Development of a Shaking Table for Educational Purposes

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Abstract

When civil structures are subjected to earthquake excitations, components of the infrastructure may become damaged. Knowledge of structural dynamics is required to understand and assess the state of a structure after it has experienced dynamic loading. The goal of this project is to develop a cost-efficient, bi-directional shaking table to be used as a practical tool by students and researchers to study the dynamic behavior of structures when they are subjected to earthquake excitations.

1. Introduction

Civil Infrastructures such as buildings, bridges and skyscrapers comes in many variations of shapes and sizes structural design, materials of construction and their foundation and land characteristics [1]. These different attributes affect how structures perform under high external loads and excitations such as earthquakes and strong winds. Structures experience deformations after being hit by earthquakes and as structural engineers, we need to pinpoint the structural defects of the building and determine if a building needs repairs and if so to what extent. Structural engineers need to accurately assess the health of the building and decide how much longer the building can sustain itself without requiring any repairs. This is where structural health monitoring (SHM) comes into play.

Structural health monitoring (SHM) aims to provide reliable data on the real conditions of a structure, and detect the appearance of structural defects [3]. In other words, SHM allows us to predict when a building or structure is going to collapse, so catastrophic failures can be avoided and the overall safety of the people and the structure can be ensured. By detecting and assessing damage and taking the necessary steps to repair a structure, a lot of time, money and labor can be saved which would otherwise go into rebuilding the whole structure.

By installing sensors that continuously measure a structure’s responses relevant to the structural conditions and other important environmental variables, it is possible to obtain an accurate description of the structure's state or health. Having a SHM system installed on a building and/or bridge can ensure the safety of the structure, improve its long-term quality, and also allow for structural management of the building. In addition, learning how a building performs in real conditions will help to design better structures in the future. This can lead to the design of cheaper, safer and more durable structures that have increased reliability, performance and safety [1].

The goal of this project is to develop a shaking table that could be used by students and researchers to study the dynamic behavior of civil structures when they are subjected to earthquake excitations. In order to understand the underlying mechanics of how structures will behave when they are subjected to dynamic loading, the MQP team took a preliminary Structural Dynamics course in the Department of Civil and Environmental Engineering at Worcester Polytechnic Institute. This course deals with the dynamic analysis and design of structures subjected to wind and earthquake loads and explores methods of analysis and practical design applications. However, it is difficult for undergraduate students to understand the fundamentals and the state of the art on structural dynamics, health monitoring and structural control. The MQP team realized that an effective hands-on activity would help students to better study and understand the dynamics involved when structures are subjected to excitations. With this in mind, our MQP team decided to develop a shaking table to be used as a testing framework for structural control and health monitoring as our Major Qualifying Project. The first step of the project is to develop the conceptual design of the shaking table. This involves researching about different components that will be used in our system (motors, power supply etc.), understanding their limitations and selecting the appropriate equipment for our system. Afterwards the MQP team needs to manufacture the product. The next step of the project is to build a scaled building model with which we will conduct our SHM experiments. Once the manufacturing of the shaking table and building model are complete, the MQP team needs to select SHM sensors to be used in this project for data acquisition. Lastly, the project team worked with programming experts to develop a virtual interface in order to control our testing system through a PC which completes the development of our structural testing framework. Based on the developed testing framework, the responses of structures under a variety of earthquake loads are measured, monitored and controlled. It is expected that the proposed testing framework will provide the means to study the seismic response of a structure under excitations and can produce a seismic model that will accurately describe the health status of a structure.

The completed shaking table will be implemented for student use in Structural Dynamics course at WPI. The coursework for Structural Dynamics will involve using the shaking table providing students with the opportunity to apply their theoretical classroom knowledge to hands-on dynamic experiments. The MQP team developed an educational module which revises the current syllabus and also includes a term project for students to incorporate the use of the shaking table for the study of structural dynamics. Details are provided in section 7 of the report. At the end of the course, students will answer a survey evaluating the effectiveness of the shaking table in helping them learn structural dynamics. More information on how to simulate earthquake excitations as well as how the MQP Team developed the design of the shaking table will be given in later sections. The organization of this report is as follows: Section 2 provides background information on shaking table and its components and the different motion systems that can be used to simulate earthquake excitations. The analysis software that our MQP group will utilize in this project will be discussed in Section 3. Section 4 proposes our shaking table designs and section 5 describes the methodologies for conducting our SHM experiments. The results and discussion are given in section 6 and the expected concluding remarks and future recommendations are given in Section 7.

2. Shaking Table

One of the ways to understand and study the seismic response and behavior of a building and/or bridge structure is by using the shaking table. Shaking table is one of the most basic models that are used to simulate ground motions. The earliest shaking table was constructed in Japan in the late 19th century and was excited through physical means [9]. The modern day technology allows engineers to design shaking tables for use with multi-degree of freedom systems. The test structures are placed and connected to the shaking table and the specimens are shaken until the point of failure. Figure 1 shows the proprietary shaking table manufactured from North America Wave Spectrum Science and Trade Inc. (NAWS).

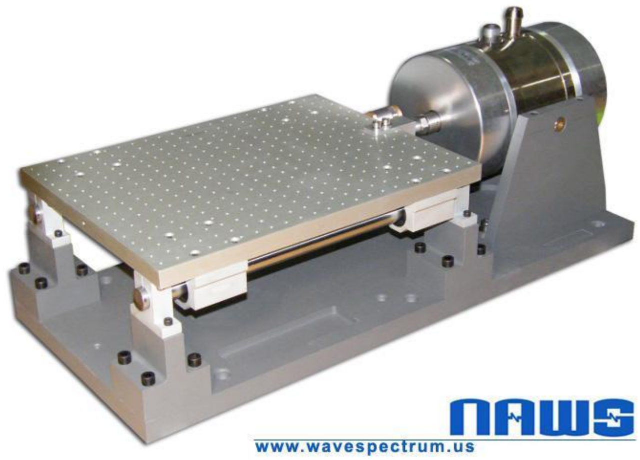


Figure 6: Manufactured One Directional Shaking Table from NAWS

Shaking tables are not limited for just small scale laboratory use. Today, engineers have designed shaking tables that are as large as forty feet by sixty feet [5]. A shaking table of this scale can be driven with 6 degrees of freedom and have enough power to vibrate 6 feet per second with maximum forces of up to 4.2g, it’s enough to simulate the most powerful earthquake that has been recorded. These shakers are designed to test full-scale civil structures. By conducting shaking table experiments; engineers are able to design buildings that are essentially earthquake-proof. There are four basic components that make up the shaking table.

2.1 Foundation

Foundation is the first component to be considered. It is important that the foundation is sturdy and solid so that any vibrations generated from the motion system can be absorbed. A good foundation would be a concrete slab or surface that would not move along with the deck and the model. Alternatively, foundation can be portable. In this case, it is recommended that the foundation is heavy, presumably steel. Despite that, it is still necessary to establish anchorage to the portable table. If the foundation is not stable, the shaking table would lose its purpose and effectiveness. The data, generated from the shaking table, would not be truly representative of the seismic response. One way to assure the stability of the foundation system is to use vibration isolation tables and platforms. These tables are designed to reduce and dissipate vibrations which are either caused due to the surrounding environment or by the objects on top of the table. Figure 2 shows the anti-vibration table upon which this shaking table will be built on.

Figure 7: Vibration Isolation Table in WPI Structural Lab

2.2 Table Deck

Typically the table deck should have the lightest possible weight. Lighter material will have faster reaction time to the slightest motion from the motion system. The most widely used table deck today is a mix of fiberglass with foam sandwiched between or wood core. The second most popular table deck is milled aluminum because Aluminum is one of the few metals that are sturdy, light and economical. It is widely used in smaller laboratory experiment. Other types of materials that are used are plywood and steel although a more powerful motion system is required when using heavier materials in order for the shaking table to perform well. In this project, the MQP team will use an aluminum base plate as our table deck.

Figure 8: Table Deck used in our system

2.3 Suspension System

Suspension system is the part of the shaking table that allows the table deck to move. Ultimately, there are two types of suspension systems; rail system and link system.

2.3.1 Link System

Link systems are easy to implement and economical in general. The largest con to the link system is that it produces some amount of vertical movement of the table deck as the links move in small arcs when it’s in motion. Since it has vertical component to its motion, it is recommended that the design of the links are longer. The use of longer links controls and limits the vertical movement component. The vertical movement of the shaking table is negligible enough when the table is operating at low speed but higher speed of operation can cause the table to perform differently from its original design. This is why we chose to go with rail system for our design.

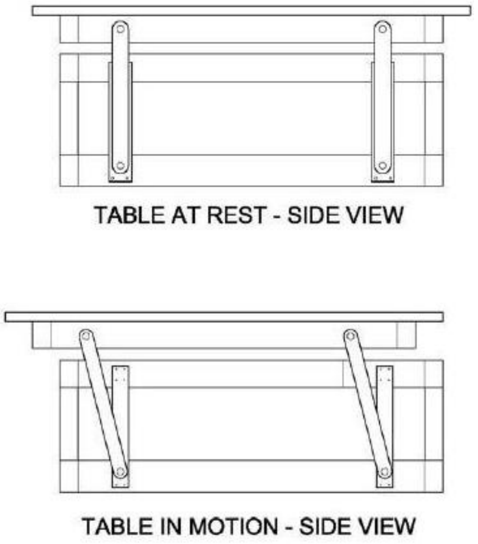


Figure 9 Link Suspension System

2.3.2 Rail Systems

Rail systems are simpler and easier to build than the link systems. They can handle heavier loads and operate better in the long run. There is no vertical component to the motion as well. The reason rail systems are better than link system is because the rail system can be designed as simply as two smooth boards sliding against each other. It can also be designed as a complex system with linear bearings that runs on machined rail. There are many more ways that the rail system can be set up. Simple standard drawer sliders can also be used to produce linear movement for the table. The drawback to using drawer slider is that a large amount of friction is generated when the table is in motion.

The most preferred rail system is the use of steel roller or ball bearing with steel rail. Ball and roller can reduce friction to a point that is negligible thus the shaking table works at an optimal level. The downside to this system is that it can be very expensive. However the cost of the system can be minimized if the system size is small and if it is only for laboratory usage.

Figure 10: Rail Suspension System

2.4 Table Motion System

The mechanism that is needed to shake the table deck would be a small motor or a linear actuator. The size and power of the motor depends on the total weight of the model and the table deck. It is essential that the motor is not only powerful but should also have fast reaction time to oscillate the shaking table. A motor with low acceleration capacity wouldn’t accurately represent the movement of the ground in an actual earthquake. Essentially, there are three different types of motors that can be used in a shaking table: servomotor, stepper motor and linear actuators.

2.4.1 Servomotors

Servomotor operates in closed-loop servo mechanism that uses position feedback to control the motion and position of the shaft. Servomotor can be as simple and cheap as motors in radio-controlled model but it can also be advance and expensive motors that are used in industrial settings. There are two types of servomotors; AC and DC. AC servomotors are designed to handle higher current surges thus they are mostly used in industrial machinery. On the other hand, DC servomotors use lower current surges and they are mainly used for smaller applications. The prices of the each type of motors are reflected in their usage and performance thus AC servomotors are more expensive than DC servomotors.

Figure 6: Servomotors

2.4.2 Stepper Motor

Stepper Motors are another type of motor that can be used in the design of our shaking table. They are referred to as stepper motor because the motor rotates in fixed angular increments or in steps. In servomotor, the motor rotates continuously. Stepper Motors are mainly used for position control thus it has the capability to replicate seismic activity. Unlike servomotors, stepper motors are classified as open-loop systems where the motors do not require the feedback encoder. This lack of feedback can be both advantageous and disadvantageous. The disadvantage of using a stepper motor is that it does not have feedback system which can limit its performance. The stepper motor can only perform within its capacity. If the stepper motor is used for a system that exceeds its capacity, the motor can miss steps and leads to positioning errors. On the other hand, not having a feedback system in stepper motor cuts the overall cost of the motor system.

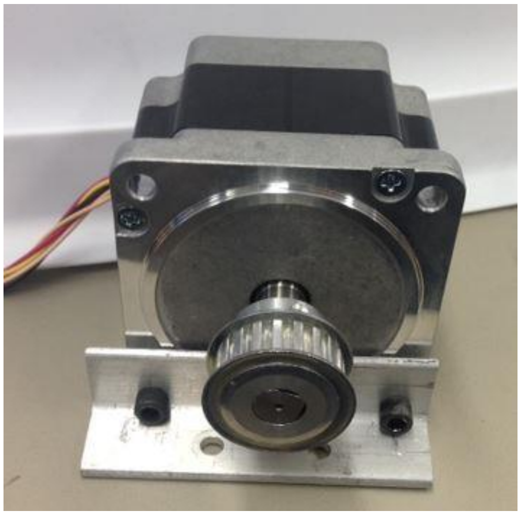


Figure 7: Stepper Motor used in this project (NI ST-34)

2.4.3 Linear Actuator

Linear actuators are a different form of motion system compared to motors. Linear actuator technology comes from the stepper motor but it creates linear motions. There are many different types of actuators; such as electric linear actuator, mechanical linear actuator, hydraulic actuator and etc. Linear actuators functions in linear movement but the linear movement is derived from non-linear force that drives the piston back and forth. The piston, in electrical linear actuator, is moved by the electric current and as the piston moves, the drive shaft moves proportionally to the piston's position. The applications of linear actuators are endless. Linear actuators are used in industries, machinery, computer peripherals and many other more. It is most common to see linear actuator in electrical devices that require linear motions such as power drill, pumps and other machines that require linear movement to move objects. In this project, linear actuators were used in the initial design as a motion device that will move the table deck in both x and y direction. More information on the use of linear actuators will be discussed in Section 4: Design of the journal.

