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Comparison of Real-Time Hybrid Testing with Shake Table Tests for an MR Damper Controlled Structure

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Abstract — **This paper compares the results of real-time hybrid testing with shake table tests at the University of Connecticut (UConn) to provide validation of a newly constructed real-time hybrid test facility at UConn. The seismic response of a two-story building employing a Magneto-Rheological (MR) fluid damper located between ground and first floor is examined for shake table testing and real-time hybrid simulation. For the shake table tests the two-story building model with Lord Corporation MR Damper (RD-1005-3) is tested on a medium-scale uniaxial seismic simulator located at UConn. In the real-time hybrid test, the building is simulated in a computer while the MR damper is physically tested in hard real-time. The newly constructed real-time hybrid testing facility at UConn provides a means to physically test critical rate dependant components of structural systems in a state-of-the-art hybrid simulation facility.**

I. Introduction

STRUCTURAL control shows great potential for hazard mitigation in civil structures. Within structural control the Magneto-Rheological (MR) fluid damper has been identified as a particularly promising type of control device for hazard mitigation in civil engineering structures (Spencer and Sain, 1997, Dyke, et al, 1996, Yang, 2001). In addition to the controllability, stability (in a bounded-input bounded-output sense), and low power requirements inherent to semiactive devices, MR fluid dampers with their large temperature operating range and relatively small device size have the added benefits of: producing large control forces at low velocities and with very little stiction; possessing a high dynamic range (the ratio between maximum and minimum force); and no moving parts, thus reducing maintenance concerns and increasing response time (compared to conventional variable-orifice dampers).

Real-time hybrid simulation provides the capability to isolate and physically test critical components of a semiactive controlled structure. The tests are conducted in real-time to fully capture any rate dependencies. Real-time hybrid simulation allows for hundreds of repeatable tests to be conducted to examine various control strategies and a range of seismic events in both an efficient and timely manner. In hybrid simulation the experiment is partitioned into simulated and physical components. For experimental verification of semiactive control, the components of interest are the semiactive control devices. As such, the simulated component is the seismically excited building. The physical component consists of semiactive MR fluid dampers.

The University of Connecticut (UConn) Advanced Hazards Mitigation Laboratory has real-time hybrid test capabilities used to experimentally verify MR fluid dampers. To validate the performance of the real-time hybrid test facility, hybrid test results are compared to a fully physical shake table test of the seismically excited MR damper controlled building.

This paper describes the real-time hybrid simulation of an MR damper semiactive control device for seismic protection of a two story build model. The hybrid test results are compared to a purely physical shake table test of the MR damper controlled structure. In the first part of this paper the experimental overview is discussed and next the system identification of the building model is presented. In section IV, the real-time hybrid test facility at the University of Connecticut is introduced and the results from two series of real-time hybrid tests and corresponding shake table tests are presented and compared.

II. Experimental Overview

The experimental overview provides a description of the two-story building model, the controllable MR fluid damper used to produce the control forces, the ground acceleration, and the evaluation criteria use to measure the performance of the MR damper controlled building model and compare the real-time hybrid and shake table tests.

A. Two-story Building Model

The building model considered in this research is a two-story shear frame comprised of four 25.4 mm (1 inch) diameter steel threaded rods for columns and two 0.37 m (24 inches) square by 25.4 mm (1 inch) thick steel plates held in place with nuts and lock washers for the rigid floors. The building model is shown in Figure 1 as mounted on the shake table at the University of Connecticut. The total height of the building is 1.8 m (63 in) with equal story heights of 0.9 m (35 in). The building model is symmetric. When excited uniaxially the torsional and out of plane motion can be ignored. The natural frequencies are obtained from the peaks

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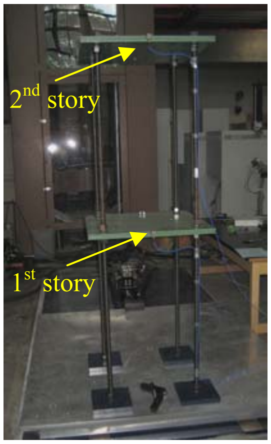

