5. DESIGN OF SHAKING TABLE SYSTEM COMPONENTS

5.1. INTRODUCTION

The method used for the design of the shaking table system components is similar to those described by Muhlenkamp [5] and Twitchell [19]. First, typical earthquake records were analyzed and chosen. Then, the hydraulic system components were chosen, based on the available sizes, their compatibility with each other and their compatibility with the Structural Laboratory hydraulic system. Furthermore, it was determined prior to construction that the structures that would be tested would typically be 1/4th scaled models of actual structures.

5.2. TYPICAL EARTHQUAKE RECORDS SELECTION

Five earthquake records were selected for the design and analysis of the shaking table components. These were selected based on their frequency content, magnitude and soil conditions. Table 5.1 shows the characteristics of the earthquakes selected.

5.3. SCALING OF PROTOTYPE GROUND MOTIONS

Two types of scaling are applied to the actual earthquake ground motion time histories used for experiments on scaled test structures [5].

5.3.1. SIMILITUDE SCALING

In this type of scaling the actual acceleration, velocity and displacement time histories applied to the actual structure (prototype) are scaled by a geometric scaling factor, λ_L, obtaining an equivalent acceleration, velocity and displacement time histories to be applied to the model structure. The geometric scaling factor was defined in Chapter 4 as,

$$\lambda_L = \frac{L_{Prototype}}{L_{Model}} \tag{5.1}$$

Table 5.1 Historical Earthquake Records Used in Analysis and Design of System Components.

Earthquake	Station	Epicentral Distance (km)	Site Geology	Magnitude	Predominant Freq. Range (Hz)	Peak Accel. (g)	Peak Veloc. (cm/s)	Peak Displ. (cm)
Imperial Valley May 18, 1940	El Centro Comp S00E	12	Alluvium	6.7	0.5 - 2.8	0.34	33.45	10.87
Kern County July 21, 1952	Taft Lincoln School Tunnel Comp. S69E	41	Alluvium (40 ft) Over Sandstone	7.2	0.5 – 3.3	0.18	15.72	6.71
Michoacan Sept 19, 1985	SCCT (Mexico City) Comp. N90W	373	Soft Clay	8.1	0.3 – 0.6	0.16	60.50	21.20
San Salvador Oct. 10, 1986	CIG (Floor 1) Comp. 90°	-	-	5.6	-	0.69	80.04	11.90
Northridge Jan. 17, 1994	Castaic – Old Ridge Route Comp. 360°	16	Alluvium	6.8	0.5 – 2.5	0.51	76.94	15.22

where L indicates a geometric length. Therefore, $\lambda_L = 4$ indicates that the model is 1/4th the size of the prototype structure. In the *Dynamic Modeling Theory* of an Adequate Model utilizing Artificial Mass Simulation (AMS) discussed in Chapter 4, the scaling factor for the time dimension is:

$$l_T = \sqrt{l_L} = \sqrt{4} = 2 \tag{5.2}$$

Therefore, the scaling factors for the acceleration and velocity are:

$$l_A = \frac{l_L}{(l_T)^2} = \frac{4}{(2)^2} = 1 \tag{5.3}$$

$$l_V = \frac{l_L}{l_T} = \frac{4}{2} = 2 \tag{5.4}$$

5.3.2. MAGNITUDE SCALING

The second type of scaling is an amplitude adjustment of the given time histories without a change in the time axis [5]. This scaling factor, K, is applied to the base acceleration, velocity and displacement records. This type of scaling will be referred to as *magnitude scaling*.

Both scaling factors, similitude and magnitude, can be applied to an earthquake ground motion to produce a model ground motion. For example, consider a 1/4th scale model ($\lambda_L = 4$) of a structure to be tested on the shaking table. The ground motion time histories are scaled for similitude, by leaving the acceleration magnitude the same (since $\lambda_A = 1$), decreasing the velocity magnitude by a factor of two (since $\lambda_V = 2$), decreasing the displacement magnitude by a factor of 4 (since $\lambda_D = \lambda_L = 4$) and compressing the time axis by a factor of 2 (since $\lambda_T = 2$). In addition, the time histories can be scaled by a magnitude scaling factor to simulate different levels of magnitude of the same seismic motions. In summary, for this particular case, the model base acceleration, velocity and displacement time histories would be given by [5]:

$$A_{model}(t_{model}) = K^*A_{prototype}(t_{prototype}/\lambda_L^{0.5})$$

$$V_{model}(t_{model}) = (K/\lambda_L^{0.5})^*V_{prototype}(t_{prototype}/\lambda_L^{0.5})$$

$$D_{model}(t_{model}) = (K/\lambda_L)^*D_{prototype}(t_{prototype}/\lambda_L^{0.5}) \quad (5.5)$$

