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HYBRID SIMULATION OF FULL SCALE SEISMIC ISOLATION BEARINGS USING THE CALTRANS SRMD TEST FACILITY

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Abstract

The dynamic response of a seismically isolated structure depends on the combined characteristics of the ground motion, bearings, and superstructure. Therefore, dynamic full-scale system level tests of isolated structures under realistic earthquake loading are desirable towards full validation of this earthquake protection strategy. Moreover, bearing properties and their ultimate behavior have been shown to be highly dependent on scale size and rate-of-loading effects. Thus, reduced-scale models may not fully capture the realistic behavior of large bearings. Uncertainties in the test results complicate the validation of numerical models and the understanding of the behavior of an isolated system especially under extreme loading conditions. With a specific interest on the in-structure response of seismically isolated buildings, hybrid simulation is shown to be a viable approach to examine bearing behavior at full scale under realistic earthquake loading and quantify the sought-after in-structure response. Current laboratory facilities can test full-scale seismic isolation bearings under prescribed displacement and/or loading protocols. The adaptation of a full-scale bearing test machine for the implementation of fast hybrid simulation is presented.

In this study the supported superstructure is expected to remain elastic, making this a well suited application for hybrid simulation with experiments capturing the nonlinear bearing behavior. These hybrid simulations employed high performance parallel computing tools to analyze large numerical structures with several thousands of degrees of freedom at near real-time rates. Challenges encountered in achieving reliable simulation results for these large scale dynamic tests are discussed. This research program demonstrates that hybrid simulation can be a viable and promising testing method to experimentally assess the behavior of large isolators at full-scale (including 3D dynamic loading) and capture interactions with the numerical models of the superstructure to evaluate system level and in-structure response.

Keywords: hybrid simulation; seismic isolation; parallel processing; full scale bearing

1. Introduction

Seismic isolation is considered an effective strategy to protect structures from the damaging effects of earthquakes [1, 2]. Especially under strong earthquake shaking, seismic isolation bearings can exhibit complex nonlinear behavior that is dependent on several factors including the axial load, temperature, and strain rate of loading. This complex behavior provides some uncertainty regarding the nonlinear seismic response of isolated structures and requires detailed experimental investigations to fully characterize their behavior [3, 4]. Component tests of individual bearings and system level tests capturing the interaction with the superstructure are essential towards fully characterize the bearing behavior.

With the dynamic response of an isolated structure dependent on the combined characteristics of the ground motion, bearings, and superstructure, standard prototype tests may not be sufficient to verify the adequacy of analytical models. Seismic isolation bearings have demonstrated path-dependent behavior with degradation parameters that depend on the rate of loading, number of cycles and scale size of the bearings. Therefore, dynamic tests of isolated complex structures under expected earthquake excitations are desired. Only a few system level tests have been conducted on full-scale building structures using shake tables [5, 6], however, testing of bearings at the scale examined here would be prohibited on a shake table due to the gravity weight required on the bearings. Realistic full-scale simulations are essential towards understanding the behavior of an isolated system, especially under extreme loading conditions and for the validation of numerical models that can be used to examine their behavior under a wider range of conditions.

2. Hybrid Simulation of Seismically Isolated Structures

Hybrid simulations at real-time or near real-time rates can be an efficient and economical approach for testing seismically isolated structures. This method combines results from experimental substructures representing critical components that exhibit complex nonlinear behavior and analytical models of the remainder of the structural system with more predictable behavior. Typically, the design of an isolated structure is such that the structure above the isolation plane remains essentially elastic while the isolation system exhibits nonlinear hysteretic behavior that localizes large deformations and provides energy dissipation. Because laboratory facilities exist to test full-scale seismic isolation bearings under prescribed displacement or loading protocols at appropriate rates and the linear superstructure can be modelled reliably, hybrid simulation provides a unique opportunity to experimentally assess the behavior of base isolated structures using full scale bearings.

3. SRMD Test Facility

The Seismic Response Modification Device (SRMD) Test Facility at the University of California, San Diego shown in Fig. 1 was designed for 6-DOF dynamic characterizations of full-scale bearing devices and dampers using predefined loading protocols [7]. The capabilities of the SRMD test facility are listed in Table 1. It is worth noting that, the longitudinal and lateral displacement capacities of 1,219 mm and 610 mm facilitates testing of bearings to large displacements while imposing axial loads up to 53,400 kN. This range of loading is generally applicable to the anticipated demands on individual bearings for buildings, bridges, and industrial structures.

Fig. 1 – SRMD test facility

The testing system consists of a prestressed concrete reaction frame box surrounding a moving platen. Four horizontal actuators control the lateral and longitudinal displacements of the platen. The platen is 3,658 mm wide by 4,750 mm long and slides over four hydrostatic low friction bearings which are attached to the floor of the concrete structure and control the vertical movement of the platen. In addition, the platen is connected to four steel outrigger arms that are supported by four pairs (i.e., upper and lower) of low friction sliding bearing actuators that are used to control the vertical and rotational motions of the platen (Fig. 2). The testing system is completed by two additional reaction structures: a removable steel cross beam and a prestressed reaction wall on the west end of the machine. The removable cross beam and the configuration of the platen make the system flexible to perform different types of tests. The facility was updated in 2003 with a digital three-variable controller (TVC) and a digital off-line simulation for performance prediction and to operate the machine in “shake table” mode. In 2014, the test facility was adapted for hybrid simulation for the purposes of the testing program described herein. More recently, an upgrade to enable digital communication was implemented in an effort to enable real-time testing that will be assessed in future studies.

