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Real-Time Hybrid Testing of a Semi-Actively Controlled Structure with an MR Damper

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Abstract—**Real-time hybrid testing is an attractive method to evaluate the response of structures under earthquake loads. The method is a variation of the pseudodynamic testing technique in which the experiment is executed in real time, thus allowing investigation of structural systems with rate-dependent components. Real-time hybrid testing is challenging because it requires performance of all calculations, application of displacements, and acquisition of measured forces, within a very small increment of time. Furthermore, unless appropriate compensation for actuator dynamics is implemented, stability problems are likely to occur during the experiment. This paper presents an approach for real-time hybrid testing in which compensation for actuator dynamics is implemented using a model-based feedforward-feedback compensator. The method is used to evaluate the response of a semi-active control of a structure employing an MR damper. Experimental results show good agreement with the predicted responses, demonstrating the effectiveness of the method to test rate-dependent and semi-active components.**

Keywords: Real-time hybrid testing, MR damper, Semi-active control

I. INTRODUCTION

Experimental testing is an essential tool for understanding how structures respond to extreme events, thus allowing the design and construction of safer structures to mitigate natural hazards. Methods currently used to determine the behavior of structural systems subjected to dynamic loading are quasi-static, shaking-table, and hybrid (or pseudodynamic) testing. Hybrid testing provides an attractive alternative for dynamic testing of structural systems, combining physical testing with numerical simulation.

Real-time hybrid testing is a variation of the hybrid testing technique in which the imposed displacements and response analysis are executed in real time. Real-time hybrid testing thus facilitates the testing of structural components associated with vibration control, including passive, semi-active, and active control devices (e.g., base isolation and dampers), which are typically nonlinear and rate-dependent. More details as to the basis and development of real-time hybrid testing can be found in Carrion and Spencer [1].

This paper presents an approach for real-time hybrid testing which implements model-based feedforward-feedback compensation for actuator dynamics (Carrion and Spencer [1]). The proposed method is used to conduct real-time hybrid tests of a semi-actively controlled structure using a magnetorheological damper (MR damper). This experiment demonstrates the effectiveness of the proposed real-time hybrid testing algorithm to test structures with semi-active components. Furthermore, testing of the MR damper demonstrates the effectiveness of the proposed approach to test specimens with complex nonlinear hysteretic response that are often encountered in building structures.

II. REAL-TIME HYBRID TESTING

Displacements in hybrid testing are generally imposed on the structure using hydraulic actuators. When displacements are applied at fast rates, the dynamics of the actuator and attached specimen become important. Dyke et al. [2] analyzed the effects of control-structure-interaction (CSI) and showed that the dynamics of the actuator and structure are intrinsically coupled through a natural velocity feedback link. This work demonstrated that neglecting phase differences between the command input and the resulting force (i.e., neglecting the CSI) resulted in an apparent time delay associated in the literature with generation of the control forces. In structural testing, this effect is not significant when displacements are applied at low rates. However, when performing fast and real-time hybrid tests, this dynamic coupling and the finite response time of the hydraulic actuators become particularly important, resulting in a *time lag* between the commanded displacement and the realization of this command by the actuator. There are also some inevitable *time delays* associated with the numerical calculations and the communication between the computer and data acquisition systems.

As a result of these delays/lags, the force measured and fed back from the experiment does not correspond to the commanded displacement (it is measured before the actuator has reached its target position), however the algorithm assumes that the measured force corresponds to the commanded displacement. For a linear-elastic system, the resulting response, as seen by the algorithm, is a counter-

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clockwise hysteretic loop, instead of a straight line corresponding to linear behavior. The effect of this counter-clockwise loop is to introduce additional energy into the simulation. Horiuchi et al. [3] demonstrated that for a linear-elastic SDOF system, the increase in the total system energy caused by the delay/lag is equivalent to introducing negative damping into the system (given by $c_{eq} = -k\tau_d$, where k is the stiffness of the system, and τ_d is the delay/lag). This artificial negative damping becomes large when either the stiffness of the system or the time delay/lag is large. When this negative damping is larger than the structural damping, the response will diverge (become unstable). Instability almost invariably occurs in practice due to the low levels of damping associated with structural frames and the large time delays/lags associated with large hydraulic actuators (Darby et al. [4]). Therefore, introduction of compensation for time delays/lags is essential when conducting fast hybrid experiments.

