DEVELOPMENT OF HIGH FLOW, HIGH PERFORMANCE HYDRAULIC SERVO VALVES AND CONTROL METHODOLOGIES IN SUPPORT OF FUTURE SUPER LARGE SCALE SHAKING TABLE FACILITIES

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SUMMARY

The earthquake engineering research community has had to wrestle with the uncertainties created by shaking table (dynamic) experiments conducted on less than full scale models due to limitations in shaking table size and payload capacity. The potential value of being able to study the failure mechanisms of full size structures under realistic earthquake motions in a controlled laboratory setting has long been recognized.

A shake table having this capability would have a surface area of approximately 15x20 meter. Accelerating a table of such size with a specimen greater than 1000 ton would require a large number of high force hydraulic actuators with precise servovalve control. MTS Systems Corporation has completed development of a new class of high flow, high performance hydraulic servovalves to support super large scale shaking table facilities.

This paper will describe the design of a new 4 stage hydraulic servovalve and present performance data from bench top flow testing conducted on a small production quantity of these valves. The digital control methods utilized for real time control of a 6x6 meter prototype table driven with (8) 500 ton force hydraulic actuators will also be presented with table performance data demonstrating the effectiveness of these methods.

The data contained in this paper support the conclusion that high fidelity seismic simulations using full scale structures is now possible. The previous limitation of precise control of large hydraulic actuators in a dynamic mode has been eliminated through advanced servovalve design and application of digital control methodologies.

INTRODUCTION

The Great Hanshin-Awaji Earthquake Disaster in 1995 produced a level of urban destruction that was previously beyond imagination. A visionary project to create a super large scale testing facility was quickly conceived and put into motion by Japan's National Research Institute for Earth Science and Disaster Prevention (NEID). This new vision called for a 3 dimensional shaking table facility large enough to study the dynamic failure mechanisms of full scale structures weighing as much as 1200 ton [NEID Document 1999]. MTS Systems Corporation was contracted for the design and manufacture of a new class of high performance servovalves to support this project.

The shaking table performance requirements indicated that a unique servovalve design concept was necessary. It was determined that a servovalve with a peak flow of 15,000 liter per minute with a pressure drop of 160 kg/cm^2 would best optimize the many performance goals. The high flow and high frequency performance requirements were meet by a four stage electro hydraulic valve design.

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The first and second stages consist of a torque motor and 20 lpm spool valve. An armature and flapper assembly (1st stage) control the volume of oil ported through the spool valve (2nd stage) based on a current applied across the coil. The 2nd stage spool ports oil to the larger intermediate stage spool valve. The position of the intermediate spool is kept under closed loop control through the use of a Linear Variable Differential Transformer. The intermediate stage spool can supply 630 lpm of oil to the main stage spool. The main stage spool provides supply pressure to the hydraulic actuator through 100 millimeter diameter control ports. A LVDT on the main stage spool provides closed loop control of up to 15,000 lpm of oil through the main stage. A photograph of the valve is shown in Figure 1.

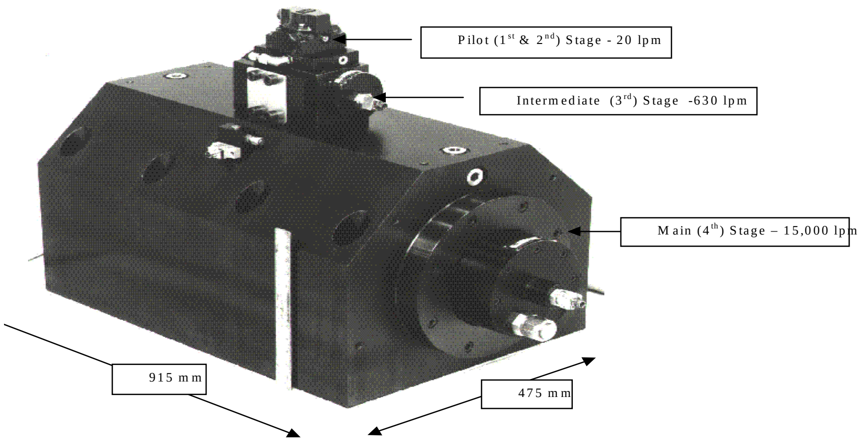

Figure 1 – 15,000 LPM Four Stage Servovalve
(10,000 lpm with 70 kg/cm^2 pressure drop)

A production run of 16 valve assemblies was completed in late 1997. Each valve was subjected to performance evaluations prior to delivery. The initial design requirements and measured performance of the servovalves are shown in Table 1.