5.4. REACTION MASS

A large reaction mass is required to minimize global simulator movement induced by the motion of the simulator platform and test structure [19]. To accomplish this, the reaction frame is rigidly connected to the strong floor at the Structural Laboratory at the UPRM Civil Engineering Department, as illustrated in Figures 5.1 (a) and (b).

The strong floor in the lab is constructed of reinforced concrete having a thickness of 12.7 cm (5.0 in). The total weight of the strong floor was calculated using the dimensions of the reaction frame connected to the floor plus 152.4 cm (5.0 ft) around the frame for a total weight of 70.54 kN (15,859 lb). Adding the reaction frame weight of 17.79 kN (4,000 lb), the total weight comes about 88.34 kN (19,859 lb). The weight of the simulator platform is 9.79 kN (2,200 lb) and the weight of the test structure (with added weight for AMS) is 9.79 kN (2,200 lb). The weight of the simulator/structure system is 19.57 kN (4,400 lb). Therefore, the weight of the reaction frame is 4.5 times the weight of the simulator/structure system. It is recommended the use of large reaction mass, about 30 to 50 times the mass of the simulator/structure system, to prevent motion of the reaction mass caused by the motion of the simulator platform and test structure [3, 6, 7, 17, 18 and 19]. Thus, it is important to measure the reaction frame's motion during tests.

(a) Middle Connection to Strong Floor.

(b) West-East Side Connection to Strong Floor.

Figure 5.1 Connection to Structural Lab Strong Floor

5.5. SIMULATOR PLATFORM (SLIP TABLE)

For the most part, uniaxial seismic simulator platforms are rectangular in shape and have the transverse dimension smaller than the longitudinal direction. The transverse dimension is arbitrary and it is only necessary for both stability and anchorage of test specimens [19].

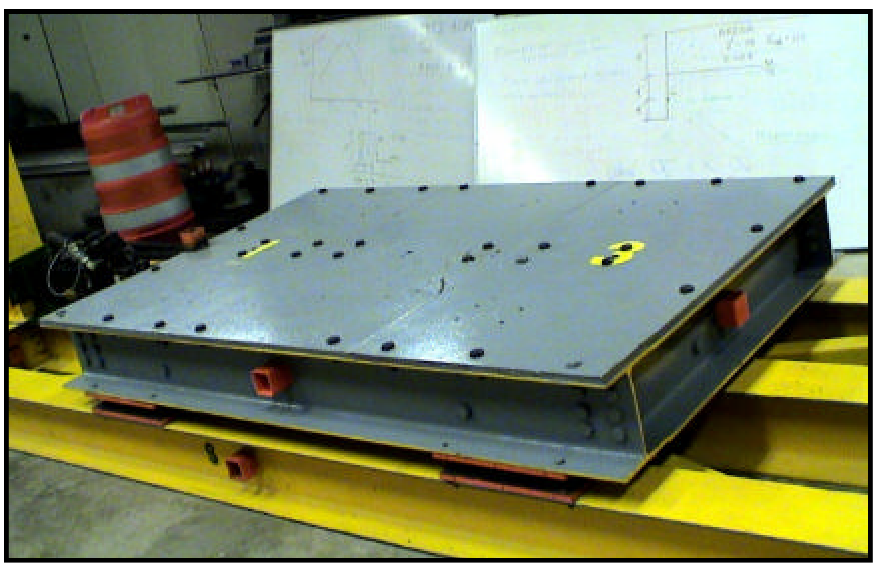
The plan dimensions of the platform were selected as 228.6 cm (7.5 ft) by 137.2 cm (4.5 ft) with the longer dimension in the translating direction. These dimensions are more than sufficient to accommodate the 137.2 cm (4.5 ft) by 91.44 cm (3.0 ft) plan dimensions of the 1:4 scale test structure.

