MODELING OF THE NHERI UCSD 6-DOF OUTDOOR SHAKE TABLE UNDER BARE TABLE AND LOADED CONDITIONS

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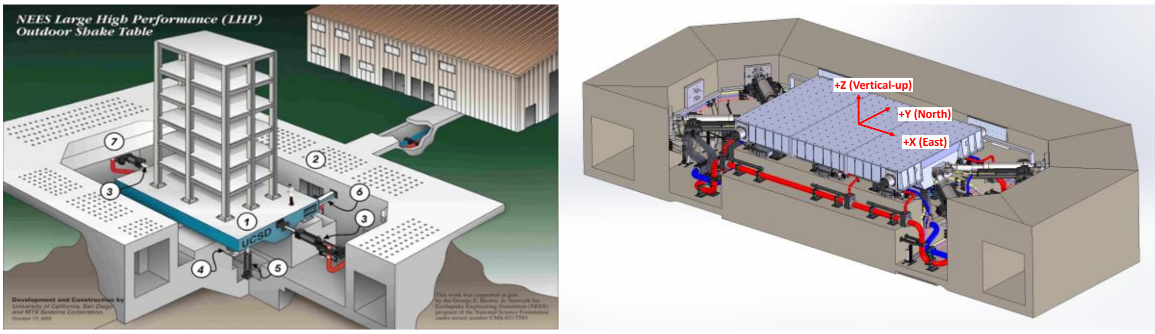
Abstract: *The NHERI UC San Diego Large High-Performance Outdoor Shake Table (LHPOST) was commissioned on October 1, 2004, and conducted a variety of high-quality large- and full-scale structural and geo-structural seismic tests. In recent years, the LHPOST was upgraded from its previous 1-DOF to its current 6-DOF configuration with funding from the National Science Foundation and University of California at UC San Diego. The 6-DOF LHPOST, referred to as LHPOST6 to distinguish it from the 1-DOF LHPOST, consists of four horizontal linear actuators (configured in V-shape) and six vertical actuators with pressure-balanced bearings to drive the steel platen, as well as three nytrogen-filled hold-down struts to provide the overturning moment capacity. The hydraulic actuators are controlled by high-flow, high-performance servovalves to generate actuator forces and velocities, while the hold-down struts passively respond to the platen motion and introduce elastic restoring forces along their axes.*

The 6-DOF LHPOST, referred to as LHPOST6 to distinguish it from the 1-DOF LHPOST, consists of four horizontal linear actuators (configured in V-shape) and six vertical actuators with pressure balanced bearings to drive the honeycomb steel platen, as wells as three nytrogen-filled hold-down struts to provide the overturning moment capacity. The hydraulic actuators are controlled by high-flow, high-performance servovalves to generate actuator forces and velocities, while the hold-down struts passively respond to the platen motion and introduce elastic restoring forces along their axes.

1 The Dynamic Model under Bare Table Condition

A numerical dynamic model of the LHPOST6 under bare table condition was developed to represent the open-loop dynamics of the shake table system (see Figure 2), namely from the servovalve command signals (for the spool displacement) to the achieved platen motion. The open-loop model is composed of three subsystems: (1) the hydraulic dynamics subsystem calculates the port flows based on the spool displacements, and then solves the mass flow continuity differential equations to find the chamber pressure and resulting actuator forces, (2) the hold-down strut dynamics subsystem represents the governing equation of the polytropic process to determine the pull down forces on the platen applied by the hold-down struts based on their displacements, and (3) the mechanical parts kinematics and dynamics subsystem calculates the total forces and moments acting on the platen, solves the translation and rotation dynamics of the rigid platen, and then convert the platen motions to the actuator and hold-down-strut displacements which are needed by the other two subsystems.



(a) *(b)*

Figure 1. Schematic picture of (a) the 1-DOF LHPOST before the upgrade and (b) the 6-DOF LHPOST6 after the upgrade, including the fixed inertial reference frame originated at the geometric center of the top surface of the platen in its control zero position.

