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ACTUATOR DELAY COMPENSATION FOR REAL-TIME HYBRID SIMULATION INVOLVING MULTIPLE LARGE-SCALE SERVO-HYDRAULIC ACTUATORS

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ABSTRACT

Real-time hybrid simulation provides an economic and efficient experimental technique to evaluate the performance of large-scale civil engineering structures subjected to dynamic loading. Actuator delay induced by servo-hydraulic dynamics needs to be compensated properly in order to achieve accurate and reliable real-time hybrid simulation results. Delay compensation for a single servo-hydraulic actuator has been investigated by numerous researchers while research on actuator delay compensation for a real-time hybrid simulation involving multiple actuators is limited. Multiple servo-hydraulic actuators are necessary in a real-time hybrid simulation when the experimental substructures have more than one dynamic degree of freedom. The structural coupling between the degrees of freedom associated with multiple actuators brings challenges when attempting to achieve accurate actuator control. This paper applies a tracking-error based adaptive compensation technique for multiple actuator control in real-time hybrid simulation. Previous research has shown that this adaptive inverse compensation method can achieve good actuator control for real-time hybrid simulation involving a single actuator. A two-story four-bay moment resisting frame with large-scale passive magneto-rheological dampers subjected to a design basis earthquake is utilized to experimentally evaluate the effectiveness of the adaptive compensation method. The delay compensation is shown to be critical to enable reliable real-time hybrid simulation to be performed involving multiple actuators. The proposed adaptive compensation method is demonstrated to enable accurate control of multiple dynamic actuators to be achieved when actuator delays are not accurately estimated before the simulation and when the actuator delays vary during the simulation.

Introduction

Real-time hybrid simulation, also known as real-time substructure testing, is a viable and economic technique for investigating the dynamic response of structural systems when subjected to earthquakes [Blakeborough et al. 2001]. The method divides a structural system into experimental substructure(s) and analytical substructure(s), and enables the complete structural system to be considered. During a real-time hybrid simulation, the displacement response of the structural system is calculated using an integration algorithm based on the restoring forces that are developed in the substructures under the imposed displacement response. The experimental and analytical substructures, the integration algorithm, and the servo-hydraulic actuator(s) combine together to form the real-time hybrid simulation system. To realistically simulate the response of the entire structure, it is important to maintain the compatibility and equilibrium at

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the interface between the experimental and analytical substructures. This poses challenges, especially for actuator control during a real-time hybrid testing since the actuator has an inevitable delay in response to the command displacement due to inherent hydraulic dynamics. Actuator delay leads to a de-synchronization between the command displacements from the integration algorithm and the restoring forces measured from the experimental substructure(s). The effect of actuator delay on real-time testing has been investigated by numerous researchers [Darby *et al.* 1999; Horiuchi and Konno 1999]. Wallace *et al.* [2005], and Mercan and Ricles [2007] used a delay differential equation to perform stability analysis for real-time hybrid simulation system when actuator delay exists in the feedback restoring force from the experimental substructure. Chen and Ricles [2008a] introduced discrete control theory to include explicit integration algorithms in the stability analysis and investigated the effect of actuator delay on the entire real-time testing system. These studies show that actuator delay is equivalent to introducing negative damping which can destabilize a real-time test if not compensated properly.

Various compensation methods have been proposed to minimize the effect of actuator delay for real-time testing. Horiuchi *et al.* [1999, 2001] proposed two compensation schemes based on the polynomial extrapolation and the linear acceleration assumption, respectively. Methods originating from control engineering practice have also been applied to real-time testing, where the servo-hydraulic system is treated as a time delay system and delay compensation methods such as phase lead compensator [Zhao *et al.* 2003] or derivative feedforward [Jung and Shing 2006] are used. Chen et al. [2009a] proposed a simplified discrete transfer function model for the servo hydraulic actuator and applied the inverse of the model for actuator delay compensation. These compensation methods are developed for a constant actuator delay in real-time tests. Chen and Ricles [2009a] show that the performance of an actuator delay compensation method can be analyzed through a frequency response analysis of the equivalent transfer function of the compensation method. Using discrete control theory, the method to compensate for actuator delay can be interpreted as an extrapolation in the time domain or as an equivalent transfer function in the frequency domain.