The simulator platform weighs approximately 9.79 kN (2,200 lb) and consists of a bolted steel frame built with three longitudinal wide flange beams, W10x33, four diagonal tube section beams at the corners, ST 3x3x0.25, and three 1.91 cm (0.75 in) thick steel plates at the top. Figure 5.2 (a) and (b) show the simulator platform with and without the steel top plates. The top plate has 32 attachments points consisting of 2.06 cm (0.8125 in) diameter holes for bolts with 1.91 cm (0.75 in) diameter and 5.08 cm (2.0 in) length.

5.6. LINEAR ROLLER BEARINGS

The support method utilized to provide the sliding surface for the simulator platform is supplied by four-high accuracy, high-load capacity, preloaded and low-friction Crossed Roller Slide Tables (Steel) (see Figure 3.1 and Figure 5.3). Model NBT-6310 Crossed Roller Slide Tables were chosen due to its long travel, high-load capacity and low-friction coefficient of 0.003 [22]. The slide tables are mounted to the underside of the simulator platform. Each positioning table consists of a base, a carriage and a pair of

(a) Simulator Platform Welded Steel Frame.



(b) Simulator Platform with Top Steel Plate on.

Figure 5.2 Simulator Platform Components.

linear bearings. The bearings are factory preloaded to eliminate side play. In order to minimize the frictional forces developed at the bearing/rail interface, the slides tables were positioned with special care considering height deviation and parallelism. Figure 5.4 (a) and (b) illustrates the dimensions of the Crossed Roller Slide Table - NBT-6310. The technical specifications of a NBT-6310 are given in Table 5.2. Also, Table 5.2 shows the accuracy specifications. The permissible moments are [22]:

1. M_1 = 23,798 N-cm (2,106.3 lb-inch)
2. M_2 = 98,587.3 N-cm (8,725.7 lb-inch)
3. M_3 = 103,516.7 N-cm (9,162.0 lb-inch)

Figure 5.5 defines the permissible moments.

