UTILIZING MODERN DIGITAL SIGNAL PROCESSING FOR IMPROVEMENT OF LARGE SCALE SHAKING TABLE PERFORMANCE

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SUMMARY

The modern shaking table has been called "the most realistic means of evaluating the response of a structure subjected to earthquake ground motions"[Seible & Shing 1995]. The validity of this statement is stronger today due to the increased performance and fidelity demonstrated on recent large scale projects. Earlier designs and analog real time control systems often struggled with the many sources of distortion and non-linear behavior exhibited by the table system components and test specimen. These questions of fidelity often made test execution and interpretation of experimental results difficult. Recent technology has been demonstrated which has overcome many of these problems.

Significant progress in shake table design and control technology has been achieved over the past four years. This paper will review the size and performance of key mechanical and hydraulic components from a recently completed large scale 6 degree of freedom project. The advanced DSP based control techniques utilized on this system will also be presented along with experimental results demonstrating a high level of simulation fidelity.

Recent table projects have demonstrated that it is now possible to test full or near full scale structures with very high levels of event fidelity. Several other significant shaking table projects that utilize the same DSP based control methods will be presented. The conclusion is supported that a new level of simulation fidelity has been established with custom designed large scale systems and robust, DSP based real time control algorithms.

ISSUES AFFECTING FIDELITY

The accuracy of the shaking table simulation, or the level of fidelity to which the achieved motion matches the desired earthquake motion has been difficult to achieve. The frequency content of recorded earthquakes, strong dynamic cross coupling between degrees of freedom, existence of non-linearities in the hydraulic and mechanical system components, and the dynamic interaction of the specimen and table system all contribute to the challenge of achieving high fidelity motions.

The bandwidth requirements of the shaking table are typically specified from .1 to 50 Hz. The range is driven in part by the varying spectral profiles of the commonly reproduced earthquake records. Model scaling considerations and other factors can push the upper frequency limit to 100 Hz. The upper limit appears low in comparison to other types of vibration testing, but the goal is much more stringent: to accurately reproduce a time history containing broad band content.

The table force input at the base of the specimen creates multiple moments of rotation about the elevated center of gravity. These moments are significant due to the high mass, center of gravity, and modes of

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typical civil engineering specimens. Table motion is also the result of many individual actuators that over constrain the system making force balance compensation routines necessary.

Detailed consideration of the role of the servovalve, table structure, reaction mass, and hydraulics on overall system fidelity has been provided [Kusner, Rood, Burton 1992]. The contribution of each component as a possible source of distortion needs to be considered during the design stage with an eye on friction, backlash, static mass, compliant behavior, and other factors. Low fidelity performance within the frequency range of interest can be designed into the system through neglect or overconfidence. This places a heavy burden on the compensation and control tools available.

An understanding of the dynamics present in large scale systems makes the goal of accurate table control appear more elusive. [Kleine-Tebbe, & Hirsch 1983] observed that the table structure, reaction mass, mass loaded suspension system, oil column, hydraulic actuator load train, and lateral bending mode of the hydraulic actuators all have a significant impact on system performance. [Clark 1992] has shown through modeling and observation that many of these components will have lowly damped modes in the frequency range of testing. The effect of dynamic coupling on table motion fidelity becomes significant as the physical size and performance of these components increases.

Shake table capacity and performance requirements specified after the Northridge and Kobe earthquakes has stretched the limits of design and control using standard industrial components and control methods. Custom engineering is necessary in order to achieve the required balance between performance, fidelity and cost issues. As larger, higher performance hydraulic and mechanical components have evolved a greater understanding of their impact on system performance has been gained. It should be noted that much of this knowledge has only been made possible through the design and installation of new large scale projects in Japan and the US.