The effects of the delays and actuator time lag have been traditionally treated together by determining a total delay which includes all these effects. However, because the actuator time lag varies with frequency, this approximation is valid only over the frequency range used for the approximation. If the conditions change significantly during the test (e.g., natural frequency of the test structure due to changes in specimen stiffness), this method is not very satisfactory because the system can become unstable (Blakeborough et al. [5]). Additionally, when the response of the test structure includes significant contributions at different frequencies (e.g., multi-degree-of-freedom-systems), approximating the actuator time lag with a single time delay may not yield satisfactory results.

Actuator time lags can be several times larger than the typical time-step used for seismic testing. Typical values reported in the literature range from 8 to 30 msec (Horiuchi et al. [6]; Darby et al. [4]; Shing et al. [7]; Nakashima and Masaoka [8]), which are significantly larger than the pure time delays (e.g., communication delays). Therefore compensation techniques that account directly for the characteristics of actuator dynamics are necessary.

III. EXPERIMENTAL SETUP

A testing system that combines fast hardware for high-speed computations and communication with dynamically-rated hydraulic components is used to conduct real-time hybrid experiments. A schematic of the testing system is provided in Fig. 1. This equipment is located at the Smart Structures Technology Laboratory (SSTL) at the University of Illinois at Urbana-Champaign (*http://sstl.cee.uiuc.edu*).

Displacement is imposed using a double-ended hydraulic actuator manufactured by Nopak with a stroke of ±152 mm (6 in) and effective piston area of 633 mm^2 (0.98 in^2). A Schenck-Pegasus 132A two-stage servo-valve rated for 10 gpm at 1,000 psi pressure drop is used. The actuator is controlled by a Schenck-Pegasus 5910 digital servo-hydraulic controller in displacement feedback mode. The displacement of the actuator is measured using a Lucas-Schaevitz 10,000 DC-EC linear variable differential transformer (LVDT) having a range of ± 254 mm (10 in). An Omega load cell with a range of ± 4,540 N (1.0 Kip) is used to measure the applied force. A computer with a dSPACE DS1003 parallel processing DSP board is used to solve the equations of motion and provide real time control.

A. *MR Damper Test Specimen*

The use of MR dampers as supplemental damping devices for reducing the response of civil engineering structures under severe earthquakes and winds is becoming increasingly accepted (Spencer and Nagarajaiah [9]). MR dampers can be used as semiactive control devices, offering the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems. Some of

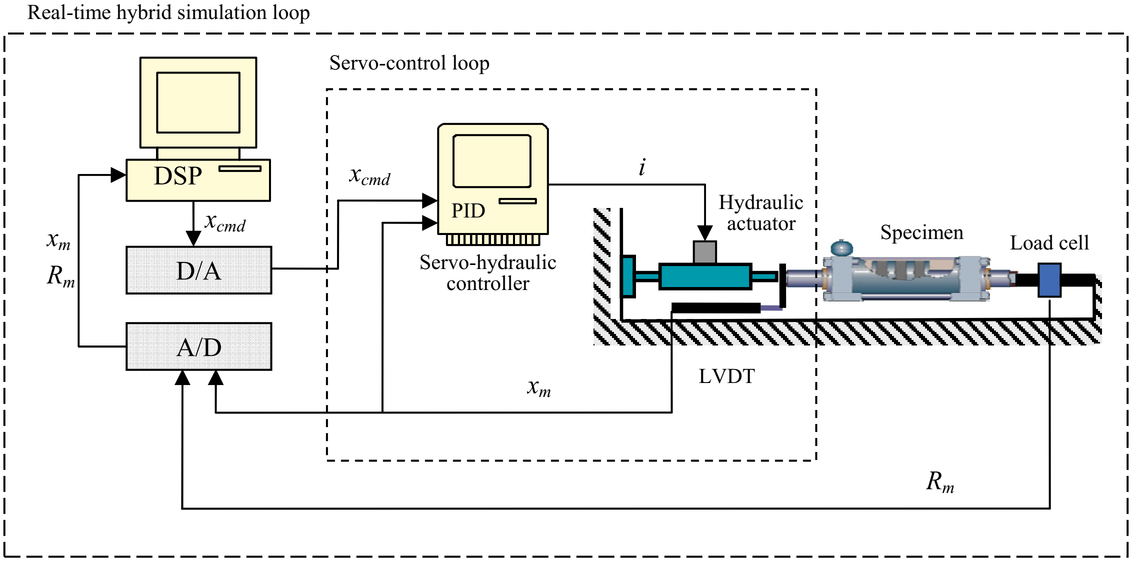

Fig. 1. Schematic of system for real-time hybrid testing (x_m = measured displacement, R_m = measured force, x_{cmd} = command displacement, and i = command to actuator)

