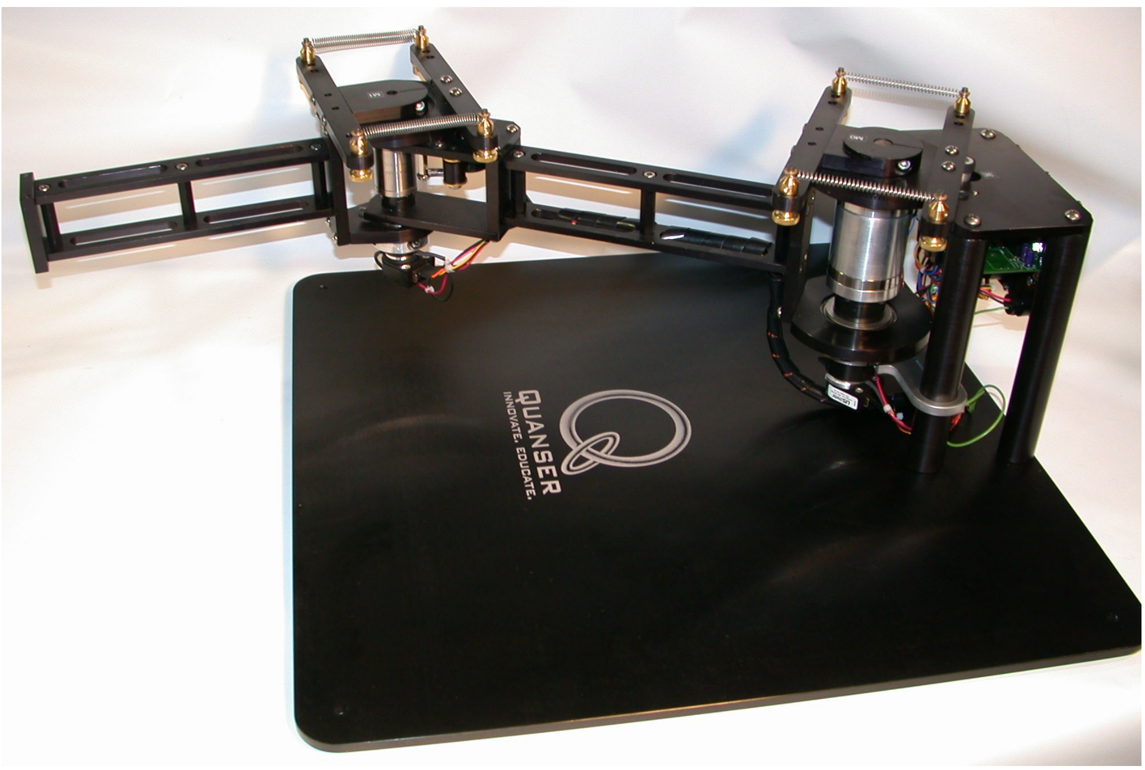
Specialty Plant: 2DSFJ Robot

2-DOF Serial Flexible Joint Robot



Reference Manual

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1. System Presentation

1.1. 2-DOF Serial Flexible Joint Robot Description

The 2-Degree-Of-Freedom (DOF) Serial Flexible Joint (2DSFJ) Robot is depicted in Figure 1. This robot system consists of two DC motors driving via harmonic gearboxes (zero backlash) and a two-bar serial linkage. Both links are rigid. The primary link is coupled to the first drive by means of a flexible joint. It carries at its end the second harmonic drive which is coupled to the second rigid link via another flexible joint. Both motors and both flexible joints are instrumented with quadrature optical encoders. Each flexible joint uses two springs that can be changed. Also a thumbscrew mechanism is available to move each spring end to different anchor points along its support bars, as desired.

The described robotic mechanism emulates torsional compliance and joint flexibility, which are common characteristics in mechanical systems such as high-gear-ratio harmonic drives or lightweight transmission shafts.

Figure 1 2-DOF Serial Flexible Joint Robot

1.2. Control Challenge

The challenge of this experiment is to design a control system to position the robot tip in a plane (2-DOF) as rapidly as possible with minimum vibrations. The end-effector planar position to track and/or regulate is of the two-bar serial-kinematic mechanism that has two flexible joints. The Multi-Input Multi-Output (MIMO) system is supplied with a decoupled state-feedback controller reducing flexibility-caused oscillations as well as link-coupling effects. However, this system is fully open-architecture and you may design any other controller you wish.

1.3. Component Nomenclature

Table 1 provides a list of all the principal elements composing the 2DSFJ plant. Every element is located and identified, through a unique identification (ID) number, as represented in Figure 2.

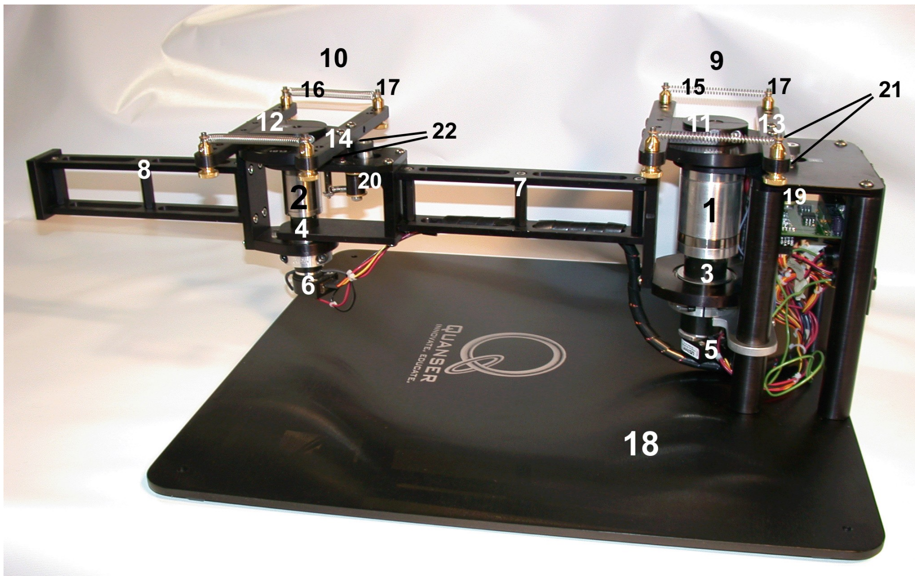


Figure 2 2-DOF Serial Flexible Joint Robot

ID #	*Description*	*ID #*	*Description*
1	Harmonic Drive #1 (Shoulder)	**2**	Harmonic Drive #2 (Elbow)
3	DC Motor #1 (Shoulder)	**4**	DC Motor #2 (Elbow)
5	Motor #1 Encoder	**6**	Motor #2 Encoder
7	Rigid Link #1	**8**	Rigid Link #2
9	Flexible Joint Assembly #1	**10**	Flexible Joint Assembly #2
11	Flexible Joint #1 Actuated Transition	**12**	Flexible Joint #1 Load Transition
13	Flexible Joint #2 Actuated Transition	**14**	Flexible Joint #2 Load Transition
15	Flexible Joint #1 Spring	**16**	Flexible Joint #2 Spring
17	Spring Fixture Mechanism	**18**	Base Plate
19	Flexible Joint #1 Encoder	**20**	Flexible Joint #2 Encoder
21	Flexible Joint #1 Limit Switches	**22**	Flexible Joint #2 Limit Switches

Table 1 2-DOF Serial Flexible Joint Robot Component Nomenclature

Table 2 provides a list of all the principal elements composing the 2DSFJ Robot connection plate. Every element is located and identified, through a unique identification (ID) number, as represented in Figure 3.

Figure 3 2DSFJ Robot Connection Panel

ID #	*Description*	*ID #*	*Description*
23	15 VDC Power Supply Connector	**24**	Limit Switch Connector
25	Motor #1 Lead Connector	**26**	Motor #2 Lead Connector
27	Motor #1 Encoder Connector	**28**	Motor #2 Encoder Connector
29	Flexible Joint #1 Encoder Connector	**30**	Flexible Joint #2 Encoder Connector

Table 2 2DSFJ Robot Connection Panel Component Nomenclature

1.4. Component Description

This Section provides a description of the individual elements comprising the 2-DOF Serial Flexible Joint robot.

CAUTION: Exposed Moving Parts.

