Verification of Real-Time Hybrid Simulation with Shake Table Tests: Phase 2 – Development of Control Algorithms

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SUMMARY:
In the last few decades, structural control has become a recognized strategy for mitigating earthquake damage in civil engineering structures. Within structural control, magnetorheological (MR) fluid damper is acknowledged as a promising method. In order to broadly evaluate the performance of MR dampers, tests are proposed using real-time hybrid simulation (RTHS) which provides researchers the opportunity to isolate and physically investigate only the more complex or critical components. Furthermore, this approach allows for a wide range of configurations to be tested using a single test specimen. This paper presents results belonging to the second phase of this study. Along the context, a numerical model of a small-scale prototype structure to be used in these tests is presented. Using proposed numerical model, performance of various control algorithms are compared under several earthquake excitations.

Keywords: real-time hybrid simulation, vibration control, MR damper

1. INTRODUCTION

Designing civil engineering structures that can withstand the test of time has been always a major challenge. As a part of this challenge, the earthquake engineers have always aimed to create redundant environments resisting destructive forces of nature such as unforgiving earthquakes, harsh winds and giant tsunamis. However, the Great Sichuan Earthquake that occurred at 14:28 CST on March, 12 2008 tried the traditional structural engineering practices once more. Despite of all engineering efforts, the toll of the earthquake was 69,226 deaths and a direct economic cost of 124.2 billion US Dollars (United Nations Centre for Regional Development 2009). The overly large amount of damage in recent events such as this earthquake demonstrated that current practices are not tolerable.

Innovation is needed in civil engineering to overcome our limitations. In the last decade, structural vibration control systems have received continuously growing attention in the civil engineering community. Up-to-day, many varieties of control devices including passive, active and semi-active types have been developed. The Great East Japan Earthquake occurred in 2011 demonstrated that such devices provided effective damage control (Taylor et. al. 2012).

Among vibration control devices currently available on the market, MR damper is known for its reliability and adaptability. Principally, MR dampers provide a novel and attractive semi-active control mechanism. By using small amount of external power source, system's stiffness and damping characteristics can be modified based on feedback of structural responses and the supplemental MR damper can consume the motion of the structure to develop necessary restoring forces. Many experimental studies demonstrated effectiveness of the MR damper in mitigating earthquake hazards (Dyke et. al. 1996b, a; Friedman et. al. 2010; Jiang et. al. 2011).

In recent years, RTHS technique has become one of the main research areas in earthquake engineering. Essentially, RTHS provides an efficient way to isolate and physically test only the more complex or critical components, where available resources do not allow researchers to test the full-scale structure. Numerous studies have already verified effectiveness of RTHS by comparing hybrid test results to numerical simulations of semi-actively controlled structures equipped with MR damper (Christenson et. al. 2008; Carrion et. al. 2009; Castaneda et. al. 2012).

To this date, no or very little research has been reported on the comparison of RTHS results with an actual structure tested on the shake table. Lin et. al. (2009) demonstrated in his study that there is a close correlation between the shake table tests and the real-time hybrid simulation, however results also show discrepancies due to actuator dynamics and modelling errors. To push the research on this area further, an international research project has been proposed which focuses on the following tasks: (i) identification and modelling of the test structure, (ii) development of control algorithms for vibration control, (iii) testing of the structure on the shake table, (iv) conducting RTHS tests where MR damper is integrated to the platform as physical substructure and (v) verification of the RTHS method by comparing the results.

As the first phase of this study, system identification tests of the test structure were discussed and several numerical models were proposed. In addition, a novel RTHS platform developed by Castaneda et. al. (2012) that is going to be used in future is being presented at the ICEER12 (Ozdagli et. al. 2012). This paper focuses on the second phase of that study. In this phase, numerical model of a small-scale prototype structure built in Harbin Institute of Technology (HIT) in China is provided. And using the proposed numerical model, the preliminary performance achieved with various control algorithms is compared under several earthquake excitations.

2. PROTOTYPE STRUCTURE AND MODELING

The prototype structure (PS) used for numerical simulations is a three-dimensional three story structure located in Harbin Institute of Technology, China, given in Fig. 2.1. The PS has a base plan dimension of 1.84 m by 2.04 m. Each story is 1.2 m tall and the total height is 3.6 m. The columns, beams and girders are made of structural steel with an elastic modulus of 206 GPa. Each joint, where members are connected to each other, is made of solid welds that do not allow free rotation. The PS is braced in one direction with v-type braces such that the system is weak in y-axis and strong along x-axis. At each story, a concrete slab weighting 250 kg is attached as seismic mass. The total mass of the structure including the self-weight of the members is calculated as 1066 kg. Section properties of the members used in the design of the PS is summarized in Table 2.1.