Figure 8: Linear Actuator

2.4.4 Control Board

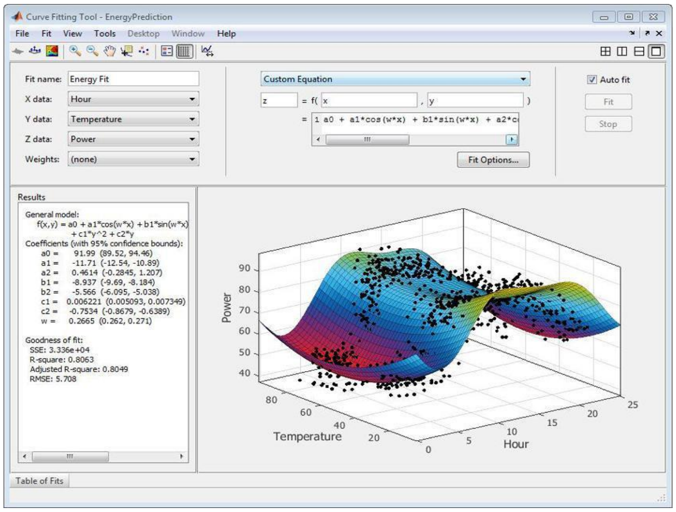
In order for the actuator to function, the actuator needs to be connected to the motor control board. The control board is responsible for relaying signals from computer to the actuator. These signals include the speed at which the actuator will move, amount of force to exert and duration of the excitation.

3. Software Applications

The development of powerful computer software and tools in the recent decades has enabled people to become more efficient at. Tasks such as collecting data, computing complex mathematical equations, simulating real-life conditions or controlling equipment and machinery precisely for tasks that require it have all been made easier with the use of modern software. The main software that will be discussed below are MATLAB, SIMULINK and LABVIEW.

3.1 MATLAB

MATLAB is a high-level language that is used by many engineers and scientists for numerical computation, visualization, and programming. More than a million engineers and scientists use MATLAB as a technical language to analyze data, develop algorithms, and create models and applications. MATLAB will be used in this MQP project for signals processing and communications, test and measurement, control systems and to develop coding to use in conjunction with Simulink and LabVIEW.



Fit name: Energy Fit
X data: Hour
Y data: Temperature
Z data: Power
Weights: (none)
Custom Equation
z = f(x , y)
= 1 a0 + a1*cos(w*x) + b1*sin(w*x) + a2*c
☑ Auto fit

```
General model:
    f(x,y) = a0 + a1*cos(w*x) + b1*sin(w*x)
             + c1*y^2 + c2*y
Coefficients (with 95% confidence bounds):
     a0 =      91.99  (89.52, 94.46)
     a1 =     -11.71  (-12.54, -10.89)
     a2 =     0.4614  (-0.2845, 1.207)
     b1 =     -8.937  (-9.69, -8.184)
     b2 =     -5.566  (-6.095, -5.038)
     c1 =   0.006221  (0.005093, 0.007349)
     c2 =    -0.7534  (-0.8679, -0.6389)
     w =     0.2665  (0.262, 0.271)

Goodness of fit:
  SSE: 3.336e+04
  R-square: 0.8063
  Adjusted R-square: 0.8049
  RMSE: 5.708
```

Figure 9 Computations in Matlab

3.2SIMULINK

Simulink is a block diagram environment for model design and simulation. Simulink contains a built-in graphical editor with a set of predefined blocks that can be combined to create a detailed block diagram of an engineering system. Tools are provided for hierarchical modeling, data management, and subsystem customization that enable us to represent even the most complex systems concisely and accurately. It is also integrated with MATLAB enabling incorporation of MATLAB algorithms into models and export of simulation results back to MATLAB for further analysis.

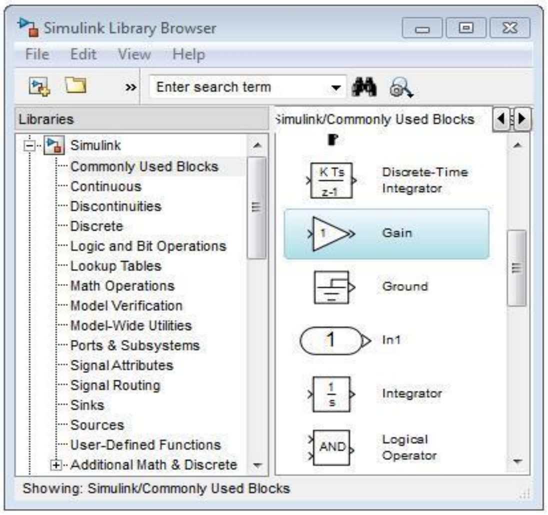
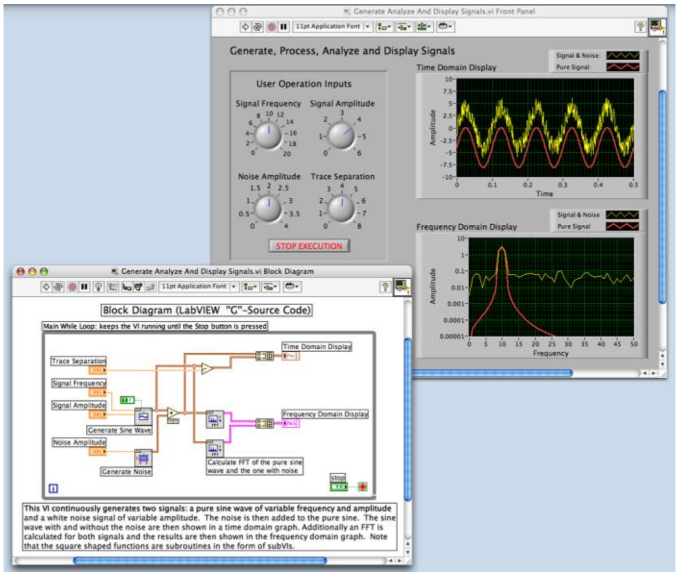


Figure 10 Simulink Library Browser

3.3 LABVIEW

LabVIEW is a graphical programming platform developed by national instruments to help engineers and scientists with designing and testing of small and large scale systems. LabVIEW provides extensive support for accessing instrumentation hardware with a large number of functions for data acquisition, signal analysis, mathematics and statistics, signal conditioning and analysis, and other specialized functions associated with data capture from hardware sensors. It is also compatible for use with a lot of computer operating systems such as Microsoft Windows, UNIX, Linux and Mac OS. LabVIEW will be used in this MQP project mainly for signal generation, signal processing, data acquisition, and motor control and automation.



This VI continuously generates two signals: a pure sine wave of variable frequency and amplitude and a white noise signal of variable amplitude. The noise is then added to the pure sine. The sine wave with and without the noise are then shown in a time domain graph. Additionally an FFT is calculated for both signals and the results are then shown in the frequency domain graph. Note that the square shaped functions are subroutines in the form of subVIs.

Figure 11 Signals Processing in LabVIEW

4. Shaking Table Designs

There are three different types of proposed testing systems in this project. Unlike the conventional, manufactured one-directional shaking system, all of the proposed testing systems in are two directional (x-y) systems. The use of two directional systems add additional degrees of freedom to the shaking table system, thus the movement created by the shaking table can represent an earthquake more accurately. Despite the similarity of having two directional systems, all three proposed systems are unique in their own ways.

4.1 Shaking Table Design 1

Our first shaking table system is based off of the rail suspension system. The rail and linear bearings are stainless steel material. The system parts are carefully chosen to withstand strong vibrations and jerking forces which will be generated from the actuator. As it can be observed from Figure-12, the rails are stacked on top of one another with the secondary rail (top rail) being perpendicular to the primary rail (bottom rail). The primary rails will be responsible for supporting the overall weight of the system while the secondary rails only have to support the weight of the building model and the table deck. It is necessary for the rails to be smooth and well-greased so that as little friction as possible is generated once the system is set in motion.

To assemble the system, the secondary rails are placed on top of a small aluminum plate (6”x8”) which is attached to the linear bearings at the bottom of the plate. These linear bearings are capable of sliding freely in the y-direction on the primary rails. The table deck is then attached to the second set of linear bearings which allows the system to move freely on the secondary rails in the x-direction. Thus the combination of the two rail movements allows the plate to move in both the x and y directions.

In Figure 13, it can be observed that there are two actuators that are attached to the plate to produce motion in two directions. One of the actuators is responsible for movement in the x-direction and the other one is responsible for the y-direction. The x-direction actuator is placed on top of the small aluminum plate and between the secondary rails. The other actuator is placed at the side of the system where the driveshaft will be connected to the aluminum plate. This actuator will produce motion in y-direction and must carry the weights of the aluminum plate, secondary rails with linear bearing units, table deck and the building model.

Table 2 Manufactured Shaking Tables from NAW

Manufactured Model	Price
NAW-Z30-10	$ 19,000
NAW-Z30-20	$ 24,000
NAW-Z30-30	$ 27,000

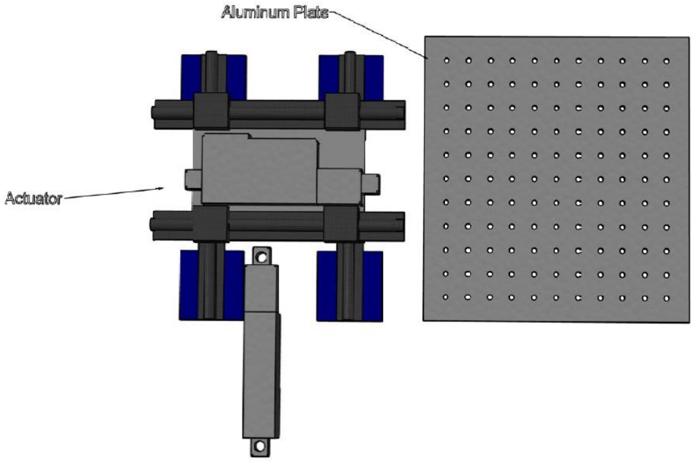


Figure 12 Plan View of Initial Design

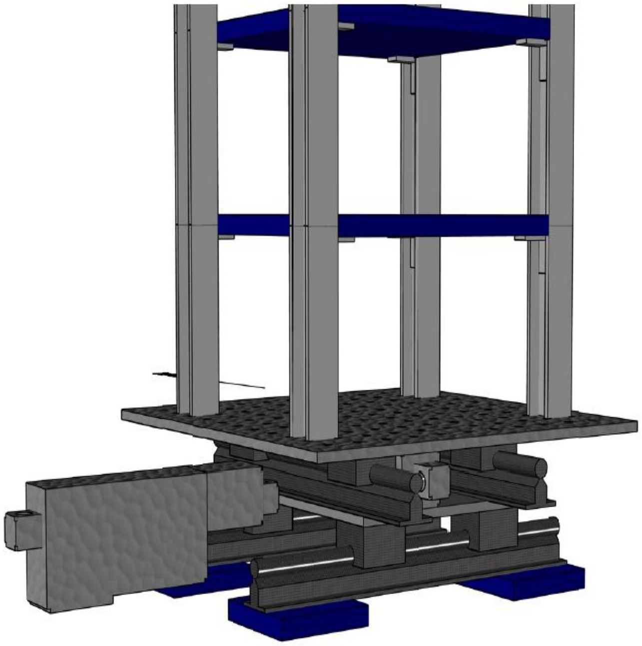


Figure 13 Side view of Initial Proposed System

4.1.1 Evaluation of Design 1

The use of double rail system worked very well in this design and the project team decided to adopt this double rail system again in our third and final design. . One other thing that worked well in this design is that we were able to keep the cost to manufacture fairly low. The costs of the manufactured shaking tables are listed in Table 1.

The most apparent disadvantage of this design is that the overall weight of the system is heavier than we expected. The secondary set of rails and linear bearings and the 6”x8” aluminum plate added extra weight to the system but in order for the system to work in both x and y directions, those three components are necessary to be part of the system.

Another aspect of the system that failed is the motion system. The linear actuators that we implemented in this design did not produce enough rpm causing the shaking table to move too slowly to be used for dynamic experimentation.

Another disadvantage of using rail system is that it generates a lot of friction. Even though the system is equipped with linear bearing units, in the real world scenario, there is some friction that is generated as the system goes into motion.

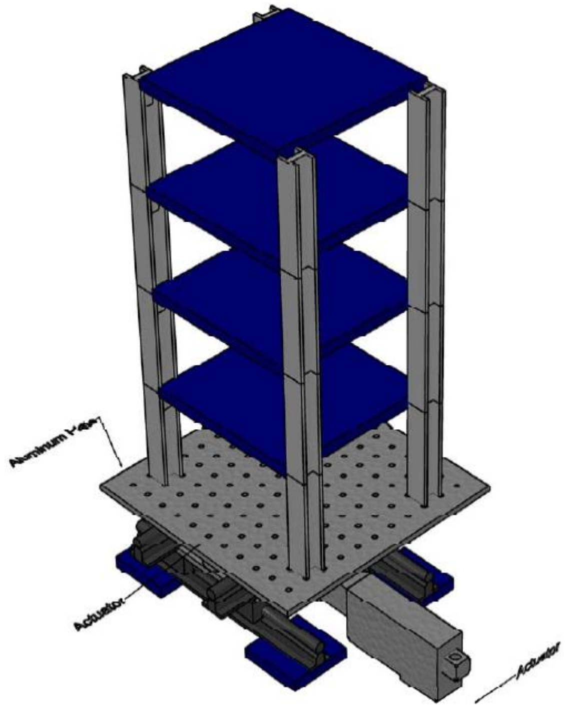


Figure 14 Initial system with building model

4.2 Shaking Table Design 2

The second design of the shaking table was assembled with the use of roller ball bearing transfer units that are attached to the shaking table. With this design, the overall weight of the system is reduced by few pounds which increases the responsiveness of the shaking table system. Figure 15 shows the roller ball bearing transfer units. These units are attached to the bottom of the table deck, aluminum plate, and together will act as a single unit which can slide on smooth surfaces. Figure 16 illustrates the roller bearing units attached to the table deck. This system is also capable of moving in both the x and y directions.