1.4.1. Harmonic Drive #1 (Component #1)

The harmonic drive #1 uses the harmonic gearhead CS-14-100-1U-CC-SP from Harmonic Drive LLC. It offers zero backlash for a gear ratio of 100:1. Also it is coupled to a Maxon

273759 precision brush motor (90 Watts).

CAUTION:
High Frequency signals applied to a motor will eventually damage the motor brushes. The most likely source for high frequency noise is derivative feedback. If the derivative gain is too high, a noisy voltage will be fed into the motor. To protect your motor, you should always band limit your signal (especially derivative feedback) to a value of **50Hz.**

1.4.2. Harmonic Drive #2 (Component #2)

The harmonic drive #2 uses the harmonic gearhead CS-8-50-1U-CC-SP from Harmonic Drive LLC. It offers zero backlash for a gear ratio of 50:1. Also it is coupled to a Maxon 118752 precision brush motor (20 Watts).

The following table summarizes some useful information regarding the 2 motors used in actuating the 2DOF Serial Flexible Joint system.

Property	*Value*
Input Voltage	± 27 V
Maximum Peak Current	3 A
Maximum Continuous Current	1.2 A

Table 3: Motor Properties of the 2DSFJ System

CAUTION:
High Frequency signals applied to a motor will eventually damage the motor brushes. The most likely source for high frequency noise is derivative feedback. If the derivative gain is too high, a noisy voltage will be fed into the motor. To protect your motor, you should always band limit your signal (especially derivative feedback) to a value of **50Hz.**

1.4.3. Digital Motor and Joint Position Measurement: Optical Encoders (Components #19 and #20)

Digital angular position measurement of both motors and both flexible joints are obtained by using high-resolution quadrature optical encoders from US Digital. All encoders have 1024 lines per revolution.

1.4.4. Joint Position Limit Switches (Components #21 and #22)

As a safety precaution, two limit switches are installed at the minimum and maximum rotational positions of each of the two flexible joints. They are magnetically-operated position sensors powered by an external ±15 VDC power supply which connects to component #23 in Figure 3. Specifically, they are the Hamlin 55100 Mini Flange Mount Hall Effect Sensors.

1.4.5. External DC Power Supply

The Two-Degree-Of-Freedom Serial Flexible Joint robot comes with an external power supply. It can provide the system with a maximum output power of 42 W at ±15 VDC. It currently supplies power to the four joint position limit switches by connecting to component # 23 in Figure 3. It is represented in Figure 4. **Always use the supplied adapter. Using other adapters may cause damage to the system.**

Figure 4 External DC Power Supply

1.4.6. Flexible Joint Springs (Components #15 and #16)

The 2DSFJ is provided with three pairs of extension springs, each of which has a different stiffness. Therefore, each flexible joint stiffness can be reconfigured by swapping pairs of springs. All the linear springs are from the Associated Spring Raymond. Specifically, their model numbers are: E0240-026-1500S, E0240-029-1500S, and E0240-031-1500S. Spring specifications are given in Table 4. The factory default for the 2DSFJ system uses the strongest pair of springs (i.e., E0240-031-1500S) for the first flexible joint (a.k.a. shoulder) and the lightest pair (i.e. E0240-026-1500S) for second flexible joint (a.k.a. elbow).

Description	*Value*	*Unit*
Extension Spring E0240-031-1500S:		
Outside Diameter	0.24	in
Wire Diameter	0.031	in
Free Length (Approximated)	1.5	in
Extended Length	2.64	in
Load At Extended Length	4.415	lb
Initial Tension	0.416	lb
Spring Rate, K_r	3.5	lb/in
	612.9	N/m
Extension Spring E0240-029-1500S:		
Outside Diameter	0.24	in
Wire Diameter	0.029	in
Free Length (Approximated)	1.5	in
Extended Length	2.89	in
Load At Extended Length	3.749	lb
Initial Tension	0.333	lb
Spring Rate, K_r	2.42	lb/in
	423.8	N/m
Extension Spring E0240-026-1500S:		
Outside Diameter	0.24	in
Wire Diameter	0.026	in
Free Length (Approximated)	1.5	in
Extended Length	3.28	in
Load At Extended Length	2.749	lb
Initial Tension	0.249	lb
Spring Rate, K_r	1.33	lb/in

Table 4: Extension Spring Specifications

1.4.7. Quanser Linear Current Amplifier Package (AMPAQ)

The 2DSFJ robot is powered by a two-channel linear current Amplifier Package (AMPAQ) from the Quanser AMPAQ-series. The two-channel AMPAQ is illustrated in Figure 5.

Figure 5 Two-Channel AMPAQ

1.4.8. Analog Current Measurement: Current Sense Resistor

A series load resistor is connected to the output of each of the linear current amplifiers. The obtained current measurement signal is available on the "Sense" RCA connector located on the AMPAQ front panel. Such a current measurement is used to monitor the current and in a feedback loop to control the current in the motor. Current control is an effective way of eliminating the effects of back-EMF as well as a means of achieving force and torque control.

1.4.9. Q8 HIL Board

The power amplifier and planar robot systems are designed to be fully compatible with the Q8 Hardware-In-the-Loop (HIL) board, which is represented in Figure 6. For details regarding the Q8 board, please refer to Reference [1].

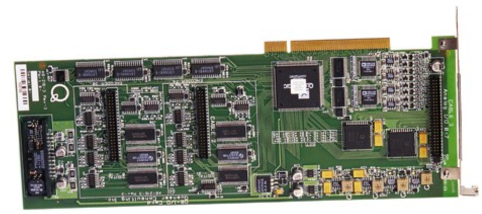


Figure 6 Q8 HIL Board

1.4.10. Cables

The different types of cables, which are supplied with the system, are described in Table 5. They are used in the wiring of the Two-Degree-Of-Freedom Serial Flexible Joint robot system.

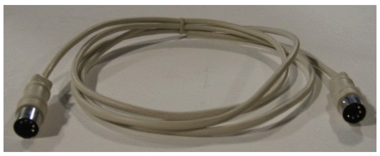
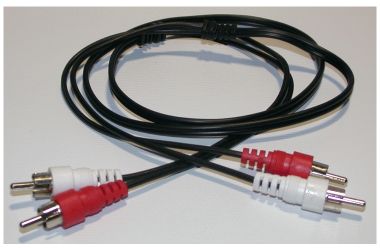
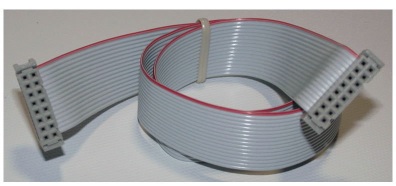
Cable	***Description***
 Figure 7 "Motor" Cable	The "Motor" cable carries the power leads from the power amplifier (AMPAQ) to one of the 2DSFJ DC motors.
 Figure 8 "Encoder" Cable	The "Encoder" cable carries encoder signals and required DC power supply. One cable is used for each of the two 2DSFJ encoders as well as for each of the two flexible joint encoders for a total of 4 encoder cables.
 Figure 9 "Analog" Cable	The "Analog" cable comprises two sets of RCA male connectors. One connects an analog output of the data acquisition (i.e. Q8) terminal board to the power module for proper power amplification. The other carries the current sense signal from the AMPAQ to the Q8 terminal board, where the signal is then available to be monitored as mentioned earlier.
 Figure 10 "Digital I/O" Cable	The "Digital I/O" cable is used to connect from the AMPAQ "Enable" SCSI 16-pin Connector to the Q8 terminal board first header. This flat ribbon cable then carries the amplifier enable signals and can be used for extra digital signals. It is also used to connect from the Q8 terminal board second header to the 2DSFJ limit switch connector (e.g. switch).
 Figure 11 "15 VDC Power" Cable	The "15 VDC Power" cable connects the external ±15 VDC power supply to the 2DSFJ "15 VDC Power Connector". It provides power to the system four limit switches.

Table 5 Cable Type Description

CAUTION: Do not connect the 15 VDC power cable to the "DIO" connector found on the

AMPAQ front panel. Although the cable seems to fit this connector it is meant to be connected to component # 23 in Figure 3 to provide the power for 2DSFJ limit switches.

2. Flexible Joint Configuration

2.1. Flexible Joint Dimensions And Spring Configuration

The 2DSFJ robot is composed of two identical flexible joints. One of them is depicted in Figure 12.