Compensation methods based on adaptive control theory have also been proposed. Darby *et al.* [2002] proposed an online procedure to estimate and compensate actuator delay during a real-time hybrid test using a proportional feedback system. Bonnet *et al.* [2007] applied model reference adaptive minimal control synthesis (*MCS*) to real-time testing, which can be classified as a model reference adaptive controller. Carrion and Spencer [2007] used a combined feedforward-feedback controller in conjunction with inverse modeling and bumpless transfer in a real-time hybrid test to compensate for a variable actuator delay that occurs when the experimental substructures include semi-active dampers. To improve the performance of the inverse compensation method for real-time testing, Chen and Ricles [2009b] proposed a dual compensation method. The actuator control error is utilized as an auxiliary signal to minimize the effect of over- or under-compensation of actuator delay when an inaccurate estimate of actuator delay is used for the inverse compensation method. To minimize the effect of an inaccurately estimated or time varying value for the actuator delay for a real-time hybrid simulation, Chen and Ricles [2009c] developed an adaptive inverse compensation method based on the inverse compensation method, which was experimentally demonstrated to effectively minimize the effect actuator delay for real-time hybrid simulation involving a single actuator. In this present study, the adaptive compensation method is applied for real-time hybrid simulation involving two servo-hydraulic actuators and its performance is evaluated using different criteria.

Adaptive Inverse Compensation for Actuator Delay Negation

The adaptive inverse compensation method developed by Chen and Ricles [2009c] can be formulated as

$$G_c(z) = \frac{(\alpha_{es} + \Delta\alpha) \cdot z - (\alpha_{es} + \Delta\alpha - 1)}{z} \tag{1}$$

In Eq. (1), z is the complex variable in the discrete z-domain; α_{es} is the estimated compensation parameter by the researchers before the simulation; and $\Delta\alpha$ is an evolutionary variable with an initial value of zero that is determined using the following adaptive control law:

$$\Delta\alpha(t) = k_p \cdot TI(t) + k_i \cdot \int_0^t TI(\tau)d\tau \tag{2}$$

In Eq. (2) k_p and k_i are proportional and integrative gains for the adaptive control law, respectively; and TI is the tracking indicator based on the enclosed area of the hysteresis in the synchronized subspace plot, as shown in Fig. 1. The calculation of TI for each time step can be formulated as [Mercan 2007]

$$TI_{i+1} = 0.5(A_{i+1} - TA_{i+1}) \tag{3a}$$

$$A_{i+1} = A_{i+1} + dA_{i+1} = A_{i+1} + 0.5(d_{i+1}^c + d_i^c)(d_{i+1}^m - d_i^m) \tag{3b}$$

$$TA_{i+1} = TA_i + dTA_i = TA_i + 0.5(d_{i+1}^m + d_i^m)(d_{i+1}^c - d_i^c) \tag{3c}$$

where d_i^m and d_{i+1}^m are actuator measured displacements at the ith and (i+1)th time step, respectively; d_i^c and d_{i+1}^c are actuator command displacements at the ith and (i+1)th time step, respectively. From the definition, a positive rate of change of the TI corresponds to an actuator response lagging behind the command displacement, where energy is introduced into the real-time testing system; while a negative rate of change of the TI corresponds to a leading actuator response, where artificial damping is added into the real-time testing system. A zero rate of change of the TI implies no actuator control error, i.e., the actuator measured and command displacements are equal to each other. When the value of the TI remains equal to zero throughout a test, perfect actuator control has been achieved throughout the real-time test.