Figure 15 Diameter Roller Ball Bearings

The set up for this design is simpler and easier than the initial design. In this design, the actuators are attached to the rail and linear bearings to allow for movement of the plate. Figure 16 illustrates the position and placement of the actuators. For instance, if the Y-actuator is at work and the X-actuator is rest, the X-actuator will be able to move in Y-direction. It would be the same for Y-actuator when X-actuator is at work. When they both work at the same times, the plate would move diagonally. It is important that the actuators are positioned at the midpoints of the table deck edges. The placement of the actuators on the rails increases the height of the position of the actuator, thus an additional connection system is needed to level the table deck and the actuator.

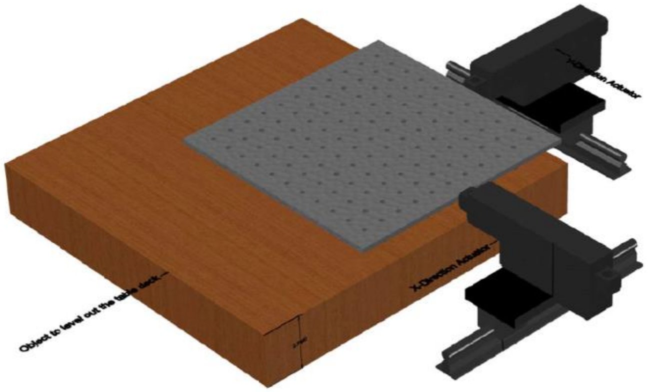


Figure 16 Side View of Second design system

The actuator and the table deck are connected by an extruded aluminum piece. This connection piece is connected to the plate with six bolts to ensure that the force that is applied to the table deck is distributed equally along the edge of the plate. Figure 18, illustrates the aluminum connector. On the other side of this extruded aluminum connector, another cylindrical aluminum connector will be attached to the extruded piece. The cylindrical piece connects the tip of the actuator through the cylindrical hole in the middle. Figure 19 illustrates the cylindrical aluminum piece with drilled holes for nuts and bolts.

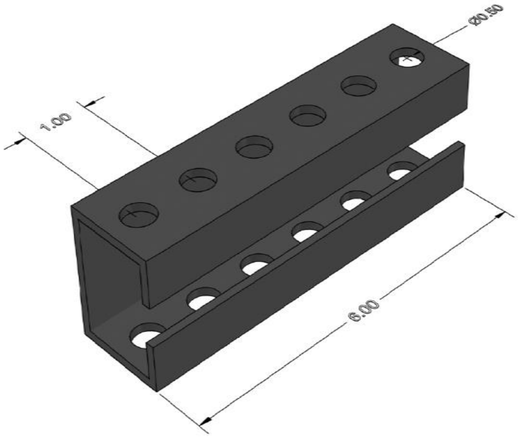


Figure 17 Extruded Aluminum Connector

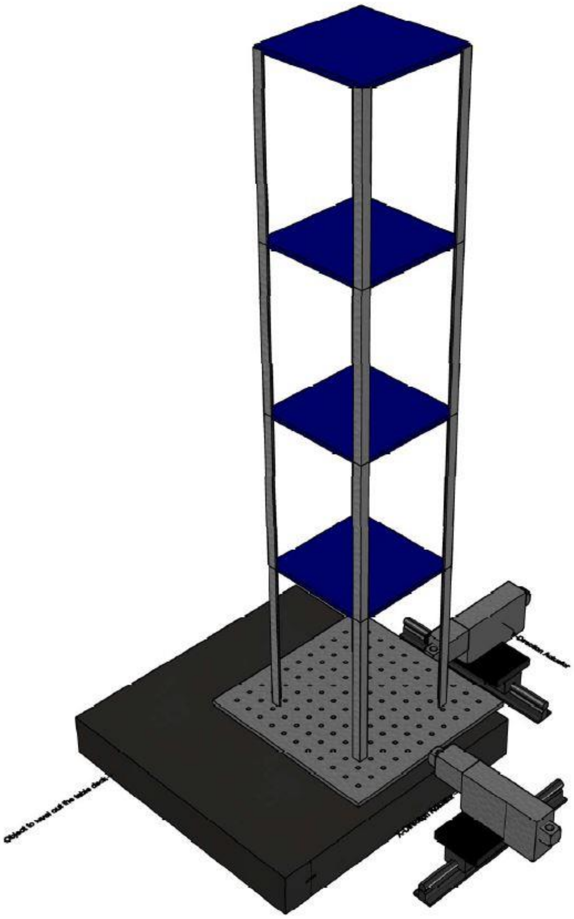


Figure 18 Second design system with building model

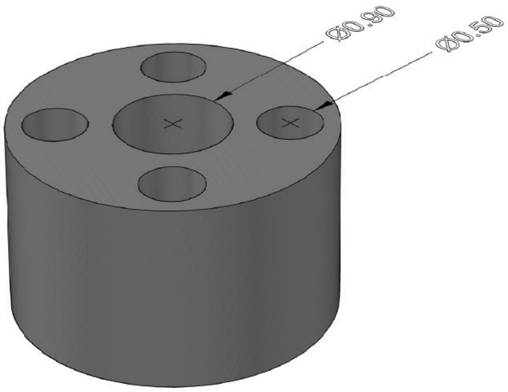


Figure 19 Cylindrical Aluminum Connector

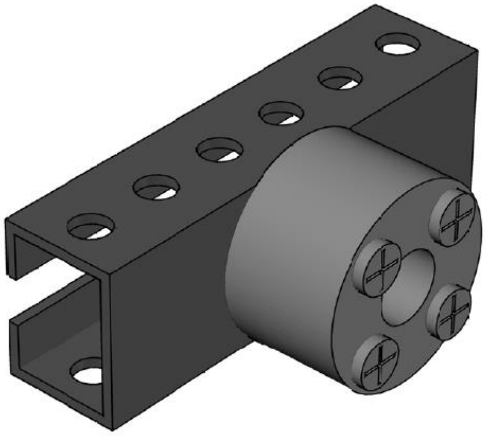


Figure 20 Connector between Table Deck and Actuator

4.2.1 Evaluation of Design 2

The most obvious advantage of the alternative design is the lightness of the overall weight. The alternative design reduces the initial design weight by approximately five pounds which is a significant weight difference. This second design is the most cost-efficient of all three developed systems mainly because the costs of the ball bearing units are much lower than the rails and linear bearing units.

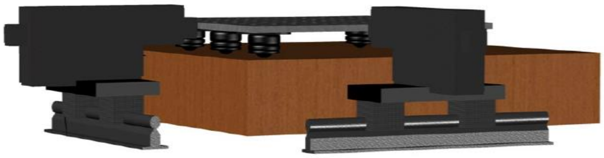


Figure 21 Side View 2 of second design system

The most alarming disadvantage of design 2 is the generation of additional moment in motion plate which occurs when the two actuators work at the same time but with difference speeds and power.. It can be assumed that the table deck will turn by pivoting at certain locations. The generated moment would disrupt the motion of the shaking table and even cause damage to the actuator. Another disadvantage of this system is that the roller ball bearings created high frictions when in contact with the surfaces. Therefore, the project team rejected this design due to the high amount of friction between the surfaces which limited the movement of the shaking table significantly in both directions.

4.3 Final Shaking Table Design

The motion system for our final shaking table design was developed by adopting the belt and pulley concept from film making equipment. In the film production equipment the camera stand is attached to the belt that runs in same direction as the rail. The movement of the camera stand is controlled by the position of the belt and the belt moves according to the rotation of the pulley (Refer to Figure 23). The rotation of the pulley is in turn controlled by the number of steps in the stepper motor. In this design, the project team decided to use stepper motors to produce motion in the system. These stepper motors produce more force and rpm making it much more suitable to conduct dynamic experiments with than the linear actuators that we used in our previous two designs. The motion of the stepper motor needs to be converted to linear motion. This is accomplished by implementing the belt and pulley concept mentioned above. In this final design, the y-directional rail system no longer uses a secondary plate for the placement of the x-directional rail system. Instead, we placed beams running in the same direction as the y-direction rails. As illustrated in Figure 23, the two beams are spaced 8 inches apart where a second set of rails can be placed on top. The belt is placed between the two beams and the pulleys are held together by specially manufactured anchors. Figures 24 and 25 illustrate the anchors for both the pulley and the motor. All other connections between the different components are joined together by bearings. The x-direction of the shaking table is assembled according to the figure shown in figure 26. The second set of rails is placed perpendicularly on top of the beam for the y-directional system. The long spans of the rails give space for placement of the motor, belt and pulley and helps avoid contact between the table deck and motor. The motor for the x-direction is placed on top of the beam which is connected to the x-direction rails. The anchor for the idle pulley is also set up in the same way as for the motor.

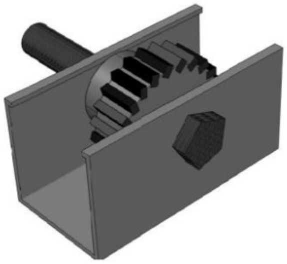


Figure 22: Anchor for Idle Pulley


Figure 23: Anchor For Motor

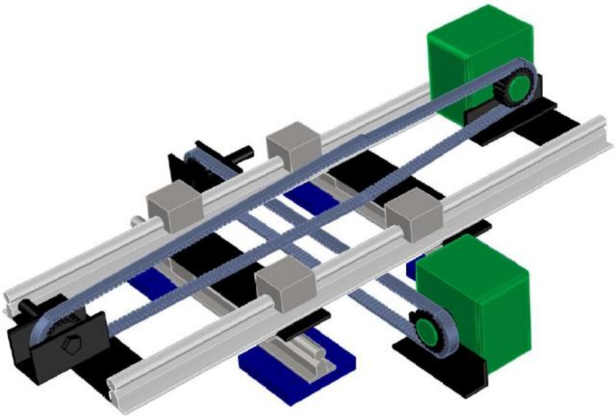


Figure 24: Belt and pulley concept

4.3.1 Evaluation of Final Design

After two trial and errors with the design of the shaking table, the project team arrived at the third and final design.

The final design for shaking table has many advantages compared to its predecessors. The project team learned from the mistakes and challenges encountered in the previous two designs and made necessary improvements in this final design. With the use of stepper motors, the shaking table can now move fast enough in any directions to replicate a real-time earthquake. As we are using the double rail system, we do not need to worry about friction thwarting the movement of the shaking table and the rails can be greased to promote even smoother movement.

The main downside to this system is that it is more costly than the previous two designs because extra accessories such as the module (Figure 32) and stepper drives (Figure 33) had to be purchased for us to run the stepper motors. But the cost can be justified by the excellent performance that the stepper motors provide to this shaking table system. Another disadvantage could be the presence of steps in the belts which may limit the motion of the shaking table in that the system can only rest in between the steps of the belt. However, this is compensated by our stepper motors which can rotate with precision of up to a single degree.

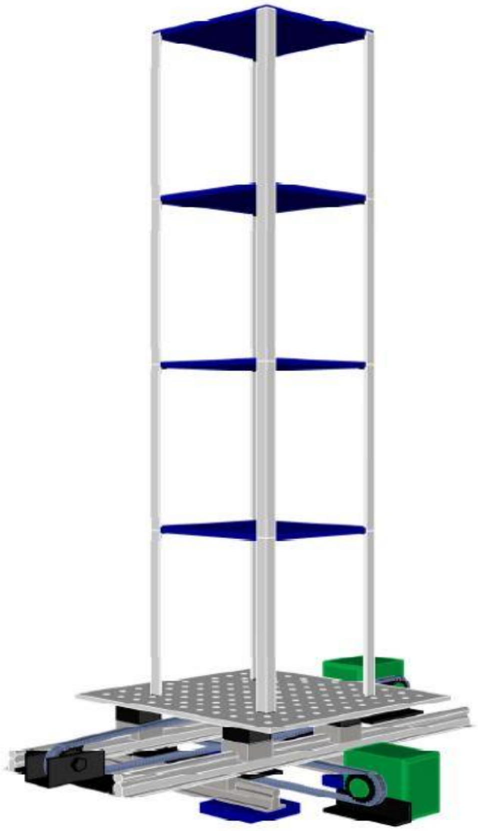
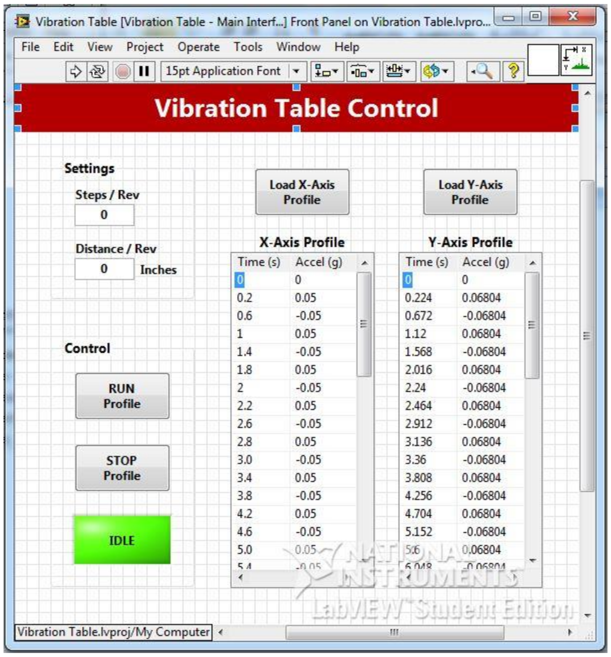


Figure 25: Final Design System

4.4 Building Model Design

The MQP team decided to use a 4-story building model to conduct our Structural Health Monitoring experiments. The building model will be placed on top of our shaking table system and subjected to excitations produced by the motion system. The building model consists of PVC floor systems. The choice of material for the floor system is PVC in order to make the building model as light-weight as possible. The PVC floors are supported by L-shaped aluminum columns that are segmented at each floor level to create a multi degree of freedoms building system. The aluminum columns will be flexible enough so that when the building model is subjected to excitations the columns will produce deflections. Nuts and bolts will be used for connections between the floors and the columns. The picture of the model is shown in figure 22 and the dimensions of the individual components that make up the building are presented in table 3.

