6. SERVO – HYDRAULIC SYSTEM

6.1. INTRODUCTION

Hydraulic power systems typically consist of an arrangement of hydraulic power supplies, remote service manifolds, and accessory equipment [24]. These components integrate into a hydraulic power distribution network to provide hydraulic fluid power to servo-controlled actuators. The hydraulic power supply provides the distribution system with constant-pressure, high filtered hydraulic fluid power. The distribution system consisting of hose kits, service manifolds and accessories, routes the fluid power to individual actuators within the system. The following sections discuss, in a general manner, the hydraulic power system used by the seismic simulator facility developed at the Structural Research Laboratory of the Civil Engineering Department at the University of Puerto Rico at Mayagüez. This discussion will be based on the MTS Manuals for the different parts of the hydraulic system.

The performance envelope of the shaking table is directly related to the physical limits of the hydraulic power supply (pump), servovalve, and actuator [5]. Theoretical performance envelopes will be given for the seismic simulator system.

6.2. HYDRAULIC POWER SUPPLY (HPS) [24]

The MTS Model 506.61 currently provides the hydraulic power to the different testing facilities of the Structural Research Laboratory at the Civil Engineering Department. The MTS Model 506.61 hydraulic power supply (HPS) or hydraulic power unit (HPU) uses a variable volume pump to provide a source of hydraulic power for hydraulic systems having flow requirements of 265.0 l/min (70.0 gpm). It provides two levels of operation at 265.0 l/min (70 gpm): 1.0 MPa (150 psi) and 21.0 MPa (3000 psi) for low and high-pressure, respectively. The MTS Model 506.61 model is specially designed to meet the exacting requirements of systems using servo-valves. Figure 6.1 illustrates the general form of operation of the MTS Model 506.61 hydraulic power unit through a block diagram.

The oil storage reservoir has an approximate 757.0 liters (200 gal) capacity. Oil is drawn from the storage reservoir and forced through the supercharger pump and then through the main pump. A return line brings the oil back to the reservoir to complete the cycle.

Filtering eliminates contaminants (dirt) from the hydraulic fluid to be used with dirt-sensitive servo-valves. For the MTS Model 506.61, the output fluid is filtered to 10 microns and reservoir fluid to the main pump passes through a 40-micron inlet filter. Also, a 3-micron filter bypasses fluid to the reservoir.

The fluid-to-water heat exchanger maintains the reservoir hydraulic fluid temperature below a maximum safe temperature. If fluid temperature exceeds a preset limit, a temperature-sensitive switch mounted on the reservoir will open and turn off the HPU. For the MTS Model 506.61 this preset limit is 60°C (140°F). Table 6.1 lists the main specifications for the MTS Model 506.61 hydraulic power system unit, as given by the manufacturer.

6.3. HYDRAULIC SERVICE MANIFOLD (HSM) [25]

The hydraulic service manifold is a modular hydraulic pressure and flow regulation device that controls the hydraulic pressure to multiple stations independently from the main hydraulic power unit (HPU). Two hydraulic service manifolds distribute fluid power from the hydraulic power unit to the different testing facilities at the Structural

Research Laboratory. The MTS Model 293.11A hydraulic service manifold (HSM) will distribute and regulate the fluid power for the shaking table facility. It also distributes hydraulic power to the wind testing facility at the Structural Research Laboratory.

