Seismic Simulation and Vibration Control using Shake Table Testing

By

Kashif Mahmood

(2009-NUST-MS PhD-Str-10)

A thesis submitted in partial fulfillment of
the requirements for the degree of

Master of Science

at

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This is to certify that the

thesis entitled

Seismic Simulation and Vibration Control using Shake Table Testing

Submitted by

Kashif Mahmood

Has been accepted towards the partial fulfillment

of

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Master of Science in Structural Engineering

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This work is dedicated to

My Grand Father

Abstract

Shake tables are an effective tool for use in lab for testing at advanced undergraduate and graduate level. A detailed study is carried out for a shake table with detailed description of the apparatus is given, followed by the system operation.

Experiments that simulate different earthquakes are run, and response of a one degree of freedom structure model is noted. Issues regarding interpretation of the response are discussed. Finally an application of the apparatus is demonstrated by comparison of active and passive mass dampers.

This research work developed the bench sale earthquake engineering laboratory setup at School of Civil and Environmental Engineering. Shake table is also used as a teaching tool to visually highlight the effect strong ground motion on different structures.

Acknowledgement

First and foremost, praises and thanks to the God, the Almighty, for the wisdom and perseverance that he has been bestowed upon me during this research project, and indeed, throughout my life.

I want to express my gratitude towards my advisor Dr. Abdul Qadir Bhatti, who gave me the opportunity to work on this project, and guided me through it.

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I am also grateful to my parents, especially my father who encouraged me more than anybody else. He was one of the biggest driving forces in convincing me to complete my research work.

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Chapter 1
Introduction

1.1 Introduction

Through history, earthquakes have been a natural event feared by men because of its catastrophic consequences, resulting in hundreds of casualties and economical lost.

Only through the understanding of this phenomenon and how structures respond to it, consequences can be diminished. Each earthquake presents an opportunity to observe and study the performance of real buildings. The lessons learned during these extreme events accelerate research work on structural performance and motivate advances in seismic design.

However, the development of our knowledge cannot depend only on the actual occurrence of these natural events. Damage observed in earthquakes highlighted the importance of accumulating real data by experimentation regarding the earthquake response, damage level, and collapse of structures. Alternative sources to acquired information must be used.

Earthquake simulators provide a versatile resource to generate earthquake-like motions making possible measurements of input and output parameters needed to analyze the behavior of models of structural systems.

Due to size constraints it is difficult to study the dynamic response of full scale buildings in a laboratory. Testing of complete structures is then limited to small-scale models.

1.2 Motivation

The pedagogical value of shake table can be realized in the fact that it can be effectively used in a number of different experiments. The flexibility of the system is such that different types of models can be tested; each experiment built around the different courses, highlighting the important and key concepts of that particular topic. In our case, the table is used to test a simple one degree of freedom steel structure, modeling a single story building. The model is instrumented, and the whole system is used in conjunction with a data acquisition and control system. The whole setup not only gives the ability to record and save the response of the model due to the base excitation given by the vibrating table (the results of the experiment), but also allows for carrying out subsequent data processing and signal analysis procedures to extract information from the saved response, and to interpret results from it.

Such uses of shake tables provide an excellent basis for an introduction to experimental methods in research in structural engineering.

1.3 Organization

In Chapter 2 we look at the hardware comprising the shake table, how the system is built, its various components and how they fit in the framework, the technical specifications. In Chapter 3 we go through the operation of the instructional shake table, and study the way the control software works, along with how experiments are made and run. In Chapter 4 we take a closer look at the experiments, namely simulation of the famous earthquakes. We see how the experiment is made and what different SIMULINK blocks that it is composed of, actually mean. We also look at response of the model structure to this earthquake. In Chapter 5 an example of the use of the shake table is given.

1.4 How to use the results of this research

Students in the structural engineering classes in the School of Civil and Environmental Engineering at NUST Islamabad will be able to build models for testing in a seismic event. A student would then be able to see how a building will react to seismic forces, and then be able to make decisions on how best to proceed with their design.

Students will also be able to build simple models to test the effects of bracing on different structures during earthquake, or test seismic dampers. Students will gain an intuitive sense of how a building will react, and can use this teaching tool as a way to create new and innovative ways of dealing with an unpredictable and damaging natural disaster.

Chapter 2
Literature Review

2.1 Introduction

Many articles on scale model tests on shake tables can be found in the literature. The most relevant ones are summarized hereafter.

Moncarz and Krawinkler (1981) summarized part of a four year study on the feasibility and limitations of small-scale model studies in earthquake engineering. The basics of similitude theory and its application to the modeling of dynamically excited structures are reviewed in this work and similitude laws for various types of models are developed. Recommendations are made for the fabrication and joining of model elements for steel structures. The research has demonstrated that model analysis can be used in many cases to obtain quantitative information on the seismic behavior of complex structures which cannot be confidently analyzed by conventional techniques. Methodologies for model testing and response evaluation were developed in the project and applications of model analysis in seismic response studies on various types of civil engineering structures were evaluated.

Wallace et al. (1985) studied a correlation between a steel braced frame scale model and a full size prototype structure. The scaled models were found to reproduce the global elastic and inelastic response characteristics of their prototype counterpart very well. It was concluded that brace buckling causes severe deterioration in story shear resistance, but the presence of a ductile moment frame surrounding the bracing system provides ductility and vertical load carrying capacity after brace buckling.

Krawinkler (1988) presented a summary of information on scale effects in commonly used experimental procedures in earthquake engineering research. An evaluation of the effects of scaling of length and time, material and fabrication effects are discussed. It is concluded that the global elastic and inelastic response characteristics of complex structures can be simulated at model scales, even at rather small scales. Thus testing to failure of complex structural configuration in a controlled laboratory environment and at an affordable cost are possible. The author also concludes that the detailed localized response, particularly at connections and joints, can often not be reproduced adequately at reduced scales.

In Barreras (1999) two methods for the empirical determination of the natural vibration periods of buildings are studied by using a steel scale model of four floors. The methods studied consisted of an analysis by impulses (Impact Hammer Test) and an analysis by environmental vibration. In order to analyze the reliability and applicability of these methods, a criterion based on the analysis of the coherence between the input and output signals measured in the base and top of the building, was used. In the analysis by impulses, the frequencies of the first two modes of vibration were identified in the Fourier spectrum of the output signal and in the transfer function. The coherence function at these frequencies has values near one, indicating a good reliability in the results obtained. In the analysis with environmental vibration, the fundamental frequency was not detected when the input signal had small amplitude. In this case, the coherence function evaluated at frequencies near the fundamental has values near zero. Using one signal with larger amplitude the natural modes were identified in the transfer function and in the Fourier spectrum of the output signal.

2.2 Apparatus

The apparatus includes the shake table, data acquisition card (DAC), universal power module (UPM) and a PC running the control software.

In this chapter the apparatus of the whole setup, i.e., the shake table, data acquisition card (DAC), universal power module (UPM) and a PC running the control software, are succinctly explained, along with their specifications. Also discussed are the way they are hooked up together and some safety issues regarding their use.

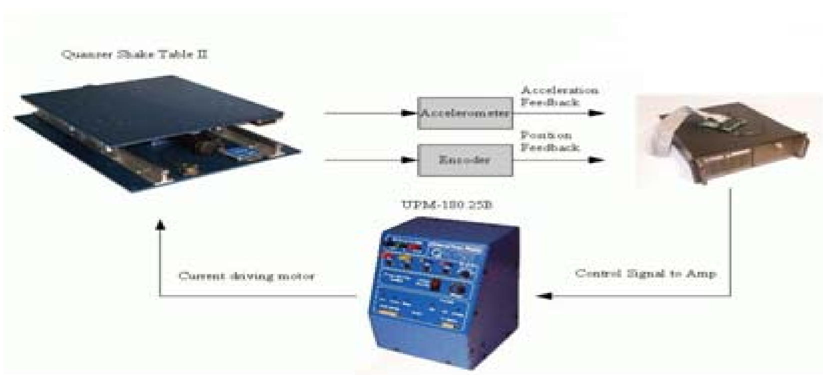


Figure 2.1: Overview of major system components

2.2.1 Shake Table

The shake table is the primary component of the apparatus. The whole idea behind the system is to be able to have a "shake table" which can be controlled in any way, i.e., it can be shaken in any user defined manner, be it a real earthquake, or any displacements defined by any other function. It can be used to teach structural dynamics, vibration isolation, feedback control, and various other topics for mechanical, aerospace, and civil engineers.

The top stage of the shake table is driven by a powerful motor that allow it to achieve an acceleration of 2.5 g when up to 7.5 kg of mass is mounted. The stage rides on two ground-hardened metal shafts using linear bearings which allows for smooth linear motions with low path deflection. When starting from center the stage is capable of moving 7.62 cm, or 3-inches, on each side. It therefore has a total travel of 15.24 cm. In order to move the top platform at a high acceleration, a robust ball-screw and motor assembly is used. The high-powered 400 Watt motor is a 3-phase brushless DC actuator. The motor contains an embedded high-resolution encoder that allows the position of the stage of be measured with an effective linear resolution is 3.10 μm. An analog accelerometer is mounted on the shake table platform in order to measure the acceleration of the stage directly.

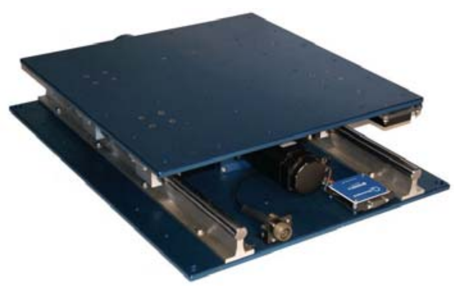


Figure 2.2: Shake Table

2.2.2 Model Structure

The structure attached to the shake table is a one floor model building. The floor of the building is made much stiffer than the steel columns. This allows the structure to be modeled as a shear beam, with horizontal translation of the floor as the only degree of freedom. The deformation of the floors is extremely small as compared to those of the columns and hence can be safely neglected for all practical purposes. This approach has long been used in structural engineering practice to model multi story buildings, and the design correspondingly is such that floors are actually constructed stiffer than the columns. The mass of floor is about 2 lbs.

Figure 2.3: Model Structure

2.2.3 Universal Power Module

The Quanser Universal Power Module (UPM) is a power amplifier that is designed to drive the actuators of various Quanser experiments. Every UPM consists of the following components:

1. Power amplified analog output
2. Regulated ±12 V DC power supply at 1-Ampere
3. Analog sensor inputs

Table 2.1 summarizes the different UPM models available and some general specifications.

Model	Max Output Voltage (V)	Max Continuous Current (A)	Type	Mode
UPM-15-03	±15.0	3.0	Linear	Voltage
UPM-24-05	±24.0	5.0	Linear	Voltage
UPM-180-25B	Varies	10.0	PMW	Current

Table 2.1: UPM models

The UPM-15-03 and the UPM-24-05 are both linear voltage-controlled amplifiers. The UPM-15-03 device, pictured in Figure 2.4, is capable of delivering a maximum continuous voltage of ±15 V and a maximum continuous current of 3 A. For actuators requiring more power, the UPM-24-05 has a maximum continuous voltage of ±24 V and a maximum continuous current of 5 A.

In more high-powered applications such as the shake table, the UPM-180-25B shown in Figure 2.5 is used. The UPM's onboard current-controlled pulse-width modulated amplifier outputs can deliver a maximum continuous current of 12.5 A. The maximum continuous voltage it can output depends on the resistance of the load attached.

Figure 2.4: UPM-15-03

Figure 2.5: UPM-180-25B

2.2.4 Accelerometers

Accelerometers are the most common instrument used for determining response of structures, and change in dynamic state of a system. It is not easy to measure the displacement response of a vibrating structure with direct measurements. They are almost universally used for response measurements, and for recording any change in the dynamic state of a vibrating system.

The instrument essentially consists of mass connected to a spring and damper. Accelerometers can be described as a combination of two transducers - the primary transducer, typically a single-degree-of-freedom vibrating mass which converts the acceleration into a displacement, and a secondary transducer which converts the displacement of the seismic mass into an electric signal. The actual construction varies according to the intended use and the range of acceleration and frequency to be measured.

For the shake table, we have two accelerometers. One of these are mounted on the floor of the model structure, and the second one is attached to the table itself to monitor the accelerations of the table, to keep a check on whether the table is actually vibrating according to the input signal or if there is a lag between the actual and desired response.

The sensor has a range of ±10 g and its noise, in the operating range of the shake table, is approximately ±5.0 mV, i.e. ±5.0 mg. The analog sensor is calibrated such that 1 Volt equals 1 g, or 9.81 m/s^2.

Figure 2.6: Accelerometer

2.2.5 Active Mass Damper

The AMD plant forms an autonomous servo system. The challenge in designing a control system that dampens out the vibrations in the building-like structure is that the top floor deflection (or horizontal displacement) is NOT measured. Instead, the structure's feedback sensor is an accelerometer mounted on the AMD's top floor. The only other sensor that is available is to measure the linear cart position. The input to the AMD system is the cart motor voltage. In order to dampen out the vibrations in the AMD flexible structure, the system is supplied with a state-feedback controller based on a full-order observer. The closed-loop control scheme drives the active mass (i.e. linear cart) by taking into account the actual cart position and floor acceleration feedback signals.

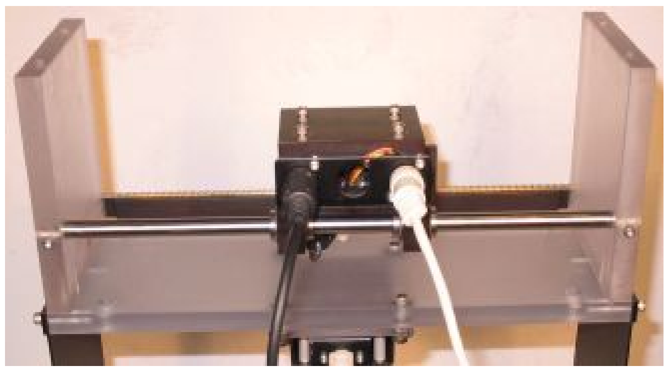


Figure 2.7: AMD

2.3 Connectivity

Before wiring the ST II system, the Q4 or Q8 data-acquisition card must first be installed and connected to Q8 Extended Terminal Board. This terminal board is made specifically to interface with the Quanser UPM-180-25B device and is different from the standard terminal boards used. See Table 2.2 below for a summary of the shake table connections.

Cable #	Cable Type	From	To	Function
1	25-pin Parallel Cable	"Table X" on the Terminal Board	"From MultiQ" on the blue UPM-180-25B	Drives the amplifier to move the stage and receives the accelerometer, stage encoder, calibration, and limit detector signals

2	15-pin Parallel Cable	"To Device" on the blue UPM-180-25B	Circuit board on the Shake Table II	Receives the encoder and limit detector signals from the shake table.
3	"Emergency Stop" Cable	E-Stop Switch	UPM E-Stop Connector	Carries the emergency stop signal.
4	4-pin Motor Cable	"Motor" Connector on the UPM-180-25B	Motor connector on the Shake Table II	Connects the shake table motor leads to the amplifier on the UPM.
5	Analog Cable: 6-pin-mini-DIN to 6-pin-mini-DIN	"S1" Connector on the on the UPM-180-25B	Accelerometer on the Shake Table II	Carries the acceleration signal of the stage to the UPM.

Table 2.2: Shake Table II wiring summary

2.4 Safety

There is some safety features built into the system to ensure that the equipment is not damaged. There is a switch on the main UPM labeled “Safety Override". This should be kept in the "OFF" position at all times. The table is equipped with Limit switches. These enable the table controller to ascertain if the end of travel limits is reached by the table. They deactivate the amplifier, so that the table cannot go off limits. Also the table should be zeroed before starting so that the chances of exceeding the limits are minimized. Also any earthquake simulations that are run on the table should be properly scaled down execution. This is discussed in the next chapters.

Chapter 3
The Software

3.1 Introduction

The whole apparatus is controlled and data collected using a standard Pentium class computer. The flexibility of the system along with the ease of use of the control software make it an attractive choice for quick and easy demonstrations of principles of structural dynamics and earthquake engineering in real time. Not only that, but also the system is highly modular, enabling the user to design virtually any kind of experiments regarding dynamics, run them, and change many parameters while running the experiments in real time. In this chapter a description is given of the different software packages that are used, how they link together, and how the system is managed using these. Also a succinct description is given of the pertinent drivers for different operations that are used to control the data acquisition card.

3.2 The Software Requirements

The software requirements depend on whether you want to run only the shake table software or if you want to design your own controllers as well. Thus there are two system configurations: shake table software and control design. The shake table software configuration only enables users to run previously made controllers. It does not let users create or modify new ones as in the control design configuration.

3.2.1 Requirements for the Shake Table II Software

In this setup, users command signal to the shake table using the shake table software. It enables users to run a sine wave, a chirp signal, and sample earthquakes on the shake table. In this system configuration however, the functionality of the existing controllers cannot be modified and new controllers cannot be created. Thus a new controller that makes the table track a saw tooth wave command could not be constructed.

Software components for the Shake Table Software configuration:

✔ Microsoft Windows XP Professional or Microsoft Windows Vista

✔QuaRC Targets 1.1

✔ QuaRC License Manager

✔ LabVIEW 8.5.1 or LabVIEW Run-Time Engine 8.5 (full)

Typically the shake table is connected to a PC with either Windows XP or Windows Vista. This PC would therefore need, at the minimum, QuaRC Targets for Windows and LabVIEW Run-Time 8.5. Note that the QuaRC Targets software is the component of QuaRC that runs the QuaRC controller.

3.2.2 Requirements for the Control Design Configuration

In the control design setup, users can run the previously constructed QuaRC controllers. In addition, users gain the ability to modify existing and create new QuaRC controllers. The Matlab/Simulink package is required for this. Here are the necessary software components for the Control Design configuration:

✔Microsoft Windows XP Professional or Microsoft Windows Vista

✔QuaRC SDE (Simulink Development Environment) Release 1.1

✔QuaRC Targets 1.1

✔ QuaRC License Manager

✔ Mat lab loaded with the following:

- ✔ Simulink
- ✔ Real-time Workshop (RTW)
- ✔ Control Design Toolbox

✔ Microsoft Visual Studio .NET 2005 or Microsoft Visual C++ 2005 Express Edition

3.3 Running the Shake Table Software

The shake table is pictured in Figure 3.1. It enables the user to run a sine wave, chirp, and sample earthquakes such as Northridge and Kobe, on the shake table. The amplitude and frequency of the sine wave can be varied as can the amplitude of the chirp signal.

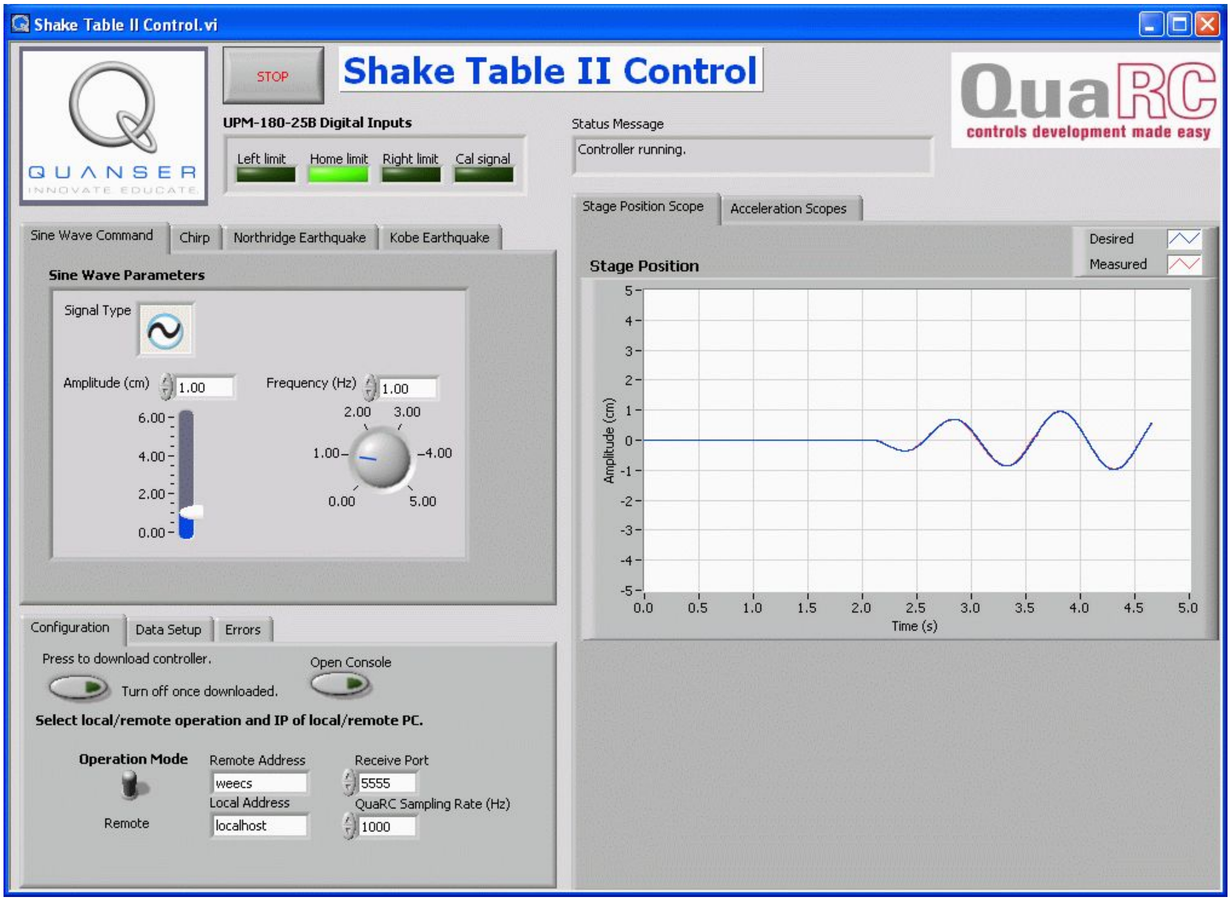


Figure 3.1: Shake Table II Software

3.4 Running the Sample QuaRC Controllers

There are five standard controllers for the Shake Table II:

1. Initializing the UPM
2. Calibrating the table, i.e. moving stage to the home position
3. Running a sine wave
4. Running a sine sweep
5. Running a predefined trajectory such as an earthquake or sine wave.

