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IMPROVE STRUCTURE TESTING WITH VIRTUAL TESTING, HYBRID SIMULATION, AND MODEL ASSISTED TESTING

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Abstract

Structure testing becomes more and more complicated because tests are set up to simulate more and more complicated events, such as earthquake coupled with wind, and earthquake coupled with fire. With complicated loading conditions, structure test becomes more and more challenging and expensive. Researchers are trying to use advanced testing and simulation methods, such as virtual testing, hybrid simulation, and model assisted testing, to achieve accurate test results.

Before physical testing, virtual testing can be conducted to simulate the physical test. Virtual model of the full testing system including controller, actuators, test specimen, and fixtures can be constructed and validated. Virtual testing can provide valuable insight of the real test and play an important role in design evaluation. In this work, a virtual testing system was created and validated to show the virtual testing process.

Hybrid simulation technique is an innovative and powerful approach of analyzing an integrated large-scale structural system under realistic loading conditions. Hybrid simulation combines the lab testing with numerical analysis to explore the benefits of both methodologies. In this study, FEA package Opensees was used to model the numerical part of a building structure. Opensees was connected to MTS test system through a unified framework of OpenFresco. The MTS controller hardware is integrated with target PC using SCRAMNet reflective memory to perform hybrid simulation. The MAST system at University of Minnesota was used as a testing system.

During tests, analysis models can be run in parallel with the test. The purpose of the model is to predict the specimen global dynamic behavior and guide physical tests in real-time. This approach is called model assisted testing. Model Assisted Compensator (MAC) was developed in this principal and was proven to be effective in compensating the cross-coupling effect and achieving accurate control and speeding up the multi-axial fatigue tests.

Virtual testing, hybrid simulation, and model assisted testing are effective ways to evaluate structure design. Through several case study tests, this work demonstrated the processes and effectiveness of virtual testing, hybrid simulation and model assisted testing.

Keywords: virtual testing, hybrid simulation, model assisted testing, reduced order model, Opensees, OpenFresco

INTRODUCTION

Due to the increasingly more sophisticated and complex structural testing that are being conducted worldwide, many of these tests consist of expensive and fragile test specimens, complicated lengthy and thus expensive test setups, and complicated control algorithms and error compensation techniques. It is possible to cause damage to the specimen when a test is not setup correctly. Also, a complicated test can go unstable if control algorithms and error compensation techniques have not been tuned correctly. Therefore, structural tests can be risky if testing commences without previously verifying that all the employed testing components are set up and operating correctly. For this reason, an increasing number of researchers are starting to virtually simulate structural tests prior to their actual execution to make sure that everything will work as expected[1][2]. In addition to mitigating risk, the virtual simulation of a test (virtual testing) can also be utilized to pre-tune control and error compensation parameters, which will lead to increased accuracy and confidence during the actual tests.

Hybrid simulation is a dynamic experimental testing method where a system is divided into numerically simulated and experimentally tested subassemblies. The simulation is then based on a step-by-step numerical integration of the equations of motion; where, for each analysis step, the numerical model calculates command signals, sends them to the experimental test system, and then collects the resulting response from instrumentation devices[3][4][5][6].

Researchers had started to conduct hybrid simulation since 1969. Since then, many hybrid simulation methods and software packages have been developed. Hybrid simulation has become a well-accepted testing method in civil, ground vehicle, wind energy, and other industries.

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Through examples, this work introduces some of the latest advances of virtual testing, hybrid simulation, and model assisted testing approaches that have been developed and used in structural testing.

VIRTUAL TESTING

Virtual testing is a method that simulates lab testing using analysis software. By rehearsing the physical tests, uncertainties can be understood ahead of time, therefore, ensuring physical testing to be conducted successfully. Rehearsing the physical tests has many advantages. It can mitigate risk, pre-tune control (PID) parameters, and validate servo valve sizing, hydraulic flow requirements, supply and return accumulation (how much and where) and test profile[7].

To make the test rehearsal realistic, test specimen, test fixture, hydraulic components, system delay and roll-off, cross-coupling effects, and control and error compensation algorithms need to be modeled in the virtual testing model. There are many methods and software packages that can be used to construct the virtual model. In the example of this work, Matlab/Simulink was used to create virtual testing model.

With loads being applied by actuators, a structural specimen deforms and a dynamic response (displacement, velocity, and acceleration) is being generated. The relationship between the load and the dynamic response can be characterized and mathematical models can be created to mimic the behavior of the test specimen. In addition to the resistance, the energy dissipation and inertia of the specimen can also be modeled. In this way, a virtual specimen is simulated to provide the response for a given command. The virtual specimen can be as simple as a linear-elastic spring or as complicated as a non-linear dynamic finite element model. A sophisticated FEA model can definitely capture the behavior of the specimen accurately. However, a full blown FEA model often requires intensive computation effort. The extra-long solving time can make virtual testing effort impractical. To reduce solving time, a reduced order model method was developed that converts a FEA model into a first order state space model. A state space model can be easily integrated with other dynamical components, such as actuators and controllers, to form a system level of virtual testing model.

State space models are very computational efficient; therefore, it allows real-time execution. Commonly used methods for creating reduced order models include Craig-Bampton method. This method combines motion of boundary points with modes of the structure assuming the boundary points are held fixed. It accounts for both mass and stiffness. The problem size is defined by frequency range. It allows for different boundary conditions at interface.

