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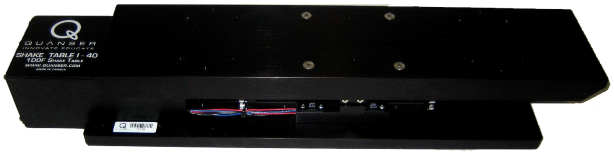
Shake Table I-40



Laboratory Guide

STI-40

Quanser Inc.
2017

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1 INTRODUCTION

This laboratory manual describes how to use the Quanser Shake Table I-40 (STI-40) system using the Shake Table I-40 Software and the Simulink® based controllers using the QUARC®. It also explains how the position control is implemented. See the Shake Table I-40 User Manual [5] for information about the hardware setup (i.e., connections) and specifications.

Topics Covered

- Calibrating the top stage to the center (i.e., mid-stroke) position.
- Running sine wave and sine sweep (i.e., chirp) signals on the Shake Table I-40 device.
- Running the supplied earthquakes on the Shake Table I-40 system (e.g., Northridge, El-Centro).
- Downloading new earthquakes from the PEER Strong Motion website.
- Transfer function model of the open-loop system, i.e., describing the dynamics between the current and stage position.
- PID-based controller used to control position of stage.
- Bandwidth curves calculated based on the imposed position, velocity, and acceleration limits of table.

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

1. See the system requirements in Section 5 for the required hardware and software.
2. Modeling and transfer function representation.
3. PID control design.
4. Basics of Simulink®.
5. Basics of QUARC®, i.e., how to build/run a Simulink model in QUARC.

2 RUNNING SHAKE TABLE I-40 SOFTWARE

The easiest way to get started with the Shake Table I-40 is to run the controllers using the Shake Table I-40 Software. This section explains how to start up and use the Shake Table I-40 Software.

2.1 Software Requirements

- QUARC® 2.5 or later, and either
- LabVIEW™ Run-Time Engine 2015 (32-bit version) or the full LabVIEW™ 2015 software (32-bit version). Run-Time Engine can be downloaded from www.ni.com.

2.2 Before Starting

The software is supplied with several QUARC® executable files for the Windows 32-bit and 64-bit Operating systems, as well as the following data acquisition systems: Q2-USB, Q8-USB, and QPIDe. You can determine the Windows operating system (32-bit or 64-bit) you have by going to Control Panel | System. The type of operating system is mentioned under *System type* (Figure 2.1).

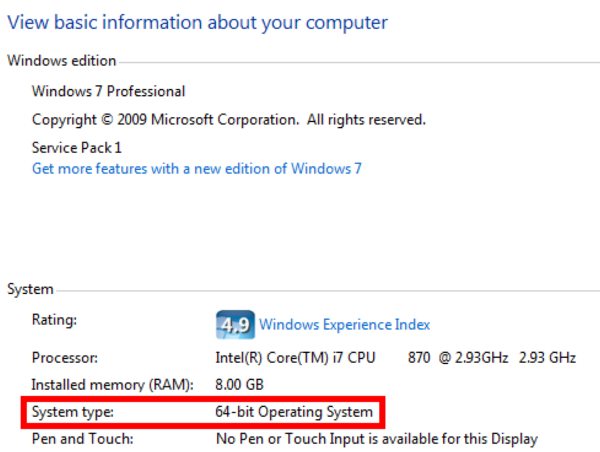


Figure 2.1: Determining type of operating system

2.3 Running Procedure

Follow these steps to run the Shake Table I-40 Software:

1. Ensure the Shake Table I-40 is setup and connected as detailed in the Shake Table I-40 User Manual [5].
2. Turn on the amplifier.
3. Start the Shake Table I-40 Software by double-clicking on *Shake Table I-40 Software.exe* file. The window similarly as shown in Figure 2.2 should load.
4. Select the type of DAQ you are using from the *Select DAQ and target model* drop down menu. This ensures that the correct QUARC® executable file associated with your operating system and DAQ is used by the control Software.

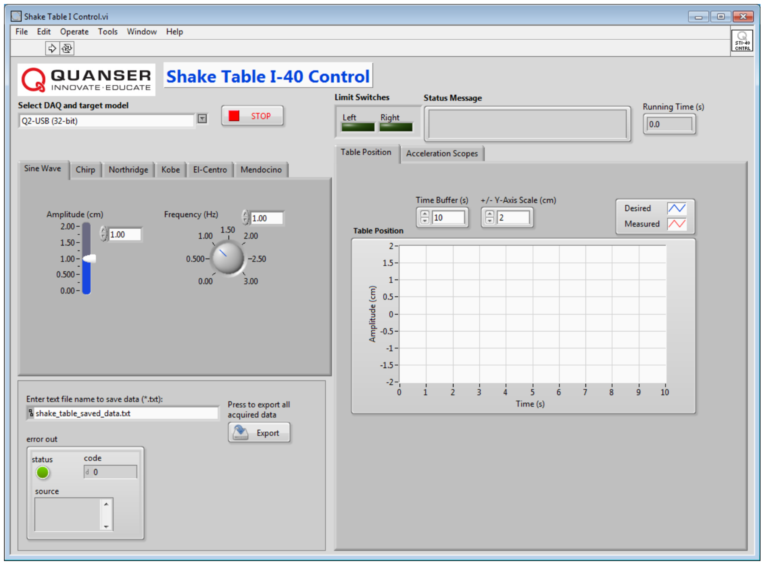


Figure 2.2: Shake Table I Software - Startup

Caution: You must select the type of DAQ prior to running the Control Software. The type of DAQ cannot be changed while the Control Software is running.

5. Click on the *Run* button to start running the software. The *Run* button is in the top-left corner (i.e. with a white arrow), as shown in Figure 2.2.

6. The table is first *calibrated* to the center (i.e. mid-stroke) position. Once this is done the table should begin tracking the commanded sine wave, as depicted in Figure 2.3. If there are operation issues, see the Shake Table I-40 User Manual. Otherwise continue with the following steps on how to give different commands.

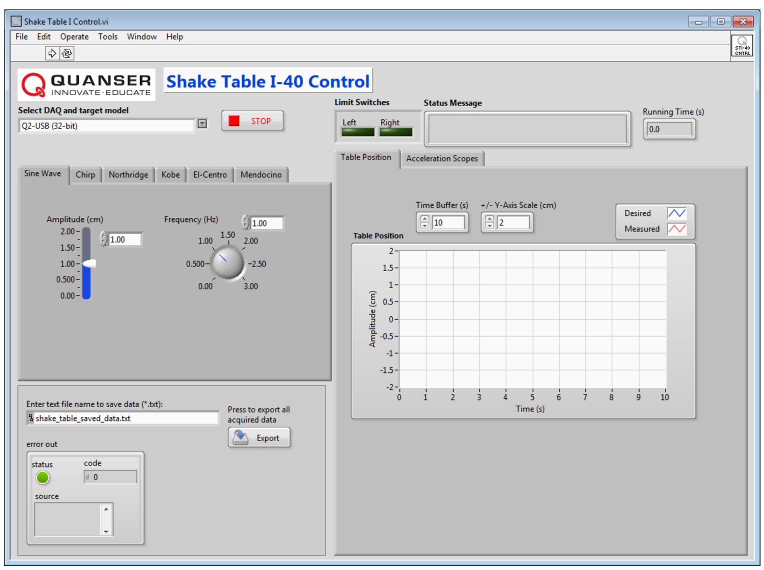


Figure 2.3: Running Shake Table I Software - calibration to center position

7. **Sine Wave**: The amplitude and frequency of the sine wave that the shake table is tracking can be changed by varying the *Amplitude (cm)* and *Frequency (Hz)* controls in the Sine Wave tab. A typical response is shown in Figure 2.4 when the amplitude and frequency of the sine wave are changed on-the-fly between 1 cm and 1.5 cm and the frequency from 0.5 to 1 Hertz. Remark that the sine wave is smoothed-out so changes in amplitude and frequency are gradual.

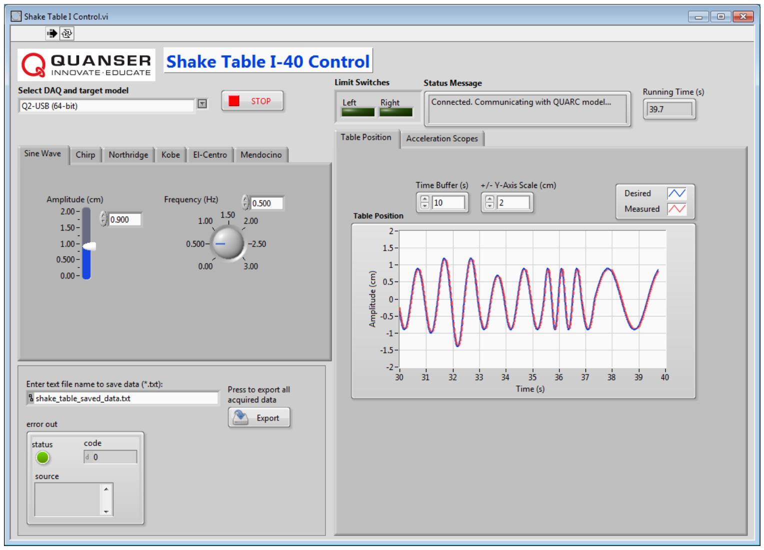


Figure 2.4: Running a sine wave

8. **Chirp**: The chirp signal is a sine wave that increases from 1.0 Hz to 10.0 Hz in 10.0 seconds and is useful, for instance, to identify the natural frequency of a structure. See the sample shown in Figure 2.5 when the amplitude is set to 0.2 centimeters. The amplitude of the sine sweep can be changed. Once the chirp signal is completed it restarts automatically.

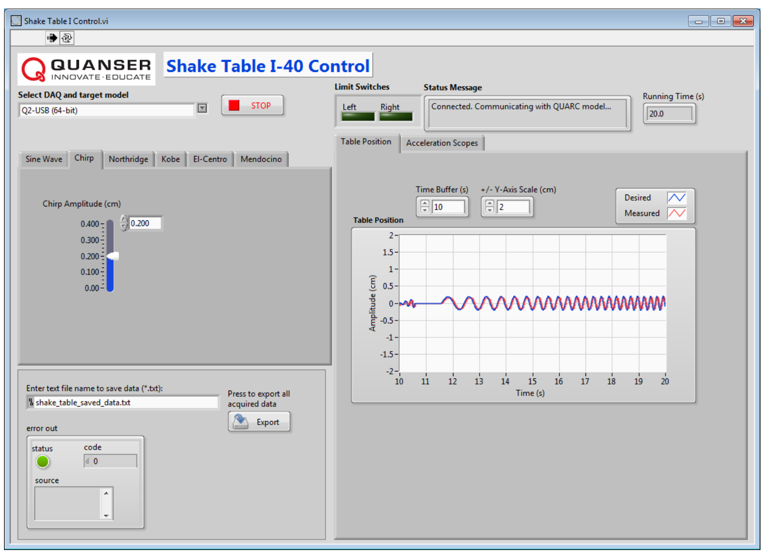


Figure 2.5: Running a chirp signal (sine sweep)

9. **Earthquake**: Four sample earthquakes are preloaded: Northridge, Kobe, El-Centro, and Mendocino. Thus when the *Northridge* tab is selected, the Northridge earthquake is replayed on the shake table, e.g. the Northridge position response is shown in Figure 2.6. The position of the tremor is scaled down but the resulting accelerations are the same as recorded in the actual earthquake. The earthquake automatically restarts when it has completed. Select the other tabs to replay that particular earthquake on the shake table.