The name of the Simulink diagram used to generate the QuaRC controller for each experiment is listed in Table 3.1, below. It also includes a description of the experiment (what the file does when ran). Note that the software outlined in the Control Design configuration in Section 3.2.2 is required to perform these experiments.

File Name	Description
qbootupm.mdl	Initializes the UPM-180-25B to make the amplifier ready-to-be-enabled. This has to be done prior to performing any of the ST II experiments.
qcal.mdl	Returns the stage to the home position. The stage should be at the home position before running any of the experiments.
qsine.mdl	Position of the stage tracks a sine wave with amplitude and frequency set by the user.
qsweep.mdl	Sends a sine sweep, i.e. chirp signal, to the shake table for generating the frequency response.
qdata.mdl	Send predefined sine wave or an earthquake, e.g. Kobe or Northridge.

Table 3.1: Simulink models used with QuaRC to run on the shake table system

3.4.1 Initializing the UPM

When the blue UPM-180-25B is first powered, the Left and Right LEDs located on its front panel should be blinking. The UPM is not ready to be enabled and in this mode cannot be used to drive the motor. To stop the blinking and initialize the UPM-180-25B device, run the q_boot QuaRC Controller as summarized here:

1. Ensure that the Safety Override switch, located on the UPM front panel, is OFF.

2. Connect the Emergency Stop cable to the connector on the side panel of the UPM.

3. Rotate the knob in the counter-clockwise direction until it is released in the upright position. The amplifier cannot drive the motor when the red knob is pushed in.

4. After power up, the Left and Right LEDs on the UPM front panel should be blinking.

5. Follow the steps given in Section 2.4.1.1 for the q_boot Simulink diagram to run the q_boot QuaRC controller.

6. When the controller is run, the Left and Right LEDs should stop flashing and the message shown in Figure 3.2 will be prompted. If the LEDs are no longer blinking, then the UPM amplifier is ready to be used for the various ST II experiments.

Figure 3.2: UPM initialization message

3.4.2 Calibrating the table, i.e. moving stage to the home position

Before running any of the experiments the stage of the Shake Table II should be in the mid-stroke position. This position is called the Home position because the Home limit sensor is triggered when the stage is centered.

Follow this procedure to calibrate the stage to the Home position:

1. Ensure the UPM180-25B has been initialized as instructed in Section 3.3.1.

2. When the controller is ran, the Cal, OK, and Enable LEDs on the front panel of the UPM should all be lit and 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 Left limit sensor. Once the Left limit sensor is hit, the stage reverses its direction and begins moving towards the mid-stroke position. The stage stops moving when the Home limit switch is triggered (the Home LED on the UPM will go ON). When complete, the message shown in Figure 3.3 is displayed.

Figure 3.3: Calibration complete message

3.4.3 Running a sine wave

In this experiment, the position of the Shake Table II stage tracks a user-specified sine wave signal. The user can specify the amplitude and frequency of the sine wave. Open the Simulink diagram q_sine.mdl shown in Figure 3.4 to run sine wave. The position response is shown in x (m) 3.5.

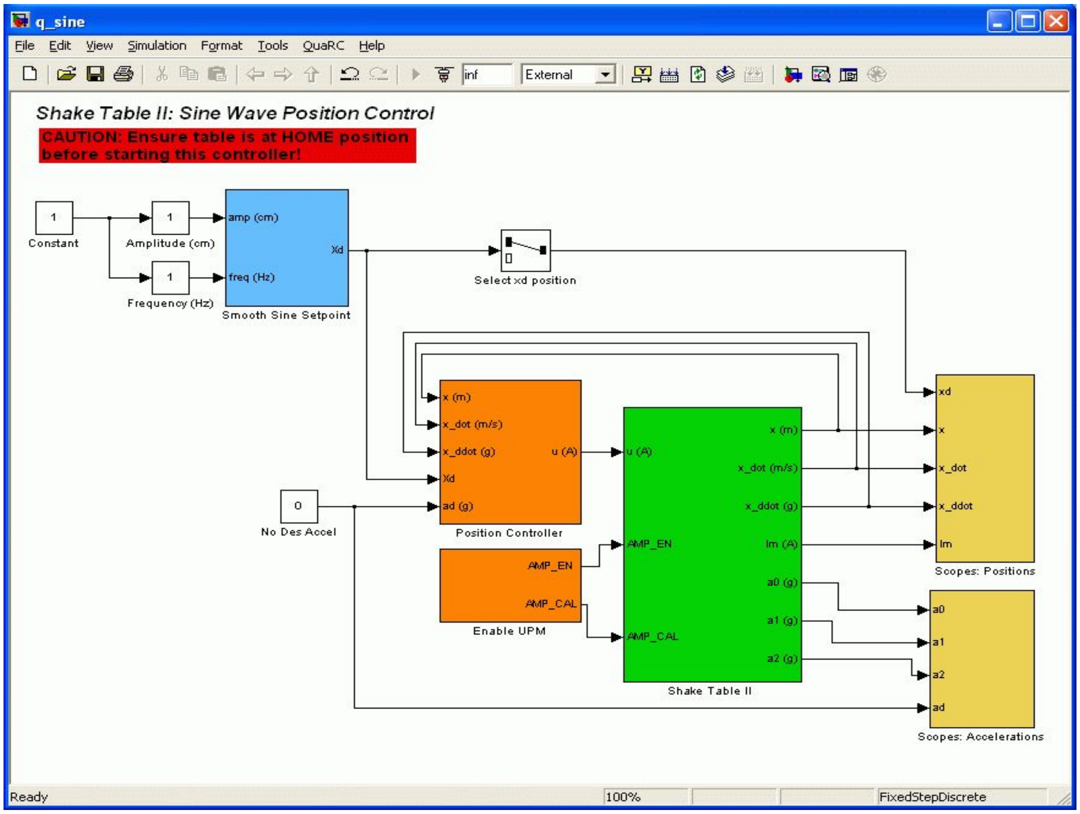


Figure 3.4: q_sine Simulink diagram

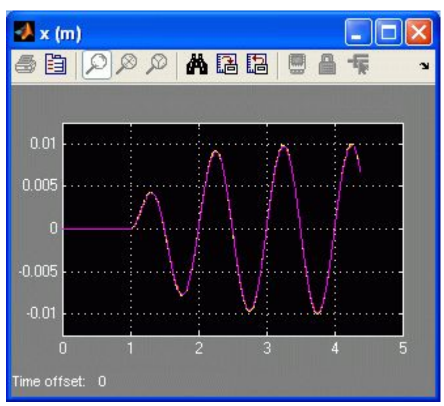


Figure 3.5: x (m) scope when starting the q_sine controller

3.4.4 Running a sine sweep

The sine sweep, also known as a chirp signal, is a sine wave with fixed amplitude that increases in frequency as time progresses. In this experiment, the stage of the shake table tracks a sine sweep that increases from 1 Hz to 7.5 Hz in 20 seconds. By default the sine amplitude is 2 mm. Of course, 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.

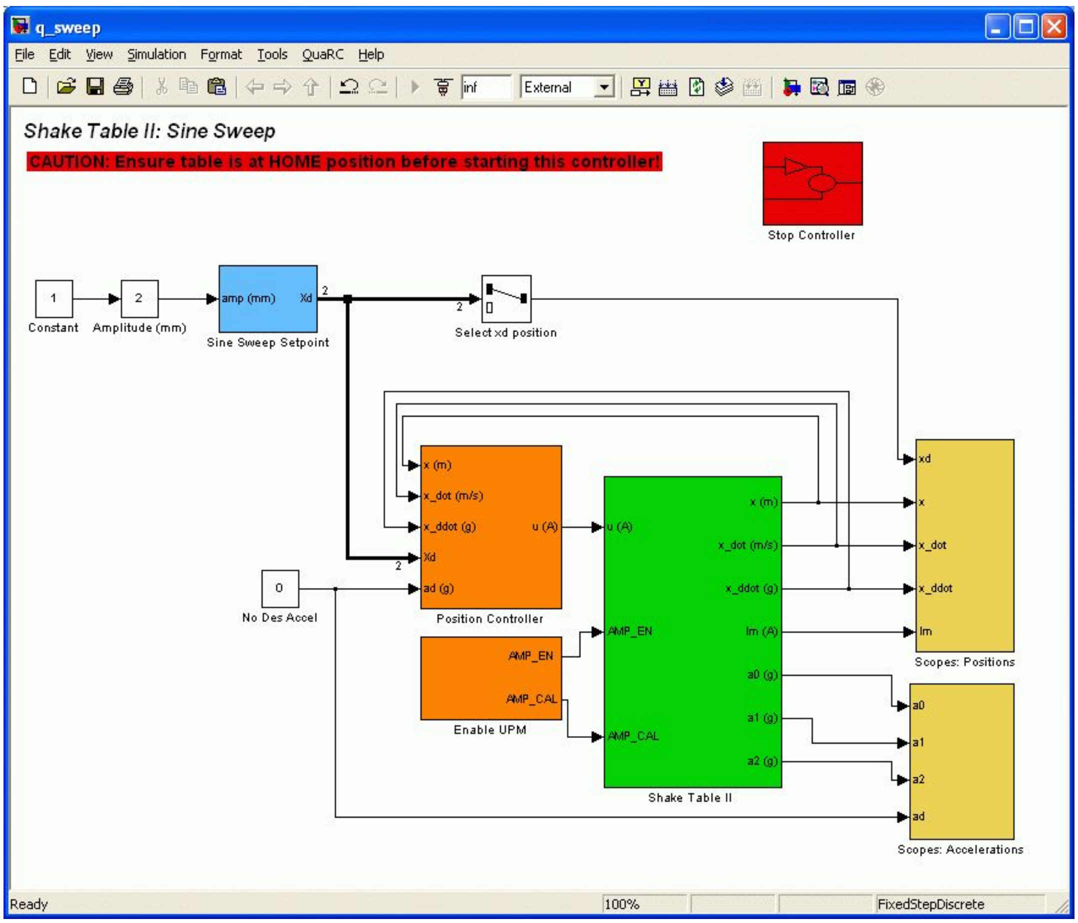


Figure 3.6: Simulink diagram used with QuaRC to run sweep controller

When the controller begins running, the stage should begin tracking an increasingly fast sine wave. Typical position and acceleration responses are shown in x (cm) and a_tbl (g) scopes in Figure 3.7 and Figure 3.8. The a_tbl (g) scope displays the acceleration measured by the table accelerometer in gravitational units, g. The sine sweep lasts 20 seconds and the controller is automatically stopped once the duration is reached.

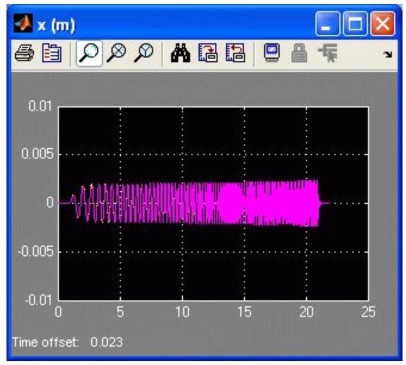


Figure 3.7: Typical position response when running sweep

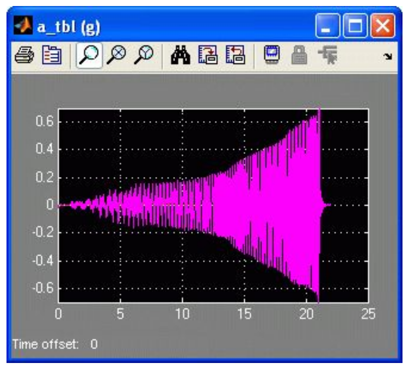


Figure 3.8: Typical table accelerometer reading when running sweep

3.4.5 Running a predefined trajectory such as an earthquake or sine wave

Recorded earthquake data that was collected when an actual earthquake occurred can be scaled down and ran on the shake table. The user can also specify and create a predefined compound sine wave trajectory. Open q_data Simulink diagram shown in Figure 3.9. Before building the QuaRC controller, the command position (and acceleration) must first be loaded into the Matlab environment. Run either the make_sine.m or make_quake.m scripts. Click on QuaRC | Build to generate the QuaRC Controller. Start the controller by clicking on QuaRC | Run or Connect to Target and Run from the tool bar. The stage should begin moving back and forth to track the loaded trajectory. The position and acceleration response when running the earthquake are depicted in Figure 3.10 and Figure 3.11. QuaRC stops automatically when the earthquake duration has been reached and a message will be prompted. Shut off the UPM-180-25B power. To generate a Bode plot of the measured table position or acceleration, run the fft_eval_pos.m or fft_eval_acc.m scripts, as described in later section.

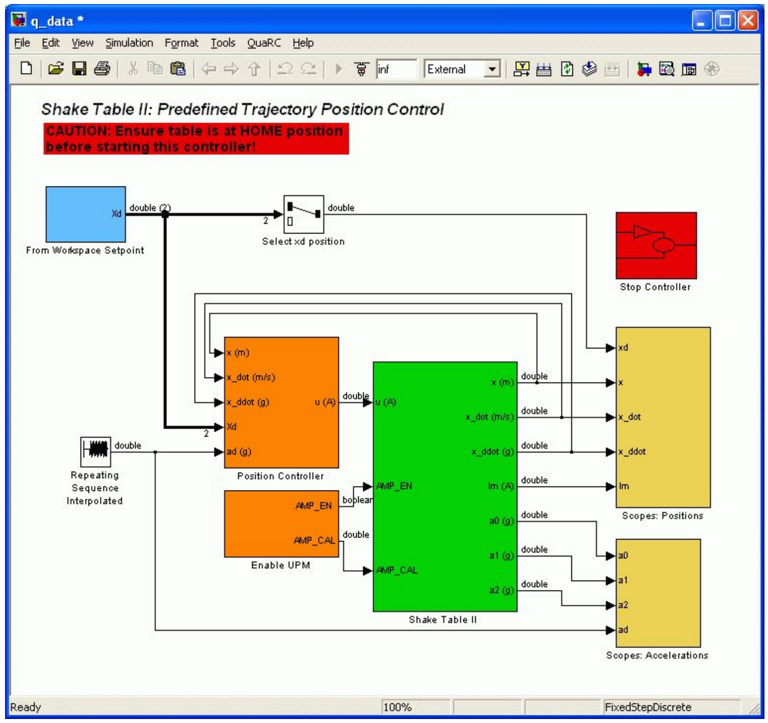


Figure 3.9: Simulink diagram used with QuaRC to run pre-defined trajectories, e.g. earthquakes

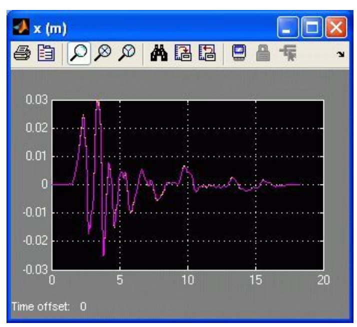


Figure 3.10: Desired and measured position in x (cm) scope after running Northridge earthquake.

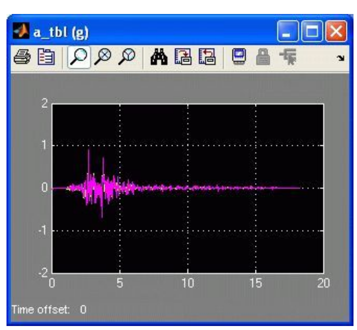


Figure 3.11: Desired and measured acceleration in a_tbl (g) scope after running Northridge earthquake.

Chapter 4
Seismic Simulation

4.1 Introduction

In this chapter we take a look at experiments that simulates the earthquakes. We look into the SIMULINK diagram closely; discuss the different blocks that are present in the model file: how they function how they link together and work to make the experiment happen in real time.

4.2 Shake Table Blocks

Most of the shake table simulink models supplied, e.g. q_sine.mdl shown in Figure 4.1, are built using the blocks described herein forth.

4.2.1. Shake Table II Subsystem

The shake table block shown in Figure 4.1, below, contains blocks from the QuaRC targets simulink library that interface with the shake table hardware. Using the HIL write block, a current is commanded to the blue UPM-180-25B that drives the ST motor. Since the amplifier cannot output more than 25.0 A, the current is saturated by this limit using a Saturation block. The saturated current is then divided by the amplifier gain, 5 A/V, to convert the signal into a voltage (because the D/A channel of the DAC board outputs voltage) and so the commanded current, u (A), equals the current driving the motor. This voltage is passed through another saturation block with the Q4/Q8 board analog output limits, ±10V, and the resulting signal is passed to the Analog Output channel of the HIL Write block. The current in the motor is sent to the subsystem output variable Im (A), which is the saturated signal multiplied by the amplifier gain. The Digital Output channels #8 and #9 are connected to the AMP_EN and AMP_CAL lines of the UPM-180-25B. They are used to initialize, calibrate and enable the UPM and the systems used to do this are described in Section 4.2.5 and 4.2.6.

The HIL read time base block pictured in Figure 4.1, above, reads the accelerometer, encoder, and limit switch signals from the table. The Analog Input channels are passed through the Accelerometers subsystem which is described in Section 4.2.3.1. How the encoder signal is used to get the linear stage position as well as the stage velocity and acceleration signals is performed in the Encoder subsystem and is described in Section 4.2.3. The Limit Switch subsystem is explained in Section 4.2.4. This show how the digital lines are used to read the Left, Right, and Home limit switches correctly. The Check if stage at home block is an Enabled Subsystem that is only active for the first 0.5 seconds of the controller. If the Home LED is not lit, i.e. the table is not in mid-stroke position, QuaRC stops the controller and prompts a message (using the Stop with Message block from the QuaRC Targets library).

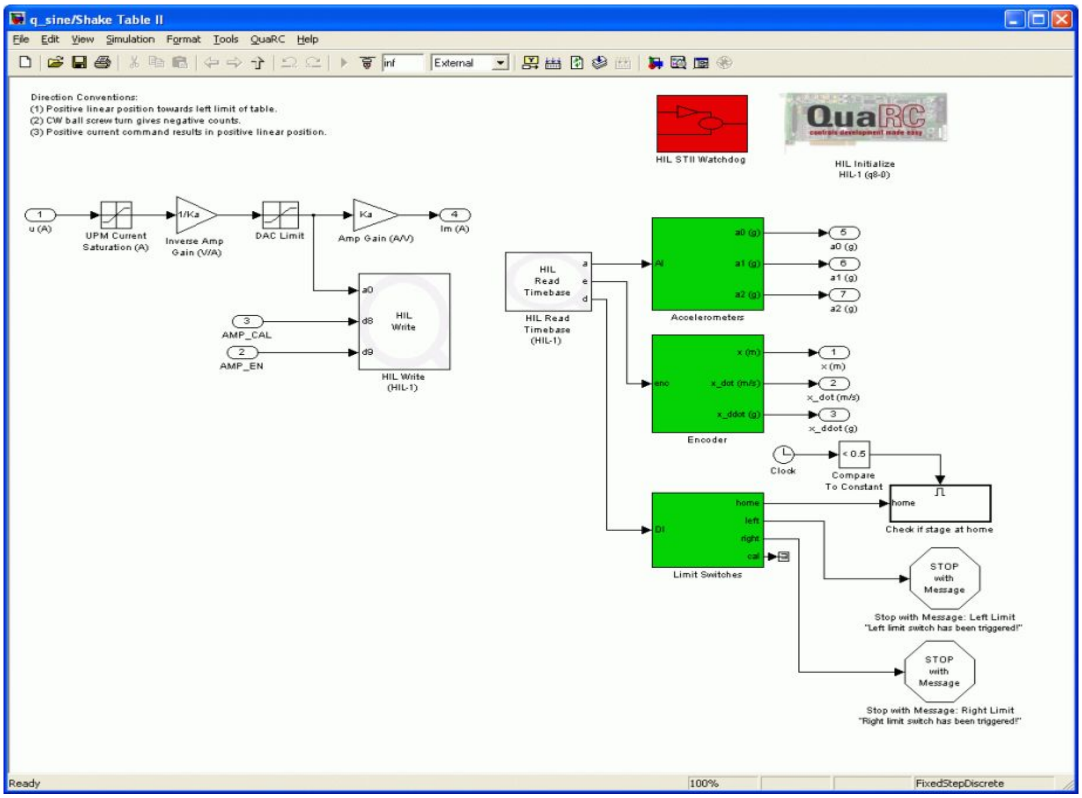


Figure 4.1: Shake Table II subsystem - contains QuaRC blocks that interface with the ST II hardware

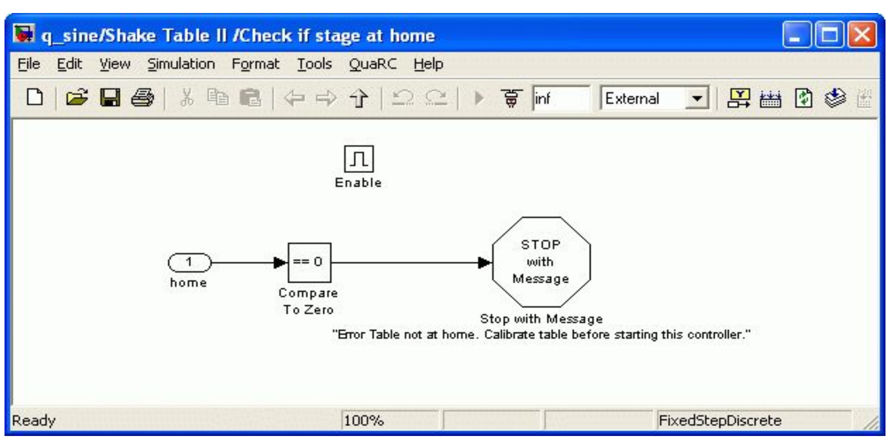


Figure 4.2: "Check if stage at home" subsystem - stops controller if table not at home

Similarly, QuaRC stops running the controller when either the Left or Right limit switch on the shake table is triggered. This is in addition to the PIC-based safety features in the UPM that disables the amplifier in the event that the Left or Right signals are activated. The q_cal model has a variation of the Shake Table II subsystem called the Shake Table II wo/limit stops subsystem and it does not include the Stop with Error blocks. When calibrating, the Left and Right sensors are used to position to the stage to the mid-stroke position and, as a result, it is not desired to deactivate the amplifier when these signals are triggered. In addition, the check if stage at home block is not included in the Shake Table II wo/limit stops subsystem. The HIL watchdog block is shown in Figure 4.3 and it stops the controller if it's running too slow. The timeout parameter in the HIL Watchdog block is set to the hil_timeout parameter, which by default is set to double the sampling interval. Thus, if the controller is supposed to run at 1 kHz and the intervals exceed 0.002 seconds (i.e. slows down to 500 Hz) then QuaRC stops the controller from running.

