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DEVELOPEMNT OF A LARGE-SCALE 6DOF HYBRID SHAKE TABLE AND APPLICATION TO TESTING RESPONSE MODIFICATION DEVICES FOR TALL BUILDINGS

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Abstract

Over the last decade, the introduction of high performance response modification devices to improve structural behavior of components and/or systems under extreme loading conditions such as earthquakes, blast, and wind has increased notably. Most of these devices, such as seismic isolation bearings, energy dissipation devices, and high performance materials, exhibit intrinsic rate dependent behavior. It is, therefore, of utter importance that experimental testing of structural systems incorporating such devices is performed at the correct loading rates.

Real-time hybrid shake table testing, sometimes referred to as smart shake table testing, provides an attractive, versatile, and cost-effective method to test structural subassemblies with response modification devices by applying RTHS principles to drive a shake table. This experimental method provides means to dynamically test subassemblies of large systems in full-scale or near full-scale that could otherwise not be tested on a shake table due to size, weight, or strength limitations imposed by the simulator platform. In general, it is beneficial to perform hybrid shake table tests instead of traditional shake table tests whenever the dynamics of the test specimen significantly affects the response of the supporting structure or soil and, therefore, alters the required input to the shake table as testing progresses. In the case that the experimentally tested portion of the structure is a non-destructive specimen, such as a high performance response modification device, the hybrid shake table testing method provides the unique ability to perform efficient parameter studies by changing the properties and behavior of the numerically modeled portion of the structure.

To develop the hybrid shake table capability on a multi-degree of freedom simulator platform, the Pacific Earthquake Engineering Research Center (PEER) shake table at the University of California Berkeley was upgraded and modified. The 20x20 ft. table is driven by a MTS 469D real-time digital controller. This digital control system provides closed-loop, three-variable-control (TVC) for all six degrees of motion. The existing system was upgraded with a shared memory network for fast communications and forty signal conditioner channels to directly feed force measurements back into the 469D controller. OpenFresco and OpenSees were installed on a special purpose, multi-core, high performance analysis machine to achieve the computation speeds required to solve large finite element analysis models in real time. Because hybrid shake table tests are a subset of real time hybrid simulations, where very precise control with minimal time delays is of absolute importance, advanced delay compensation techniques were employed for this testing system.

A series of experimental tests were then carried out using response modification devices that consisted of a large mass isolated by triple friction pendulum bearings or lead plug rubber bearings. Both of these bearings exhibit significant nonlinear behavior. For the analytical portion of the hybrid model, various building models were investigated in two and three dimensional configurations. Control of the rotational degrees of freedom (roll and pitch) of the hybrid shake table was included for the taller building models to investigate the effects on the behavior of the isolation systems.

Keywords: hybrid shake table, real time hybrid simulation, tall building, seismic isolation, tuned mass damper

1. Introduction

Over the last decade, the introduction of high performance response modification devices to improve structural behavior of components and/or systems under extreme loading conditions such as earthquakes, blast, and wind has increased notably. Most of these devices, such as seismic isolation bearings, energy dissipation devices, and high performance materials, exhibit intrinsic rate dependent behavior. It is, therefore, of utter importance that experimental testing of structural systems incorporating such devices is performed at the correct loading rates.

Real-time hybrid shake table testing, sometimes referred to as smart shake table testing [1, 2, 3], provides an attractive, versatile, and cost-effective method to test structural subassemblies with response modification devices by applying real-time hybrid simulation (RTHS) principles to drive a shake table. This experimental method provides means to dynamically test subassemblies of large systems in full-scale or near full-scale that could otherwise not be tested on a shake table due to size, weight, or strength limitations imposed by the simulator platform. In general, it is beneficial to perform hybrid shake table tests instead of traditional shake table tests whenever the dynamics of the test specimen significantly affects the response of the supporting structure or soil and, therefore, alters the required input to the shake table as testing progresses. In the case that the experimentally tested portion of the structure is a non-destructive specimen, such as a high performance response modification device, the hybrid shake table testing method also provides the unique ability to perform efficient parameter studies by changing the properties and behavior of the numerically modeled portion of the structure.

One area where the application of response modification devices has become increasingly more popular and significant research is currently being carried out is the application of seismic isolation devices in tall buildings. Because global trends towards urbanization have led to unprecedented numbers of people working and living in tall buildings, for cities located in regions susceptible to strong earthquake ground shaking, seismic resiliency of these costly, high-occupancy, tall building is of critical concern for engineers and the general public. To improve the overall response of tall buildings and to mitigate risks associated with earthquake ground shaking, isolators can be placed at the base of the structure, at a midlevel higher up in the building [4, 5], or towards the top of the building to act as a tuned mass damper (TMD) [6]. In the case of base isolation, the goal of introducing seismic isolation is to concentrate deformations in the isolation plane and simultaneously provide supplemental energy dissipation. Because tall buildings are already flexible and have long modal periods, the idea of shifting the fundamental period to larger values, and thereby reducing seismic demands in terms of forces that are being transmitted into the building superstructure, does not apply here. For the midlevel seismic isolation, there is the additional benefit of the un-tuned mass damper effect that is introduced by the isolated superstructure. This concept can improve the response not just of the isolated superstructure, but also the supporting substructure. If the isolation level is placed towards the top of the tall building, isolating the last few stories of the building or a large supplemental mass, the goal is not so much to concentrate structural deformations, but to alter the dynamic response of the building through the large TMD at the top. In all of these three applications of seismic isolation to tall buildings, large overturning moments in the isolation level and/or overturning rotations of the isolation plane need to be considered and designed for. Large overturning moments can cause tension or uplift in the isolation devices and overturning rotations of the isolation plane affect the hysteretic behavior and the stability of the isolation devices.