Figure 2.6: Running the Northridge earthquake

10. **Exporting/Logging Data to file**: To export data to a command-delimited (CSV) text file (*.txt):

    (a) Click on the *Export* button shown in Figure 2.7 **before running the software**.

    (b) Enter a file name with the *.txt extension in the *Enter text file name to save data* field. The text file is saved into the same folder as the software.

    (c) When the software is stopped, the response collected while running the software will be saved to the text file set. This can be imported into other software, such as Microsoft Excel.

    (d) This includes desired and measured table position, table acceleration, and floor 1 acceleration (sensor attached to the S2 connector on the amplifier).

    (e) **Note:** Ensure that the path and file names are valid. The software overwrites any existing files. Therefore, ensure that a new file name is used each time data is saved or move the older file out of the folder.

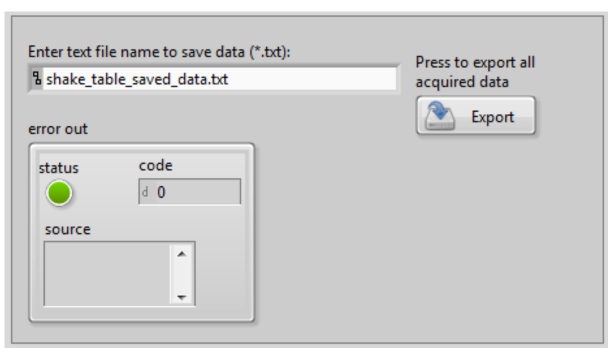


Figure 2.7: Exporting data to Excel

11. Click on the *Stop* button to stop running the software.

3 RUNNING QUARC CONTROLLERS

As detailed in Section 2, the easiest way to get started is to run the Shake Table I-40 Software. However, for more flexibility users can run the same controllers (and potentially design their own) using QUARC®. The procedures for this are explained in this section.

3.1 Calibration

Before running any of the experiments the stage of the Shake Table I-40 should be in the center position, which is in the middle of the left and right limit switches.

Follow this procedure to calibrate the stage:

1. Follow the steps given in Section 5 for the q_STI_40_cal Simulink diagram, shown in Figure 3.1.

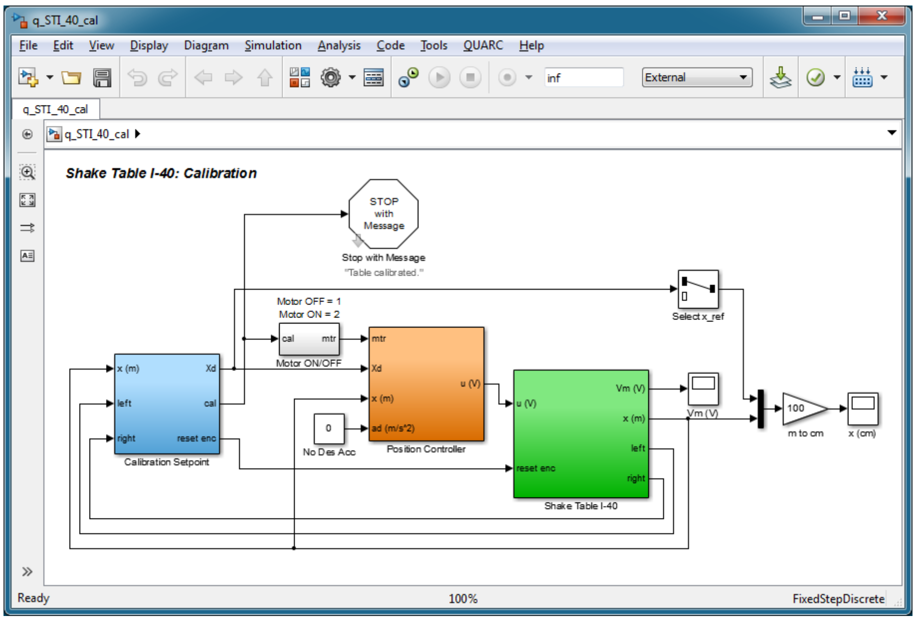


Figure 3.1: Simulink diagram used with QUARC to calibrate STI-40 device

2. When the controller is ran, the stage should begin moving. If the *Left* or *Right* limit sensor was already triggered, then the stage begins to immediately move towards the center. If no limit switch was initially triggered, then the stage will begins to move towards *Right* limit sensor. Once the *Right* limit sensor is hit, the stage reverses its direction and begins moving towards the mid-stroke position. The stage stops moving when it is in the middle or center position (between the two limit switches) and the message shown in Figure 3.2 is prompted.

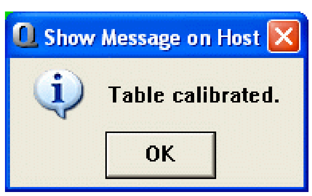


Figure 3.2: Calibration complete message

Running from Windows: Once built, the *q_STI_40_cal* QUARC controller can be ran from Windows Explorer by double-clicking on *q_STI_40_cal-rt.windows*.

3.2 Sine Wave

This q_STI_40_sine controller commands a sine wave to the Shake Table I-40 for the stage to track. The q_STI_40_sine Simulink diagram is shown in Figure 3.3. The user can specify the amplitude and frequency of the sine wave on-the-fly and read corresponding position and acceleration measurements.

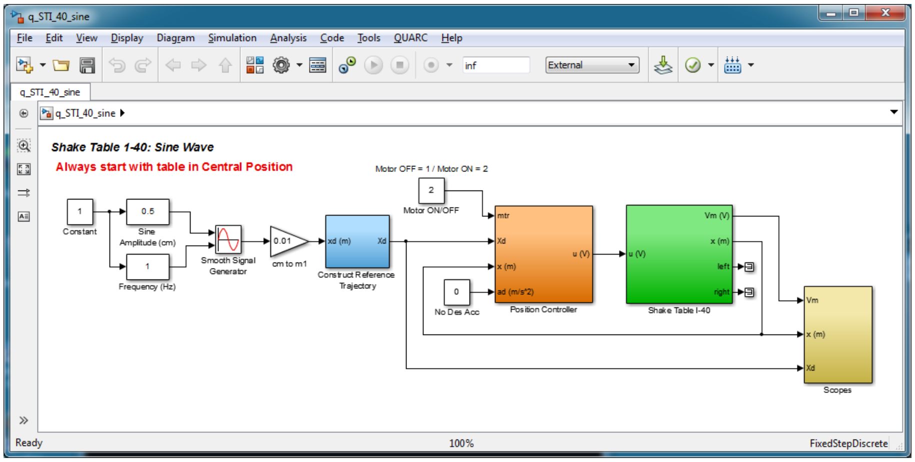
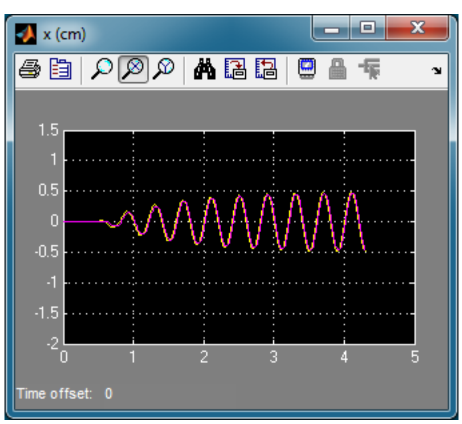


Figure 3.3: Simulink model used to command a sine wave to the Shake Table I-40 using QUARC.

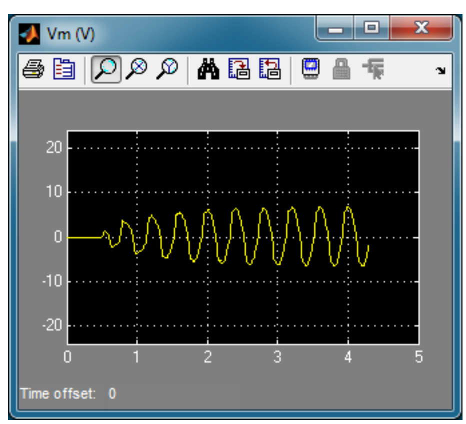
Caution: **Make sure the top stage is at the center position before running this experiment!** If its not in the middle, then go through the calibration procedure in Section 3.1.

1. Run setup_STI_40.m in Matlab.
2. Open the q_STI_40_sine.mdl Simulink model open, shown in Figure 3.3. For more information on configuring q_STI_40_sine, see Section 5.4.
3. Build the QUARC controller.
4. Run the QUARC controller. The table should begin tracking the sine wave set in the controller.

   Caution: **PRESS DOWN on the RED BUTTON of the E-Stop switch to stop the table from running.** This deactivates the amplifier and cuts off the DC motor power.
5. Open the *x (m)* scope shown in Figure 3.10. The yellow trace displayed in this plot is the commanded or desired position and the purple plot line is the measured stage position. The measured position should match the desired trace very closely.



(a) Position



(b) Motor Voltage

Figure 3.4: Sine wave starting

6. To change the sine wave, vary the *Amplitude (cm)* and *Frequency (Hz)* slider gain blocks in q_STI_40_sine.
7. Click on Stop button in the Simulink diagram tool bar to stop running the controller.
8. Shut off the power amplifier.

3.3 Sine Sweep

The sine sweep, also known as a chirp signal, is a sine wave with a fixed amplitude that increases in frequency as time progresses. In this experiment, the stage of the Shake Table I-40 tracks a sine sweep that increases from 1 to 5 Hz in 8 seconds. This is done using Simulink diagram shown in Figure 3.5, using QUARC®. By default the sine amplitude is 3 mm. The initial and final frequency of the sweep along with the amplitude can all be changed in the Simulink diagram. Typically the sine sweep is used to find the frequency response of a structure that is mounted on the table stage.