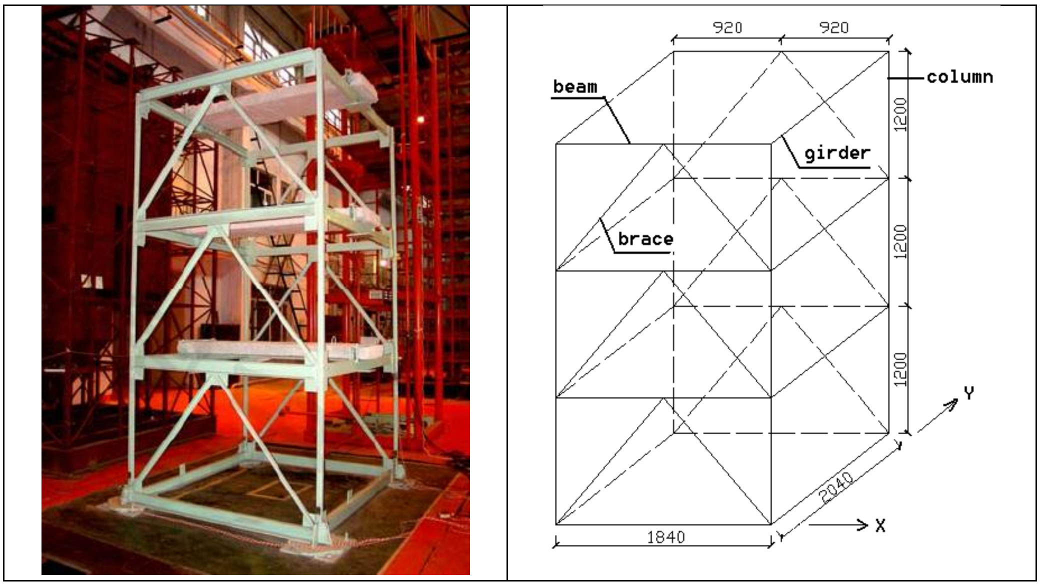
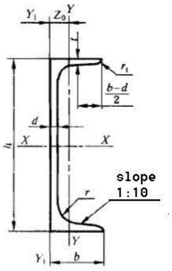
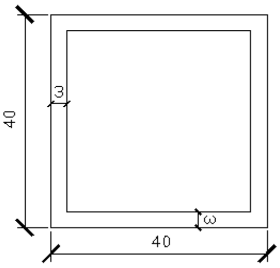
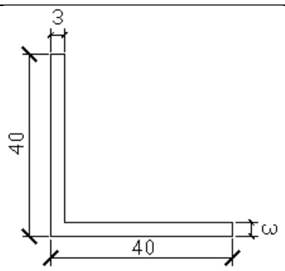


Figure 2.1. Experimental structure and stick figure representation

Preliminary system identification tests are conducted in order to reveal dynamic characteristics of the structure. The tests concluded that the PS has many modes in x- and y-axis and also torsional direction. For this study, only modes in y-axis are considered. The identified natural frequencies of the structure are: 2.71 Hz, 8.11 Hz and 13.03 Hz.

Table 2.1. Section Properties of the prototype structure

Beam and Girder					**Column**					**Brace**				
														
A cm^2	$I_{X\text{-}X}$ cm^4	$I_{Y\text{-}Y}$ cm^4	J cm^4	ρ Kg/m	A cm^2	$I_{X\text{-}X}$ cm^4	$I_{Y\text{-}Y}$ cm^4	J cm^4	ρ Kg/m	A cm^2	$I_{X\text{-}X}$ cm^4	$I_{Y\text{-}Y}$ cm^4	J cm^4	ρ Kg/m
12.74	198.3	25.6	223.9	10.0	4.44	10.2	10.2	20.4	3.487	2.31	3.59	3.59	7.20	1.814