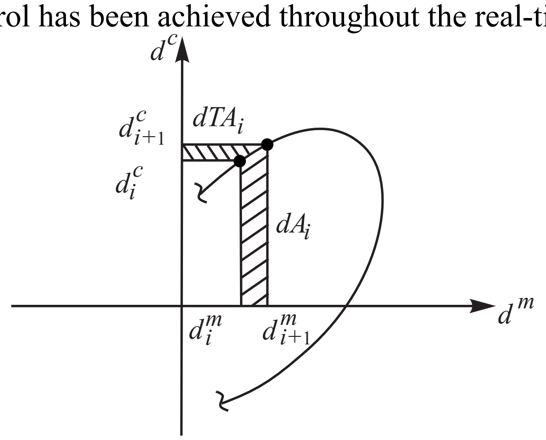

Figure 1. Hysteresis developed in synchronized subspace plot from actuator delay

When α_{es}, k_p, and k_i are set equal to zero, no actuator delay compensation is used during the real-time hybrid simulation. Generally, a larger value of k_p results in a faster response and a larger oscillation in the evolutionary variable, while increasing the integrative gain k_i reduces the oscillation and leads to a smaller steady state error. In this paper, the integrative gain k_i is selected to be one tenth of the proportional gain k_p based on studies involving numerical simulations, where $k_i = 0.1k_p$ was found to produce good adaptation with a small error.

Prototype Steel Moment Resisting Frame and Experiment Setup

A 2-story 6-bay by 6-bay office building is selected as the prototype structure to experimentally evaluate the adaptive inverse compensation method for multiple actuator control. The building is assumed to be located on a stiff soil site near Los Angeles and has four identical perimeter steel moment resisting frames (MRFs) to resist earthquake lateral forces. Fig. 2 shows the plan view and the perimeter frames of the prototype structure. The experimental study presented in this paper focuses on one typical perimeter MRF, which is designed with MR dampers as shown in Fig. 2(b). The simplified design procedure developed by Lee *et al.* [2005] is used to design the MRF with MR dampers, where the properties of the resulting MRF are tabulated in Table 1. The MR dampers are assumed to be in passive mode with a nominal capacity of 200 kN at the maximum current input of 2.5 Amps [Bass and Christenson 2007]. A total of six and four MR dampers are required in accordance with the simplified design procedure to achieve the objective performance of a 1.7% maximum story drift under the design earthquake [Chen *et al.* 2009b].

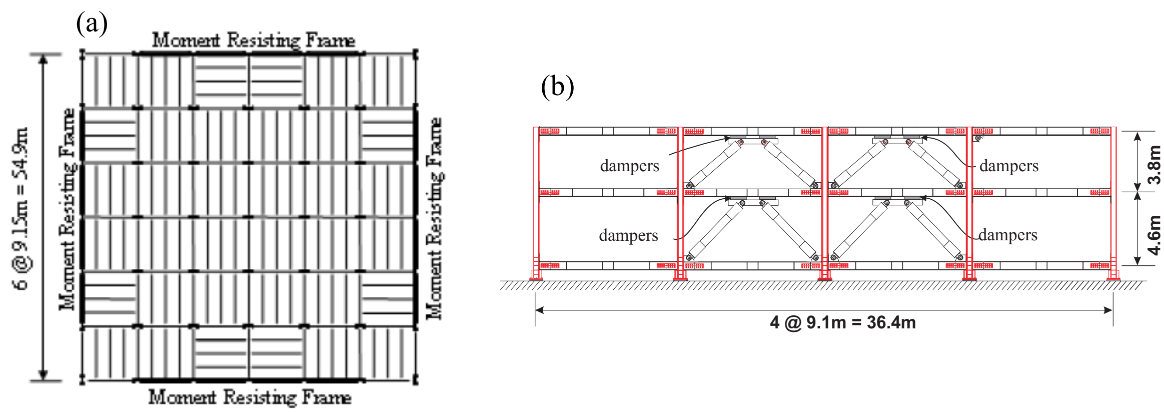

Figure 2. Prototype building (a) plan view; (b) perimeter MRF with dampers and braces

Table 1. Properties of MRF

Column	Beams		T_1 (sec.)	Story Stiffness (kN/m)	
1st and 2nd story	1st story	2nd story	1.42	1st story	2nd story
W14x120	W24x55	W18x40		36007	23894