Figure 1. Physical Building Model at the University of Connecticut

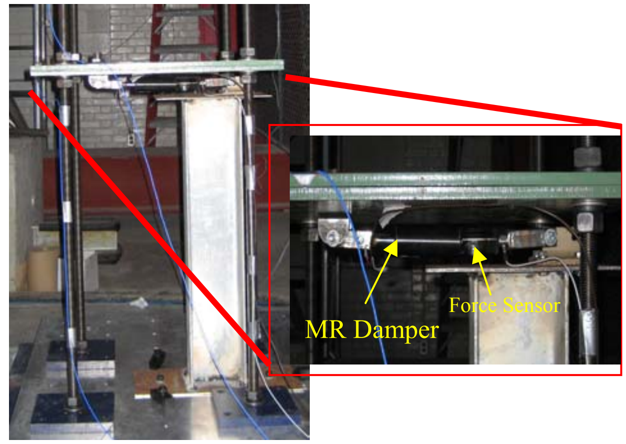

Figure 3. Magneto-Rheological (MR) fluid damper [RD-1005-3]

of the experimentally determined frequency response functions of the uncontrolled building to be 4.41 Hz and 11.75 Hz for the first and second bending modes, respectively. The mode shapes are determined from the experimentally determined magnitude and phase (Craig and Kurdilla, 2006) and are shown in Figure 2 with the corresponding natural frequencies.

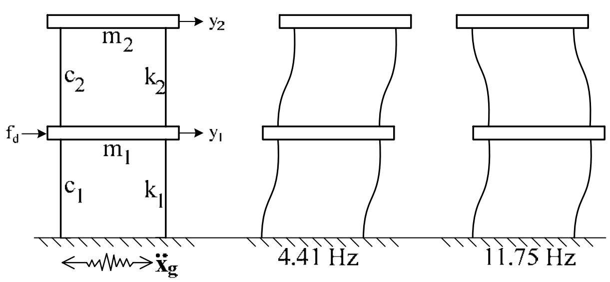

Figure 2. Two-story shear building with associated vibration modes and corresponding frequencies

B. *Magneto-Rheological (MR) Fluid Damper*

An MR fluid damper is placed between the ground and first floor of the building model to provide a control force for the seismic protection of the building frame. The MR damper, shown in Figure 3, is an RD-1005-3 damper manufactured by the Lord Corporation. The damper force is controlled with a 0-1 amp low voltage command signal. The damper current is regulated by an Advanced Motion Controls pulse-width modulated (PWM) current driven amplifier. The amplifier is powered with a 20 volt direct current. The command signal to the amplifier is a 0-5 volt signal generated by a Quanser Consulting Q4 Multi-Q board running WinCon 5.1.10 software. The resulting damper force is measured with a PCB Piezotronics (PCB) force transducer. The maximum force of the RD-1005-3 MR damper is 2.2 kN with a 1 amp current. The available stroke of the MR damper is approximately 60 mm (2.5 in).

C. *Ground Excitation*

The shake table tests described in this paper are conducted on a medium-scale uniaxial seismic simulator. This medium-scale seismic simulator has a 1.52 by 1.52 m (60 in by 60 in) slip table with a $\pm 150\ mm$ (6 in) available stoke. The ground accelerations used for the input of the hybrid tests are the actual measured accelerations of the shake table measured with a PCB accelerometer.

Two ground motions are considered in this paper, obtained by taking the ground acceleration measurements from the Northridge and El Centro earthquakes, integrating twice, removing any bias, to obtain the source displacement time histories. These displacement records are then scaled in amplitude and used as the input command displacement to the shake table. For the El Centro earthquake the N–S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940, is used. For the Northridge earthquake the N–S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994, is used. The measured ground accelerations are shown in Figure 4.