A simple mass-damper-spring model of the structure is developed based on the description given above. The model has three degrees of freedom (DOF), where each node represents a floor. The seismic masses are lumped at nodes. The model generates only horizontal responses (displacement, velocity and acceleration) when a disturbance is applied as means of ground motion or external force. A state space representation of the model is given as below:

$$\dot{x} = Ax + Bf + E\ddot{x}_g \tag{2.1}$$

$$y = Cx + Df + F\ddot{x}_g \tag{2.2}$$

where, x is the state vector, y is system responses, f is the vector of input forces and $\ddot{x}_g$ is the ground acceleration. State space matrices of the system given in Eqn. 2.1 are:

$$[A] = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix},\ [B] = \begin{bmatrix} 0 \\ M^{-1}P \end{bmatrix},\ [E] = \begin{bmatrix} 0 \\ -M^{-1}G \end{bmatrix} \tag{2.3}$$

where, M, C and K are the mass, damping and stiffness matrices respectively, P and G are influence matrices of applied external force and ground motion excitation. $[C]$, $[D]$ and $[F]$ matrices depend on the chosen output vectors. For a system with displacement, velocity and acceleration responses, the matrix coefficients can be described as:

$$[C] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix},\ [D] = \begin{bmatrix} 0 \\ 0 \\ M^{-1}P \end{bmatrix},\ [F] = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{2.4}$$

To construct the state space matrices given above, M, C and K matrices are first estimated with a preliminary 3-DOF model. Then, C and K matrices are updated to represent the experimental structure in most effective way. The modified stiffness and damping matrices are computed using Eqns. 2.5 and 2.6 as proposed by Giraldo et. al. (2004):

$$K_u = M\Phi[2\pi f_e]^2\Phi^T \tag{2.5}$$

$$C_u = M\Phi(2\xi[2\pi f_e])\Phi^T \tag{2.6}$$

where, Φ is normalized modal matrix of $M^{-1}K$, f_e is the diagonal matrix containing natural frequencies of the structure identified from experimental structure in Hertz and ξ is diagonal matrix containing detected damping ratios. Eventually, modified damping and stiffness matrices are used to generate state space of the model.

Fig. 2.2 shows the transfer functions from the impact force on third floor to floor accelerations. The modified model is able to capture the dominant dynamics of the structural system. However, the model is not successful in tracing the zeros of the experimental transfer function partially due to the fact that the model only contains system dynamics in y-direction. A more refined and three-dimensional model will yield a better result.

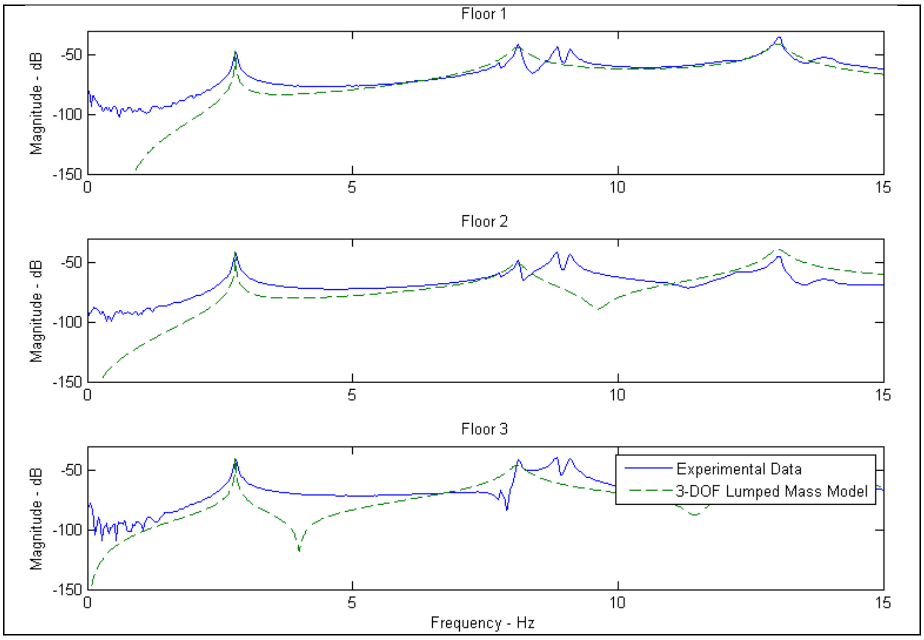


Figure 2.2. Transfer function comparison between experimental and model data

3. MAGNETORHEOLOGICAL DAMPER MODEL AND CONTROL DESIGN

To perform vibration control on the structure, a small scale 2500-N MR damper developed by Lord Corporation is used. The MR fluid contained by the damper is a suspension of oil and micron-size ferro-magnetic iron particulates. The damper has a length of 248 mm with a stroke of ±12.7 mm and weights 0.92 kg. The damper resides a magnetic circuit inside that can be excited by a low energy voltage. The magnetic field can be controlled by a command voltage produced by a controller device embedded with a pulse width modulator (PWM) circuitry. Even though the controller device and damper can endure up to 5 Volts, to protect the equipment from overloading, 3 Volts are selected as a limit. The damper can sustain up to 1500-N at this limit rate. A schematic of the damper used in this study is provided in Fig 3.1.