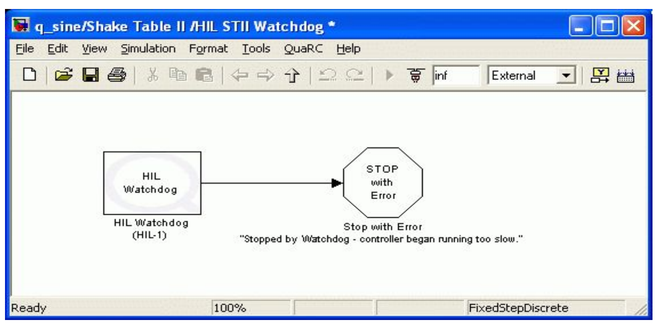


Figure 4.3: HIL Watchdog subsystem - stops controller if running too slow

4.2.2. Accelerometers Subsystem

The accelerometer is mounted underneath the top stage of the shake table and it is capable of measuring the acceleration in both the x and y directions. The Accelerometers block is contained in the shake table subsystem and is shown in Figure 4.4. The AI source carries three signals: the acceleration from Accelerometer #0 (already mounted on table), the acceleration Accelerometer #1 (may or may not be mounted), and the acceleration Accelerometer #2 (may or may not be mounted). As illustrated in Figure 4.4, the accelerometer signals are fed to ACC 0: Bias and Filter, ACC 1: Bias and Filter, and ACC 2: Bias and Filter blocks.

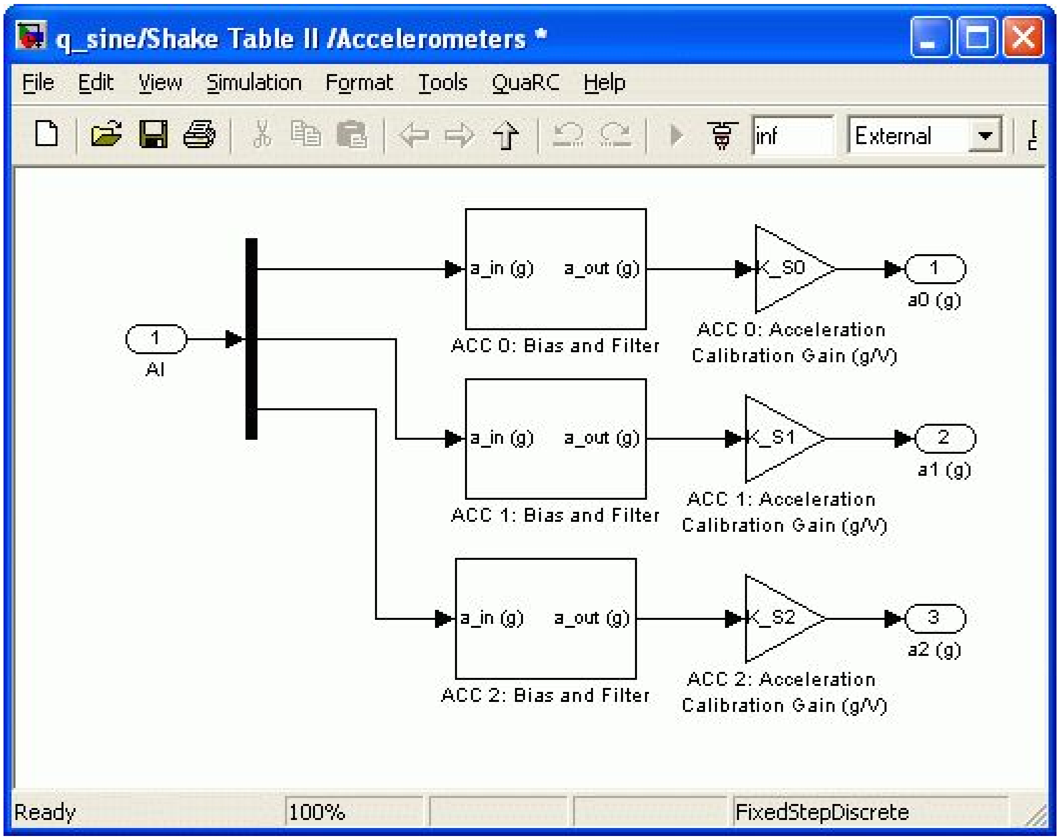


Figure 4.4: Accelerometers subsystem - reads accelerations from accelerometers

The inside of the ACC 0: Bias and Filter block is shown in Figure 4.5. The Bias Removal block removes any initial non-zero measurement in the measured acceleration to ensure the readings are zero before beginning the experiment. In order to remove some noise in the analog acceleration signal, the resulting biased signal is passed through a second-order filter. The parameters for these filters are set in the setup.m script.

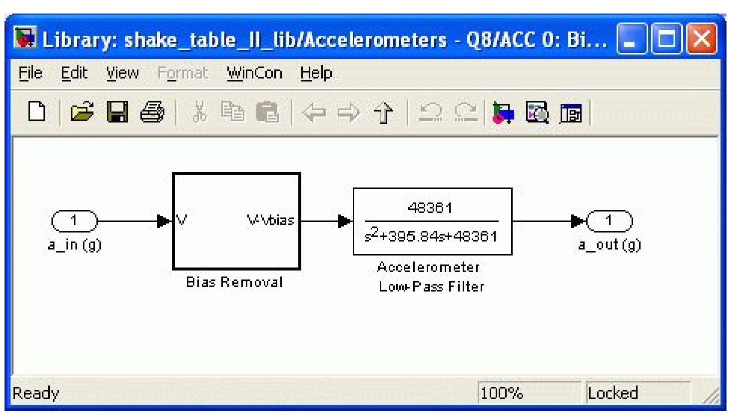


Figure 4.5: Subsystem used to remove initial bias and filter accelerometer signal

In order for the accelerometer to be synchronized with the encoders, i.e. give positive measurements on positive encoder counts, the ACC 0: Acceleration Calibration (g/V) gain is set to the K_S0 parameter. The accelerometer calibration gain, K_S0, is set in the analog_sensor_calib.m file. This file can be used to set the other, K_S1 and K_S2, calibration gain parameters for the analog sensors connected to analog input channels #1 and #2, i.e. to the S2 and S3 input on the UPM-180-25B device.

4.2.3. Encoder Subsystem

The number of counts measured by the shake table encoder corresponds to the angular position of the ball-screw. As shown in Figure 4.6, the linear position of the stage is calculated by multiplying the number of counts times the encoder sensitivity gain, K_ENC. The velocity is computed using a high-pass filter, i.e. taking the derivative and low-pass filtering the result. This is implemented using the Discretized Transfer Function block from the QuaRC Targets library. The Calculate Acceleration from Encoder block is discussed below, in Section 4.2.3.1.

4.2.3.1. Acceleration from Encoder Subsystem

The interior of the Calculate Acceleration from Encoder block is shown in Figure 4.7. This system computes the acceleration of the stage as opposed to measuring its acceleration directly using the accelerometer sensor. This is used in the feed-forward control but can also be used if the table is not equipped with an accelerometer or if under some circumstances this acceleration seems to yield better results (perhaps it has less noise when the stage is tracking a certain signal).

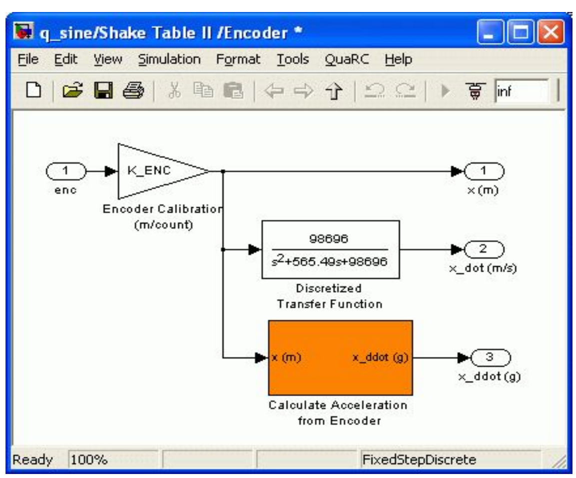


Figure 4.6: Encoders subsystem - outputs stage position, speed, and acceleration

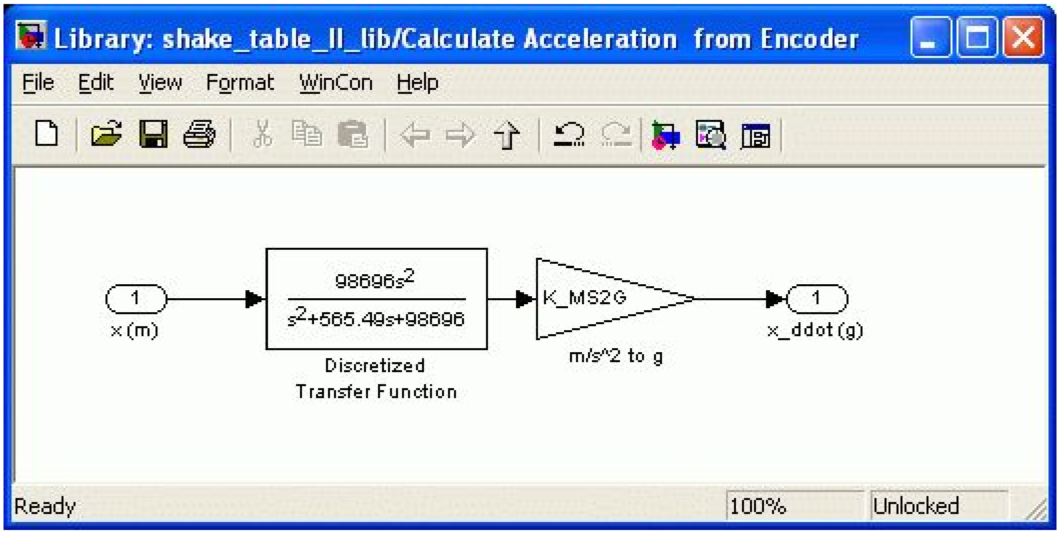


Figure 4.7: Calculates acceleration from position measurement subsystem

The acceleration is calculated by taking the double-derivative of the position measurement and then passing that result though a low-pass filter. Thus the table position is passed through the following transfer function

$$\frac{A_{x,enc}(s)}{X(s)} = \frac{\omega_f^2 s^2}{s^2 + 2\zeta_f \omega_f s + \omega_f^2} \quad [1]$$

where zf is the damping ratio of the filter and wf is the cutoff frequency of the filter. These filter parameters are set in the lpf_cutoff_freq Matlab M-File. The $A_{x,enc}(s)$ variable is the Laplace transform of the resulting acceleration. The acceleration calculation is initially in m/s2 but, as shown in Figure 4.7, is converted to gravitational units, g, using the K_MS2G parameter.

4.2.4 Limit Switches Subsystem

The interior of the Limit Switches block is given in Figure 4.8. As mentioned earlier, the digital readouts of the limit sensors are read using the HIL read block shown in Figure 4.1 and these are fed to the DI input of this subsystem. The micro-vibrations from the ball-screw and the high-frequency switching of the amplifiers motor leads can cause the limits sensors to be triggered unexpectedly. That is, they can output a high signal even though the table has not reached its maximum travel distance. As a result, the limit sensor signals are passed through a digital debounce system.

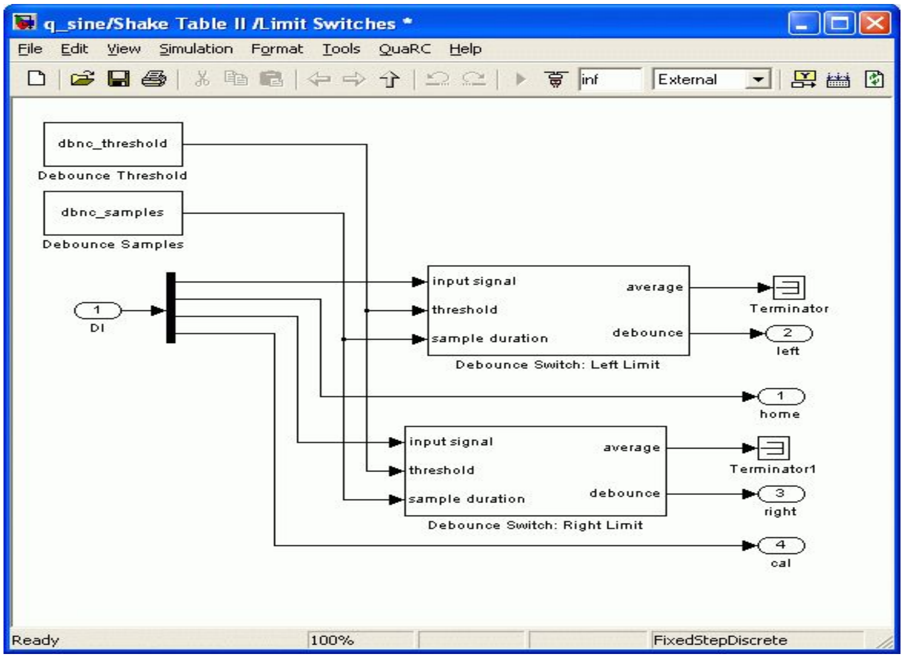


Figure 4.8: Limit Switches subsystem - outputs left, right, home, and cal sensors

The Debounce Switch block keeps track of the last sample duration samples of the input signal. For example, if the sample duration is 100 then the debounce system stores the last 100 samples of the input signal. The average of these samples is compared with the threshold input. If the average of the samples is larger than the threshold the debounce output is set to 1, otherwise it is set to 0. Figure 4.9 illustrates the debounce operation and how it ignores some of the noise. In this illustration, the sample duration is 100 samples and the sampling rate of the controller is 1 kHz. Thus the debounce averages the last 1 millisecond of input signal data.

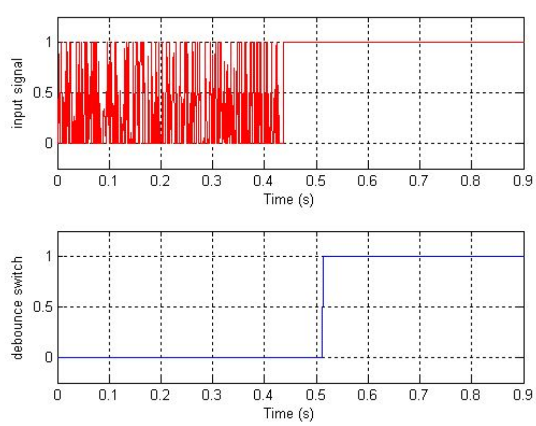


Figure 4.9: Demonstrating the digital debounce switch

4.2.5. Enable Mode Subsystem

The Enable UPM block, shown in Figure 4.10, is required to enable the power amplifier in order to drive the ST II motor and therefore perform experiments. The amplifier is therefore not enabled unless the QuaRC is running a controller that was built from a Simulink model that included this block.

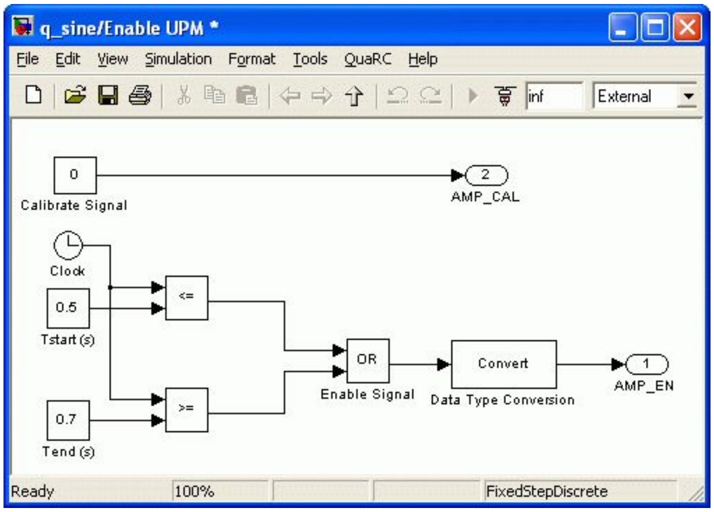


Figure 4.10: Enable subsystem -used to enable the UPM amplifier

4.2.6. Calibration Mode Subsystem

The Calibrate UPM-180-25B block, shown in Figure 4.11, is required to place the UPM-180-25B device in calibration mode in order to center the stage of the shake table. When in the calibration mode, the amplifier is enabled and remains enabled even if the Left or Right limit switch is triggered (unlike in the Enable mode). It becomes deactivated, however, when the Home proximity sensor goes on.

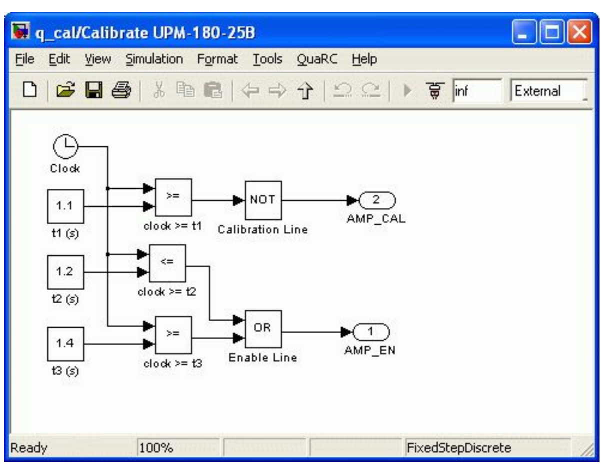


Figure 4.11: Calibrate subsystem - used to place UPM in calibration mode

4.2.7. Position Controller Subsystem

The Position Controller subsystem shown in Figure 4.12 calculates the motor input current needed to move the stage to the desired position.

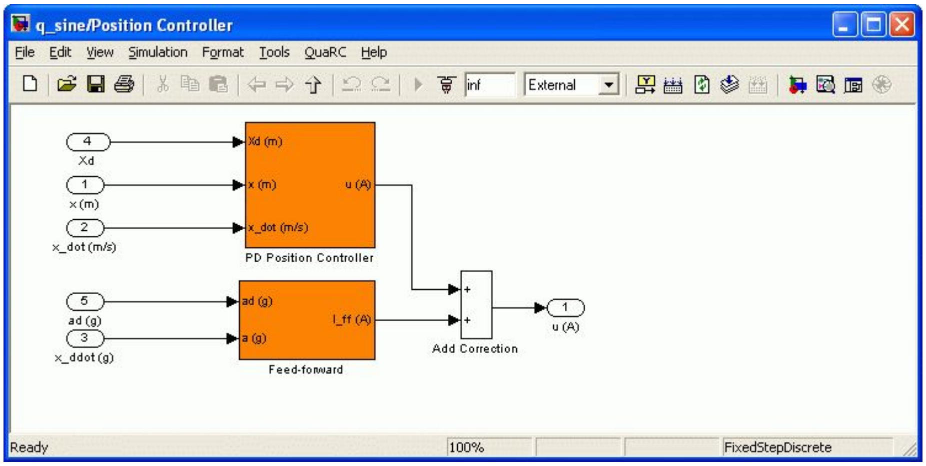


Figure 4.12: Position Controller subsystem - computes current needed to achieve desired stage position

The feedback loop it implements is shown in Figure 4.13. The bulk of the control is done using a proportional-derivative compensator. However, when the desired position is predefined the feed-forward control uses the known accelerations to obtain better control performance, e.g. when running earthquake on the table.