D. *Evaluation Criteria*

The response of the building used to measure the performance of the MR damper is the absolute acceleration at both story levels. The MR damper force is also measured for comparative purposes. For the shake table tests capacitive accelerometers from PCB are placed on the first and second stories of the building model. For the hybrid tests the story acceleration is a simulation output of the building model. Peak responses are used to compare the real-time hybrid to shake table test results.

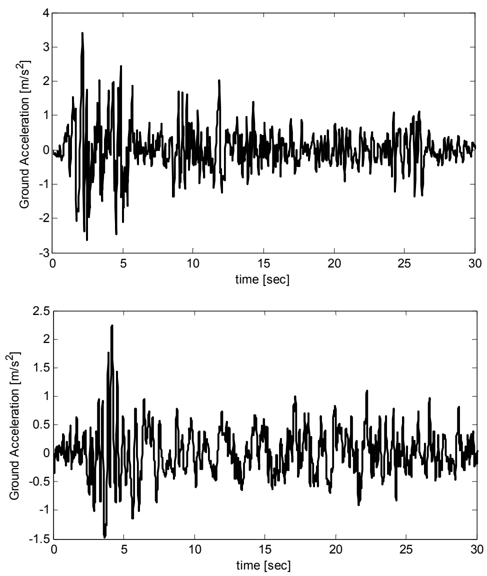

Figure 4. Actual measured ground accelerations of El Centro-like and Northridge-like ground motions.

III. SYSTEM IDENTIFICATION

A multi-input multi-output (MIMO) model of the seismically excited semiactive controlled two-story building is developed that captures the salient characteristics of the physical building model. A schematic of the MIMO system is shown in Figure 5.

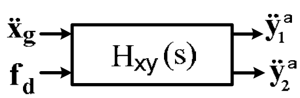

Figure 5. MIMO model of two-story building

A. Multi-Input Multi-Output Frequency Response Functions

The MIMO transfer function matrix H_{XY} is experimentally measured, where $H_{x1y1}(s)$ and $H_{x1y2}(s)$ are transfer functions of the ground acceleration input x1 to the first and second floors absolute acceleration outputs, y1 and y2, respectively, and $H_{x2y1}(s)$ and $H_{x2y2}(s)$ are transfer functions of the damper force input x2 to the first and second floors absolute acceleration outputs y1 and y2, respectively. Hence, subscript X (x1 and x2) is a vector of inputs and Y (y1 and y2) a vector of the outputs. The resulting transfer function matrix is

$$H_{XY}(s) = \begin{bmatrix} H_{x1y1}(s) & H_{x1y2}(s) \\ H_{x2y1}(s) & H_{x2y2}(s) \end{bmatrix}. \quad (1)$$

The ground acceleration input signal to shake table, x1, and the current input signal to MR damper (which varies the damper force x2) are uncorrelated band-limited white noises.

The transfer function matrix is determined experimentally using spectral density functions, where G_{XY} and G_{XX} are the matrices of the one-sided cross-spectral density functions and the autospectral density functions of the system such that

$$H_{XY}(s) = G_{XX}(s)^{-1} G_{XY}(s) \quad (2)$$

where, $G_{XX}(s)^{-1}$ is the inverse matrix of $G_{XX}(s)$, and

$$G_{XY}(s) = \begin{bmatrix} G_{x1y1}(s) & G_{x1y2}(s) \\ G_{x2y1}(s) & G_{x2y2}(s) \end{bmatrix} \quad (3)$$

$$G_{XX}(s) = \begin{bmatrix} G_{x1x1}(s) & G_{x1x2}(s) \\ G_{x2x1}(s) & G_{x2x2}(s) \end{bmatrix}. \quad (4)$$

The spectral density functions themselves are defined using finite Fourier transforms where, for example,

$$G_{yy}(f) = 2 \lim_{T\to\infty} \frac{1}{T} E\left[\left|Y(f,T)\right|^2\right] \quad (5)$$

where Y is the finite Fourier transform of the measured output.