4.5 LabVIEW User Interface



Settings

Steps / Rev: 0

Distance / Rev: 0 Inches

Control

X-Axis Profile

Time (s)	Accel (g)
0	0
0.2	0.05
0.6	-0.05
1	0.05
1.4	-0.05
1.8	0.05
2	-0.05
2.2	0.05
2.6	-0.05
2.8	0.05
3.0	-0.05
3.4	0.05
3.8	-0.05
4.2	0.05
4.6	-0.05
5.0	0.05
5.4	-0.05

Y-Axis Profile

Time (s)	Accel (g)
0	0
0.224	0.06804
0.672	-0.06804
1.12	0.06804
1.568	-0.06804
2.016	0.06804
2.24	-0.06804
2.464	0.06804
2.912	-0.06804
3.136	0.06804
3.36	-0.06804
3.808	0.06804
4.256	-0.06804
4.704	0.06804
5.152	-0.06804
5.6	0.06804
6.048	-0.06804

Figure 26: VI to control stepper motors

Figure 27: Overall System Setup

4.5 Overall System Setup

This section describes the overall testing and control system of this project. The design of the shaking table allows two stepper motors to be attached to it. The stepper motors are powered up by an external power supply. There is a module which acts as a controller and is housed by a chassis which in turn is connected to the computer. The user will ultimately control the stepper motors via the computer using LabVIEW software. There are two stepper drives each connected to a stepper motor that acts to translate the signal from the module into signal that the motors can understand. When the user sends earthquake signal via LabVIEW software, the module receives it and then sends it to the stepper drive which will then notify the motors what to do (e.g. Turn 100 steps in clockwise direction). The two motors will create two directional motions in the shaking table and the movement of the system will represent an earthquake. While the building model is subjected to earthquake motion, acceleration, strain, and deflection data will be collected for analysis using structural dynamics. More information on data acquisition, sensor systems, and analysis are provided in Section 5.

4.6 Cost Analysis

One of the objectives of this project was to develop the shaking table while trying to keep it as low cost as possible. The project team went through two design changes as presented earlier in the journal before arriving at the third and final design. Table 3 below summarizes the materials required for each of the designs and their costs. The costs for design 1 and design 2 are just around $650 but our final design came out to be $1098. However it is still much more economical than manufactured shaking tables that are in the market whose prices start around $20,000 (Refer to Table 1 above).

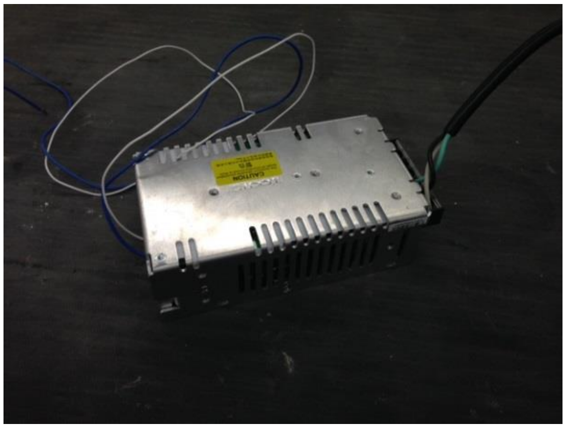


Figure 28: Power supply for motor

Figure 29: Module and Chassis

Figure 30: Stepper Driver

Table 2 Building Model Specifications

Model Dimension	Density (lb/in)	Proposed Dimension	Weight (lb)	Quantity
Floor system (PVC)	0.025	7x7x1/2	0.6125	4
Column (aluminum)	0.0966	40x1x1/8	0.483	4
Connection System	-	-	3-5	-
		Total Weight	12.11	lbs

Table 3 Cost Comparison

Parts	Design 1	Design 2	Design 3
Aluminum Plate	$ 161.00	$ 161.00	$ 161.00
Rails (x 2 sets)	$ 120.00	$ 120.00	$ 120.00
Linear Bearing Unit (8 pieces)	$ 34.00	$ 17.00	$ 34.00
Ball Bearing Units (6 pieces)	-	$ 6.00	-
2 Linear Actuators (DC Motor)	$ 200.00	$ 200.00	-
Actuator Controller	$ 120.00	$ 120.00	-
Building Model	$ 17.00	$ 17.00	$ 17.00
Module	-	-	$ 289.00
Stepper Motor (x 2)	-	-	$ 338.00
Power Supply	-	-	$ 139.00
Total Cost	$ 652.00	$ 641.00	$ 1,098.00

4.7 Capstone Design Fulfillment

This MQP project satisfies all of Accreditation Board for Engineering and Technology (ABET) requirements. Our project team incorporated almost all of our classroom knowledge that we attained at WPI in order to complete this project. Additionally, the project team undertook a preliminary structural dynamics course specifically before starting this project and also conducted research in numerous fields where our previous knowledge wasn’t sufficient.

The project team wanted to develop our shaking table for educational purposes. As it is intended for students who want to study and understand structural dynamics in a way that is practical and applicable, the project team aimed to manufacture the shaking table in the most cost-efficient manner as not many universities are willing to invest a huge amount of money on the shaking table. The project team went through two complete design changes before arriving at our third and final design. At each stage during the conceptual design process, the team had to consider the manufacturability of the design and make the design feasible to construct. The team also had to keep the costs in mind when making design changes as the conceptual design reflects the overall costs of the project.

By developing the shaking table, the project team is providing a way to learn about structural health monitoring which can be applied to real-time building structures in an effort to assess and improve the safety and quality of civil structures. Thus, we are contributing to society by helping to enhance the health and safety of the people.

Knowledge of structural dynamics is required for the team when developing the design of our building model and to assess the performance of our shaking table by collecting data and doing analysis. The project team also utilized design software AutoCAD extensively in conceptualizing our shaking table designs. However, the scope of the project extends beyond the field of civil engineering. The project team had to do research into electrical systems in order to assemble, configure and control our stepper motors and drives and understand how these electrical devices send signals to each other and so forth. The team also had to learn about programming using LabVIEW software because we needed to develop a program to run our testing setup and collect the appropriate data when conducting experiments.

The project team also decided to make this project sustainable by utilizing sustainable materials such as steel and aluminum in building our shaking table. And even after our project team completes the project, the shaking table will continue to be at WPI and can be further modified and optimized for use in the future.

5. Data Acquisition

5.1 Earthquake Simulation

The earthquake simulation system consists of an aluminum base plate that represents the ground and two stepper motors that will produce the required force to create motion of the base plate. The building model will be placed on top of the aluminum plate and the stepper motors will exert forces on the plate that will produce earthquake excitations. The speed, and direction motors will be controlled via an electrical setup that consists of two stepper drives and a module housed in a chassis that is in turn connected to a PC. The earthquake simulation system will be monitored through LabVIEW software. The MQP team will develop a program in LabVIEW so that real-time earthquake signals such as Kobe, El Centro and many other recorded earthquakes can be sent to the stepper motors to replicate real-time earthquakes and conduct our SHM experiments.

5.2 Earthquake Response Measurements

A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment. In structural health monitoring, it is important to measure some responses of the building structure such as its acceleration, velocity, and deformations after it has been through an earthquake. These variables are important in determining the state of a building structure such as - if it is damaged or undamaged through dynamics analyses. A multitude of sensors and sensor arrays as well as combinations of various response measurement systems are currently used for dynamic testing in the field of structural health monitoring [10]. Some monitoring techniques that the MQP team took into consideration are the use of accelerometers, fiber optics sensors, GPS measurement, laser scanning, and microwave radar.

5.2.1 Accelerometer

Accelerometer is a device that measures the actual acceleration relative to gravity. It does not measure the acceleration that is the rate of change of velocity but rather measures the acceleration due to gravity, or the g-force acceleration. Accelerometers have multiple applications in industry and science. In SHM, accelerometers are primarily used for measuring the displacements of structural members that they are attached to [12]. However, accelerometers do not provide information about the absolute position of the structure making it useless to detect permanent deflections/deformations. Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement can then be measured to give the acceleration. In this project, we utilized four accelerometers with each of the accelerometers attached to each of the four floors of the building system.

Figure 31: Accelerometers

5.2.2 Fiber Optics Sensors

Fiber optic cable is composed of two layers of glass, or plastic polymer. The inner layer is called the core. The outer layer is called the cladding. Light is transmitted through the core by utilizing the phenomena of total internal reflection. This phenomenon is possible because the cladding has a lower index of refraction than the core. The cladding acts as a waveguide that helps to maintain signal intensity. Fiber optics is a material that is impervious to electromagnetic interference making it ideal to be used as a sensor. Fiber optic sensors are great for use in SHM because they are lightweight, flexible and durable to corrosion [13]. Another property of optical fiber that makes it ideal for use in SHM is that the light intensity of the optical signal decreases when the fiber is strained perpendicular to its length; light intensity can increase or decrease if the fiber is stretched or compressed (along its length). This makes fiber optics to be a valuable indicator of strain or displacement [12]. Many different fiber optic sensor technologies exist and offer a wide range of performances and suitability for different applications. We rejected using fiber optics sensors because they are costly and requires proper training to be able to decode optical signals.

Figure 32: Fiber Optics Sensor

5.2.3 GPS Measurement

Global positioning systems (GPS) technology can provide accurate displacement measurements of structures and structural elements in real time using the known positions of Department of Defense (DOD) satellites and the travel time of electromagnetic signals between them and the target [14]. The stress and strain conditions of the structures can then be computed using finite-element models and numerical analyses. The GPS measurement system consists of a number of small mobile GPS receiver units (sensors) installed on the object to be monitored, plus one or more reference receivers installed at fixed, surveyed locations around the object. Every remote sensor will collect GPS observation data for a sufficient amount of time, and the data will be transmitted to the base station for post-processing [15]. Depending on the application, remote units are individually linked to the base station by a cable, a radio link or a cellular modem. The base station has the task of collecting the data from all receivers in the network while overseeing the single stations for correct operation. The data will be processed together, and the result will consist of the relative position of the various moving sensors with respect to the reference sensors. Damage localization and severity in structures can also be identified using the dynamic characteristics of structures obtained from GPS. However the MQP team rejected using GPS due to the high costs of the remote sensors and believes that it would be more suitable for use in large scale real-time structures than for laboratory use.

5.2.4 Linear Variable Displacement Transducer

The Linear Variable Displacement Transducer (LVDT) is a device used to measure the relative displacement between two fixed locations based on the principle of induction [16]. The device is constructed with three collinear coil windings, one primary and two secondary coils. The primary coil is electrified with an alternating current excitation voltage. A metal ferromagnetic rod, the LVDT core, is allowed to translate within a cylinder housing the three coils. Depending on the core’s location, two different currents are induced into the secondary coils. These different currents can then be measured. The displacement can then be calculated depending on the sensitivity of the LVDT.

Figure 33: Linear Variable Displacement Transducer

5.2.5 Strain Gauge

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain may be compressive or tensile and is measured by strain gages. Strain gages are designed to convert mechanical motions into electronic signals. The strain is proportional to the changes in capacitance, inductance, or resistance that is experienced by the sensor. If a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. This changes its resistance in proportion to the strain sensitivity of the wire's resistance. The ideal strain gage would change resistance only due to the deformations of the surface to which the sensor is attached. However, in real applications, there are other factors such as temperature, material properties and the stability of the metal which affect the detected resistance. There are different strain gauges that are designed to measure different types of strains such as axial, Poisson, bending and torsional. The MQP team rejected using strain gauge because we are mainly interested in the axial strain of the structure but torsional strain will complicate data acquisition due to the shaking table having two directional motions.

6. Theoretical Analysis

After setting up the shaking table, building model and response measurements, structural analysis and structural modeling can be conducted on the system. In this project, the proposed system will be a dynamic system where the structure members will be subjected to the dynamic loadings. Dynamic loadings are unstable and non-constant such as wind, earthquake, traffic, impact blasts and people. In this project, the main focus of study will be on the lateral forces, either at the top or bottom, acting on the structure. Structures under dynamic loadings cannot be analyzed by static analysis, therefore dynamic analysis is required to determine the displacements, time history and modes [17]. Simple dynamic system can be calculated manually but for more complex problems, finite element analysis can be used to determine the modes and frequencies. Dynamic systems can be modeled and analyzed to predict the performance of the dynamic system operating under specified environmental conditions. The model can be consisted of various stages; input, dynamic systems and output.

6.1 Mass-Spring Model

The most widely used model in dynamic analysis is the mass-spring model. Mass-spring model is the simplest dynamic model that can model either single degree or multi-degree of freedom systems. Degree of freedom (DOFs) is defined as the number of independent displacements required to define the displaced positions of all the masses relative to their original position [17]. For instance, the structure only contains one DOF, lateral displacement, thus we call this a single-degree-freedom system. Likewise, if the structure contains two or more DOFs, we can call this a multi-degrees-freedom system. The system can also be linear or nonlinear system. A linear system is a system where the relationship between the lateral (external) force and the resulting deformation are linear and vice versa.

When using the mass-spring model, it is necessary to apply Newton’s Second Law of motion. Newton’s Second Law is states that the acceleration of a particle is proportional to the resultant force acting on it and is in the direction of this force

$$F = m*a. \tag{1}$$

Using this relationship, the Free-Body Diagram (FBD) can be developed and Equations of Motion (EOM) can be derived using the FBD.

6.2 Type of Vibrations

There are two different types of systems that influence the analysis; free vibration or forced vibration. Free vibration is when a structure is said to be undergoing free vibration when it is distributed from its static equilibrium position and then allowed to vibrate without any external force. Forced vibration, steady-state vibration, is when the structure is excited by a certain external force and then allowed to vibrate. These vibrations can be affected by the damping factor in which case the free vibration steadily diminished in amplitude [17]. Thus the two different analysis can be broken down into four different analysis; free vibration undamped, forced vibration undamped, free vibration damped, and forced vibration damped.