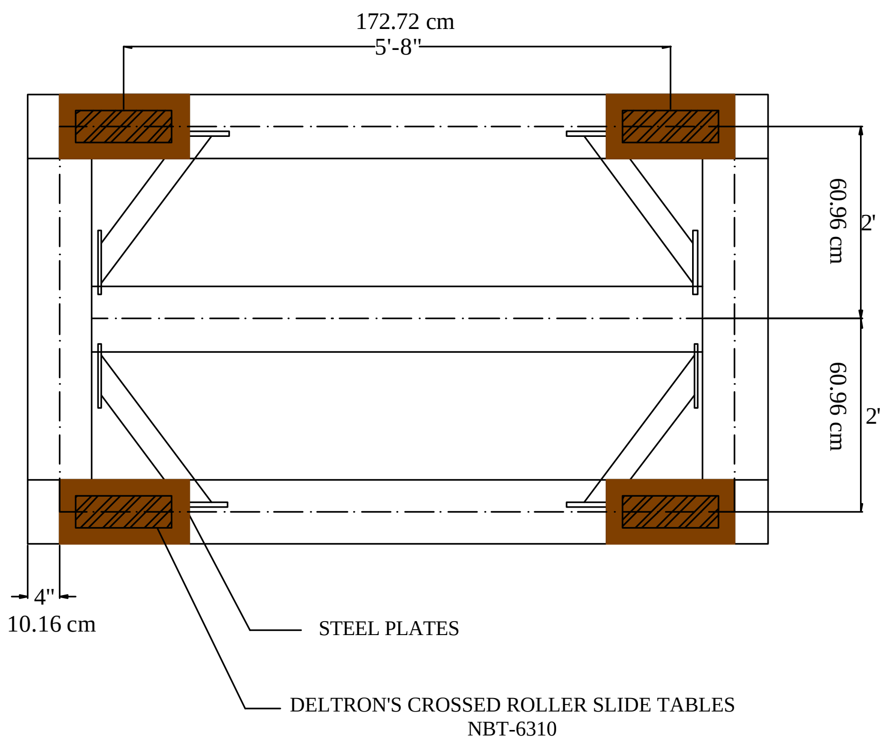
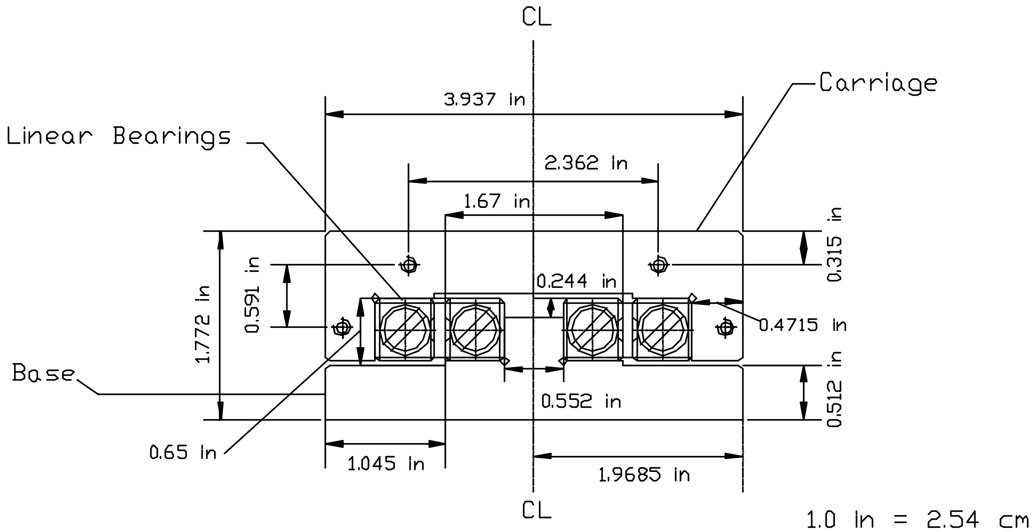
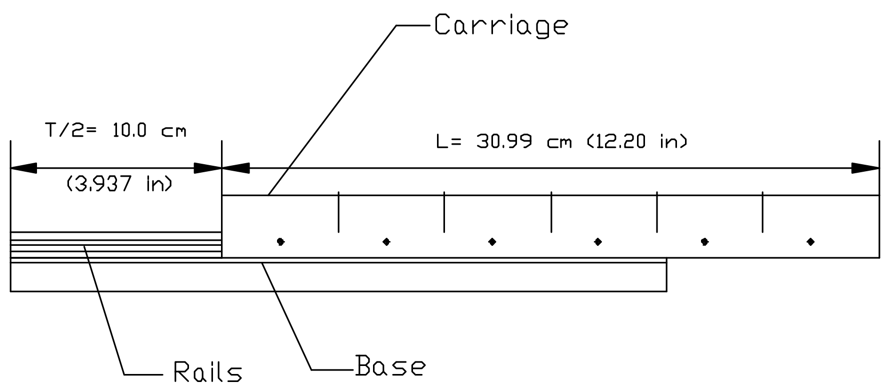


Figure 5.3 Plan View of Simulator Platform showing Locations of Sliding Bearings.



(a) Cross - Section of NBT-6310.



(b) Travel and Length Specifications.

Figure 5.4 Dimensions of a Crossed Roller Slide Table NBT-6310 [22].

Table 5.2 Technical Specifications of Linear Bearing System[1]

Dimensions Linear Bearing System	Distance (in)
Total height, cm	7.041 (2.772)
Width, cm	20.32 (8.0)
Length, cm	40.64 (16.0)
Horizontal centerline distance, cm	121.92 (48.0)
Longitudinal centerline spacing, cm	172.72 (68.0)
Crossed Roller Slide Tables	
Height, cm	4.50 (1.772)
Width, cm	10.0 (3.937)
Length, cm	30.99 (12.200)
Travel, cm	19.99 (7.87)
Load Capacity, N	11,743.3 (2,640 lb)
Horizontal centerline distance, cm	5.0 (1.9685)
Longitudinal centerline spacing, cm	15.494 (6.100)
Lateral height deviation accuracy, mm	0.006096 (0.00024)
Longitudinal height deviation accuracy, mm	0.003048 (0.00012)
Crossed Roller Rail Set	
Height, cm	1.501 (0.591)
Width (set), cm	3.101 (1.221)
Length, cm	30.254 (11.911)
Horizontal centerline distance between Slide Table and Rail Set, cm	±2.250 (±0.886)

Note: 1. Modified from [22].