DESCRIPTION OF LARGE SCALE SYSTEM

The implementation of the 8x8 meter 6 degree of freedom shake table at the Public Works Research Institute Ministry of Construction in Tsukuba-shi, Japan demonstrates the level of performance that can be achieved with a custom engineered solution. The system was designed to subject civil engineering specimens to motions in excess of those recorded during the 1995 Hyogo-ken Nanbu Earthquake. Full performance was required with specimens weighing up to 100 ton. A unique experimental hybrid test facility was also planned which required the attachment of a large, self reacting biaxial load frame and laminar soil box to the table surface [PWRI-MOC Document 1998]. The total payload with the special hybrid configuration is 300 ton. The system level performance specification is shown in Table 1 below.

Table 1 - System Level Performance Specifications of PWRI-MOC 8x8 Meter Table

Axis	Dynamic Stroke (peak-peak)	Velocity	**ACCELERATION (W/100 TON SPECIMEN)**
Lateral	1.2 meter	2.0 meter/sec	2.0 G
Longitudinal	1.2 meter	2.0 meter/sec	2.0 G
Vertical	0.6 meter	1 meter/sec	1.0 G
Frequency of Operation: DC to 50 Hz all Axes			

Meeting the demanding system performance specifications required the design and development of custom hydraulic actuators with hydrostatic rod bearings, high flow high performance servovalves, large capacity low friction swivels, and a large servo controlled blow down accumulator bank for peak flow conditions. A system engineering approached targeted at eliminating frictional effects was successful in reducing background noise levels to less than 5 gal even under the low frequency high stroke requirements of recorded Kobe time histories.

A total of (12) 100 ton dynamic force actuators were utilized for control of the table in the lateral, longitudinal, and yaw degree of freedoms. Four 150 ton force vertical actuators mounted below the table in a recessed pit allow for control of vertical, roll, and pitch motions. Low friction, dry spherical swivel bearings attached the actuators to the table and the concrete reaction mass. An overhead photograph of the table during construction is show in Figure 1. The (12) horizontal actuators are visible with the foundation cover plates removed. The mounting details in the table surface for the 300 ton experimental hybrid test facility can also be seen.

Figure 1 - PWRI-MOC 8x8 meter table under construction.

A high performance 3000 lpm servovalve was designed to provide high response flow to the hydraulic actuators. Two valves per actuator were required to meet the table velocity specifications. A servo controlled, blow down accumulator bank was designed that provided peak oil flow in excess of 50,000 lpm. Figure 2. shows the hydraulic actuator and vertical static support assemblies.

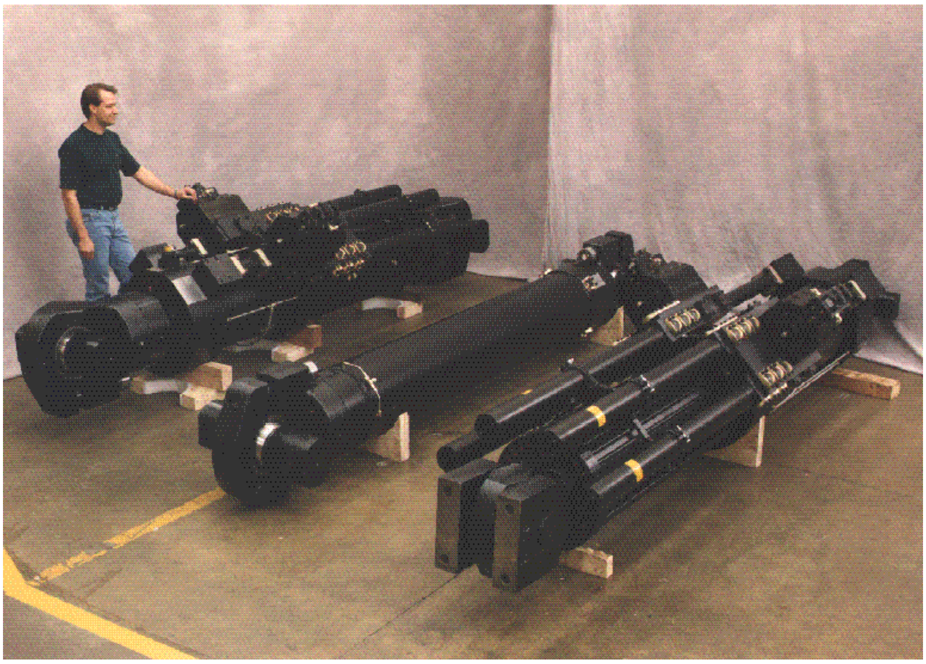

Figure 2 - Hydraulic Actuator & Static Support Assemblies.