6.3 Single DOF vs. Multi DOFs

There are three different components that governs the dynamic analysis; stiffness, damping, mass. Without these basic components, it is nearly impossible to analyze the dynamic system. These components can be determined through experimentally or using static analysis approach. Using these components, the solution of the dynamic analysis can be developed using differential equation. For system with single DOF, the differential equation, derived from equation of motion, will be second order differential equation. These differential equations can be solved using classical approach, Laplace transform or a Fourier transform.

For analyzing multi DOFs, obtaining solution through differential equation is quite complex. Thus it is recommended to use Modal Analysis. Modal Analysis is study of dynamic properties of structure under external excitation. Modal Analysis uses mass and stiffness to find the various period of vibration at which the structure will resonate. It is important that the period of vibration does not resonate with the external force frequency. If the vibration of the structure and the vibration of the external force are the same, the structure will resonate and the serious damage can be caused to the structure.

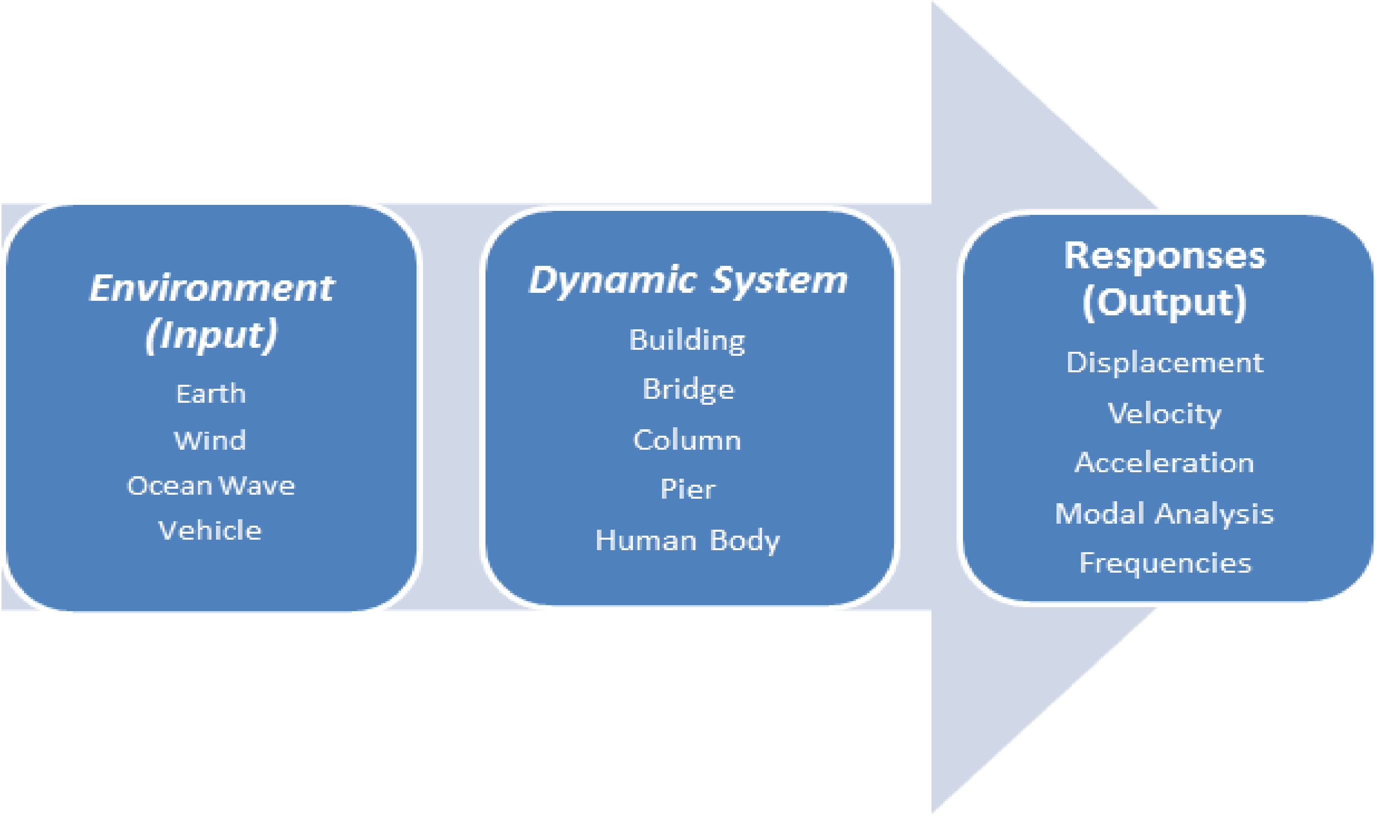


Figure 34: Dynamic System and Modeling

6.4 State Space Formulation

Another way to analyze dynamic conditions is the use of State Space Formulation. State space formulation is widely used among mechanical engineering. Its application is beyond mechanical engineering thus we can utilize this method efficiently for the civil structures. In civil engineering, state space formulation is used to solve the time domain problems of dynamic systems. It is desirable to change the form of the equation for a multi DOFs system with P 2nd orders differential equation to 2 P 1st order differential equation. The 1st order form of equation of motion is known as state space form. The solution of the state space is governed by its system matrix, input matrix and output matrix.

Matrix of M, K and C for Four Story Building

$$M = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & m \end{bmatrix} \quad (3)$$

$$K = \begin{bmatrix} 2k & -k & 0 & 0 \\ -k & 2k & -k & 0 \\ 0 & -k & 2k & -k \\ 0 & 0 & -k & k \end{bmatrix} \quad (4)$$

$$C = \begin{bmatrix} 2c & -c & 0 & 0 \\ -c & 2c & -c & 0 \\ 0 & -c & 2c & -c \\ 0 & 0 & -c & c \end{bmatrix} \quad (5)$$

State Space Matrices

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ \multicolumn{4}{c}{-K/M} & \multicolumn{4}{c}{-C/M} \end{bmatrix} \quad (6)$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \multicolumn{4}{c}{-1/M} \end{bmatrix} \quad (7)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (9)$$

6.5 Structural Health Monitoring

After performing the dynamic analysis on the model, it is also important to analyze the system as a damaged system. SHM experiments can be performed on the building model by first loosening some of the bolts and connections or taking out a column somewhere in the building model representing a damaged building system. Next earthquake will be simulated on the building model and the responses will be measured and analyzed. These damaged responses will be compared to the experiment done on undamaged building. This way, it can be determined whether our structural testing framework is accurate or not. Since real-life testing on an actual damaged structure are not possible and limited, dynamic analysis of the damaged structure on the building model is quite important. It is necessary to compare the results of the normal system to the damaged system and apply Structural Health Monitoring (SHM) techniques.

Another SMH method that is now widely used in Civil engineering is the Machine Learning Technique. Machine learning technique is a form of artificial intelligence where the system learns from series of data. Machine learning greatly depends on the amount of inputs there are in the system. The idea of machine learning is to make prediction on new and unseen problems while using learning experience from previous data sets.

7.0 Results and Discussion

The following data has been collected from the two story building model that has been shaken by using the prototype shaking table. The results are collected from shaking the table manually and the data has been collected using accelerometers that are attached at two different floor stories of the model. It can be interpreted that the g-gravitational force presented in the second floors are greater than compare to the first floor. The following results were collected by conducting 3 different experiments. First the model is shaken in only X-direction; figure 39 and 40 represents the g in each floor of the building model. Secondly, the model is shaken only in Y-direction; figure 41 and 42 represents the *g* in first and second floor of the model.

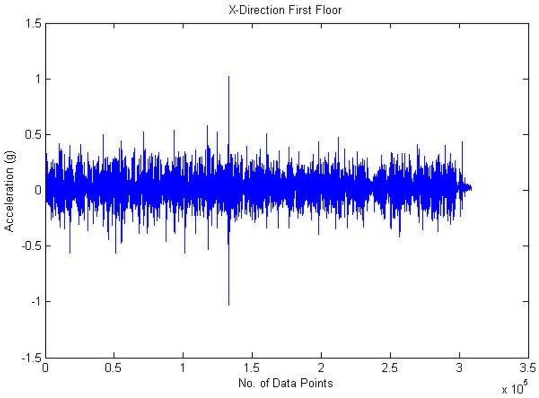


Figure 35: Acceleration of First Floor in X-Direction

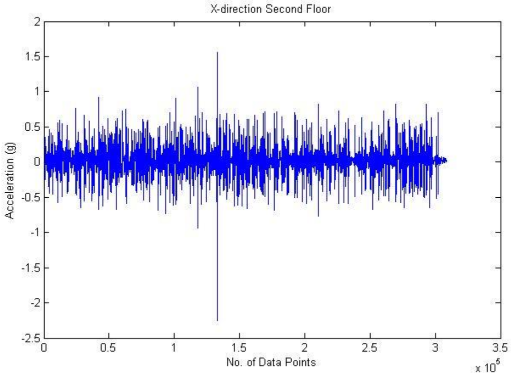


Figure 36: Acceleration of Second Floor in X Direction

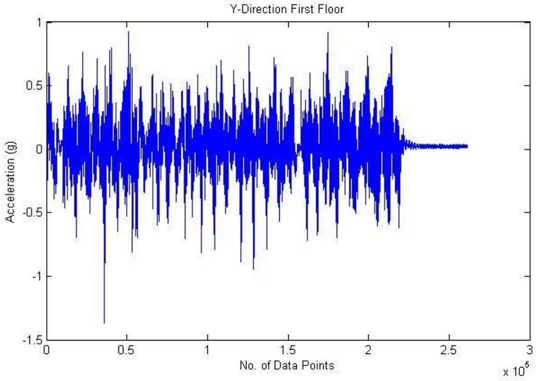


Figure 37: Acceleration of the First Floor in Y Direction

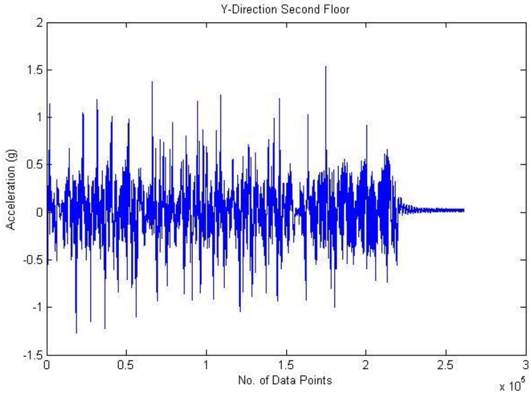


Figure 38: Acceleration of Second Floor in Y-Direction

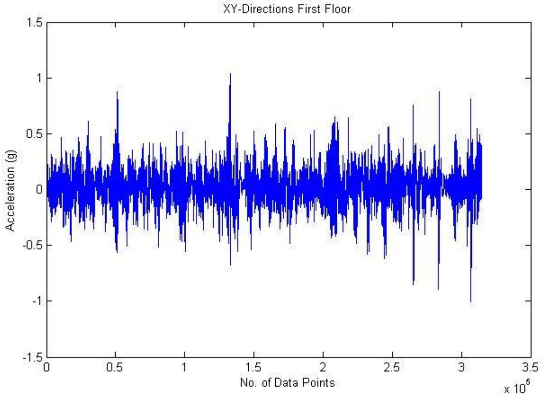


Figure 39: Acceleration of First Floor in Both X-Y Directions

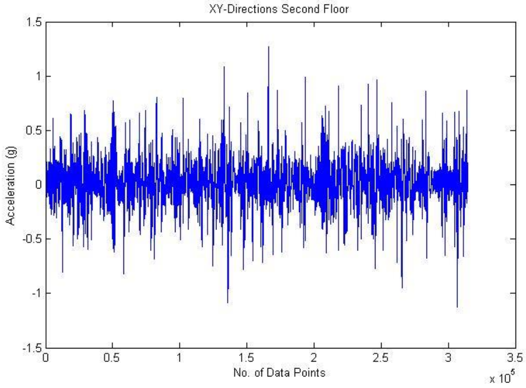


Figure 40: Acceleration of Second Floor in X-Y Directions

Once historical earthquake data are scaled accordingly, the data could be loaded on the vibration profile software developed through LabVIEW. To monitor the accuracy of the shaking table, an accelerometer could be attached to table deck and the output acceleration graphs would be compared to the scaled earthquake graph. If the acceleration graphs are identical, a structural dynamic experiment could be conducted. In this project, the expected results of the four-story building model are calculated using through State Space formulation analysis. The damping coefficient, ξ, was assumed to be 5%. As it can be interpreted from Figure 44 and Figure 45, the deflections and velocity in fourth floor are relatively larger compared to that of the first floors. This result is what is to be expected from the experiment data. If the experimental data has higher value than the calculated data, it would indicate that the damping coefficient needs to be larger and vice versa.