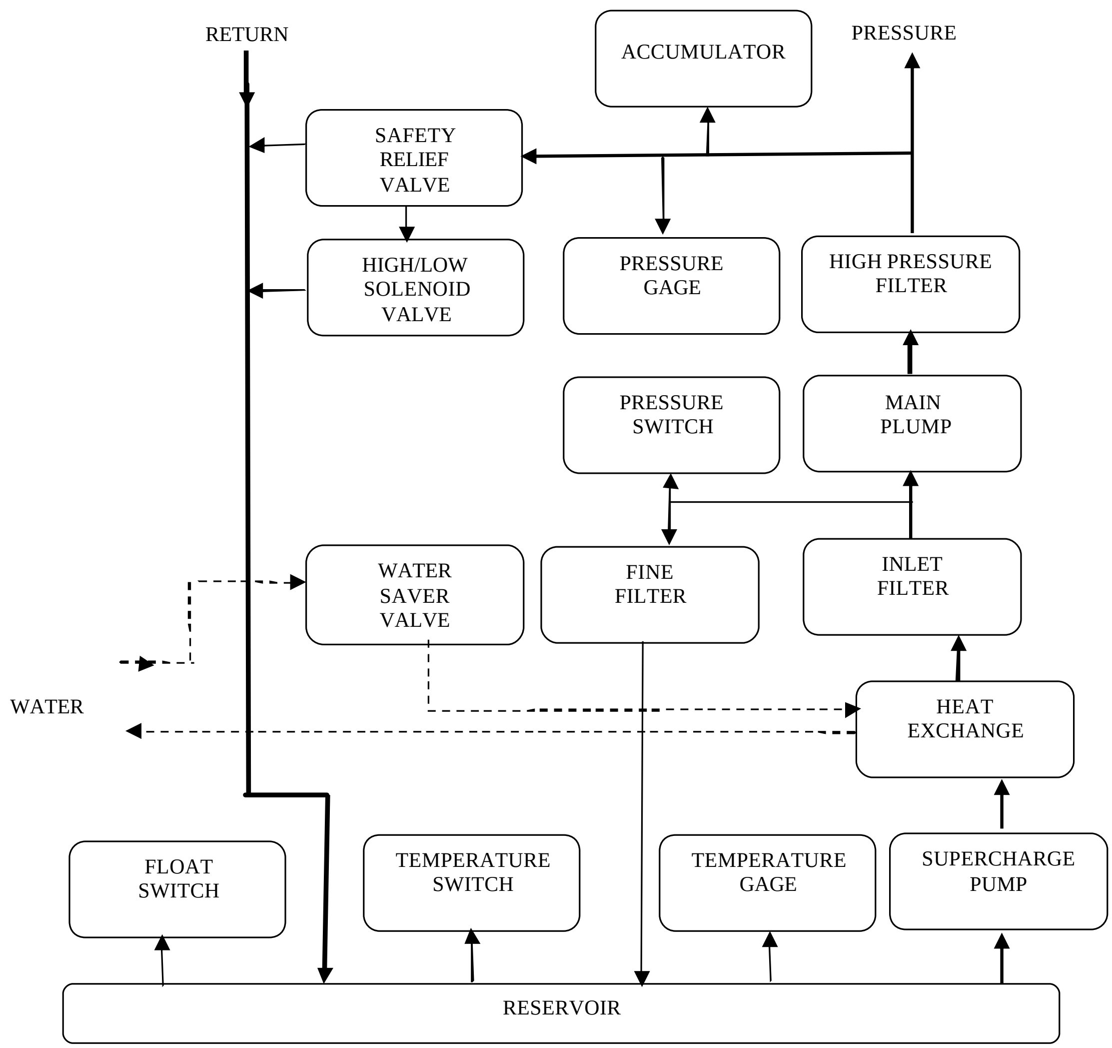

Figure 6.1 Block Diagram for MTS Model 506.61 Hydraulic Power Supply [24].

The service manifold is connected between the hydraulic power unit and the different hydraulic channels. A hydraulic channel is associated with an actuator and a servovalve system. The MTS Model 293.11A has a nominal hydraulic capacity of 190.0 l/min (50 gpm) and a control voltage of 24 volts (DC). It has two operating pressures at the nominal flow: 1.0 MPa (150 psi) and 21.0 MPa (3,000 psi) for low and high pressure, respectively. Figure 6.2 shows the different components of the MTS Model 293.11A remote service manifold. The various components form a system of fluid flow, pressure control, filtering and accumulators.

Table 6.1 MTS Model 506.61 HPS Specifications[1].

Parameter	Specifications
Reservoir Capacity, l	757.0 (200.0 gal)
Flow Capacity at: l/min	265.0 (70.0 gpm)
Pressure, MPa	21.0 (3,000 psi)
Frequency	60.0 Hz
Filtration (microns)	
Full Flow	2
Nominal/Absolute	10
Hydraulic Fluid	A/W Hydraulic 46
Pump Motor at: kW	95.0 (125.0 HP)
Frequency	60.0 Hz
Starter (3-Phase, 380V, 60Hz)	Part Winding
Inrush	380
Continuous Amps	195
Max. Ambient Operating Temperature, °C	40.0 (104°F)
Min. Ambient Operating Temperature, °C	4.4 (40°F)
Water Flow at:	
18.3°C (65°F)	56.78.0 l/min (15.0 gpm)
29.4°C (85°F)	132.0 l/min (35.0 gpm)
Height, cm	154.94 (61.0 in)
Length, cm	226.06 (89.0 in)
Width, cm	111.76 (44.0 in)
Weight, with Fluid, N	22,241.1 (5,000 lb)

Note: 1. Modified from [24].

The hydraulic fluid from the HPS enters the HSM at the pressure in port at the main manifold, where the fluid is filtered through a 10-micron filter. After filtration, the fluid passes to the control manifold (through the distribution manifold), fills the pressure accumulator and exits the HSM through the pressure out port. The control manifold distributes hydraulic fluid to and from a single hydraulic channel. The control manifold contains a low and high-pressure solenoid valves, a main valve, a slow-turn on accumulator and a pressure gage. The control manifold applies hydraulic pressure to the servovalve, and controls whether the pressure is high or low at the HSM pressure out ports. The low and high-pressure solenoid valves allow that pressure control. High-pressure output is typically maintained at 21.0 MPa (3,000 psi). Return fluid from the actuator enters the return in port, flows through the return accumulator and exits to the HPS through the return out port. Drain ports provide a path for collecting excess fluid and returning it to the HPS.