SHAKE TABLE CONTROL METHODOLOGY

Accurate control of shaking tables often requires the use of a dual scheme consisting of a closed loop real time controller and an off line frequency response based iterative compensation process. The closed loop controller must be sufficiently robust to balance the conflicting goals of accuracy and stability in the presence of significant distortion sources. The off line compensation routine is utilized when fidelity, usually defined as an error measurement between the desired and achieved acceleration, is lacking. The success of this off line technique is directly related to the real time controller's ability to accurately reproduce the earthquake time history. An efficient, robust real time control system creates a minimum initial error and a short cycle of iterations. Attempts at improving simulation fidelity through iterative compensation when using weak real time control methods requires many trials of high energy excitation before convergence is achieved between the desired and achieved time histories. This type of brute force correction has limited application, as many civil engineering specimens are unable to withstand repeated excitations without damage. For these reasons, an effective means of real time control of seismic shake tables remains a key part of the overall control solution. The following sections of this paper will focus on the DSP real time control implemented on the 8x8 meter 6DOF table mentioned earlier.

DIGITAL CLOSED LOOP THREE VARIABLE CONTROL

A digital real time controller was implemented on the 8x8 meter 6 DOF table described earlier. Dedicated Digital Signal Processors perform the geometric transformations and kinematic equations which allow the individual transducer signals to describe the table motion in world coordinates. The table displacement, velocity and acceleration are used simultaneously for closed loop control. This process of Three Variable Control was described by [Filiatrault &Trembly 1996] as "a very robust and stable technique for accurately reproducing earthquake ground motions." Clark's paper describes the implementation of this control method and the achieved gains in shaking table fidelity. A simplified block diagram of the Three

Variable Control concept around a single actuator is shown in Figure 3. This concept is expandable for multiple axis shaking tables with a TVC controller around each of the 6 Degrees of Freedoms.

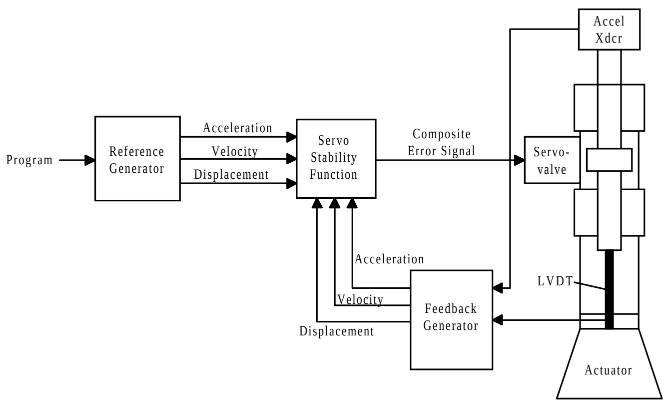

Figure 3 - Simplified TVC Diagram

RESONANCE COMPENSATION WITH NOTCH FILTERS

The core TVC controller was improved through the application of a technique known as Resonance Cancellation with Non Linear Notch Filters. This allows the test operator to create and insert non-linear notch filters in the real time closed loop TVC controller. The depth, and leading and trailing slopes of the digital filter are defined based on prior knowledge of the system dynamics. The filters can be used to attenuate or accentuate the system response in each of the 6 degrees of freedom. The frequency response of a pair of notch filters used to compensate for the expected resonance and anti resonance of a large flexible specimen is shown in Figure 4.