the attractive features of MR dampers include: very low power requirements (allowing operation under battery power), the ability to provide a readily controllable damping force, large achievable force capacity, and low sensitivity to temperature changes (Spencer et al. [10]).

A small scale MR damper is used as a test specimen. The damper is a RD-1005 MR fluid damper manufactured by Lord Corporation. The damper has a stroke of ± 25.4 mm (1.0 in) and can generate forces up to about 3,000 N (0.67 kip). The damper has a precharge resulting in an initial force which is removed from all force measurements. By selecting the input current, the characteristics of the damper may be changed in real-time to vary the forces exerted by the damper. The response of the damper to a 0.4 in (10.16 mm) sinusoidal displacement excitation with a frequency of 1.273 Hz is shown in Fig. 2. Two cases are presented: without input current and with maximum current applied to the damper. As observed the response of the damper is velocity-dependent and nonlinear, and the magnitude of the force generated by the damper increases significantly with the input current (i.e., magnetic field).

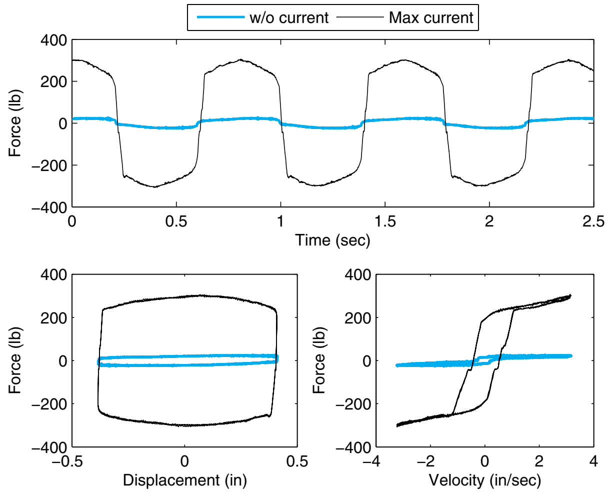

Fig. 2. Response of MR damper to sinusoidal command displacement

B. *System Characterization*

The dynamics of the actuator and the resulting time-lag of the actuator are critical parameters in real-time hybrid testing. To understand the behavior of the system over a wide range of frequencies, the transfer function from the commanded displacement to the measured displacement was determined using a random excitation as input. The excitation signal was a bandlimited white noise with a bandwidth of 50 Hz and an RMS of 0.01 in. Fig. 3 shows the frequency response of the actuator for the two extreme cases of input voltage to the MR damper; minimum input voltage ($v = V_0$) and maximum input voltage ($v = V_{max}$), which correspond to the cases of no current and maximum current to the MR damper, respectively. As can be observed, the dynamic response of the actuator is different for both cases. When the MR damper specimen is subjected to voltage changes, its properties change significantly, and because of actuator-specimen interaction, the dynamics of the actuator are also affected.