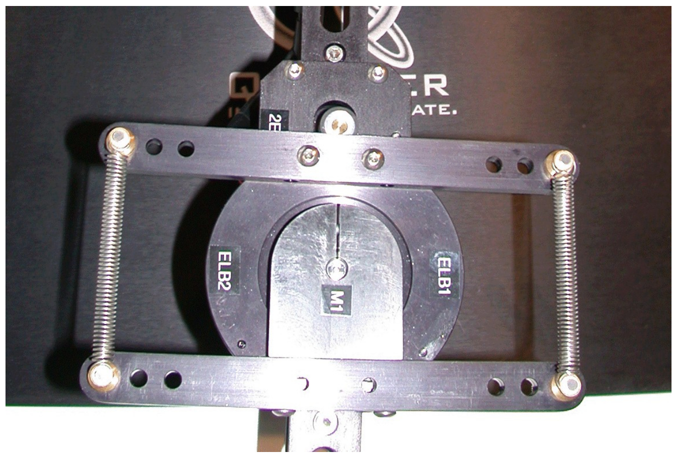


Figure 12 Flexible Joint: Default Spring Configuration

The two springs of the flexible joint as illustrated in Figure 12 are set up in the their default configuration. Both extension springs are mounted on the outer holes of the two opposed support bars of the flexible joint.

Also the factory default for the 2DSFJ system uses the strongest pair of springs (i.e., E0240-031-1500S) for the first flexible joint (a.k.a. shoulder) and the lightest pair (i.e. E0240-026-1500S) for second flexible joint (a.k.a. elbow).

Table 6 provides the characteristic dimensions of the spring mounting holes in the flexible joint.

Joint Dimensions	*Symbol*	*Value*	*Unit*
Distance From The Joint Centerline To The Outer Hole	d_1	86.36	mm
Radius From The Joint Axis Of Rotation To The Outer Hole	r_1	97.60	mm
Distance From The Joint Centerline To The Middle Hole	d_2	73.66	mm
Radius From The Joint Axis Of Rotation To The Middle Hole	r_2	85.56	mm
Distance From The Joint Centerline To The Inner Hole	d_3	60.96	mm
Radius From The Joint Axis Of Rotation To The Inner Hole	r_3	74.91	mm

Table 6 Flexible Joint Dimensions

The flexible joint torsional stiffness, K_s, with its two linear springs in the default configuration can be approximated by the following equation:

$$K_s = 2\, K_r\, r_1\, d_1$$

where K_r is the spring rate (a.k.a. stiffness constant), as defined in Table 4.

2.2. Setting Up The Springs On The Flexible Joint

Three pairs of springs of different stiffnesses are provided with the 2DSFJ system.

The procedure to mount the linear springs on the flexible joint is as follows:

Step 1. For each of the two flexible joints, position the four spring anchor mechanisms into the desired mounting holes located on the support bars. Do so by using the anchor thumbscrews. As an example, this is illustrated in Figure 12.

Step 2. Insert the spring support posts into the previously positioned anchor devices. One of the posts is depicted in Figure 13.

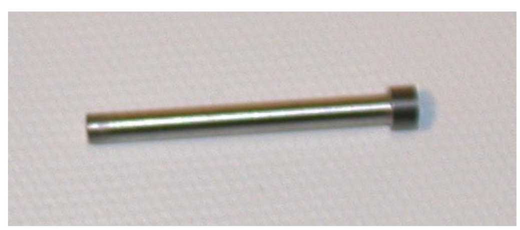


Figure 13 Spring Mounting Post

Step 3. Insert each spring end hook onto each support post. Then also insert the brass retainer on top of the spring hook. This is illustrated in Figure 14. The resulting spring assembly should be similar to the one shown in Figure 15.

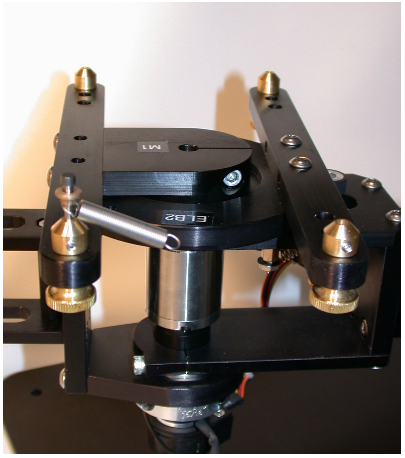


Figure 14 Inserting One Spring And Retainer

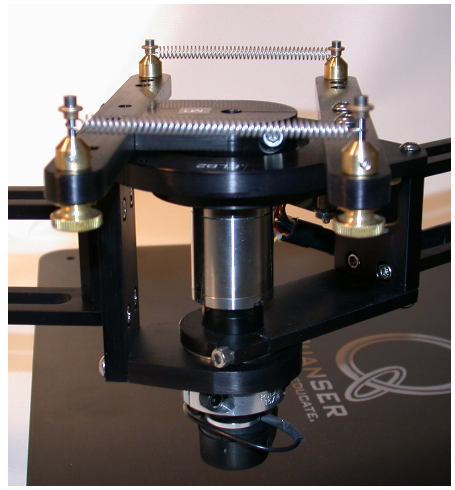


Figure 15 Intermediary Spring Assembly

Step 4. Clamp all four mounting posts by tightening the corresponding set-screws. This is shown in Figure 16. To do so, use a (1/16)" Allen key.

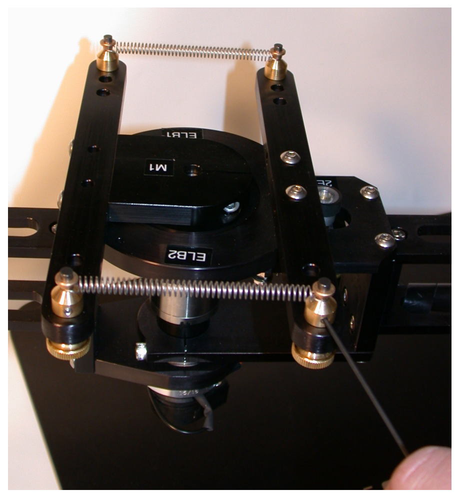


Figure 16 Tightening The Setscrews

3. System Parameters

The specifications on the 2-Degree-Of-Freedom Serial Flexible Joint Robot model parameters are given in Table 7 on the next page.

Description	*Value*	*Unit*
Flexible Joint #1 System:		
Motor #1 Torque Constant	0.119	N.m/A
Motor #1 Back-EMF Constant	0.119	V.s/rad
Motor #1 Maximum Continuous Current	0.944	A
Motor #1 Armature Resistance	11.5	Ω
Drive #1 Armature Inductance	3.16	mH
Harmonic Drive #1 Gear Ratio	100	
Motor #1 Rotor Moment Of Inertia At Motor Shaft	6.28E-6	$kg.m^2$
Moment Of Inertia Of Drive #1 Transition System	930.91E-6	$kg.m^2$
Moment Of Inertia Of Compounded Load Transition System	0.23041858	$kg.m^2$
Flexible Joint #1 Torsional Stiffness Constant (With Strongest Spring In The Default Position)	9.0	N.m/rad
Motor #1 Mechanical Time Constant	5	ms
Flexible Joint #2 System:		
Motor #2 Torque Constant	0.0234	N.m/A
Motor #2 Back-EMF Constant	0.0234	V.s/rad
Motor #2 Maximum Continuous Current	1.21	A
Motor #2 Armature Resistance	2.32	Ω
Drive #2 Armature Inductance	0.24	mH
Harmonic Drive #2 Gear Ratio	50	
Motor #2 Rotor Moment Of Inertia At Motor Shaft	1.03E-6	$kg.m^2$
Moment Of Inertia Of Drive #2 Transition System	930.91E-6	$kg.m^2$
Moment Of Inertia Of Load #2 Transition System	0.010724	$kg.m^2$
Flexible Joint #2 Torsional Stiffness Constant	4.0	N.m/rad
Motor #2 Mechanical Time Constant	4	ms
Linear Current Amplifier (Each Channel):		
Linear Amplifier Maximum Continuous Current	3	A

Description	*Value*	*Unit*
Linear Amplifier Peak Current	5	A
Linear Amplifier Maximum Continuous Voltage	28	V
Linear Amplifier Peak Power	300	W
Linear Amplifier Bandwidth (Current Mode)	10	kHz
Linear Amplifier Gain	0.5	A/V
Drive & Joint Optical Encoders:		
Encoder Line Count	1,024	lines/rev
Encoder Resolution (In Quadrature)	4,096	counts/rev
Encoder Angular Resolution (In Quadrature)	0.0015	rad/count
Drive #1 Encoder Sensitivity (In Quadrature)	1.534E-5	rad/count
Drive #2 Encoder Sensitivity (In Quadrature)	1.918E-5	rad/count
Flexible Joint Encoder Sensitivity (In Quadrature)	23.968E-5	rad/count
Encoder Type	TTL	
Encoder Signals	A, B, Index	
External Power Supply:		
Power Supply Power	42	W
Power Supply Voltage	±15	VDC
Current Sense:		
Current Sense Calibration At ±10%	2.0	V/A

Table 7 Two-Degree-Of-Freedom Serial Flexible Joint System Model Parameter Specifications

The 2-Degree-Of-Freedom Serial Flexible Joint robot main device dimensions and workspace are given in Table 8.