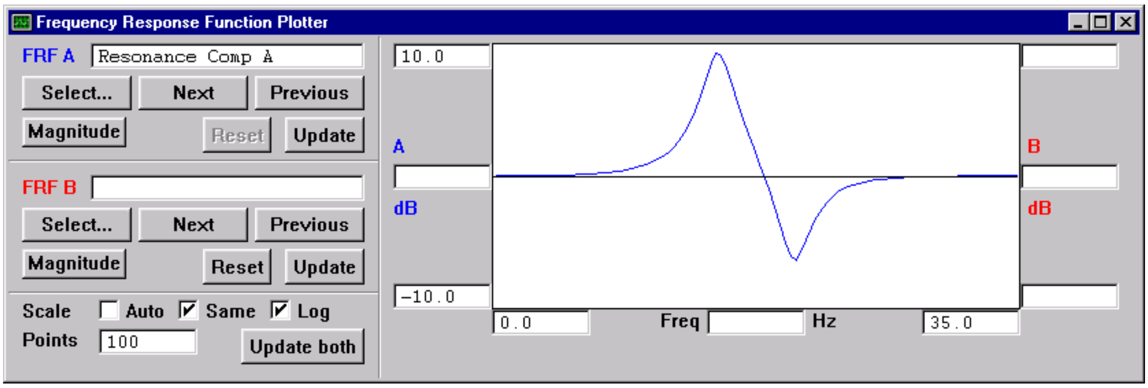

Figure 4 - Frequency Response of Notch Filter Pair

ADAPTIVE FREQUENCY BASED COMPENSATION

A large and complex shaking table experiment such as the hybrid test undertaken by the Ministry of Construction prohibits complete knowledge of all significant system resonances. Furthermore, in many cases these resonances will change during the course of testing due to specimen yielding. An Adaptive Inverse Control compensation method was used to reduce the affects of the changing specimen and provide a compensation for unknown system dynamics. This method utilizes Digital Signal Processors to evaluate the overall response of the shaking table specimen combination and control system. An inverse frequency response filter is automatically created based an error minimization algorithms. This IFRF is than inserted into the control loop between the program source and the TVC Controller. A matrix of 36 IFRF filters must be created in real time to compensate for the dynamic cross coupling between each of the six degrees of freedom and each other. A simplified diagram showing the placement of the compensation filters (inside the Adaptive Controller block) is shown in Figure 5.

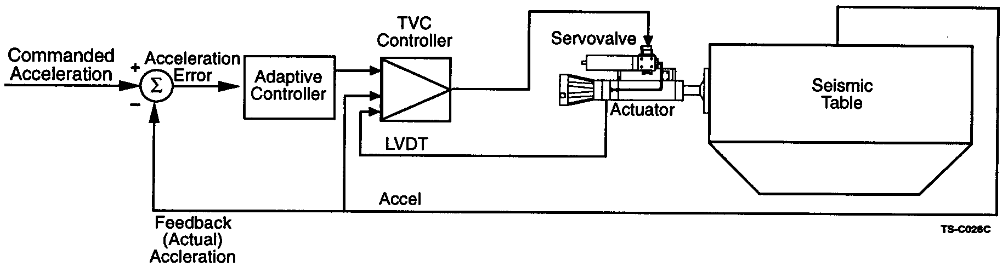

Figure 5 - Simplified Adaptive Control Block Diagram

RESULTS FROM INSTALLED SYSTEM

The following data was recorded on the 8x8 meter 6 DOF shaking table at the Ministry of Construction in Tsukuba-shi, Japan. The data was recorded by MTS Seismic Engineers during the installation and commissioning phase of the project completed in 1997. The data was recorded during table tuning with the hybrid experimental test specimen mounted on the table. The specimen consists of a large steel load frame approximately 10 meter in height that applied vertical and horizontal forces to a soil box used for studying soil/foundation interactions during seismic events. There where significant control challenges related to the induced over turning moments created by this specimen. The specimen, as well as the extremely long stroke horizontal actuators (1.2 meter peak to peak), also exhibited significant mechanical resonances within the frequency range of the test.