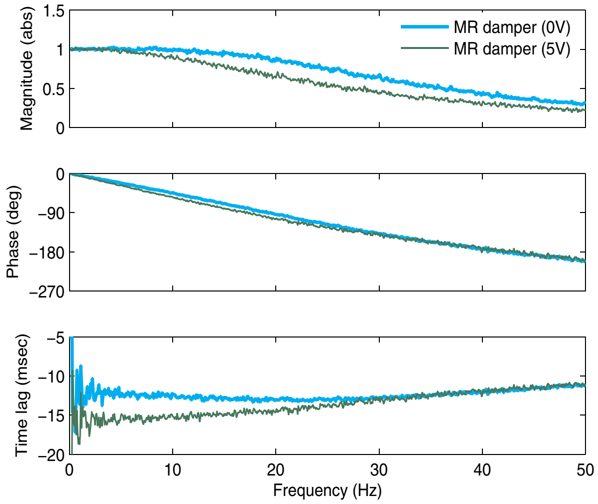

Fig. 3. Actuator dynamics for different MR damper excitations

Both magnitude and phase lag (and therefore time lag) are not constant but vary with frequency. Because time lag varies with frequency, traditional compensation techniques based on the time delay approximation become difficult to implement for structures that present significant responses at different frequencies, like for example multi-degree-of-freedom-systems. Additionally, the actuator transfer function is dependent on the specimen that is attached to the actuator (i.e., actuator-specimen interaction). Consequently the dynamics of the actuator may vary during the experiment because of changes in the properties of the test specimen (e.g., stiffness). Therefore, when the characteristics of the specimen change significantly and frequently (e.g., semi-actively controlled MR dampers), traditional delay-compensation methods may not perform adequately.

IV. MODEL-BASED FEEDFORWARD-FEEDBACK COMPENSATION

The dynamics of the actuator and testing system can be accurately approximated by the actuator transfer function $G_{xu}(s)$, from the commanded displacement to the measured displacement. This transfer function includes the effects of the actuator, servovalve, servo-controller, and test specimen. The proposed approach is to add an outer controller or outer-loop that performs the compensation for actuator dynamics, while the control performed by the actuator servo-controller is treated as an internal or inner loop.

Fig. 4 shows a schematic block diagram of the configuration for the additional compensation for actuator dynamics, where d is the desired displacement (or reference signal), u is the command to the actuator servo-controller generated by the outer controller, and x is the measured displacement actually imposed by the actuator. For the outer controller performing the compensation for actuator dynamics, the plant or system to be compensated is the closed-loop system represented by the actuator transfer

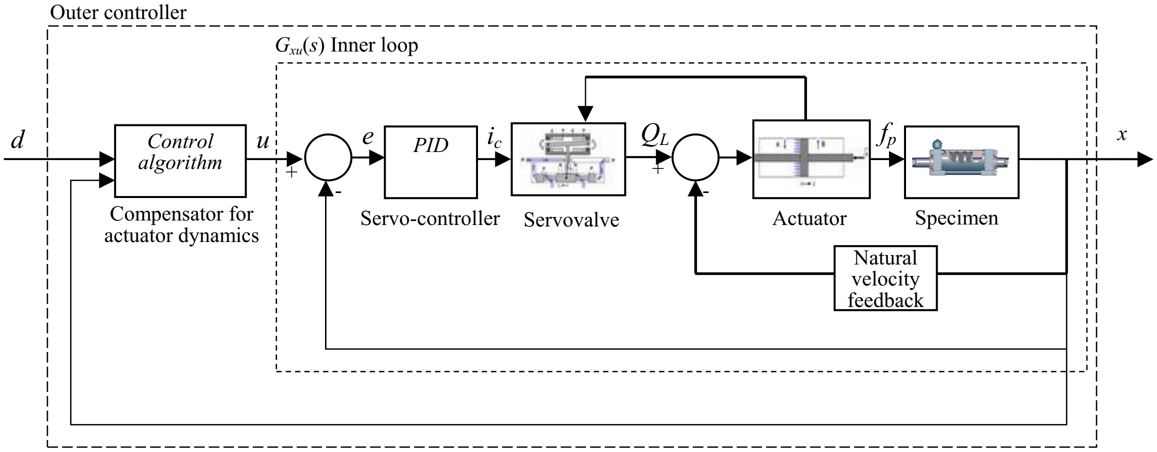

Fig. 4. Schematic block diagram of compensation for actuator dynamics

function $G_{xu}(s)$. The main objective of the additional control is to make the measured displacement x as close as possible to the desired displacement d, minimizing phase lag and amplitude changes, i.e., providing accurate tracking of the reference signal.

The compensator for actuator dynamics includes both, feedforward and feedback terms. By using knowledge of the plant, the feedforward control improves the system's speed of response while the feedback control reduces the effect of inaccuracies in the modeling or identification of the plant on the controller performance. The total control command is obtained by adding the two individual control signals from the feedforward and feedback controllers.

The feedforward controller is realized using an inverse of the plant dynamics in series with a low-pass filter, with appropriate dynamics to make the controller stable. More discussion on the derivation of the feedforward controller can be found in Carrion and Spencer [1]. For the feedback term, a proportional gain is used.