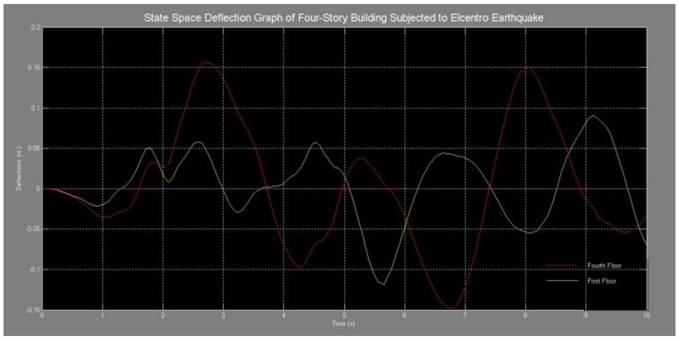


Figure 41: State Space Deflection Graph of Fourth and Second Floor

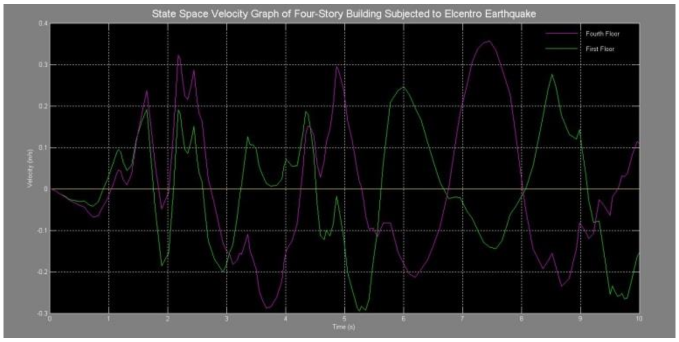


Figure 42: State Space Velocity Graph of Fourth and Second Floor

8.0 Conclusion

The MQP team believes that development and use of the shaking table is an excellent way to create earthquake simulations. The design of the shaking table in itself is unique and it is a good educational tool for analyzing the dynamic response of structures. Our proposed testing framework consists of designing and manufacturing the shaking table and building model, conducting Structural Health Monitoring experiments and analyzing dynamic responses of the structure. This testing framework is also able to accurately detect if a structure is damaged or not. Moreover, the MQP team has developed the shaking table system that is able to move in two directions and costs only around $1100 to manufacture. Other shaking tables on the market that are two directional are priced well over $100,000. In conclusion, the development and use of the shaking table is a great way to study structural dynamics experimentally. The high costs of manufactured shaking tables has limited the use of shaking table to study the dynamics of structures. However, the development of our cost-efficient shaking table along with the methodology for construction, will provide colleges and universities with the opportunity to acquire a shaking table for educational and research purposes. In addition, our shaking table can be put to use in other civil engineering courses such as building systems, and materials of construction lab. Our shaking table can also be introduced to new civil engineering students in their introductory courses at WPI featuring testing of basic structural models such as spaghetti bridges. Upon completion of this MQP, the design of our shaking table will be patented.

8.1 Educational Module

The MQP team developed a program to implement the use of shaking table in Structural Dynamics course at WPI. There will be weekly lab exercises involving the use of shaking table. In the beginning labs, students will learn and familiarize how to operate the shaking table and collect data. Students can choose to work with civil model of their choice (e.g. building or bridge) and will be asked to find the natural frequencies and damping ratios of their structure in labs that follow. In essence, students will come up with the theoretical results for their building model using structural dynamics and compare them to experimental results. They will be graded on the accuracy and analysis of their results. There will be a term project that will involve knowing all the activities done in previous lab exercises.

At the end of the course, students will answer a survey evaluating the effectiveness of the shaking table in helping them learn structural dynamics and rate their personal experiences with operating this shaking table. The detailed educational program is provided in the table below:

Table 4: Suggested Educational Module

Exercises	Assignment Details
Lab 1	• Study how to operate the Shaking Table and learn to replicate a desired earthquake. • Build or acquire a civil model (building or bridge structure) to be used in exercises through the term. • Study about LabVIEW and sensors (e.g. accelerometer and LVDT) to be used.
Lab 2	• Determine the mass of the structure. • Determine the stiffness of the structure using axial test. • Students will obtain the acceleration data for their civil structure using accelerometers.
Lab 3	• Find deflections data of their structure after subjecting it to an earthquake. • Using experimental data collected so far, plot seismic graph of the structure using Matlab/Simulink and compare it with theoretically developed seismic graph.
Lab 4	• Find the natural periods and natural frequencies of the structure using the shaking table. • Obtain the damping ratio of the structure. • Do research on Structural Health Monitoring (SHM).
Term Project	• The final term project will be to perform a SHM experiment. • Collect data to produce a seismic graph of the civil structure in the normal state of the structure. • Damage the structure by loosening some bolts and columns. • Recollect data and produce seismic graph of the structure in its damaged state • Write a report comparing and analyzing the two responses.

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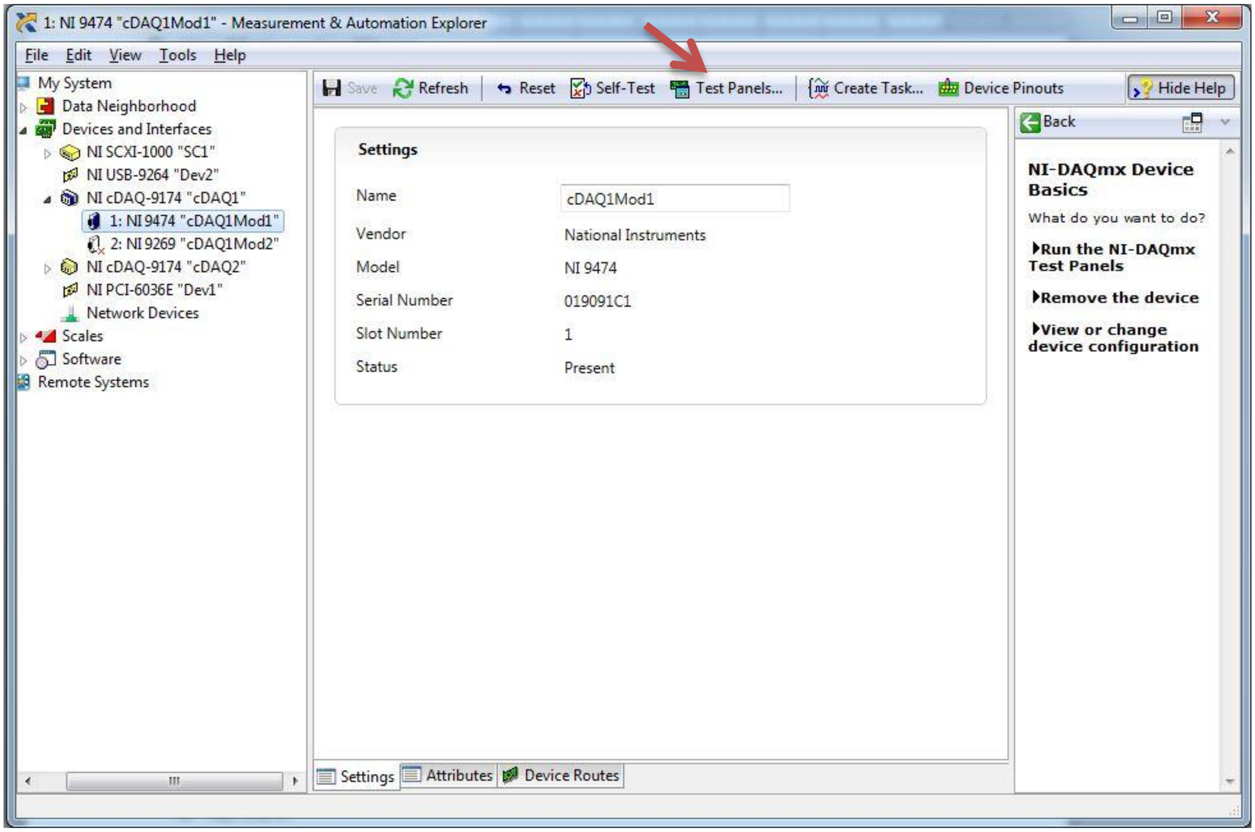
<u>Appendix A: Stepper Motor Control</u>

Testing Motor using NImax

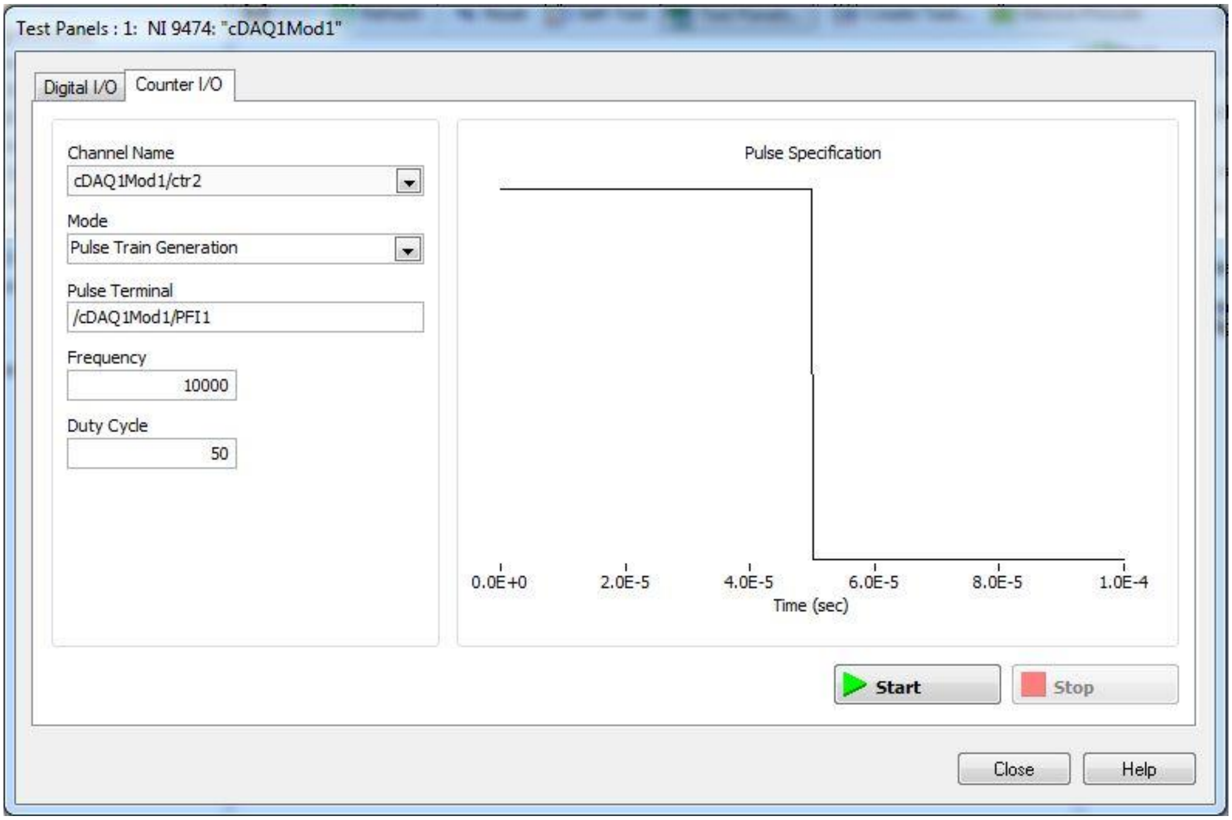
1. Open NImax (check the wire connections between motor, stepper drive, and module)
2. Under “Devices and Interfaces”==>”NI cDAQ 9174”==>”NI 9474”, choose Test Panels



Settings

Name cDAQ1Mod1
Vendor National Instruments
Model NI 9474
Serial Number 019091C1
Slot Number 1
Status Present

3. To check rotation of motor, use “Counter I/O” (counter 2 and counter 2 port) and set frequency to 10,000 Hz


Test Panels : 1: NI 9474: "cDAQ1Mod1"

Channel Name: cDAQ1Mod1/ctr2

Mode: Pulse Train Generation

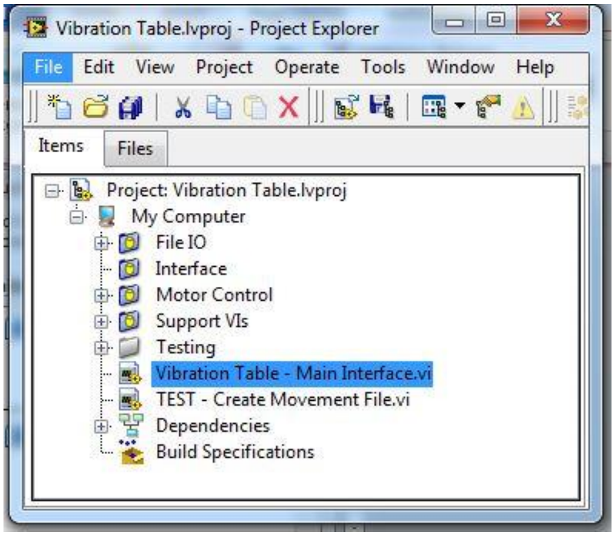
Pulse Terminal: /cDAQ1Mod1/PFI1

Frequency: 10000

Duty Cycle: 50

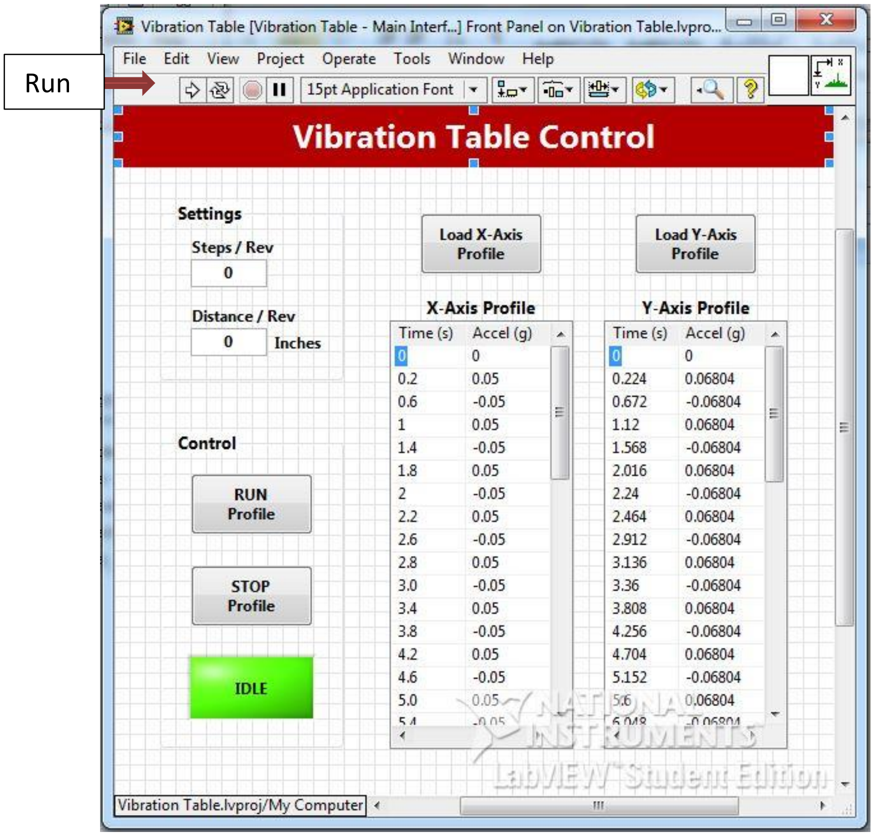
Vibration Control Manual

1. Folder (Bloomy)
2. Open “Vibration Table ”
3. In labVIEW Project Explorer, Open “Vibration Table - Main Interface ”


Vibration Table.lvproj - Project Explorer

- Project: Vibration Table.lvproj
  - My Computer
    - File IO
    - Interface
    - Motor Control
    - Support VIs
    - Testing
    - Vibration Table - Main Interface.vi
    - TEST - Create Movement File.vi
    - Dependencies
    - Build Specifications