Consequently, if hybrid shake table testing techniques are being applied to experimentally assess the behavior and performance of seismic isolation in tall buildings, it is essential that the simulator platform can impose not only horizontal motions, but also vertical and rotational motions to the experimental specimen tested on the shake table. Utilizing a hybrid shake table testing facility that can control all six degrees of freedom, it is possible to study vertical ground motion and overturning effects on the seismic isolation system.

To develop the hybrid shake table capability on a multi-degree of freedom simulator platform, the six degree of freedom PEER shake table at the University of California Berkeley was upgraded and modified. The 6x6 m reinforced concrete table is driven by a MTS 469D real-time digital controller. This digital control system provides closed-loop, three-variable-control (TVC) [7] for all six degrees of motion. The existing system was upgraded with a shared memory network for fast communications and forty signal conditioner channels to directly feed force measurements back into the 469D controller. OpenFresco and OpenSees were installed on a special purpose, multi-core, high performance analysis machine to achieve the computation speeds required to solve large finite element analysis models in real time. Because hybrid shake table tests are a subset of real time hybrid simulations, where very precise control with minimal time delays is essential, advanced delay compensation techniques were employed for this testing system.

A series of experimental tests were then carried out using response modification devices that consisted of a large mass isolated by triple friction pendulum bearings or lead plug rubber bearings. Both of these bearings exhibit significant nonlinear behavior and strong rate-dependency either due to their temperature dependence and/or velocity dependence of the materials and mechanical mechanisms involved. In addition, dynamic inertia force effects contribute significantly to the force interaction at the base of the test specimen. Hence, it was essential that these hybrid simulations were performed in real time. For the analytical portion of the hybrid model, various building models were investigated in two and three dimensional configurations. Control of the rotational degrees of freedom (roll and pitch) of the hybrid shake table was included for the taller building models in order to investigate the effects on the behavior of the isolation systems.

2. Hybrid Shake Table Concept and Theory

Hybrid simulation is an experimental testing method where a test is executed based on a step-by-step numerical solution of the governing equations of motion for a hybrid analysis model. The hybrid analysis model consists of both numerically modeled and physically tested components of the overall structural system that is being investigated. In contrast to purely numerical simulations, where the entire structure is modeled analytically, the hybrid simulation method obtains forces related to the structural resistance, energy dissipation, and inertia from a laboratory test of the physical portions of the system. These forces are then synchronously combined with forces from the numerically simulated portions of the system. As such, hybrid simulation can be viewed as an advanced form of experimental testing, where the loading history is determined during the course of an experiment for a given system subjected to a specific loading hazard.

Traditionally, the physical portions of a structure are tested in a laboratory using static and/or dynamic actuators to impose computed target deformations to the experimental test specimen, while instrumentation devices, such as load-cells, are used to measure force feedbacks. Hybrid simulations can be executed quasi-statically if the behavior of the test specimen is not rate dependent. On the other hand, if the test specimen exhibits rate dependent behavior, a hybrid simulation can also be executed in real time.

In a hybrid shake table test, the physical portion of the structural system is tested on a shake table, while the numerical portion of the structural system simultaneously computes the required response to drive the shake table platform. As with traditional hybrid simulations, forces at the interface between the numerical and experimental portions of the structure need to be measured and fed back to the hybrid model, such that the analysis can advance to the next step in the numerical solution process. For hybrid shake table testing, this means that forces at the base of the test specimen, where it is connected to the shake table simulator platform, need to be acquired. Because a shake table test needs to be executed in real time, the forces that are produced by the test structure and that need to be measured at the table surface include: resisting forces, energy dissipation forces, and inertia forces. Hence, hybrid shake table testing is a special form of real time hybrid simulation.

As with all real time hybrid simulations, the numerical solution of the equations of motion for the hybrid model needs to be computed in real time for each integration time step size so that the actuators (or in this case the shake table platform) can be driven in real time. For small hybrid models consisting of only a few numerical elements with linear-elastic behavior, the real-time execution of the analysis is unproblematic. However, for larger hybrid models with many degrees of freedom and/or hybrid models where a substantial number of geometric and material nonlinearities are modeled numerically, the speed at which the equations of motion can be assembled and solved becomes an important factor. For the approach that is taken here, where finite element software acting as the computational driver is deployed, high performance computing techniques that can execute software in parallel on very fast hardware can facilitate hybrid simulations of large highly nonlinear systems in real time. Alternatively, it is possible to implement and execute the numerical portion of the hybrid model in a real-time environment (such as Simulink Real-Time). However, this approach is very problem specific and difficult to adapt and is thus not further discussed here.