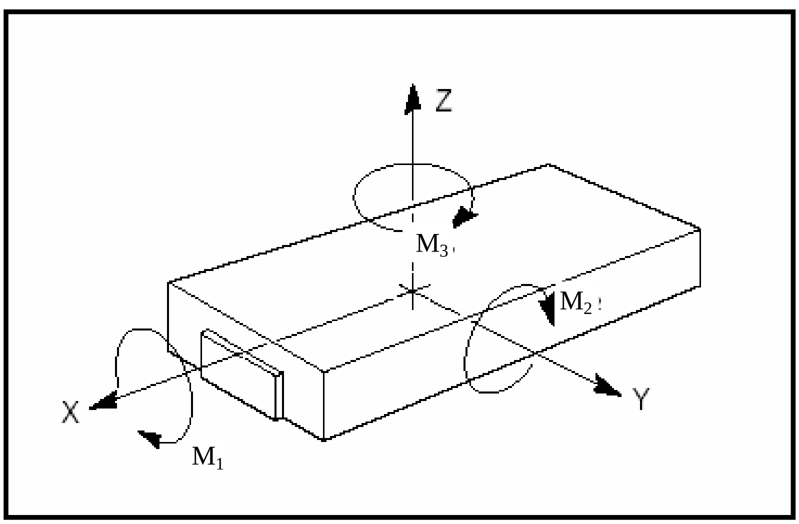


Figure 5.5 Permmisible Moment Load Ratings [22].

5.7. PAYLOAD

For the particular case of the UPRM shaking table the maximum design payload capacity of the shaking table will depend on three factors [5]:

1. Desired maximum base acceleration, A_{max}
2. The force that can be applied by the actuator, F_{max}
3. The load bearing capacity of the Linear Bearing System

The maximum weight of the test structure plus the slip table, W_{max} is:

$$W_{max} = \frac{F_{max}}{A_{max}} g \tag{5.6}$$

in which g denotes the acceleration of gravity.

5.8. HYDRAULIC ACTUATOR

The maximum force required by the actuator to reproduce the five historical earthquakes chosen was determined by an analysis on the response of a three-story scale-model test structure. The test structure was modeled as a shear type structure with lumped masses at each floor level. The weight of the lumped masses varied from 0.0 N (0 lb) to 3,558.6 N (800 lb). For the analysis, each earthquake record was magnitude scaled to a peak ground acceleration of 1.0 g and compressed in time by a factor of two to account for similitude requirements. The results are shown in Figure 5.6. Based on the results shown on Figure 5.6, for a story weight of 2,224.1 N (500 lb) and with a factor of safety of 1.5, a 48.93 kN (11.0 kip) actuator will give the necessary force to reproduce the five representatives historical earthquakes. For story weights greater than 2,224.1 N (500 lb) and smaller than 3,559 N (800 lb), the 48.93 kN (11.0 kip) actuator would work too but with a smaller factor of safety, except for the Northridge record. Therefore, a 48.93 kN (11 kip) maximum actuator force was chosen.