Table 1 – SRMD machine technical specifications [7]

Component	Capacity	Accuracy of application	Accuracy of readout
Vertical force	53,400 kN	±5%	0.5% full range
Longitudinal force	8,900 kN		1.0% full range
Lateral force	4,450 kN		1.0% full range
Vertical displacement	±0.127 m	±2%	1.0% full range
Longitudinal displacement	±1.22 m	±2%	1.0% full range
Lateral displacement	±0.61 m	±2%	1.0% full range
Vertical velocity	±254 mm/sec	±10%	
Longitudinal velocity	±1,778 mm/sec	±10%	
Lateral velocity	±762 mm/sec	±10%	
Rotation (roll, pitch, and yaw)	±2 degrees		

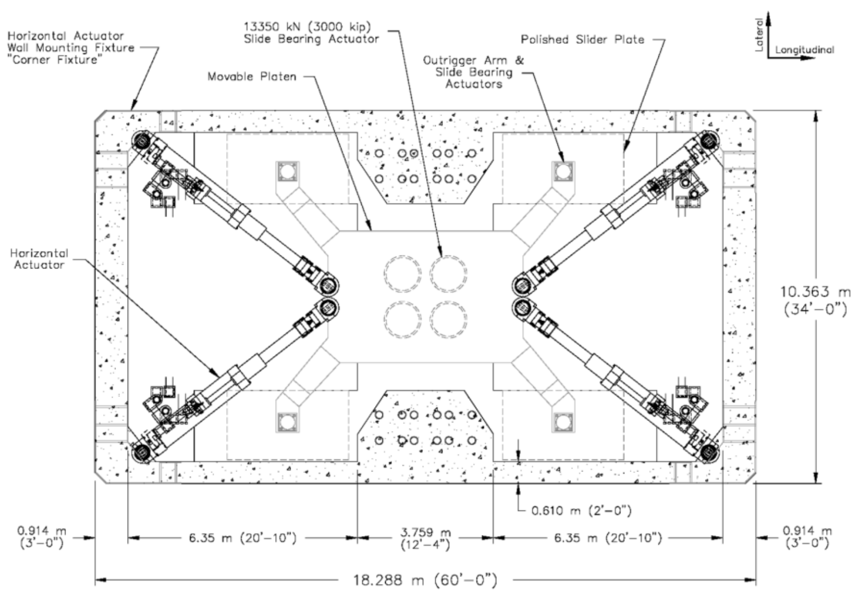

Fig. 2 – SRMD plan view [7]

4. Hybrid Simulation using SRMD

While the SRMD was not originally designed with the intent of conducting hybrid simulations, it includes different software and hardware components that allow for this adaptation. Performance limitations such as actuator delay and the communication speed determine the rate of testing that can be achieved. While the implementation discussed herein is for the SRMD, the challenges discussed can be faced by other researchers attempting hybrid simulations of large scale structures under multiple components of excitation. The tests reported are unique in terms of the scale of the structures examined, the multiple components of loads and displacements applied on the experimental substructure, and the large number of degrees of freedom in the numerical substructures.

4.1 Hardware configuration

In general, a hybrid simulation requires a computational driver to solve the equations of motion of the hybrid structural model using time-stepping integration algorithms and such driver is linked to at least one experimental substructure. For this implementation, the hybrid model communicated with the SRMD control system to load the specimen and obtain the necessary feedback signals. Continuous communication of commands to the SRMD controller was achieved with the configuration shown in Fig. 3. It includes the computational driver, the SRMD control systems and a real-time digital signal processor [9] to communicate between the digital computers and the analog input/outputs of the SRMD control system. While the SRMD controller has mainly been used for conventional cyclic dynamic testing with a predefined loading signal, for the hybrid simulations the longitudinal and lateral displacement commands and the vertical force command were controlled through external reference channels. The different components of this hybrid simulation system are discussed in the following sections. The additional components that were added to achieve the external command generation and feedback acquisition are described next.

4.1.1 Digital signal processor for real-time signal generation

A real time DSP [9] was used in the test setup consisting of a dSpace ACE 1104 Hardware Kit. The DSP processor resides on a PCI card with an external connector panel with 8 ADC (Analog to Digital Converter) inputs, 4 with 16 bit resolution and 4 with 12 bit resolution, and 8 DAC (Digital to Analog Converter) outputs with 16 bit resolution. The DSP is used for signal generation, to send commands, and to receive feedbacks at deterministic rates of 1000 Hz (1 msec), which is the rate of operation of the SRMD controller. The dSpace command signals were calibrated to the same volt-displacement/force ratio as the command displacement/force of the SRMD facility for all the different degrees of freedom. During hybrid simulations, the digital control signals generated by the predictor-corrector algorithm running on the DSP were converted to analog signals and then transmitted to the SRMD control system through its analog input panel.