Reduced order models are typically used in system level of virtual testing to achieve fast computation speed. The main goal for the system level simulation is to obtain global information, such as forces and displacements at important locations. In this sense, reduced order models do not have major negative impact on model accuracy for many of the structural virtual testing applications because many structures are fairly linear. After solving the system level, the global information obtained from the system level model can be applied to much refined FEA models for specific components to obtain local information, such as local stresses and strains.

To construct a virtual testing model, hydraulic components need to be modeled. At MTS, Matlab/Simulink models were created for nearly all of hydraulic components, such as actuators, servo valves, accumulators, and hydraulic pumps, MTS manufactures. The actuators models consider effects of volumetric and compressibility flows, cross-piston leakage flow, parasitic damping, additional trapped oil volume, and seal friction were modeled in these actuator blocks. The servo valve models include effects such as bandwidth limitations and flow gain variation due to pressure switching. The accumulator blocks compute hydraulic supply pressure changes with net flow demand. These hydraulic component models have been validated and proven to be accurate.

The controller models were built using Simulink as well. The virtual controllers model the closed loop control with all parameters and filters in the physical controllers. The controller models were validated by comparing the output signals of the controller models with the same output signals from the physical controllers for same commands.
The hydraulic component and controller models are modularized so that blocks for different types and sizes of the components can be easily assembled together by changing some parameters. Model parameters are the numeric representations of the physical properties of the physical system that are required as input for the virtual testing models. These parameters are both determined from product literature and from direct measurement of the system.

To improve the solving speed, S-Function (user-defined blocks written in C and compiled) blocks were used to model calculation intensive components, such as PID controller and matrix transformation.

To demonstrate the process of virtual testing, the test system shown in Figure 1 was used to conduct both physical and virtual tests. This actual test system consists of a real-time controller, four hydraulic actuators, and a steel plate as a specimen. Closed loop control was accomplished by a real-time controller that computes servo valve command updates based on force sensor feedbacks. A reduced order model of the plate was created based upon an ANSYS model of that plate. The specimen model was integrated with the hydraulic component and the controller models of this system forming a system level virtual testing model.

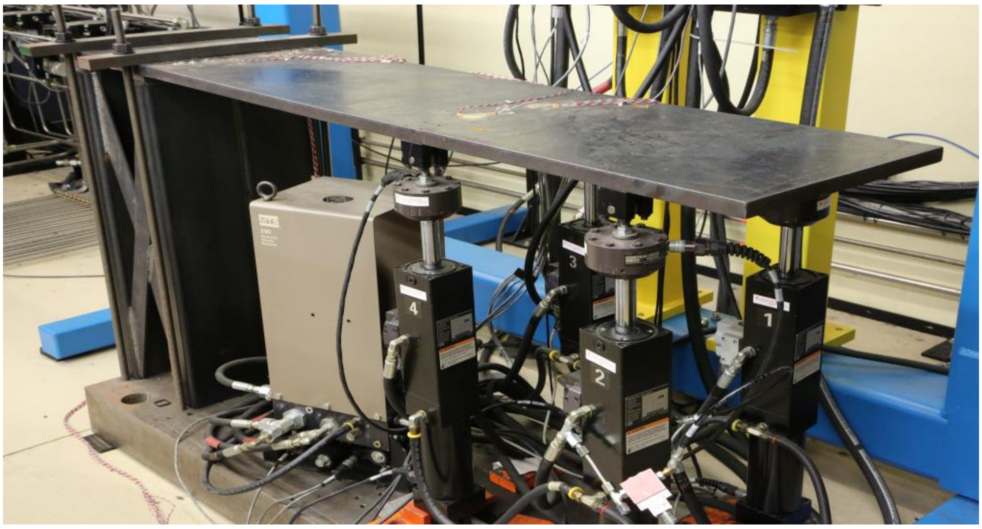

Figure 1: ***Demonstration test system.***

To demonstrate the accuracy of this virtual testing system, some square wave command signals were played out through the virtual and physical testing systems. Response signals, such as actuator forces, actuator displacements, and servo valve output, were collected for comparison purpose. Figure 2 shows the comparison of actuator forces from virtual model and physical measurement when P Gain was set to be 6 for Actuator No. 4. The figure shows that the actuator forces matched very well. Also, both virtual and physical testing results showed stable control. Figure 3 shows the actuator force comparison for P Gain to be 8 for the same actuator. The figure still shows good match between model prediction and actual measurement. More importantly, both virtual prediction and physical measurement showed some degree of instability demonstrating the capability of virtual testing in obtaining tuning parameters of the physical system. Figure 4 shows the zoom in view of the square wave response.

Figure 5 and Figure 6 show actuator displacement and servo valve command comparison between virtual and physical tests. These signals matched very well.

It is worth mentioning that the virtual model was compiled to C++ code and downloaded to a target pc. During test execution, the controller software sent command to both physical controller driving physical actuators and the virtual testing model to conduct virtual testing. The virtual and physical testing were conducted in parallel in real-time demonstrating that the virtual testing model is computationally efficient.