A. Actuator Dynamics for MR Damper with Variable Input Voltage

When the MR damper specimen is subjected to voltage changes, its properties change significantly, and because of actuator-specimen interaction, the dynamics of actuator are also affected (see Fig. 3). Because the feedforward part of the compensator for actuator dynamics is based on a model of the plant, it is important to account these plant variations also in the controller.

Models of actuator dynamics for the cases of zero and maximum input voltage (V_0 and V_{max}, respectively) to the MR damper were developed independently. The characteristics of the transfer function (i.e., number of zeros and poles) were determined based on theoretical models of actuator dynamics (Carrion and Spencer [1]). Then, using the experimentally measured frequency response data, rational polynomial transfer function models of the system dynamics were identified.

These models were then combined using a smooth or bumpless transition. The resulting algorithm for actuator dynamics, in addition to provide a smooth transition between the two states V_0 and V_{max}, also provides a representation of the system dynamics for intermediate values of the input voltage v.

This model of actuator dynamics was then used in the feedforward term of the combined controller to include effects of changes on the plant dynamics due to variations of the properties of the MR damper, based on the commanded voltage to the damper.

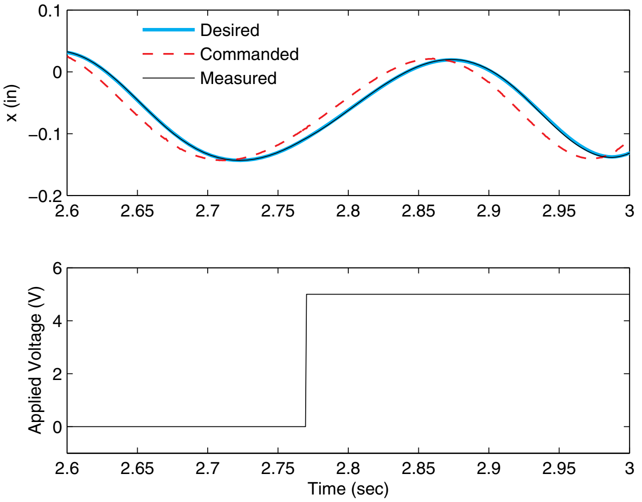

Fig. 5. Test results of feedforward controller for bandlimited white noise reference signal and variable input voltage to MR damper (close-up view)

B. Experimental Verification

The compensator for actuator dynamics was verified experimentally using the MR damper specimen subjected to changes on the applied voltage. The reference or desired displacement was a bandlimited white noise with a bandwidth of 5 Hz and an RMS of 0.11 in (2.85 mm). Simultaneously a square voltage signal having 0.5 Hz frequency and changing from 0 to 5 V was applied to the MR damper. Fig. 5 shows the results from the experiment during a time interval where there is a change on the voltage applied to the damper. As can be observed, the measured displacement matches very well the desired displacement, demonstrating the good performance of the compensation.

V. REAL-TIME HYBRID TESTING OF SEMI-ACTIVELY CONTROLLED STRUCTURE

Real-time hybrid testing is used to evaluate the response of a semi-actively controlled structure that incorporates an MR damper. The test structure considered is a full-scale version of the structure used by Dyke et al. [11]-[12]. This structure is a three-story steel building which has an MR damper installed between the ground and the first floor. The building is assumed equipped with a number of sensors to provide feedback for the control algorithm. These measurements include the absolute acceleration at each of the three floors, the displacement of the damper, and the force applied by the damper to the structure (i.e., control force).

The semi-active controller is assumed to be adequate to keep the response of the structure in the linear range; therefore the dynamic response of the semi-actively controlled structure is given by the equation of motion

$$\mathbf{M}_s\ddot{\mathbf{x}} + \mathbf{C}_s\dot{\mathbf{x}} + \mathbf{K}_s\mathbf{x} = G_s f - \mathbf{M}_s L_s \ddot{x}_g \qquad (1)$$

where $\mathbf{M}_\mathrm{s}$, $\mathbf{C}_\mathrm{s}$, and $\mathbf{K}_\mathrm{s}$ are the mass, linear damping, and stiffness matrices of the structure, respectively; $\mathbf{G}_\mathrm{s}$ and $\mathbf{L}_\mathrm{s}$ are the influence vectors for the MR-damper force and structural mass, respectively; $\mathbf{x}$ the displacement vector; $\ddot{x}_g$ is the ground acceleration; and f is the measured damper force. The dots denote differentiation with respect to time. The numerical values of the structural parameters were obtained using the parameters of the small-scale model and scaling factors reported by Dyke et al. [11] and can be found in Carrion and Spencer [1].