Table 1 – Design Target & Measured Performance

Metric	Target	Measured Performance
Rated flow at pressure drop of	15,000 liters/minute	15,000 liters/minute maximum flow
100% Full Flow Frequency	> 20 Hertz	> 25 Hertz
Small signal 90 ° point	> 30 Hertz	30 Hz with PID controller
Null leakage	< 100 liters/minute	Approximately 50-60 liters/minute
Lapping	0.0 - 0.1%	< 0.1% (about .05% maximum)
Drain Flow	< 2 liters/minute	Drain flow is about 1-1.5 liters/minute
Maximum Phase Angle between	< 2º for all valves	Most valves tuned within 1ºof each

Additional bench top flow tests were conducted to determine the valves dynamic response characteristics to very low level command inputs. This input sensitivity was of concern due to the large main stage spool. The large 4 stage servovalve was shown to have excellent small signal sensitivity. Figure 2 demonstrates that the 4th stage spool moves easily with less than 0.1% command change. The main stage spool position feedback is offset from the command signal to allow viewing of command and feedback dynamic change. The full scale command voltage for the main stage spool is 10 volts.

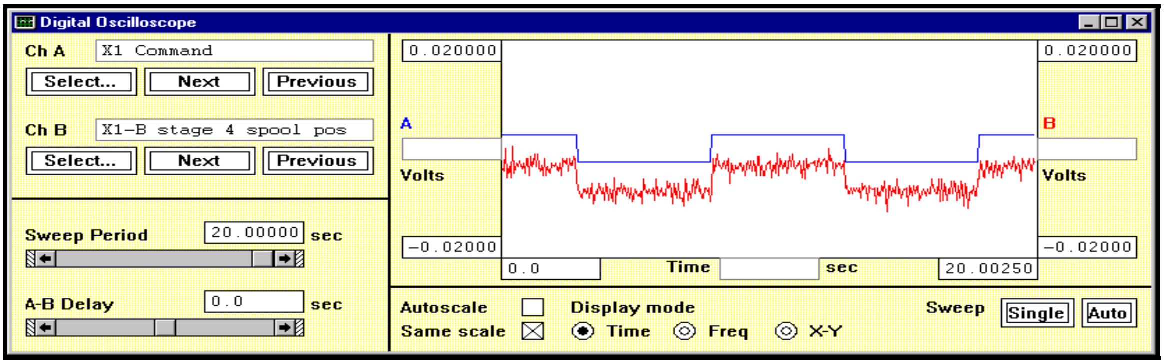

Figure 2 - Input Sensitivity

The shaking table test facility will not be able to supply a continuous flow of hydraulic oil at constant pressure due to the prohibitive facilities costs. As is common practice, a large bank of hydraulic accumulators will be utilized to store pressurized hydraulic oil for discharge when conducting a shaking table test. This creates a pressure drop in the oil supply as the test is being conducted. This change in pressure can have adverse affects on the fidelity of the simulation if the servovalve response has a high sensitivity to supply pressure. Figure 3 shows the valve response to a pressure change from 210 kg/cm^2 to 170 kg/cm^2 and then back to 210 kg/cm^2. The valves main stage spool shifts approximately 0.3 % of full scale opening despite the dramatic step change in supply pressure.