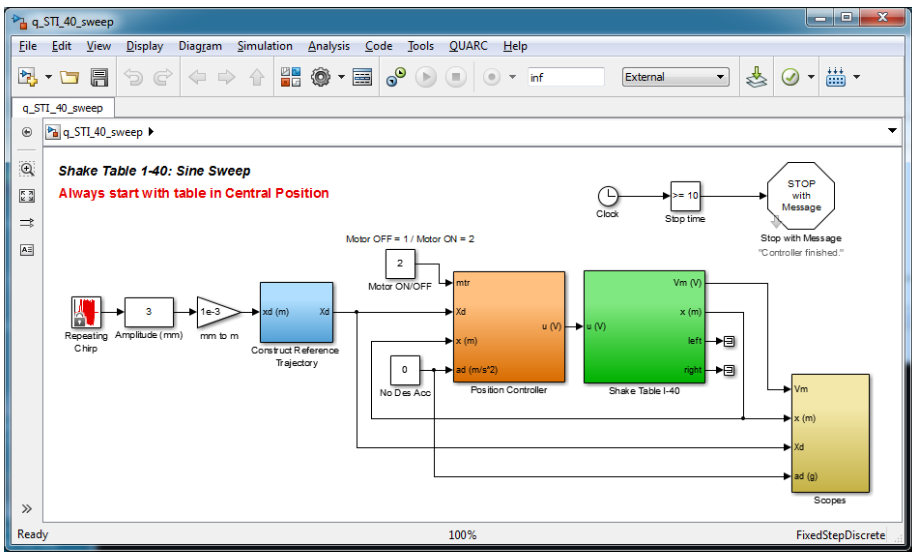
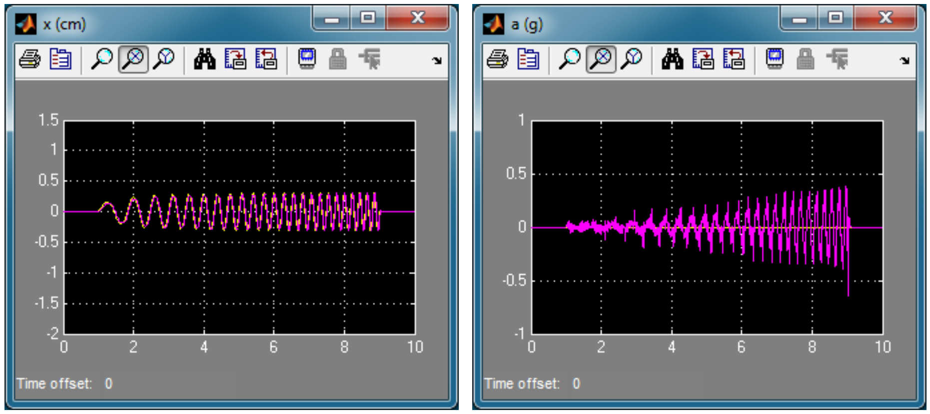


Figure 3.5: Simulink model used to command a sine sweep to the Shake Table I-40 using QUARC.

Caution: Make sure the top stage is at the center position before running this experiment! If its not in the middle, then go through the calibration procedure in Section 3.1.

1. Run setup_STI_40.m in Matlab.
2. Open the q_STI_40_sweep.mdl Simulink model, shown in Figure 3.5. For more information on configuring q_STI_40_sweep, see Section 5.5.
3. Build the QUARC controller.
4. Run the QUARC controller. The top stage should begin tracking an increasingly fast sine wave.

   Caution: PRESS DOWN on the RED BUTTON of the E-Stop switch to stop the table from running. This deactivates the amplifier and cuts off the DC motor power.
5. Open the *x (m)* and *a (g)* scopes shown in Figure 3.10. The yellow trace displayed in *x (m)* is the commanded or desired position and the purple plot line is the measured stage position. The measured position should match the desired trace very closely. The *a (g)* scope displays the acceleration calculated by the *acceleration estimator* in gravitational units, g. Typical position and acceleration responses are shown in Figure 3.6.
6. By default, the controller is set to last 10 seconds and is automatically stopped once the duration is reached. You can change the duration of the controller by setting the *Stop Time* source block.



(a) Position (b) Acceleration

Figure 3.6: STI-40 stage position and acceleration when performing sine sweep.

7. To change the sweep amplitude, change the value in the *Amplitude (mm)* slider gain block in the q_STI_40_sweep Simulink diagram. You can also change the target time, initial frequency, and target frequency of the sweep signal in the *Repeating Chirp* block. **Important**: Make sure when setting the new values that the amplitude is not set too large. Refer to the bandwidth plots in Section 4.3 for a guideline but start conservative with the amplitude.
8. Click on the *Stop* button in the Simulink diagram tool bar to stop running the controller.
9. Shut off the power amplifier.

3.4 Earthquake

The q_STI_40_quake Simulink diagram shown in Figure 3.7 can be used to replay earthquake on the Shake Table I-40 system using QUARC®. Recorded earthquake data, i.e., data collected when an actual earthquake occurred, can be scaled down and ran on the shake table. Four historical earthquakes have been supplied for the user: Northridge, Kobe, El-Centro, and Mendocino. The user can also specify and create a pre-defined compound sine wave trajectory.

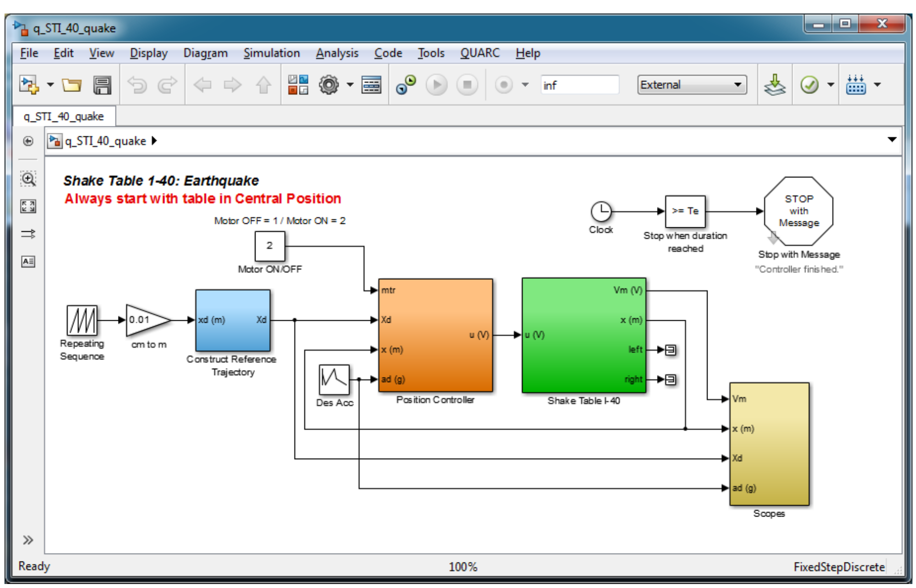
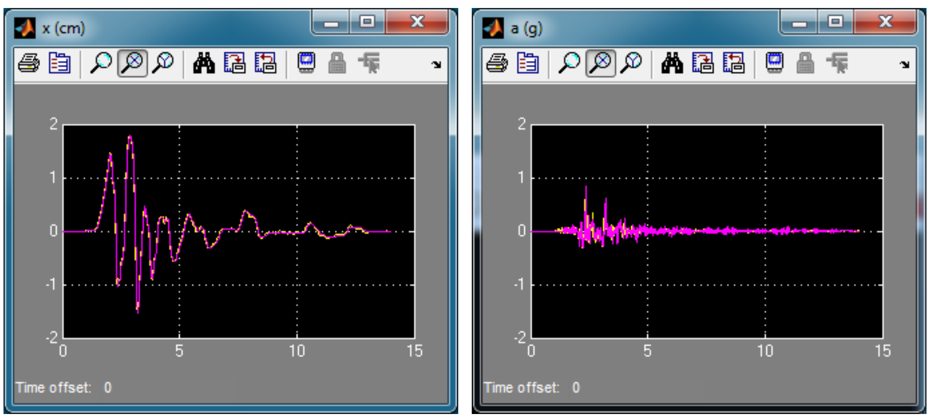


Figure 3.7: Simulink model used to command earthquake to the Shake Table I-40 using QUARC

Caution: **Make sure the top stage is at the center position before running this experiment!** If its not in the middle, then go through the calibration procedure in Section 3.1.

1. Run setup_STI_40.m in Matlab.
2. Open the q_STI_40_quake.mdl Simulink model, shown in Figure 3.7. For more information on configuring q_STI_40_quake, see Section 5.6.
3. The command position (and acceleration) must first be loaded into the Matlab environment. **Run either the make_sine.m or make_quake.m scripts**. For more information about using these scripts to generate a sine wave or earthquake, see sections 5.8 and 5.9.
4. Build the QUARC controller.
5. Run the QUARC controller. The top stage should begin tracking the loaded earthquake (or sine wave).

   Caution: **PRESS DOWN on the RED BUTTON of the E-Stop switch to stop the table from running.** This deactivates the amplifier and cuts off the DC motor power.
6. Typical position and acceleration responses when running the Northridge earthquake is shown in Figure 3.8.



(a) Position (b) Acceleration

Figure 3.8: STI-40 stage position and acceleration when running Northridge earthquake.

7. The controller stops by itself when the duration of the earthquake (or sine) is reached.
8. Power off the power amplifier if no more experiments will be conducted.
9. To plot the FFT of the position or acceleration, run *fft_eval_pos.m* or *fft_eval_acc.m*. See Section 3.6 for instructions.

For instructions on how to download new earthquakes, see Section 4.4.

3.5 Active Mass Damper

The *q_STI_40_AMD* Simulink diagram commands a sine wave to the Shake Table I-40 for the stage to track and implements the AMD-1 controller. The Simulink diagram is shown in Figure 3.9. The user can specify the amplitude and frequency of the sine wave on-the-fly and read corresponding position and acceleration measurements.

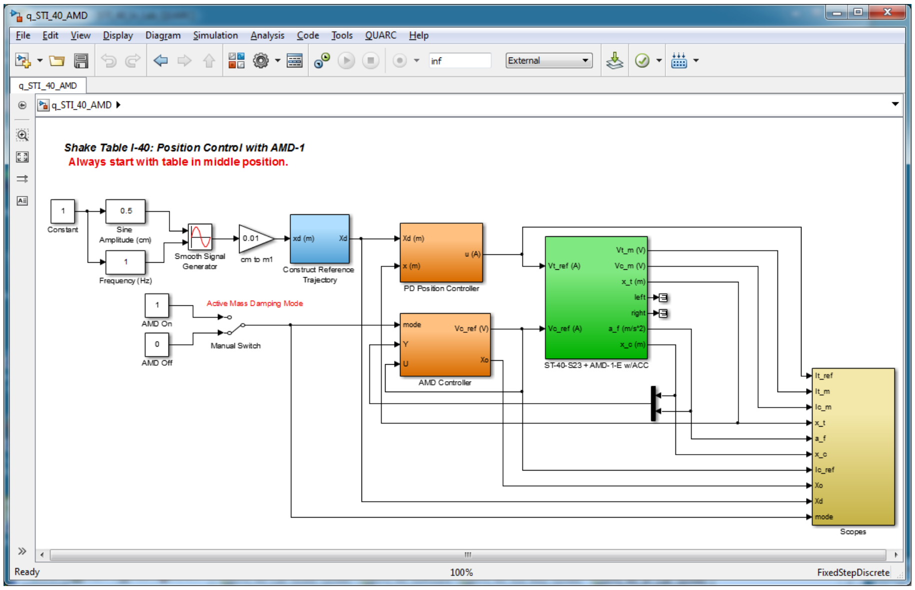
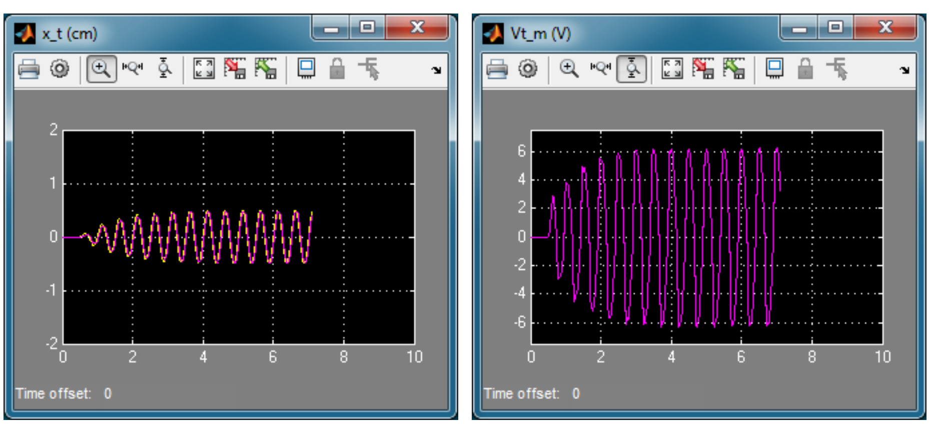