The natural frequencies of the structure corresponding to the first, second, and third mode are 1.09 Hz, 3.17 Hz, and 4.74 Hz, respectively, with corresponding damping ratios of 0.31%, 0.62%, 0.63%.

Semi-active control is implemented using the clipped-optimal control algorithm based on acceleration feedback proposed by Dyke et al. [11]. In the clipped-optimal controller, the approach is to append a force feedback loop to induce the MR damper to produce approximately a desired control force f_c. Fig. 6 shows a block diagram of the clipped-optimal semi-active control system. The attractive feature of this control strategy is that the feedback for the controller is based on acceleration measurements, which are readily available, therefore making the controller implementable for full-scale applications.

A. Real-Time Hybrid Experiment

Real-time hybrid testing is used to experimentally verify the response of the semi-actively controlled building. The structure is divided into two substructures: the MR damper is tested experimentally (physical substructure) while the rest of the structure is modeled numerically (numerical substructure).

The structure was subjected to the NS component of the 1940 El Centro earthquake with an amplitude scale factor of 0.8. Compensation for actuator dynamics was performed using the model-based approach presented previously. The feedback gain of the combined compensator was set to zero, i.e., providing feedforward compensation only. Hardware limitations prevented the full implementation of feedfoward-feedback compensation with the MR damper specimen, which will be resolved in future studies. The model of the structure, structural control algorithms, and compensation for actuator dynamics were implemented in SIMULINK using continuous time systems. Numerical integration was performed using the fourth-order Runge-Kutta solver of SIMULINK. Because the MR damper is small-scale, a length scale factor S_L = 7.25 and force scale factor S_F = 60 were used during the real-time hybrid experiments to relate the response of this component to the rest of the structure.

During the real-time hybrid experiments, all the states (displacements, and velocities at every degree-of-freedom)

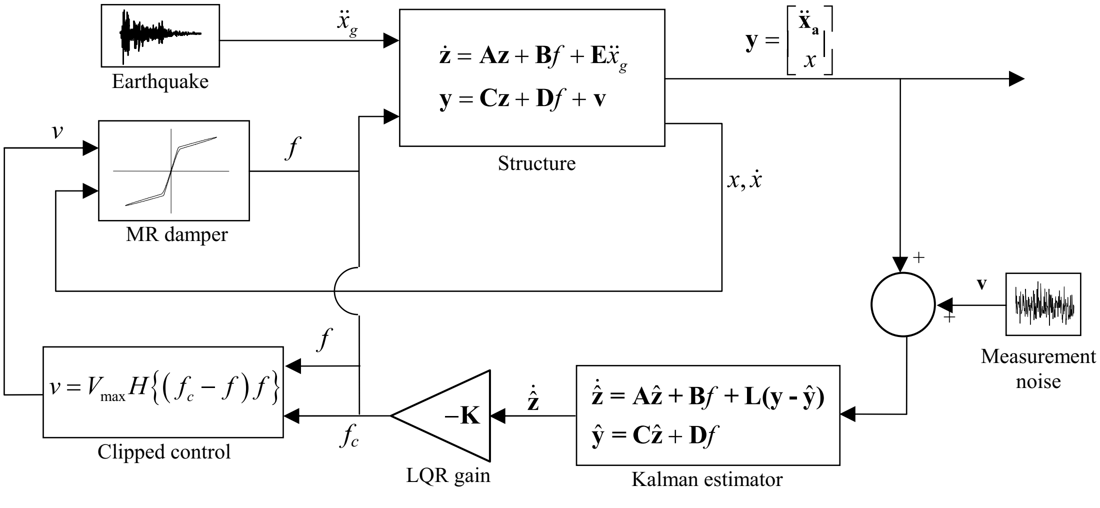

Fig. 6. Block diagram of semi-active control system

and all the accelerations are available for feedback to the LQG controller (since they can be calculated numerically at each time step). However, using all these parameters as available measurements is not realistic for an actual implementation. Therefore only the absolute accelerations, damper force, and damper displacement were used as feedback to the controller during the real-time hybrid experiment. The remaining states of the system required by the structural control algorithm were estimated using the Kalman filter.