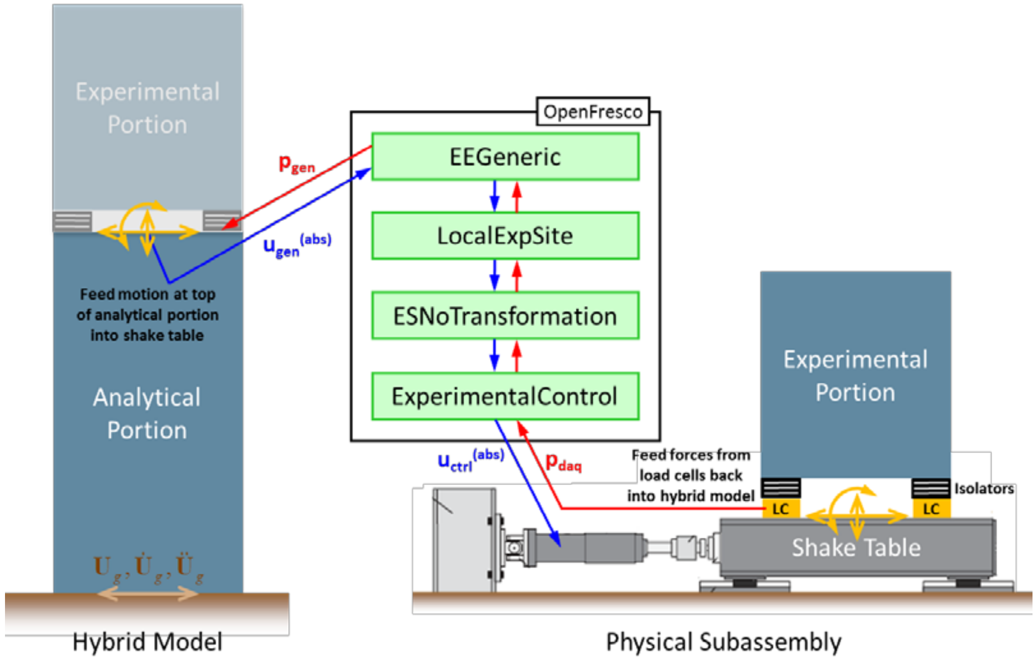

Fig. 1 – Components and data exchange for a hybrid shake table test

In a hybrid shake table test where real-time hybrid simulation is utilized to drive the shake table, the equations of motion that are solved for each integration time step need to be expressed in total (or absolute) response quantities (structural response plus ground response). This is essential because the shake table simulator platform needs to be controlled with absolute response quantities, such that inertia forces in the test specimen are correctly generated. Hence, the equations of motion are expressed as follows:

$$\mathbf{M}^A\,\ddot{\mathbf{U}}_{\mathbf{t},i+1} + \mathbf{C}^A\,\dot{\mathbf{U}}_{\mathbf{t},i+1} + \mathbf{P}_\mathbf{r}^A\left(\mathbf{U}_{\mathbf{t},i+1}, \dot{\mathbf{U}}_{\mathbf{t},i+1}\right) + \mathbf{P}_\mathbf{r}^E\left(\mathbf{U}_{\mathbf{t},i+1}, \dot{\mathbf{U}}_{\mathbf{t},i+1}, \ddot{\mathbf{U}}_{\mathbf{t},i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{\mathbf{0},i+1} \tag{1}$$

where the terms with superscripts A are assembled from the analytical portions of the structure and the terms with superscripts E are assembled from the experimental portions of the structure. $\mathbf{M}^A$ and $\mathbf{C}^A$ are the mass and viscous damping matrices assembled from only the analytical subassemblies and $\mathbf{P}_\mathbf{r}^E$ includes the inertia, damping, and resisting forces of the test specimen excited by the total accelerations, total velocities, and total displacements. It is important to note that, unlike the typical equations of motion that are expressed relative to the ground, this modified system of equations, Eq. (1), also includes the degrees of freedom at the supports of the structure. For earthquake excitations, this means that no external loads are applied at any of the degrees of freedom so that the external load vectors $\mathbf{P}_{i+1}$ and $\mathbf{P}_{\mathbf{0}\ i+1}$ are zero. Instead, as can be seen from Fig. 1, seismic motions are directly imposed at the support degrees of freedom in terms of ground displacements, ground velocities, and ground accelerations. It is worth noting that in OpenSees [8] (Open System for Earthquake Engineering Simulation), this approach is readily available through the existing multi-support excitation load pattern capabilities.

During a hybrid shake table test, the following sequence of operations (shown in Fig. 1) is executed: starting from the given ground displacements, ground velocities, and ground accelerations, the equations of motion in the hybrid model are solved to determine the global absolute response quantities of the entire structure. Using the OpenFresco [9, 10] (Open-source Framework for Experimental Setup and Control) middleware, a generic experimental element (EEGeneric) is defined at the interface between the numerical and experimental portions of the structure. Because the computed nodal response consists of absolute response quantities, the generic experimental element receives absolute displacements, $\mathbf{u}_{gen}^{(abs)}$, velocities, and accelerations in the global coordinate system. These trial response quantities are then sent to the local experimental site. The local experimental site is employed here because the hybrid shake table test needs to be performed in real time and the numerical analysis and experimental test are collocated and not distributed across a network. From the local experimental site, the response is sent to the ESNoTransformation experimental setup. The ESNoTransformation experimental setup object is used here because the shake table platform is already being controlled in table degrees of freedom (the origin of the table coordinate system is located at the center of the shake table surface) and no transformations to actuator degrees of freedom need to be performed in OpenFresco. Typically, transformations from table to actuator degrees of freedom are preferably performed in the real-time control system to account for nonlinear coupling effects, inertia, and friction force effects, and to balance forces in over constrained systems where there are more actuators than table degrees of freedom present. From the experimental setup, the trial response quantities are sent to the experimental control object which provides the interface to transmit control displacements, $\mathbf{u}_{\mathrm{ctrl}}^{(\mathrm{abs})}$, to the control systems of the shake table. Next, forces, $\mathbf{p}_{\mathrm{daq}}$, at the base of the structure (at the interface with the shake table platform) need to be acquired through the data acquisition system. To this end it is preferable to install load cells under the test specimen, so that the forces acting at the interface degrees of freedom can be measured directly. Alternatively, it is possible to use observer techniques to compute forces at the shake table surface from the axial load cells on the actuators, measured table accelerations, and an estimate of the moving table mass obtained through system identification techniques. However, interface forces obtained in this way are typically less accurate and more susceptible to be contaminated by noise and control system dynamics effects. The measured force response (which includes resisting, energy dissipation, and inertia force contributions) is then fed back through the OpenFresco experimental control, setup, and site objects until it reaches the generic experimental element. Finally, the generic experimental element saves and assembles the measured forces, $\mathbf{p}_{\mathrm{el}} = \mathbf{p}_{\mathrm{gen}}$, into the global resisting force vector, $\mathbf{P_r}^{E}$, such that the equations of motion can be solved for the new trial response quantities at the next integration time step. This sequence of operations is then repeated for the total number of transient analysis steps.