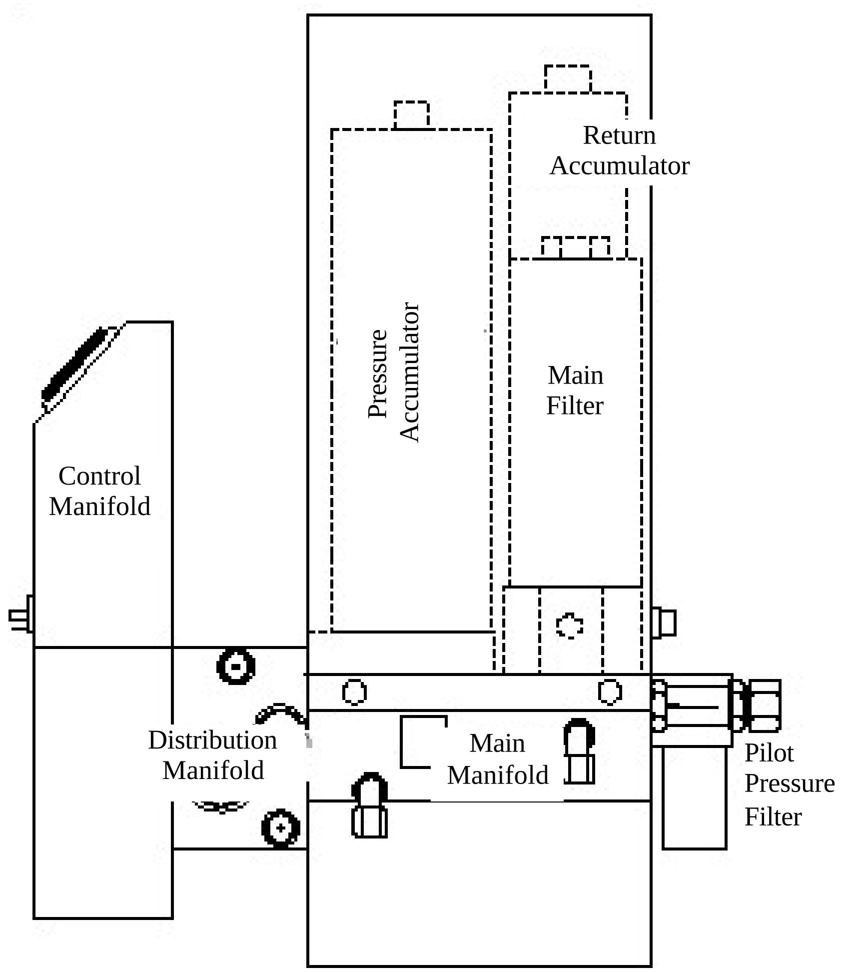

Figure 6.2 MTS Model 293.11A HSM Parts [25].

The pressure and return accumulators reduce flow fluctuations caused by changing system demands. In most cyclic test programs, the average servovalve flow requirement is much less than the peak hydraulic requirement. Accumulators store hydraulic power during the low portion of each cycle. The type and frequency of the servovalve command signal affects the efficiency of the accumulator. Square waves cause a greater demand than sine or ramp signals. The pressure accumulator reduces the inertia and line restriction considerations. Fluid inertia is generated when the fluid flow in the lines stop at low frequencies. The return accumulator reduces movement of hoses and hammering of hard lines caused by the varying amounts of fluid being discharged into the lines as the actuator moves. Table 6.2 lists the main technical specifications for the MTS Model 293.11A hydraulic service manifold, given by the manufacturer.

Table 6.2 MTS Model 293.11A HSM Specifications[1].

Division	Parameter	Specification
Model		293.11A
	Control Voltage	24 V (DC)
	Pilot Pressure	No
Environmental	Temperature	4.4°C (40°F) to 50°C (122°F)
	Humidity	0% to 80% relative, non-condensing
Dimensions	Height, cm	74.93 (29.5 in)
	Length, cm	35.56 (14.0 in)
	Width, cm	36.83 (14.5 in)
Weight	Main Manifold and Accumulators, N	689.5 (155 lb)
	Control Manifold Weight, N	35.6 (8.0 lb)
Number of Channels		2
Filtration	Main Supply	10 μ main supply
	Pilot Pressure Supply	3 μ pilot pressure supply
Operating Pressure	Variable Low Pressure, MPa	1.0 to 21.0 (150 to 3000 psi)
	High Pressure, MPa	21.0 (3000 psi)
Nominal Flow, l/min		190.0 (50 gpm)
Slow on/off Ramp Time		5.0 to 9.0 seconds
Maximum Solenoid Current		1.5 A at 24 V (DC)
Accumulators	Pressure, l	7.57 (2.0 gal)
	Return, l	0.45 (0.12 gal) standard

Note: 1. Modified from [25].

6.4. SERVOVALVE [23]

The servovalve provides the final control element in a closed-loop servo-hydraulic system. Figure 3.3 shows a diagram of a closed-loop servo - hydraulic system. A control signal is the driving element in a closed-loop system. The servovalve uses the control signal to operate a valve that regulates the movement of a hydraulic actuator.