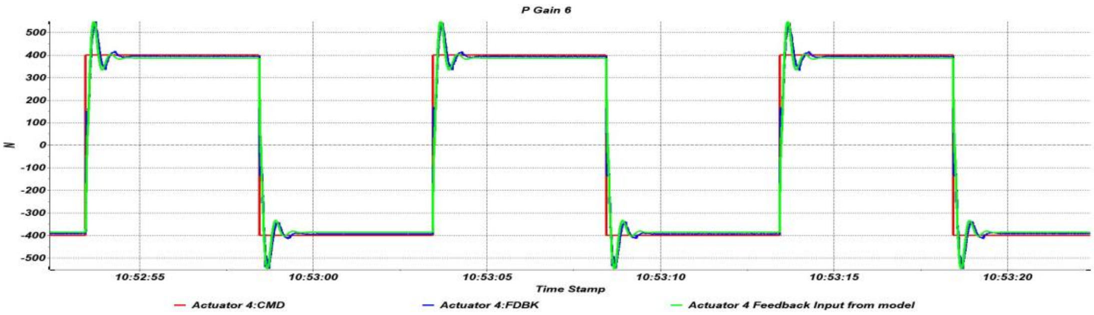

Figure 2: ***Square wave actuator force response for P Gain = 6.***

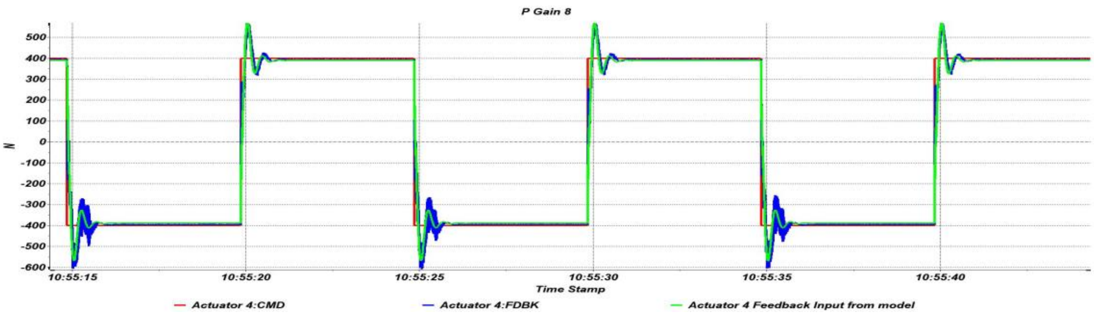

Figure 3: ***Square wave actuator force response for P Gain = 8.***

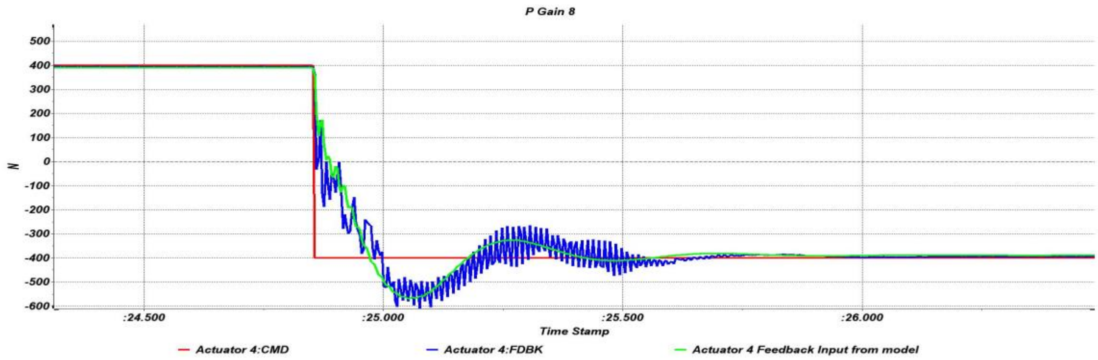

Figure 4: ***Zoom in square wave response for P Gain = 8.***

The virtual testing model, with this level of accuracy and efficiency, can be used to accurately mimic the physical tests. Through test rehearsing, test engineers can optimize the test design, discover potential problems, and determine the tuning parameters before physical tests are conducted.

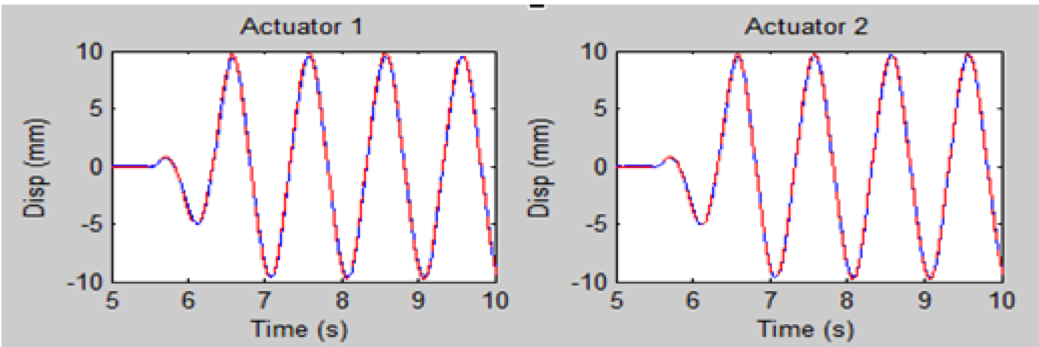

Figure 5: ***Actuator displacement comparison between virtual and physical tests***