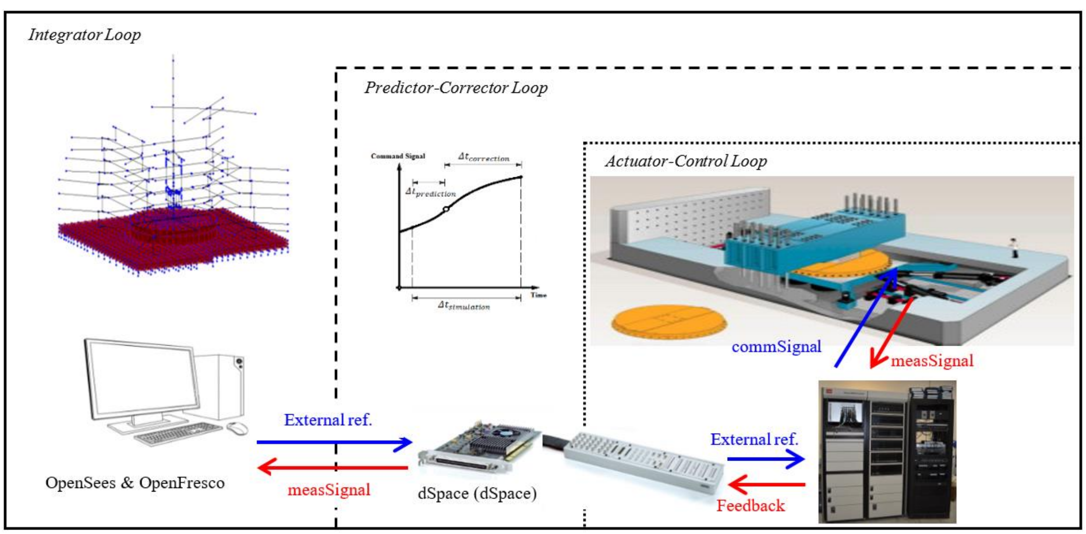

Fig. 3 – dSpace experimental control

4.1.2 Control system of the SRMD

The SRMD applies loads through a 6 DOF platen system governed by movements of its collective actuators. The digital real-time controller provides closed-loop, six degrees-of-freedom (DOF) control of system motion including vertical, lateral, and longitudinal displacements, and yaw, pitch, and roll rotations. This facility was primarily designed to apply large displacements at relatively high velocity as well as high axial loads on seismic isolation devices. Each actuator is controlled using multi-stage closed-loop control principles, where the inner loop controls the poppet valves and the outer loop controls actuator displacements. Four stage poppet valve assemblies are used in place of the more common multi-stage servo valves typically employed in structural testing. This is necessary to provide the high volume of oil needed to facilitate the fast movement of these actuators, but comes at the expense of more accurate control. This can be of particular concern for hybrid simulation since displacement control errors can propagate through the numerical model and potentially lead to instability. However, careful control of these errors can result in reliable simulation results as will be demonstrated here.

4.2 Software configuration

Integrated software and hardware is necessary to be able to conduct hybrid simulations. In general, a fast computational solver needs to communicate with the hydraulic controller through a middleware that bridges numerical and physical portions of the hybrid simulation testing system. These software components need to communicate throughout the test in order to run smooth hybrid simulations in the laboratory. The key software components for a hybrid simulation, as implemented at the SRMD facility for this test series, are described below. Several improvements and additions that were specifically developed for this project include the deployment of multi-processor computational driver software and updated OpenFresco middleware software.

4.2.1 OpenSees and OpenSees*SP*

The use of OpenSees in hybrid simulation provides advanced capabilities for modeling and analyzing the nonlinear response of structural systems using a wide range of material models, elements, and solution algorithms. OpenSees is designed for parallel computing (OpenSees*SP*) to allow for scalable simulations on high-performance computing platforms [10]. Using OpenSees*SP* in hybrid simulation provides researchers the ability to expand to more complex and nonlinear numerical models with many degrees of freedom executing them at a faster rate. The rate of testing in a hybrid simulation depends on the computational time of the numerical model and the rate of loading of the testing facility.

The application of the MUMPS (MUltifrontal Massively Parallel sparse direct Solver) [11] solver in OpenSees*SP* increased the speed of solving the system of equations of the 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 [12]. 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 [13]. 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 and experimental facilities. 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.

4.2.2 OpenFresco

The OpenFresco (Open-source Framework for Experimental Setup and Control) software framework is a middleware used to connect the finite element model with the SRMD control and data acquisition systems [14]. A new experimental bearing element was developed in OpenFresco that is able to transfer three translational and three rotational degrees of freedom to the experimental substructure. In addition, this new experimental bearing element provides the user-selectable option to either transfer axial deformation or axial force to the test specimen. Due to the high axial stiffness of the bearings being tested, force control is preferred in the vertical direction. This enables 3D testing that can capture the vertical-horizontal coupled behavior of large scale seismic isolation bearings with variability in axial force due to overturning moment and vertical ground excitation.