Figure 3.9: Simulink model used with QUARC to run the Shake Table I-40 and AMD-1 controller

1. Run setup_STI_40.m in Matlab.
2. Open the q_STI_40_sine.mdl Simulink model open, shown in Figure 3.9. For more information on configuring q_STI_40_sine, see Section 5.7.
3. Manually move the cart on the AMD-1 structure to the middle of the track.
4. Turn off the active mass damping by setting the Manual Switch block to the *AMD Off* position.
5. Build the QUARC controller.
6. Run the QUARC controller. The table should begin tracking the sine wave set in the controller.Because the AMD is off, the cart maintains its initial position (i.e., no control being performed). ⚠ **Caution: PRESS DOWN on the RED BUTTON of the E-Stop switch to stop the table from running.** This deactivates the amplifier and cuts off the DC motor power.
7. The *x_t (cm)* and *Vt_m (V)* scopes, similarly as in Section 3.2, displays the commanded and measured table positions and the motor input voltage.

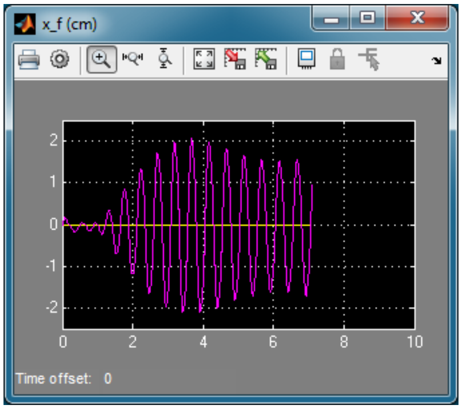


(a) Table Position (b) Table Motor Voltage

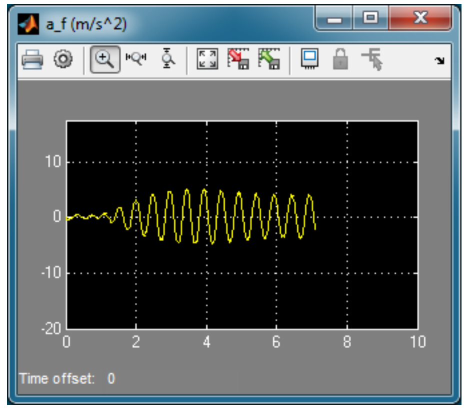
Figure 3.10: Sine wave starting

8. To change the sine wave, vary the *Amplitude (cm)* and *Frequency (Hz)* control slider and knob.

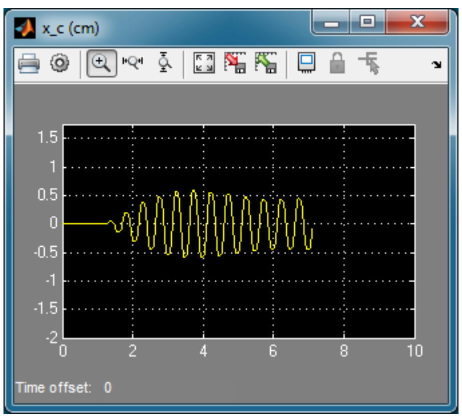
9. The response when the sine wave amplitude is set to 0.5 cm and the frequency is slowly increased to 2 Hz is depicted in Figure 3.11. The *x_f (cm)* scope displays the estimated AMD-1 structure deflection, the *x_c (cm)* scope shows the measured cart position, and the *Vt_c (V)* scope display the applied AMD-1 cart motor voltage from the control. The floor acceleration is shown in *a_f (g)* as well. Notice how the estimated building deflection (in red) goes up to around $\pm$1.5 cm.



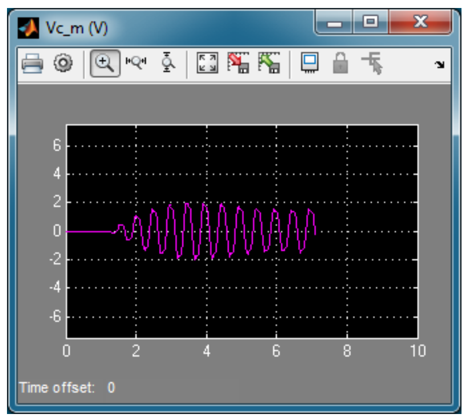
(a) Floor Deflection Estimation



(b) Floor Acceleration



(c) Cart Position

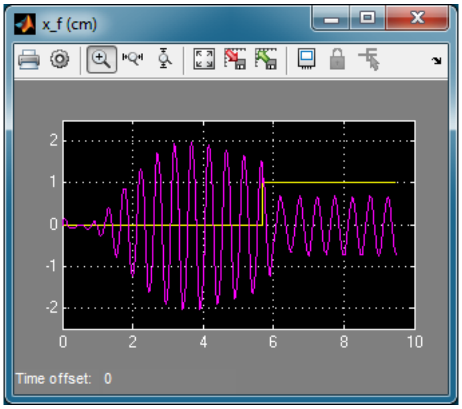


(d) Cart Motor Voltage

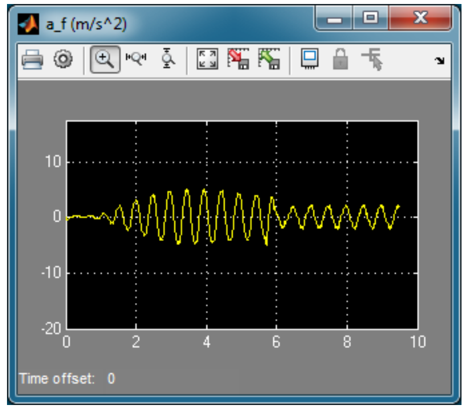
Figure 3.11: AMD scopes when running sine wave and without active mass damping

10. Press on the *AMD ON/OFF* button to turn the active mass damping on. The cart should now start moving to minimize the motions of the building. Visually, you should notice that the building does not sway as much.

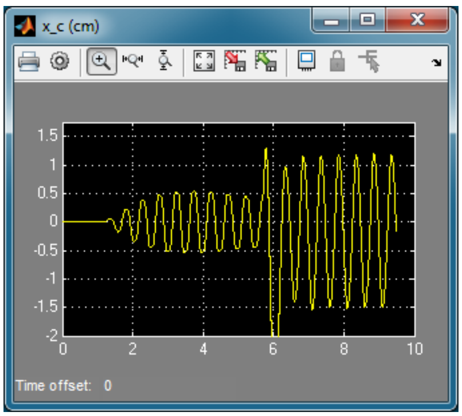
11. Sample responses when the AMD-1 is turned on are shown in Figure 3.12. When the AMD is activated, just before the 6 second mark, the cart position (blue) increases to compensate for the motions of the structure. The floor deflection then reduces from $\pm$1.4 cm to about $\pm$0.7 cm and the floor acceleration drops from $\pm$5 m/s^2 down to $\pm$2.5 m/s^2.



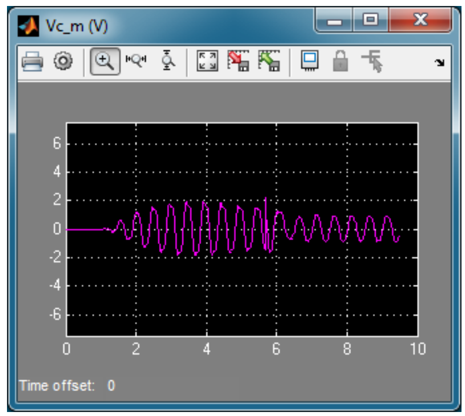
(a) Floor Deflection Estimation



(b) Floor Acceleration



(c) Cart Position



(d) Cart Motor Voltage

Figure 3.12: AMD scopes when turning ON the active mass damping

12. The *Kamd* variable is the state-feedback gain used in the AMD-1 control and the *Gamd* is the gain used in the observer to estimate the floor deflection. To design new gains, you can use the *setup_amd1.m* script.
13. Click on *Stop* button to stop running the controller.
14. Shut off the power amplifier.

3.6 FFT Analysis

This section shows how to evaluate the **power spectrum** of the commanded and measured shake table position and acceleration signals using the *fft_eval_pos.m* and *fft_eval_acc.m* scripts. Given a time-based signal $g(t)$, the power spectrum shown on the plot generated is given by $|G(\omega)|$, where $G(\omega)$ is the Fast-Fourier Transform (FFT). The FFT, $G(\omega)$, is computed using the Matlab® fft command. See the power_spectrum.m script for further details.

1. Run an earthquake or sine wave using the q_STI_40_quake QUARC controller, as described in Section 3.4. After q_STI_40_quake is ran, the commanded and measured position and acceleration data are automatically saved to the Matlab data files *data_x.mat* and *data_a.mat*.
2. To produce the $|X(\omega)|$ position power spectrum similar to Figure 3.13, run *fft_eval_pos.m*. The desired or commanded position is the blue trace and the measured position (from the encoder) is the red plot line.

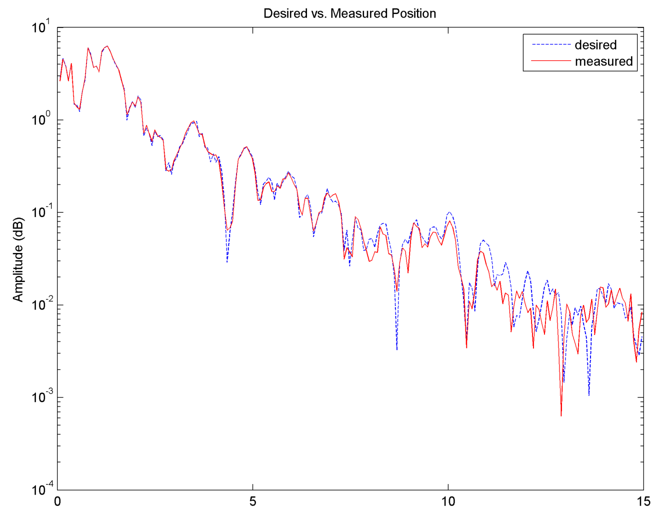


Figure 3.13: FFT of desired and measured position.