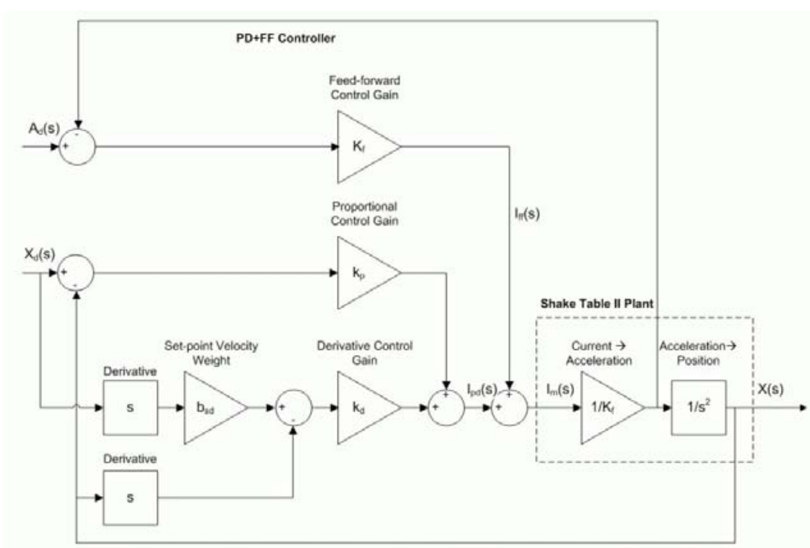


Figure 4.13: Block diagram of proportional-derivative plus feed-forward position controller

4.2.7.1 PD Position Controller

The interior of the PD Position Controller subsystem is shown in Figure 4.14 and it implements the proportional-derivative feedback loop depicted in Figure 4.13.

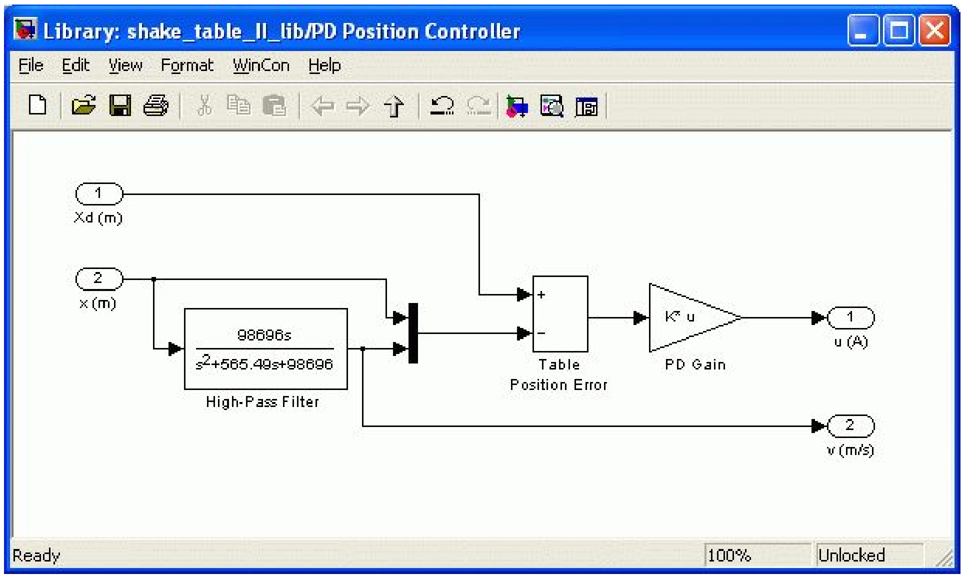


Figure 4.14: Proportional-derivative controller subsystem

As illustrated under the Shake Table II Plant heading in Figure 4.15, the transfer function that describes the transition between the current applied to the motor, I_m, and the position, x, is

$$X(s) = \frac{I_m(s)}{K_f s^2}$$

[2]

where s is the Laplace operator, $I_m(s)$ is the Laplace transform of the motor current, X(s) is the Laplace representation of the stage position, and K_f is the open-loop gain. The open-loop model parameter is described

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

[3]

where M_t is the total mass being moved by the motor, P_b is the ball-screw pitch, and K_t is the motor current-torque specifications. To control the position of the stage a proportional-derivative, or PD, control scheme is used. The PD controller is illustrated in Figure 4.15 and can be described by the transfer function equation

$$I_m(s) = -k_p\,(X(s) - X_d(s)) - k_d\,(s\,X(s) - s\,b_{sd}\,X_d(s)) \quad [4]$$

where $X_d(s)$ is the Laplace of the desired motor position (i.e. the setpoint), k_p is the proportional gain, k_d is the derivative gain, and b_{sd} is the velocity set-point weight. Substituting the PD controller given in Equation [4] into the open-loop model, Equation [2], and solving for $X(s)/X_d(s)$ results in the closed-loop transfer function of the system

$$\frac{X(s)}{X_d(s)} = \frac{k_p + k_d\,s\,b_{sd}}{K_f\,s^2 + k_p + k_d\,s} \quad [5]$$

The closed-loop transfer function describes how the stage position responds to a given position command. The PD controller implemented in the PD Position Controller block, shown in Figure 4.14, is structured as follows

$$u = K\,(X_d - X) \quad [6]$$

where K is the control gain, X_d is the setpoint state, and X is the measured state. The control gain vector is defined

$$K = [k_p, k_d]^T \quad [7]$$

and the setpoint state

$$X_d = [x_d, v_d]^T \quad [8]$$

includes the desired stage position x_d, along with the desired stage velocity v_d. The desired position and velocity are generated via Simulink blocks as explained later in sections 4.4, 4.5, and 4.6. The state of the system is defined

$$X = [x, v_x]^T \quad [9]$$

where x is the measured stage positions and v_x is the velocity of the stage. There is no sensor measuring the velocity of the Shake Table II stage directly, e.g. such as with tachometer. It is therefore computed by taking the derivative of the measured position and then filtering the result to eliminate noise. Effectively, the velocity is calculated using a second-order high-pass filter of the form

$$\frac{V_x(s)}{X(s)} = \frac{\omega_d^2}{s^2 + 2\,\zeta_d\,\omega_d\,s + \omega_d^2} \qquad [10]$$

where ζ_d is the damping ratio of the filter and ω_d is the cutoff frequency of the filter (in rad/s). These filter parameters are set in the lpf_cutoff_freq Matlab M-File and in effect change the shape and bandwidth of the velocity response.

4.2.7.2. Feed-Forward

When the desired position is predefined, the known desired acceleration can be used in a feed-forward loop to assist the PD compensator and attain better position control performance. The Feed-Forward subsystem is shown in Figure 4.15.

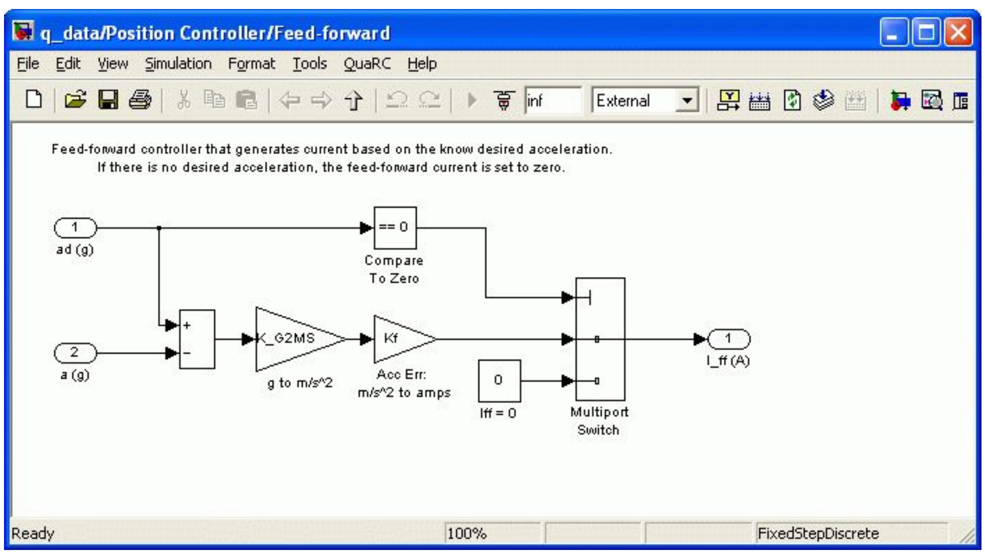


Figure 4.15: Feed-forward subsystem - takes advantage of know acceleration for better position control performance

Feed-forward takes advantage of the fact that the setpoint or command position is predefined to help minimize lag and make the position tracking more responsive. Given the currently measured acceleration and the desired acceleration, the feed-forward gain computes the current needed to move the stage in order to attain the desired acceleration. If no desired acceleration is defined, such as with the q_sine and q_sweep controllers, then the feed-forward current is set to zero. Also, note that the acceleration calculated from the encoder is used for acceleration feedback and not the accelerometer measurement.

4.2.8. Scope Subsystems

The Scopes: Positions subsystem contains scopes based on the stage position in metric and imperial units. For example, the x (in) plot displays the desired and measurement position of the shake table stage in inches. The Scopes: Accelerations blocks have scopes that display the acceleration data from up to three accelerometers.

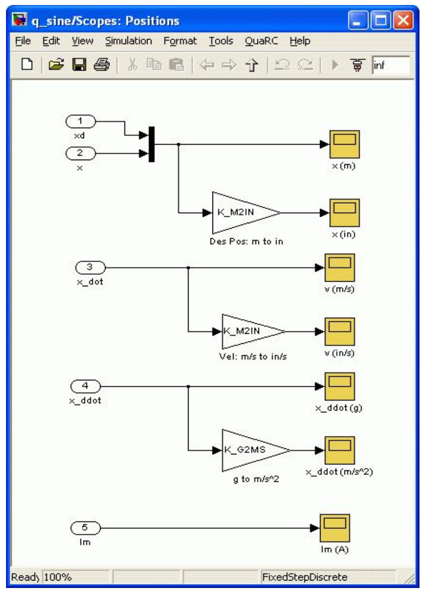


Figure 4.16: Positions scopes subsystem

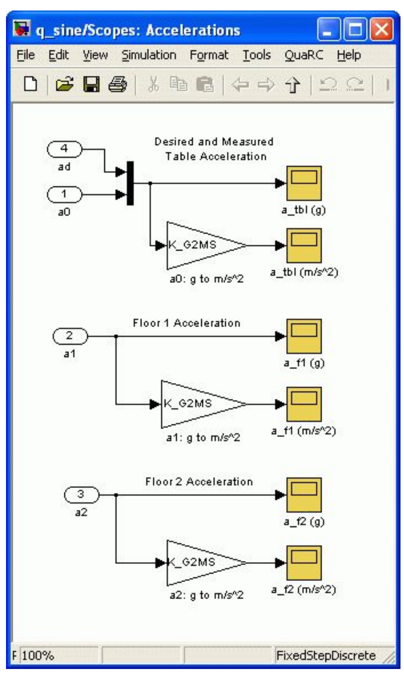


Figure 4.17: Acceleration scopes subsystem

4.2.9. Stop Controller Subsystem

The interior of the Stop Controller subsystem is depicted in Figure 4.18. This block is used in the q_sweep and q_data Simulink diagram when using a predefined trajectory. The duration or length of the trajectory is stored in the tf parameter. When the running time of the associated QuaRC controller exceeds the tf variable, by 0.5 seconds the stop with message block stops the controller from running and prompts the message “controller finished.” message to the user. Note that the stop with error block is from the QuaRC targets simulink library.

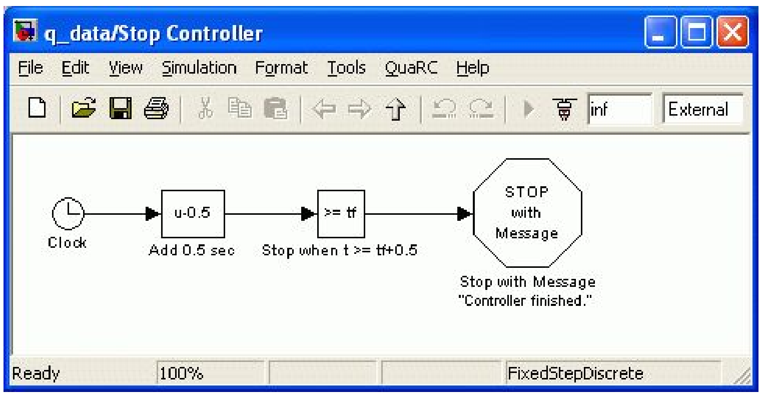


Figure 4.18: Stop Controller subsystem - stops QuaRC when duration of trajectory reached

4.2.10. Ramp Up Subsystem

This inside of the Ramp Up subsystem is depicted in Figure 4.19. The power amplifier in the UPM-180-25B device is only enabled after 0.7 seconds of starting the QuaRC Controller (see the Enable block description in Section 4.2.5). As a result, the setpoint is set to 0 for the first second. After this period, the setpoint is slowly introduced to the table to prevent large stage movements. After 1.0 second, the Ramp 0 to 1 block is triggered and it begins to output a slow ramp signal that goes from 0 to 1. This is multiplied with the commanded setpoint signal, e.g. sine or sweep, to obtain a smooth transition between the table being motionless and the desired position. This prevents the table from having to “catch up” to a potentially large setpoint signal, e.g. going from 0 to 3.0 cm in one sample.

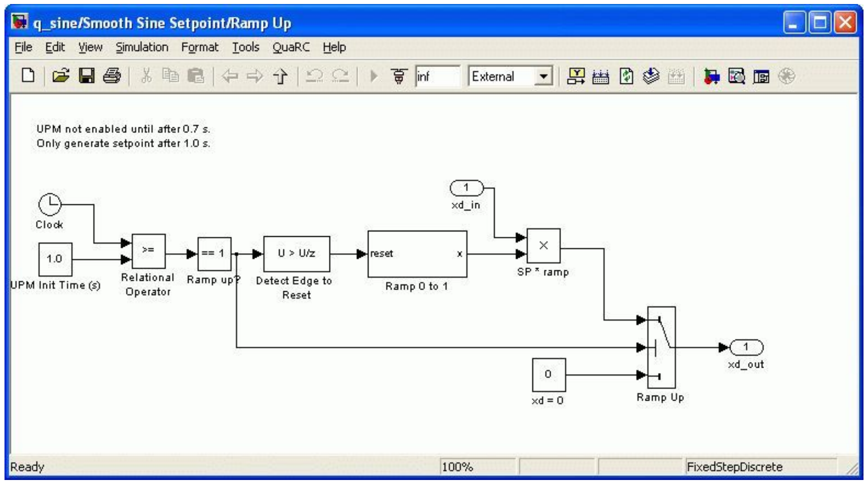


Figure 4.19: Ramp Up subsystem - introduces a smooth transition to the setpoint when the controller is starting

4.3 Matlab Scripts

There are five major scripts that are depicted in Figure 4.20 by the shaded square boxes: setup.m, make_quake.m, make_sine.m, fft_eval_pos.m, and fft_eval_acc.m. Figure 4.20 depicts the various file dependencies and calls made between many of the Matlab script files supplied. The setup.m is the main Matlab script that needs to be run before building a QuaRC Controller from any of the Shake Table II Simulink diagrams and before running other scripts such as make_quake.m. As described in Section 4.3.1, setup.m calls various Matlab script functions to load the ST II system parameters, calculate the position control gains, compute velocity and acceleration limits, and set filter parameters, and so on.

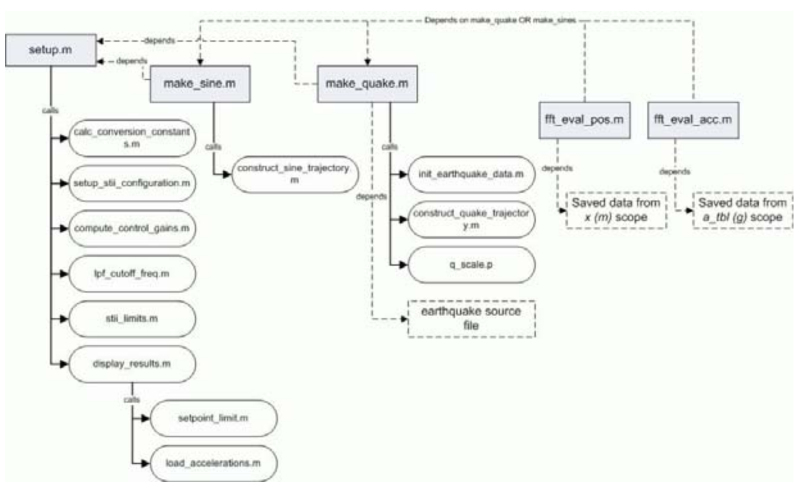


Figure 4.20: Dependencies and various M-File function calls

The make_sine.m and make_quake.m scripts generate trajectories that can are used with the q_data Simulink model. As described in Section 4.3.2, the make_sine.m script is used to generate a compound sine wave. The make_quake.m M-File is used to replay an earthquake on the shake table and is explained in Section 4.3.3. This script needs a raw earthquake data file and calls several Matlab scripts, listed in Figure 4.20, to construct a trajectory. The fft_eval_pos.m script generates a Bode plot that compares the desired position of the shake table and the resulting measured position of the shake table after running an experiment. Similarly, the fft_eval_acc.m file plots the Bode of the desired and measured acceleration data. Both of these files need actual measured data stored in an MAT file. See Section 4.3.4 for details on how to use these scripts.

4.3.1. Setup Script: setup.m

The Matlab script setup.m has to be run before building any of the supplied Simulink models. It sets the parameters for the sensors, amplifiers, and controllers.

Follow these steps for instructions on how to run and configure the setup.m script:

1. Load Matlab.

2. Through the Current Directory window, go to the STII\Lab Files\QuaRC Controllers folder on your PC (which was copied from the ST II CD).

3. Double-click on setup.m file to open it in the Matlab Editor window.

4. In the USER INPUT section shown in Text 4.1 below, the user can set the revision of the Shake Table II system, whether to use imperial or metric units, change the Universal Power Module type, and vary the maximum D/A output voltage of the data-acquisition board. By default and as depicted in Text 4.1, the script is configured for a Revision 4 table, the results are displayed in metric units, the blue UPM-180-25B is used, and the maximum voltage of the Q4/Q8 is used. Users may wish to change conversion variable to display the results in either imperial or metric units.

```
% ************************************************************************
% USER INPUT
% ************************************************************************
% Enter revision of Shake Table II: REV1, REV2, REV3, or REV4.
STII_REV = 'REV4'; % 'REV1', 'REV2', 'REV3', or 'REV4'
% See results in IMPERIAL or METRIC.
conversion = 'METRIC'; % 'IMPERIAL' or 'METRIC';
% Enter type of UPM being used.
UPM_TYPE = 'UPM_180-25B';
% Maximum voltage deliverable by Q4/Q8 HIL (V)
VMAX_DAC = 10;
```

Text 4.1: The "USER INPUT" section in the setup.m script

5. The CONTROL PARAMETERS section lets users specify the natural frequency and damping ratio of the position controller. See Section 4.3.1.1 for more information on the control gain design.

```
% ************************************************************************
% CONTROL PARAMETERS
% ************************************************************************
% Desired natural frequency of closed-loop system (Hz)
f0 = 15;
% Desired damping ratio of closed-loop system
zeta = 0.75;
```

Text 4.2: The "CONTROL PARAMETERS" section in the setup.m script

6. In the DEBOUNCE THRESHOLD section, users can change the threshold of the digital debounce system and number of samples used to take the mean of the input signal. See Section 4.2.4 for more information on the debounce S-Function used in Limit Switches subsystem.

```
% ************************************************************************
% DEBOUNCE THRESHOLD
% ************************************************************************
% Debounce is triggered when the average of the last 'dbnc_samples' is
% greater than the threshold.
dbnc_threshold = 0.8;
% Number of samples in input signal used in average calculation.
dbnc_samples = 250;
```

Text 4.3: The "DEBOUNCE THRESHOLD" section in the setup.m script

7. Users can change the maximum allowable amplitude and the end time of the sine sweep signal used in the q_sweep Simulink diagram by varying the SWEEP_MAX and tf_sweep parameters, respectively, shown in Text 4.4. By default the amplitude of the sweep is limited to 4 mm.

```
%% SWEEP SIGNAL
% Maximum amplitude of sine sweep (m)
SWEEP_MAX = 4e-3;
% Target time (s)
tf_sweep = 20;
```

Text 4.4: The "MAX SWEEP AMPLITUDE" section in the setup.m script

8. Run the Matlab M-File by clicking on Debug | Run in the Editor menu bar or clicking on the Run icon in the Editor tool bar.