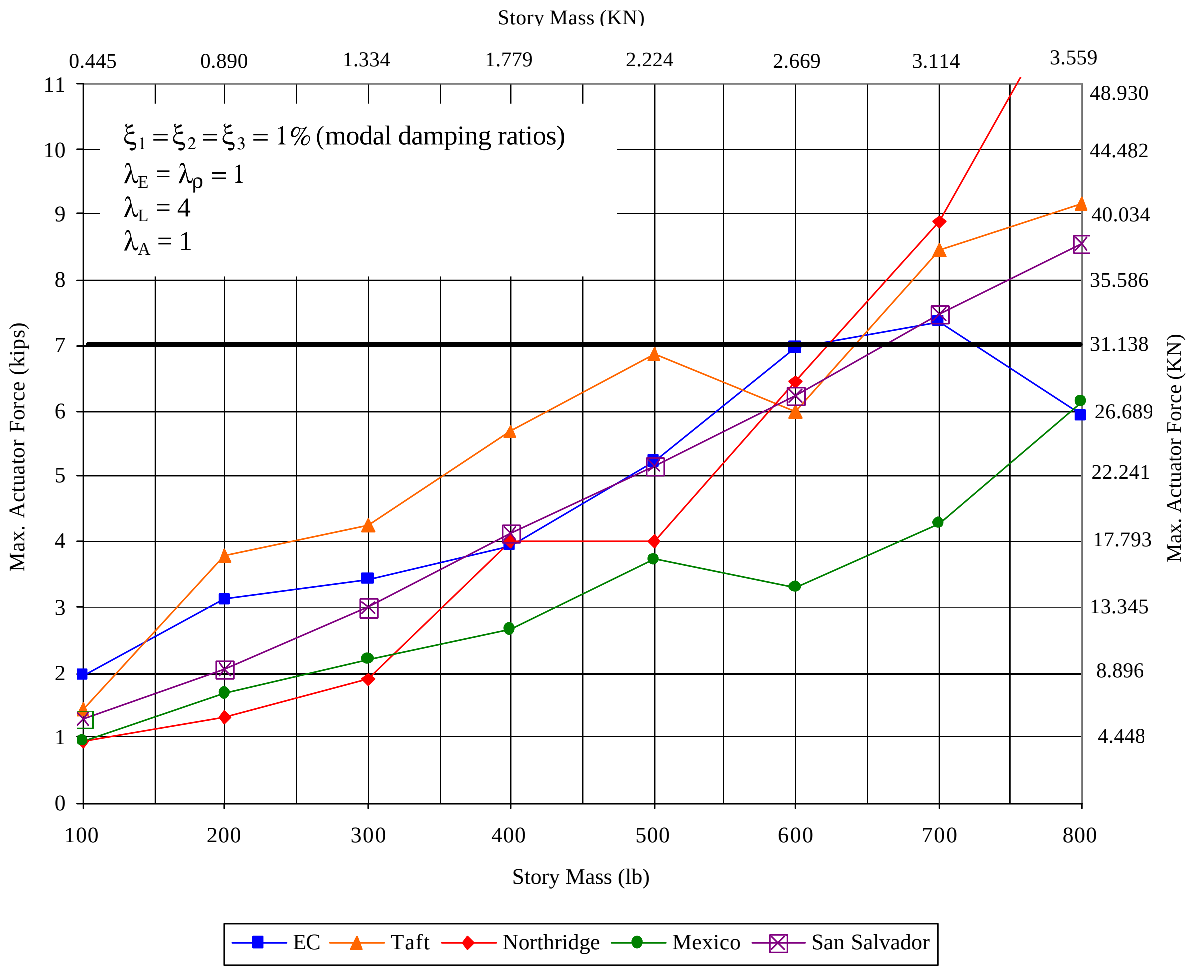


Figure 5.6 Maximum Actuator force for Five Representative Earthquake Records.

The hydraulic pressure available is 20,684.3 kN/m^2 (3,000 psi) (standard), therefore the required effective piston area was determined to be:

$$A = \frac{F}{P} = \frac{48.93kN}{20{,}684.3\, kN/m^2} = 0.002366m^2 = 23.66cm^2 = 3.67in^2 \qquad (5.7)$$

The actuator that was selected with these characteristics was an MTS Model 244.21 Hydraulic actuator rated at 48.93 kN (11 kips) and with an effective area of 25.16 cm^2 (3.90 in^2) and a stroke of ±7.62 cm (± 3.00 inches) [20].

5.9. SERVO-HYDRAULIC SYSTEM

The servo-hydraulic system was designed and chosen to be able to reproduce typical seismic motions, such as those depicted in Table 5.1, and based on their compatibility with the available hydraulic system at the UPRM Structural Laboratory and between each other. From Table 5.1, it can be seen that the maximum peak ground acceleration is about 0.7g, the maximum peak ground velocity is 80.04 cm/sec (31.51 in/sec) and the maximum peak ground displacement is 21.20 cm (8.35 in). Therefore, the maximum values of acceleration, velocity and displacement at model scale, using the geometric factor of 4, would be 0.7g, 40.02 cm/sec (15.75 in/sec) and 5.3 cm (2.087 in), respectively. The maximum displacement is compatible with the span of the Model 244.21 linear hydraulic actuator of ±7.62 cm (± 3.00 in).