3. To produce the acceleration power spectrum, $A(\omega)$, similar to Figure 3.14, run *fft_eval_acc.m*. The blue and red traces are the desired and measured accelerations, respectively.

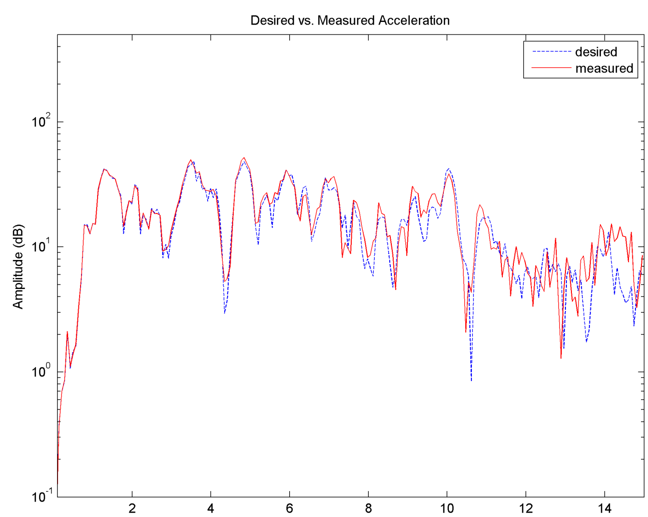


Figure 3.14: FFT of desired and measured acceleration.

4. In both the *fft_eval_pos.m* and *fft_eval_acc.m* scripts, you can adjust the frequency range by adjusting the *f_min* and *f_max* variables:

```
% min/max frequencies for plotting (Hz)
f_min = .1;
f_max = 15;
```

4 BACKGROUND

4.1 Modeling

The Shake Table I-40 model can be represented by the transfer function

$$X(s) = \frac{1}{K_f\, s^2}\, I_m(s) \tag{4.1}$$

where $X(s) = \mathcal{L}[x(t)]$ is the Laplace of the stage position, $I_m(s)$ is the Laplace of the applied motor current, and K_f is the model gain. The model gain is given by

$$K_f = \frac{M_t P_b}{K_t} \tag{4.2}$$

where M_t is the total mass being moved by the motor (i.e., both pre-load and payload), P_b is the pitch of the lead-screw, and K_t is the current-torque of the motor. The current applied is based on the voltage and is defined

$$I_m(s) = \frac{V_m(s) - K_m s \Theta(s)}{R_m}. \tag{4.3}$$

The Laplace of the applied voltage is $V_m(s)$, the motor back-emf parameter is K_m, the motor resistance R_m, and the Laplace of the lead-screw angle is denoted $\Theta(s)$. The stage moves by P_b per lead-screw revolution, or 2π radians. Therefore the lead-screw angle relates to the linear position with the relationship:

$$\theta = \frac{2\pi x}{P_b}.$$

Applying this to Equation 4.3 and inserting that into Equation 4.1, we obtain the model based on the voltage

$$X(s) = \frac{P_b}{K_f P_b R_m s^2 + 2\pi K_m s} V_m(s)$$

4.2 Position Controller Design

This section describes the PID-based control that is used to control the Shake Table I-40 stage position. The proportional-derivative and feed-forward (PD+FF) control used to regulate its position has following structure

$$v_m(t) = k_p\,(x_d(t) - x(t)) + k_d\,(b_{sd}\dot{x}_d(t) - \dot{x}(t)) + K_f \ddot{x}(t) \tag{4.4}$$

where k_p is the proportional control gain, k_d is the derivative control gain, K_f is the feed-forward gain (i.e., model gain defined in Equation 4.2), b_{sd} is the set-point velocity weight, $x_d(t)$ is the setpoint or reference position, $x(t)$ is the measured stage position, and $i_m(t)$ is the applied motor current. The block diagram of the control is given in Figure 4.1.

To find the closed-loop transfer function, $X(s)/X_d(s)$, for the position control of the STI-40, first take the Laplace transform of the controller given in Equation 4.4. Ignoring the feed-forward element (i.e., $K_f = 0$), we obtain

$$V_m(s) = k_p\,(X_d(s) - X(s)) + k_d s\,(b_{sd} X_d(s) - X(s))\,. \tag{4.5}$$

Substituting the plant model transfer function given in 4.1 into the control above and solving for $X(s)/X_d(s)$ gives the closed-loop transfer function

$$\frac{X(s)}{X_d(s)} = \frac{k_p + b_{sd} k_d s}{K_f P_b R_m \left(s^2 + \frac{2K_m\pi + P_b k_d}{K_f} s + \frac{k_p}{K_f R_m}\right)} \tag{4.6}$$

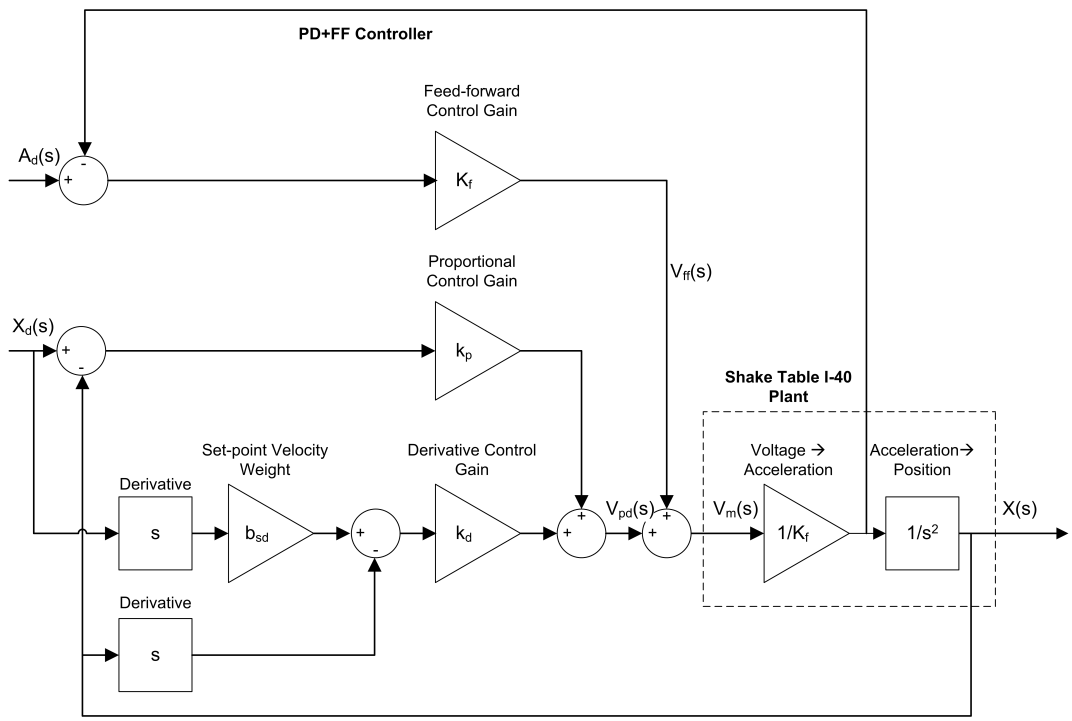


Figure 4.1: Block diagram of Shake Table I-40 position control

The closed-loop equation matches the *standard second-order* system

$$\frac{X(s)}{X_d(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\,\omega_n\,s + \omega_n^2} \tag{4.7}$$

where ω_n is the natural frequency and ζ is the damping ratio. To match this equation, we need the following PD gains

$$k_p = K_f R_m \omega_n^2$$

and

$$k_d = 2\frac{\zeta\omega_n K_f P_b R_m - K_m \pi}{P_b}.$$

By default, to obtain a peak time of 0.04 sec and a percent oveshoot of 5 %, the desired natural frequency and damping ratio closed-loop control is: $\omega_n = 2\pi \times 17.27 = 108.5$ rad/s (17.3 Hz), and $\zeta = 0.69$. When no load is added, the total moving mass of the table equals $M_t = 2.62$ kg (i.e., the pre-load mass). This results in the model gain $K_f = 0.2854$ A/(m/s^2). Using the above PD gain equations, we obtain the following control gains:

$$k_p = 4874 \text{ V/m}$$

and

$$k_d = 4.387 \text{ V-s/m}.$$

Caution: These are the default PD control gains that are used in the Shake Table I-40 software controller and **should NOT be tuned by the user** unless it is necessary for application-specific reasons.

Computing Velocity and Acceleration

In the software control, direct derivatives of the stage position are not taken to avoid noisy signals. The following second-order filter is used to find the stage velocity

$$\frac{V_x(s)}{X(s)} = \frac{\omega_d^2 s}{s^2 + 2\zeta_d\omega_d s + \omega_d^2}$$

where ω_d is the cutoff frequency and ζ_d is the damping ratio.

The acceleration of the stage that is computed from the measured position, and used in the feed-forward control shown in Figure 4.1, is calculated using the transfer function

$$\frac{A_x(s)}{X(s)} = \frac{\omega_f^2 s^2}{s^2 + 2\zeta_f \omega_f s + \omega_f^2}$$

where ω_f and ζ_f are the cutoff frequency and damping ratio. Note that the acceleration of the stage is also be computed using an observer.

4.3 Bandwidth Curves

The bandwidth curve shown in the top plot of Figure 4.2 shows the maximum amplitude of sine wave that the table can track for a certain frequency. This plot takes the position, velocity, and acceleration limits of the Shake Table I-40 system into account. The dash-dot blue line is the mechanical position limit of stage, the red line is the limit due to velocity, the green line is the limit due to acceleration, and the black line is the combined limit.