9. As shown in Text 4.5, the script prompts the user for the mass of the load that is added to the top stage. Enter the mass of the payload in kilograms or pounds (depending

on how the script is configured). If nothing is added, type 0 or simply press the ENTER key. Text 4.5 shows the typical output of the script after it is ran.

```
Enter any additional load on the top stage of the table (kg): 0

ENCODER CALIBRATION
   K_ENC = 1.55e-006 m/counts

LOAD
   Mass of top stage and bearing parts = 7.74 kg
   Load added = 0 kg
   Total load = 7.74 kg
   NOTE: Shake Table II specified for moving 15 kg at 2.5 g

LIMITS
   Position limit of table = +/- 76.2 mm
   Max velocity deliverable by motor = 664.9 mm/s
   Max force deliverable by motor = 708.661 N
   Max load acceleration = 2.5 g

Do you want to view the setpoint limitations plot? (y/[n]) y
```

Text 4.5: Output in Matlab Command Window after running setup.m script

The encoder calibration gain, K_ENC, which is used to calculate the linear position of the stage from the measured encoder counts, is displayed. Next the pre-load, added load and total amount of mass that is being moved by the motor is summarized. Finally, the maximum strokes, velocity, force, and acceleration are displayed.

10. The script also gives the user the option to plot the setpoint limitations plot shown in Figure 4.21. Enter 'y' to view the plot. To skip the plot, either press the ENTER key or enter 'n'.

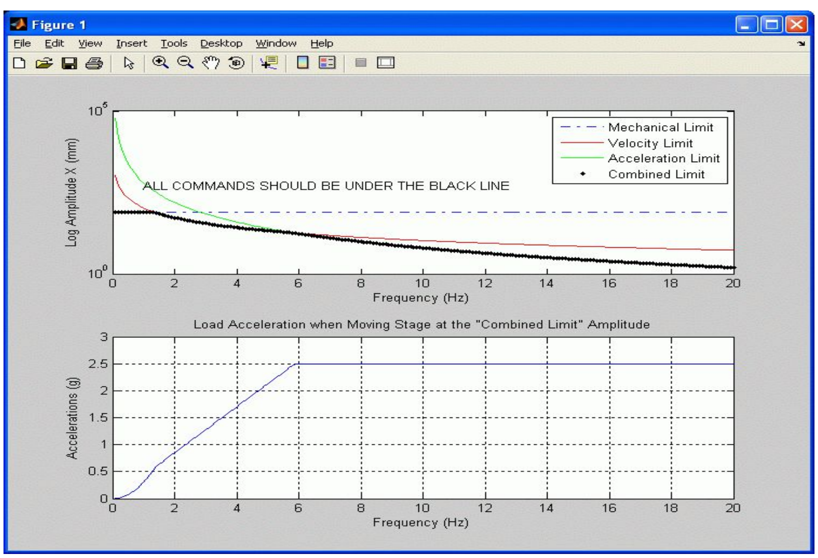


Figure 4.21: For a 0 kg load, this plot illustrates the maximum setpoint amplitude over a range of frequencies

For a range of frequencies, the top plot in Figure 4.21 shows the maximum sine wave amplitude that can be commanded to the table for the stage to track. This plot takes the position, velocity, and acceleration limits of the Shake Table II 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. Low frequency commands in 1.0-1.25 Hz range are limited due to the table travel. When in the 1.25-6.0 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 II. 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 amplitude that exceeds 8.4 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 25.7 mm, the load would reach accelerations of 1.68 g. See Section 4.3.1.2 for details on generating this plot.

That is, after placing a load mass on the stage of the shake table always test the system using the control gains computed for a 0 kg load. These are called the default control gains. The default gains usually give reasonable performance regardless of the load that has been added. However to design the control gains based on a load mass entered in order to achieve better performance, see the last section in the setup.m script shown in Text 4.6 below.

```
%% ************************************************************************
% CALC CONTROL and FILTER PARAMETERS
% ***********************************************************************
% IMPORTANT: Always test the controller with control gains calculated from
% having no load.
% Added load mass for control calc (kg)
Ml = 0;
% Total Load Mass = pre-load mass + added load mass (kg)
Mt = Mp + Ml;
% Calculate the PD control gains
[Kf, K] = compute_control_gains(Kt,Mt,Pb,f0,zeta);
% Set low-pass filter parameters
[wf,zf,wa,za,wd,zd] = lpf_cutoff_freq( );
```

Text 4.6: Control design section in setup.m script

Simply enter a mass, in kilograms, for the Ml parameter. Do not begin with the full load mass. Slowly increment the Ml parameter and test the system accordingly. Having large control gains can make the system go unstable.

4.3.1.1. Control Gain Design: compute_control_gains.m

The control gains are calculated in the M-File called compute_control_gains.m. This function is called by setup.m to design the proportional control gain, k_p, and the derivative control gain, k_d, based on the ST II model parameters, the load mass, and the control specifications. Table 4.1 lists some sample control gains generated by the script for various added load mass, M_l. The maximum load that can be added to the stage to achieve the rated ST II acceleration of 2.5 g is 7.26 kg.

M_l (kg)	M_t (kg)	f_0 (Hz)	ζ	k_p (V/m)	k_d (V.s/m)
0.0	7.74	15.0	0.75	2425.4	38.6
2.5	10.4	15.0	0.75	3208.8	51.1
5.0	12.4	15.0	0.75	3992.2	63.5
7.26	15.0	15.0	0.75	4700.4	74.8

Table 4.1: Sample controls gains calculated for a varying load mass

The total mass being moved by the motor is denoted by the M_t variable. There are two design control parameters that are used to generate the control gains: the natural frequency, f_0, and the damping ratio, ζ. Generally speaking, the natural frequency determines the speed of the response and the damping ratio determines the shape of the response (i.e. the overshoot). In order to satisfy these specifications, both controls gains increases as the load mass is augmented. The control design is explained next to give some background on how these gains are generated. The closed-loop transfer function that describes the response of the stage given a desired position was developed earlier and given in Equation [5] in Section 4.2.7. It is a second-order system and when the set-point velocity parameter $b_{sd} = 0$, it can be mapped to the general second-order transfer function

$$H(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \qquad [11]$$

where ω_0 is the natural frequency and ζ is the damping ratio. Note that ω_0 is the natural frequency in radians per second while f_0 is the natural frequency in Hertz. The relation between the two is

$$\omega_0 = 2\pi f_0 \qquad [12]$$

The denominator of the Shake Table II closed-loop transfer function in Equation [5] can be mapped to the denominator of transfer function [11], which is known as the characteristic equation, by setting the controls gains to

$$k_p = \omega_0^2 K_f \qquad [13]$$

and

$$k_d = 2\zeta\omega_0 K_f \qquad [14]$$

The gains listed in Table 4.1 are generated by setup.m using the proportional gain relationship [13] and the derivative gain formula defined in [14].

4.3.1.2. Computing the Maximum Setpoint: setpoint_limit.m

The setup.m script gives the option to generate the maximum setpoint plot. When the stage of the Shake Table II is tracking a sine wave, the maximum amplitude and frequency of the waveform must be known. By taking into account the Shake Table II limits, the maximum setpoint plot illustrates the maximum amplitude of the sine wave position command when it is being run at a certain frequency.

Consider the sine wave position setpoint

$$x_d = A_d \sin(2\pi f t) \qquad [15]$$

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

$$v_d = 2 A_d \cos(2\pi f t)\pi f \qquad [16]$$

and the corresponding acceleration is

$$a_d = -4 A_d \sin(2\pi f t)\pi^2 f^2 \qquad [17]$$

The maximum sine wave amplitude that shake 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. When starting at the center or home position, the stage is mechanically limited to moving ±3-inches. Therefore the maximum position of the table is

$$x_{max} = 0.07620\ [m] \qquad [18]$$

The velocity and acceleration limits of the table are computed in the Matlab M-File called stii_limits.m. Given the back-emf parameter of the ST II motor, K_m, and the maximum output voltage of the UPM-180-25B, VMAX_UPM, the maximum angular rate of the Shake Table II motor equals

$$\Omega_{max} = \frac{VMAX\_UPM}{K_m} \qquad [19]$$

The linear velocity of the stage is therefore

$$v_{max} = \frac{1}{2}\frac{\Omega_{max} P_b}{\pi} \qquad [20]$$

where P_b is the ball-screw pitch. The maximum force that can be delivered by the actuator is

$$F_{max} = \frac{K_t\ IMAX\_UPM}{P_b} \qquad [21]$$

where IMAX_UPM is the maximum peak current of the power amplifier and K_t is the current-torque constant of the ST II motor. The maximum load acceleration depends on the load mass, M_t, and the rated acceleration of the table, A_LIM_RATED = 2.5 g. It is expressed

$$a_{max} = \min\left(\frac{F_{max}}{M_t}, A\_LIM\_RATED\right) \qquad [22]$$

Evaluating equations [20] and [22] using the ST II parameters in Table 4.2 and the UPM-180-25B specifications, the maximum velocity and acceleration are

$$v_{max} = 0.665\left[\frac{m}{s}\right] \qquad [23]$$

and

$$a_{max} = 24.5 \left[\frac{m}{s^2} \right] \qquad [24]$$

Table 4.2 lists the equations to calculate the maximum setpoint amplitude due to the position limit $A_{max,p}$, due to the maximum velocity $A_{max,v}$, and due to the acceleration constraint $A_{max,a}$.

Limit	Maximum Sine Wave Amplitude
Position	$A_{max,p} = x_{max}$
Velocity	$A_{max,v} = \frac{1}{2} \frac{v_{max}}{\pi f}$
Acceleration	$A_{max,a} = \frac{1}{4} \frac{a_{max}}{\pi^2 f^2}$
Combined	$A_{max} = \min\left(x_{max}, \frac{1}{2} \frac{v_{max}}{\pi f}, \frac{1}{4} \frac{a_{max}}{\pi^2 f^2} \right)$

Table 4.2: Equations used to find the maximum setpoint amplitude

With the equations given in Table 4.2, the top plot shown in Figure 4.21 can be generated. 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. It is calculated in the Matlab script called load_accelerations.m with the equation

$$a_{max} = 4 A_{max,a} \pi^2 f^2 \qquad [25]$$

4.3.2. Generating Composite Sine Wave: make_sine.m

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

$$x_d = A_1 \sin(2 \pi f_1 t) + A_2 \sin(2 \pi f_2 t) + A_3 \sin(2 \pi f_3 t) \qquad [26]$$

the velocity

$$v_d = 2A_1\cos(2\pi f_1 t)\pi f_1 + 2A_2\cos(2\pi f_2 t)\pi f_2 + 2A_3\cos(2\pi f_3 t)\pi f_3 \quad [27]$$

and the acceleration

$$a_d = -4A_1\sin(2\pi f_1 t)\pi^2 f_1^2 - 4A_2\sin(2\pi f_2 t)\pi^2 f_2^2 - 4A_3\sin(2\pi f_3 t)\pi^2 f_3^2 \quad [28]$$

Follow these steps to use the script:

1. Load Matlab.

2. Through the Current Directory window, go to the STII\Lab Files\QuaRC Controllers folder on your PC (which was copied from the ST II CD).

3. Open the make_sine.m file.

4. The INPUT section of the make_sine script is shown in Text 4.7 below. Set the amplitude vector, A_d, and frequency vector, f_d, to create a desired compound sine wave. Generally speaking amplitude of $A_d = [A_1, A_2 ... A_n]$ and $f_d = [f_1, f_2 ... f_n]$ can be defined.

```
% ************************************************************************
% INPUT
% ************************************************************************
% sine wave amplitude for each excitation (mm)
Ad  = [2.5, 2, 0.5];
% axes sine wave excitation frequencies (Hz)
fd = [1, 4, 10];
% time duration (s)
tf = 3;
% sampling period (s/sample)
dt = default_sample_time;
```

Text 4.7: "INPUT" section in the make_sine.m script

5. The MAKE SINE WAVE section of the make_sine.m script is shown in Text 4.8. The construct_sine_wave_trajectory file creates the position, velocity, and acceleration time-based array. Because the UPM-180-25B amplifier is not enabled for the first 0.7 seconds, the first second of the compound sine wave is always padded with zeros. The total duration of the waveform is therefore t_f+1 seconds.

```
% ************************************************************************
% MAKE SINE WAVE
% ************************************************************************
% construct sine wave trajectory
[t, xd_mm, vd_mm, ad_mm] = construct_sine_trajectory(fd, Ad, tf, dt);
% Desired position (m)
xd = xd_mm / 1000;
% Desired velocity (m/s)
vd = vd_mm / 1000;
% Desired acceleration (g)
ad = ad_mm / 1000 / 9.81;
```

Text 4.8: "MAKE SINE WAVE" section in make_sine.m script

6. Run the Matlab M-File by clicking on Debug | Run in the Editor menu bar or clicking on the Run icon in the Editor tool bar.

7. After generating the sine wave, the make_sine.m script generates a plot. The plot pictured in Figure 4.22 was generated when using the A_d and f_d vectors specified in Text 4.7.

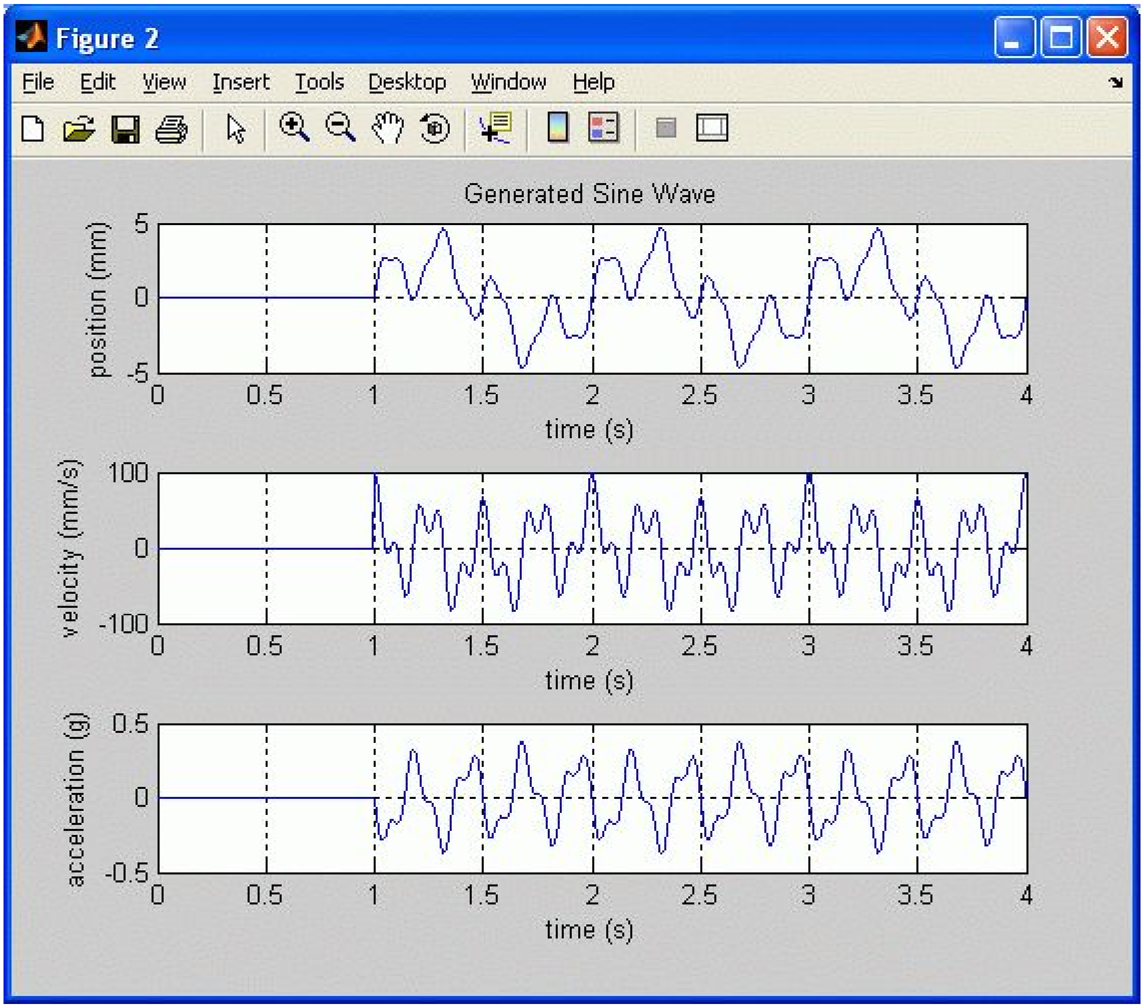


Figure 4.22: Composite sine wave plot generated by the make_sine.m script

4.3.3. Constructing Scaled Earthquake: make_quake.m

The make_quake.m script builds a trajectory that can be used in the q_data 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. Section 4.3.3.1 describes how to run the make_quake.m script in order to do this.

4.3.3.1. Running the Script

Follow these steps to run the make_quake.m file:

1. Load Matlab.

2. Through the Current Directory window, go to the STII\Lab Files\mdl folder on PC.

3. Open the make_quake.m file.

4. The INPUT section of the make_quake script is shown in Text 4.9 below. Enter the name of earthquake file that is to be replayed on the shake table. As shown in Text 4.9, the file is set to "HIK000.AT2" which is the Kobe earthquake. The x_max parameter determines the maximum position of the scaled setpoint trajectory.

```
% ************************************************************************
% INPUT
% ************************************************************************
% name of data source file, ex. 'HIK000.AT2' or 'SYL090.AT2'
input_filename = 'HIK000.AT2';
% Maximum scaled position (cm). NOTE: Set below 7.62 cm stroke limit.
x_max = 3.0;
```

Text 4.9: "INPUT" section in the make_sine.m script

5. The MAKE QUAKE section is shown in Text 4.10. As illustrated in Figure 4.23, there are three main steps to create the position setpoint, x_d, from recorded earthquake data.

```
% ************************************************************************
% MAKE QUAKE
% ************************************************************************
% load recorded acceleration earthquake data in workspace (g) and sample
% time (s)
[dt,acc_data] = init_earthquake_data(input_filename);
% construct trajectory
[t,a] = construct_quake_trajectory(acc_data,dt);
%
% Compute desired position of STII to achieve actual quake accelerations.
%    t        Setpoint time array (s).
%    xd_cm    Position setpoint array (cm)
%    ad       Desired acceleration array (g)
%    tf       Duration of the scaled earthquake trajectory (s)
[t, xd_cm, ad, tf] = q_scale(t, a, x_max);
% Convert desired scaled position (m)
xd = xd_cm / 100;
```

Text 4.10: "MAKE QUAKE" section in make_sine.m script

The init_earthquake_data.m function 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. The construct_quake_trajectory.m script creates a trajectory containing the recorded earthquake acceleration data, [t,a]. Then, 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.

Figure 4.23: Steps to generating the setpoint trajectory from a raw earthquake file

6. Run the Matlab M-File by clicking on Debug | Run in the Editor menu bar or clicking on the Run icon in the Editor tool bar. The output displayed in the Matlab Command Window should be similar to Text 4.11 below. The Kobe earthquake had a maximum displacement of 3.09 cm and this was scaled down to 3.0 cm (as set by x_max). In order to achieve the same acceleration as Kobe, the time of the generated trajectory is compressed from 77.98 to 76.82 seconds.

```
*** Usage : [Tc,Xc,Ac,Te]=q_scale(t,a,xmax)
t   : array of time at equal sampling intervals in seconds
a   : array of acceleration record in g to match t
xmax: maximum amplitude of motion that you want in cm
Note that this should not exceed the limits of the table !!
Tc  : Command time array
Xc  : Position command array that should be commanded to the table in cm
Ac  : Acceleration array in g that is the result of differentiating Xc
twice
Te  : Duration of the run

 Original time step:    0.02000
 Step 1 of 3: Get displacements
 Step 2 of 3: Scale records
 Ratio of table displacement to ground displacement: 0.970064

 Step 3 of 3: Scaling time
 Time step after scaling = 0.019698
*** Done ***
*** Displacement scaled from original movement of  3.09 cm to  3.00 cm
*** Time scaled from original duration of 77.98 seconds to 76.82 seconds
*** Record size is  3950 samples
```

Text 4.11: Output of make_quake.m script in Matlab Command Window

7. The q_scale.p function script also generates a plot, which is pictured in Figure 4.24 for the Kobe earthquake, that displays the desired acceleration and recorded

earthquake acceleration in the top plot (in gravitational units) and the scaled position setpoint in the bottom plot (in centimeters). Notice that 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. As a result, the two plots are layered on top of each other.