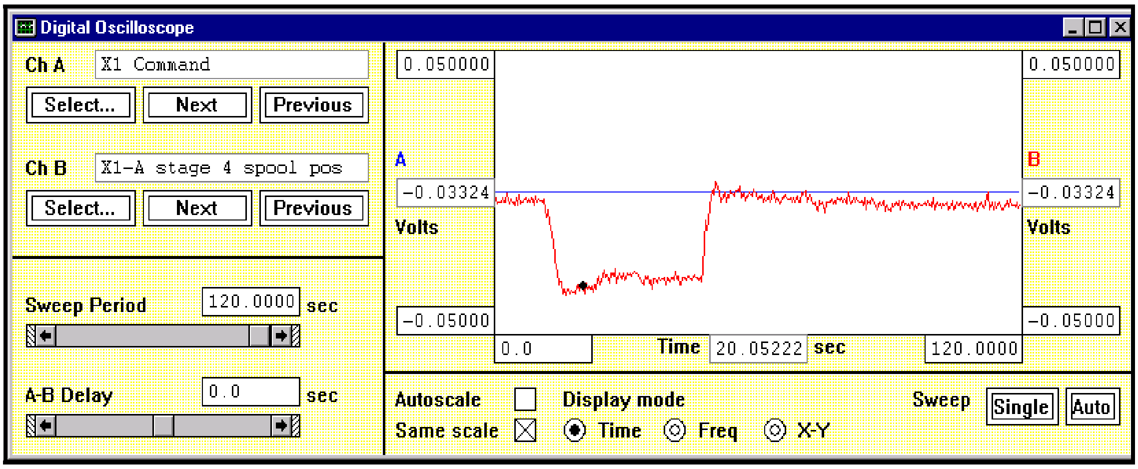

Figure 3 - Pressure Sensitivity

SERVOVALVE CONTROLLER

The design of the valve controller determines the dynamic performance that can be achieved with any servovalve. It was understood from practice that a standard PID Controller would not be able to close the 4th stage control loop and achieve satisfactory results. The use of single and double derivative lead terms were proposed for increasing the frequency response of the servovalve. The sum of the two lead terms, as shown in Equation 1, were added to the proportional control error signal as shown in Figure 4. It was necessary to add a low pass filter to the lead terms to eliminate high frequency noise. The valve controller and lead terms were implemented with a modified version of a standard MTS Digital Seismic Controller.

Sum of Lead Terms = $(K_L) \times (s) \times (s+ \alpha)$

{1}

Where $s = j \times \omega = j \times 2 \times \pi \times$ frequency

$j = (-1)^{½}$

K_L = Lead term gain

α = constant x 2 π x $frequency_o$

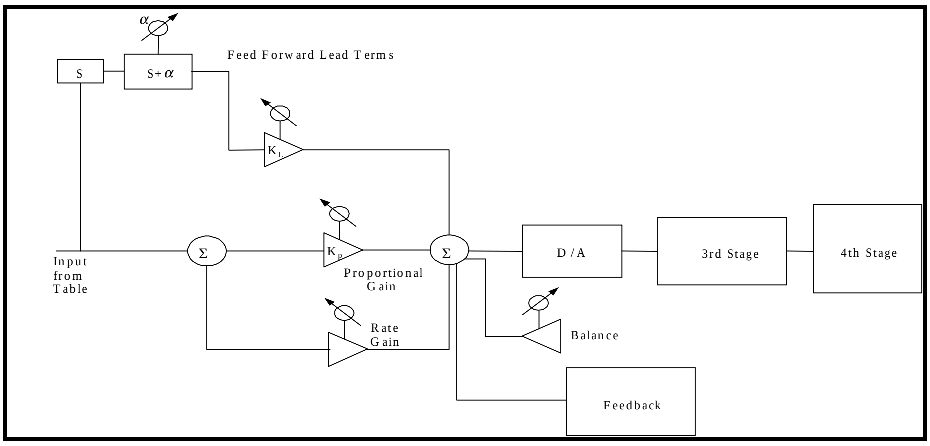

Figure 4 – Valve Controller Block Diagram

Figures 5 and 6 show the result of using the two lead terms to extend the bandwidth of the servovalve. A flat transfer function magnitude was demonstrated to 100 Hz. The linerization of the phase angle allows the performance of several valves to be matched within a very tight band. This was a critical requirement of the valve design as each horizontal actuator on the prototype table required the combined flow from three valves, and the table motion is the result from many individual actuators. The actual phase match for the production run of 16 servovalves was within 1 degree for frequencies as high as 35 Hz.