4.2.3 Real-time predictor-corrector

The SRMD control system operates at a rate of 1000 Hz, updating the actuator commands and getting feedback signals from sensors on the current position of the platen. For smooth control and movement of the actuators, the commands to the actuators from the hybrid controller should be updated at a similar rate. However, the numerical portion of the hybrid simulation may not be running in a real-time environment and could require variable calculation times that randomly exceed the allowed time (a fraction of the integration time step size) to calculate the new target values for the control system. Therefore, a real-time Predictor-Corrector algorithm is needed to generate smooth command signals updated at the same rate as the actuator controller while receiving displacement targets from the numerical model at a non-deterministic rate.

The Predictor-Corrector algorithm [15, 16], was programmed in Simulink and Stateflow within the MATLAB environment as shown in Fig. 4 [17] and then downloaded to run on the DSP in real-time. A polynomial is fitted to the displacement targets received from the numerical model to generate a continuous command signal at the desired rate. The order of the fitted polynomial can simply be modified and should be selected based on trial iterations. For these simulations, the polynomials were first or second order. In these particular tests, fitted polynomials to the command displacements were used to calculate the velocity and acceleration of the table platen. These were required to compute on-line corrections of force feedbacks as discussed later. Velocity and acceleration could have been calculated or obtained based on measured displacement or acceleration feedback directly acquired from sensors. However, it was found that using calculated command velocity and acceleration was more reliable due to the noise level inherent in the measured data.

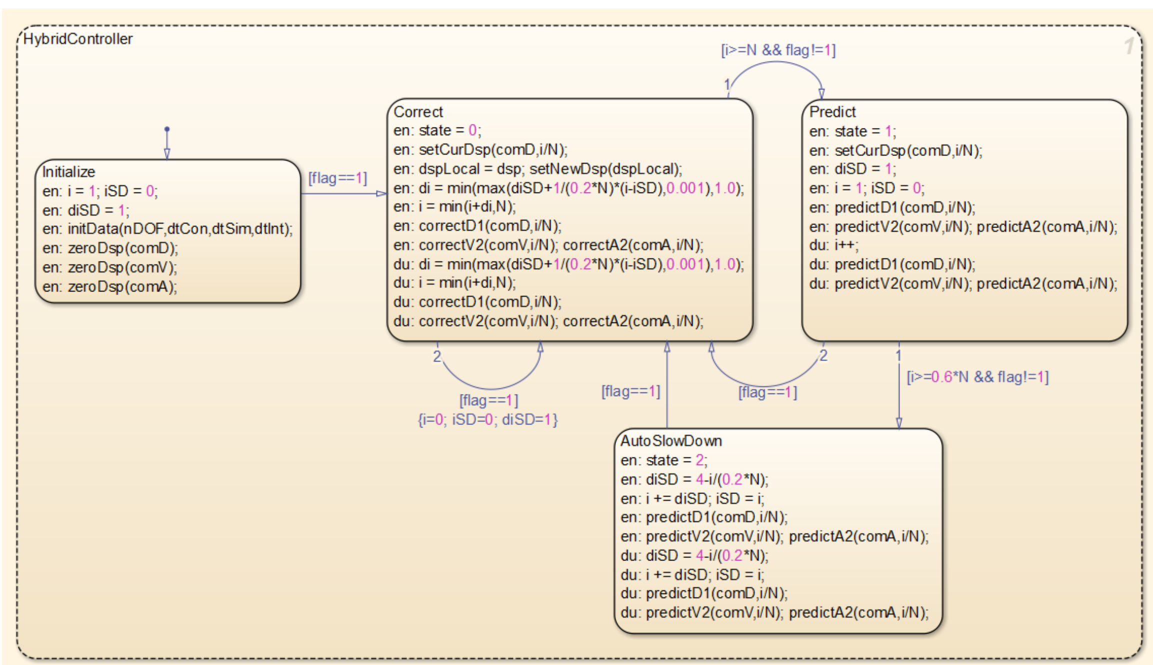

Fig. 4 – Predictor-Corrector algorithm in Stateflow [16]

4.2.4 Communication between hybrid simulation components

As described in the previous section, several components are necessary to conduct hybrid simulations with the SRMD. The numerical model is programmed in OpenSees*SP* to solve the governing equations of motion at each integration time step for the hybrid model. OpenSees*SP* calculates new target displacement values for the next time step and it sends these to all elements, including numerical elements and to OpenFresco which generates the desired loads on the isolator test specimen. OpenFresco transforms the target signals from global degrees of freedom to actuator degrees of freedom and then communicates with the real-time DSP running the Simulink model of the hybrid controller. This Simulink model running in real-time is able to generate smooth command signals by updating an analog output signal each 1 msec using a predictor-corrector algorithm within the simulation time step.

The SRMD real-time controller receives these commands signal as external reference signals and commands the motion of the platen accordingly.