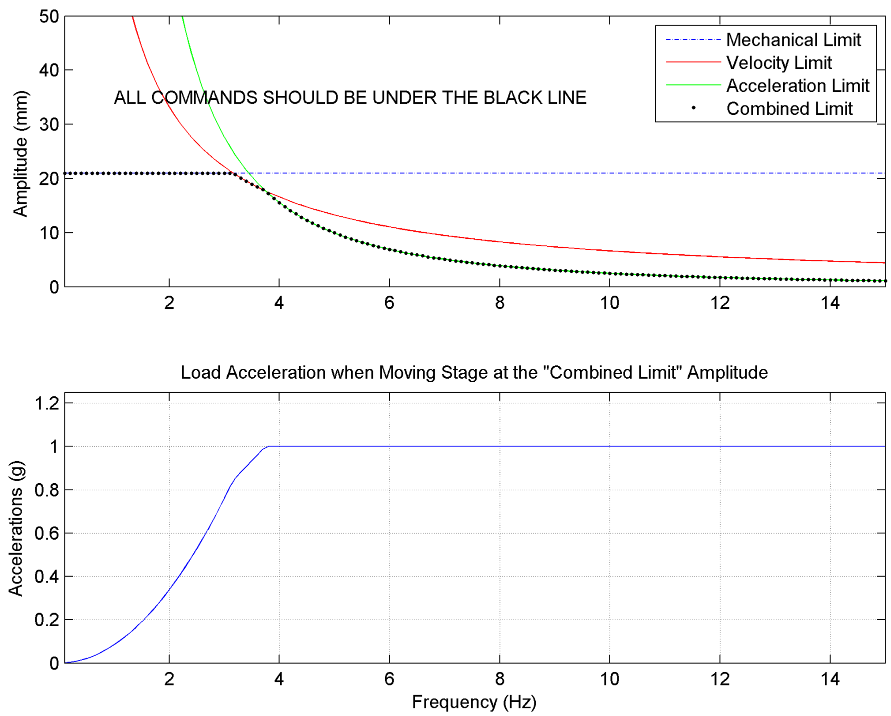


Figure 4.2: Shake Table I-40 bandwidth curve with 0 kg load

Low frequency commands up to the 3.1 Hz are limited due to the table travel. When in the 3.1-3.7 Hz range, the amplitude is constrained by the velocity limitations of the table. For higher frequencies, the command is constrained by the imposed acceleration limitation of the Shake Table I-40. **All sine commands to the table should fall under the black line**. For instance, when tracking a sine wave with a frequency of 8 Hz the user should not command an amplitude that exceeds 4 mm. The bottom plot shows the acceleration of the load when the stage is tracking a sine wave at varying frequencies with an amplitude specified by the combined limit. For example, when running a sine wave at 4 Hz with an amplitude 15.4 mm, the load would reach accelerations of 1.0 g.

Consider the desired sine wave position (i.e., setpoint)

$$x_d = A_d \sin 2\pi f t$$

where A_d is the amplitude, f is the frequency, and t is continuous time. The velocity and acceleration of the desired position are

$$\dot{x}_d = 2\pi f A_d \cos 2\pi f t$$

and

$$\ddot{x}_d = -4\pi^2 f^2 A_d \sin 2\pi f t.$$

The maximum sine wave amplitude that the table stage can track given a certain frequency depends the following constraints: the maximum stroke of the table, the maximum stage velocity, and the maximum acceleration.

Position Limit

When starting at the center position, the stage is mechanically limited to its stroke of $\pm$ 21 mm,

$$x_{max} = 2.1 \text{ cm}.$$

Velocity Limit

Given the back-emf parameter of the shake table motor, K_m, and the maximum output voltage of the amplifier, $V_{amp,max}$, the maximum angular rate of the Shake Table I-40 motor equals

$$\Omega_{max} = \frac{V_{amp,max}}{K_m}$$

The linear velocity of the stage is therefore

$$v_{max} = \frac{\Omega_{max} P_b}{2\pi} \tag{4.8}$$

where P_b is the lead-screw pitch. Using the STI-40 parameters given in the Shake Table I-40 User Manual ([5]) and the maximum voltage of the amplifier $V_{amp,max} = 24$ V (see [4] for more details), the maximum velocity is

$$v_{max} = 0.42 \text{ m/s}$$

Acceleration Limit

The maximum force that can be delivered is

$$F_{max} = \frac{K_t I_{max}}{P_b}$$

where I_{max} is the maximum peak current of the power amplifier and K_t is the current-torque constant of the motor. The maximum acceleration depends on the load mass, M_t, and the rated acceleration of the table of 1.0 g and is given by

$$a_{max} = \min\left\{\frac{F_{max}}{M_t}, 9.81\right\}. \tag{4.9}$$

Using the STI-40 parameters given in the Shake Table I-40 User Manual ([5]) and the maximum peak current of the amplifier $I_{max} = 4$ A (see [4] for more details), the maximum acceleration *with no load added* is

$$a_{max} = \min\left\{\frac{36.7}{2.62}, 9.81\right\} = 9.81 \text{ m/s}^2 = 1.0 \text{ g}.$$

Under a 0 kg load, the stage can be accelerated at 1.42 g (i.e., $36.7/2.62 = 14.0$ m/s^2). However, the maximum acceleration is limited (in this case) by the rated limit of 1.0 g (i.e., 9.81 m/s^2).

Maximum Sine Wave Amplitude

The position, velocity, and acceleration limit curves are shown in the top plot of Figure 4.2 are given by

$$\begin{aligned} A_{max,pos} &= x_{max} \\ A_{max,vel} &= \frac{v_{max}}{2\pi f} \\ A_{max,acc} &= \frac{a_{max}}{4\pi^2 f^2} \end{aligned}$$

The black line in Figure 4.2 is the combined limit of these curves and is the maximum setpoint amplitude

$$A_{max} = \min\left\{x_{max}, \frac{v_{max}}{2\pi f}, \frac{a_{max}}{4\pi^2 f^2}\right\}$$

Load Acceleration

The bottom plot displays the acceleration of the load when the stage is tracking a sine wave at various frequencies at the amplitude specified by the combined limit. Given the amplitude of the sine wave, A_{max}, at a certain frequency, f, the load acceleration is given by

$$a_{max} = 4\pi^2 f^2 A_{max}.$$

4.4 Downloading New Earthquakes

There are a variety of resources on the Internet where real earthquake data can be downloaded. This section explains how to download and use the records from the Pacific Earthquake Engineering Research Center (PEER) Ground Motion Database website at: http://peer.berkeley.edu/peer_ground_motion_database/site

On the PEER website, each earthquake has various measurement stations and each station contains recorded displacement, velocity, and acceleration data of the tremor at different directions. The default download setting is acceleration, which is required when using the supplied make_quake.m file detailed in Section 5.9. To illustrate how to download and run an earthquake, the procedure below shows how to find the Kobe tremor recorded at the HIK station:

1. Go to the PEER Ground Motion Database at: http://peer.berkeley.edu/peer_ground_motion_database/site
2. Click on the *Unscaled* button.
3. In the *Event Name* field, enter *Kobe, Japan* as illustrated in Figure 4.3.

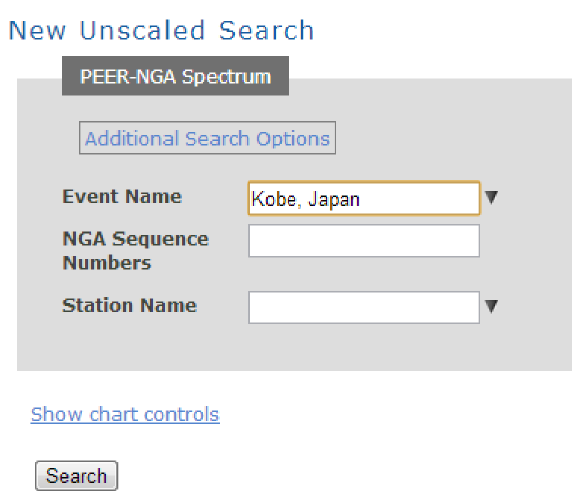


Figure 4.3: Searching for the Kobe earthquake on PEER Ground Motion Database

4. Click on *Search*.
5. As shown in Figure 4.4, the *Results* section displays all the stations that recorded the Kobe earthquake.
6. Select Result #2 to download the recorded Kobe acceleration that was measured at the HIK station.
7. Click on the *Save Original Unscaled Time Series Records* button.

Results

*Click on the record below to display Spectra and Time series

Plot Selected Refresh

	Result#	Comp.	NGA#	Pulse	Tp(s)	D5-95(s)	Event	Year	Station
☐	1	GM	1103	0 0	-- --	34.4 38.2	Kobe, Japan	1995	FUK
☑	2	GM	1105	0 0	-- --	18.5 10.5	Kobe, Japan	1995	HIK
☐	3	GM	1106	1 0	1.0 --	9.6 8.1	Kobe, Japan	1995	KJMA
☐	4	GM	1107	0 0	-- --	17.6 10.4	Kobe, Japan	1995	Kakogawa
☐	5	GM	1109	0 0	-- --	26.4 21.2	Kobe, Japan	1995	MZH
☐	6	GM	1111	0 0	-- --	9.5 11.1	Kobe, Japan	1995	Nishi-Akashi
☐	7	GM	1112	0 0	-- --	14.6 17.8	Kobe, Japan	1995	OKA
☐	8	GM	1113	0 0	-- --	58.6 71.8	Kobe, Japan	1995	OSAJ
☐	9	GM	1116	0 0	-- --	13.3 9.4	Kobe, Japan	1995	Shin-Osaka
☐	10	GM	1117	0 0	-- --	20.2 23.7	Kobe, Japan	1995	TOT
☐	11	GM	1119	1 0	1.4 --	5.1 3.4	Kobe, Japan	1995	Takarazuka
☐	12	GM	1120	1 0	1.6 --	10.8 11.9	Kobe, Japan	1995	Takatori

Save Original Unscaled Time Series Records | Save Search Spectra

Figure 4.4: Kobe earthquake records on PEER Ground Motion Database

8. Save the ZIP file to your PC and extract its contents to the *Shake Table I-40\Controllers* folder. This particular record contains the measured acceleration for three different direction: NGA_no_1105_HIK000.AT2, NGA_no_1105_HIK090.AT2, and NGA_no_1105_HIK-UP.AT2.

9. To use NGA_no_1105_HIK000.AT2, go to make_quake.m and set the *input_filename* variable as follows:

```
% name of data source file:
input_filename = 'NGA_no_1105_HIK000.AT2';
```

10. Run make_quake.m as explained in Section 5.9.

11. Follow the directions given in Section 3.4 to run this earthquake on the Shake Table I-40 system.

5 SYSTEM REQUIREMENTS

Required Software

- Microsoft Visual Studio (MS VS)
- Matlab® with Simulink®, Real-Time Workshop, and the Control System Toolbox
- QUARC®

See the QUARC® software compatibility chart in [3] to see what versions of MS VS and Matlab® are compatible with your version of QUARC and for what operating system.

Required Hardware

- Data acquisition (DAQ) device that is compatible with QUARC®. This includes Quanser DAQ boards such as Q2-USB, Q8-USB, QPID, and QPIDe devices. For a full listing of compliant DAQ cards, see Reference [1].
- Quanser Shake Table I-40.
- Quanser VoltPAQ Series power amplifier.

Before Starting Lab

Before you begin this laboratory make sure:

- QUARC®is installed on your PC, as described in [2].
- DAQ device has been successfully tested (e.g., using the test software in the Quick Start Guide or the *QUARC Analog Loopback Demo*).
- Shake Table I-40 and amplifier are connected to your DAQ board as described its User Manual [5].

5.1 Overview of Files

The main files used with the system are summarized in Table 5.1. Other files used in the system are described in Table 5.2.