The data acquisition system is a SignalCalc 730 Dynamic Signal Analyzer and SignalStar Vector Vibration controller manufactured by Data Physics Corporation. Data is collected at 1000 Hz (a sample time of 0.001 sec).

The experimentally determined transfer functions, as determined from Eq. (2), are shown in Figures 6 and 7.

B. Curve Fitting and Model Reduction

The experimentally determined transfer functions are curve-fit to determine the appropriate input-output mappings. Equations (6)-(9) show the transfer function numerator and denominator polynomials determined from this curve-fitting.

$$H_{x1y1}(s) = \frac{5\times10^{-4}s^2 + 5.6\times10^{-3}s + 1}{1.5\times10^{-3}s^2 + 1.2\times10^{-3}s + 1} \quad (6)$$

$$H_{x1y2}(s) = \frac{9.5\times10^{-3}s + 1}{1.5\times10^{-3}s^2 + 1.2\times10^{-3}s + 1} \quad (7)$$

$$H_{x2y1}(s) = \frac{1.03\times10^{-2}s^2}{5\times10^{-4}s^4 + 9\times10^{-4}s^3 + 3s^2 + 2.4s + 2000} \quad (8)$$

$$H_{x2y2}(s) = \frac{1\times10^{-4}s^3 + 2.08\times10^{-2}s^2}{9\times10^{-4}s^4 + 1.5\times10^{-3}s^3 + 5.7s^2 + 4.5s + 3800} \quad (9)$$

Each transfer function element is converted into canonical state space representation. The state matrices are then stacked such that

$$\begin{bmatrix} \dot{x}_{g1} \\ \dot{x}_{d1} \\ \dot{x}_{g2} \\ \dot{x}_{d2} \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 & 0 \\ 0 & A_{21} & 0 & 0 \\ 0 & 0 & A_{12} & 0 \\ 0 & 0 & 0 & A_{22} \end{bmatrix} \begin{bmatrix} x_{g1} \\ x_{d1} \\ x_{g2} \\ x_{d2} \end{bmatrix} + \begin{bmatrix} B_{11} & 0 \\ 0 & B_{21} \\ B_{12} & 0 \\ 0 & B_{22} \end{bmatrix} \begin{bmatrix} \ddot{x}_g \\ f_d \end{bmatrix} \quad (10)$$

and

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{21} & 0 & 0 \\ 0 & 0 & C_{12} & C_{22} \end{bmatrix} \begin{bmatrix} x_{g1} \\ x_{d1} \\ x_{g2} \\ x_{d2} \end{bmatrix} + \begin{bmatrix} D_{11} & D_{21} \\ D_{12} & D_{22} \end{bmatrix} \begin{bmatrix} \ddot{x}_g \\ f_d \end{bmatrix} \quad (11)$$

The system is balanced using a Gramian-based balancing technique. Small entries in the vector of Hankel singular values indicate states that can be removed to simplify the original global state space representation (MATLAB functions *balreal* and *modred*). The order of the original global state space system is 16 states and the resulting reduced order model has 10 states. The reduced order model can be written, in state space form as

$$\dot{x} = \bar{A}x + \bar{B}u \tag{11}$$

$$y = \bar{C}x + \bar{D}u \tag{12}$$

The comparison between experimentally determined frequency response functions and the reduced order model of the structure are shown in Figures 6 and 7. As observed in these figures the reduced model matches very closely the experimental data over the frequency range of interest, namely 0-20 Hz. Therefore, the analytical model is considered a good representation, from a frequency domain perspective, of the physical building model. A comparison in the time domain, not presented here, confirms the accuracy of the reduced order model.