At the end of each simulation time step when the target displacement is reached by the SRMD, measurements of each desired degree of freedom are obtained and then sent back to the numerical model. These are also referred to as feedback. For a 2D hybrid simulation the measurements are two horizontal displacements and their corresponding horizontal forces. These feedback forces not only consist of internal forces in the physical specimen but may also include inertia and friction forces of the platen. While it is desirable to have a load cell directly beneath the bearing, this would have been difficult and very costly considering the magnitudes and multiple components of the forces that need to be measured. Thus, the forces measured directly from actuator axial load cells included inertia and friction forces that need to be subtracted from the feedback signals before sending them to the numerical model to obtain the proper bearing restoring force. This correction of the feedback forces was implemented within the Simulink real-time model described earlier. Once the numerical simulation receives the restoring forces from the numerical and experimental elements, the analysis proceeds to the next integration time step.

4.3 Preparation for hybrid test

Before executing a hybrid simulation, there are a few preliminary checks required to ensure that different components are communicating properly and that the feedback signals to the numerical model are accurate. For these tests, the numerical model calculates the command signals for the SRMD controller, which then returns feedback signals consisting primarily of the shear forces generated in the bearing. These calculated numerical values were converted to corresponding voltage and calibrated to give the desired displacement in the SRMD controller (Fig. 5). Based on the output voltage and also the resolution of each channel, the noise level in each degree of freedom was investigated. This voltage range can be modified to full, half or other ratios in order to minimize noise level with respect to the required range of values. Moreover, signal calibration on each degree of freedom was applied by linear regression to obtain gain values and required offset voltages for command reference signals sent to and feedbacks received from the SRMD controller.

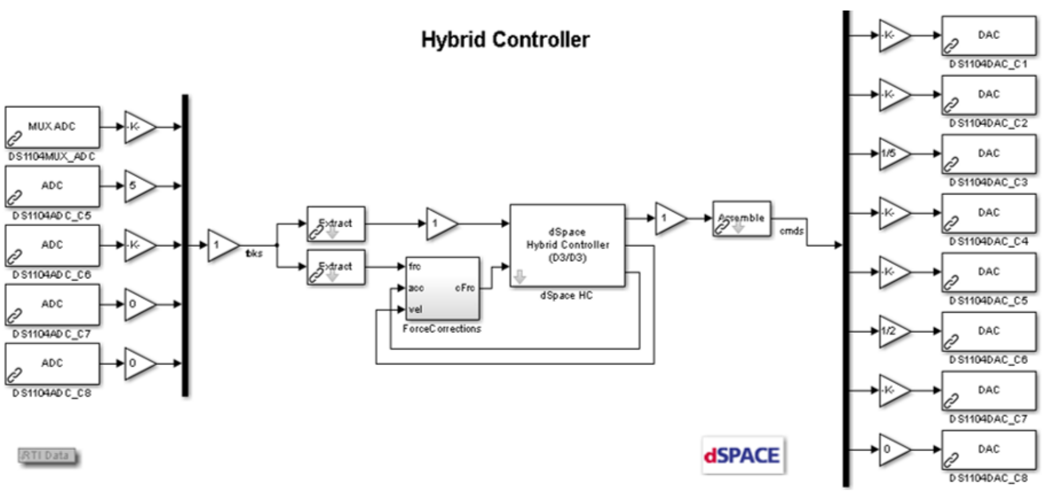

Fig. 5 – Hybrid controller configuration

4.3.1 Delay

Delay is an important parameter in hybrid simulation that needs proper compensation. In general, delay is the time difference between the command signal and its measured response. In order to assess delay in the system during a hybrid simulation, cross correlation functions and minimization of RMS (root mean square) errors were used for system identification. The SRMD was estimated to have about 60 msec of delay when commanded from its internal control system. This delay is mainly due to a lag in the response of the hydraulic actuators driven by the four-stage poppet valve assembly. When generating the command from the DSP, the built-in D/A converters introduce additional delays. Comparing the commands generated by the DSP to the measured feedback signals, delays on the order of 100 msec were observed. Implementing more advanced control strategies, such as feedforward control can reduce this delay. Further studies are needed to better characterize the SRMD control system and the variation of delay within a signal, especially considering the significant oil pressure drop in the system while running a dynamic test.

For coupled multi degree-of-freedom testing configurations, as is the case here, it is important to examine the delay and compensation approach for each DOF. Compensating by a single time value for all degrees of freedom may result in the actuators moving out of sync and exciting the higher modes in the system [18]. This is of particular concern in the SRMD since the vertical degree of freedom operates in force control while the other degrees of freedom are displacement controlled and can therefore have large relative differences in the delay. It should also be noted that the two horizontal displacement degrees of freedom were observed to have different delays. Compensating for the delay in each degree of freedom independently is necessary to achieve accurate results and was done so accordingly.

In an effort to further reduce the delay through more advanced control strategies, an additional feed-forward gain control parameter was activated in the SRMD controller. Enabling this feature and tuning the system for feed-forward gain provided a significant performance improvement (Fig. 6). For the slower tests, the feedforward gain eliminated the delays in longitudinal and lateral degrees of freedom, which were previously 110 and 105 msec (communication and control delays combined), without causing additional overshoot.