The real-time hybrid simulations presented in this study were performed using the NEES Real-Time Multi-Directional (RTMD) Facility at Lehigh University. Fig. 3 shows the experimental setup for the real-time hybrid simulation, which consists of two experimental substructures (two MR dampers), two servo-hydraulic actuators with supports and roller bearings; reaction frames, and beams securing the MR dampers to the strong floor. The two actuators each have a 500 mm stroke but a different maximum force capacity of 1700 kN and 2300 kN, respectively. Two servo-valves, each with a flow capacity of 2500 liters/min, are mounted on each actuator to enable them to achieve a maximum velocity of 760 mm/sec and 560 mm/sec, respectively. The MR fluid dampers have a stroke of 584 mm and an Advanced Motion Control Pulse Width Modulation (PWM) servo-amplifier is utilized to control the electrical current input for the dampers. Since the MR dampers at the same story level are placed in parallel in the MRF, they are assumed to be subjected to the same velocity and displacement. Hence each of the MR damper test setups in the laboratory represents all of the dampers in a story of the MRF. The measured restoring force from each MR damper setup is multiplied by the number of dampers in a story to obtain the total restoring force of all the dampers at the story level in the MRF. The MRF is analytically modeled using a nonlinear finite element program with a total 122 DOF and 71 elements [Karavasilis *et al.* 2009]. The highest natural frequency of the MRF is around 20 kHz.

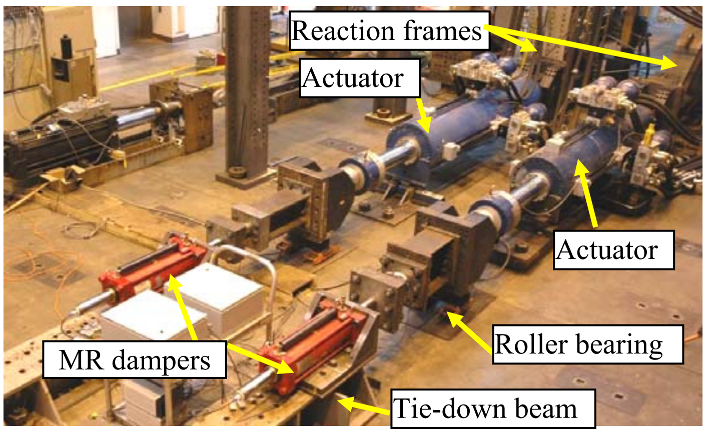

Figure 3. Experimental setup for real-time hybrid simulation

Real-Time Hybrid Simulation Results

The N196E component of the 1994 Northridge earthquake recorded at Canoga Park was selected as the ground motion and scaled to DBE by employing the scaling procedure of Somerville [1997]. A total of eight real-time hybrid simulations were conducted to systematically evaluate the performance of the adaptive inverse compensation for multiple actuator control. Table 2 presents the parameter values for the real-time hybrid simulations presented in this study, where the subscripts *1* and *2* refer to the two actuators. An unconditionally stable explicit CR integration algorithm [Chen and Ricles 2008b, Chen *et al.* 2009a], referred to as the CR algorithm, is used for the real-time hybrid simulation in the present study and the time step Δt is selected as 10/1024 sec.

Table 2. Summary of parameter values for real-time hybrid simulations

Test No.	Estimated Delay		Adaptive Gain	
	α_{es1}	α_{es2}	k_{p1}	k_{p2}
1	0	0	0.0	0.0
2	0	0	0.4	0.4
3	30	30	0.0	0.0
4	30	30	0.4	0.4
5	60	60	0.0	0.0
6	60	60	0.4	0.4
7	0	60	0.4	0.4
8	60	0	0.4	0.4

The maximum tracking error (*MTE*), root mean square of tracking error (*RMS*) and maximum tracking indicator (*MTI*) are used to evaluate actuator tracking for the real-time hybrid simulations. *MTE* and *RMS* are defined as

$$MTE = \max(ABS(d^c - d^m)) \tag{4a}$$

$$RMS = \sqrt{\sum_{i=1}^{N}\left[d_i^c - d_i^m\right]^2 / \sum_{i=1}^{N}\left[d_i^c\right]^2} \tag{4b}$$

Real-Time Hybrid Simulation with α_{es1}=0, α_{es2}=0, k_p=0, and k_i=0: As discussed in the previous section, when all of the parameters are set to zero, no actuator compensation for real-time hybrid simulation occurs. With no actuator compensation, unstable results are observed, as shown in Fig. 4 where the command displacements from the integration algorithm increase exponentially and suddenly increase at about 1.25 sec., causing the servo-hydraulic system to shut down. A time delay can also be observed between the command and measured displacement for both actuators. This indicates that the multiple actuator delays can destabilize a real-time hybrid simulation if not compensated properly even when physical damping is introduced by the MR fluid dampers.