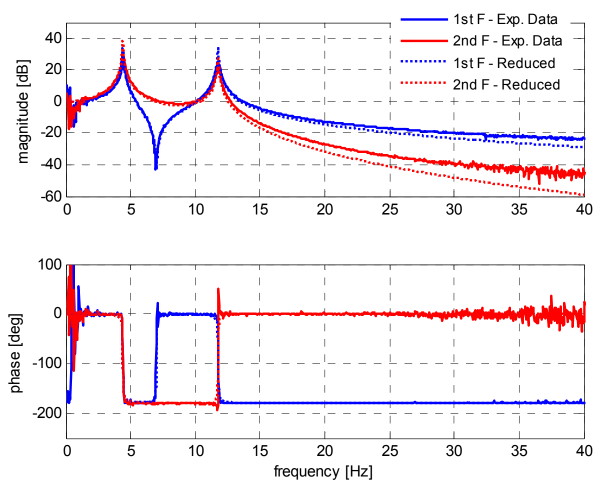

Figure 6. Experimental Data vs. Reduced Model of ground motion input

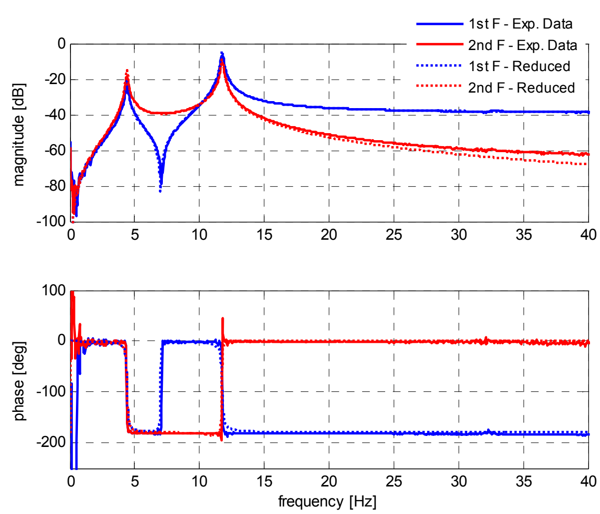

Figure 7. Experimental Data vs. Reduced Model of damper force input

IV. Real-Time Hybrid Test System

Real-time hybrid simulation, also called real-time dynamic substructuring or real-time pseudodynamic testing, is a relatively new method of testing made more feasible by the recent advances in computing power, digital signal processing, and hydraulic control. This section describes the laboratory equipment used in the real-time hybrid test system and discusses the stability of the hybrid system in the presence of actuator dynamics.

A. Test Equipment

The real-time hybrid simulation facilities at the University of Connecticut include a servo-hydraulic actuator and corresponding motion controller and PC with Quanser Consulting Q4 data acquisition board running WinCon in hard-real time with Ardence's RTXa, as shown in Figure 8. This section describes the equipment used for real-time hybrid simulation.

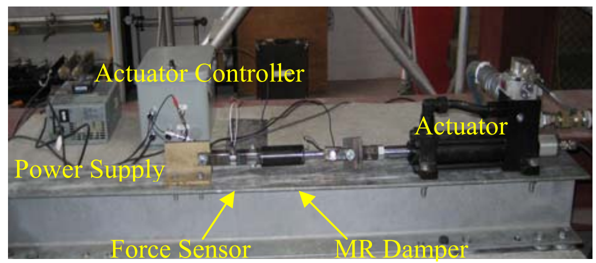

Figure 8 Real-time hybrid test equipment at UConn

The servo-hydrautic actuator, shown in Figure 8, can provide maximum speed up to 760 mm/s and 9 kN force with a bandwidth up to 30 Hz. The actuator is a Quincy Ortman Cylinder with 190 mm stroke and MOOG servovalve.

The motion controller is manufactured by Parker Hannifin Corporation (Model 23-7030). The displacement feedback is provided by a Micropulse linear position transducer.

The hybrid algorithm controller is developed using Simulink and executed in hard real time using WinCon. The MultiQ I/O board has 13-bit analog/digital (A/D) and 12-bit digital/analog (D/A) converters with four input and four output analog channels. The Simulink code is converted to C code using the Real Time Workshop in Matlab and interfaced through the WinCon software to run the real-time hybrid simulation on the CPU of the PC.