The maximum required flow of oil into the actuator, Q_{max}, is calculated as follows [5]:

$$Q_{max} = A_{effective} * V_{max} \quad (5.8)$$

Where $A_{effective}$ = the actuator piston effective area = 25.16 cm^2 (3.90 in^2)

V_{max} = the maximum velocity at model scale = 40.02 cm/sec (15.75 in/sec)

Therefore:

$$Q_{max} = (25.16\ cm^2)(40.02\ cm/sec) = 1006.9\ cm^3/sec = 60.414\ liters/min$$

$$= (3.90\ in^2)(15.75\ in/sec) = 61.425\ in^3/sec = 15.93\ gpm$$

The servovalve selected was a dual MTS Model 252.25 two-stage servovalves, rated at 56.0 l/min (15gpm) each for a total of 112.0 l/min (30gpm) maximum flow [23]. For simulation of earthquake-like motions, the pump must be able to provide an average sustained flow equal to [5]:

$$Q_{pump} = \frac{Q_{\max}}{\frac{3p}{2}} = \frac{60.414}{\frac{3p}{2}} = 12.82\ {}^{l}\!/_{\min} \tag{5.9}$$

The Hydraulic Power Supply (pump) installed in the laboratory is a MTS Model 506.61 and is rated at 265.0 l/min (70 gpm) of steady flow [24]. A Hydraulic Service Manifold (HSM) MTS Model 293.11, with a rated capacity of 190.0 l/min (50 gpm), is mounted between the HPS and the servovalves [25]. The purpose of the HSM is to distribute the hydraulic power to the different actuator channels.

5.10. CONTROLLER SPECIFICATIONS

The purpose of the controller is to regulate the position of the actuator arm [5]. The controller chosen was the TestStar IIs AP System, composed of the Model 493.01 Servo-Controller and the Control computer (PC) with the software to control the Servo-Controller. The TestStar IIs digital controller performs the control system's real time functions, including high-speed closed-loop control, data acquisition, function generation and transducer conditioning [26]. The Servo-Controller is a **PIDF** controller, it has displacement feedback and the gains of the **PIDF** algorithm can be adjusted for optimum table response for changing loading conditions [5].

The PC provides the link between the TestStar IIs digital controller and the user. The PC is where the user defines and run the applications and store and analyze data. The software is the heart of the TestStar IIs System. The Basic TestWare program is the basic software that comes with the PC software. It let the operator to set-up and run simple monotonic and cyclic test by defining the rate, frequency, amplitude, and mean for sine, triangle, square, and ramp command signals. While the test is running, the Basic TestWare can capture the test data for analysis and display. Data can be acquired as various types, such as the peak/valley, minimum/maximum, timed data, and level crossing. All of the user's test set-ups in Basic TestWare can be saved and recalled for use at any later time.

However, for the needs of the UPRM tests, a special software called MultiPurpose TestWare was needed. This program has special attributes such as testing flexibility were the user can create his/her own test sequences and data acquisition [27]. The user is not limited as one might be with a fixed-function application. The program has a special command called *"Profile Command"* where the user can create a file made up a series of cyclic, dwell and other segment commands, read by the PC and translate them to the Servo-Controller in servovalve openings. Using this command, the earthquake time histories were generated.

5.11. DATA ACQUISITION SYSTEM SPECIFICATIONS

The Data Acquisition Computer stores the data of the accelerometers mounted on the simulator platform and reaction mass. This computer is equipped with an Iotech signal processing board and DasyLab software. We also use Dewetron's Model DAQ-PV for signal conditioning of the accelerometers. The DAQ-PV module has selectable ranges of voltages and filters to condition the accelerometer raw signal into a standardized voltage output to send to the computer's signal processing board.

The signal processing board model installed at the Data Acquisition PC (DAQ) is an Iotech model 16-bit board called DAQ BOARD-200A. It has a 100 kHz A/D converter and eight differential or sixteen single-ended analog input channels.