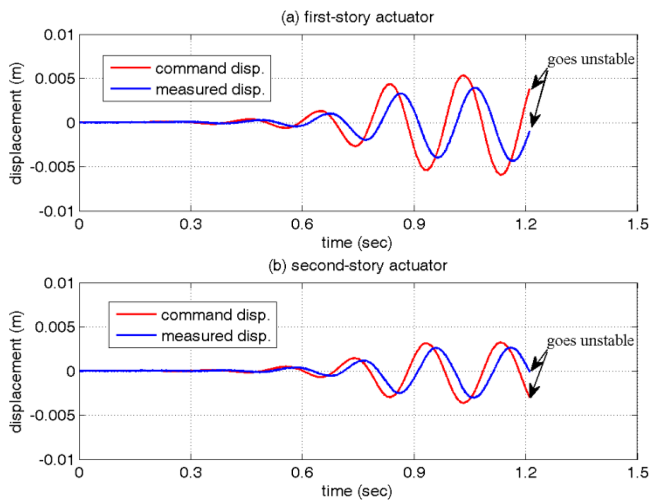

Figure 4. Real-time hybrid simulation results with α_{es1}=0, α_{es2}=0, k_p=0, and k_i=0

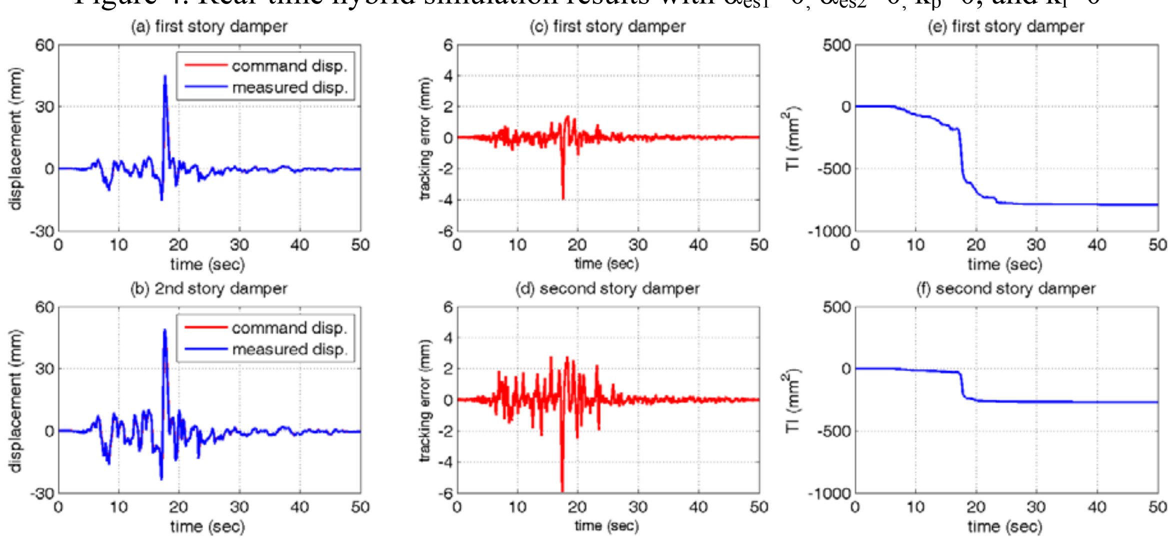

Figure 5. Real-time hybrid simulation results with α_{es1}=60, α_{es2}=60, k_p=0, and k_i=0