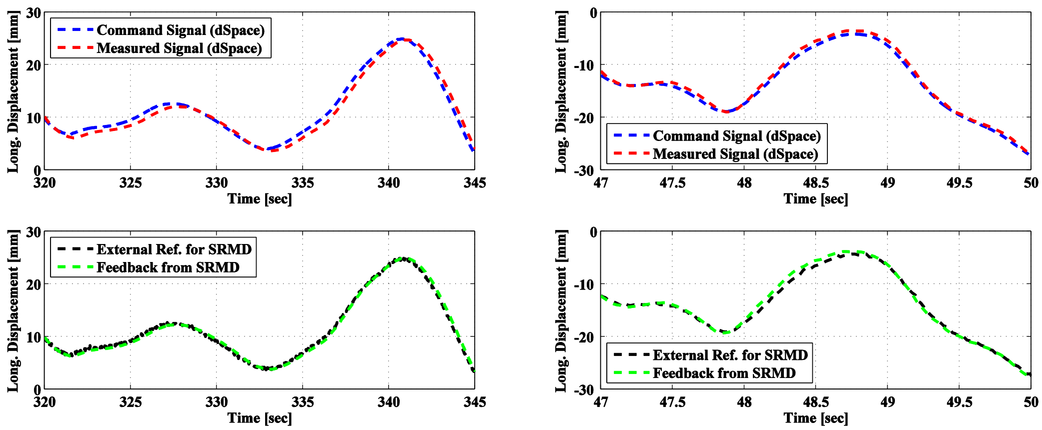

Fig. 6 – Tracking signal for delay (left: no feedforward, right: with feedforward)

Unfortunately, feedforward compensation was not helpful in the vertical direction for which the machine was operated in force control mode. Therefore, 1D or 2D hybrid testing (controlling translational degrees of freedom in longitudinal and/or lateral directions) could be implemented to run relatively fast while 3D hybrid tests (controlling the axial force on the bearing as well as the horizontal displacement degrees of freedom) were limited to a slower rate.

4.3.2 Correction of feedback forces for inertia and friction force

Feedback forces in the SRMD controller were obtained from load cells on the actuators. The measurements include not only the resisting forces in the bearing but also the friction and inertia forces of the SRMD platen. Prior to sending these feedback signals as restoring forces, some corrections were required to take out these additional forces from the measured signal. A model was developed to correct for friction and inertia on the fly in order to return a corrected value during the test as is required for a hybrid test. In all previous cyclic testing of bearings on the SRMD, these effects are corrected for during post-test analysis, often by subtracting the measured forces from an empty table run of the same input motion. While an empty table run should ideally provide zero shear force readings in the absence of friction and inertia, large forces on the order of 2,000 kN are observed during fast tests with significant accelerations. This is mainly due to inertia forces of the platen mass and friction by the platen sliding on the vertical actuators and outrigger supports. The friction model, schematically shown in Fig. 7, was calibrated by trying to reduce the measured force to zero during empty table runs. Fig. 8 shows an example of a correction procedure for an empty table. Ideally, there should be zero residual force after correction for inertia and friction. As shown, the residual force is mostly below 10 KN (~ 0.011 % of the longitudinal force capacity) which is well within the expected range of force accuracy of the SRMD.