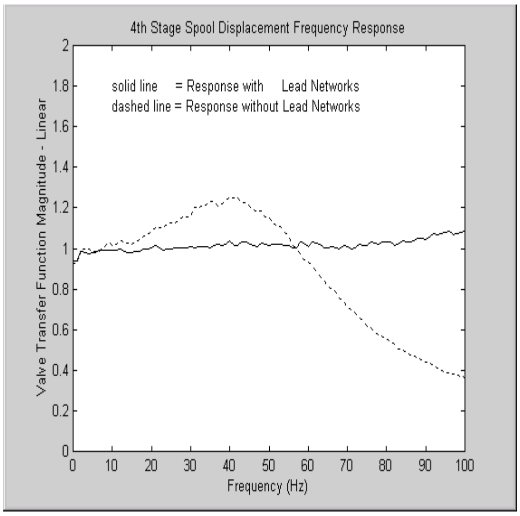

Figure 5 - Magnitude Response

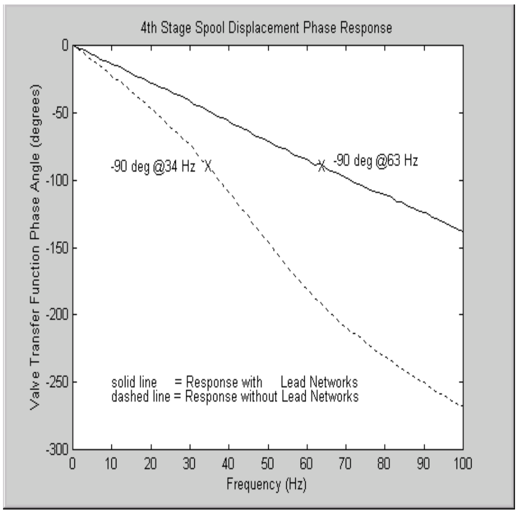

Figure 6 - Phase Response

The lead terms help open the 3^{rd} stage of the valve which extends the maximum frequency at which full flow can be developed through the 4^{th} stage of the valve. Figure 7 displays the maximum performance of the 4 stage valve main spool opening. The plot indicates that the valve is capable of switching a flow of 15,000 lpm of pressurized oil 25 times per second.

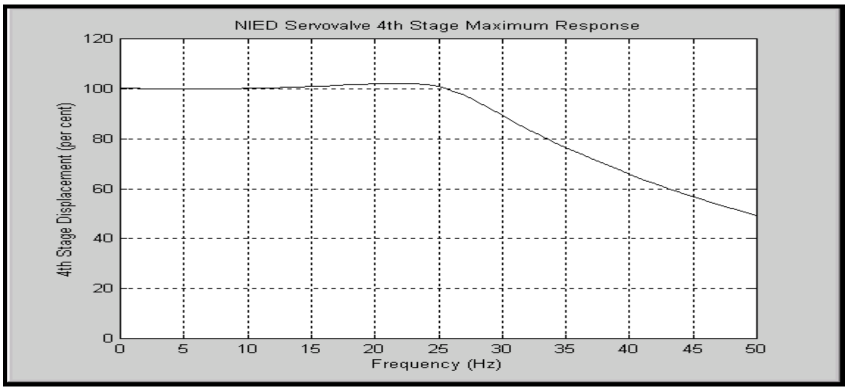

Figure 7 - Maximum Flow Performance

TABLE PERFORMANCE

A prototype of the planned 15x20 meter shaking table system was constructed at the Mitsubishi Heavy Industries Shipyard in Shimonoseki, Japan to evaluate the new servovalves, high force actuators, control methods, and other new system components. The prototype table measured 6x6 meter and utilized (8) full size 500 ton force dynamic actuators for 6 DOF motion. Each horizontal actuator was supplied by three servovalves, providing 2.0 meters/second velocity capability. One servovalve supplied each vertical actuator providing 0.7 meters/second velocity capability[Ogawa, Ohtani, Katayama, & Shibata 1999]. The total moving mass of the table, test specimen, actuator pistons and flexible linkages was 350 ton. A photograph of the prototype shaking table is shown in Figure 8.