Real-Time Hybrid Simulation with α_{es1}=60, α_{es2}=60, k_p=0, and k_i=0: With both proportional and integrative gains set equal to zero, the adaptive compensation method reduces to the inverse compensation method which is developed for constant actuator delay. The real-time hybrid simulation was observed to be stable as shown in Figs. 5(a) and 5(b). The actuator tracking errors in Figs. 5(c) and 5(d) have *MTE* values of 3.9 mm and 5.9 mm for the two actuators attached to the first and second story damper, respectively, which correspond to 8.7% and 12% of the maximum damper deformation. It can also be observed that the maximum tracking error occurs when the experimental substructures (i.e., the MR fluid dampers) develop their maximum deformation shown in Fig. 5(a) and (b). The pulse-like damper deformation imposes higher demand on the actuators, leading to a sudden variation of actuator delay and a subsequent increase in actuator tracking error. The RMS for actuator tracking error is equal to 11.2% and 7.7%, indicating that in spite of a stable simulation the experimental results may not be accurate. The negative values for tracking indicator shown in Figs. 5(e) and 5(f) imply that an over-compensation and actuator tracking error is induced by the initial estimates of α_{es1} and α_{es1} during the hybrid simulation.

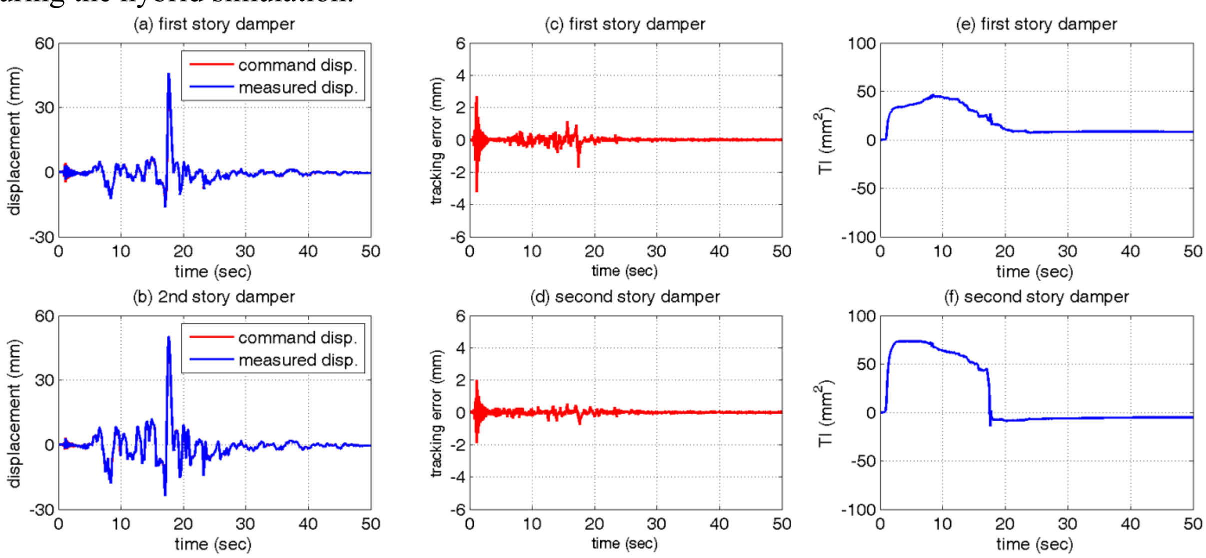

Figure 6. Real-time hybrid simulation results with α_{es1}=0, α_{es2}=0, k_p=0.4, and k_i=0.04

Real-Time Hybrid Simulation with α_{es1}=0, α_{es2}=0, k_p=0.4, and k_i=0.04: Unlike the simulation results presented in Fig. 4, the adaptive inverse compensation stabilized the real-time hybrid simulation with zero initial estimates of actuator delay, as shown in Fig. 6(a) and 6(b). However, small high-frequency oscillations can be observed at the beginning of the simulation. This is due to the fact that the adaptive compensation method tried to minimize the destabilizing effect induced by zero estimates (α_{es1}=0 and α_{es2}=0). Good agreement can be observed between the command and measured displacements in Fig. 6(a) and 6(b) for the rest of the simulation, where the MR dampers are observed to develop maximum deformations of 50.2 mm and 45.8 mm for the first and second story, respectively. The maximum actuator control errors shown in Fig. 6(c) and 6(d) have an *MTE* of 3.2 mm and 2.0 mm for the actuators attached to the first and second story damper, respectively. The maximum actuator control error in Fig. 6(c) and 6(d) can also be observed to occur at the very beginning of the simulation and therefore can be attributed to the poor estimate for actuator delay. The RMS for tracking error for two actuators is equal to 5.2%