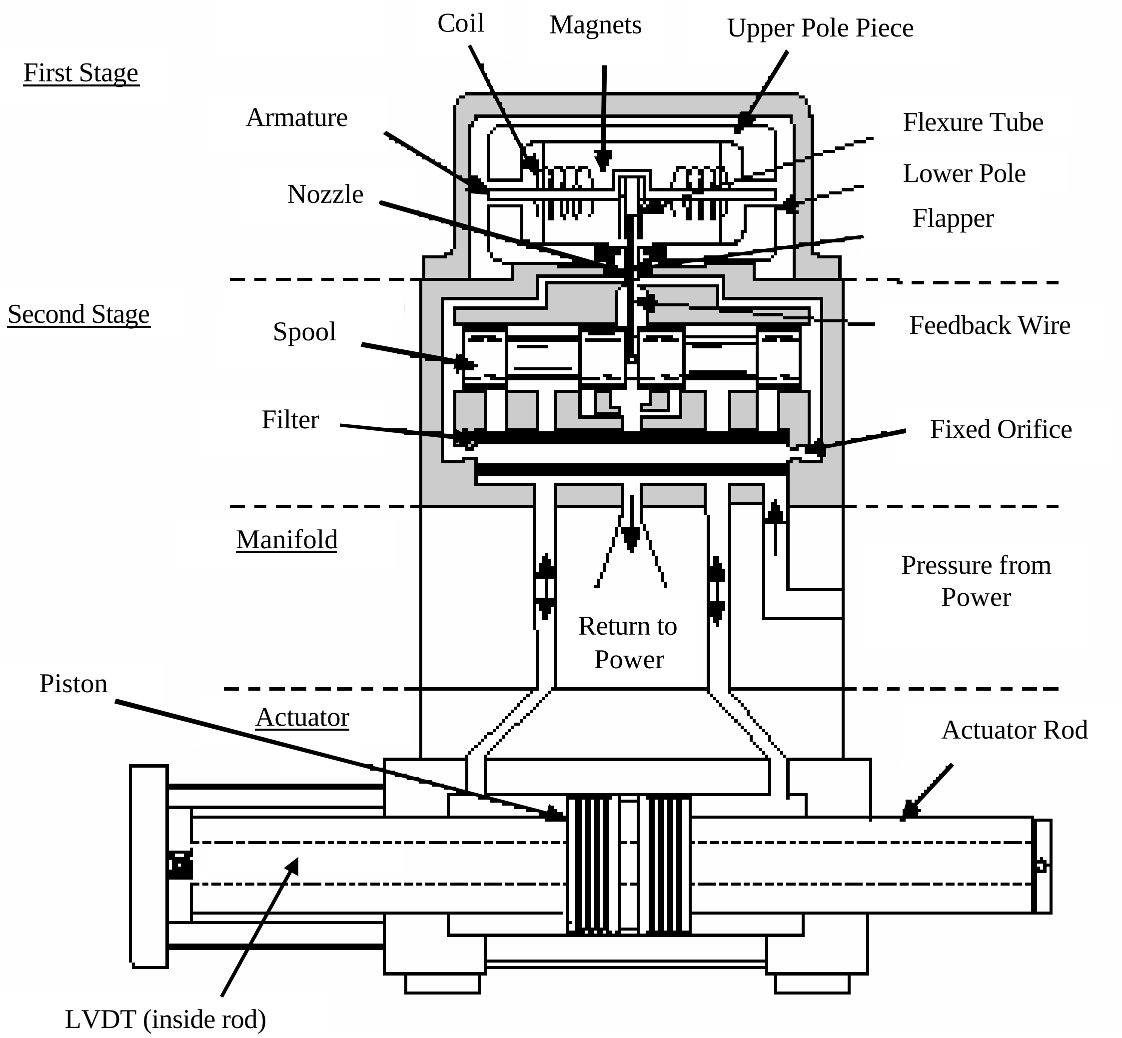

Figure 6.3 Functional Diagram of a Single Servovalve and Manifold Mounted to the Actuator [23].

The servovalve converts this control signal to a physical movement of an internal spool, allowing the controlled porting of hydraulic fluid to and from the actuator. A functional diagram of a two-stage servo valve is shown in Figure 6.3. The polarity of the control signal determines the direction the spool will move and the amplitude of the control signal determines how far the spool will move thus, controlling the direction and rate of hydraulic fluid through the servovalve. When the amplitude of the control signal reaches zero (desired actuator position) the spool returns to its null (non-flow) position, thereby stopping the flow of hydraulic fluid to and from the actuator. Single or dual servovalves can be mounted directly to the actuator or mounted to a manifold, which

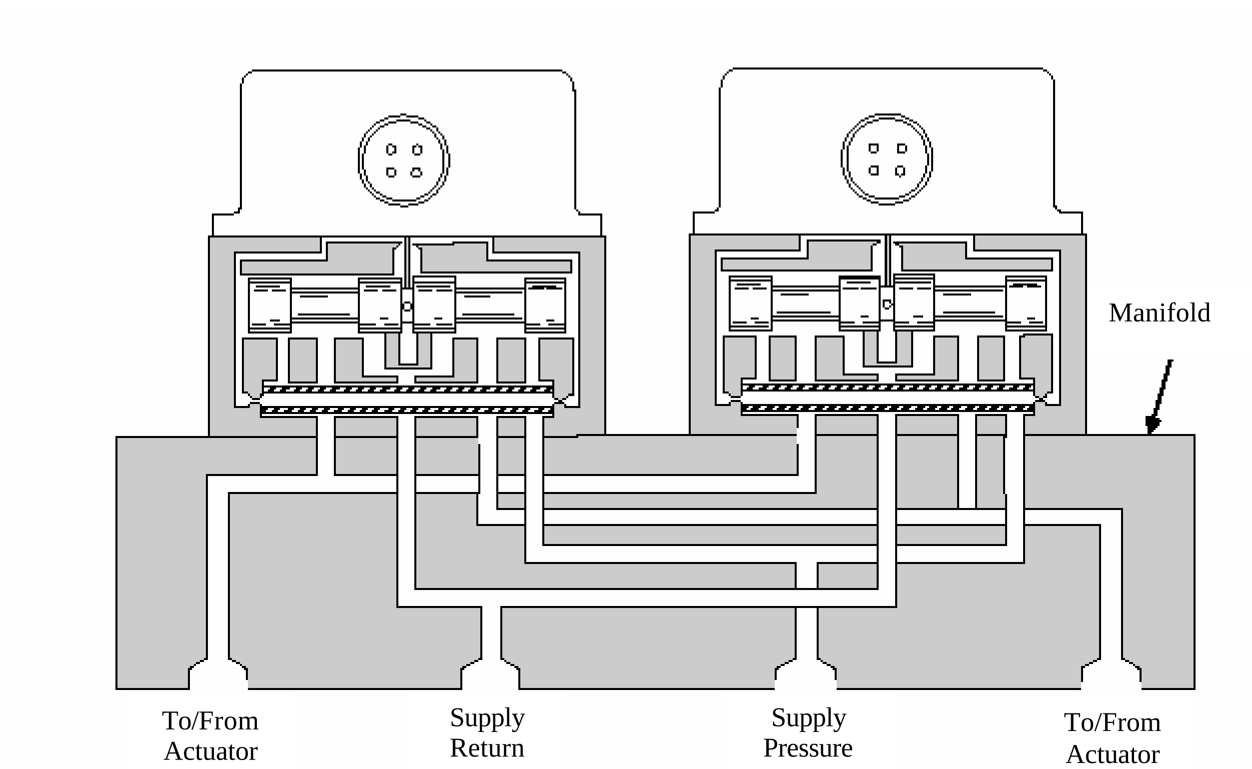

Figure 6.4 Cross-Section of Dual Servovalves Mounted to Servovalve's Manifold [23].

in turn is mounted to an actuator. The manifold, in the case of dual servovalves, is a metal block that connects the ports of each servovalve to the ports of the actuator, as shown in Figure 6.4. The manifold doubles the hydraulic flow rate of the two servovalves.

