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A fully dynamic magneto-rheological fluid damper model

Z Jiang[1] and R E Christenson[2]

[1] Structural Engineering Professional, Skidmore, Owings & Merrill LLP, One Front Street, Suite 2500, San Francisco, CA 94111, USA
[2] Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, Unit 2037, Storrs, CT 06279, USA

E-mail: zhaoshuo.jiang@som.com

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Abstract
Control devices can be used to dissipate the energy of a civil structure subjected to dynamic loading, thus reducing structural damage and preventing failure. Semiactive control devices have received significant attention in recent years. The magneto-rheological (MR) fluid damper is a promising type of semiactive device for civil structures due to its mechanical simplicity, inherent stability, high dynamic range, large temperature operating range, robust performance, and low power requirements. The MR damper is intrinsically nonlinear and rate-dependent, both as a function of the displacement across the MR damper and the command current being supplied to the MR damper. As such, to develop control algorithms that take maximum advantage of the unique features of the MR damper, accurate models must be developed to describe its behavior for both displacement and current. In this paper, a new MR damper model that includes a model of the pulse-width modulated (PWM) power amplifier providing current to the damper, a proposed model of the time varying inductance of the large-scale 200 kN MR dampers coils and surrounding MR fluid—a dynamic behavior that is not typically modeled—and a hyperbolic tangent model of the controllable force behavior of the MR damper is presented. Validation experimental tests are conducted with two 200 kN large-scale MR dampers located at the Smart Structures Technology Laboratory (SSTL) at the University of Illinois at Urbana-Champaign and the Lehigh University Network for Earthquake Engineering Simulation (NEES) facility. Comparison with experimental test results for both prescribed motion and current and real-time hybrid simulation of semiactive control of the MR damper shows that the proposed MR damper model can accurately predict the fully dynamic behavior of the large-scale 200 kN MR damper.

(Some figures may appear in colour only in the online journal)

1. Introduction

Structural control shows great potential for reducing vibrations in various civil structures under dynamic loading. Structural control can be classified by the type of device used to impart the control force. The three general classes of structural control devices include passive, active, and semiactive (Spencer *et al* 1997). Semiactive devices may be more appropriate for field applications since they offer the reliability associated with passive control devices, maintain the versatility associated with active control devices and only need a low-power supply (Spencer and Nagarajaiah 2003). Numerous semiactive control devices have been proposed for structural control of civil engineering structures. The magneto-rheological (MR) fluid damper appears to be a particularly promising type of semiactive control device (Dyke *et al* 1998, Johnson *et al* 1998). In semiactive control the damper force is controlled in real-time with the intent of improving performance and reducing unwanted responses of the system. In addition to the controllability, stability (in a bounded-input bounded-output sense), and low-power requirements inherent to semiactive devices, MR dampers,

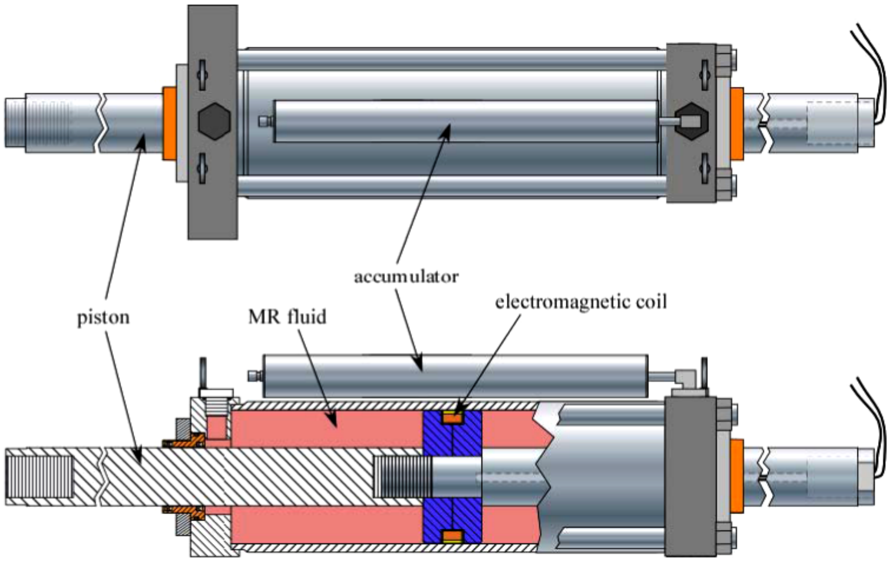

Figure 1. Large-scale semiactive damper schematic.

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 force and minimum force at any given time); and having fewer moving parts, thus reducing maintenance concerns and increasing the response time (compared to conventional variable-orifice dampers).