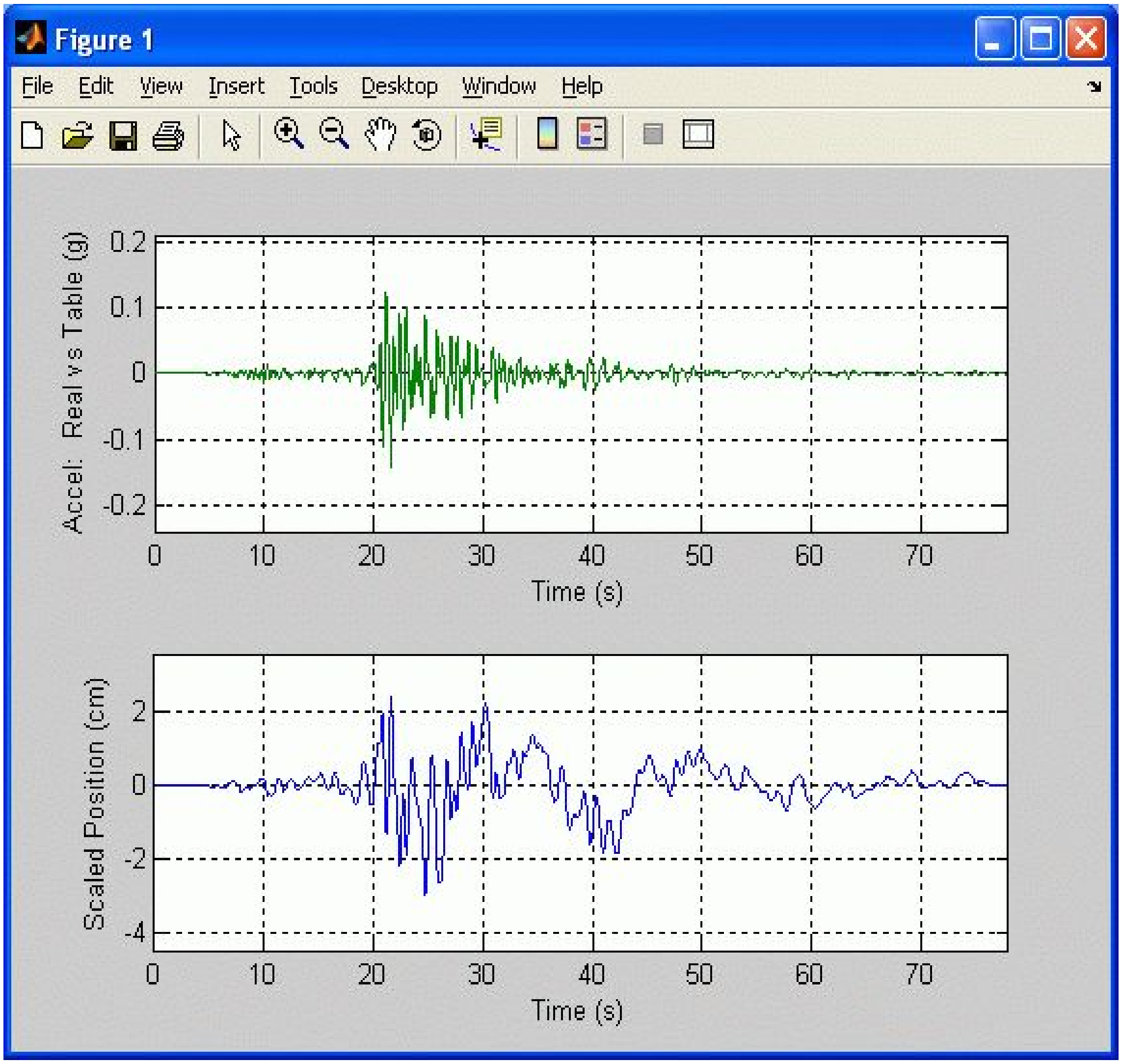


Figure 4.24: Plot generated by q_scale.p showing generated acceleration and scaled position

Once the setpoint is generated, the q_data Simulink Model can be used to replay the earthquake on the Shake Table II. See Section for the procedure to run the tremor on the table. The next sections explain how to download additional earthquake data and generate Bode plots.

4.3.3.2. Downloading an Earthquake

There are a variety of resources on the Internet where real earthquake data can be downloaded. Two example sources are the Pacific Earthquake Engineering Research Center (PEER) Strong Motion Database website at http://peer.berkeley.edu/smcat/search.html from the University of California and the Lamont-Doherty Earth Observatory of Columbia University at http://www.ldeo.columbia.edu/nceer/ strongmo.html. 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. Follow the procedure below to find the Kobe earthquake acceleration data recorded at the HIK station from the PEER database by searching:

1. Open an Internet browser and enter the following address to search for an earthquake:

http://peer.berkeley.edu/smcat/search.html

2. As shown in Figure 4.25, select Kobe 1995/01/16 20:46 under the Earthquake drop-down menu and click on the Search button.

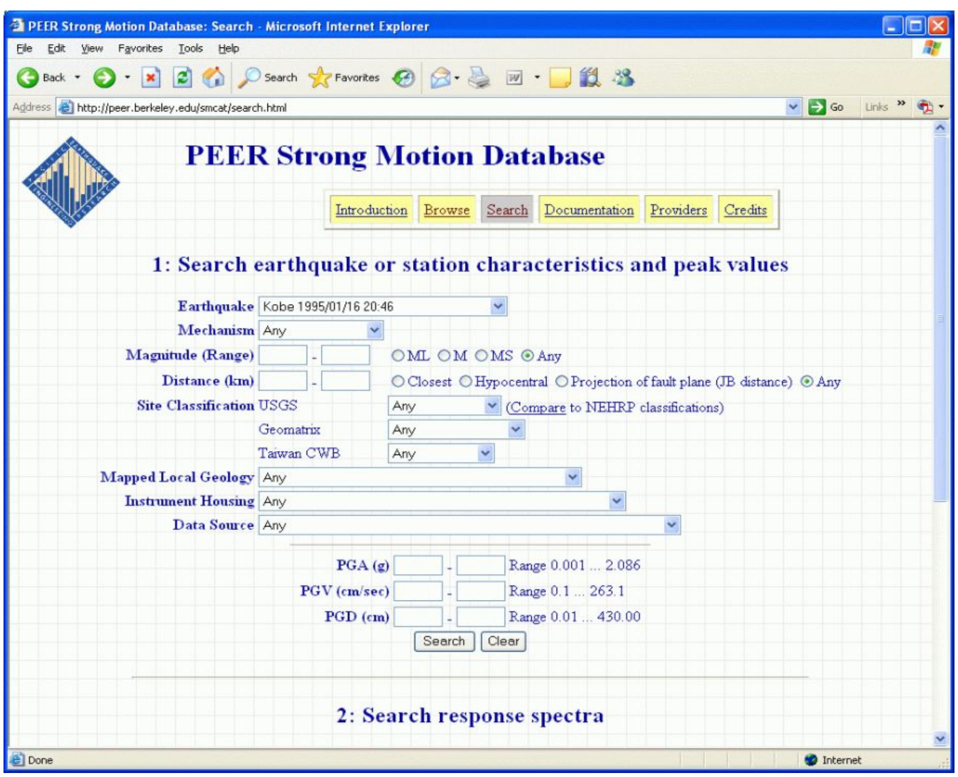


Figure 4.25: Searching for an earthquake on the Berkeley website

3. The Query Results page is displayed and it lists all the stations that recorded the Kobe earthquake. Click on Record ID P1040 to view the results from the HIK station. The P1040: Earthquake and Station Details web page shown in Figure 4.26 loads.

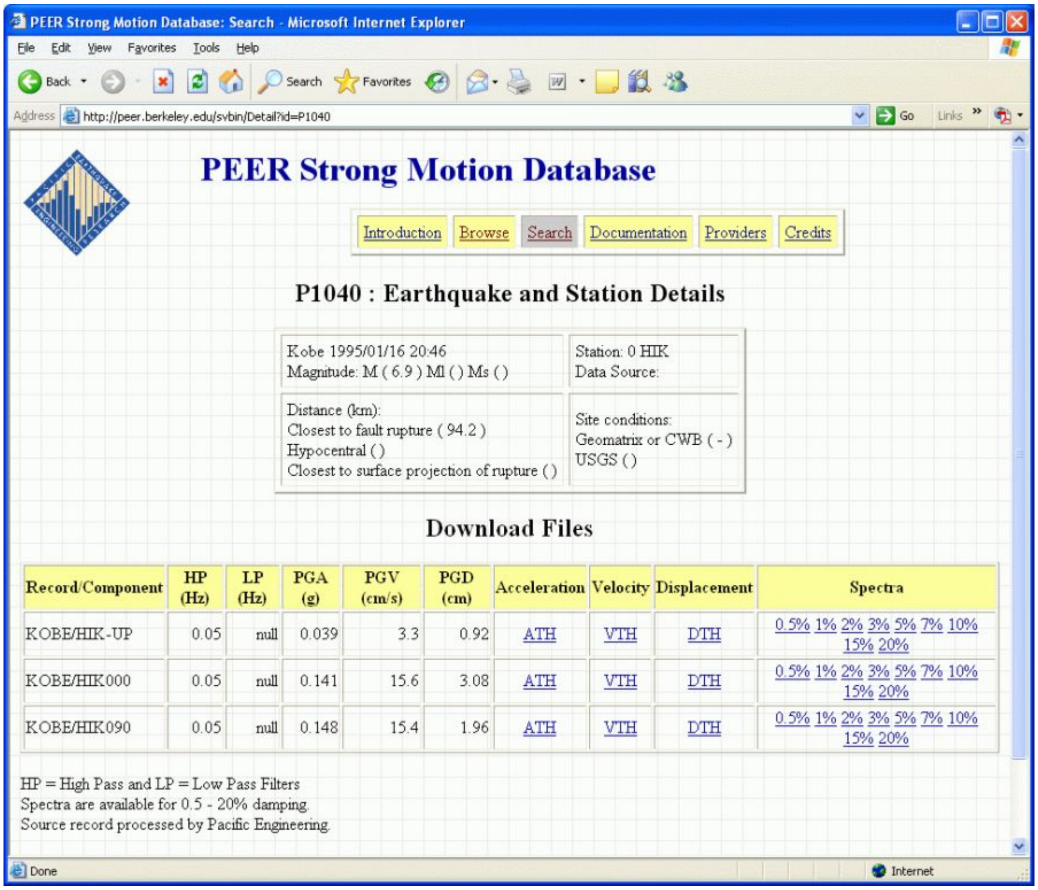


Figure 4.26: Web page showing data collected for Kobe tremor at the HIK station

4. As depicted in Figure 4.27, right-click on the ATH link under the KOBE/HIK000 record to download the displacement data for the Kobe earthquake in the 000 direction.

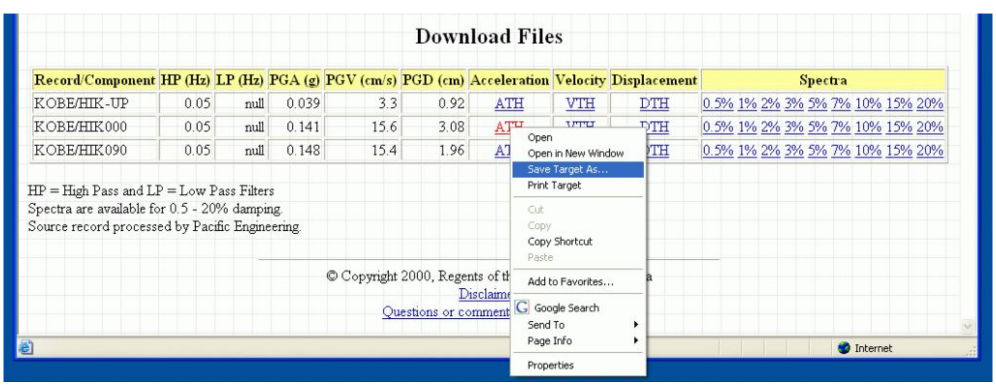
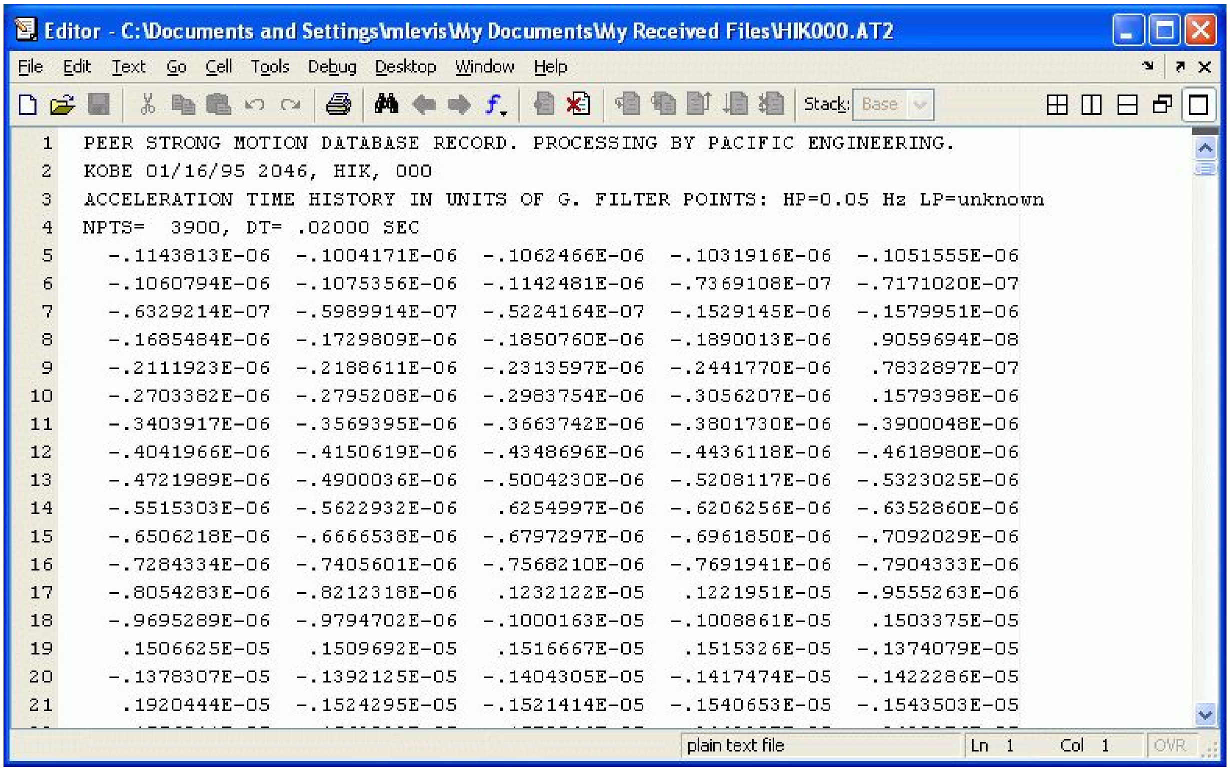


Figure 4.27: Saving earthquake acceleration record

5. Once the earthquake record is downloaded, save the AT2 text file in the STII\Lab Files\mdl folder on your PC. When opened in Matlab Editor, the HIK000.AT2 file appears as shown in Figure 4.28.




```
PEER STRONG MOTION DATABASE RECORD. PROCESSING BY PACIFIC ENGINEERING.
KOBE 01/16/95 2046, HIK, 000
ACCELERATION TIME HISTORY IN UNITS OF G. FILTER POINTS: HP=0.05 Hz LP=unknown
NPTS=  3900, DT= .02000 SEC
  -.1143813E-06  -.1004171E-06  -.1062466E-06  -.1031916E-06  -.1051555E-06
  -.1060794E-06  -.1075356E-06  -.1142481E-06  -.7369108E-07  -.7171020E-07
  -.6329214E-07  -.5989914E-07  -.5224164E-07  -.1529145E-06  -.1579951E-06
  -.1685484E-06  -.1729809E-06  -.1850760E-06  -.1890013E-06   .9059694E-08
  -.2111923E-06  -.2188611E-06  -.2313597E-06  -.2441770E-06   .7832897E-07
  -.2703382E-06  -.2795208E-06  -.2983754E-06  -.3056207E-06   .1579398E-06
  -.3403917E-06  -.3569395E-06  -.3663742E-06  -.3801730E-06  -.3900048E-06
  -.4041966E-06  -.4150619E-06  -.4348696E-06  -.4436118E-06  -.4618980E-06
  -.4721989E-06  -.4900036E-06  -.5004230E-06  -.5208117E-06  -.5323025E-06
  -.5515303E-06  -.5622932E-06   .6254997E-06  -.6206256E-06  -.6352860E-06
  -.6506218E-06  -.6666538E-06  -.6797297E-06  -.6961850E-06  -.7092029E-06
  -.7284334E-06  -.7405601E-06  -.7568210E-06  -.7691941E-06  -.7904333E-06
  -.8054283E-06  -.8212318E-06   .1232122E-05   .1221951E-05  -.9555263E-06
  -.9695289E-06  -.9794702E-06  -.1000163E-05  -.1008861E-05   .1503375E-05
   .1506625E-05   .1509692E-05   .1516667E-05   .1515326E-05  -.1374079E-05
  -.1378307E-05  -.1392125E-05  -.1404305E-05  -.1417474E-05  -.1422286E-05
   .1920444E-05  -.1524295E-05  -.1521414E-05  -.1540653E-05  -.1543503E-05
```

Figure 4.28: Raw earthquake data file HIK000.AT2 shown when opened in Matlab Editor

Chapter 5

Application of Shake Table

5.1 Introduction

The aim of this chapter is to demonstrate the usefulness of shake table to carry out structural dynamics experiments to gain insight into behavior of structures and to explore methods to do so. We discuss how the Active Mass Damper can be used to control the structural response "actively". We compare the response recorded from the accelerometer for two simulations, i.e. with and without the Active Mass Driver running, and observe the difference in response.

5.2 Energy Dissipation Systems

Earthquake imparts kinetic energy in a structural system which causes displacement and damage. Modern engineering practice enables the buildings to absorb earthquake shocks and dissipate the imparted energy through few special members. Structural engineers control the response of structure by conventional and modern elements. Structural control can be divided in two categories; Passive Control and Active control.

5.2.1 Passive Structural Control

Passive control is done by use of special members like base isolators and dampers. This is called passive because structure and members are carefully designed and we wait for an earthquake event. During the entire duration of the earthquake no modification can be done to the performance characteristics of these members and structure is passive to the environmental event. In 1980's Ron Mayes, a structural engineer from California started on the concept of base isolation for seismic resistance of buildings. In 1990,s there was a virtual explosion in use of another high technology member known as damper. Damper is either added to a bracing member or attached between floor and brace. In the event of an earthquake the relative difference in displacement of two adjacent floors imparts a force at the end of floors which reduces the displacement.

5.2.2 Active Structural Control

This type of control is more complex, where the performances of specially manufactured members are modified according to forcing function as it occurs. The devices are inactive till a threshold of earthquake is reached than the monitoring is real time. The system is mobilized in such a way so as to work against the forcing function and control the excessive displacements. Active control involves placing hydraulic rams or other actuating devices within the structure, which introduce forces counter to those caused by the earthquake, thus opposing some or all of the seismic demand. To determine how much force to apply to an actuator involves a real-time solution of the dynamics of the structure. Sensors must determine the ground motion at the base of the structure, a structural analysis for these accelerations must be performed on a dedicated processor, and the optimum pattern of forces must be determined which are then applied via quick-response actuators during a time interval equal to or less than the dynamic response of the structure. Some of the techniques currently under investigation are: tuned mass dampers, active tensioning of tendons and reliance on liquid sloshing (Tapal K Sen, 2008).

5.3 Seismic Excitation and Vibration Control

Shake Table Testing was done for scaled time history data, each time history was separately evaluated as the shake table is unidirectional, and the linear cart was modeled to behave passively and actively to seismic excitation, and the observed damping was compared for both cases. The actual aim of this work is to effectively compile a Simulink model and back hand Matlab working codes, which can be used for testing for any excitation.

Various groups have proposed different control algorithms for use in tall buildings and towers (Soong, 1990; Housner et al. 1997). The experimental setup investigated the probability of minimizing the stresses on a single floor. Several simulations were developed on Matlab/Simulink during experimental work to input the desired earthquake loading and different cases were evaluated, the module was amplified to obtain comparable result. Seismic excitation and other functions were also evaluated; the graphical results show the efficiency of the model Figure 5.7 and Figure 5.8.

5.3.1 System

In order to understand the experimental setup a brief summary of the setup is necessary. It is conceptually similar to active mass dampers used to suppress vibrations in tall structures (e.g. high-rise buildings) and to protect not only against earthquakes but also, for example, strong winds (e.g. hurricanes). This laboratory takes advantage that the dynamics of the active mass (i.e. cart) are tightly coupled to these of the building-like structure to which it is attached. Therefore, the active mass can either be used to excite or to dampen the flexible structure vibration. The purpose of the AMD is to design a switching-mode control system that first excites the vibration mode of the one-story structure and then dampens the structure oscillation.

The top of the structure accommodates a rack and a shaft designed to work with a linear cart, which thus constitutes the controllable mass at the top of the structure. The cart is free to move along in the same direction as the structure. Specifically, it is a precisely machined solid aluminum cart which is driven by a high quality DC motor equipped with a planetary gearbox. The cart slides along a stainless steel shaft using linear bearings. When the motor turns, the torque created at the output shaft is translated, through the rack and pinion mechanism, to a linear force (i.e. control force) which results in the cart's motion.

5.3.2 Mathematical model

A simplified model for active mass damper was determined, as seen in Figure 5.1.