Description	***Value***	***Unit***
Device Geometry:		
Base Plate Length	0.508	m
Base Plate Width	0.508	m
Device Height	0.240	m
2-DOF Flexible Link Total Length	0.610	m
Link #1 Length (From Drive #1 To Drive #2 Shafts)	0.343	m
Link #2 (End-Effector Arm) Length	0.267	mm
Maximum Payload (At Link #2 End-Effector)	1.0	kg
Workspace From Mid-Range Position:		
Flexible Joint #1 Maximum Rotation	90	degrees
Flexible Joint #1 Minimum Rotation	-90	degrees
Flexible Joint #2 Maximum Rotation	90	degrees
Flexible Joint #2 Minimum Rotation	-90	degrees

Table 8 Two-Degree-Of-Freedom Serial Flexible Joint Robot Dimensions And Workspace

4. Cabling Of The Two-DOF Serial Flexible Joint System

This section describes the standard and common wiring procedure for the Two-Degree-Of-Freedom Serial Flexible Joint robot. The following hardware, accompanying the 2DSFJ system, is assumed:

- AMPAQ-series Power Amplifier: Two-Channel Linear Current Amplifier.
- Data Acquisition Card: Quanser's Q8 / Q4 HIL board.
- ±15 VDC External Power Supply for the Limit Switcehs

The following assumes that the Q8 (or Q4) HIL board has been successfully installed in your PC. Please refer to Reference [1], the Q8 Installation Guide, for details.

4.1. Cabling Procedure

Figures 17, 18, and 19 show, respectively, the back panel of the Two-Degree-Of-Freedom Serial Flexible Joint (2DSFJ) plant, the Q8 Terminal board, and the AMPAQ-series two-channel linear current amplifier, all connected with the cabling required to safely use the 2DSFJ system.

Note:
Perform all connections with the PC, external power supply, and the AMPAQ turned off.

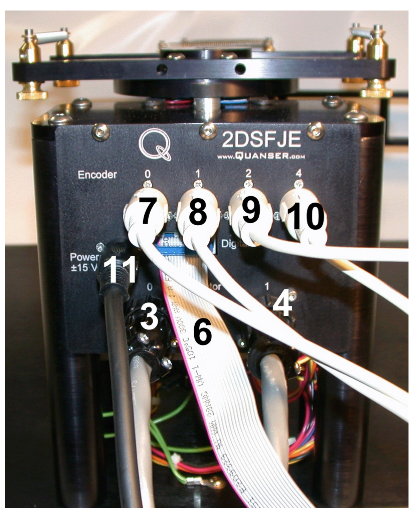


Figure 17 2DSFJ Connections: Back Panel

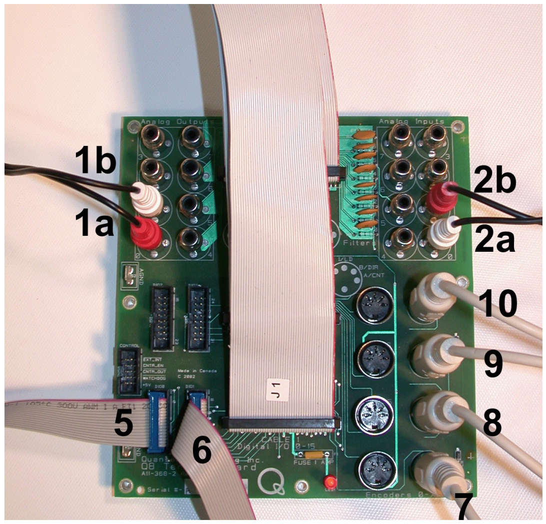


Figure 18 Q8 Terminal Board Connections

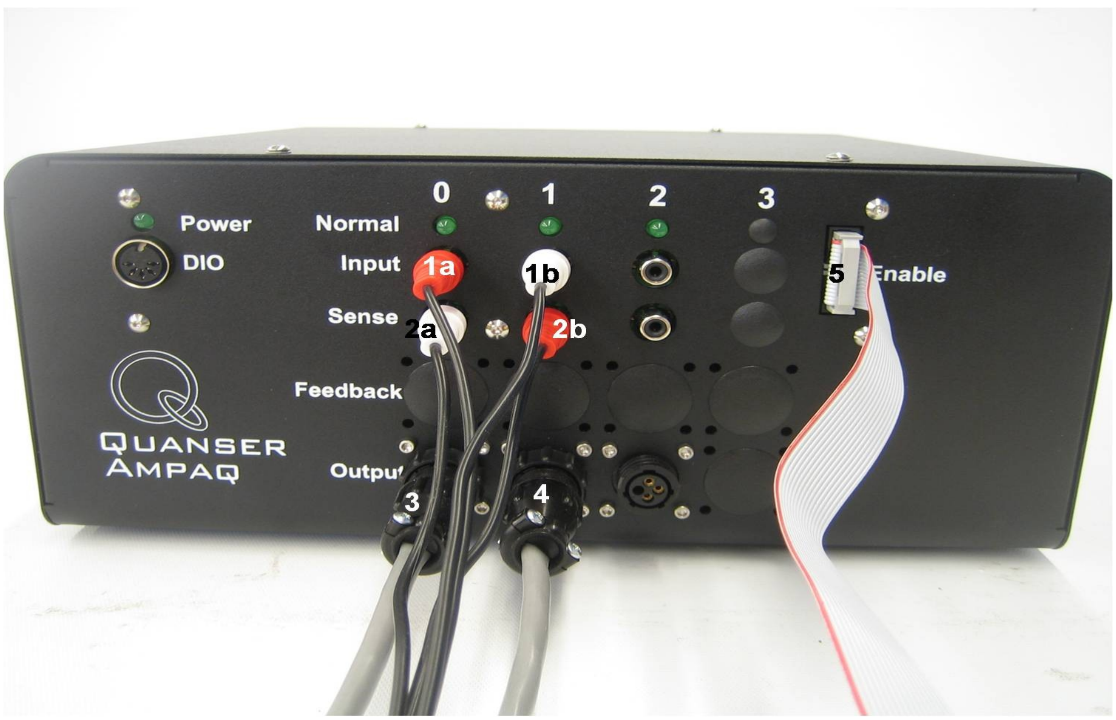


Figure 19: Two-Channel AMPAQ Connections

Please follow the wiring procedure detailed below in Table 9 and illustrated in Figures 17, 18, and 19.