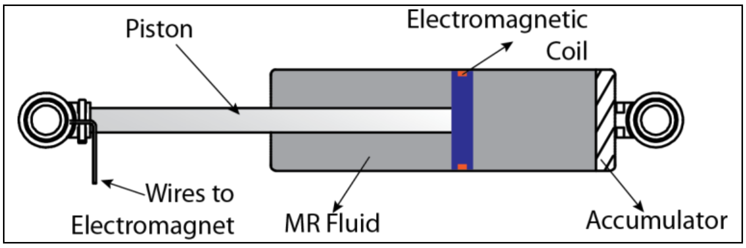


Figure 3.1. MR damper schematic

A model of the damper to be used in numerical simulations was developed to accurately predict the behaviour of the MR damper. The model is based on phenomenological Bouc-Wen model (illustrated in Fig. 3.2) proposed by Spencer et. al. (1997). Accordingly, the damper can be characterized by the following equations:

$$c_1\dot{y} = \alpha z + k_0(x - y) + c_0(\dot{x} - \dot{y}) \tag{3.1}$$

$$\dot{z} = -\gamma|\dot{x}_d - \dot{y}|z|z|^{n-1} - \beta(\dot{x}_d - \dot{y})|z|^n + A(\dot{x}_d - \dot{y}) \tag{3.2}$$

$$F = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \tag{3.3}$$

where, F represents the total damper force, k_1 represents the accumulator stiffness, c_0 represents the viscous damping observed at larger velocities, c_1 produces roll-off at low velocities, k_0 controls the stiffness at large velocities and x_0 is the initial displacement of spring, k_1.

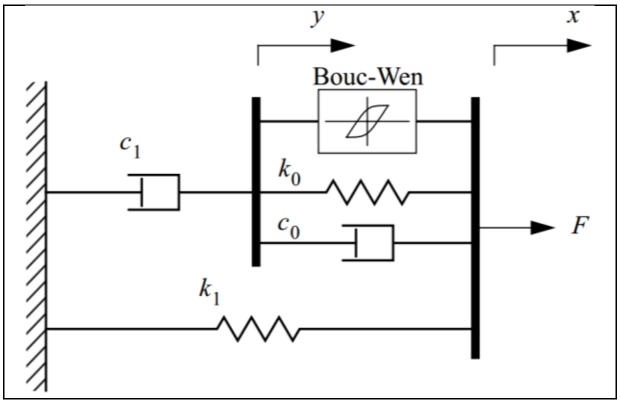


Figure 3.2. Phenomenological Bouc-Wen model

For a passive damper system, where voltage kept constant, identifying the parameters mentioned above is adequate. However, for achieving optimal performance, a semi-active control scheme needs to be implemented through commanding voltage signal. In view of that, any change in voltage will create a fluctuation in the magnetic field. In other words, damping constants given in Eqns. 3.1, 3.2 and 3.3 will vary linearly with the applied voltage. The equations given below reveal this relationship:

$$\alpha(u) = \alpha_a + \alpha_b u\ ,\ c_1(u) = c_{1a} + c_{1b}u\ ,\ c_0(u) = c_{0a} + c_{0b}u \tag{3.4}$$

$$\dot{u} = -\eta(u - v) \tag{3.5}$$

where, v is the applied voltage. Eqn. 3.5 can be recognized as a filter that defines dynamics of MR fluid reaching rheological equilibrium. Eqns. 3.1-3.5 are implemented as an input-output block in Simulink / Matlab (The MathWorks Inc. 2011).

The damper parameters mentioned in the Eqns. 3.1-3.5 are determined based on the characterization tests conducted in Purdue University. To obtain the parameters, a constrained optimization algorithm is used, which has already been implemented in Matlab (The MathWorks Inc. 2011). In Table 3.1, all values regarding the phenomenological Bouc-Wen model are provided.