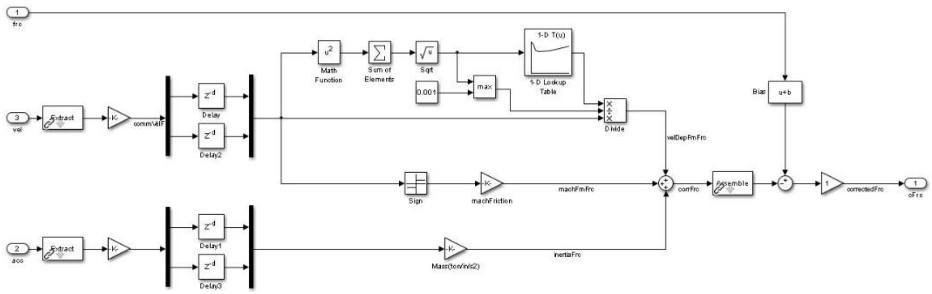

Fig. 7 – Simulink model to correct for friction, inertia and offset

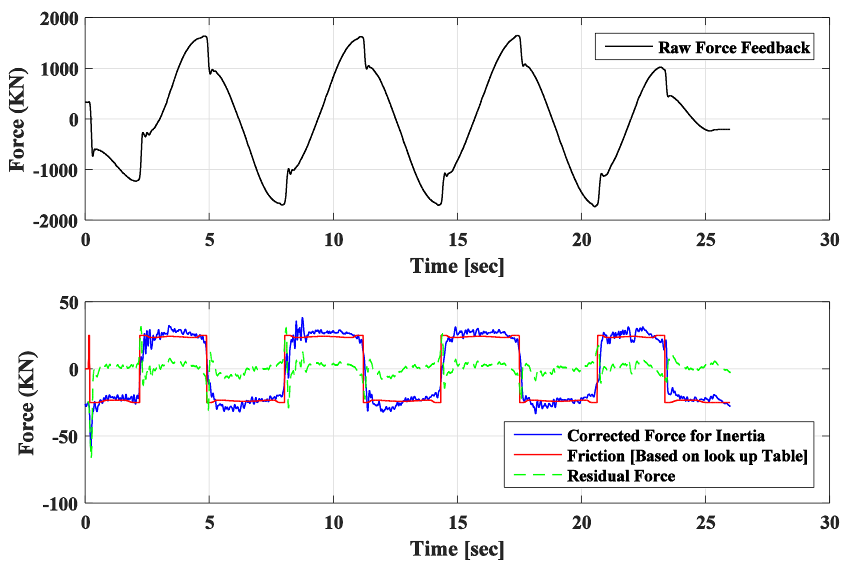

Fig. 8 – Sample correction of feedback forces (longitudinal direction) [top: raw force feedback, bottom: friction forces and residual error between actual and predicted friction]

The inertia forces due to the table platen were corrected for based on the effective mass of the setup consisting of the weight of specimen, test setup, platen, and also moving parts of the actuators, and the estimated accelerations in each direction. In these tests, accelerations were calculated through the predictor-corrector algorithm to obtain a smoother signal, similar to the calculation of velocities for the friction correction. Although the measured acceleration was considered a more accurate source for friction correction, the noise in the feedback signals tended to add additional high frequency content to the corrected feedback forces that could excite the hybrid model. The effective mass of the table changes for different setups to accommodate different specimens, here the effective mass of the platen and bearing was estimated with system identification techniques to be 1228 kN.

Previous studies [7] of the SRMD have identified the dependence of the friction force values on velocity as shown in Fig. 9. Additionally, friction forces have been shown to be dependent on the direction of sliding; indicating different friction values in the longitudinal and lateral directions. Two different assumptions can be made to estimate the friction forces: (a) square root of sums of squares (SRSS) of both (longitudinal and lateral direction) velocities to calculate the peak velocity dependent friction force and then distribute them based on their components, or (b) calculating the corresponding friction force for each horizontal degree of freedom based on its own velocity.

Based on empty table runs, the second approach was found to work better to correct for friction. It was first attempted to calculate velocity directly from the measured table displacements and/or accelerations, but the resulting signal contained significant noise. Signal filtering added additional delays, so the preferred technique was to use the command signal sent to the controller from Simulink. In this case the signals are not guaranteed to be in phase with the actual motion of the table due to variable delays, however, this approach provided better results. Due to noise and delays, the parameters and methods for the friction correction were calibrated based on zeroing out forces measured during empty table runs over the expected range of velocity during the test. The velocity at which to cap the maximum friction force had to be selected because it was not possible to capture the static friction force below a certain threshold. Also, large oscillations in the force feedback were observed, especially at displacement reversals when the velocity changed its sign. Consequently, the friction force was set to zero for values below a lower threshold. During low level excitation when the velocity is oscillating, large changes in the friction force would cause high frequency noise in the measured signals.

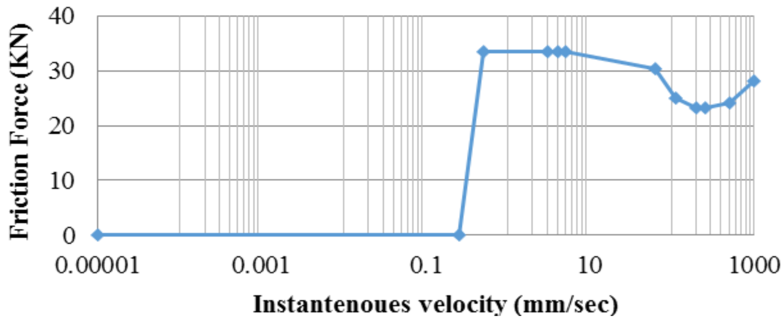

Fig. 9 – Friction force for different instantaneous velocity

Based on a study by Shortreed et. al. [7], there is also another source for friction force in the SRMD that depends on vertical loads. Movement of the platen will involve nine different friction surfaces, eight on the outrigger actuator contact surfaces and one on the four vertical actuators beneath the table platen, see Fig. 10. This vertical load dependent friction force is a function of the direction of motion, outrigger forces, vertical load and lift pressure. Based on the expected vertical load on the bearing during the hybrid simulations, constant single friction values can be calculated for different directions. This friction force could be calculated in each time step and updated values could be used for the correction. However, variations of this portion of the friction force were found to be negligible for most tests.