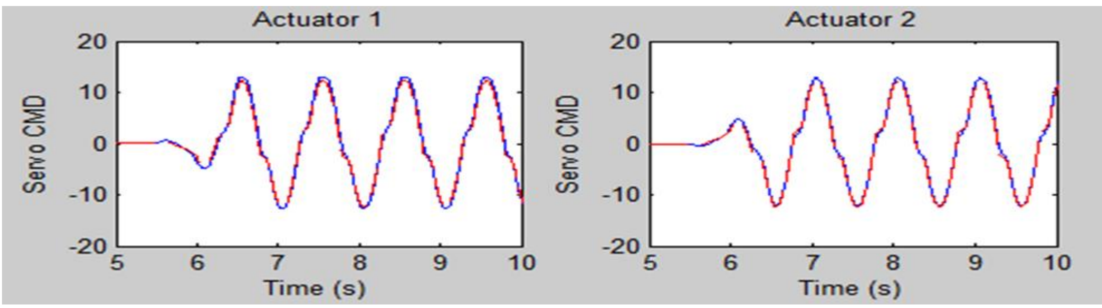

Figure 6: ***Servo valve CMD comparison between virtual and physical tests***

HYBRID SIMULATION

Hybrid simulation is a dynamic experimental testing method where a system is divided into numerically simulated and experimentally tested subassemblies. This method enables the hard to model components to be tested in the lab. As a result, it greatly reduces the requirement for an accurate analysis model and improves the accuracy for the simulation. Hybrid simulation is based on a step-by-step numerical integration of the equations of motion; where, for each analysis step, the numerical model calculates command signals, sends them to the experimental test system, and then collects the resulting response from instrumentation devices.

There are different types of hybrid simulation approaches. Real-time hybrid simulation requires both solving of analytical model and loading of physical structure to be real-time. For fast solving, the analysis model needs to be converted into C++ code and run on a pc with a highly efficient operating system. The connection between the analysis model and the test rig controller is mostly through Scramnet interface. Real-time hybrid simulation is required for studying rate dependent specimens.

Another type of hybrid simulation allows analysis model to be solved at a much slower pace. In this case, the physical test only provides response of a structure due to stiffness change. This approach is widely used in studying rate independent structures. In this approach, different analysis packages, such as Ansys, Abaqus, ADAMS, LS DANA, Matlab, Simulink, and Opensees, can be used for model creation and solving. There are different kinds of interfacing software connecting the analysis model and the controller. OpenFresco is one of them. Developed by UC Berkeley, OpenFresco is an open source software for hybrid simulation deployment [8][9]. It uses a user defined experimental element to send displacement commands from FEA models and receive force feedbacks from test systems. MTS has developed an interfacing software (named CSI) that can receive and send signals from and to OpenFresco and map them to different channels in MTS controllers.

In this work, a slow hybrid simulation work was conducted by using the Multi-Axial Sub-Assemblage Testing (MAST) at University of Minnesota[10]. This system can deliver large forces and strokes at the top of the specimens (i.e. bottom of the crosshead) in 6 spatial degrees of freedom (DOF) at the crosshead. The DOFs are defined in global coordinates as shown in Figure 8. Given the large forces that the vertical actuators can carry, hydraulic bearings are used at both ends of all vertical actuators to reduce friction to a negligible amount.

A "host" computer runs both OpenSees analysis model and OpenFresco is connected to the MAST system through a "target computer." Displacement feedback, force feedback and external signals from the MAST system are shared directly with the "target" computer through the ScramNet interface. The analysis software communicates through OpenFresco to send and receive control signals to the "target" computer, provide new targets, and receive feedback from the MAST 6DOF Controller.

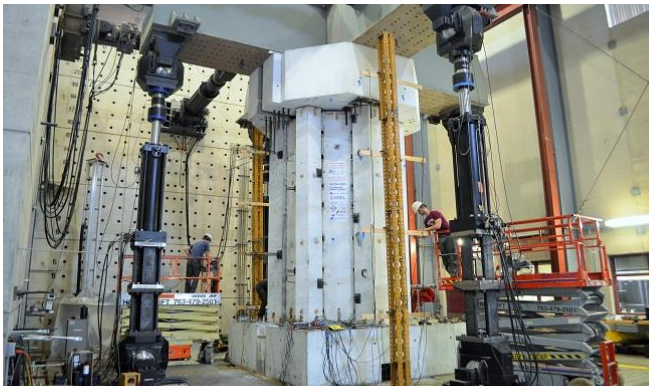

Figure 7: MAST system with a structural specimen

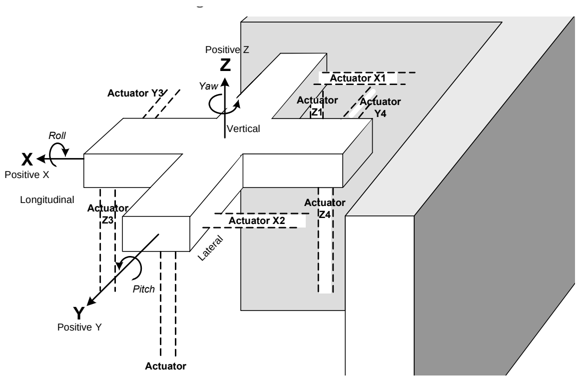

Figure 8: Schematic of the MAST global DOFs

A three-story L-shape steel moment resisting frame structure is used in the hybrid system validation tests. The structural story height is 5.5 m (18 ft) and bay width is 9.5 m (31.2 ft) in both *X* and *Y* directions, with three bays in the *X* (east-west E-W) direction and two bays in the *Y* (north-south N-S) direction. The strong axis of the columns is in the N-S direction. The steel columns are W12×190 ASTM 572 Gr. 50 (345 Mpa) section, the column bases are modelled as fixed at the ground level. The building floor system is comprised of W12x106 steel beams acting compositely with the floor slab. In accordance with common practices, the rigid floor diaphragm assumption is implemented as multi-point constraints in OpenSees at each column beam joint node. The inertia effects are represented as concentrated mass of 25 tons at the column beam joints. The resulting structural natural frequencies and mode shapes are shown in Table 1 and Figure 9, respectively. The Raleigh damping ratio of 5% is assumed for the first two modes.