Two MTS Model 252.25 two-stage servovalves will regulate the hydraulic flow of the linear actuator to be used to drive the shaking table at the Structural Research Laboratory. The full flow rating of each MTS Model 252.25 servovalve is 57.0 l/min (15 gpm) for a 6.9 MPa (1,000 psi) pressure drop across the servovalve. The maximum operating pressure and standard operating pressures are 31.0 MPa (4,500 psi) and 21.0 MPa (3,000 psi), respectively. Table 6.3 gives the main technical specifications for the MTS Model 252.25 two-stage servovalves, provided by the manufacturer.

Table 6.3 MTS Model 252.25 Servovalves Specifications[1].

Parameter	Specification
Maximum Operating Pressure, MPa	31.0 (4500 psi)
Minimum Operating Pressure, MPa	1.4 (200 psi)
Operating Temperature Range, °C	-40 to 135.0 (-40°F to +275°F)
Rated Full-Flow Input Signal Current	
Series	25 mA
Differential	50 mA
Parallel	50 mA total
Coil Resistance	80 O per coil
Weight, N	10.23 (2.3 lb)
Servovalve Flow Ratings	
Full-Flow Rating, l/min [1]	190.0 (15.0 gpm)
90 Point at 10% Command	160 Hz
Null Flow, l/min [2]	2.27 (0.60 gpm)

Notes: 1. Flow ratings are for 7.0 MPa (1000 psi) pressure drop across the servovalve.
2. The maximum internal null flow is specified at 21.0 MPa (3000 psi).
The null flow at the fist stage is 0.76 l/min (0.20 gpm).

The MTS flow versus frequency performance curve of the Model 252.25 two-stage servovalve is shown in Figure 6.5. Flows versus frequency performance curves indicate the typical performance capabilities of the servovalve at various frequencies. The curves are derived by driving the servovalve, at the indicated frequency, with a sine wave control signal and ± full current to the coil.

The full flow rating of 190.0 l/min (15 gpm) is maintained up to a frequency of 30 Hz, and then drops to 7.57 l/min (2 gpm) at a frequency of 600 Hz. At frequencies higher than 30 Hz, servovalve performance is a function of variables introduced by system components, actuator response and characteristics of the specimen.

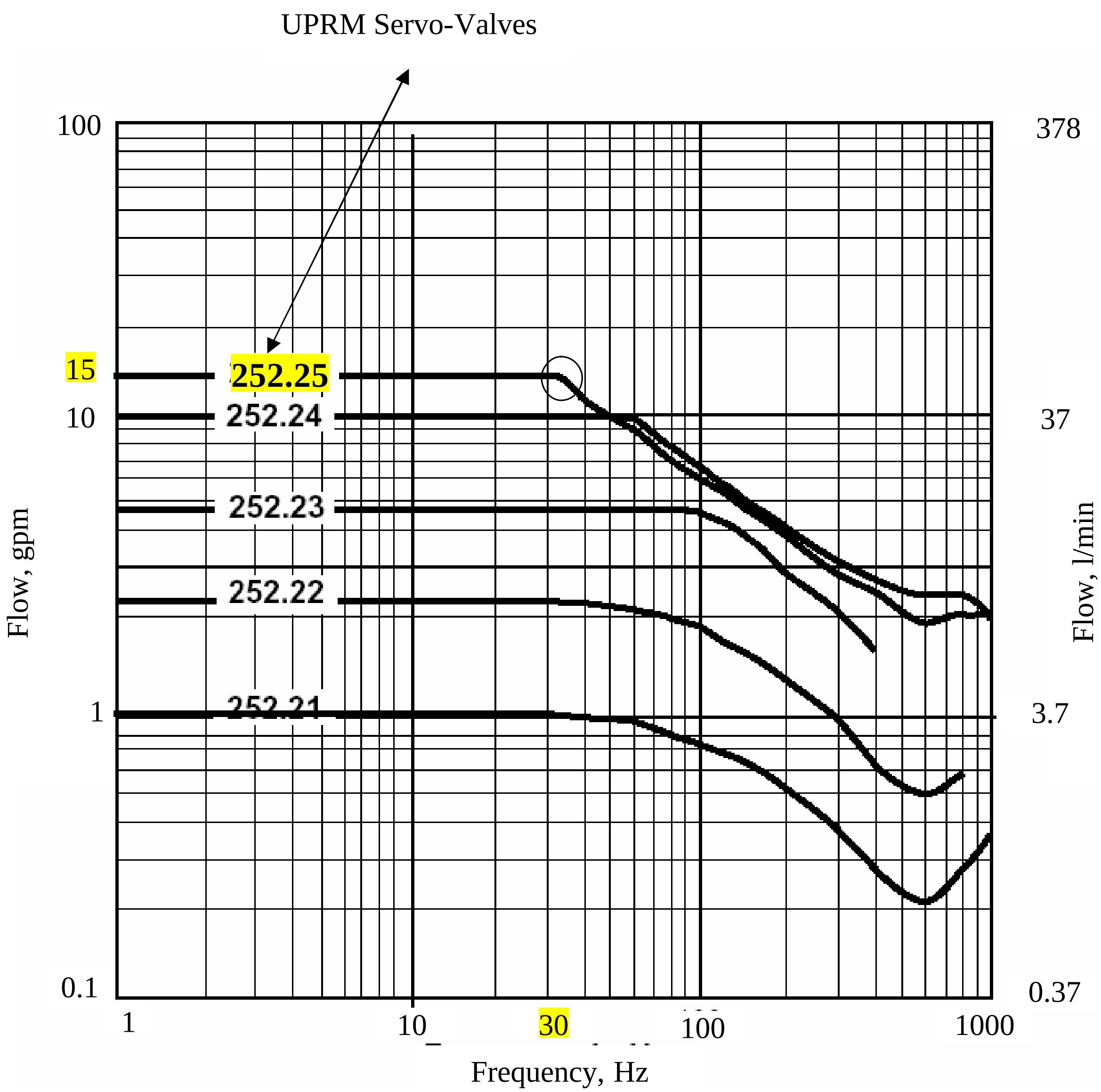

Figure 6.5 MTS Theoretical Performance Curves for the Series 252 Servovalves [23].