The following plots show the frequency response of the achieved table motion to the command table motion with a 50 Hz random input [Larson 1998]. A theoretical, perfect response would be shown with a horizontal line with a magnitude of 1 from .1 Hz to 50 Hz. A variety of control methods were used to control the table in real time including 3 Variable Control, Adaptive Inverse Control and Resonance Canceling Notch Filters. The frequency response of the system in the longitudinal, lateral, and vertical degree of freedoms is shown in Figures 6, 7, and 8. There is a near perfect frequency response across the entire bandwidth of interest. It should be noted that this level of performance was achieved using only the real time MTS 469D Digital Controller and did not include any type of off line iterative compensation.

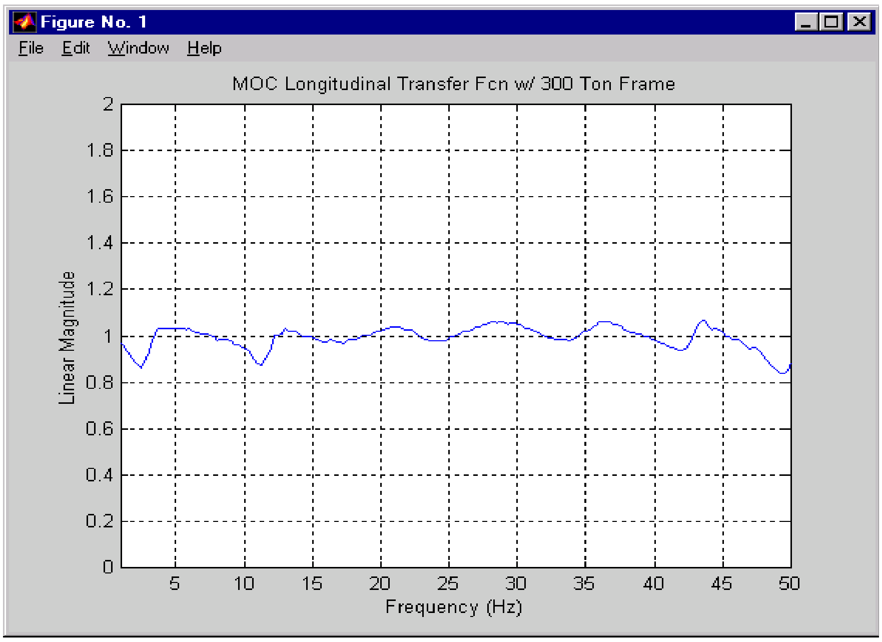

Figure 6 - Frequency Response (Longitudinal Magnitude) of PWRI-MOC Table

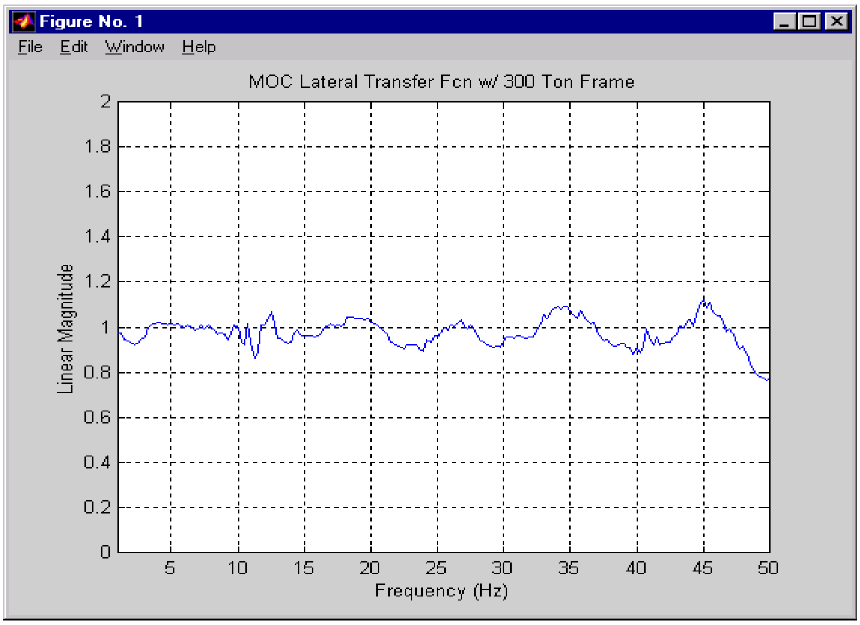

Figure 7 - Frequency Response (Lateral Magnitude) of PWRI-MOC Table

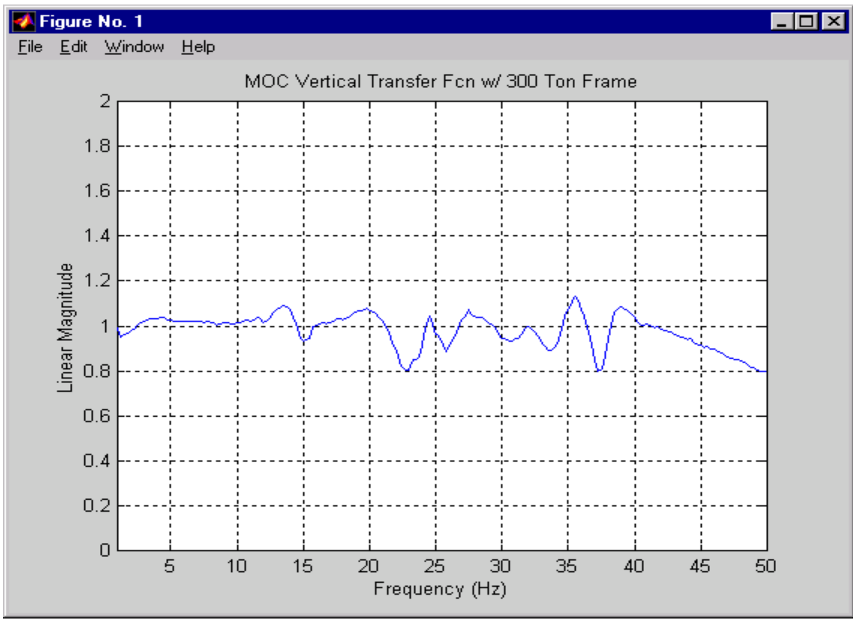

Figure 8 - Frequency Response (Vertical Magnitude) of PWRI-MOC Table

ADDITIONAL INSTALLED SYSTEMS WITH DSP BASED REAL TIME CONTROL

Several other large scale shaking table projects of note have been implemented with similar DSP based real time control systems. These systems are shown in Table 2. The core of each system controller was the digital TVC and adaptive compensation algorithms described above. There are some variations among the control algorithms utilized on each system due to date of installation and table system configurations. However, similar results were achieved during system commissioning. It should be noted that all of these laboratories continue to utilize an off line iterative technique for compensation when testing highly nonlinear specimens.