Four different cases of structural control were considered: (1) *uncontrolled structure*: structure without MR damper, (2) *passive-OFF* case: MR damper used as a passive device with zero input voltage, (3) *passive-ON* case: MR damper used as a passive device with constant maximum input voltage (i.e., 5 V), and (4) *controlled* case: voltage to MR damper varies during the experiment as determined by the clipped-optimal control algorithm.

The response of the structure without the MR damper (uncontrolled case), was determined analytically using numerical integration. For the other three cases, which use the MR damper (passive-OFF, passive-ON, and clipped-optimal control), the response of the structure was determined from real-time hybrid experiments. Because the significant responses occur during the initial portion of the earthquake, only the first 20 sec of the response were determined during the experiments. For each case, the response of the building was also determined numerically using a Bouc-Wen model of the MR damper (Carrion and Spencer [1]).

Initially, real-time hybrid experiments were conducted for the two passive cases (passive-OFF and passive-ON), to verify the testing strategy. Results from the real-time hybrid experiments as well as the analytically predicted responses are presented in Figs. 7 and 8 for the physical MR damper substructure.

As can be observed, there is very good agreement between the experimental and analytical results. Some small discrepancies are assumed caused by differences between the model used for the MR damper and the actual specimen.

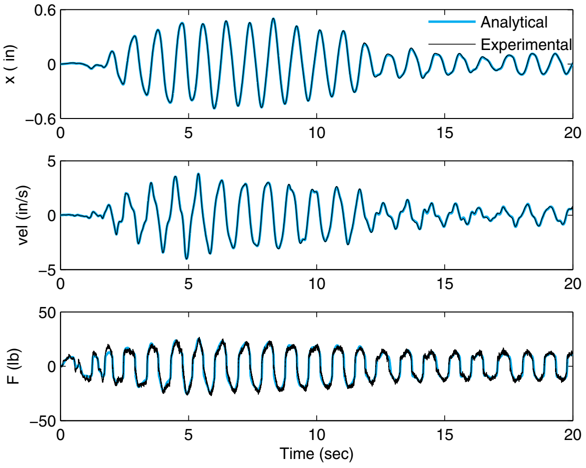

Fig. 7. Results from real-time hybrid experiment for Passive-OFF case

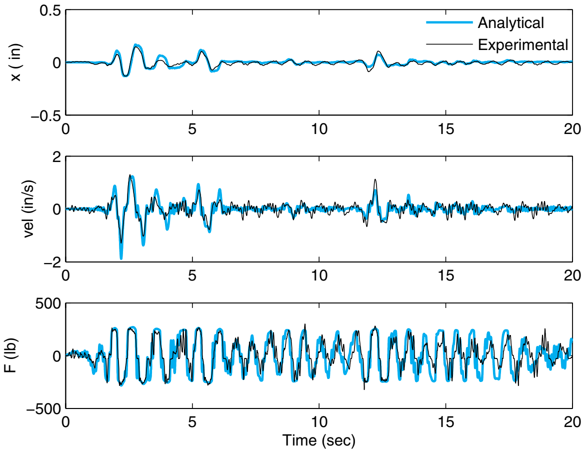

Fig. 8. Results from real-time hybrid experiment for Passive-ON case

Real-time hybrid testing for the clipped-optimal semi-active control case was conducted next. Fig. 9 shows a comparison of the time-histories from the experiment and predicted by the model. As can be observed, although there are some small differences on the force and input voltage to the MR damper, the experimental response is in good agreement with the analytically predicted response, demonstrating the accuracy of real-time hybrid testing and the compensation technique.