Cable	*From*	*To*	*Signal*
1a	Terminal Board: DAC #0	AMPAQ "Input" 0	Analog Cable: control signal to the linear current amplifier #0.
1b	Terminal Board: DAC #1	AMPAQ "Input" 1	Analog Cable: control signal to the linear current amplifier #1.
2a	Terminal Board: ADC #0	AMPAQ "Sense" 0	Analog Cable: current measurement signal from the linear amplifier output #0.
2b	Terminal Board: ADC #1	AMPAQ "Sense" 1	Analog Cable: current measurement signal from the linear amplifier output #1.
3	AMPAQ "Output" 0	2-DOF SFJ "Motor #1 Connector"	Motor #1 Cable: power leads from the amplifier to DC motor #1 (shoulder).
4	AMPAQ "Output" 1	2-DOF SFJ "Motor #2 Connector"	Motor #2 Cable: power leads from the amplifier to DC motor #2 (elbow).
5	Terminal Board: DIO0 (first header)	AMPAQ "Enable"	Digital I/O Cable: digital output signals to the AMPAQ.
6	Terminal Board: DIO1 (second header)	2-DOF SFJ "Limit Switch Connector"	Digital I/O Cable: digital input signals from the 2-DOF SFJ robot.
7	Terminal Board: Encoder Channel #0	2DSFJ "Motor #1 Encoder Connector"	Encoder Cable: motor #1 output shaft position signal.
8	Terminal Board: Encoder Channel #1	2DSFJ "Joint #1 Connector"	Encoder Cable: flexible joint #1 angular position signal.
9	Terminal Board: Encoder Channel #2	2DSFJ "Motor #2 Connector"	Encoder Cable: motor #2 output shaft position signal.
10	Terminal Board: Encoder Channel #3	2DSFJ "Joint #2 Connector"	Encoder Cable: flexible joint #2 angular position signal.
11	External Power Supply	2DSFJ "±15 VDC Power Connector"	Power Leads: ±15 VDC power supply to the 2DSFJ limit switches.

Table 9 Two-Degree-Of-Freedom Serial Flexible Joint System Wiring Summary

4.2. Q8/Q4 Digital Input And Output (DIO) Connection Table

Table 10 details the Digital Input and Output (DIO) connections between the Q8 (or Q4), 2DSFJ, and AMPAQ-series amplifier attained by using two Digital I/O Cables.

Q8 DIO Channel	*Signal*	*Function*	*High: 1*	*Low: 0*
DIO #0	Linear Amplifier #0 Enable	Output	Disable	Enable
DIO #1	Linear Amplifier #1 Enable	Output	Disable	Enable
DIO #2	Linear Amplifier #2 (if any) Enable	Output	Disable	Enable
DIO #3	Linear Amplifier #3 (if any) Enable	Output	Disable	Enable
DIO #4-7	User-Defined Switches	User-Defined	User-Defined	User-Defined
DIO #8	Limit Switch #0 (SH1)	Input	Disable	Enable
DIO #9	Limit Switch #1 (SH2)	Input	Disable	Enable
DIO #10	Limit Switch #2 (ELB1)	Input	Disable	Enable
DIO #11	Limit Switch #3 (ELB2)	Input	Disable	Enable
DIO #12-15	User-Defined Switches	User-Defined	User-Defined	User-Defined

Table 10 Q8 DIO Connection Nomenclature

Table 10 summarizes the enable features of the linear current amplifiers contained in the AMPAQ. Each current amplifier can be individually enabled using one of the DIO lines from channels 0 to 3 of the Q8 (or Q4) board. Table 10 also describes the connection of the 2DSFJ position limit switches and the definition of their respective states. Finally, more switches can be implemented and defined by the user on the digital lines from channels #4 to #7 and from channels #12 to #15.

4.3. Powerup Procedure

Once the system is fully wired as previously described, the PC can be started. Once the PC has completely booted up, the external power supply can be plugged in and the AMPAQ powered up. On the AMPAQ front panel, the status of the following lights should be as follows:

i) "Power" light:
The "Power" LED should be on. It indicates that the AMPAQ is switched on and operational.

ii) "Normal" light:
The "Normal" LED should be off. It indicates that the corresponding linear current amplifier is not enabled. The digital input to enable the amplifier is active low.

5. QuaRC Application Examples

5.1. About QuaRC

QuaRC is Quanser's new, state-of-the-art rapid prototyping and production system for real-time control. QuaRC integrates seamlessly with Simulink to allow Simulink models to be run in real-time on a variety of targets, such as Windows, and QNX. For details on installing QuaRC, please see [2]. For information about using the QuaRC software please see [3]. With QuaRC interfacing to hardware becomes as easy as placing blocks in your Simulink diagram.

CAUTION:
For safety reasons when interfacing to the 2DSFJ drive #1, the *Saturation* block should be used to limit the current sent to the corresponding DC motor. Its parameters should have the following values: *Upper Limit*: **0.94** A, and *Lower Limit*: **-0.94** A. These settings are illustrated in Figure 20 and agree with the system specifications given in Table 7.

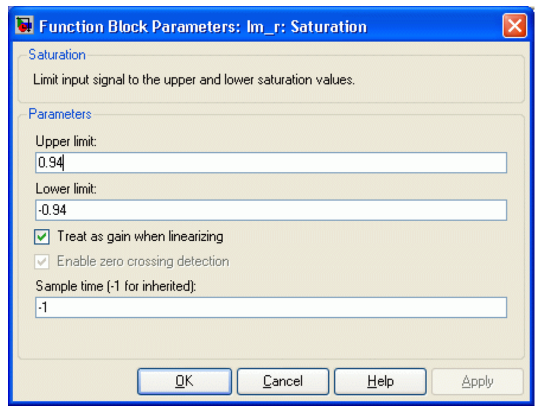


Figure 20 Saturation Settings For Drive #1

5.2. Two-DOF SFJ Robot – Decoupled System: Vibration Control

This Section outlines the design of a control system to reduce the vibration of the Two-Degree-Of-Freedom Serial Flexible Joint robot. A decoupled approach is used, which is to say that link coupling of the serial mechanism is neglected. Both drives are commanded independently of each other, each using a separate state-feedback control loop obtained using Linear Quadratic Regulation.

5.2.1. Operating Procedure

Note:

Before running the following example, ensure that the system is cabled and configured as detailed in Section 4.1. Also ensure that all four encoders of the 2DSFL system are working properly before proceeding. The controller tuning described hereafter assumes that no load is attached to the 2DSFJ end-effector.

Open the Simulink model named *q_2DSFJ_robot_QuaRC.mdl*. Align the two flexible joints in their central position and start the *q_2DSFJ_robot_QuaRC.mdl* model. Please note that you need to run the setup script called *setup_2DSFJ_robot.m* prior to running the model as this file sets the required parameters for proper operation of the Simulink model and the hardware itself.

Each of the two flexible joints (i.e., stage 1 and stage 2) should now be tracking two ± 20-degree angular position trajectories in the form of square waves.. Typical system responses should look similar to the ones represented in the Scopes shown in Figures 21, 22, 23 and 24 where the square waves frequency is 0.1 Hz. In order to command each link tip of the device to a desired position, each of the two actuators (harmonic drives) has its own position control loop. Each uses a state-feedback control scheme tuned with the Linear-Quadratic Regulator (LQR) algorithm. The vibration of both links should be significantly minimized by the two state-feedback controllers. If the system does not track the prescribed trajectory, please review your wiring or contact Quanser technical support as detailed in the Obtaining Support section of this document.

Figures 21, 22, 23, and 24, depict the responses of the 2DSFJ system from the same run. For example Figure 21 corresponds to the Scope located at *q_2DSFJ_robot_QuaRC/2-DOF SFJ Robot + Q8: Actual Plant/Stage 1/Scopes/theta11 (deg)*, which plots the reference/desired (green trace), simulated (red trace), and actual position (blue trace) responses of the 2DSFJ θ_{11} angular output in degrees. It can be seen in Figures 21, 22, 23, and 24 that both square wave trajectories are out of phase. This is done so that link coupling can be best observed. It is uncompensated for, as the implemented controller design assumed a decoupled system.