and 2.5%, respectively. Similarly, due to the poor estimates for actuator delay, the time history of the tracking indicator in Figs. 6(e) and 6(f) shows a rapid increase at the beginning of the simulation. However, the adaptive inverse compensation adjusted the compensation parameters, which subsequently led to smaller changes in the values of the tracking indicator. At about 19 sec., where the sudden increase in damper deformation and the maximum displacements in Figs. 6(e) and 6(f) occurs, the tracking indicator changes again due to the variable actuator delay that is introduced by the command displacement. Figs. 7(a) and 7(b) present the time history of evolutionary variable $\Delta\alpha$ for the two actuators. The adaptive inverse compensation method is observed to make fast and noticeable adjustments to the compensation parameters throughout the simulation. The hysteresis of the MR fluid dampers are presented in Figs. 7(c) and 7(d), where energy dissipation can be observed.

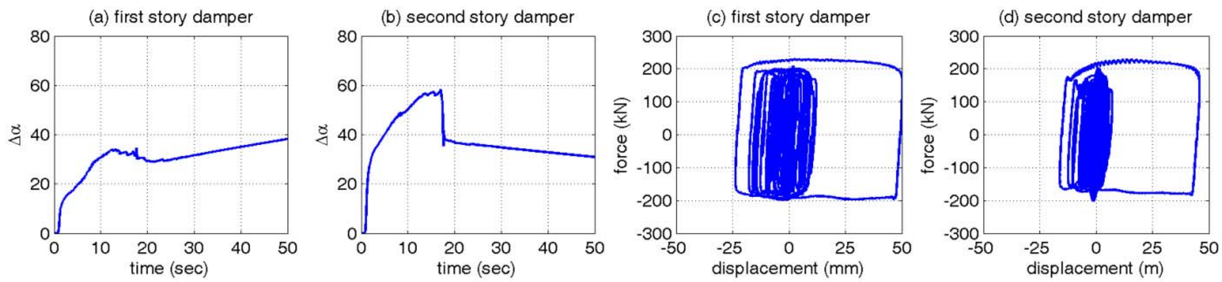

Figure 7. Real-time hybrid simulation results for evolutionary variable

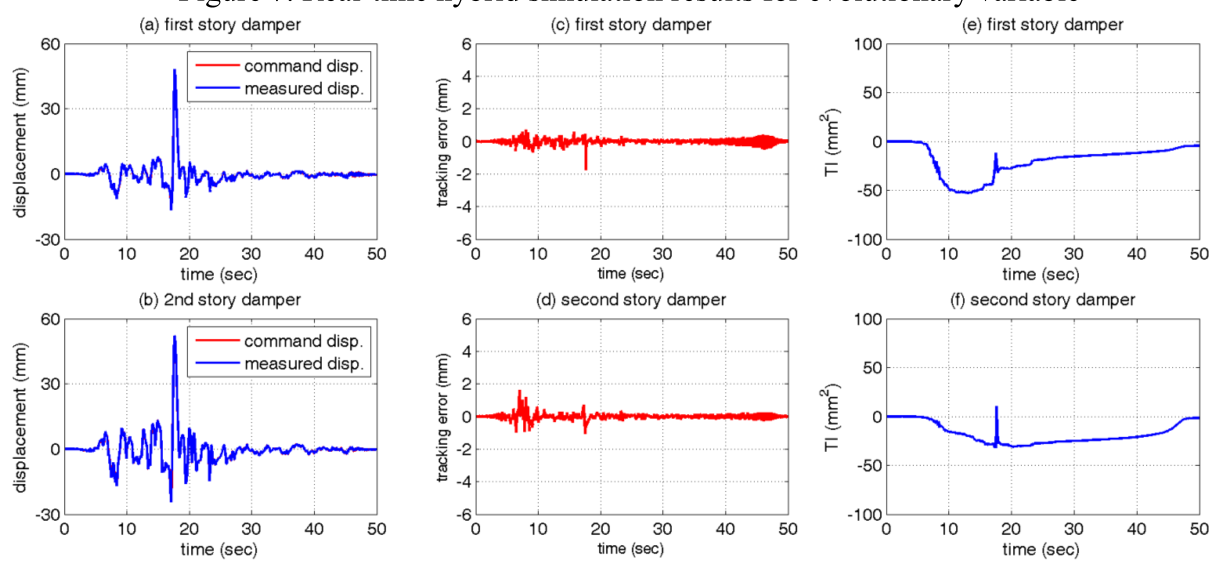

Figure 8. Real-time hybrid simulation results with α_{es1}=60, α_{es2}=60, k_p=0.4, and k_i=0.04

Real-Time Hybrid Simulation with α_{es1}=60, α_{es2}=60, k_p=0.4, and k_i=0.04: The real-time hybrid simulation results with α_{es1}=60, α_{es2}=60, k_p=0.4, and k_i=0.04 are presented in Fig. 8. Similar MR damper response to that in Fig. 6(a) and 6(b) can be observed in Figs. 8(a) and 8(b). The actuator control error in Fig. 8(c) and 8(d) is observed to have *MTE* values of 1.8 mm and 1.6 mm for the two actuators, which are a 54% and 73% reduction in the corresponding *MTE* values of Fig. 5(c) and 5(d). The corresponding RMS for the actuator tracking error is reduced to 3.3% and 2.8%. These results imply that actuator control improved with the adaptive inverse compensation. The tracking indicators in Figs. 8(e) and 8(f) show much smaller values than those in Figs. 5(e) and 5(f), again indicating better actuator control. When compared with the test results in Fig. 6, slightly different amplitudes of the *MTE* and maximum *TI* can be observed although different values of α_{es1} and α_{es2} were used. This implies that the adaptive inverse compensation can achieve good performance when different estimates are used.