6.5. LINEAR ACTUATOR [20]

The slip table of the shaking table facility at the Structural Research Facility will be driven by a MTS Model 244.21 linear actuator. A linear actuator consists of a cylinder that contains a piston. The MTS Model 244.21 actuator is a double-acting and double-ended actuator that operates under precision servovalve control in a closed-loop servo-hydraulic system. Double-acting means the hydraulically powered piston can extend (tension) or retract (compression). A double- ended actuator can provide equal power in tension and compression.

The linear actuator system consists of force (load cell) and displacement (LVDT assembly) transducers, high-pressure fluid ports, cushions and swivel-end connections.

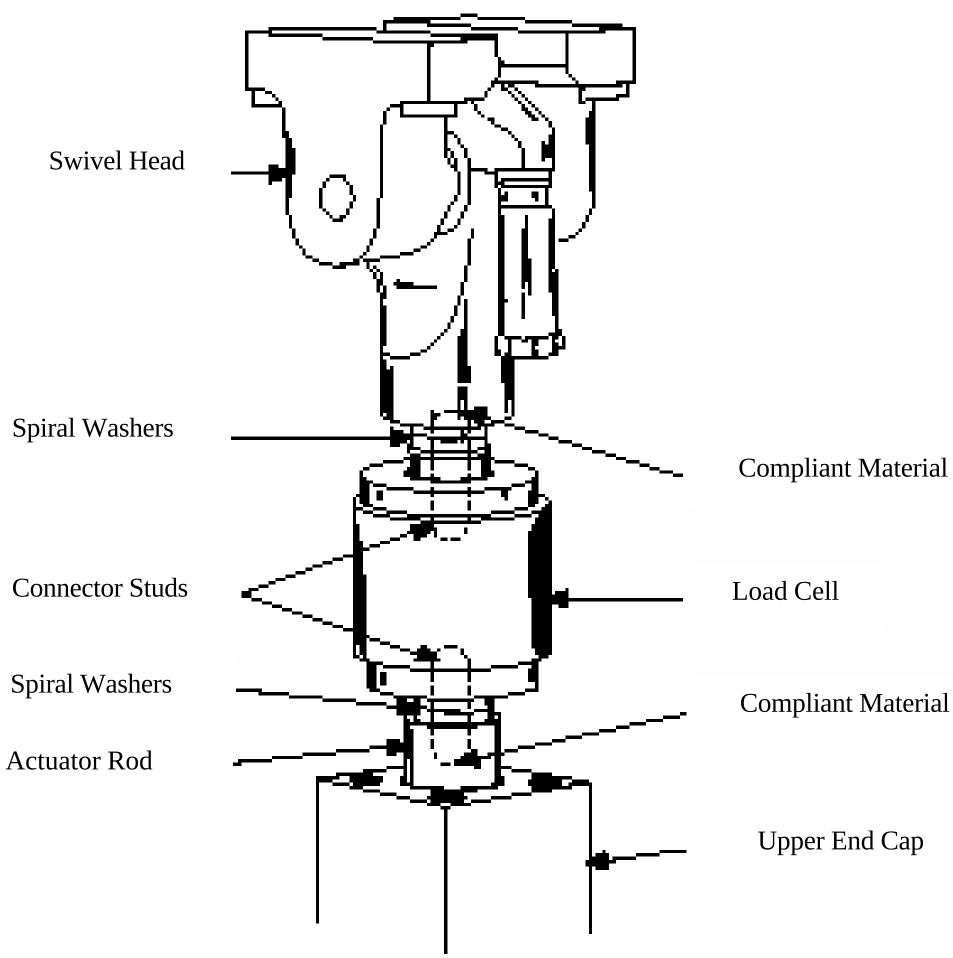

Figure 6.6 Force Transducer [20].

Figure 3.8 shows the different components of the MTS Model 244.21 linear actuator. The actuators force and displacement transducers are shown in Figure 6.6 and 3.8, respectively.

As previously discussed, actuator piston rod movement is accomplished by supplying high pressure hydraulic fluid to one side of the actuator piston and opening the other side to the return line. High-pressure hydraulic fluid is ported into the cylinder through the retraction port or the extension port. The differential pressure across the piston forces the piston rod to move. The amount of hydraulic fluid, and the speed and direction of piston rod movement is controlled by the servovalve. When the piston rod contacts an external reaction point (test specimen) then a force is applied to that reaction point. The force equals the effective piston area times the actuating pressure. The force applied is measured with a force transducer, in this case a load cell as shown in Figure 6.6. The load cell is connected at the end of the actuator's piston rod and in turn to a swivel mounting head. The swivel head connects the actuator-load cell system to the test specimen (slip table). Spiral washers are used to provide fatigue-resistant connections between elements of the force train and to minimize backlash. Backlash is caused by loose fitting or worn stud threads.

The MTS Model 244.21 actuator has a double-ended piston rod. The double-ended piston has equal areas on both sides for balanced performance. As illustrated in Figure 3.8, the hollow piston rod has an internally mounted LVDT that indicates the actuator piston rod displacement. The LVDT, an electromechanical device, provides an output voltage proportional to the displacement of the moveable core extension. The core extension moves as the piston rod moves.