File Name	Description
Shake Table I-40 User Manual.pdf	This manual describes the hardware of the STI-40 system and explains how to setup and wire the system for the experiments.
Shake Table I-40 Laboratory Guide.pdf	This document demonstrates how to run the QUARC controllers, gives some background on the PID-based control design, and describes the Simulink diagrams supplied.
Shake Table I-40 Software.exe	Double-click on this file to run the Shake Table I-40 Software.
q_STI_40_cal.mdl	Calibrates the stage of the STI-40 to the HOME, mid-stroke position.
q_STI_40_sine.mdl	Commands a sine wave with a user-defined amplitude and frequency to the STI-40.
q_STI_40_sweep.mdl	Commands a sine sweep signal to the STI-40.
q_STI_40_quake.mdl	Commands an earthquake (or a pre-defined sine wave) to the STI-40.
q_STI_40_AMD.mdl	Commands a sine or sweep signal to the STI-40while also controlling the cart on the Quanser AMD-1 system.
setup_STI_40.m	Calculates various parameters used in all supplied Simulink models. **Run this before any attempting to build/run any QUARC controller.**
make_quake.m	Packages raw earthquake file into format usable to run on shake table using q_data.
make_sine.m	Constructs compound sine waves that are usable in q_data.
setup_amd1.m	Run this when using the Quanser AMD-1 system to set the necessary PV cart control gains and the state-feedback and observer gains for active damping. **Run the file before q_STI_40_AMD.mdl.**
fft_eval_acc.m	Creates FFT plot of the desired and measured table accelerations.
fft_eval_pos.m	Creates FFT plot of the desired and measured table positions.
power_spectrum.m	Computes the power spectrum of a signal.

Table 5.1: Files supplied with the Shake Table I-40

File Name	Description
calc_conversion_constants.m	Loads useful conversions factors.
config_STI_40.m	Load various parameters for the STI-40 system such as sensor calibration gains, modeling parameters, amplifier gains, and so on.
d_STI_40_filter_specs.m	Loads the filter parameters used in the control.
d_STI_40_limits.m	Computes maximum velocity, force, and acceleration of load given its mass and the ST I actuator specifications.
d_STI_40_pd.m	Calculates control gains based on specifications given.
d_STI_40_display_results.m	Displays encoder resolution, various load mass information, and limits of the shake table.
d_setpoint_limit	Calculates the maximum amplitude and frequency position command that can be handled by the STI-40.
d_load_acceleration	Finds the acceleration of the load when tracking a sine wave at a specified amplitude and frequency.
q_scale.p	Produces a scaled position trajectory given desired acceleration data. When ran on the shake table, the measured acceleration matches the given desired acceleration.
construct_quake_trajectory.m	Constructs a time-based array from a matrix of data and the sampling time.
construct_sine_trajectory.m	Constructs a composite sine wave time-based array given the frequency, amplitude, duration, and sampling time.
init_earthquake_data.m	Re-formats raw earthquake data file.
NGA_no_1105_HIK000.AT2	Sample Kobe earthquake acceleration data file.
NGA_no_1086_SYL090.AT2	Sample Northridge earthquake acceleration data file.
NGA_no_180_H-E05140.AT2	Sample El-Centro earthquake acceleration data file.
NGA_no_825_CPM000.AT2	Sample Mendocino earthquake acceleration data file.
config_amd1.m	Sets various AMD-1 model parameters, amplifier limitations, maximum stroke, and sensor calibration gains.

Table 5.2: Additional files supplied with the Shake Table I-40

5.2 Setup script

Before running any of the QUARC controllers supplied, you must run the **setup_STI_40.m** script. This section shows how to run the script and discusses its settings.

Follow these steps:

1. Load the Matlab® software.
2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).
3. Double-click on the setup_STI_40.m to open this Matlab script.
4. In the USER INPUT section, the user can set the load added to the table, change the table controller specifications, and enable/disable the table watchdog.

```
%% USER INPUT
% Added load mass (kg)
Ml = 0;
% Enable/Diable table watchdog: set to 0 to diable or 1 to enable
TBL_WATCHDOG = 1;
% Amplifier type
AMP_TYPE = 'VoltPAQ';
```

```
% Amplifier gain (V/V)
% Important: Make the gain switch on the amplifier is set to the same.
K_AMP = 3;
```

5. Enter the mass of the payload in kilograms in the *Ml* variable.

6. Make sure the gain switch on the VoltPAQ amplifier hardware is set to the same value as in the script. The default setting is 3.

7. The CONTROL PARAMETERS section lets users specify the desired peak time and percent overshoot of the shake table position controller. The default settings should suit most needs. See Section 4.2 for more information on the control gain design.

```
%% CONTROL PARAMETERS
% PV Controller Design Specifications
% Spec #1: maximum percent overshoot
PO = 5.0;
% Spec #2: time of first peak
tp = 0.04;
```

8. Run the setup_STI_40.m script (click on Debug | Run in the Editor menu bar or on the *Run* icon in the Editor tool bar) to setup the Matlab workspace.

9. To view the bandwidth curve shown in Figure 4.2 and discussed in Section 4.3, enter 'y' and then press ENTER.

Note: The control gains calculated are not based on the load mass entered by the user in the prompt. The load entered is only used to generate the bandwidth curve shown in Figure 4.2 (see Section 4.3 for more information). The gains computed are always based on a 0 kg payload. Even if a load is added on the table, the control gains for a 0 kg payload will be suitable. **It is NOT recommend to change this**.

5.3 Calibrate

Follow these steps to open and configure the q_STI_40_cal.mdl QUARC controller:

1. Load Matlab®.

2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).

3. Open the *q_STI_40_cal.mdl* Simulink model.

4. Set the *Board type* in the HIL Initialize block inside the Shake Table I-40 subsystem to the data acquisition (DAQ) device you are using, e.g., Q8-USB. See the QUARC User Manual ([1]) for more information on configuring the HIL Initialize block.

5. Make sure the Simulink model solver is set to quarc_windows.tlc for Win32 systems and quarc_win64.tlc for Win64 systems.

6. Run the setup_STI_40.m script as described in Section 5.2.

7. Go to QUARC | Build to build the QUARC controller.

8. See Section 3.1 for further instructions (e.g., how to run the controller).

5.4 Sine Wave

Follow these steps to open and configure the q_STI_40_sine.mdl QUARC controller:

1. Load Matlab®.
2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).
3. Open the *q_STI_40_sine.mdl* Simulink model.
4. Set the *Board type* in the HIL Initialize block inside the Shake Table I-40 subsystem to the data acquisition (DAQ) device you are using, e.g., Q2-USB. See the QUARC User Manual ([1]) for more information on configuring the HIL Initialize block.
5. Make sure the Simulink model solver is set to quarc_windows.tlc for Win32 systems and quarc_win64.tlc for Win64 systems.
6. Run the setup_STI_40.m script as described in Section 5.2.
7. Go to QUARC | Build to build the QUARC controller.
8. Make sure the top stage is in the center position. To do this, run the q_STI_40_cal controller as described in Section 3.1.
9. Run the QUARC controller by clicking on QUARC | Start.
10. See Section 3.2 for further instructions (e.g., how to change the commanded sine wave).

5.5 Sine Sweep

Follow these steps to open and configure the q_STI_40_sweep.mdl QUARC controller:

1. Load Matlab®.
2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).
3. Open the *q_STI_40_sweep.mdl* Simulink model.
4. Set the *Board type* in the HIL Initialize block inside the Shake Table I-40 subsystem to the data acquisition (DAQ) device you are using, e.g., Q2-USB. See the QUARC User Manual ([1]) for more information on configuring the HIL Initialize block.
5. Make sure the Simulink model solver is set to quarc_windows.tlc for Win32 systems and quarc_win64.tlc for Win64 systems.
6. Run the setup_STI_40.m script as described in Section 5.2.
7. Go to QUARC | Build to build the QUARC controller.
8. Make sure the top stage is in the center position. To do this, run the q_STI_40_cal controller as described in Section 3.1.
9. Run the QUARC controller by clicking on QUARC | Start.
10. See Section 3.3 for further instructions.

5.6 Earthquake

Follow these steps to open and configure the q_STI_40_quake.mdl QUARC controller:

1. Load Matlab®.
2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).
3. Open the *q_data.mdl* Simulink model.
4. Set the *Board type* in the HIL Initialize block inside the Shake Table I-40 subsystem to the data acquisition (DAQ) device you are using, e.g., Q2-USB. See the QUARC User Manual ([1]) for more information on configuring the HIL Initialize block.
5. Make sure the Simulink model solver is set to quarc_windows.tlc for Win32 systems and quarc_win64.tlc for Win64 systems.
6. Run the setup_STI_40.m script as described in Section 5.2.
7. The command position (and acceleration) must first be loaded into the Matlab environment. **Run either the make_sine.m or make_quake.m scripts**. For more information about using these scripts to generate a sine wave or earthquake, see sections 5.8 and 5.9.
8. Go to QUARC | Build to build the QUARC controller.
9. Make sure the top stage is in the center position. To do this, run the q_STI_40_cal controller as described in Section 3.1.
10. Run the QUARC controller by clicking on QUARC | Start.
11. See Section 3.4 for further instructions.

5.7 Active Mass Damper

Follow these steps to open and configure the q_STI_40_AMD.mdl QUARC controller:

1. Load Matlab®.
2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).
3. Open the *q_STI_40_AMD.mdl* Simulink model.
4. Set the *Board type* in the HIL Initialize block inside the Shake Table I-40 subsystem to the data acquisition (DAQ) device you are using, e.g., Q2-USB. See the QUARC User Manual ([1]) for more information on configuring the HIL Initialize block.
5. Make sure the Simulink model solver is set to quarc_windows.tlc for Win32 systems and quarc_win64.tlc for Win64 systems.
6. Run the setup_STI_40.m script as described in Section 5.2.
7. Run the setup_amd1.m script to load the AMD control gain, *Kamd*, observer gain, *Gamd*, and the cart proportional-velocity gain, *Kp_c* and *Kv_c*.

```
AMD-1 Cart PV control gains:
Kp = 305.8609 V/m
Kv = 7.7029 V.s/m

AMD-1 state-feedback gain vector:

Kamd =

   45.0945 -213.8050    4.3052   -4.5640
```

8. Make sure the top stage is in the center position. To do this, run the q_STI_40_cal controller as described in Section 3.1.
9. Manually move the AMD cart to the middle of the track.
10. In the q_STI_40_AMD Simulink diagram, go to QUARC | Build to build the QUARC controller.
11. Run the QUARC controller by clicking on QUARC | Start.
12. See Section 3.5 for further instructions.