Table 1: Structural Dynamic Modes

Dynamic Mode no.	**1**	**2**	**3**	**4**
Natural Freq. (Hz)	0.59	0.75	1.88	2.70

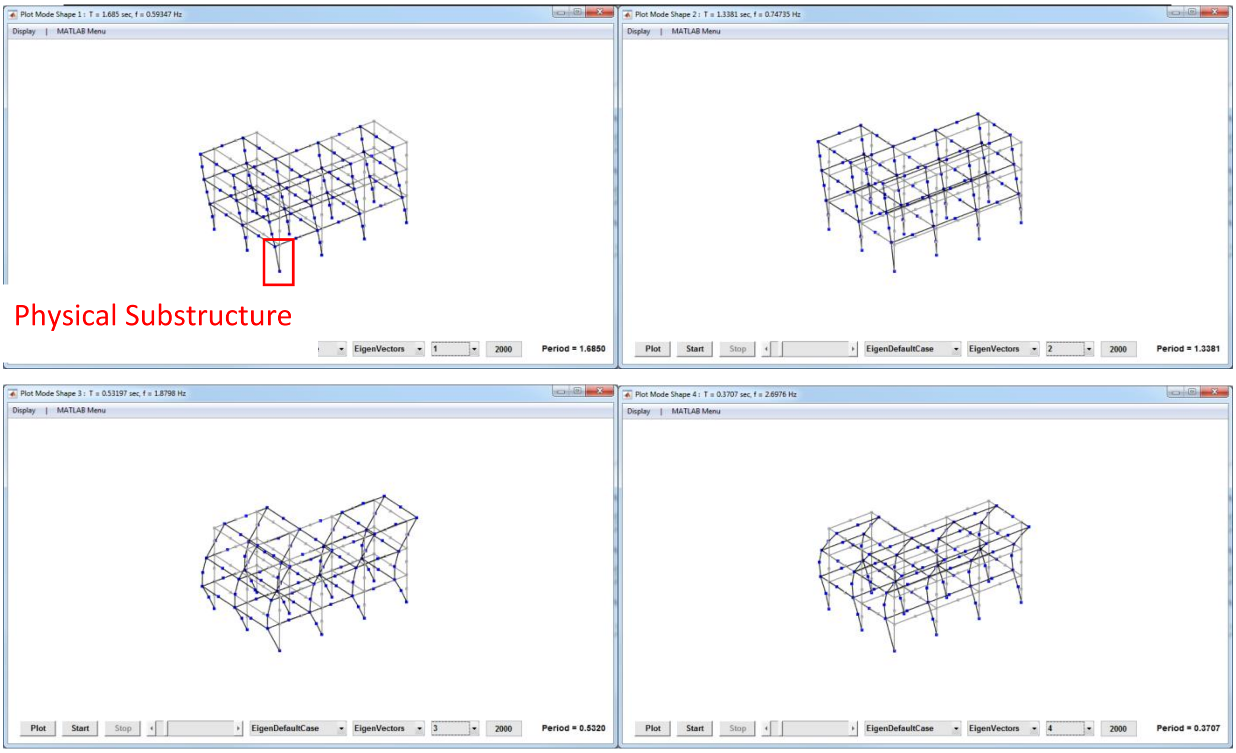

Figure 9: Structural Dynamic Mode Shapes

In the hybrid simulation test cases, the vertical DOF *Z* is controlled by applying constant downward load of 222 kN (50 kips) to simulate the gravitational effect. All other 5 DOFs (*X*, *Y*, *RX*, *RY*, *RZ*) are in displacement control with commands generated from the numerical substructure. The earthquake records used N–S (360) and E-W (090) components recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994. The first test uses 50% Northridge earthquake records in both *X* and *Y* directions. Only the first 15 seconds of the earthquake data (this segment contains all earthquake peaks) is tested in order to shorten the testing time. The AlphaOS generalized integration scheme is selected and the numerical integration time step is 0.01 sec. The comparison of pure FEA (solid lines) and hybrid simulation numerical substructure responses (dashed lines) are presented in Figure 10. The nodal displacements/rotation angles of all DOFs are compared at the interface node (the top of the physical column). Excellent correlations are observed between two sets of results. This test validates the experimental setup is representative of the analysis assumptions, e.g. the initial stiffness of the physical column is very close to the fixed-fixed boundary condition assumed in the FEA. The displacement in the *Z* direction is very small due to low excitation and the high axial stiffness of the column specimen. Therefore, the *Z* DOF controlled in force instead of displacement. In the future, it is desirable to have an accurate force control capability integrated in hybrid simulation framework. The rotational angle *RZ* is small due to the rigid floor diaphragm assumption.