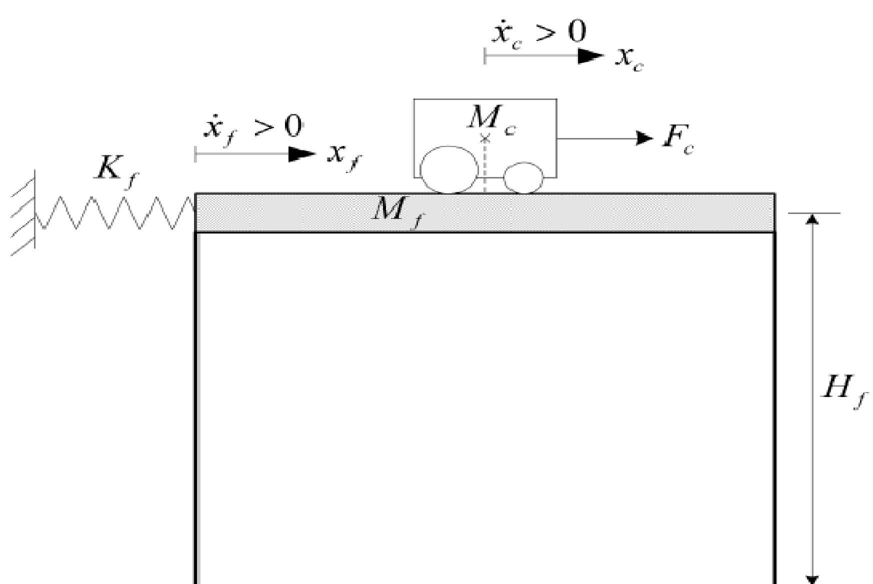


Figure 5.1: Simplified Model of the Arrangement

Parameters of model are given below:

Flexible Structure Length = 0.32 m

Flexible Structure Height = 0.5 m

Flexible Structure Depth = 0.11 m

Overall Cart Rack Length = 0.31 m

Overall Cart Rack Height = 0.13 m

Overall Cart Rack Depth = 0.11 m

Structure Floor Height, H_f = 0.53 m

Flexible Structure Total Mass, M_s = 1.60 kg

Structure Top Floor Mass, M_{tf} = 0.68 kg

Rack Mass, M_r = 0.70 kg

Top Floor Natural frequency, f_n = 2.5 Hz

5.3.3 Equations of Motion

The general dynamic equations of the Active Mass Damper – One Floor (AMD-1) system are now explained. The Lagrange's method is used to obtain the dynamic model of the system. In this approach, the single input to the system is considered to be Fc. To carry out the Lagrange's approach, the Lagrangian of the system needs to be determined. This is done through the calculation of the system's total potential and kinetic energies. Let us first calculate the system's total potential energy VT. The potential energy in a system is the amount of energy that that system, or system element, has due to some kind of work being, or having been, done to it. It is usually caused by its vertical displacement from normality (gravitational potential energy) or by a spring-related sort of displacement (elastic potential energy). Here, there is no gravitational potential energy since both AMD-1cart and structure are assumed to stay at a constant elevation (i.e. no vertical displacement from normality), for small angular structure oscillations. However, the AMD-1 top floor is modelled as a linear spring-mass system. Therefore, the AMD-1's total potential energy is only due to its elastic potential energy. It results that the total potential energy of the AMD-1 plant can be fully expressed as:

$$V_T = \frac{1}{2} K_f x_f(t)^2 \qquad [1]$$

It can be seen from Equation [1] that the total potential energy can be expressed in terms of the system's generalized coordinates alone.

Let us now determine the system's total kinetic energy TT. The kinetic energy measures the amount of energy in a system due to its motion. Here, the total kinetic energy is the sum of the translational and rotational kinetic energies arising from the motorized linear cart (since the cart's direction of translation is orthogonal to that of the rotor's rotation) and the translational kinetic energy of the flexible structure's floor. In other words, the total kinetic energy of the AMD-1 system can be formulated as below:

$$T_T = Tt_c + Tr_c + Tt_f \qquad [2]$$

First, the translational kinetic energy of the motorized cart can be expressed as a function of its centre of gravity's linear velocity, as shown by the following equation:

$$Tt_c = \frac{1}{2} M_c \left(\left(\frac{d}{dt} x_c(t) \right) + \left(\frac{d}{dt} x_f(t) \right) \right)^2 \qquad [3]$$

Second, the rotational kinetic energy due to the cart's DC motor can be characterized by:

$$Tr_c = \frac{1}{2} \frac{J_m K_g^2 \left(\frac{d}{dt} x_c(t) \right)^2}{r_{mp}^2} \qquad [4]$$

Third and last, the structure floor's translational kinetic energy can be characterized as follows:

$$Tt_f = \frac{1}{2} M_f \left(\frac{d}{dt} x_f(t) \right)^2 \qquad [5]$$

Thus by replacing Equations [3], [4], and [5] into Equation [2], the system's total kinetic energy results to be such as:

$$T_T = \left(\frac{1}{2} M_c + \frac{1}{2} \frac{J_m K_g^2}{r_{mp}^2} \right) \left(\frac{d}{dt} x_c(t) \right)^2 + M_c \left(\frac{d}{dt} x_f(t) \right) \left(\frac{d}{dt} x_c(t) \right)$$

$$+ \left(\frac{1}{2} M_c + \frac{1}{2} M_f \right) \left(\frac{d}{dt} x_f(t) \right)^2$$

[6]

It can be seen from Equation [6] that the total kinetic energy can be expressed in terms of the generalized coordinates' first-time derivatives. Let us now consider the Lagrange's equations for our system. By definition, the two Lagrange's equations, resulting from the previously-defined two generalized coordinates, xc and xf, have the following formal formulations:

$$\left(\frac{\partial}{\partial t \, \partial \frac{d}{dt} x_c(t)} L \right) - \left(\frac{\partial}{\partial x_c} L \right) = Q_{x_c}$$

[7]

and:

$$\left(\frac{\partial}{\partial t \, \partial \frac{d}{dt} x_f(t)} L \right) - \left(\frac{\partial}{\partial x_f} L \right) = Q_{x_f}$$

[8]

In Equations [7] and [8], above, L is called the Lagrangian and is defined to be equal to:

$$L = T_T - V_T$$

[9]

For our system, the generalized forces can be defined as follows:

$$Q_{x_c}(t) = F_c(t) - B_{eq} \left(\frac{d}{dt} x_c(t) \right) \qquad \text{and} \qquad Q_{x_f}(t) = 0$$

[10]

It should be noted that the (nonlinear) Coulomb friction applied to the linear cart has been neglected. Furthermore, the viscous damping force applied to the structure floor has also been neglected. Calculating Equation [7] results in a more explicit expression for the first Lagrange's equation, such that:

$$\frac{(M_c r_{mp}^2 + J_m K_g^2)\left(\frac{d^2}{dt^2}x_c(t)\right)}{r_{mp}^2} + M_c\left(\frac{d^2}{dt^2}x_f(t)\right) = F_c - B_{eq}\left(\frac{d}{dt}x_c(t)\right)$$

[11]

Likewise, calculating Equation [8] also results in a more explicit form for the second Lagrange's equation, as shown below:

$$M_c\left(\frac{d^2}{dt^2}x_c(t)\right) + (M_c + M_f)\left(\frac{d^2}{dt^2}x_f(t)\right) + K_f x_f(t) = 0$$

[12]

Finally, solving the set of the two Lagrange's equations, as previously expressed in Equations [11] and [12], for the second-order time derivative of the two Lagrangian coordinates results in the following two equations:

$$\frac{d^2}{dt^2}x_c(t) = \frac{r_{mp}^2 M_c x_f(t) K_f}{M_c r_{mp}^2 M_f + J_m K_g^2 M_c + J_m K_g^2 M_f} + \frac{r_{mp}^2(-M_c B_{eq} - M_f B_{eq})\left(\frac{d}{dt}x_c(t)\right)}{M_c r_{mp}^2 M_f + J_m K_g^2 M_c + J_m K_g^2 M_f}$$

$$+ \frac{r_{mp}^2(M_c F_c + M_f F_c)}{M_c r_{mp}^2 M_f + J_m K_g^2 M_c + J_m K_g^2 M_f}$$

and:

[13]

$$\frac{d^2}{dt^2}x_f(t) = -\frac{(M_c r_{mp}^2 + J_m K_g^2) x_f(t) K_f}{M_c r_{mp}^2 M_f + J_m K_g^2 M_c + J_m K_g^2 M_f} + \frac{M_c B_{eq} r_{mp}^2\left(\frac{d}{dt}x_c(t)\right)}{M_c r_{mp}^2 M_f + J_m K_g^2 M_c + J_m K_g^2 M_f}$$

$$- \frac{M_c F_c r_{mp}^2}{M_c r_{mp}^2 M_f + J_m K_g^2 M_c + J_m K_g^2 M_f}$$

[14]

Equations [13] and [14] represent the Equations of Motion (EOM) of the system. It can be noticed, in the case of the AMD-1 system, that the EOM are linear.

As a remark, if both Beq and Jm are neglected, Equations [13] and [14] become:

$$\frac{d^2}{dt^2} x_c(t) = \frac{K_f x_f(t)}{M_f} + \frac{(M_c + M_f) F_c}{M_c M_f} \quad [15]$$

and:

$$\frac{d^2}{dt^2} x_f(t) = -\frac{K_f x_f(t)}{M_f} - \frac{F_c}{M_f} \quad [16]$$

5.3.4 Seismic Excitation

Various earthquake data was checked in the model which was obtained from peer database, but for this research work Kashmir, 2005 earthquake is used as shown in Figure 5.2 (a-f). As there was a limitation of ±7.62cm of maximum stroke limit for the Shake table this earthquake data was scaled to a limit of ± 3cm to simulate an earthquake on the Shake Table system, the data was in gravitational acceleration units (g).

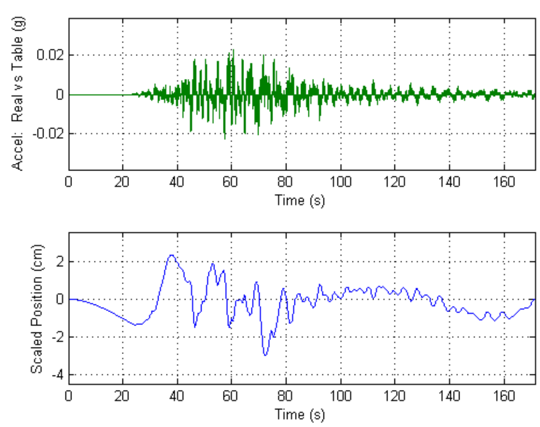


Figure 5.2(a): Scaled inputs used with Shake table (NIL-EW)

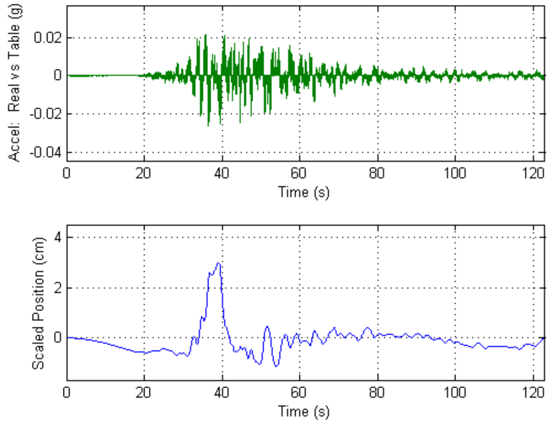


Figure 5.2(b): Scaled inputs used with Shake table (NIL-NS)

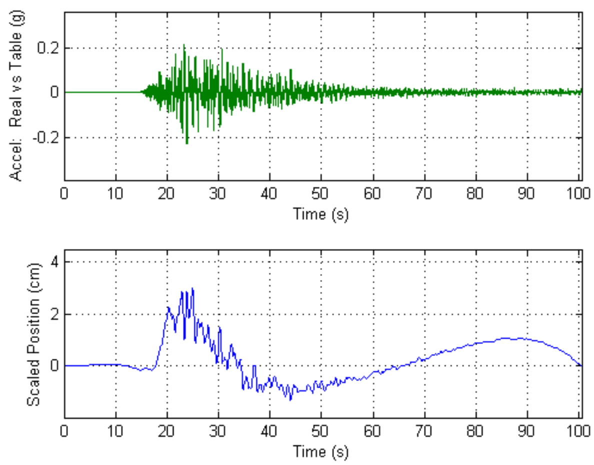


Figure 5.2(c): Scaled inputs used with Shake table (ABT-EW)

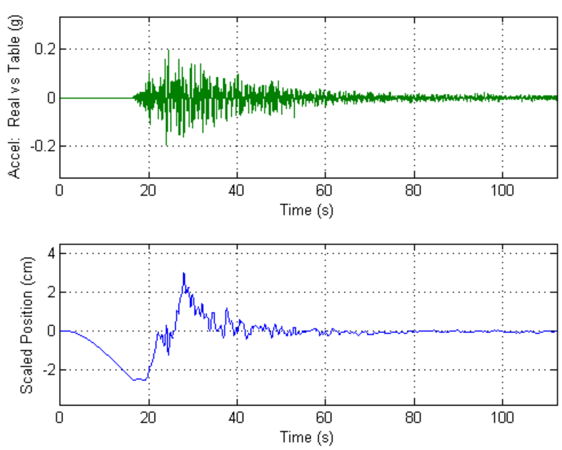


Figure 5.2(d): Scaled inputs used with Shake table (ABT-NS)

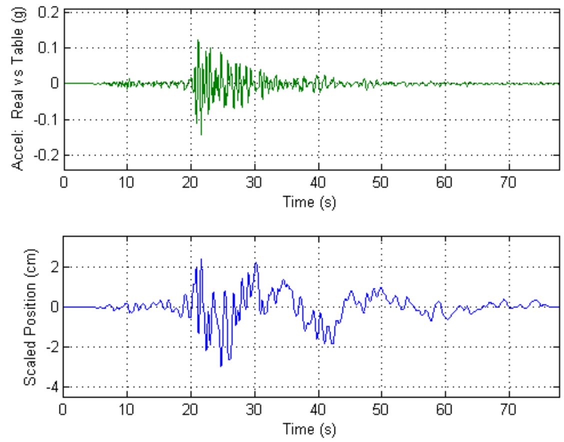


Figure 5.2(e): Scaled inputs used with Shake table (KOBE)

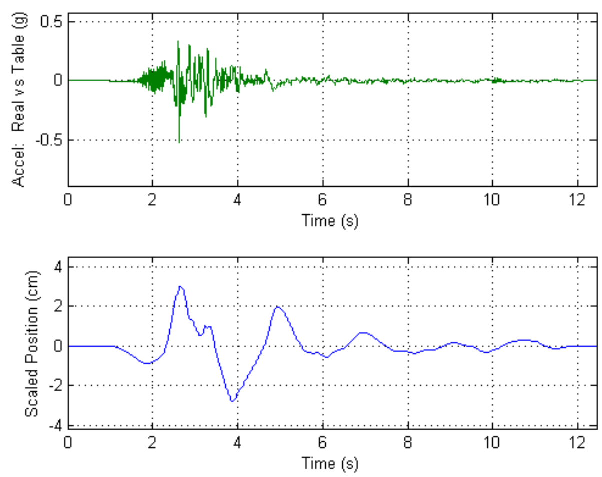


Figure 5.2(f): Scaled inputs used with Shake table (ELCENTRO)

5.3.5 Simulation

Simulations were developed and a state feedback controller was used to regulate the motion of the carts on the floor of the structure. The simulations were designed in Simulink as shown in Figure 5.5 and Figure 5.6. These simulations stars with input set points from Matlab workspace which can be any excitation, which is forwarded to the position controller where it is converter to input accelerations, velocities and displacements. These units go to the Shake table as input command then after shaking the signals are received from the shaker table which is displayed in different scopes attached at the end (right side) of the simulation model. There is a stop controller placed which commands the controller to stop when the excitation duration is complete. These blocks are added from Simulink library, and placed in sequence of input and output requirement and are connected by instructional priority, and scopes collect data from the accelerometers and Damper unit, placed at Table and Floor level. Figure 5.4 captures the Simulink simulation prepared for any excitation predefined in Matlab, which was extended for the use with Damper in Figure 5.6.

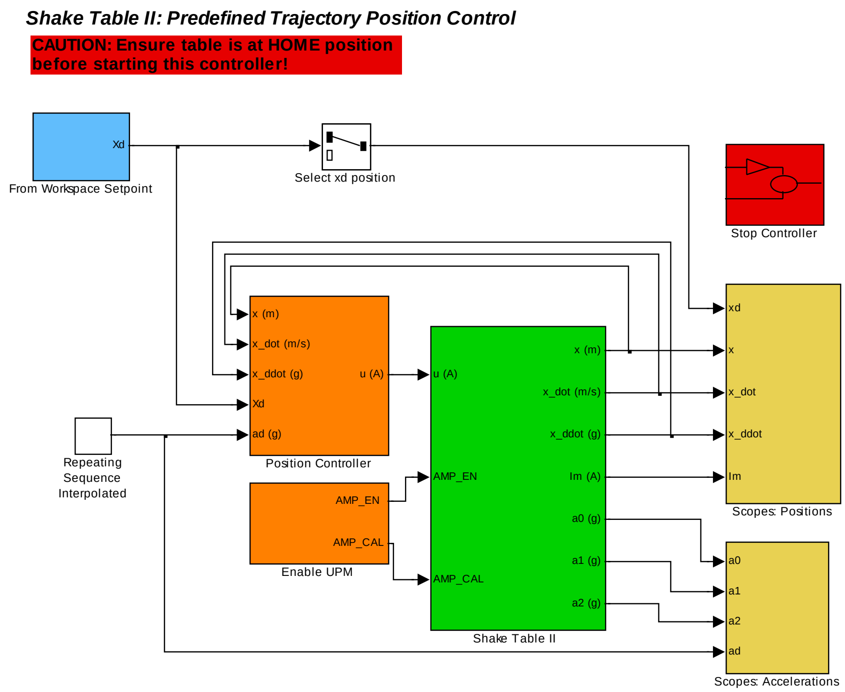


Figure 5.4: Simulation modeled in Simulink for any predefined excitation to be used as input trajectory for Shake table

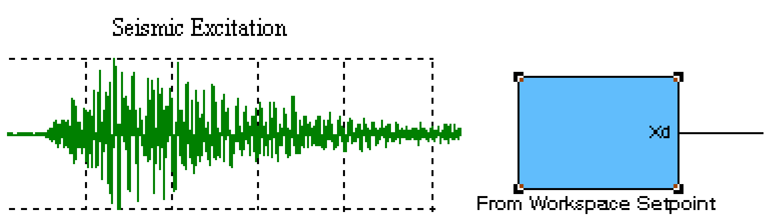


Figure 5.5: Schematic diagram showing predefined excitation to be saved as workspace set-point in Matlab for Simulink simulations

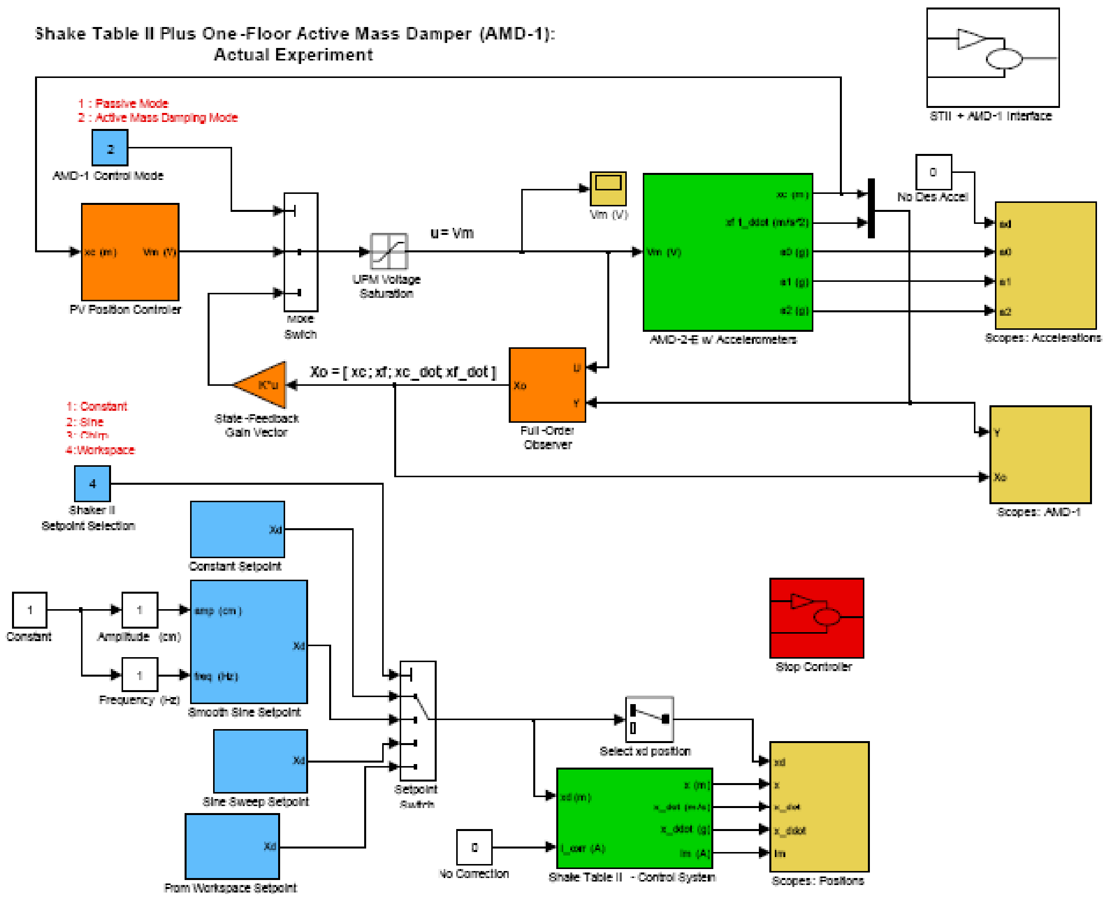


Figure 5.6: Simulation modeled in Simulink: Upper part of Scheme implements the mass damping control as active or passive and lower part implements any predefined excitation to be used as input trajectory for shake table

Figure 5.6 shows the extended version of the SIMULINK simulation of Figure 5.4, the simulation had two schemes, one for the shaker table excitation, and the other for damper control, the Upper Scheme is for damper and two control cases were modeled in it, one as a Passive mass damping Unit and one for Active mass damping Unit, which can be selected before the starting of test, knowing the cart unit is physically centralized. The lower scheme is basically same as the simulation of Figure 5.6 the added feature were four options of excitation that are for a constant force, a sine function, a Chirp function and an Earthquake Function. The Interface and Stopping function blocks are same as before. After summing the individual state-gain contributions to the input signals, saturation block is placed on signal for the control voltage to cart. This is done to limit the voltage range, which the controller can impart to the cart in order to avoid electrical damage to the motor or mechanical damage to the rack-and-pinion mechanism.