The force generated by the MR damper cannot be controlled directly, however, by varying the voltage input; the magnetic field must be adjusted such that a desired force history is induced. Nevertheless, a control algorithm needs to be implemented to achieve an optimal control force. For this study, clipped optimal control (COC) proposed by Dyke et. al. (1996b) is used to utilize desired force. The control force is determined via a linear optimal controller gain, calculated based on displacement and velocity states of the structure. To reflect a realistic control case, only acceleration states obtained from sensors located on the structure are measured. Through a linear quadratic Gaussian (LQG) regulator, unknown states and desired damper force can be estimated. At this point, as given in Eqn. 3.6, COC compares the desired force with the measured force of the damper and applies zero voltage or maximum voltage, accordingly.

$$v = V_{max} H((f_c - f_m) f_m) \tag{3.6}$$

where, f_c represents selected optimal control force, f_m represents measured damper force and $H(x)$ is the Heaviside step function.

Table 3.1. MR damper modelling parameters

Parameter	Value	Parameter	Value
c_{0a}	5.88 $N\ sec/cm$	α_a	33.64 N/cm
c_{0b}	3.52 $N\ sec/cm\ V$	α_b	11.05 $N/cm\ V$
k_0	5.86 N/cm	γ	23.20 cm^{-2}
c_{1a}	81.79 $N\ sec/cm$	β	23.20 cm^{-2}
c_{1b}	12.00 $N\ sec/cm\ V$	A	154.60
k_1	0.01 N/cm	n	2
x_0	0 cm	η	60 sec^{-1}

4. NUMERICAL SIMULATION RESULTS

The performance of the COC is evaluated through numerical simulations. Various cases such as no-control, passive -off and -on control are compared to COC under several ground motion excitations to evaluate the compatibility of the MR damper for control of this structure. The PS is used as the target structure and MR damper is attached between the first floor and the ground. Minimization of the absolute acceleration responses was selected as the main objective for the optimal linear control. For the estimation of the unknown states via a Kalman filter, all available acceleration responses are used. Additionally, the measured force of the damper force is used by the estimator, and the Clipped Optimal Controller is applied (Dyke 1996b). All control cases are compared and evaluated according to numerous evaluation criteria tabulated in Table 4.1 (Spencer et. al. 1998; Jansen et. al. 2000).

Table 4.1. Selected evaluation criteria

Criteria Value	Criteria Equation	Criteria Description
J_1	$max\left(\frac{\lvert x_i(t)\rvert}{x^{max}}\right)$	Ratio of the maximum controlled relative floor displacement to the uncontrolled value
J_2	$max\left(\frac{\lvert d_i(t)\rvert}{d_n^{max}}\right)$	Ratio of the maximum controlled interstory displacement to the uncontrolled value
J_3	$max\left(\frac{\lvert \ddot{x}_{ai}(t)\rvert}{\ddot{x}_a^{max}}\right)$	Ratio of the maximum controlled floor accelerations to the uncontrolled value
J_4	$max\left(\frac{\lvert f_i(t)\rvert}{W}\right)$	Ratio of the maximum measured damper force to the weight of the structure

For the numerical simulations four earthquake input are used: El Centro, Hachinohe, Kobe and Northridge. Each earthquake is amplitude scaled in such a way that the first floor displacement does not exceed maximum stroke of the MR damper in passive-off case. The following scaling factors are used, respectively: [0.75 0.55 0.16 0.21]. The simulations of each earthquake yielded uncontrolled responses as follows: $x^{max} = [3.75\ 3.59\ 3.46\ 3.29]cm$; $d_n^{max} = [1.69\ 1.60\ 1.53\ 1.47]cm$; $\ddot{x}_a^{max} = [1.19\ 1.12\ 1.10\ 1.04]g$. The results evaluated based on aforementioned criteria are presented in Table 4.2. Smaller numbers are in favor of the control algorithm.

It has been observed that the passive-off control can reduce maximum relative floor displacement, maximum interstory displacement and maximum absolute floor acceleration by 20%, 20% and 16%, respectively, averaged upon four earthquake results. The decrease is even more dramatic for passive-on control. COC yielded responses relatively close to passive-on case. The results indicate that the MR damper being considered is appropriate for the control of this particular structure.