The focus of this paper is on the modeling of large-scale 200 kN MR dampers for use in the semiactive control of civil structures. The large-scale MR dampers are manufactured by the Lord Corporation. A schematic of the large-scale MR damper used in this paper is shown in figure 1. The damper is 1.47 m in length, having a mass of approximately 280 kg, and an available stroke of 584 mm. The damper's accumulator can accommodate a temperature change in the fluid of 27 °C. The damper can provide control forces of over 200 kN.

The MR damper is controlled with a low-voltage, current-driven command signal. An Advanced Motion Controls pulse-width modulated (PWM) Servo Amplifier is powered by an 80 V DC, 5 A unregulated linear power supply. The servo amplifier is used to provide the command signal that controls the electromagnetic field for each damper. The PWM Servo Amplifier is controlled by a 0–5 V DC signal and utilizes pulse-width modulation for current control. The input control signal can be switched at a rate of up to 1 kHz. Each damper has been fitted with a 1.5KE75A transient voltage suppressor to protect the MR damper electromagnetic coils from unintended and damaging voltage peaks, limiting the peak voltage to 75 V.

Experimental testing is critical in structural dynamics, in particular to validate structural control strategies (Housner *et al* 1994). Full-scale experimental verification of structural control is a challenging proposition. The concept of hybrid simulation was proposed and has been further refined over the past four decades to provide the capability to isolate and physically test only critical components of a structure, while the rest of the structure is simulated numerically in the computer (Hakuno *et al* 1969, Takanashi 1975, Takanashi and Nakashima 1987, Mahin *et al* 1989, Shing *et al* 1996). With the continued advancement of computational technology and hydraulic actuation, a real-time realization of hybrid simulation, called real-time hybrid simulation (RTHS), is now possible to capture the rate-dependent characteristic of physical components (Nakashima 2001). Recent research on RTHS of MR dampers has been conducted for large-scale MR dampers (Park *et al* 2008, Christenson and Lin 2008, Christenson *et al* 2008, Chen *et al* 2010, Phillips *et al* 2010). Prior models for the large-scale MR damper are not able to capture the time-varying effect of the command current on the dynamic force response of the semiactive device. An accurate model of the MR damper that is capable of fully capturing the nonlinear and fully dynamic behavior of these controllable devices is necessary to move toward model-based simulation of large-scale semiactive control for civil structures.

This paper presents a new MR damper model, which is able to extend the previous MR damper models to fully capture the time varying effect of the damper command current for large-scale 200 kN MR dampers. Validation of the proposed model is conducted using large-scale MR dampers located at the Smart Structures Technology Laboratory (SSTL) at the University of Illinois at Urbana-Champaign and the Lehigh University Network for Earthquake Engineering Simulation (NEES) facility. Test results for time varying current commands in step-up tests, a back-driven test, and RTHS of a three-story one-bay steel frame building under El Centro earthquake record with semiactive control are all provided in this paper.

2. Existing MR damper models

Much effort has been devoted by numerous investigators to developing models that identify the hysteretic behavior of MR dampers. Many models have been developed as a result

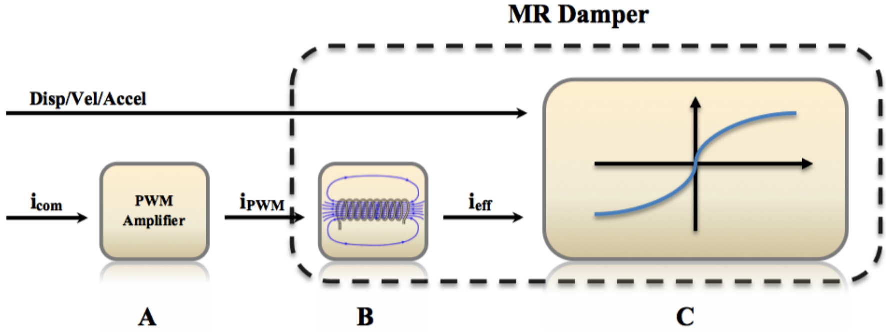

Figure 2. Proposed system and current flow.

of these efforts. The existing models can be classified into two main categories: non-parametric models in which the model parameters do not necessarily have physical meanings; and parametric model in which model parameters have some physical meaning. These models have all been developed from constant-current commands provided to the MR damper and thus represent the behavior of the MR damper for a constant level of current. While the work by Yang (2001) addressed time-varying current by incorporating the dynamics of the amplifier and a fixed inductance in the damper coils, the response time of the MR damper force is observed in recent testing to be a function of time-varying inductance. There has yet to be any model proposed to fully capture the time-varying effect of current on the MR damper force response.

Non-parametric models for MR dampers include Chebyshev polynomials (Ehrgott and Masri 1992, Gavin *et al* 1996), neural networks (Chang and Roschke 1998, Wang and Liao 2004, Du *et al* 2006) and neuro-fuzzy networks (Schurter and Roschke 2000, Wilson and Abdullah 2005). Parametric models consist of some mechanical elements, such as linear viscous, friction, springs, etc. Experimental test results are necessary to identify the parameters associated with these mechanical elements. Although non-parametric models can effectively represent MR damper behavior, they are highly complicated and require massive experimental datasets for model development (Sahin *et al* 2010).