4. Run the VI



Steps / Rev: 0

Distance / Rev: 0 Inches

X-Axis Profile

Time (s)	Accel (g)
0	0
0.2	0.05
0.6	-0.05
1	0.05
1.4	-0.05
1.8	0.05
2	-0.05
2.2	0.05
2.6	-0.05
2.8	0.05
3.0	-0.05
3.4	0.05
3.8	-0.05
4.2	0.05
4.6	-0.05
5.0	0.05
5.4	-0.05

Y-Axis Profile

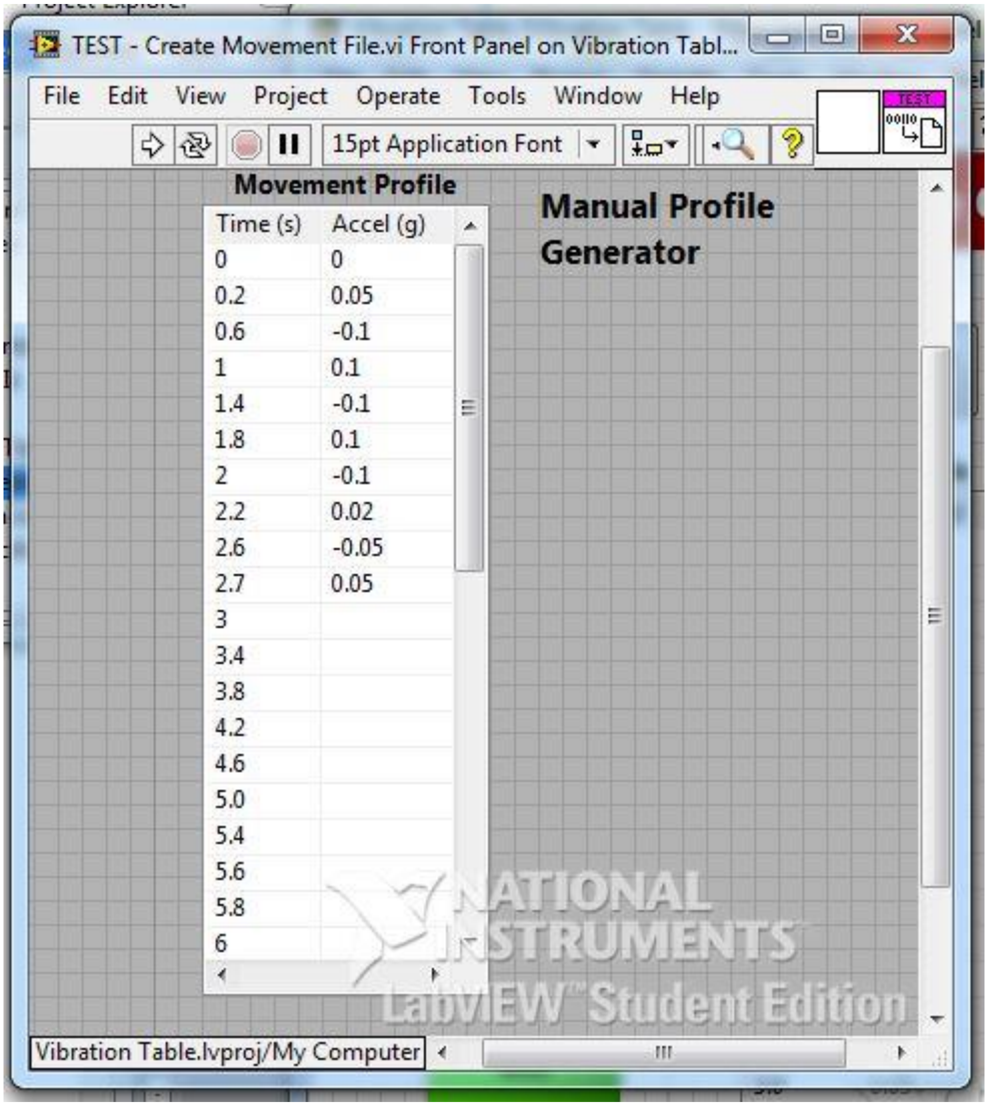
Time (s)	Accel (g)
0	0
0.224	0.06804
0.672	-0.06804
1.12	0.06804
1.568	-0.06804
2.016	0.06804
2.24	-0.06804
2.464	0.06804
2.912	-0.06804
3.136	0.06804
3.36	-0.06804
3.808	0.06804
4.256	-0.06804
4.704	0.06804
5.152	-0.06804
5.6	0.06804
6.048	-0.06804

5. Load “X-Axis Profile” and “Y-Axis Profile” from “test folder”
6. “Steps/Rev” can be specified to adjust the speed of the motors. The default value is 5000 steps/rev.

Note: Before a set of earthquake profile is loaded and ready to be tested on earthquake table, study the behavior of the earthquake produced by the motor so that the table deck does not collide against the motor.

Part 2. **Manual Profile Generator**

1. Open “Test – Create Movement File” to create artificial earthquake



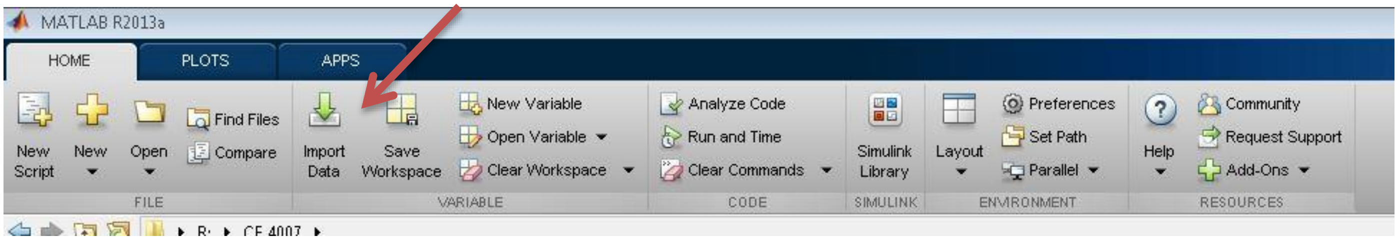
Movement Profile

Time (s)	Accel (g)
0	0
0.2	0.05
0.6	-0.1
1	0.1
1.4	-0.1
1.8	0.1
2	-0.1
2.2	0.02
2.6	-0.05
2.7	0.05
3	
3.4	
3.8	
4.2	
4.6	
5.0	
5.4	
5.6	
5.8	
6	

2. Sample earthquake profiles can be found under the folder “Bloomy” saved on the desktop on the computer in the lab.
3. Acceleration Profiles extensions are “.txt”
4. Note: Scaled historical earthquake data cannot be reproduced in the shaking table currently because the software needs further calibration.

Part 3. **Earthquake Profile Conversion**

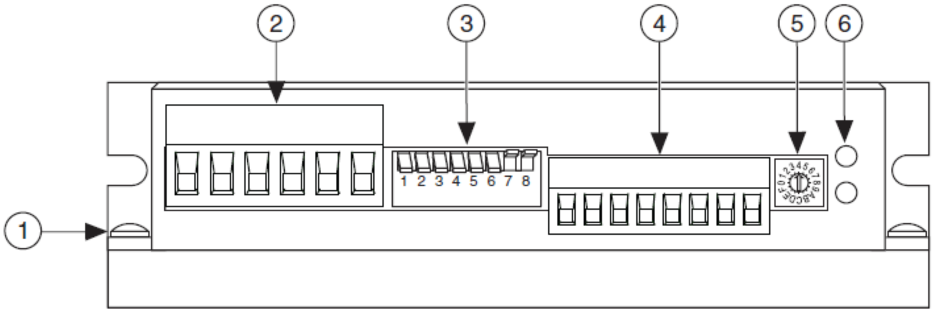
1. Earthquake Data can be found under “Bloomy=>EarthquakeData”
2. The following earthquake data can be accessed using Matlab by importing the file



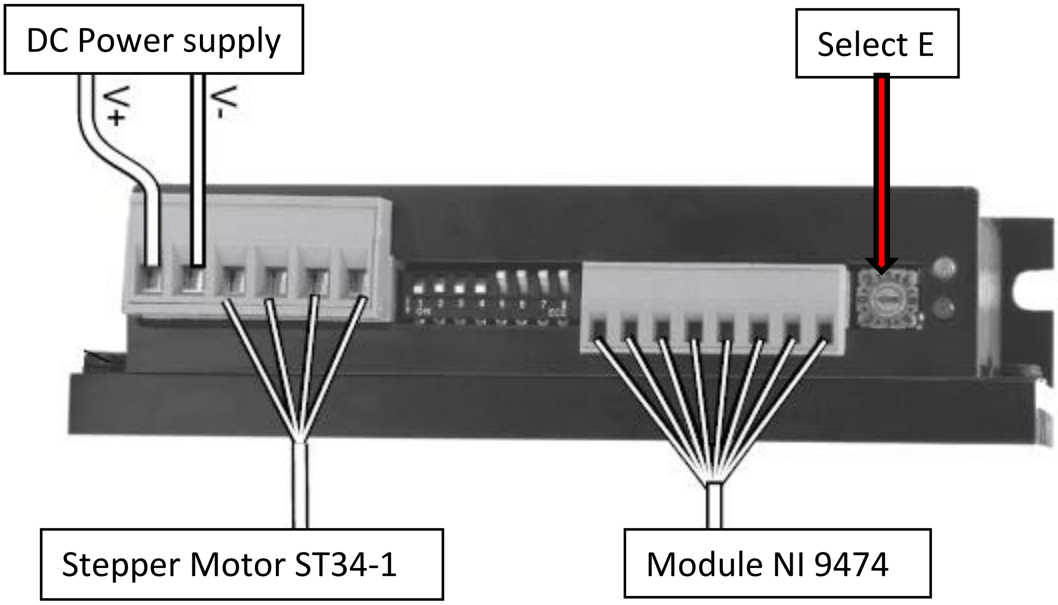
3. The data can be scaled in Matlab or copied to excel to be scaled

Stepper Drive

Figure 2. NI SMD-7611/7612 Stepper Drive Connectors

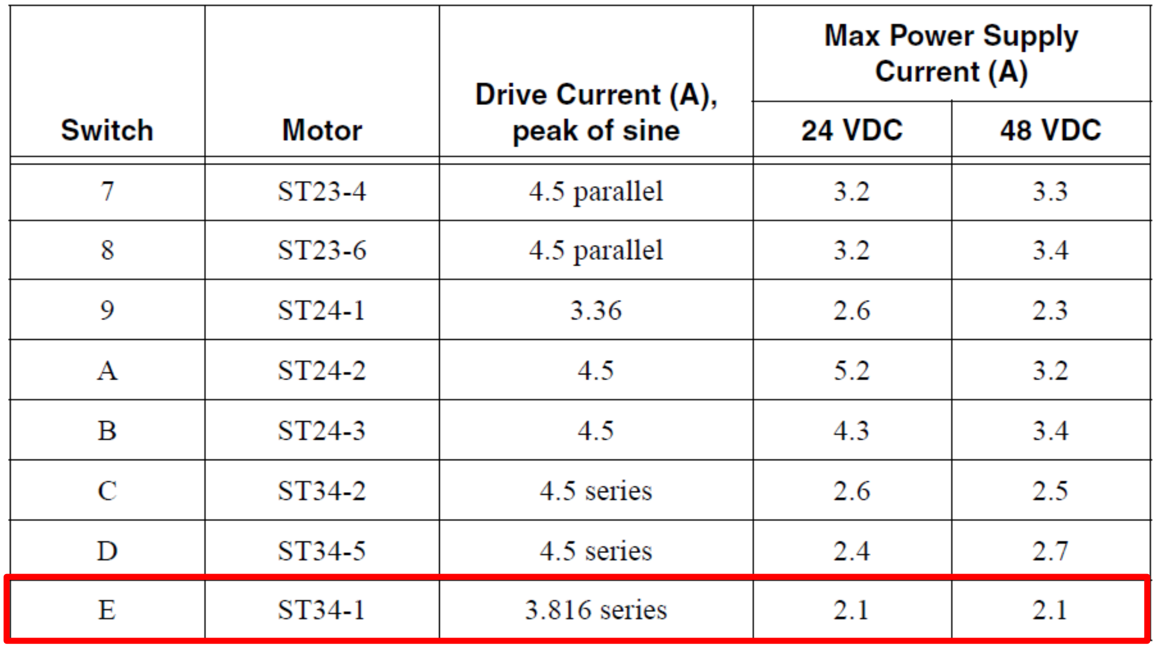


1 Chassis Grounding Screw
2 Motor and Power Supply Connector
3 Drive Configuration DIP Switches
4 Input and Output Signals
5 Motor Selector Switch
6 Drive Status LEDs