Table 2 -Large Scale Shaking Tables Utilizing DSP Based Real Time Control

Location	Type of System	Commissioned
University of Nevada at Reno	Multiple table (2) system for testing bridge structures and components.	1997
Kyoto University Disaster Prevention Research Center	6 DOF Underwater Table for evaluating off shore structures.	1997
Power Reactor Nuclear Fuel Development Corporation of Japan	Multiple table (3) system for testing large specimens of varying geometries.	1997
Housing & Urban Development Research Institute (Hachioji, Japan)	6 DOF table for testing building models and components.	1997
Nippon Telephone & Telegraph	Long stroke, high velocity 6 DOF system for seismic qualification of equipment.	1998
University of California at San Diego	SRMD Machine for evaluating full scale isolation bearings under maximum load conditions in multi axis excitation.	1999

CONCLUSION

The results presented demonstrate that a new level of simulation fidelity is possible with large scale, multiple degree of freedom shaking table systems. The transfer function plots from the 8 x 8 Meter 6 DOF Shaking Table at the Ministry of Construction show a matching in magnitude between the achieved and desired table motions within ± 2 dB over the frequency range of DC to 50 Hz. This level of simulation fidelity was achieved despite the presence of significant resonant behaviors. Comparable results have been obtained on other recent shaking table systems that have utilized similar DSP Real Time Control methods.

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