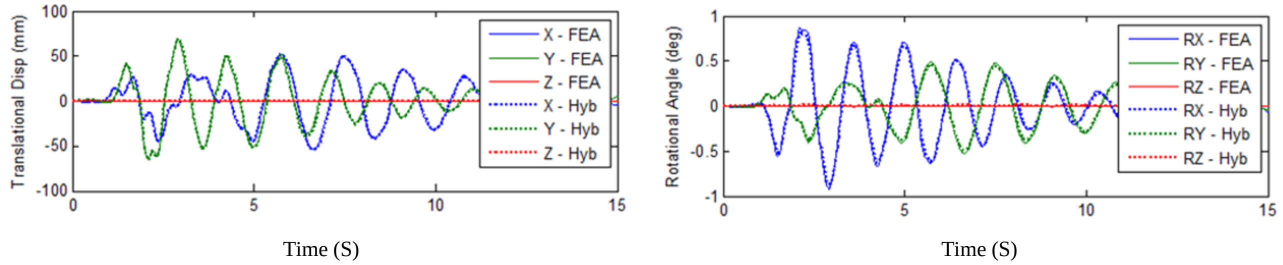

Figure 10: Pure FEA vs Hybrid Sim – 50% Northridge

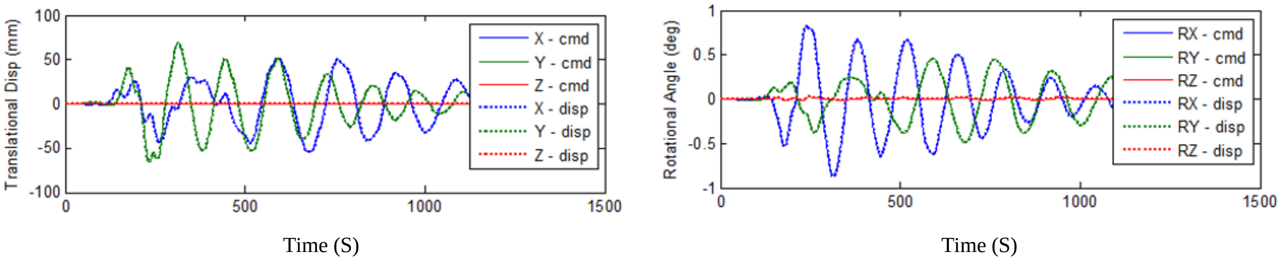

Figure 11: Measured command vs feedback – 50% Northridge

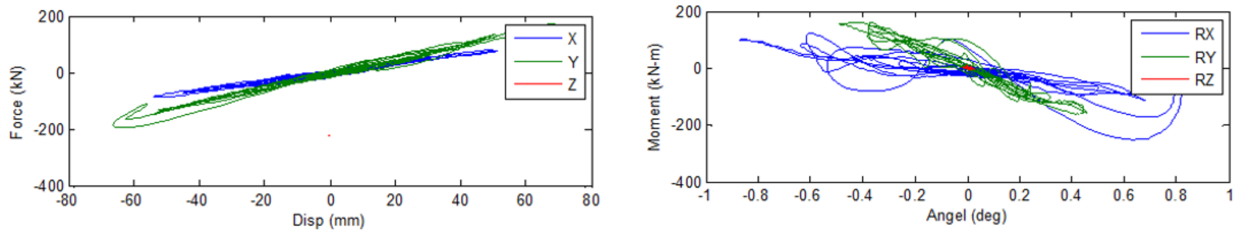

Figure 12: Force vs disp hysteresis – 50% Northridge

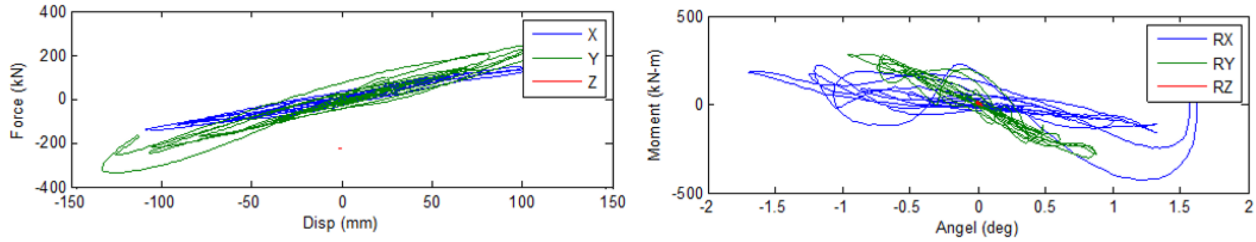

Figure 13: Force vs disp hysteresis – 100% Northridge

Under 50% Northridge, the measurements of commands and feedbacks of all DOFs are presented in Figure 11. The hybrid simulation is slowed down by a factor of 100, which is mostly determined by the maximum loading velocity of the MAST system. For each DOF, the feedback tracks the command very well without local instability or non-smoothness. It demonstrates the MAST is a high-performance system, with small system imperfections including friction and cross-coupling etc. The measured force/moment and displacement/rotation hysteresis relations are presented in Figure 12. The *X* and *Y* responses are mostly linear under the 50% Northridge magnitude. The *RX* and *RY* responses exhibit some hysteresis since they are more sensitive to the system imperfections.