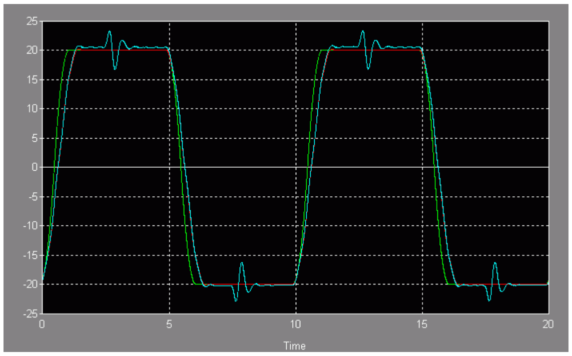


Figure 21 Drive #1 Load Shaft Angular Response: θ_{11}

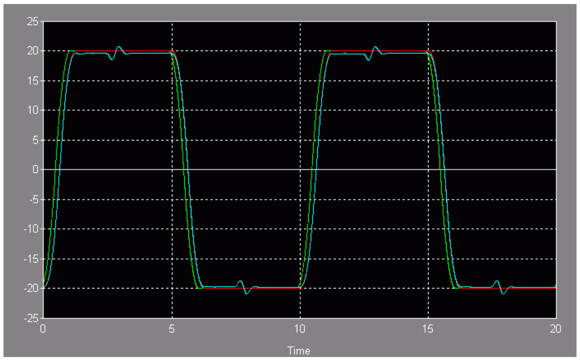


Figure 22 Flexible Joint #1 Angular Response: θ_{12}

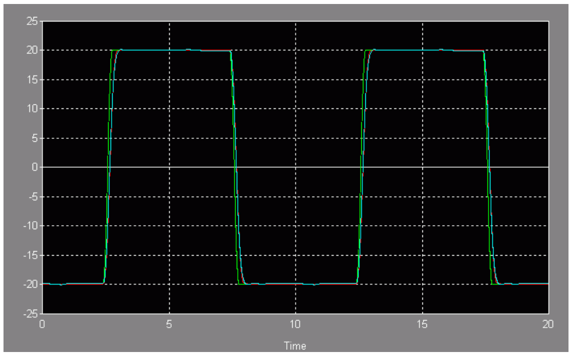


Figure 23 Drive #2 Load Shaft Angular Response: θ_{21}

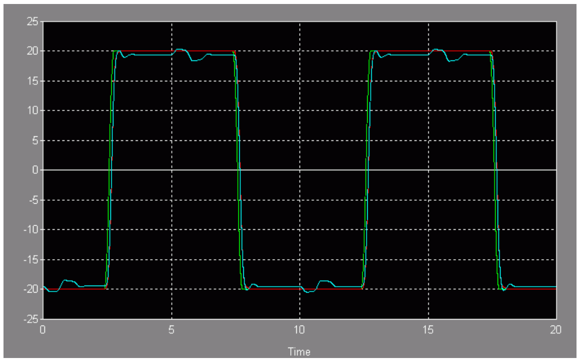


Figure 24 Flexible Joint #2 Angular Response: θ_{22}

Moreover, the square wave setpoint generation for each drive is done using the *Continuous Sigmoid* block (which is located under *QuaRC Targets* | *Sources* | *Sigmoids* library in the Simulink Library Browser) in order to limit the setpoint maximum velocity and maximum acceleration. This is done so that the physical limitations of the system are respected. It results that both command currents never go into saturation. Also the maximum flexible joint deflection is limited, as shown by the two Scopes represented in Figures 25 and 26 (obtained from the same run as previously described).

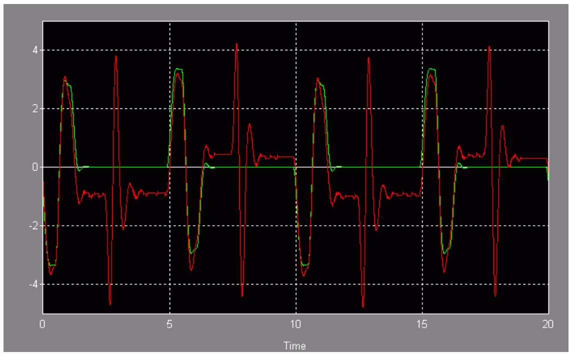


Figure 25 Flexible Joint #1 Deflection: $d\theta_1 = \theta_{12} - \theta_{11}$

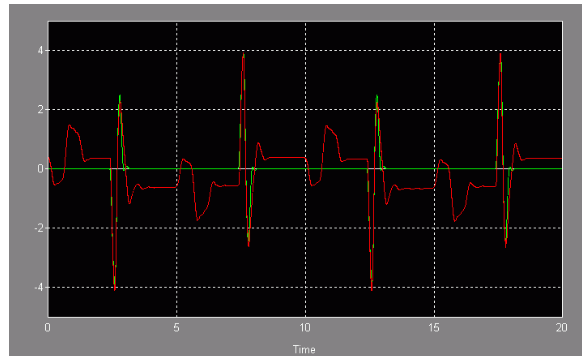


Figure 26 Flexible Joint #2 Deflection: $d\theta_2 = \theta_{22} - \theta_{21}$

In Figures 27, 28, 29, and 30, the controller switches between Full-State Feedback (FSF) and Partial-State Feedback (PSF) once every other square wave period. This is done to best demonstrate the improvement due to FSF, when compared to PSF, in terms of vibration minimization and speed of response of the first flexible joint output angle, as seen in Figures 27, 28. During this run, the second flexible joint controller tries to regulate a constant zero position. The coupling due to the first flexible joint can also be seen in Figures 29 and 30. In Full-State Feedback (FSF) mode for flexible joint #1, all four system position states are used by the control law. In Partial-State Feedback (PSF) mode, the flexible joint angle and angular velocity feedbacks are removed (i.e., multiplied by zero) and only drive #1 output shaft position is controlled. In PSF, the torsional load is actually ignored by the controller and it can then be considered as being in open-loop, oscillating at its natural frequency.

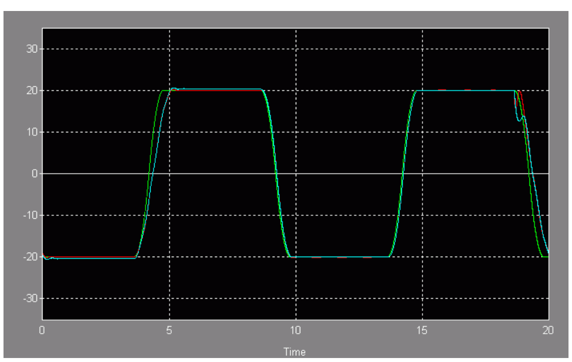


Figure 27 Drive #1 Response – FSF vs. PSF: θ_{11}

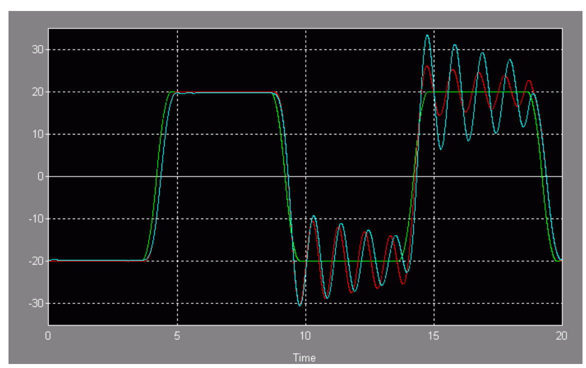


Figure 28 Flexible Joint #1 Response – FSF vs. PSF: θ_{12}

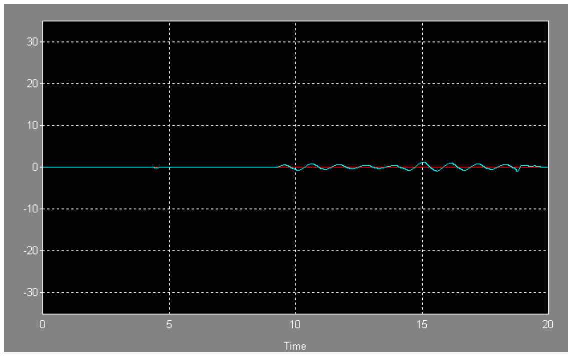


Figure 29 Drive #2 Response – FSF vs. PSF: θ_{21}

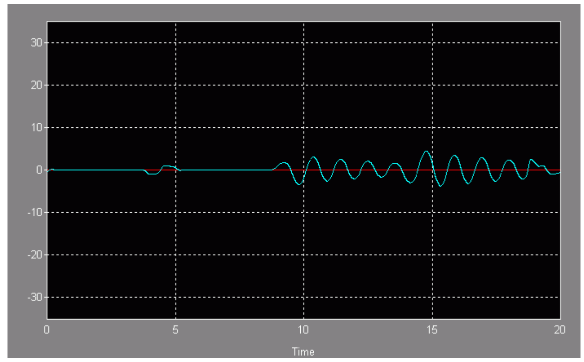


Figure 30 Flexible Joint #2 Response – FSF vs. PSF: θ_{22}

The two state-feedback controller gain vectors and the model parameters are initialized in the MATLAB workspace by running the file *setup_2DSFJ_robot.m* in the MATLAB prompt. In order to control each flexible joint output to a desired position, the LQR algorithm is used. You can modify both *q_2DSFJ_robot_QuaRC.mdl* and/or *setup_2DSFJ_robot.m* files and re-generate the corresponding real-time code using QuaRC. To compile the real-time code corresponding to the controller diagram, use the *QuaRC | Build* option from the Simulink menu bar. After successful compilation click on *QuaRC | Start* in order to start running the real-time code on the actual plant.