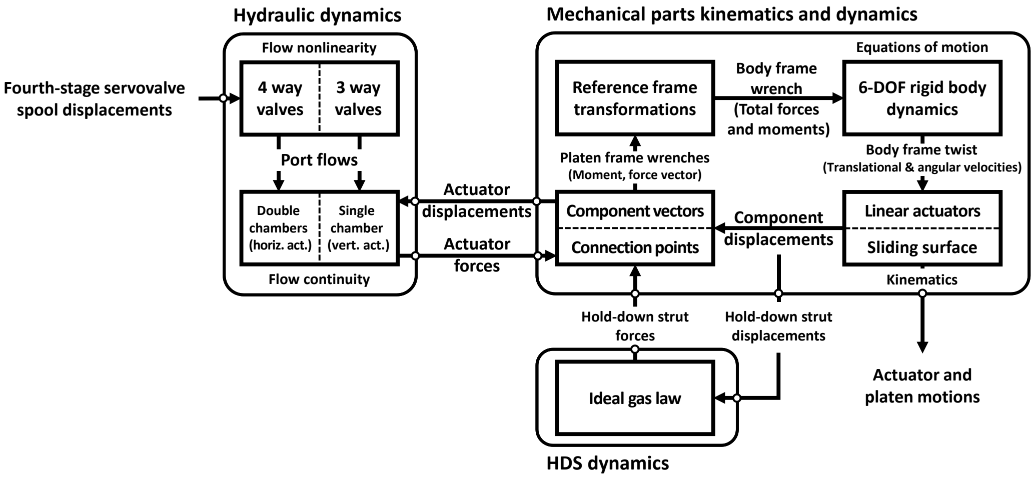


Figure 2. A high-level block diagram of the mechanics-based numerical open-loop model of the LHPOST6.

The numerical model was applied in both open-loop and closed-loop (or controller-in-the-loop) simulation (simulation without and with, respectively, the MTS 469D controller integrated in the shake table model). The block diagram of the closed loop simulation (see Figure 3) shows the open-loop numerical model of the LHPOST6 in Simulink is interacting with the 469D controller via the UDP communication protocol module provided by MTS Corporation, and the two sets of signals transferred between the 469D and Simulink are: (1) the fourth-stage servovalve commands transferred from the 469D to Simulink, and (2) the platen acceleration (computed at the feedback accelerometer locations), actuator displacements, and actuator forces transferred from Simulink to the 469D. The model was validated by using experimental data acquired during the acceptance and characterization tests performed on the LHPOST6 in the period July 2021 – April 2022, and the results are presented in the PEER report submitted in September 2023.

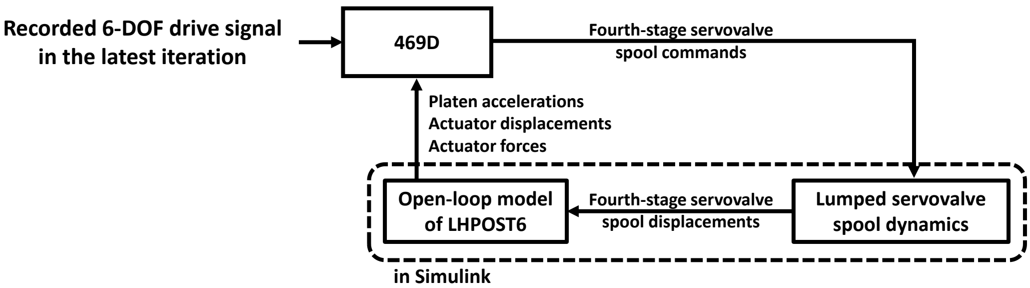


Figure 3. Block diagram of the closed-loop simulation under bare table condition (469D controller + open-loop LHPOST6 model).

2 The Dynamic Model under Loaded Table Condition

The dynamic model of LHPOST6 under bare table condition proposed above is very useful when studying the shake table system dynamics itself and validating the system parameters (hydraulic properties, friction between components, and effective inertia mass of the mechanical parts). However, the shake table system is seldom used under bare table condition. Therefore, the study of the shake table system under the loaded condition is necessary. The entire closed-loop dynamics of LHPOST6 under the loaded condition is composed of three main components and the interactions between them (see Figure 4): the motion controller (MTS 469D controller), the shake table system (LHPOST6), and the specimen mounted on top of the platen. Especially, the interaction between the shake table system and the specimen is called the table-specimen interaction, which includes the platen acceleration driving the specimen and the total base shear forces and moments of the specimen acting on the platen.

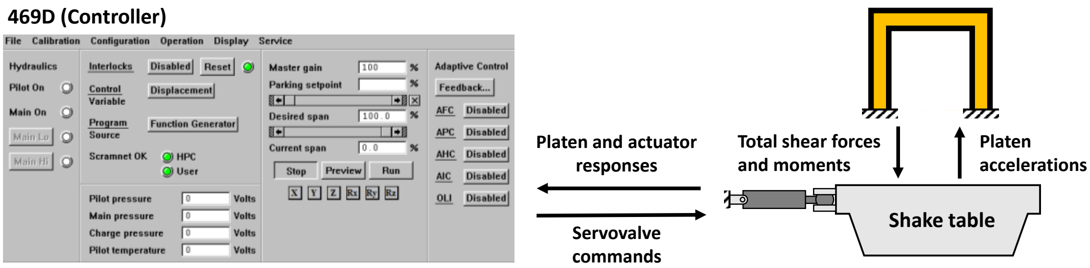


Figure 4. Interaction between the 469D controller, LHPOST6, and the specimen.