To solve the system of equations in Eq. (1) during a hybrid shake table test and to advance the solution in time, direct integration methods that are based on Newmark's method are typically employed. However, for real-time hybrid simulations, the traditional, implicit Newmark method is not well suited. Instead, it is better to deploy explicit or operator-splitting methods which require only one communication with the shake table per integration time step and are thus faster than iterative techniques. Some of these direct integration methods also possess favorable error propagation properties and can provide some adjustable amount of algorithmic (numerical) energy dissipation to suppress the excitation of higher mode effects. See Schellenberg et al. [11] for a more in depth discussion of direct integration methods specialized for hybrid simulation, in general, and for real-time hybrid simulation, specifically.

3. Implementation on the 6DOF PEER shake table

To develop the previously discussed hybrid shake table capability on a multi-degree of freedom simulator platform, the PEER) shake table at the University of California Berkeley was upgraded and modified specifically for this purpose. Upgrades included both hardware and software modifications to make hybrid shake table testing possible. The 20x20 ft. PEER shake table is still the largest six degree-of-freedom (6 DOF) shake table in the United States. It is configured to produce three translational components of motion: vertical and two horizontal; plus three rotational components: pitch, roll and yaw. These 6 DOF can be programmed to reproduce any waveform within the capacities of force, velocity, displacement and frequency of the shake table system. As such, the PEER shake table can subject structures, weighing up to 100 kip, to horizontal accelerations of 1.5 g. Given that shake table performance is a function of mass, overturning moment and model interaction, actual system performance is a function of these variables.

Due to aging hydraulic and mechanical hardware, systematic experimental errors such as system delays and test system dynamics as well as random experimental errors such as feedback noise play an important role in terms of the performance and accuracy that can be achieved during hybrid simulations at this testing facility. While the implementation details discussed herein are for the PEER shake table, the overall approach (as well as specific solutions) can be helpful to other researchers attempting to set up and conduct hybrid shake table tests of large scale structures on multi-degree of freedom shake table simulator platforms.

3.1 Hardware upgrade and configuration

The PEER shake table has been upgraded fairly recently from an analog control system to the latest MTS 469D control system. However, the feature to use an external command for control was not available through this upgrade. In order to interface the control system with OpenFresco and synchronize the non-deterministic execution of the numerical analysis with the real-time control system, the three-loop architecture [12, 11] was implemented, as shown in Fig. 2.

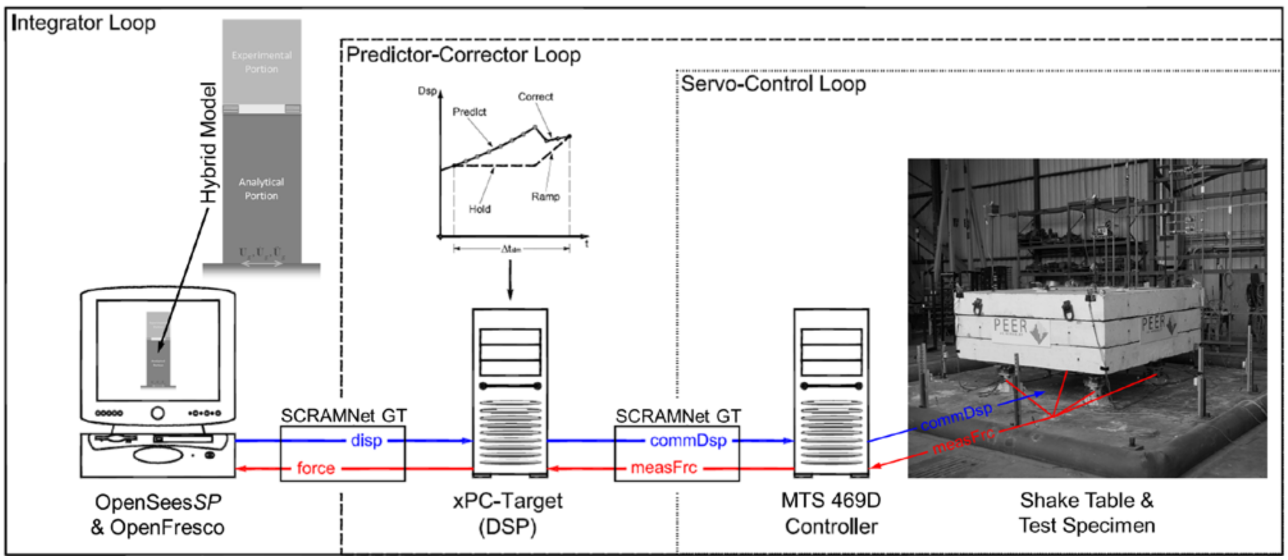

Fig. 2 – Hardware configuration based on three-loop architecture

First, the MTS 469D controller was upgraded with a shared common RAM network (SCRAMNet GT200) to add the capability to send external commands to the controller. The SCRAMNet GT200 real-time network ring allows for high-speed, low-latency data exchange among the three different machines (see Fig. 2) on the network ring. Because it was decided to measure interface forces at the base of the test specimen through four five-component (Px-Vy-Vz-My-Mz) load cells, rather than using the less accurate observer techniques, it was necessary to acquire a total of 20 force measurements from the load cells. Given that the synchronization of the control and data acquisition systems is critical in a real-time hybrid simulation, the independent data acquisition system was eliminated from the test configuration. Instead, the MTS 469D controller was extended with 40 additional user analog-to-digital (A/D) converters, which allow for the measurement of all the forces from all the load-cells installed under the experimental test specimen. Utilizing the data acquisition system built into the MTS 469D control system, ensured that all measurements are synchronized with and recorded at the same sampling rate as the controller update rate of 2048 Hz.