5.8 Creating Sine Wave

The Matlab script file called *make_sine.m* generates a compound sine waveform that can be used with the q_data Simulink model to command the shake table. Given a set of sine wave amplitudes, e.g., $A_d = [A_1, A_2, A_3]$, and a corresponding set of frequencies, e.g., $f_d = [f_1, f_2, f_3]$, the script generates a time-based array with the sine wave position

$$x_d = A_1 \sin(2\pi f_1 t) + A_2 \sin(2\pi f_2 t) + A_3 \sin(2\pi f_3 t),$$

the velocity

$$\dot{x}_d = 2\pi f_1 A_1 \cos(2\pi f_1 t) + 2\pi f_2 A_2 \cos(2\pi f_2 t) + 2\pi f_3 A_3 \cos(2\pi f_3 t),$$

and the acceleration

$$\ddot{x}_d = -(2\pi f_1)^2 A_1 \sin(2\pi f_1 t) - (2\pi f_2)^2 A_2 \sin(2\pi f_2 t) - (2\pi f_3)^2 A_3 \sin(2\pi f_3 t).$$

Follow these steps to use the script:

1. Load Matlab®.
2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).
3. Open the *make_sine.m* script.
4. Set the amplitude vector, *Ad*, and frequency vector, *fd*, to create a desired compound sine wave. For example to generate the sine wave $x_d = \sin(2\pi) + 0.5\sin(2\pi 2.5) + 0.25\sin(2\pi 5)$ that lasts 3 seconds set the script as follows:

```
% sine wave amplitude for each excitation (mm)
Ad  = [1, 0.5, 0.25];
% sine wave excitation frequencies (Hz)
fd = [1, 2.5, 5];
% duration (s)
t_dur = 3;
% sampling period (s/sample)
dt = qc_get_step_size;
```

Note: The construct_sine_wave_trajectory.m script called by make_sine.m creates the position, velocity, and acceleration time-based array and automatically pads the first second with zeros. This way, the table does not immediately begin tracking the sine wave when the controller is started.

5. Run the make_sine.m script (click on Debug | Run in the Editor menu bar or on the *Run* icon in the Editor tool bar) to generate the sine wave. This will generate a plot similar to Figure 5.1.

   Note: Make sure q_data is open before running the make_sine.m script. The sampling time set in q_data is used in make_sine.m (using the QUARC command qc_get_step_size). Otherwise a missing variable error message will be prompted.

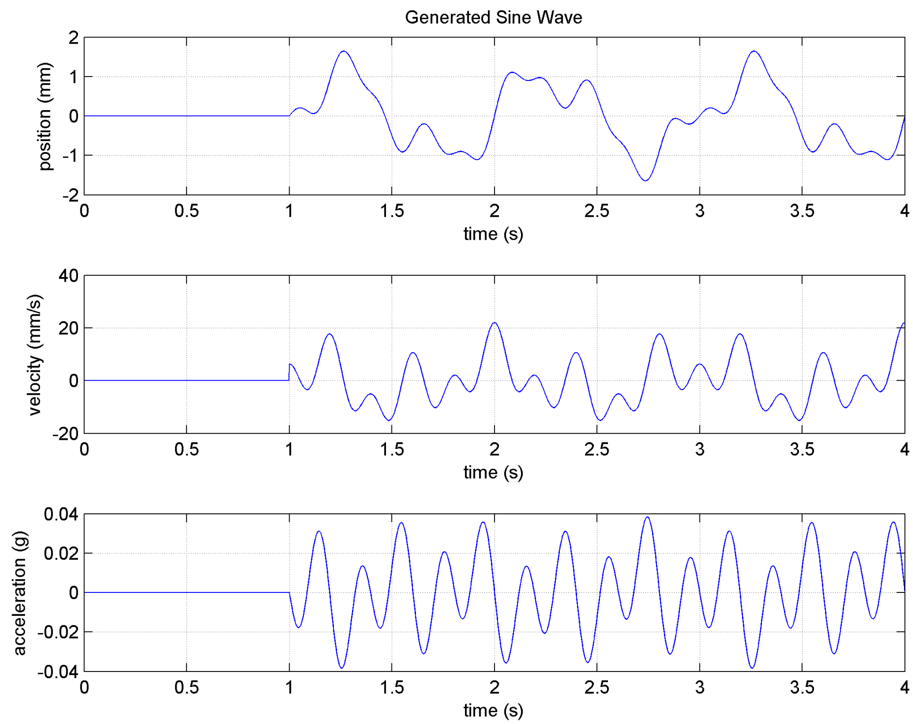


Figure 5.1: Sine wave created by make_sine.m script

6. Once the script is ran, the q_STI_40_quake Simulink Model can be used to replay the sine wave on the Shake Table I-40. See Section 3.4 for the procedure to run the sine wave on the table.

5.9 Creating an Earthquake

The make_quake.m script builds a trajectory that can be used in the q_STI_40_quake Simulink diagram and ran on the shake table. The resulting trajectory created is the setpoint or command position that is to be tracked by the stage in order to achieve the same accelerations as the recorded earthquake.

As listed in Table 5.2, the Northridge, Kobe, El-Centro, and Cape Mendocino raw earthquake acceleration files are already supplied. Additional earthquake data files can be downloaded from the Internet from locations such as the PEER Ground Motion website, as explained in Section 4.4.

Follow these steps to run the make_quake.m file:

1. Load Matlab®.

2. In the *Current Directory* window, go to the Shake Table I-40 files on your PC (copied from the Shake Table I-40 CD).

3. Open the *make_quake.m* script.

4. Set the *input_filename* variable in script to the name of the earthquake file that is to be replayed on the shake table. As shown below, set the variable to NGA_no_1086_SYL090.AT2 for the Northridge earthquake. The *x_max* parameter determines the maximum position of the scaled setpoint trajectory.

```
% name of data source file:
input_filename = 'NGA_no_1086_SYL090.AT2';
% Maximum scaled position (cm). NOTE: Set below 2.0 cm stroke limit.
x_max = 1.8;
```

Caution: Do not set x_max greater to value greater then the maximum stroke of the table! Keep the variable under 2.0 cm.

5. Run the make_quake.m script (click on Debug | Run in the Editor menu bar or on the *Run* icon in the Editor tool bar) to generate the earthquake wave. This will generate a plot similar to Figure 5.2. The desired acceleration and recorded earthquake acceleration is shown in the top plot (in gravitational units) and the scaled position setpoint in the bottom plot (in centimeters).

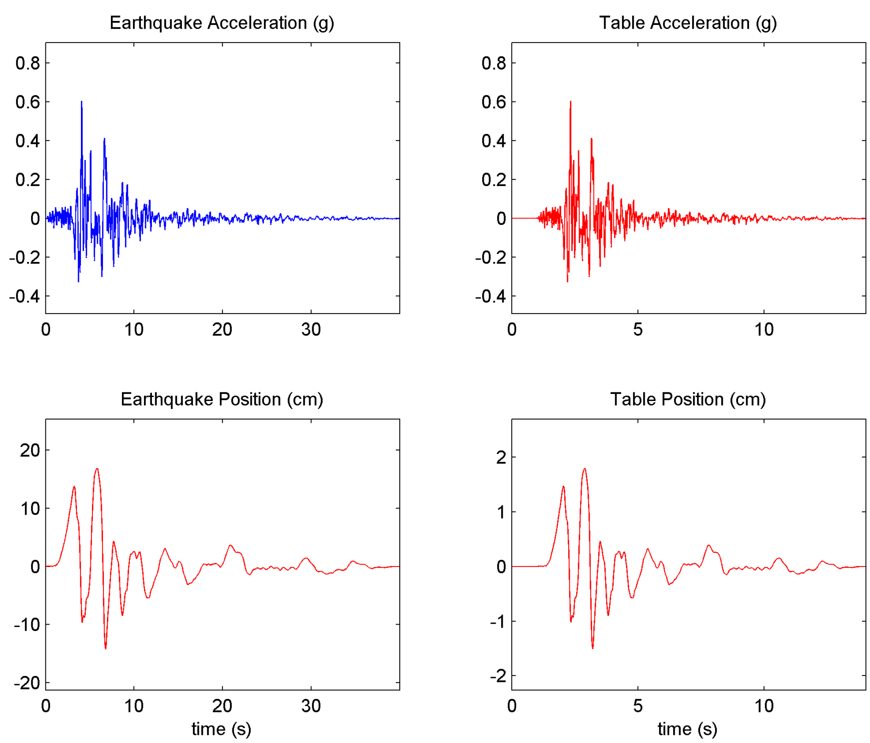


Figure 5.2: El-Centro earthquake plot created by make_quake.m script

Note: The desired acceleration, *ad*, which is computed from the scaled position setpoint *xd_cm*, is the same as the actual recorded acceleration of the earthquake, *a*.

6. After make_quake.m is ran with NGA_no_1086_SYL090.AT2 at x_max = 1.8 cm, the following output displayed in the Matlab Command Window:

```
*** Quanser Consulting Inc.
*** Use of this Software is under license from Quanser Consulting Inc.
```

```
*** Any results derived from this use should be duly acknowledged by the statement:
*** Acceleration and position scaling performed using software licensed from Quanser Consulting Inc.

   [Tc,Xc,Ac,Xu,Au] = q_scale(t,a,xmax)
   t = array of time at equal sampling intervals (s)
   a = array of acceleration record that matches "t" above (g)
   xmax = maximum amplitude of motion (cm)
   Do NOT exceed the limits of the table with xmax!

   Tc = Scaled command time array (s)
   Xc = Scaled table position command array (cm)
   Ac = Acceleration array, found by differentiating Xc twice (g)
   Tu = Earthquake time array (s)
   Xu = Computed earthquake displacement (not scaled) (cm)
   Au = Earthquake acceleration array (g)

 Original time step:    0.02000
 Step 1 of 3: Get displacements
 Step 2 of 3: Scale records
 Ratio of table displacement to ground displacement: 0.106367

 Step 3 of 3: Scaling time
 Time step after scaling = 0.006523

*** Done ***
   Displacement scaled from original movement of 16.92 cm to  1.80 cm
   Time scaled from original duration of 39.98 s to 13.05 s
   Record size  =  2153 samples
```

The Northridge earthquake had a maximum displacement of 16.92 cm and this was scaled down to 1.8 cm (as set by x_max). In order to achieve the same acceleration, the time of the generated trajectory is compressed from 39.98 to 13.05 seconds.

7. Once the script is ran, the q_STI_40_quake Simulink Model can be used to replay the earthquake on the Shake Table I-40. See Section 3.4 for the procedure to run the tremor on the table.

Files used for Earthquake Scaling

Three functions are called in make_quake.m to create the scaled position command from the recorded earthquake data:

1. init_earthquake_data.m: this script extracts the sampling time information of the recorded earthquake, *dt*, and compiles the acceleration data from the AT2 file, which is the four column format, into an array called acc_data.
2. construct_quake_trajectory.m: creates a trajectory containing the recorded earthquake acceleration data, *[t,a]*.
3. q_scale.p: goes through a scaling algorithm and outputs the time of the trajectory t, the scaled position setpoint in centimeters *xd_cm*, the desired acceleration *ad*, and the duration of the tremor *tf*.

REFERENCES

[1] Quanser Inc. *QUARC User Manual*.

[2] Quanser Inc. *QUARC Installation Guide*, 2009.

[3] Quanser Inc. *QUARC Compatibility Table*, 2010.

[4] Quanser Inc. *VoltPAQ User Guide*, 2010.

[5] Quanser Inc. *Shake Table I-40 User Manual*, 2012.