Moreover, the Simulink-implemented controller model comes with two position watchdogs. They would stop the controller if the first flexible joint deflection exceeds ± 25° (as set by default by the *DTH1_MAX* variable in the setup script) or if the second flexible joint goes beyond ± 25° (as set by default by the *DTH2_MAX* variable in the setup script).

Running the *setup_2DSFJ_robot.m* script can also, if the corresponding flag variables (e.g., *SYS_ANALYSIS_1*, *PLOT_RESPONSE_1*) are enabled, simulate, analyse, and plot the Two-Degree-Of-Freedom Serial Flexible Joint system responses, using the MATLAB Control System Toolbox. For example the simulated magnitude Bode response plots for the second flexible joint, in both FSF and PSF modes, are represented in Figures 31 and 32. Comparing Figure 31 with Figure 32 shows the elimination of the resonance peak of the torsional system position response (θ_{22}).

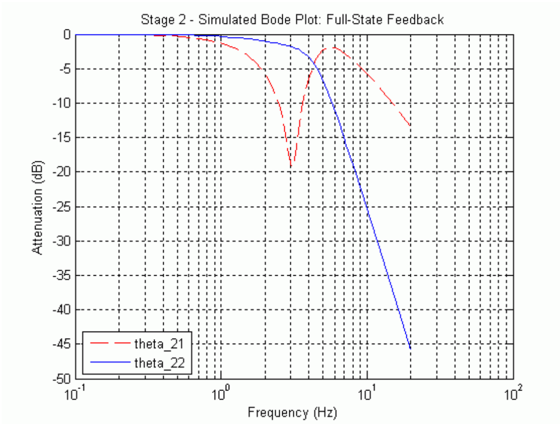


Figure 31 2nd Flexible Joint Magnitude Bode Plot: FSF

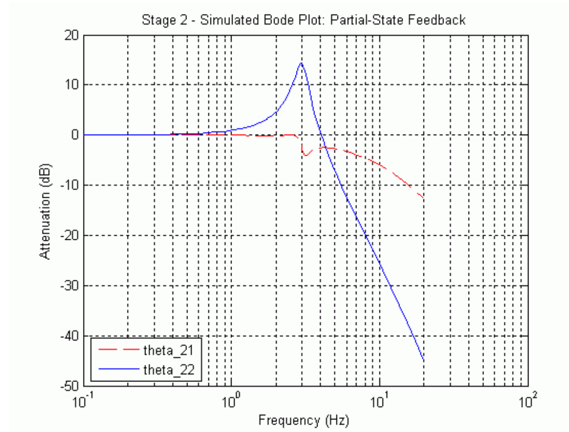


Figure 32 2nd Flexible Joint Magnitude Bode Plot: PSF

5.2.2. LQR Controller Design

A schematic of the Two-Degree-Of-Freedom Serial Flexible Joint (2DSFJ) system is represented in Figure 33. It depicts the two flexible joints connected in series and each actuated by its own drive system.

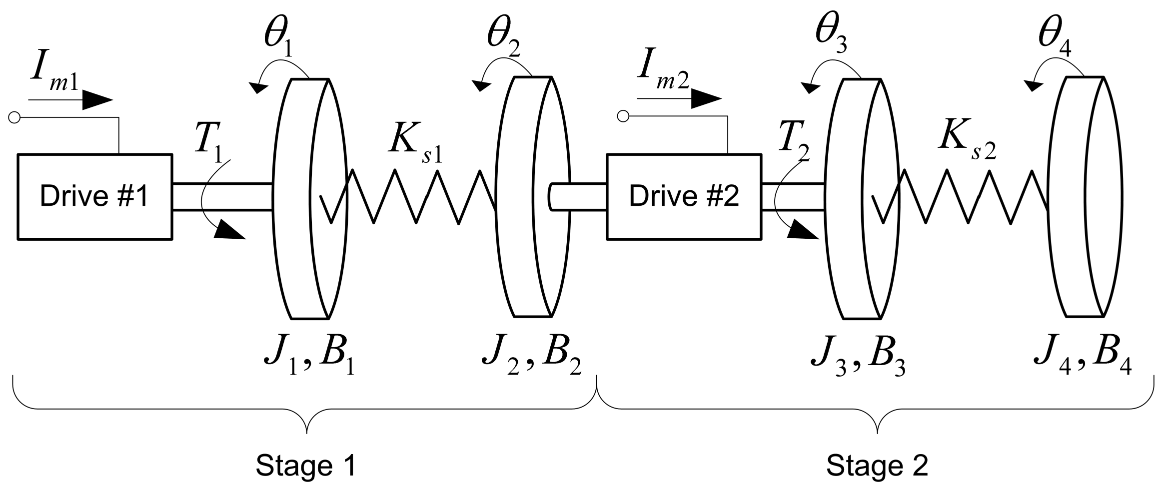


Figure 33 Schematic of the Two-Degree-Of-Freedom Serial Flexible Joint (2DSFJ) System

where K_{s1} and K_{s2} are the first and second flexible joint torsional stiffness constants, I_{m1} and I_{m2} the drive currents, J_i (for i = 1, 2, 3, 4) the intermediary load moments of inertia, and B_i (for i = 1, 2, 3, 4) the intermediary load viscous damping coefficients.

Sign Convention:

The positive direction of rotation, as illustrated in Figure 33 for all four load angles è$_i$ (for *i* = 1, 2, 3, 4) is chosen to be to CounterClockWise (CCW) when looking at the robot from top.

In the controller design procedure described hereafter, the 2DSFJ system is considered decoupled and split into two separate and independent stages: Stage 1 and Stage 2, as depicted in Figure 33. Each stage has its own LQR state-feedback control loop.

Let us first consider the stage 1 system of the 2DSFJ plant. Its schematic is represented in Figure 34.

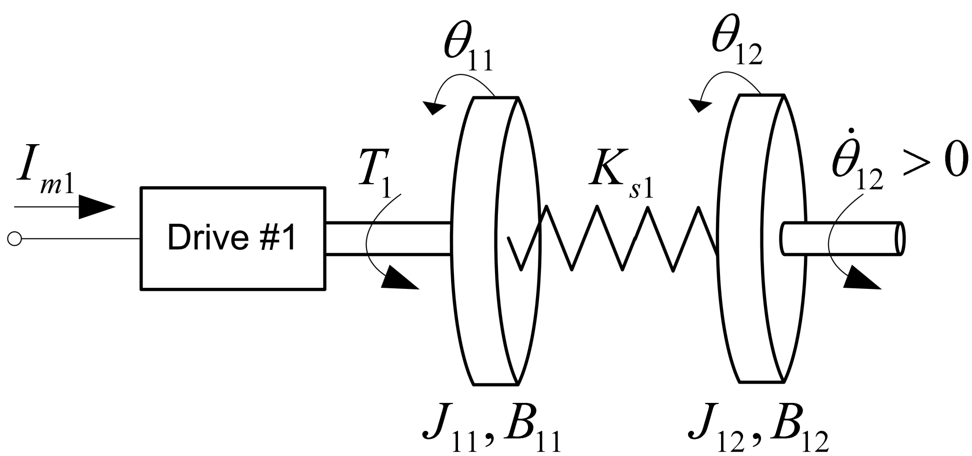


Figure 34 Schematic of the 2DSFJ Robot Stage 1 System

Table 11 provides a nomenclature of the symbols used in the 2DSFJ Stage 1 system mathematical modeling, as presented in this manual.