Second, a high performance, overclocked, multicore machine was custom built to serve as the real-time digital signal processor (DSP) that runs the predictor-corrector algorithm programmed in Simulink. The DSP is responsible for synchronizing the non-deterministic integrator loop with the determinist real-time servo control loop, by generating command signals and acquiring feedback signals at the same rate as the control system sampling rate of 2048 Hz. To further minimize communication delays, the predictor-corrector algorithm was up-sampled by a factor of 2-5, meaning that the sampling rate was 4096-10240 Hz. In addition, delay compensation algorithms (see section 3.3) that are based on computationally expensive least squares approaches were also executed on the DSP for all 6 DOF of the shake table. Hence, the high performance DSP was built to guarantee that all these extensive computations are performed in real time at the required fast sampling rate without overloading the processor. Finally, the machine was also equipped with an ultra-fast solid state drive, so that it was possible to record all the signals passing through the DSP at the 2048 Hz sampling rate.

Third, a similar high performance overclocked multicore machine was custom built to serve as the none-real-time analysis machine running OpenSees*SP* and OpenFresco. To record OpenSees and OpenFresco results at the fastest rate possible, an ultra-fast solid state drive was additionally installed into the analysis machine. Both of the custom-built, high performance machines were also equipped with SCRAMNet GT cards to achieve the required high speed exchange of data among all three machines on the network ring.

3.2 Software configuration

OpenSees*SP* (the parallel version of OpenSees for analyzing very large models) was deployed as the computational driver analyzing the hybrid model. OpenSees*SP* is designed to allow for scalable simulations on high-performance, multicore, computing platforms [13]. Using OpenSees*SP* to drive hybrid simulations provides researchers the ability to run larger and more complex hybrid models with many degrees of freedom while executing them at a faster rate. The application of the MUMPS (MUltifrontal Massively Parallel sparse direct Solver) [14] solver in OpenSees*SP* increased the speed of solving the system of equations of very large hybrid model by up to 2.5-times. When running on a parallel machine with n processors, a single processor is running the main interpreter and processing commands from the main input script while the other processors are running Subdomain objects. On the first execution of the analyze() command in the TCL script, the model is partitioned, that is, the elements are split and distributed among n-1 processors to solve the system of equations in parallel. The computational model needs to be suitable for parallel processing. Specifically for hybrid simulation, experimental element related computations must remain on the main CPU (interpreter) in order to maintain communication with the real-time DSP through OpenFresco. This can be achieved by calling a partition function and setting the partition for the experimental element to 0 (main processor) before the first call of the analyze() command.

As described in detail in section 2, OpenFresco was utilized as the middleware connecting the finite element analysis model in OpenSees*SP* with the MTS 469D controller driving the shake table in the laboratory. One important task in hybrid shake table testing is the application of gravity loads onto the numerical substructure before running the dynamic analysis. Gravity loads that need to be applied consist of the self-weight of the numerical substructure as well as the weight of the physical superstructure. In contrast to typical hybrid simulations, the gravity load on the physical test specimen is always present and can thus not be applied through the control system. Hence, it is necessary to apply gravity loads to the numerical substructure before any of the OpenFresco objects are added to the hybrid model. Once the gravity load analysis is completed, the OpenFresco components can be added to the hybrid model to establish the connection with the shake table. Additionally, displacement commands that are being sent to the shake table control system need to be relative to the state at the end of the gravity load analysis, to not create an initial displacement discontinuity in vertical direction. This feature, to utilize relative instead of absolute trial displacements, is directly built into OpenFresco, so that users do not have to make any special changes when performing hybrid shake table tests.

As mentioned earlier, a predictor-corrector algorithm, programmed in Simulink and executed in real-time on the xPC-target DSP, is used to bridge the difference between a typical numerical analysis time step size (10/2048 sec was chosen for these tests) and the smaller control system time step size (1/2048 sec). To synchronize the nondeterministic execution of the OpenSees*SP*/OpenFresco analysis with the determinist execution of the control system, the predictor-corrector algorithm performs the following tasks: 1) while the analysis software solves the equations of motion for the new target displacement, the pc-algorithm generates command displacements based on polynomial forward prediction; 2) once the new target displacement has been received, the pc-algorithm switches into the correction mode where it generates command displacements driving the shake table response towards the new target displacement; 3) if the new target displacement is not received within 60% of the simulation time step size (6/2048 sec), the pc-algorithm gradually slows down the command displacements until the new target displacement is received. Therefore, in order to achieve a real-time execution of the hybrid shake table test without any slowdowns, the analysis software needs to compute a new target displacement in less than 6/2048 sec. Predictor-corrector states were monitored and recorded for all hybrid tests. No slowdowns were encountered and on average the pc-algorithm performed 1/2048 sec of prediction and 9/2048 sec of correction, hence, real-time execution was achieved for all the tests.