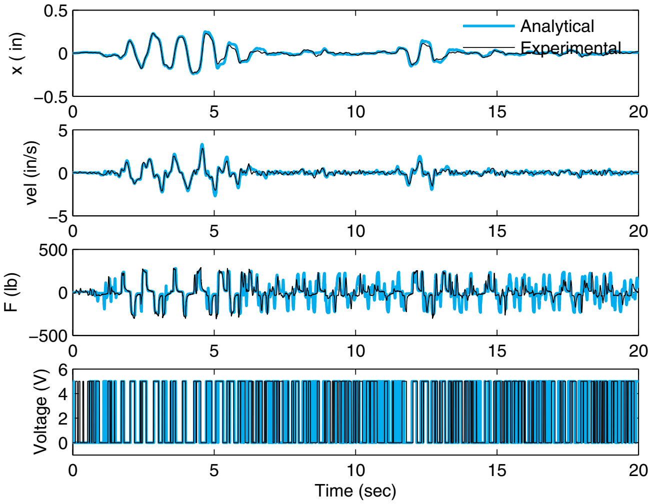

Fig. 9. Results from real-time hybrid experiment for Clipped-Optimal case

The model-based compensator for actuator dynamics performed very well during the real-time hybrid experiments for both cases, constant and variable input voltage to the MR damper. The effect of actuator dynamics on real-time hybrid experiments (i.e., the introduction of an equivalent negative damping) is more severe on systems with low structural damping than in systems with high damping. When the natural frequencies of the test structure are small or the forces generated from the test specimen are small compared to the forces from the numerical substructure, the effect of actuator dynamics is in general also small. However, when the forces from the test specimen are relatively large, the effects of actuator dynamics become significant even for high damping devices. Fig. 10 shows the results from the real-time hybrid test for the passive-ON case conducted without using actuator dynamics compensation. As can be seen the results without compensation are poor (with significant oscillatory behavior) and very different from those using compensation. These results demonstrate that accurate actuator dynamics compensation is necessary even when testing systems with high damping.

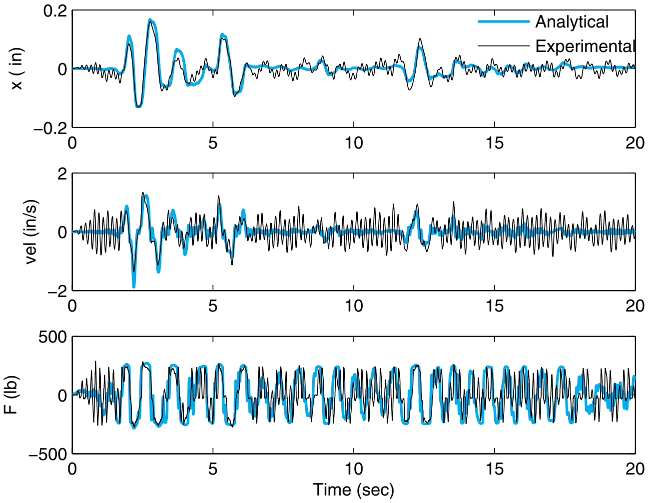

Fig. 10. Results from real-time hybrid experiment without actuator dynamics compensation for Passive-ON case

VI. LARGE SCALE TESTING

The experiments conducted using the small scale MR damper and with the model-based feedforward-feedback compensation have demonstrated that real-time hybrid testing is an effective technique to evaluate the response of structures using semi-active control devices. In order to effectively verify control algorithms to mitigate natural hazards in real structures, testing of large scale MR dampers is needed. MR damper specimens of this size bring about a number of anticipated challenges for real-time hybrid testing and compensation methods.

Large scale MR dampers are more massive and thus exhibit significant inertial forces. These inertial forces must be accounted on the compensation techniques and real-time hybrid experiment. Additionally, large scale MR dampers exhibit a slower response to input current commands, making structural control strategies more challenging. Testing of large scale MR dampers requires actuators with high force capacity. At this scale, flow restrictions prevent the actuators from responding quickly, therefore increasing the actuator time lag. These larger time lags require higher reliance on actuator dynamics compensation methods for accurate and stable experiments. The control of large scale dynamic actuators typically requires the use of three stage servo-valves to achieve the required flow rates, which is in itself challenging.

Experiments are currently under way at SSTL to use the techniques presented in this paper for testing large scale MR dampers.

VII. CONCLUSIONS

This paper presented an approach for real-time hybrid testing in which compensation for actuator dynamics is implemented using a model-based feedforward-feedback compensator. The method was used to evaluate the response of a semi-active control of a structure employing an MR damper. Experimental results showed good agreement with the predicted responses, demonstrating the effectiveness of the method to test rate-dependent and semi-active components. More details of the work presented in the paper can be found in Carrion and Spencer [1]. Future experiments will employ real-time hybrid testing and the model-based feedforward-feedback compensator to test large scale MR dampers.

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