Another hybrid simulation test run was conducted at 100% Northridge in *X* and *Y* directions. The hybrid simulation is slowed down by a factor of 200 in this run. The force and displacement hysteresis is presented in Figure 13, which shows noticeable nonlinear hysteresis in *X* and *Y* DOFs since the column starts to yield under the 100% earthquake magnitude. The strain measurements in Figure 14 show the maximum is about 2500 micro-strain at 1/3 height of the column. It demonstrates the MAST system is quite capable of performing nonlinear tests on full-scale structural components.

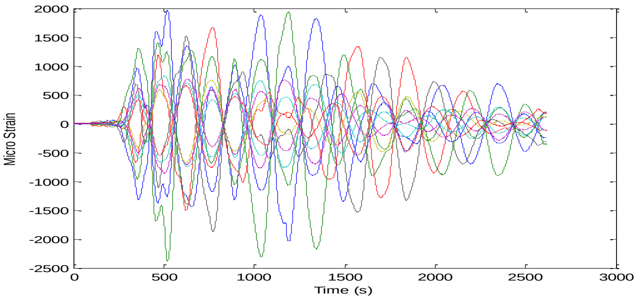

Figure 14: Strain measurements – 100% Northridge

MODEL ASSISTED TESTING

Model assisted testing is an approach that uses an analysis model to guide physical testing during test execution. The analysis model runs in real-time in parallel with the test providing compensation signals.

To test a structure dynamically, usually there are multiple loading actuators involved to reproduce the load distribution. If the structure is fairly rigid, there will be a high level of cross coupling effect among loading actuators causing complicated control problems. As a result, the test has to be slowed down significantly to avoid stability issues. To achieve better control, a reduced order model based cross coupling compensation method, Model Assisted Compensator (MAC), was developed. In this method, the real-time reduced order model of the specimen runs in parallel with the physical test on a target PC. The controller publishes signals onto the shared memory and controls when the model is solved. The reduced order model predicts the cross-coupling effect in term of stiffness at each loading point and provide that information to the controller through Scramnet interface. The control software can then adjust compensation signals for each control channel in order to decouple the cross-coupling effect.

To demonstrate the effectiveness of MAC, test system shown in Figure 1 was used to conduct tests with a sinusoidal and a load profile command. In this test setup, a thick steel plate is loaded with four vertical actuators generating a very high level of cross coupling effect. Without compensation, the test speed must be very slow in order to have adequate control.

Both sinusoidal and realistic fatigue test were conducted using the test system. Figure 15 shows actuator forces command and feedback for the sinusoidal test. At beginning of the test, the MAC was turned on. After a period of time, MAC was turned off one channel at a time. After that, MAC was turned on at the same time for all four channels. Figure 16 shows the zoomed in view of the plot. In a highly coupled system like this if a single actuator is cycled while the other actuators are holding zero then the cross-coupling effect is shown in the feedback for the non-cycling channels not being zero. If the compensator is correct, then the cycling actuator has the command and feedback in phase and the non-cycling channels are tracing zero. It is clear that, after MAC was turned off, the non-cycling channels can no longer hold zero load. Once MAC was turned back on, the feedbacks for all channels track their commands very closely. The figures also show that, by turning on and off MAC, the system did not experience much instability effect. The MAC is also able to keep the feedback close to the command as the single actuator cycling changes frequency. Simple phase compensators need to be adjusted if the amplitude or frequency of the cycle is changed.

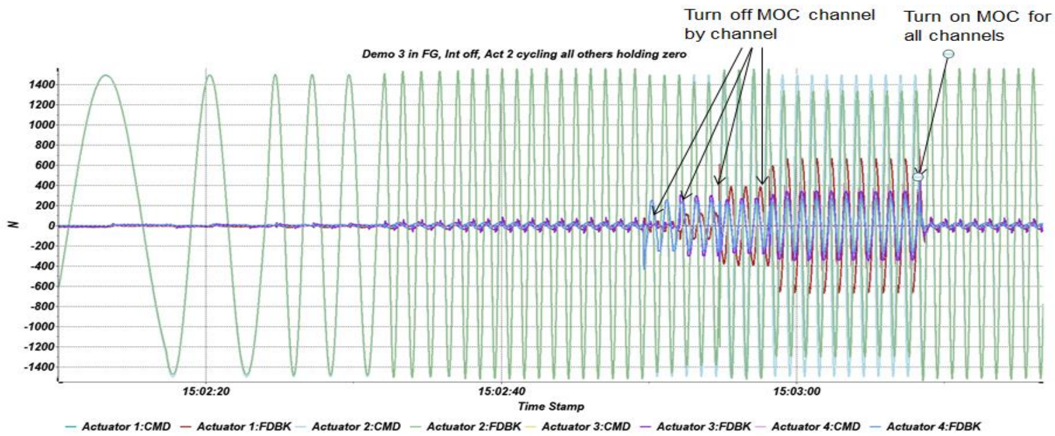

Figure 15: Sine sweep test to validate the effectiveness of MAC

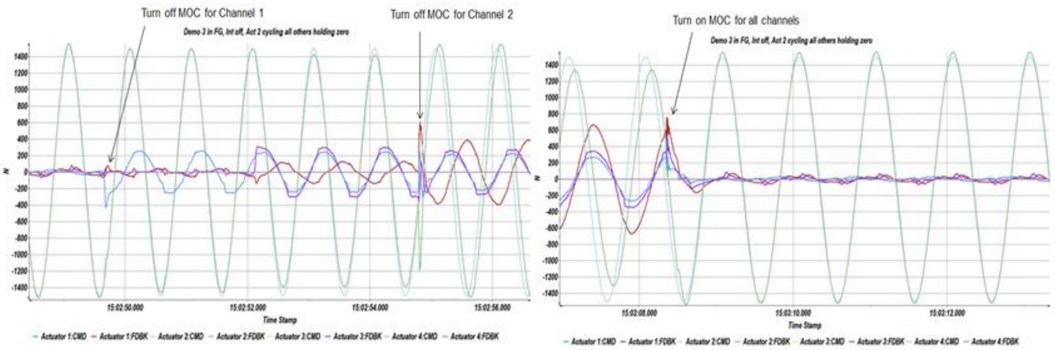

Figure 16: Zoom in picture of the sine sweep test to validate the effectiveness of MAC