B. Hybrid Stability

A control systems approach, as opposed to a numerical analysis approach, is taken in the implementation of the hybrid testing algorithm. Siva showed the equivalence of these two approaches (Siva, 2006). The real-time hybrid test algorithm is implemented in Matlab's Simulink using the hardware/software identified previously. A fixed-step Runge-Kutta numerical integration scheme is employed with a fixed step size of 1 msec (0.001 sec).

Stability is a main concern in real-time hybrid simulation. The dynamic interaction of the hydraulic actuator and physical component contains a velocity feedback of the hydraulic supply that can significantly affect the performance of the actuator system (Dyke et al., 1995). For highly nonlinear systems such as the MR fluid damper this dynamic interaction, while present, is difficult to characterize. The effects of the dynamic interaction and the actuator dynamics is often manifested in steady state or unstable high frequency oscillations (Kyrychko et al., 2006). A number of researchers have examined the effect of an apparent time delay on real-time hybrid simulation. The time delay adds energy into the whole simulation resulting in system instabilities and potential unstable behavior (Colgate, et al., 1995). Horiuchi et al. (1999) first equated the effect of actuator time delay in a physical sense to that of adding negative damping into the simulation.

The apparent time delay of the hybrid test actuator system, resulting from the actuator dynamics, was determined experimentally by measuring the frequency response function of the output displacement of the actuator to a white noise input command displacement. The experimentally determined frequency response function is shown in Figure 9. The estimated time delay, as shown in the figure, is 18 msec.

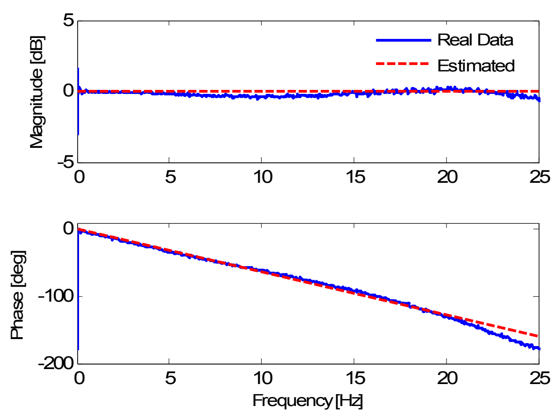

Figure 9. The Transfer Function of the Servo-Hydraulic Actuator

An approach to improve system stability in the presence of a time delay is to introduce a virtual coupling between the physical and numerical components (Colgate et al. 1995; Adams and Hannaford, 1998, 1999; Zilles and Salisbury 1995; and Ruspini et al., 1997). One realization of virtual coupling for the stability of the fast hybrid simulation with inherent time delay is to place a virtual spring in parallel with a virtual damper, as shown in Figure 10, where k_c and c_c are stiffness and damping of the virtual coupling network, where H(s) is the transfer function of the two-degree-of-freedom system for damper force input, x2, and C(s) is the virtual coupling controller.

This approach, like many of the compensation methods, is independent of a particular integration scheme and experimental system. For the hybrid test system in this paper the values for virtual stiffness and damping are set to 70,000 N/m and 4,456 N-sec/m, respectively.

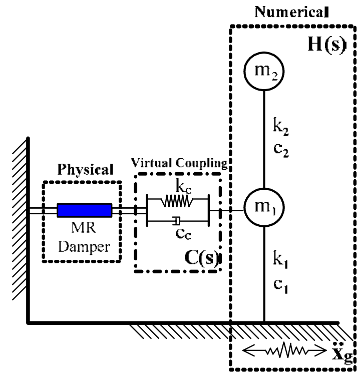

Figure 10. Hybrid Testing System with Virtual Coupling

V. Experimental Results

The results of the real-time hybrid simulation are compared to the results of the shake table (experimental) test. For these tests the MR damper is operated with a constant current of 0 amps. The first and second story accelerations are shown in Figures 11 and 12. Figure 11 shows the comparison for the 1940 El Centro-like earthquake. Figure 12 shows the response comparison for the 1994 Northridge-like earthquake.