Symbol	***Description***	***Units***
I_{m1}	First (Shoulder) Motor Armature Current	A
K_{t1}	First (Shoulder) Drive Torque Constant	N.m/A
T_1	Torque Produced by Drive #1, at the Load Shaft	N.m
θ_{11}	First (Shoulder) Driving Shaft Absolute Angular Position	rad
$\frac{d}{dt}\theta_{11}(t)$	First (Shoulder) Driving Shaft Absolute Angular Velocity	rad/s
θ_{12}	First Rigid Link Absolute Angular Position	rad
$\frac{d}{dt}\theta_{12}(t)$	First Rigid Link Absolute Angular Velocity	rad/s
J_{11}	First Flexible Joint Actuated Transition Equivalent Moment Of Inertia	$kg.m^2$
B_{11}	First Flexible Joint Actuated Transition Equivalent Viscous Damping Coefficient	N.m.s/rad
J_{12}	First Flexible Joint Load Transition Equivalent Moment Of Inertia (Compounded With The Stage 2 System)	$kg.m^2$
B_{12}	First Flexible Joint Load Transition Equivalent Viscous Damping Coefficient (Compounded With The Stage 2 System)	N.m.s/rad
K_{s1}	First Flexible Joint Torsional Stiffness Constant	N.m/rad

Table 11 First Stage Of The 2-DOF SFJ Robot Model Nomenclature

Reference [4] details and derives the general dynamic equations of the 2DSFJ Stage 1 system. The Lagrange's method is used to obtain the dynamic model of the system. In the described modeling, the system's state vector, X_1, is chosen to include the generalized coordinates as well as their first-order time derivatives. It is defined by its transpose, as shown below:

$$X_1^T = \left[\theta_{11}(t), \theta_{12}(t), \frac{d}{dt}\theta_{11}(t), \frac{d}{dt}\theta_{12}(t)\right]$$

The system input, U_1, is the current to the first motor, that is to say:

$$U_1 = I_{m1}$$

The state-space matrices A_1 and B_1 are defined to give a dynamic representation of the 2DSFJ Stage 1 system, such that:

$$\frac{\partial}{\partial t} X_1 = A_1 X_1 + B_1 U_1$$

From the system's two equations of motion, the A_1 matrix can be determined as follows:

$$A_1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{K_{s1}}{J_{11}} & \frac{K_{s1}}{J_{11}} & -\frac{B_{11}}{J_{11}} & 0 \\ \frac{K_{s1}}{J_{12}} & -\frac{K_{s1}}{J_{12}} & 0 & -\frac{B_{12}}{J_{12}} \end{bmatrix}$$

Likewise, the transpose of the B_1 matrix characterizing the system can be seen below:

$$B_1^T = \begin{bmatrix} 0 & 0 & \frac{K_{t1}}{J_{11}} & 0 \end{bmatrix}$$

To control the stage 1 system position, a state-feedback controller is implemented according to the following feedback control law:

$$I_{m1} = -K_1 X_1$$

where K_1 is the gain vector for the stage 1 system.

The design file *setup_2DSFJ_robot.m* calculates the state-feedback gain K_1 using the LQR tuning algorithm. You may edit the file to change the system closed-loop behaviour. By default, the m-file returns the following state-feedback gains:

$$K_1 = [76.57, 81.55, 2.86, 23.02]$$

Likewise, let us now consider the stage 2 system of the 2DSFJ plant. Its schematic is represented in Figure 35.

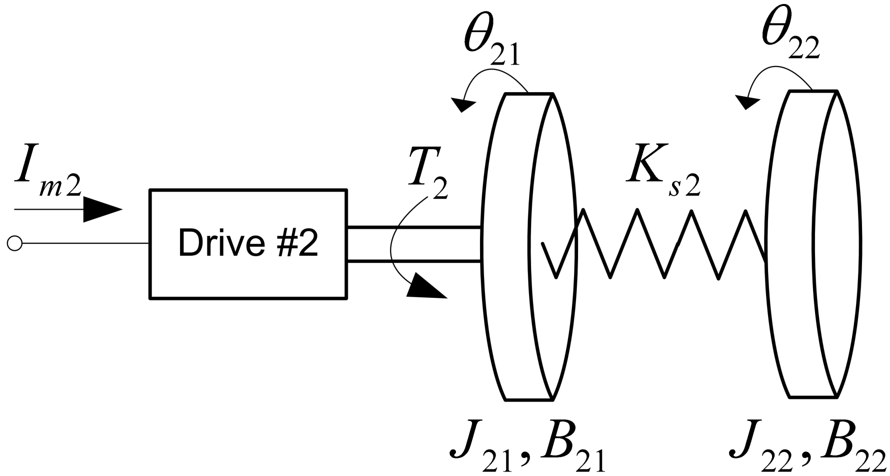


Figure 35 Schematic of the 2DSFJ Robot Stage 2 System

Table 12 provides a nomenclature of the symbols used in the 2DSFJ Stage 2 system mathematical modeling, as presented in this manual.

Symbol	***Description***	***Units***
I_{m2}	Second (Elbow) Motor Armature Current	A
K_{t2}	Second (Elbow) Drive Torque Constant	N.m/A
T_2	Torque Produced by Drive #2, at the Load Shaft	N.m
θ_{21}	Second (Elbow) Driving Shaft Angular Position Relative To Link #1	rad
$\frac{d}{dt}\theta_{21}(t)$	Second (Elbow) Driving Shaft Angular Velocity Relative To Link #1	rad/s
θ_{22}	Second Rigid Link Angular Position Relative To Link #1	rad
$\frac{d}{dt}\theta_{22}(t)$	Second Rigid Link Angular Velocity Relative To Link #1	rad/s
J_{21}	Second Flexible Joint Actuated Transition Equivalent Moment Of Inertia	$kg.m^2$
B_{21}	Second Flexible Joint Actuated Transition Equivalent Viscous Damping Coefficient	N.m.s/rad
J_{22}	Second Flexible Joint Load Transition Equivalent Moment Of Inertia	$kg.m^2$
B_{22}	Second Flexible Joint Load Transition Equivalent Viscous Damping Coefficient	N.m.s/rad
K_{s2}	Second Flexible Joint Torsional Stiffness Constant	N.m/rad

Table 12 Second Stage Of The 2-DOF SFJ Robot Model Nomenclature

Reference [5] details and derives the general dynamic equations of the 2DSFJ Stage 2 system. The Lagrange's method is used to obtain the dynamic model of the system. In the described modeling, the system's state vector, X_2, is chosen to include the generalized coordinates as well as their first-order time derivatives. It is defined by its transpose, as shown below:

$$X_2^T = \left[\theta_{21}(t), \theta_{22}(t), \frac{d}{dt}\theta_{21}(t), \frac{d}{dt}\theta_{22}(t) \right]$$

The system input, U_2, is the current to the second motor, that is to say:

$$U_2 = I_{m2}$$

The state-space matrices A_2 and B_2 are defined to give a dynamic representation of the 2DSFJ Stage 2 system, such that:

$$\frac{\partial}{\partial t} X_2 = A_2 X_2 + B_2 U_2$$

From the system's two equations of motion, the A_2 matrix can be determined as follows:

$$A_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{K_{s2}}{J_{21}} & \frac{K_{s2}}{J_{21}} & -\frac{B_{21}}{J_{21}} & 0 \\ \frac{K_{s2}}{J_{22}} & -\frac{K_{s2}}{J_{22}} & 0 & -\frac{B_{22}}{J_{22}} \end{bmatrix}$$

Likewise, the transpose of the B_2 matrix characterizing the system can be seen below:

$$B_2^T = \begin{bmatrix} 0 & 0 & \frac{K_{t2}}{J_{21}} & 0 \end{bmatrix}$$

To control the stage 2 system position, a state-feedback controller is implemented according to the following feedback control law:

$$I_{m2} = -K_2 X_2$$

where K_2 is the gain vector for the stage 2 system.

The design file *setup_2DSFJ_robot.m* calculates the state-feedback gain K_2 using the LQR tuning algorithm. You may edit the file to change the system closed-loop behaviour. By default, the m-file returns the following state-feedback gains:

$$K_2 = [47.95, -7.13, 0.67, 2.90]$$

6. References

[1] Q8 Data Acquisition System User Guide

[2] QuaRC Installation Guide

[3] QuaRC HTML MATLAB Help Pages

[4] Dynamic Equations For The First Stage Of The Serial Flexible Joint (2DSFJ) Robot – Maple Worksheet or HTML File.

[5] Dynamic Equations For The Second Stage Of The Serial Flexible Joint (2DSFJ) Robot – Maple Worksheet or HTML File.

7. Obtaining Support

Note that a support contract may be required to obtain 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 requested software version and hardware information and a description of the problem encountered. Submit the form. Be sure to include your email address and a telephone number where you can be reached. A qualified technical support person will contact you.

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