The servovalves, and corresponding table motion, were controlled by a modified MTS Digital Seismic Control system. A variety of compensation routines were provided to reduce the effects of mechanical resonant behavior within the system. The 4 stage servovalves provided sufficient dynamic response to

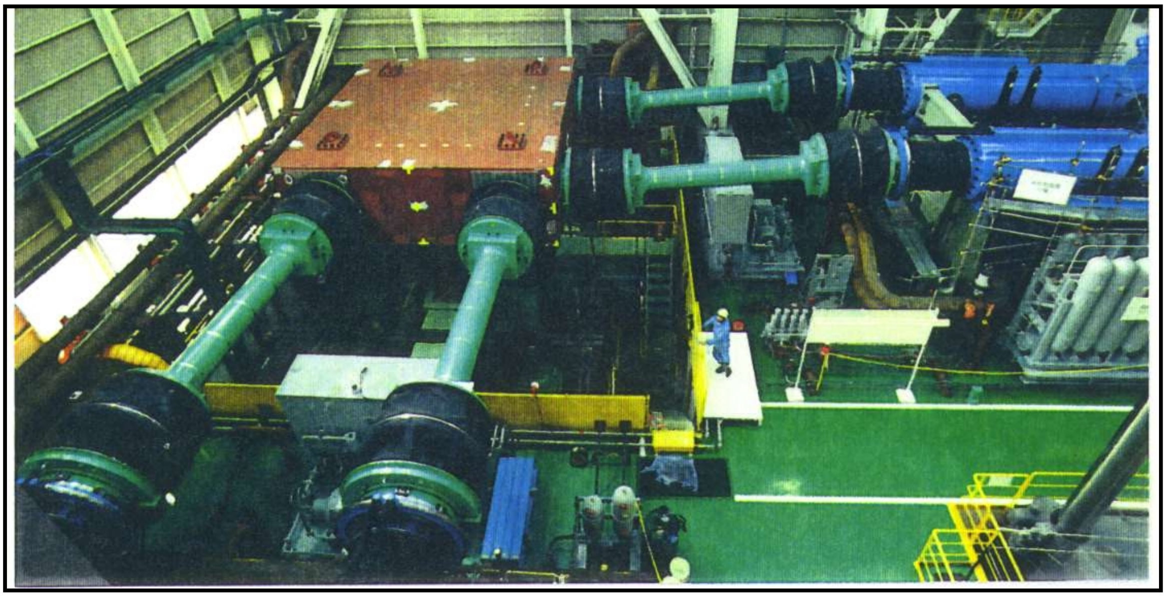

Figure 8 – 6x6 Meter Prototype Table with (16) 15,000 lpm Servovalves

execute the corrections needed to compensate for multiple disturbances. Figure 9 compares transfer function measurements of the desired and achieved lateral motions with and without compensation. The plot demonstrates that the servovalves and controller were successful in compensating the response of the table for the affects of two significant resonant behaviors [Larson 1998]. The compensation technique was based on the application of nonlinear notch filtering in the control loop.