3.3 Control system and delay compensation

The PEER shake table is controlled by a by a MTS 469D real-time digital controller. This digital control system provides closed-loop, three-variable-control (TVC) for all six degrees of motion. Three- or multi-variable control utilizes not only displacement for control, but adds velocity, acceleration, and jerk to the control process. The internal structure and implementation details for the TVC method are presented in [7]. Given this multi-variable control, it is possible to achieve better tracking performance over a wider range of frequencies. While displacement control provides good tracking in the low frequency range, velocity control improves tracking in the mid frequency range, acceleration control helps in the high frequency range, and jerk can boost the response above the oil-column frequency. It is typical in hybrid simulation to generate command displacements, but not command velocities and accelerations. Therefore, these reference displacements sent to the TVC are low-pass filtered and differentiated to generate all the reference variables required for control. It is important to note that other advanced control strategies exist in literature which can be beneficial for hybrid shake table testing. Due to time constraints, only TVC has been employed so far, however, for future testing, it is recommended that the method developed by [15] is investigated as well.

While the application of the TVC was able to improve tracking performance in the higher frequency range, there was still a delay of 25 to 30 milliseconds in the different table degrees of freedom present. Systematic experimental errors, such as system delays, introduce artificial energy into the hybrid system and can thus deteriorate accuracy and, in the worst case, even destabilize a hybrid simulation. To compensate for the remaining delays, the adaptive time series (ATS) delay compensation technique developed by Chae et al. [16] was employed here. The ATS delay compensator is based on a least squares approach and continuously updates the coefficients of the system transfer function to compensate for changing delays. To apply the ATS compensator to the hybrid shake table tests, two minor modifications were made. First, the algorithm was extended to perform adaptive delay compensation individually for all six degrees of freedom of the shake table. Second, the ATS was modified to utilize reference velocities and accelerations directly from the predictor-corrector algorithm instead of computing them by differentiating reference displacements. Because the predictor-corrector algorithm utilizes polynomials for extrapolation and interpolation, it was possible to directly differentiate the displacement polynomials to obtain velocity and acceleration polynomials. This modification produced more accurate velocity and acceleration references than the original implementation.

4. Application to seismic isolation in tall buildings

To verify the newly implemented hybrid simulation capabilities of the PEER shake table, a series of hybrid shake table tests were carried out using a response modification device as the test specimen installed on the table. The experimental response modification device was then applied to several different tall building models that were modeled numerically in OpenSees.

4.1 Superstructure test specimen

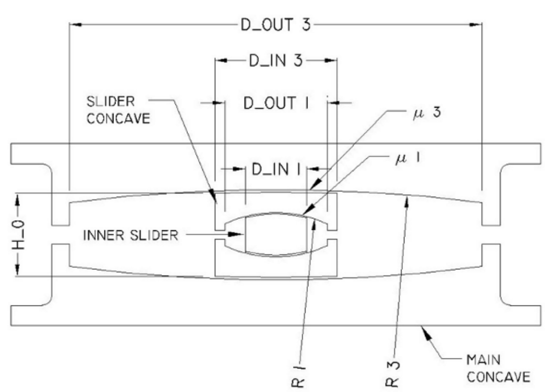

Fig. 3 – Test specimen on PEER shake table and cross section of triple pendulum bearing

The physical response modification device consisted of a large mass isolated by triple friction pendulum (TFP) bearings (see Fig. 3). The total weight of the rigid mass block was 53 kip and it was supported by four bearings 6 ft. apart. In addition, three small oscillators with different natural periods where installed on top of the rigid mass block. The three effective pendulum lengths of the bearings were L_1 = 2.175 in. and $L_2 = L_3$ = 17.17 in. and from these the corresponding bearing periods can be calculated to be T_1 = 0.67 sec, T_2 = 1.41 sec, and T_3 = 1.87 sec. The total displacement capacity of the triple pendulum bearings is 6.85 inches. The coefficients of friction were estimated at $\mu_1 = 0.01$, $\mu_2 = 0.08$, and $\mu_3 = 0.13$.

4.2 Numerical substructures and input ground motions

Several numerical substructures of varying complexity were implemented in OpenSees. To verify that the system had been set up correctly and to determine shake table performance and tune control as well as delay compensation parameters, a function generator model (Model A) was first created in OpenSees. The model consisted of a single lumped mass corresponding to the shake table weight of 86.8 kip. The generic experimental element with three translational degrees of freedom was then connected to this mass. Next, the multi-support load pattern in OpenSees was utilized to impose three-component ground displacements, velocities and accelerations for the 1989 Loma Prieta - Gilroy Array #4 motion and the 1987 Superstition Hills - Westmorland Fire Station motion. To integrate the equations of motion, the NewmarkExplicit, the HHTGeneralizedExplicit, and the AlphaOSGeneralized (with $\rho_{inf} = 0$) integration methods were used. The integration time step size was selected to be 10/2048 seconds.

The second numerical substructure (Model B) was based on a 15 DOF shear building that was reduced to a first mode equivalent 3 DOF stick model (see Fig. 4a). The effective height of the simplified model was 0.647*(5*144) = 465.8 in. and the effective weight was 0.886*(4*100+50) = 398.7 kip. The weight of the experimentally tested TMD was equal to 12% of the numerically modelled total building weight. The story stiffnesses of the building were selected such that the first mode frequencies in the three principal directions were f_{H1} = 1 Hz, f_{H2} = 1.25 Hz, and f_V = 11 Hz. The third numerical substructure (Model C) consisted of the original 15 DOF shear building. Both of these substructures did not consider roof rotations because they were modeled as shear buildings. Thus, only translational table degrees of freedom were controlled for the hybrid shake table tests that were based on these two models. 5% initial stiffness proportional damping was assigned to both models.