Table 4.2. Numerical Simulation Results

El Centro Earthquake			
Criteria	**Passive-Off**	**Passive-On**	**Clipped-Optimal**
J_1	0.758	0.356	0.449
J_2	0.750	0.321	0.462
J_3	0.764	0.429	0.466
J_4	0.013	0.119	0.113
Hachinohe Earthquake			
J_1	0.800	0.233	0.361
J_2	0.795	0.210	0.378
J_3	0.816	0.252	0.355
J_4	0.014	0.099	0.090
Kobe Earthquake			
J_1	0.826	0.210	0.399
J_2	0.830	0.188	0.424
J_3	0.824	0.229	0.365
J_4	0.014	0.096	0.093
Northridge Earthquake			
J_1	0.886	0.537	0.674
J_2	0.861	0.491	0.704
J_3	0.932	0.615	0.639
J_4	0.014	0.125	0.129

5. CONCLUSION AND FUTURE WORK

This paper considers the second phase of an international partnership project. Here, we focused on the preliminary control of a three-story, medium-scale structure. Using a 2D numerical lumped-mass model of the structure, the results of three control cases are compared to the responses of uncontrolled structure. Clipped-optimal control has shown effective capability in reducing peak floor acceleration responses for the selected earthquakes. The numerical results are being used to perform a preliminary evaluation of the compatibility of this MR damper to control the structure being considered.

In future, more refined models will be constructed to minimize the errors between numerical simulations and experimental structure. The control scheme will be fine-tuned towards better performance in reducing structural responses. Subsequently, all the simulation results will be verified with shake table tests conducted at Harbin Institute of Technology, China. In addition, RTHS will be employed on the MR damper level. Ultimately, the outcomes of all three phases will be evaluated to demonstrate effectiveness and efficiency of RTHS methods.

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REFERENCES

Carrion, J. E., Spencer, B. F., and Phillips, B. M. (2009). "Real-time hybrid testing of a semi-actively controlled structure with an MR damper." *American Control Conference, 2009. ACC '09.*, 5234-5240.

Castaneda, N., Gao, X., and Dyke, S. (2012). "A real-time hybrid testing platform for the evaluation of seismic mitigation in building structures." *ASCE Structures Congress, 2012*, Chicago, Illinois.

Christenson, R., Lin, Y. Z., Emmons, A., and Bass, B. (2008). "Large-Scale Experimental Verification of Semiactive Control through Real-Time Hybrid Simulation." *Journal of Structural Engineering*, 134(4), 522-534.

Dyke, S. J., Spencer, B. F., Sain, M. K., and Carlson, J. D. (1996a). "Experimental Verification of Semi-Active Structural Control Strategies Using Acceleration Feedback." *Proc., 3rd Int. Conf. on Motion and Vibr. Control*, Chiba, Japan.

Dyke, S. J., Spencer, B. F., Sain, M. K., and Carlson, J. D. (1996b). "Modeling and control of magnetorheological dampers for seismic response reduction." *Smart Materials and Structures*, 5(5), 565.

Friedman, A., Zhang, J., Phillips, B. M., Jiang, Z., Agrawal, A., Dyke, S. J., Ricles, J. M., Spencer, B. F., Sause, R., and Christenson, R. (2010). "Accommodating MR Damper Dynamics for Control of Large Scale Structural Systems." *5th World Conference on Structural Control and Monitoring*.

Giraldo, D., Yoshida, O., Dyke, S. J., and Giacosa, L. (2004). "Control-oriented system identification using ERA." *Structural Control and Health Monitoring*, 11(4), 311-326.

Jansen, L. M., and Dyke, S. J. (2000). "Semiactive Control Strategies for MR Dampers: Comparative Study." *Journal of Engineering Mechanics*, 126, 795-803.

Jiang, Z., and Christenson, R. (2011). "A comparison of 200 kN magneto-rheological damper models for use in real-time hybrid simulation pretesting." *Smart Materials and Structures*, 20(6), 065011.

Lin, Y. Z., and Christenson, R. E. (2009). "Comparison of real-time hybrid testing with shake table tests for an MR damper controlled structure." *American Control Conference, 2009. ACC '09.*, 5228-5233.

Ozdagli, A. I., Xi, W., Ding, Y., Zhang, J., Dyke, S., and Wu, B. (2012). "Verification of Real-Time Hybrid Simulation with Shake Table Tests: Phase 1 – Modeling of Superstructure." *International Conference on Earthquake Engineering Research Challenges in the 21st Century*, Harbin, China.

Spencer, B. F., Dyke, S. J., and Deoskar, H. S. (1998). "Benchmark problems in structural control: part I—Active Mass Driver system." *Earthquake Engineering & Structural Dynamics*, 27(11), 1127-1139.

Spencer, B. F., Dyke, S. J., Sain, M. K., and Carlson, J. D. (1997). "Phenomenological Model for Magnetorheological Dampers." *Journal of Engineering Mechanics*, 123(3), 230-238.

The MathWorks Inc. (2011). "MATLAB version 7.10.0." Natick, Massachusetts.