PEER "Research Nuggets"

Title: Dynamic Modeling of the UC San Diego NHERI Six-Degree-of-Freedom Large High-Performance Outdoor Shake Table

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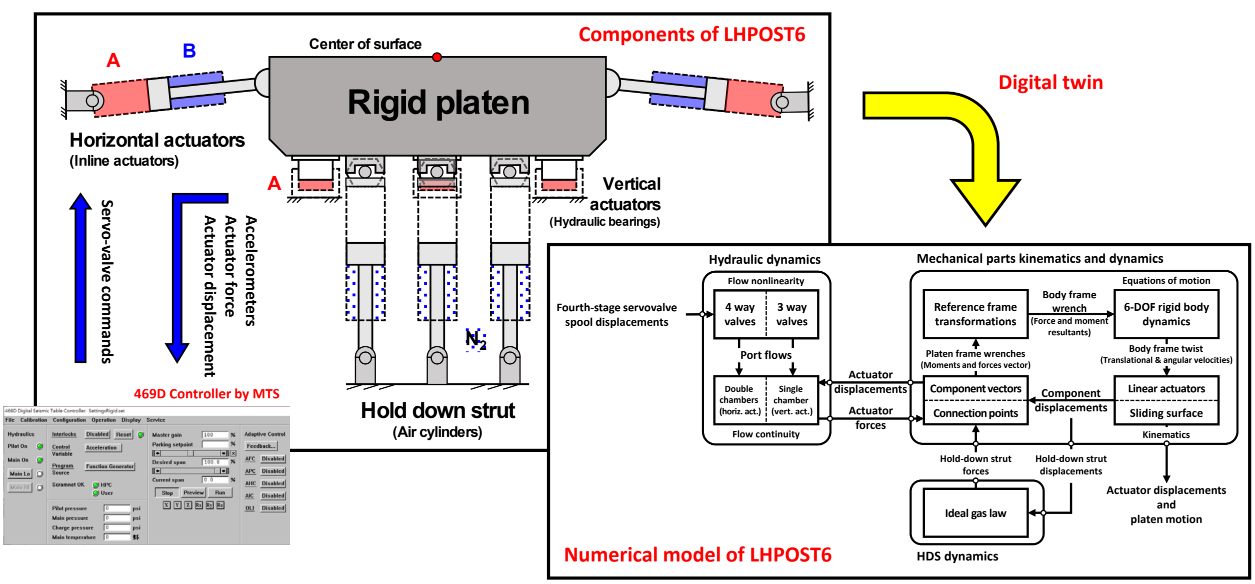
Motivation: The UC San Diego Large High-Performance Outdoor Shake Table (LHPOST), which was commissioned on October 1, 2004, as a shared-use experimental facility of the National Science Foundation (NSF) Network for Earthquake Engineering Simulation (NEES) program, was upgraded from its original one degree-of-freedom (LHPOST) to a six degree-of-freedom configuration (LHPOST6) between October 2019 and April 2022.

Given the intricate nature of shake table dynamics and the presence of various nonlinearities within its components, achieving a high level of signal reproduction remains challenging. While white noise tests are commonly employed to acquire the system transfer function for improving signal tracking performance through preconditioning of the desired or target signal time history, this approach assumes that the combined "shake table – specimen" system dynamics is linear. However, this assumption is often inaccurate, leading to insufficient accuracy in signal reproduction by the shake table. Hence, conducting a comprehensive study involving detailed nonlinear modeling and simulation of the shake table system is imperative. Such an approach is necessary as the actual system dynamics cannot be adequately represented by a linear transfer function derived from low-amplitude white noise excitation around the control zero-position of the platen.

Objectives: The main objective and innovative contribution of this report is to develop a high-fidelity mechanics-based numerical model (or digital twin) of the LHPOST6 under bare table condition with full 6-DOF dynamics, as depicted in the figure below.



Methodology: The model includes: (i) a rigid body kinematic model that relates the platen motion to the motions of components attached to the platen, (ii) a hydraulic dynamic model that calculates

the hydraulic actuator forces based on all fourth-stage servovalve spool positions, (iii) a hold-down strut model that determines the pull-down forces produced by the three hold-down struts, (iv) a 2-D and various 1-D Bouc-Wen models utilized to represent the dissipative forces in the shake table system, and (v) a 6-DOF rigid body dynamic model governing the translational and rotational motions of the platen subjected to the forces from the various components attached to the platen. In this report, the rigid body dynamics is studied utilizing the platen twist (combination of platen translational and rotational velocities) and wrench (combination of force and moment resultants acting on the platen) following principles from the robotic analysis literature. The numerical model of the LHPOST6 is validated extensively using experimental data from the acceptance tests performed following the shake table upgrade.

Results: The numerical model of the LHPOST6 is validated through three phases of comparison studies: (I) In the first phase, the inertia forces, total dissipative forces, and the hold-down strut restoring forces are simulated using the recorded/measured platen motion which is imposed on the model. The results indicate that the relevant sub-models and their parameter values effectively represent the characteristics of the LHPOST6. (II) The open-loop simulation is performed by feeding the LHPOST6 model with the recorded fourth-stage servovalve commands of all hydraulic actuators obtained during shake table tests. The output, including the forces and moments acting on the platen and resulting platen motion, closely aligns with the corresponding experimental results. (III) The closed-loop simulation entails the utilization of the MTS 469D Digital Control System, employing the identical (optimal) drive signal and 469D controller settings as those recorded and saved during earthquake shake table tests conducted on the actual LHPOST6. The comprehensive comparative analysis between numerically simulated and experimental results for intermediate control signals (fourth-stage servovalve commands of all actuators) and system response (platen motion) demonstrate a high level of agreement, thereby validating the numerical model of the LHPOST6 system presented in this report.

Conclusions: The validated numerical model of the LHPOST6 serves various purposes, including: (1) Pre-test simulation (“dry-runs”) of shake table tests for example to assess the LHPOST6’s signal tracking performance before constructing the specimen. (2) Off-line tuning or pre-tuning of the shake table controller in a virtual setting with the specimen on the table.

<u>Future directions/References</u>: The validated mechanics-based numerical model of the LHPOST6 presented in this report can be coupled with finite element models of shake table test specimens installed on the rigid platen to study the dynamic interaction between the shake table system and the specimens. Another important potential use of the model is to improve the motion tracking performance of the LHPOST6 through either off-line tuning of the shake table controller and/or development of more advanced shake table controllers.

Keywords: (1) LHPOST6,
(2) six-degree-of-freedom shake table,
(3) servo-hydraulic shake table,
(4) mechanics-based shake table model,
(5) shake table tests,
(6) experimental model validation.