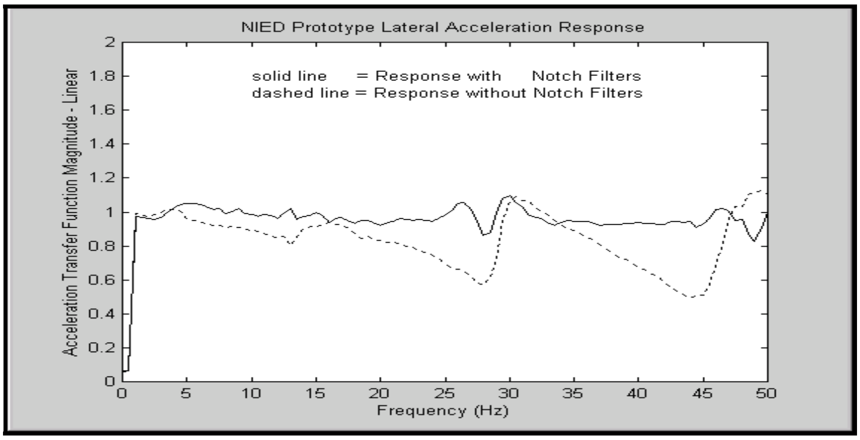

Figure 9 - Prototype Table Response (Lateral Magnitude)

The acceleration response of the vertical axis is shown in Figure 10. The plot shows the magnitude response of the table using three different tuning techniques. A standard PID Displacement control loop shows that the system response would start to roll off almost immediately. The 25 Hz resonance prevents the addition of higher gain settings to boost system response. A Three Variable Control Scheme allows the system to be tuned to a frequency just past the first resonance. The addition of a non-linear notch filter in the control loop about the 25 Hz resonance allows for aggressive system tuning out to a frequency of 50 Hz. The notch filter allows for higher gain settings without the damaging excitations created by system and specimen dynamics.

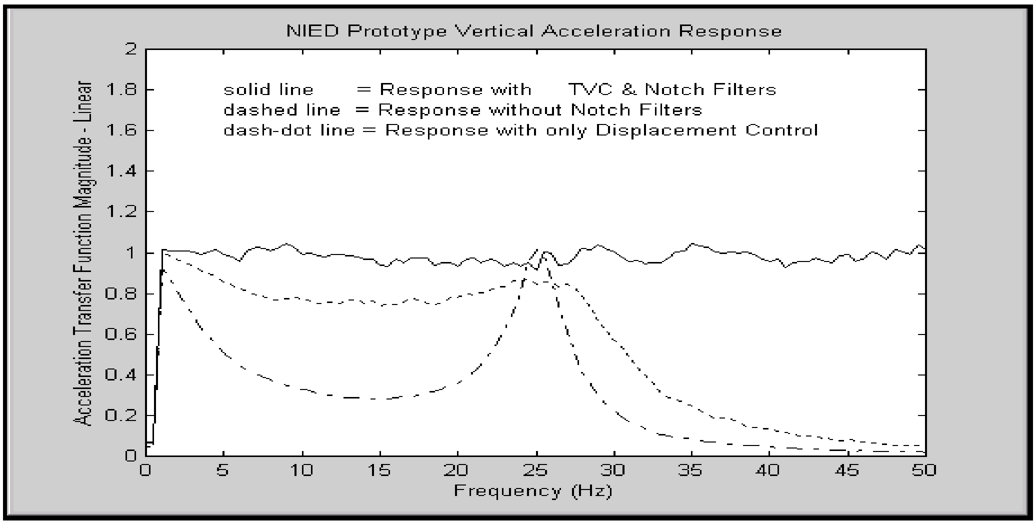

Figure 10 - Prototype Table Vertical Response

CONCLUSION

A new high performance, high flow four stage servovalve has been developed to support super large scale shaking table facilities. The servovalve is capable of supplying 15,000 lpm of pressurized hydraulic oil at frequencies up to 25 Hz with advanced digital servo control. This is the largest servovalve ever manufactured. Bench top flow testing indicates that the new servovalve design meets or exceeds all performance criteria.

A prototype of a super large shaking table was created to test the feasibility of such a project. A 6x6 meter table with 6 degree of freedom capability was constructed using (8) 500 ton force dynamic actuators. A total of (16) of the new 4 stage servovalves were used to control the table motion. The total moving mass of the table, actuator piston rods, specimen and attached linkages was 350 ton. The table demonstrated that acceptable simulation fidelity is now possible for super large scale shaking tables. A proposed project for a table measuring 15x20 meters is in the construction phase. It will soon be possible to study the dynamic failure mechanisms of full size civil engineering structures in a controlled laboratory environment.

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