The experimental results for all real-time hybrid simulations are summarized in Table 3. The real-time hybrid simulation with the adaptive inverse compensation (Tests 2, 4, 6, 7 and 8) can be observed to have better actuator control and smaller actuator tracking error than the corresponding simulation without the adaptive inverse compensation (Tests 3 and 5) or no compensation (Test 1). It can also be observed from Table 3 that better estimates for the delay constants (e.g., other than zero) can help further improve the performance of the adaptive inverse compensation method but are not necessary to achieve an accurate and reliable real-time hybrid simulation.

Table 3. Summary of actuator control for experimental results

Test No.	*MTE* (mm)		RMS (%)		Maximum *TI* (mm^2)	
	1st story	2nd story	1st story	2nd story	1st story	2nd story
1	-	-	-	-	-	-
2	3.2	2.0	5.15	2.52	46.84	73.53
3	2.3	0.6	3.66	1.33	160.2	9.10
4	1.6	0.8	2.01	1.35	10.85	50.94
5	5.9	3.9	11.24	7.67	-790.7	-269.9
6	1.8	1.6	3.31	2.80	53.03	31.98
7	1.9	1.5	3.90	2.77	-55.53	90.01
8	1.9	1.1	3.02	2.43	52.71	-31.21

Summary and Conclusions

A two-story four-bay steel moment resisting frame with large-scale passive magneto-rheological dampers subjected to a design basis earthquake is utilized to experimentally evaluate the effectiveness of the adaptive compensation method for real-time hybrid simulation involving multiple servo-hydraulic actuators. Different estimates for delay constants and adaptive gains are used to provide a systematic evaluation of actuator control error in terms of maximum tracking error, RMS of tracking error and maximum tracking indicator. The adaptive compensation method is demonstrated enable good control of two actuators to be achieved when actuator delay is not accurately estimated before the simulation and when the actuator delay varies throughout the simulation. This is consistent with previous findings when the adaptive inverse compensation was applied to real-time hybrid simulation involving a single actuator. The experimental results confirm that the adaptive inverse compensation can be applied to real-time hybrid simulation involving multiple servo-hydraulic actuators to enable accurate results to be achieved.

Acknowledgments

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