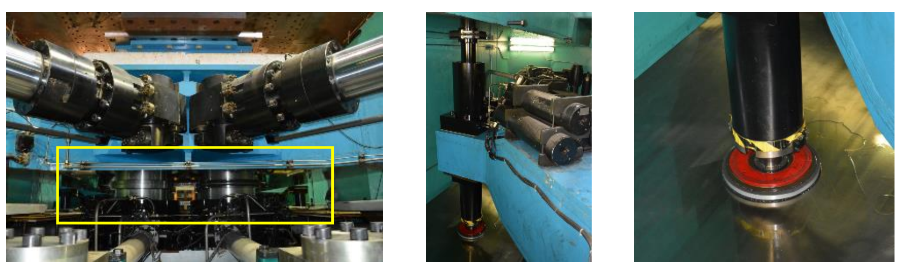

Fig. 10 – Machine contact surfaces: Vertical actuators under platen (left), Top and bottom outriggers (middle), Outrigger sliding surface (right)

5. Hybrid Simulation Test Results

Sample results for a hybrid simulation test conducted on an isolated nuclear power plant under bi-directional ground excitation are summarized in and compared to a pure analytical model in Fig. 11. In this example, one bearing element (lead plug rubber bearing) represented all the bearings beneath the superstructure for both analytical and hybrid simulations. The rate of testing for the experiment was 25 times slower than real time. The analytical model utilized a bearing element based on the Bouc-Wen model [19] with the same parameters that were determined from unidirectional characterization tests. More information and details on the hybrid simulations conducted at the SRMD are reported in Schellenberg et. al [20]. The maximum bidirectional displacement demand from the analytical simulation was 559 mm, which is larger than the 531 mm demand from the hybrid simulation test. While there is a good match of the bearing’s hysteresis in the longitudinal direction, the match in the lateral direction is not satisfactory. Comparing the hysteresis loops in either direction, it is evident that the analytical bearing model again captures the initial stiffness, the initial lead-core yield strength and the post-yield stiffness quite well. For these large shear strains, the analytical bearing model was not able to capture the roundedness of the hysteresis loops, the change of the lead-core yield strength, which occurs as the bearing heats up, or any of the more complicated phenomena, such as the short-term Mullins' effect or long-term scragging effect. A comparison of the floor response spectra demonstrates a decent match between the analytical and hybrid simulation results; see Fig. 11. Note that the analytical simulation consistently overpredicted spectral accelerations around the fundamental frequencies of the different parts of the superstructure.

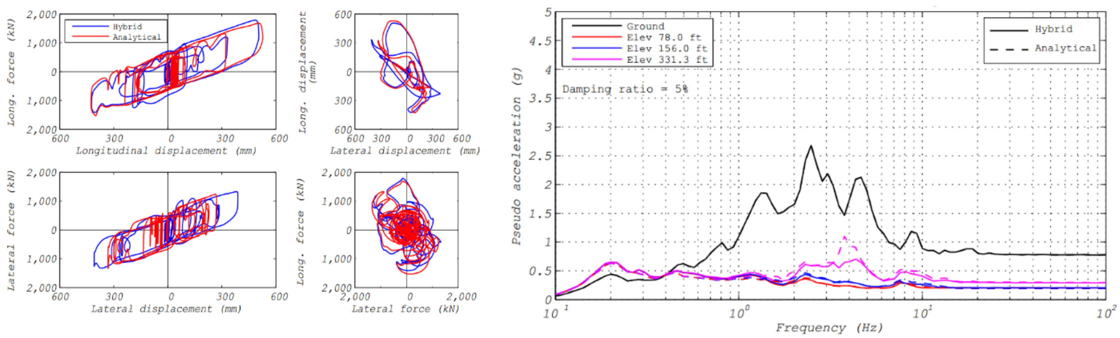

Fig. 11 – Comparison of responses from hybrid and analytical simulations – Test No. 55 (left: hysteresis loops, horizontal orbits, and shear force interaction surfaces, right: response spectra comparison) [20]

6. Concluding Remarks

This research program confirmed that hybrid simulation can be a viable testing method to experimentally assess the seismic behavior of large isolation bearings at full-scale. Through this research project, the SRMD test facility was successfully adapted to perform fast hybrid simulations including large and complex numerical models. Despite the lack of a load cell to directly measure the experimental bearing forces, reliable results were obtained by measuring forces from actuator load cells and correcting for machine friction and inertia forces. It was also demonstrated that a high performance computing platform with parallel processing capabilities (OpenSees*SP*) can be used to perform hybrid simulations of very large structures with many degrees of freedom at rates up to 2.5 times faster. With this testing configuration, it was possible to apply realistic seismic loading on a bearing including the effect of varying axial force due to overturning and vertical excitation in 3D hybrid simulations at near real-time loading rates to assess rate dependent behavior and heating effects. Findings related to the behavior of the isolators revealed that both of the tested bearing types showed substantial vertical-horizontal coupling. While this behavior had negligible effect on bearing displacement demands, it had a significant effect on floor response spectra for the superstructure. It was determined that it is essential to include vertical ground motion input to accurately predict floor response spectra near the vertical frequencies of the superstructure. Floor response spectra show small increases in spectral accelerations due to overturning effects. It is these coupling effects that make hybrid simulation a valuable asset to the seismic isolation engineering community since interactions between the numerical models of the superstructure and isolation system can be evaluated and the implications directly evaluated by in-structure response.

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