To study the interaction between the shake table system and the specimen, the LHPOST6 dynamic model programmed in Matlab/Simulink is featured with the flexibility to interact with structural analysis software (e.g., OpenSees) via TCP/IP protocol by transferring the two sets of signal: (1) the platen acceleration along each of its 6-DOFs from the shake table model to the specimen model (developed in the structural analysis software) and (2) the total base reaction forces and moments from the specimen model to the shake table model. The block diagram of the entire closed loop dynamics of LHPOST6 under loaded condition is shown in Figure 5.

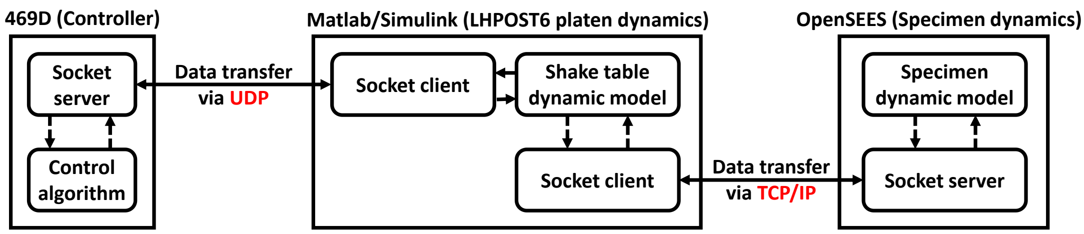


Figure 5. Block diagram of the closed-loop simulation under loaded condition (469D controller + open-loop LHPOST6 model in Simulink + specimen model in OpenSees).

Current study will focus on correctly implement the interaction between the shake table model and the specimen model. Therefore, two main goals herein are: (1) to construct a reliable and high-speed TCP/IP communication module to transfer the data between Simulink and OpenSees, and (2) to find out an efficient way to calculate the total (inertial) base forces and moments in OpenSees since there is no built-in functions for this purpose. Meanwhile, due to the nature of interacting two software programs (Simulink and OpenSees), the dynamic equilibrium equations of the shake table with tested specimen are not solved at the exact time step. When solving the dynamic equations of the specimen in OpenSees, the ground acceleration excitation from the shake table model in Simulink comes from the previous time step since the two software programs must work serially, and hence, errors are introduced here. The study will also propose an iterative method to improve the accuracy while solving the coupling dynamic problem in two different software programs. A schematic diagram of the working principle of the iterative method is shown in Figure 6.

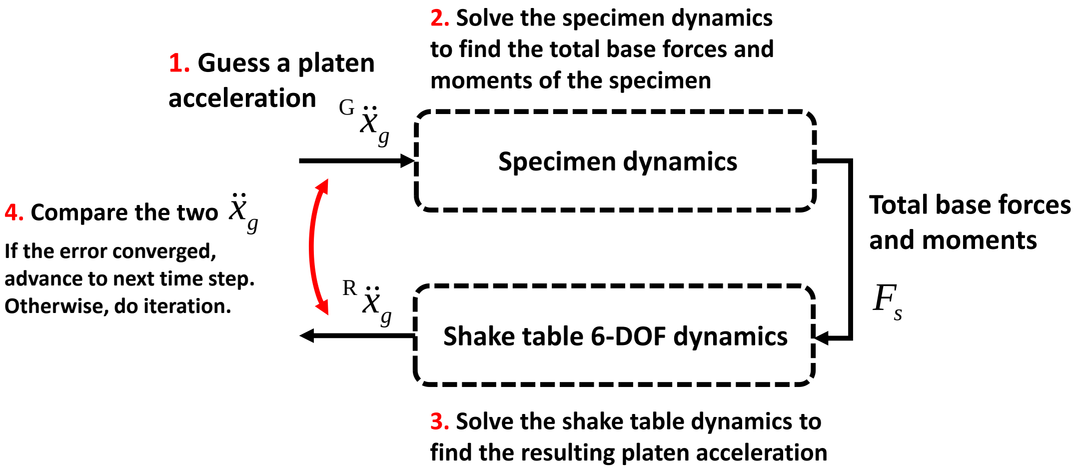


Figure 6. Schematic block diagram of solving the dynamics of a shake table system with a tested specimen in two software programs by using an iterative method.

The dynamic model of the LHPOST6 under loaded condition will be validated by the shake table tests of the full-scale 10-story TallWood Building specimen conducted from May 2023 (see Figure 7), and will be used to investigate the table-specimen interaction during these landmark tests. The validated numerical dynamic model of the LHPOST6 loaded with a test specimen can then be used for: (1) pre-test simulation of shake table tests, and (2) off-line tuning of the shake table controller, It will also be instrumental in developing: (1) hybrid shake testing techniques, and (2) the next-generation of shake table controllers.

Figure 7. 10-story TallWood building on the UCSD Large High Performance Outdoor Shake Table. (Need a better picture)