The MTS Model 244.21 actuator has a piston rod diameter of 6.985 cm (2.75 in) and an effective actuator area of 25.16 cm^2 (3.90 in^2). The theoretical maximum applicable force for a 21.0 MPa (3,000 psi) operating pressure is 49.24 N (11.7 kips). However, the nominal maximum force given by the manufacturer is 48.93 N (11 kips). The maximum dynamic stroke of the actuator is 15.24 cm (6.0 in), while in static conditions the maximum stroke is 17.27 cm (6.8 in).

6.6. PERFORMANCE ENVELOPES

The performance of the hydraulic system is dependent on the frequency content of the commanded motion [5]. There are two types of commanded signals of interest in the area of shaking tables and they are harmonic and random signals. Two other physical limitations play a major role in determining the performance envelope of the shaking table system and they are the span and force [5]. The theoretical performance envelope curves for the UPRM hydraulic system will be given. The following procedure is derived from Muhlenkamp [5].

6.6.1. FLOW LIMITS FOR HARMONIC AND RANDOM ACTUATOR MOTION

The HPS is able to provide a constant flow of hydraulic flow to the HSM and then to the servovalves. When the command signal is harmonic and the ratio of the q_{peak} to q_{avg} is 1.571, this indicates that accumulators are needed to help provide the additional (57%) hydraulic fluid during peak flow periods.

When the command signal is random, like an earthquake ground motion, the flow rate time history is characterized by a very peaked (jagged) and random behavior. The manufacturer, MTS, specifies that with accumulators, q_{peak} is about three times the q_{peak} value for harmonic loading [5]. That is,

$$q_{\max}^{seismic} = 3q_{\max}^{harmonic} = 4.71q_{\max}^{pump} \tag{6.1}$$

This indicates that accumulators help to reach an actuator q_{peak} equal to 4.71 times the pump maximum steady flow.

The reproduction of earthquake ground motions containing high velocity components will simultaneously require a high fluid flow rate and a large volume of fluid [5, 19]. In order for the accumulator to provide for such additional fluid demands, it must be designed for the proper flow rate and volume capacity. For harmonic flow conditions, this volume of fluid is [5]:

$$V_{accum} = 0.421AC \tag{6.2}$$

where A is the piston's effective area and C is the harmonic signal amplitude.

To find the maximum table velocity we simply use the basic fluid mechanics principle and the following equation:

$$v_{\max} = \frac{Q_{\max}}{A_p} \tag{6.3}$$

where Q_{max} is the maximum flow rate into the actuator and A_p is the effective piston area. The maximum flow rate into the actuator depends on the pump, accumulator and servovalve characteristics, as discussed earlier. A list of the hydraulic flow rates available from the different components of the UPRM servo-hydraulic system is shown in Table 6.4.

Table 6.4 Components of the Servo-Hydraulic System.

Component	Model	Specification
Pump (HPS)	MTS 506.61	265.0 l/min (70 gpm)
Service Manifold (HSM)	MTS 293.11A	190.0 l/min (50 gpm)
Accumulators	MTS 111	7.57 l (2.0 gal) Pressure 0.45 l (0.12 gal) Return
Servovalves	MTS/Moog 252.25	Dual/ 56.78 l/min = 113.56 l/min Dual/15 gpm = 30 gpm

Therefore, the maximum mean velocity generated by the actuator v $_{max}$ is:

$$v_{max} = \frac{Q_{max}}{A_p} = \frac{1892.67\ cm^3/\sec}{25.16 cm^2} = 75.23\ cm/\sec = \frac{115.5\ in^3/\sec}{3.90 in^2} = 29.62\ in/\sec$$

However, the ability of the servovalves to provide their full flow rate capacity diminishes beyond motions with frequencies of about 30 Hz as illustrated in Figure 6.5.

6.6.2. SPAN AND FORCE LIMITS

The maximum displacement capacity of the seismic simulator is the span or stroke of the actuator. Span is the maximum distance that the piston can travel [5], which is 15.24 cm (6.0 in), ±7.62 cm (±3.0 in) from the center position, for the dynamic stroke of the MTS Model 244.21 actuator. For harmonic flow conditions, span and frequency are inversely proportional. Therefore the maximum span decreases for increasing frequency [5].

The maximum acceleration of the seismic simulator is limited by the properties of the servo-hydraulic system and the mass that the system is driving. The maximum force that the actuator can produce is 48.93 kN (11 kip). For a given table mass and using Newton's Second Law, the maximum table acceleration is:

$$a_{\max}^{bare} = \frac{F_{\max}}{W_{table}/g} = \frac{F_{\max}}{W_{table}} g \qquad (6.4)$$

where $a_{\max}^{bare}$ is the maximum bare table acceleration, $F_{\max}$ represents the maximum actuator force, and W_{table} represents the weight of the bare table, and g is the gravitational acceleration constant, 981 cm/sec^2 (386.4 in/sec^2). Therefore, the maximum bare table acceleration is:

$$a_{\max}^{bare} = \frac{48{,}930N}{9{,}786N} g = \frac{11{,}000lbs}{2{,}200lbs} g = 5.0g$$

However, when the table is loaded with a test structure, the maximum acceleration diminishes. Given a test structure mass, for example 3,113 N (700 lb), and considering the simulator platform and test structure to behave as a rigid mass, the maximum acceleration is:

$$a_{\max}^{700} = \frac{48{,}930N}{12{,}899N} g = \frac{11{,}000lbs}{2{,}900lbs} g = 3.8g$$

With the same considerations as above but with a test structure with lumped masses of 3,558 N /floor (800 lbs /floor), the maximum acceleration is:

$$a_{\max}^{800} = \frac{48{,}930N}{23{,}575N} g = \frac{11{,}000lbs}{5{,}300lbs} g = 2.1g$$

It should be noted that the friction force between the sliding bearings and rails is neglected in Equation 6.4. The MTS Theoretical Performance Envelopes for the bare table are shown in Figure 6.7 through Figure 6.9. Figure 6.7 shows the displacement vs. frequency performance envelope. Figure 6.8 shows the velocity vs. frequency performance envelope and Figure 6.9 displays the acceleration vs. frequency performance envelope. The blue curve shows a 0.0 N (0.0 kip) force and the green curve shows a 48.93 KN (11.0 kip) force.