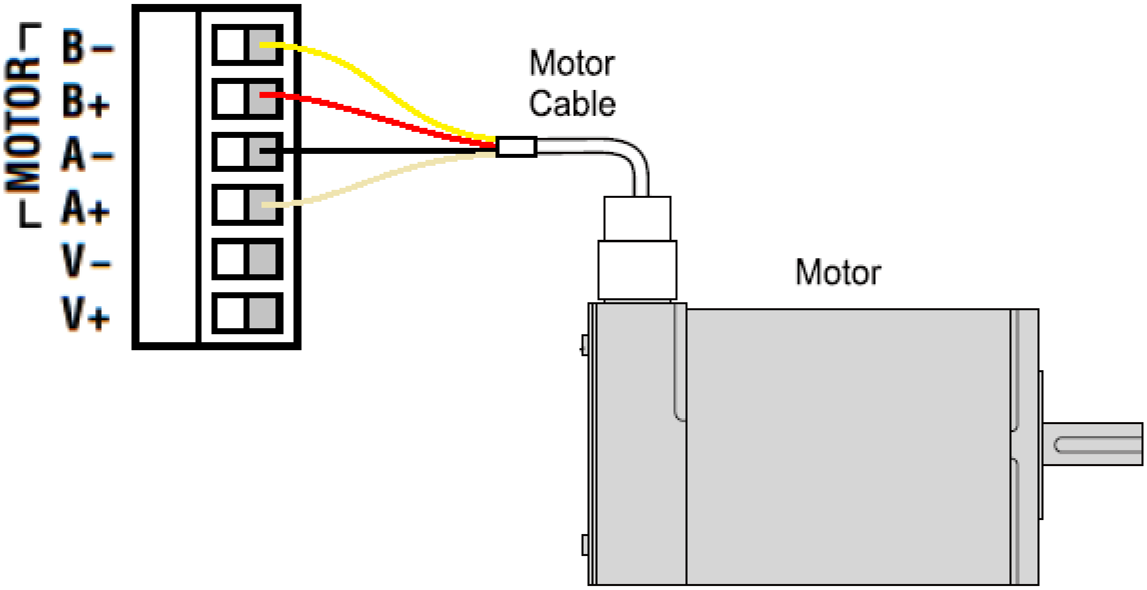
Connecting Motor and Power supply:

Table 1. NI SMD-7611 Power Supply Current (Continued)

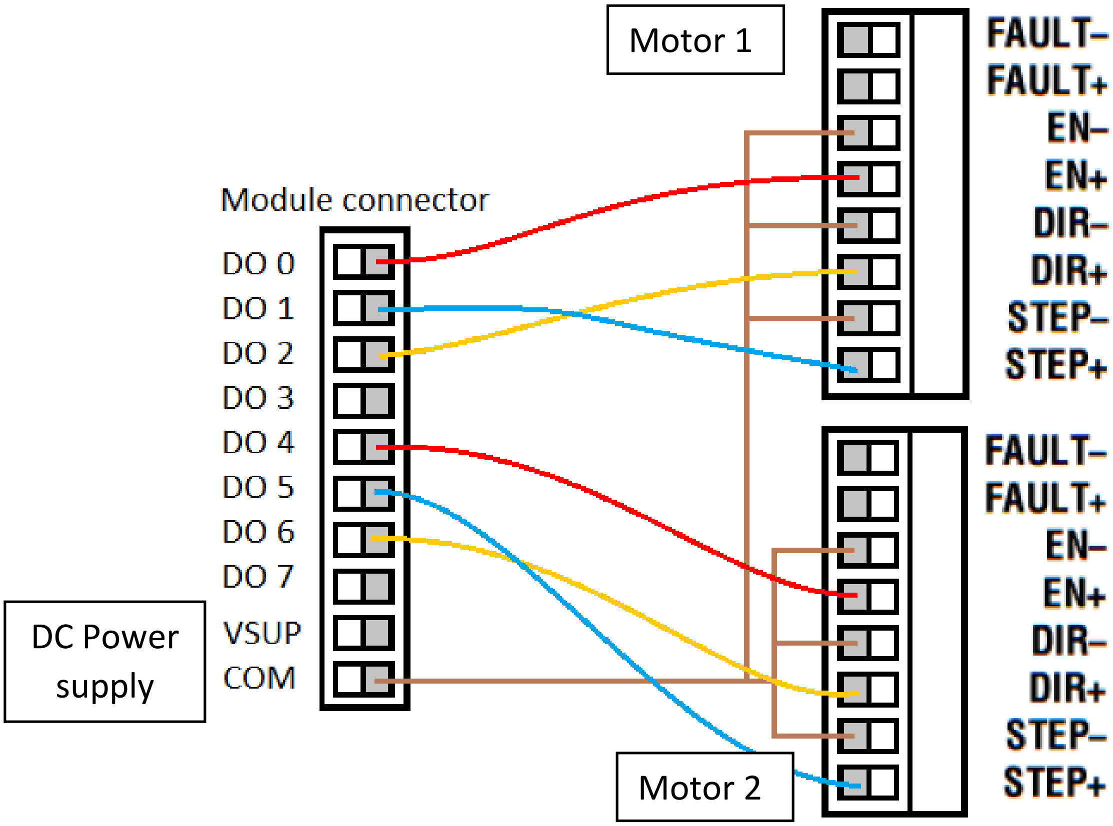


Switch	Motor	Drive Current (A), peak of sine	Max Power Supply Current (A)	
			24 VDC	48 VDC
7	ST23-4	4.5 parallel	3.2	3.3
8	ST23-6	4.5 parallel	3.2	3.4
9	ST24-1	3.36	2.6	2.3
A	ST24-2	4.5	5.2	3.2
B	ST24-3	4.5	4.3	3.4
C	ST34-2	4.5 series	2.6	2.5
D	ST34-5	4.5 series	2.4	2.7
E	ST34-1	3.816 series	2.1	2.1

Figure 4. Motor/Power Connector



Connecting Module and stepper driver:



Drive status LEDs

In the event of an error, the green LED on the main board will flash one or two times, followed by a series of red flashes. The pattern repeats until the alarm is cleared.

Table 12. Status LED Blink Code Definitions

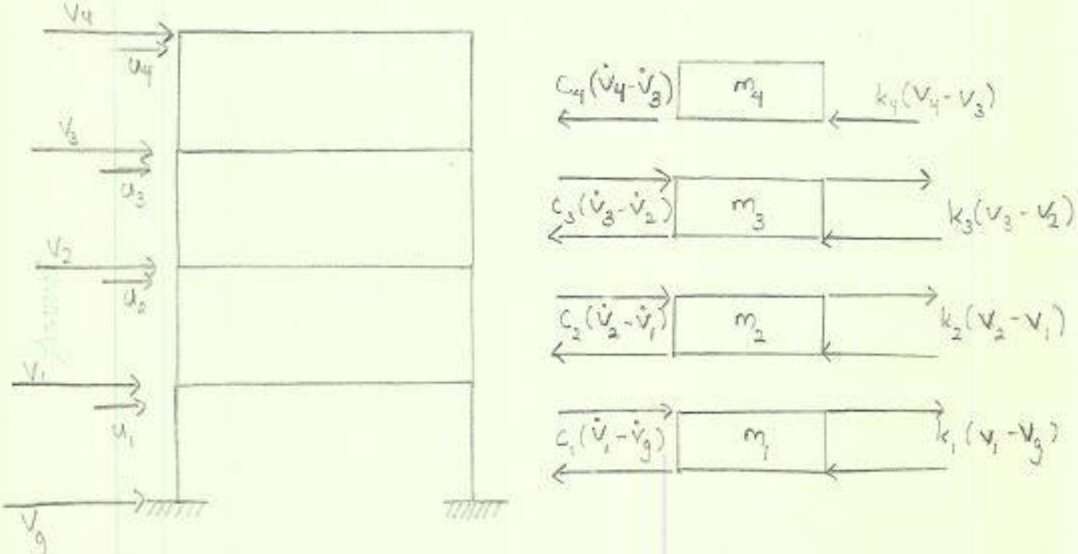
Blink sequence	Code	Error
G	Solid green	No alarm, motor disabled
GG	Flashing green	No alarm, motor enabled
RR	Flashing red	Configuration or memory error, contact NI support for assistance
RRRGG	3 red, 2 green	Internal voltage out of range
RRRRG	4 red, 1 green	Power supply voltage too high
RRRRGG	4 red, 2 green	Power supply voltage too low
RRRRRG	5 red, 1 green	Over current/short circuit
RRRRRRG	1 green, 6 reds	Open motor winding

For more information, refer to National Instruments: NI SMD 7611 Stepper Driver Manual.

http://www.ni.com/pdf/manuals/374107a.pdf

<u>Appendix B: State Space Calculation</u>

State Space Formulation of 4-story Building in 2-D analysis



Assume $V_1 = u_1 + v_g$

For m_1

$$F_1 = m_1\ddot{u}_1$$

$$-k(v_1-v_g) - c_1(\dot{v}_1-\dot{v}_g) + k_2(v_2-v_1) + c_2(\dot{v}_2-\dot{v}_1) = m_1\ddot{v}_1$$

$$-k(u_1+\cancel{v_g}-\cancel{v_g}) - c_1(\dot{u}_1+\cancel{v_g}-\cancel{v_g}) + k_2(u_2-u_1) + c_2(\dot{u}_2-\dot{u}_1) = m_1(\ddot{u}_1+\ddot{v}_g)$$

For m_2

$$F = m_2\ddot{u}_2$$

$$-k_2(v_2-v_1) - c_2(\dot{v}_2-\dot{v}_1) + k_3(v_3-v_2) + c_3(\dot{v}_3-\dot{v}_2) = m_2\ddot{v}_2$$

$$-k_2(u_2-u_1) - c_2(\dot{u}_2-\dot{u}_1) + k_3(u_3-u_2) + c_3(\dot{u}_3-\dot{u}_2) = m_2(\ddot{u}_2+\ddot{v}_g)$$

For m_3

$$F = m_3\ddot{u}_3$$

$$-k_3(v_3-v_2) - c_3(\dot{v}_3-\dot{v}_2) + k_4(v_4-v_3) + c_4(\dot{v}_4-\dot{v}_3) = m_3\ddot{v}_3$$

$$-k_3(u_3-u_2) - c_3(\dot{u}_3-\dot{u}_2) + k_4(u_4-u_3) + c_4(\dot{u}_4-\dot{u}_3) = m_3(\ddot{u}_3+\ddot{v}_g$$

For m_4 $\quad F = m_4 \ddot{u}_4$

$$-k_4(v_4 - v_3) - c_4(\dot{v}_4 - \dot{v}_3) = m_4 \ddot{v}_4$$

$$-k_4(u_4 - u_3) - c_4(\dot{u}_4 - \dot{u}_3) = m_4(\ddot{u}_4 + \ddot{v}_g)$$

State Space Matrices

Mass Matrix

$$\overset{M}{\begin{bmatrix} m_1 & 0 & 0 & 0 \\ & m_2 & 0 & 0 \\ & & m_3 & 0 \\ & & & m_4 \end{bmatrix}} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \\ \ddot{u}_4 \end{Bmatrix} + \overset{K}{\begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & -k_3 & k_3+k_4 & -k_4 \\ 0 & 0 & -k_4 & k_4 \end{bmatrix}} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}$$

$$+ \overset{C}{\begin{bmatrix} c_1+c_2 & -c_2 & 0 & 0 \\ -c_2 & c_2+c_3 & -c_3 & 0 \\ 0 & -c_3 & c_3+c_4 & -c_4 \\ 0 & 0 & -c_4 & c_4 \end{bmatrix}} \begin{bmatrix} \dot{u}_1 \\ \dot{u}_2 \\ \dot{u}_3 \\ \dot{u}_4 \end{bmatrix} = -\begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \end{bmatrix} \ddot{v}_g = F$$

$x_1 = u_1$

$x_2 = \dot{u}_1$

$\dot{x}_1 = \dot{u}_1 = x_2$

$\dot{x}_2 = \ddot{u}_1 = \frac{1}{m}\left(F - cx_2 - kx_1\right)$

$x_3 = u_2$

$x_4 = \dot{u}_2$

$\dot{x}_3 = \dot{u}_2$

$\dot{x}_4 = \ddot{u}_2$

$x_5 = u_3$

$x_6 = \dot{u}_3$

$\dot{x}_5 = \dot{u}_3$

$\dot{x}_6 = \ddot{u}_3$

$x_7 = u_4$

$x_8 = \dot{u}_4$

$\dot{x}_7 = \dot{u}_4$

$\dot{x}_8 = \ddot{u}_4$

Formulation

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_3 \\ \dot{x}_5 \\ \dot{x}_7 \\ \dot{x}_2 \\ \dot{x}_4 \\ \dot{x}_6 \\ \dot{x}_8 \end{bmatrix} = \underset{8\times 8}{\left[\begin{array}{c|c} \text{zeros}(4,4) & \text{eye}(4,4) \\ \hline -K/M & -C/M \end{array}\right]} \begin{bmatrix} x_1 \\ x_3 \\ x_5 \\ x_7 \\ x_2 \\ x_4 \\ x_6 \\ x_8 \end{bmatrix} + \underset{8\times 4}{\left[\begin{array}{c} \text{zeros}(4,4) \\ \hline 1/M \end{array}\right]} F$$

A : System Matrix

B

C Matrix

$$\begin{array}{r|c} \text{Displacement} & y_1 \\ & y_3 \\ & y_5 \\ & y_7 \\ \text{Velocity} & y_2 \\ & y_4 \\ & y_6 \\ & y_8 \end{array} = \underset{8\times 8}{\begin{bmatrix} \text{eye}(8,8) \end{bmatrix}} \begin{bmatrix} x_1 \\ x_3 \\ x_5 \\ x_7 \\ x_2 \\ x_4 \\ x_6 \\ x_8 \end{bmatrix}$$

D Matrix

zeros (8, 8)