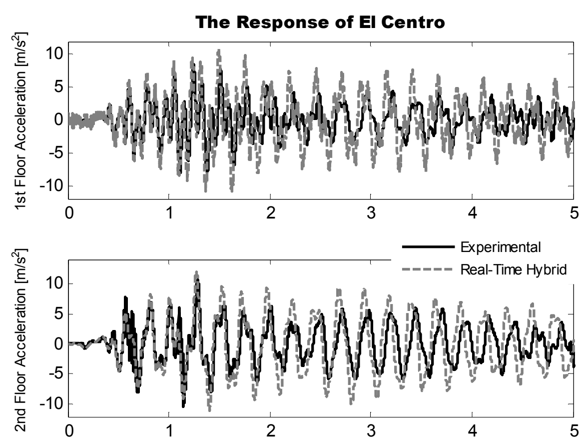

Figure 11. Simulation vs. Experimental Data of El Centro

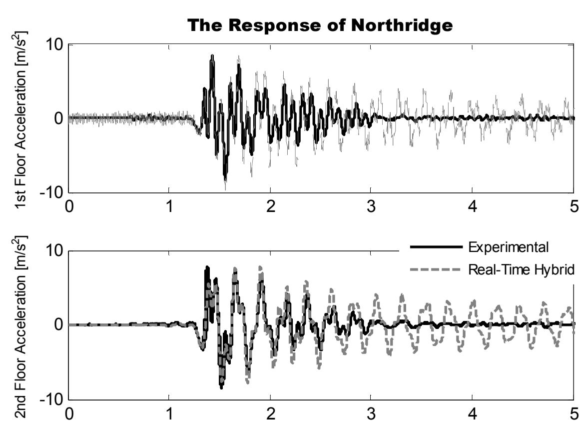

Figure 12. Simulation vs. Experimental Data of Northridge

For the 1940 El Centro-like earthquake, the peak story acceleration is reduced from 13.9 m/sec^2 for the uncontrolled building (shake table) to 10.6 m/ sec^2 and 11.9 m/ sec^2 for the controlled building in shake table and hybrid tests, respectively.

For the 1994 Northridge-like earthquake, the peak story acceleration is reduced from 9.97 m/ sec^2 for the uncontrolled building (shake table) to 8.46 m/ sec^2 and 7.83 m/ sec^2 for the controlled building in shake table and hybrid tests, respectively.

While the general behavior of the shake table and real-time hybrid tests are similar, there is clearly a difference between the hybrid tests and shake table tests. This is likely due to two factors. First, the difference between the analytical building model used in the hybrid tests and the actual building model used in the shake table test will certainly cause a difference between the results of the two test procedures. Second, there is an inherent variability in the in the MR damper which can result in difference responses in subsequent tests. In addition to these factors, the real-time hybrid tests, while stable in a bounded-input bounded-output sense do exhibit higher frequency oscillations associated with the actuator dynamics instability encountered in hybrid testing. These oscillations contribute to the discrepancy in real-time hybrid and shake table tests.

VI. CONCLUSION

A two-story building employing a MR fluid damper located between the ground and first floor is examined for a shake table test and a real-time hybrid simulation. System identification of the building resulted in an analytical model of the building that is able to accurately capture the dynamic qualities of the two-input, two-output seismically excited building with damper system. A newly constructed small-scale real-time hybrid testing facility at the University of Connecticut is described. Story acceleration and MR damper force responses are presented for both shake table and hybrid tests for the building/damper system subjected to two different ground motions. The results show a close correlation between the shake table tests and the real-time hybrid simulation.

Future research will focus on a more complete comparison of these two test methodologies and more extensive quantification of the error in each test method. Real-time hybrid testing is shown in these initial results to achieve similar testing results to a fully physical shake table test.

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