Figure 17 shows the result of a load profile test. The profile contains multiple segments with different stiffness modes such as bending, twist, and vertical rigid body motions. In this test, MAC was turned on for all channels. The figure shows that for all four actuators, the feedbacks followed commands very well. Without MAC, this level of accuracy could not be achieved. Accurate test control enabled the test to be conducted in a much faster speed resulting significant time saving for the fatigue test.

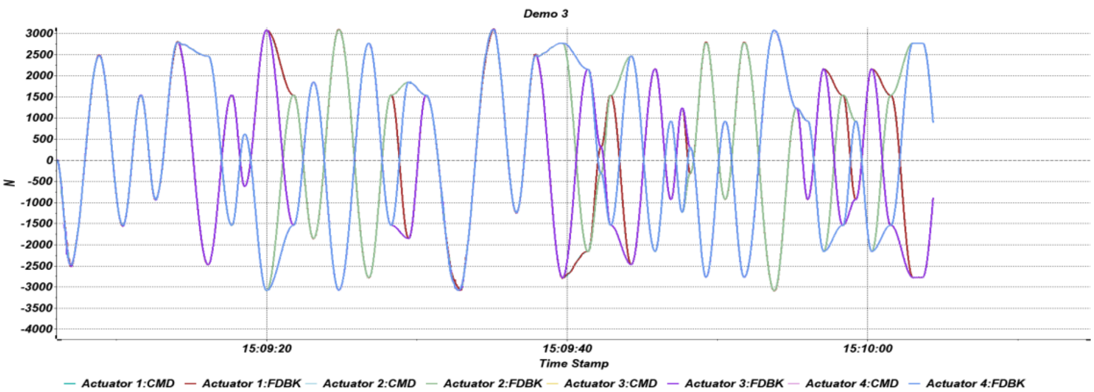

Figure 17: Commands and feedbacks of a realistic fatigue test with MAC

CONCLUSION

It is a clear trend that more and more advanced virtual testing, hybrid simulation, and model assisted testing methods are going to be used in evaluating structure designs. This work demonstrated virtual testing models can be used to accurately predict the performance of physical test systems. Virtual testing systems can be used to setup physical tests, obtain tuning parameters, and rehearse the tests.

Hybrid simulation enables testing only part of the structure and model the rest. As a result, both analysis model and physical testing can potentially be simplified significantly. Since hybrid simulation does not require all components to be tested physically, it can be conducted at a much earlier development stage.

MAC is an effective cross-coupling compensator that can improve accuracy and speed of large-scale structural tests. With better control, the structural tests become safer as well.

ACKNOWLEDGEMENT

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REFERENCES

[1] You, S. and Schellenberg A. (2017). *Test Rehearsal Methods for Quasi-Static and Real-time Hybrid Simulations*.16th World Conference on Earthquake, Santiago Chile.

[2] You S, Fricke D. (2011), *Advances of Virtual Testing and Hybrid Simulation in Automotive Performance and Durability Evaluation*, SAE Paper No. 11M-0297.

[3] Schellenberg A, Huang Y, Mahin SA (2008): *Structural FE-Software Coupling through the Experimental Software Framework, OpenFresco*. Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China.

[4] Schellenberg AH, Mahin SA, Fenves GL (2009): *Advanced Implementation of Hybrid Simulation*. Pacific Earthquake Engineering Research Center, Report No. PEER 2009/104, Berkeley, CA, USA.

[5] Nakashima M, Kato H, Takaoka E (1992): *Development of real-time pseudo-dynamic testing*. Earthquake Engineering and Structural Dynamics, 21, 79–92.

[6] Chen C, Ricles JP, Entwistle J (2009): *Analysis of actuator delay compensation methods for real-time testing*. Engineering Structures, 31, 2643–2655.

[7] Thoen B, Laplace P (2004): *Offline Tuning of Shaking Tables*. 13th World Conference on Earthquake Engineering, Paper No. 960

[8] Schellenberg AH, et al. (2006), *Application of an Experimental Software Framework to Hybrid Simulation of Structures Through Collapse*, First European Conference on Earthquake Engineering and Seismology, Paper Number: 1221, Geneva, Switzerland.

[9] McKenna FT (1997): *Object-oriented finite element programming: frameworks for analysis, algorithms and parallel computing*. Ph.D. Thesis, University of California, Berkeley, CA, USA.

[10] Schultz, A.E. and Bergson, P.M. (2017). *State-of-the-Art Structural Testing for Simulated Earthquake and Wind Loading,* 6th Structural Engineers World Congress, SEWC 2017, Cancún, Mexico, November 14-17.