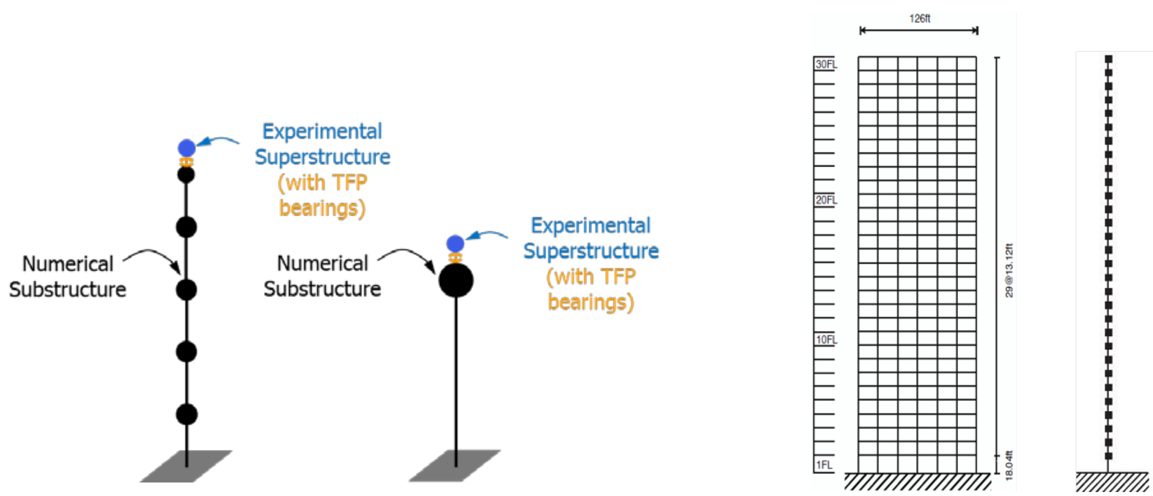

Fig. 4 – 15 DOF shear building with equivalent 3 DOF stick model and 30 story steel moment frame building with simplified 30 DOF shear building stick model

To include rotational degrees of freedom and capture overturning effects, a flexural building model (Model D) was next generated. Using modal analysis, the full building model was again reduced to a first mode equivalent 5 DOF stick model. Equivalent flexural and shear properties were calculated and assigned to the ElasticTimoshenkoBeam element in OpenSees such that the first mode frequencies turned out to be similar to the shear building. As before, 5% initial stiffness proportional damping was assigned to the model.

The last numerical substructure (Model E) considered in these tests was a 30 story, steel moment resisting frame (see Fig. 4b). The total height of the building is around 400 ft with a height-to-width ratio around 3.2. The total weight of the building is about 63,000 kip. The fundamental vibration period of the building is around 3.7 seconds. A simplified 2D shear building stick model was constructed in OpenSees. As shown in Fig. 4b, for each story, one elastic element is used to represent the horizontal shear behavior. Element sizes were determined based on the total floor horizontal stiffness of the prototype building.

4.3 Control system results

Only very limited results are shown here. To confirm that the ATS delay compensator is working well, the target displacement command versus the measured displacement feedback for one of the horizontal degrees of freedom for Model B are plotted in Fig. 5. As can be seen from the plots, the ATS compensator is able to reduce the average delay over the whole displacement history to less than 1 msec (from the original 30 msec without ATS). The maximum displacement error is about 0.01 inches which corresponds to about 0.5% of the maximum absolute table displacement amplitude. Also, the Mercan tracking indicator [17] confirms the excellent tracking performance that was achieved in this test. A similar excellent performance was obtained in the perpendicular horizontal direction and a slightly reduced performance (with an average delay of 2 msec) was obtained in the vertical direction.

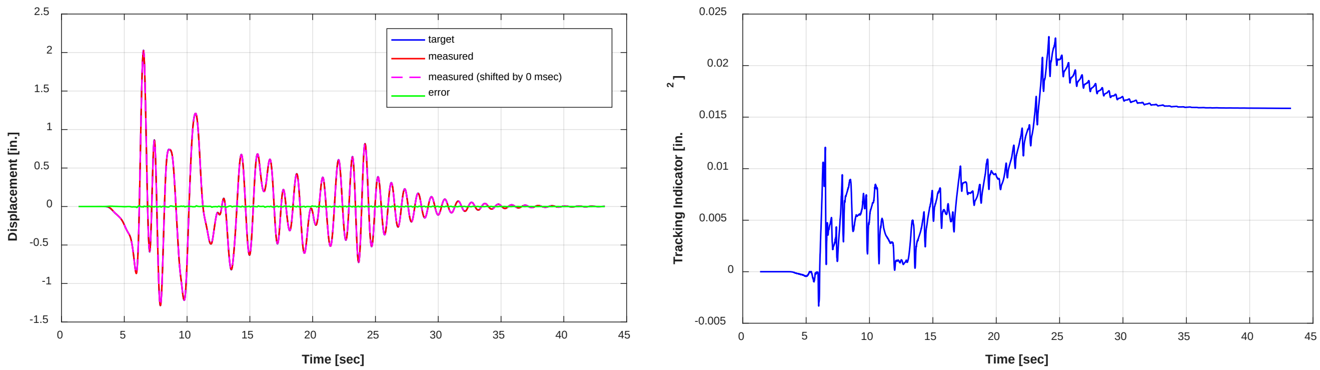

Fig. 5 – Error with average delay between target and measured displacement and tracking indicator for DOF 1

For Model C, where the substructure consisted of 15 degrees of freedom (5 in each of the three principal directions), similar but slightly reduced tracking performance was achieved. However, Model C with multiple degrees of freedom in each direction produced much noisier force feedbacks than Model B. It was found that due to the ageing hydraulic and mechanical hardware as well as the large shake table mass, test and control system dynamics effects were feeding into the load cell measurements at the base of the test specimen. These erroneous high frequency force measurements were then fed back into the hybrid analysis models. Model B, with fundamental periods well below this high frequency noise, was not affected by these experimental force errors. However, this was not true for Model C, where higher modes were excited by the experimental force errors and ultimately produced inaccurate responses of the overall structure including the TMD.