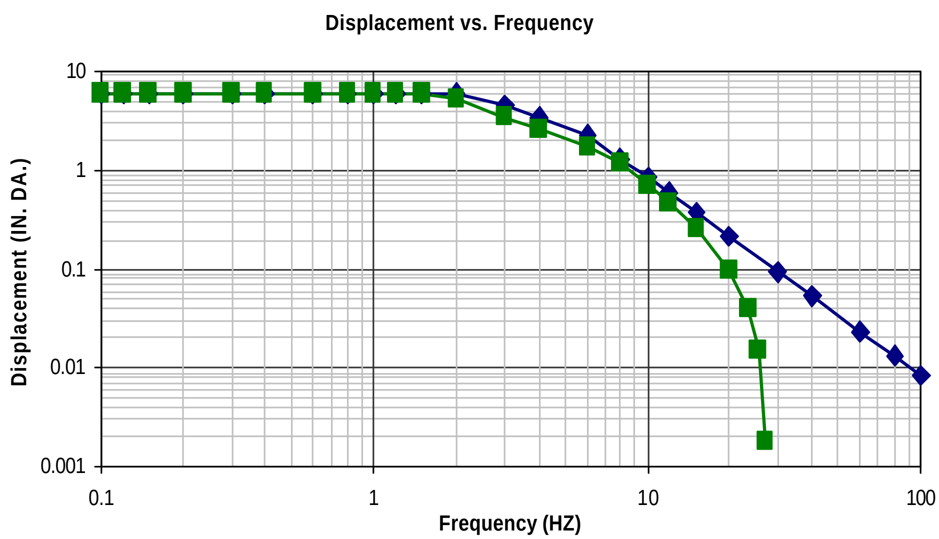

Figure 6.7 Displacement vs. Frequency Performance Envelope.

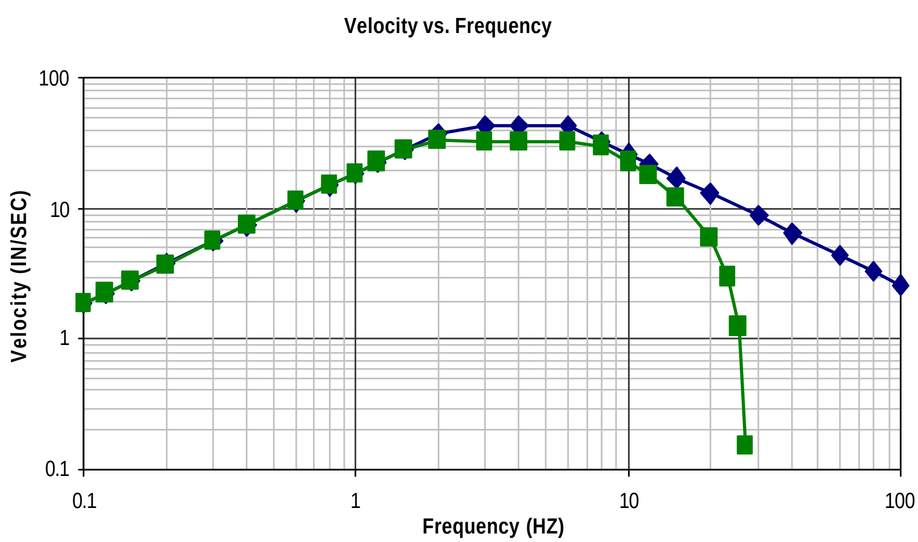

Figure 6.8 Velocity vs. Frequency Performance Envelope.

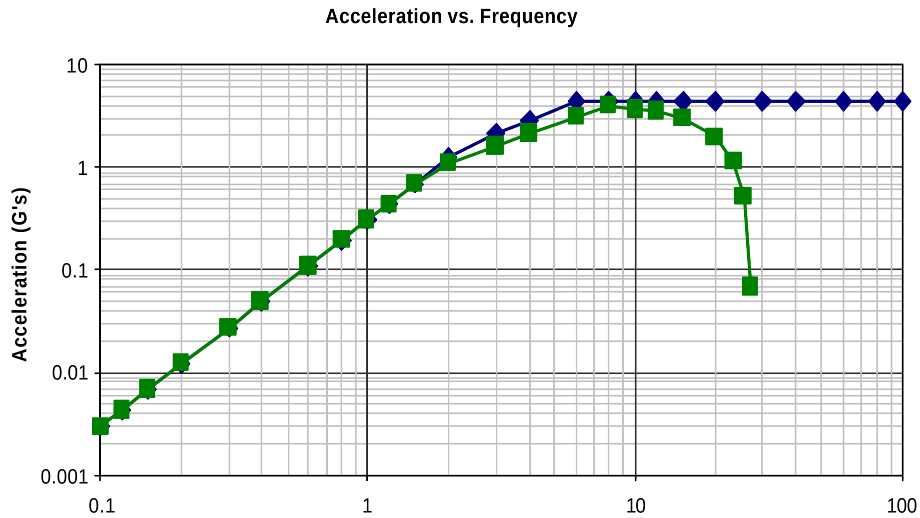

Figure 6.9 Acceleration vs. Frequency Performance Envelope.