The responses and accelerations which were seen in different scopes were real time signals obtained from the built in transducer of an accelerometer, in order to record the data obtained during the test a ".mat" file block was added to desired scopes to record the data, as a row matrix file, this file was finally processed and plotted in MATLAB and shown in Figure 5.7.

The simulation was modeled in such a way that uses the seismic excitation as MATLAB workspace set point input and any input excitation wave Figure can be selected for Shake table input impulse this excitation as mentioned was scaled, different scopes were attached to the model to monitor the accelerometer values and the model integrate the values twice to yield displacements.

5.4 Vibration reduction

After the controller was implemented, we evaluated the response of the system subject to different inputs and of seismic scaled waves. Figure 5.7 (a-f) shows the displacement for the floor for without damping and with Passive and Active case.

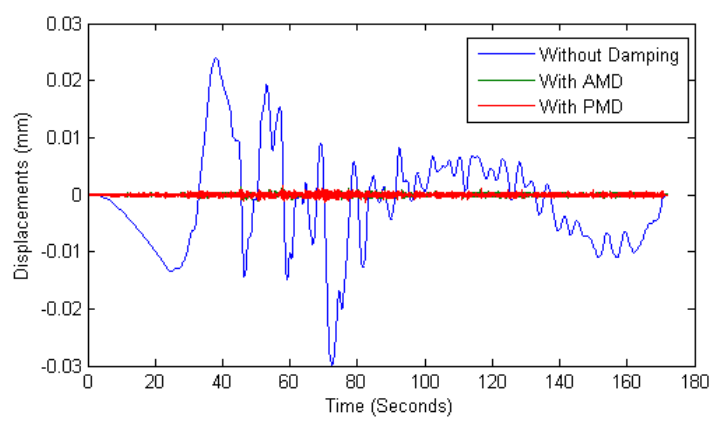


Figure 5.7(a): Floor Response to Earthquake Excitation (NIL-EW)

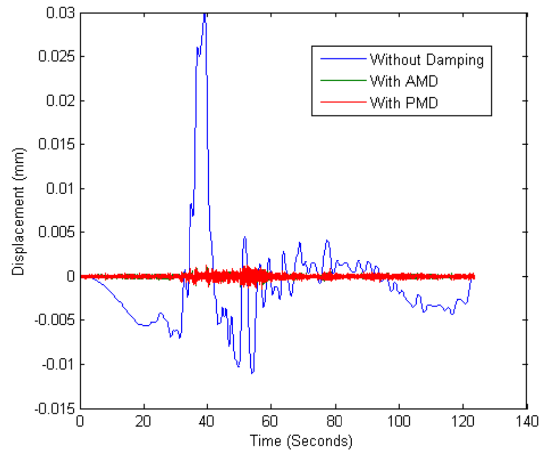


Figure 5.7(b): Floor Response to Earthquake Excitation (NIL-NS)

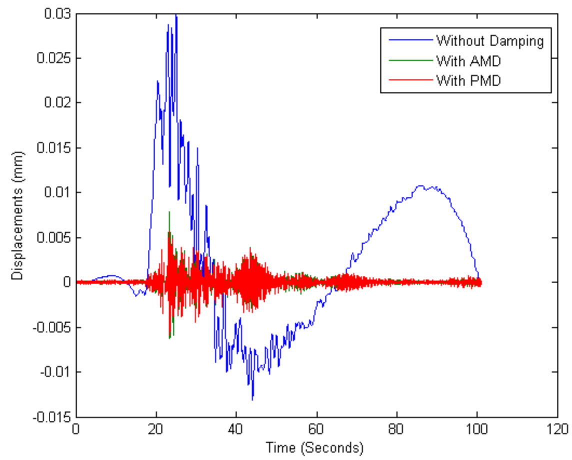


Figure 5.7(c): Floor Response to Earthquake Excitation (ABT-EW)

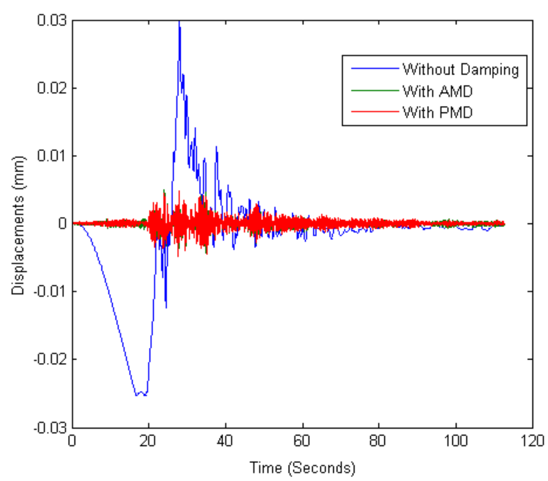


Figure 5.7(d): Floor Response to Earthquake Excitation (ABT-NS)

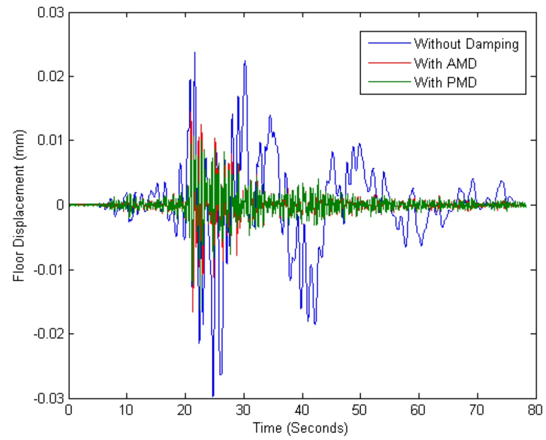


Figure 5.7(e): Peak Floor Response to Earthquake Excitation (KOBE)

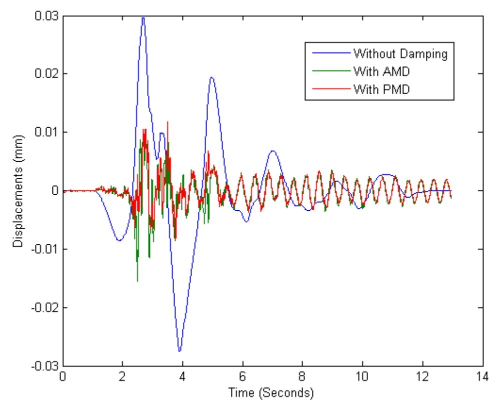


Figure 5.7(f): Floor Response to Earthquake Excitation (ELCENTRO)

Figure 5.7 (a-f) shows the values of Floor Responses which are the displacement of floor when the control is implemented to the seismic excitation. It can be seen that there is a considerable reduction in the displacement when Active Mass Damper is implemented, although damping observed in Passive Mass Damping is almost same but the efficiency is more effective in Active Mass Damping cases as shown in Figure 5.8 (a-f). This efficient damping should reduce the lateral stresses induced during earthquake, and is efficient in dissipating the energy. In future work friction of bearings in the model should be incorporated to obtain small displacement control.

The object for damping scaled excitation will considerably reduce the stresses on the building like structures. Inherently any seismic excitation wave can be used as input in the simulation; the results would positively conform to a reduction in displacement. The results are quite encouraging and the damping obtained is realistic.

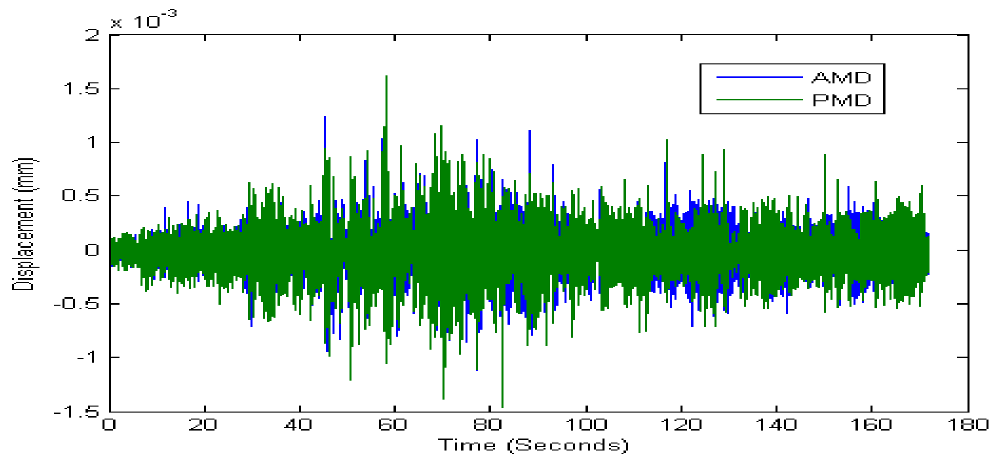


Figure 5.8(a): Floor Response to Earthquake Excitation (NIL-EW)

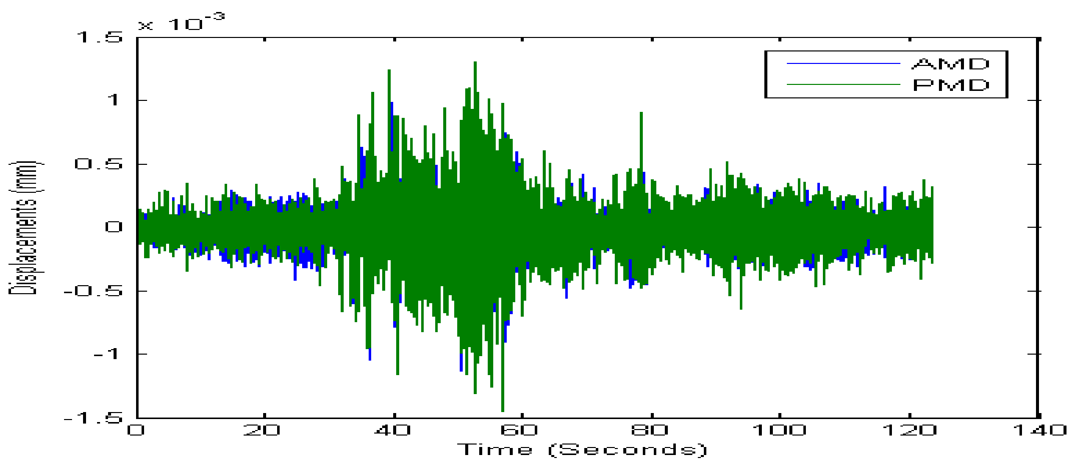


Figure 5.8(b): Floor Response to Earthquake Excitation (NIL-NS)

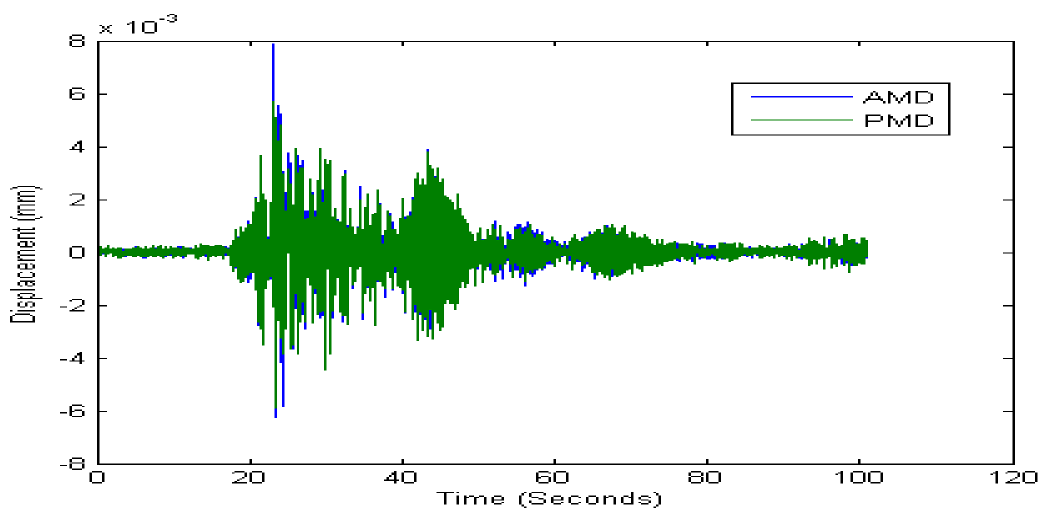


Figure 5.8(c): Floor Response to Earthquake Excitation (ABT-EW)

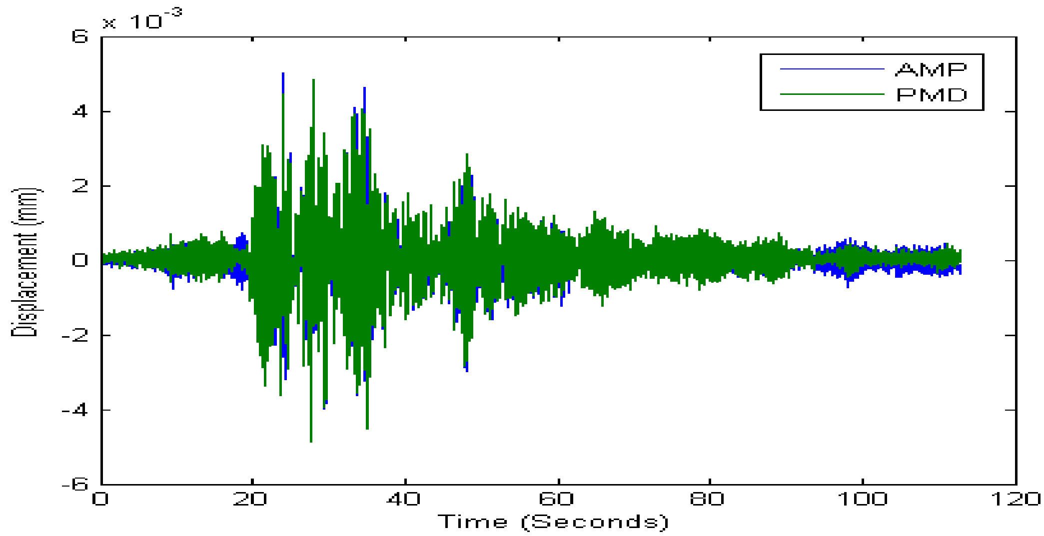


Figure 5.8(d): Floor Response to Earthquake Excitation (ABT-NS)

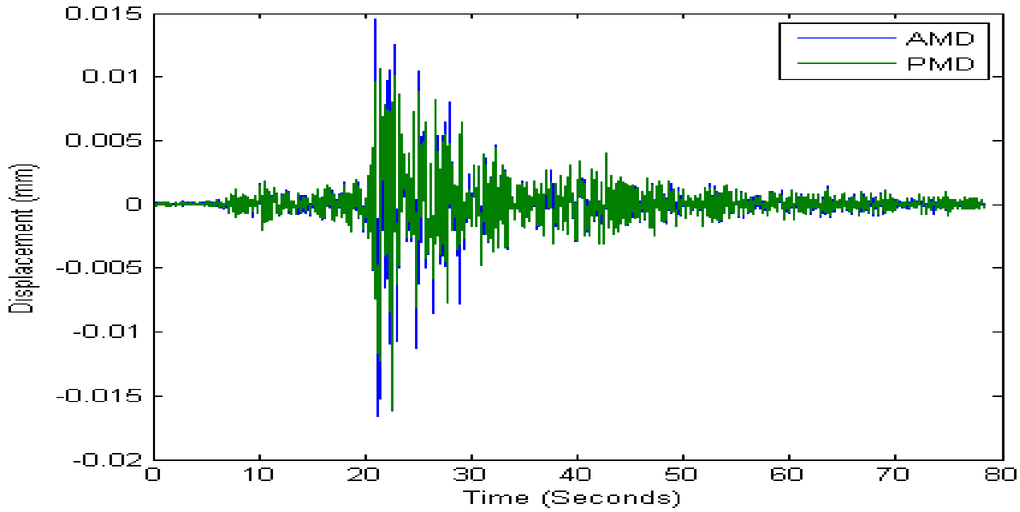


Figure 5.8(e): Peak Floor Response to Earthquake Excitation (KOBE)

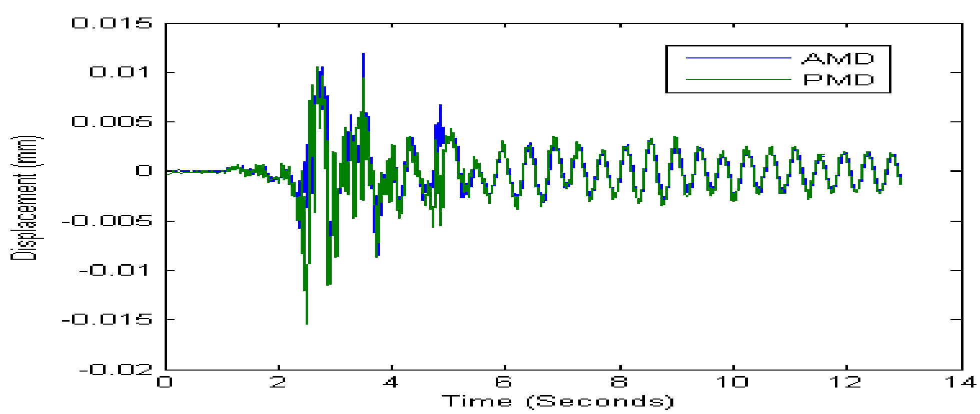


Figure 5.8(f): Floor Response to Earthquake Excitation (ELCENTRO)

5.5 Conclusions

The objective of dampening the vibrations in the building-like structure for Seismic Excitation was met. The simulations were successful in operating all the functions of the shake table, these simulations and connecting algorithms of Matlab/Simulink adds to the data bank for seismic testing and evaluation at demonstrational level at NUST, this work can be extended to full scale testing or testing of irregularly oriented models. Furthermore, investigation of the effects of various weighting alterations can be used to obtain even better control. The excitation in our study were unidirectional and captures the basic idea of the behavior in earthquake, this can be extended to bi directional and tri directional excitation.

Chapter 6
Conclusions

6.1 Advantages of Shake Table

The use of shake table system for demonstration of concepts in structural dynamics and earthquake engineering is a very convenient and effective way of bringing to life many theoretical aspects taught in these disciplines. The usual curricula that are followed in most colleges traditionally focus heavily on theoretical aspects, going into the mathematical details. While these mathematical and theoretical aspects are extremely important and cannot be dispensed with, the fact remains that without actual hands on experience, they mostly tend to remain mere mathematical abstractions. Without actually experiencing the physical meaning of these concepts and seeing how the underlying mathematics relates to the physics of the problem, it is hard for the student to have a good knowledge grasp.

6.2 Public Awareness to Earthquake Hazards

The Shake Table can be a very effective tool in increasing public awareness regarding earthquake hazards. Earthquake models can bring to light, the ways building responds and how changing the structural properties of a building, can change the response to an earthquake, rendering the building safer or more hazardous. Any major earthquake usually sparks up a lot of public interest and there is a general desire to know more about the hazards and effects of earthquake on structures, especially buildings. Shake tables can be used to great advantage for such public education, thus potentially promoting construction methods and materials that are suitable to seismically active regions, resulting in better earthquake resistant structures. Such outreach activities can be a great source of public education regarding earthquake hazard mitigation.

6.3 Conclusions

This research work developed the bench sale earthquake engineering laboratory setup at School of Civil and Environmental Engineering. The use of shake table for demonstrations in structural dynamics proved to be a good experience overall. After testing of equipment, an experiment was developed which incorporated the use of Active

Mass Damper to control the vibrations of the model structure. This experiment proved to be quite successful.

It is further concluded that an analytical model must be developed for the numerical simulation of the dynamic response along with observations from experimental results.

6.4 Recommendations for Further Research

The use of shake table put forward the ideas clearly and students are actually able to see the implementation of the theory they study in class. Strategies should be developed to use the shake table in the education process. Possible strategies include building different types of models and running them with different major worldwide earthquakes, such as wood models and steel models. Apart from this, the shake table can be used for various other courses involving different fields, like geotechnical engineering. The table can be effectively used to demonstrate the liquefaction of sand and soft soils under dynamic loads. Smaller model structures can build and soil structure interaction under seismic conditions can be studied.

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