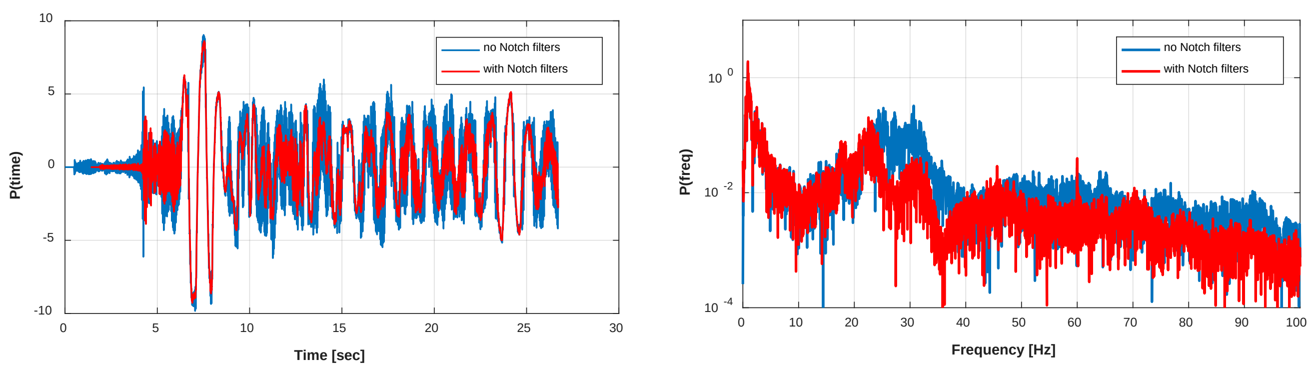

Fig. 6 – Effect of Notch filtering on force feedbacks in time domain and frequency domain

These problems manifested themselves particularly in the vertical direction due to the high vertical stiffness of the substructure. Significant time was invested trying to filter force feedbacks using Notch filters (see Fig. 6), Butterworth filters, and moving average filters. It was found that all of these filtering solutions were either not very effective or removed too much of the actual force response from the test specimen. Given that upgrading the shake table hardware is not an option (due to the high costs of such improvements), additional filtering techniques, including Kalman filters, will be investigated in the future.

Root mean square errors at the end of each test normalized by the signal range are shown in Table 1. As it can be seen, high accuracy was achieved in the two horizontal directions and a somewhat lower accuracy was obtained in the vertical direction because of the reasons mentioned above. The larger normalized RMS errors for the two rotational degrees of freedom in Model D, were caused by delays of 4 msec in R1 direction and 14 msec in R2 direction. Shake table tracking performance for the roll and pitch degrees of freedom was not as good as for the horizontal degrees of freedom and the ATS compensator was not able to remove delays completely. Additional tuning of the ATS parameters for the rotational degrees of freedom will be investigated in the next phase of testing.

Table 1 – Normalized RMS errors in [%] at the end of selected tests

Model	H1	H2	V	R1	R2
B	0.08	0.05	0.26	-	-
C	0.09	0.06	0.79	-	-
D	0.09	0.05	-	0.80	1.64
E	0.11	-	-	-	-

4.4 Hybrid model results

Fig.7 shows the comparison of the tall building (Model B) response from a purely numerical analysis of the building without the TMD and the hybrid shake table test with the TMD. It can be seen from the displacement histories that despite the positive peak roof displacements being nearly identical, displacement amplitudes in most other cycles are significantly smaller when the TMD is installed on the roof of the building. Also, the floor response spectrum at the roof of the tall building is significantly reduced over a fairly wide frequency range for the case with the TMD. Hence, the benefit of the TMD is clearly visible from these results.

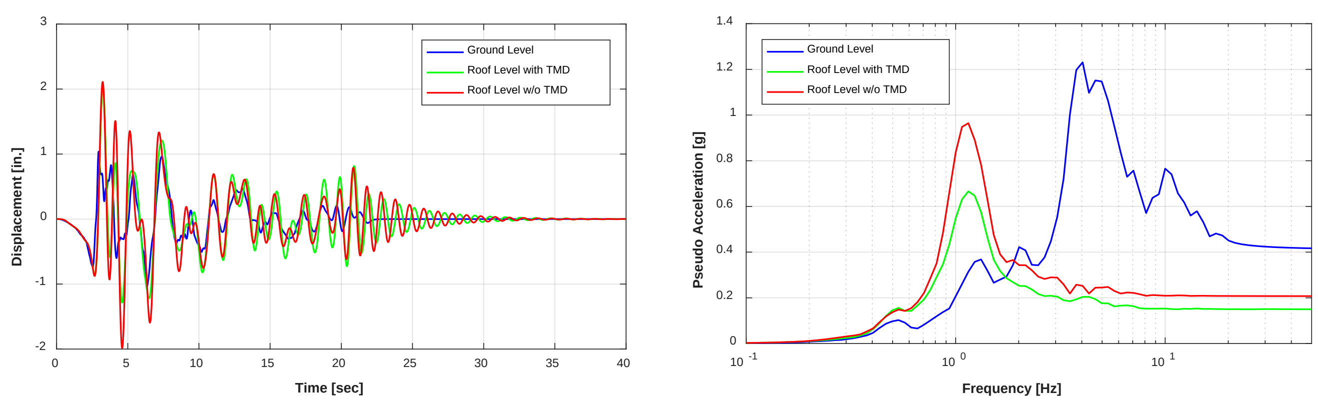

Fig. 7 – Comparison of displacement histories and floor response spectra to assess TMD benefit

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