Parametric models include the Bingham visco-plastic model (Stanway *et al* 1987), visco-elastic–plastic model (Gamato and Filisko 1991), nonlinear hysteretic biviscous model (Wereley and Pang 1998), Bouc–Wen model (Spencer *et al* 1997, Yang 2001, Domingez *et al* 2006, Ali and Ramaswamy 2009), polynomial model (Choi *et al* 2001), hyperbolic tangent model (Bass and Christenson 2007), Dahl model (Dahl 1968, Ikhouane and Dyke 2007, Aguirre *et al* 2008), algebraic model (Guo and Hu 2005, Kwok *et al* 2006, Sahin *et al* 2010), and LuGre dynamic friction model (Canudas de Wit *et al* 1995, Alvarez and Jimenez 2002). While the majority of these models are for relatively small-scale (2.0–20 kN) dampers, a subset of the models (Yang 2001, Bass and Christenson 2007, Aguirre *et al* 2008) are for large-scale (180–200 kN) MR dampers.

This paper will make use of an existing parametric model, the hyperbolic tangent model, although the newly developed model of the inductance dynamics of the large-scale MR dampers coils and surrounding MR fluid from this paper can be applied to any of the parametric or non-parametric models.

3. Proposed model

Dynamic response time is an important characteristic for determining the performance of MR dampers in practical civil engineering applications (Yang 2001). For a controllable MR damper, the dynamic behavior can be considered a function of three effects: (1) the controllable and nonlinear force behavior of the MR damper for a constant level of current (effective current, i_{eff}); (2) the dynamic response of the current being commanded (i_{com}) through the pulse-width modulated (PWM) amplifier (i_{PWM}); and (3) the dynamics of the inductance in the damper, which provides the mapping between i_{PWM} and i_{eff}. Typically MR damper models are developed and calibrated at constant currents, which capture the first effect. The dynamics of the time-varying current controlling the dampers must be modeled separately. Yang (2001), provided a model to capture the second effect listed above, namely the PWM amplifier dynamics. A model for the third dynamic effect is proposed in this paper for the large-scale MR dampers. As such, the MR damper model proposed here contains three dynamic components to fully capture the behavior of the large-scale MR damper: a model of the PWM servo amplifier providing current to the damper (A in figure 2); a model of the inductance dynamics of the large-scale MR damper coils and surrounding MR fluid (B in figure 2); and a model of the controllable force behavior of the MR damper (C in figure 2). It should be noted, as indicated by the dashed line in figure 2, that models B and C capture the behavior of the physical MR damper itself, while model A is for the PWM amplifier.

3.1. *Dynamics of PWM amplifier*

A controllable current is provided to the MR damper to achieve the desired control forces. A PWM servo amplifier is used, in place of a voltage driven power supply, since it offers substantial reductions in the response time (Yang 2001). The PWM amplifier used in this research is the 30A8 PWM servo drive manufactured by Advanced Motion Controls. The PWM amplifier, as connected to the MR damper, has its own dynamics that need to be captured. Yang (2001)

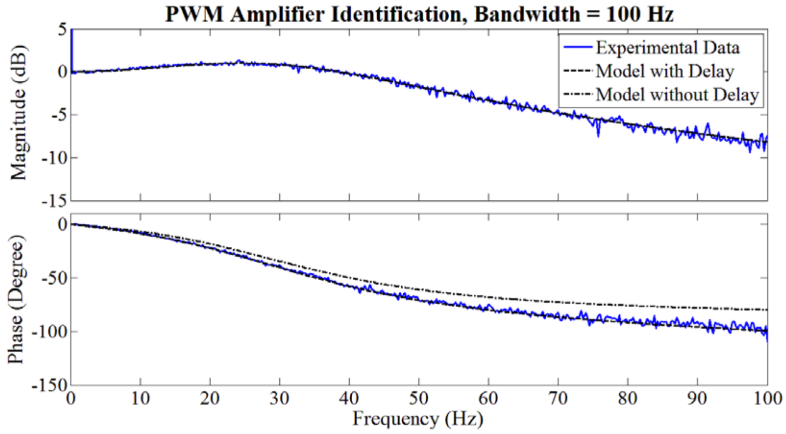

Figure 3. PWM amplifier identification.

proposed a second-order differential equation to describe the PWM servo amplifier with a PI controller. The PWM amplifier identification tests for this study were conducted at the Lehigh University NEES facility. A band-limited Gaussian white noise with 100 Hz bandwidth is sent to the PWM amplifier. The input, command current, and the output, measured current, of the PWM amplifier are recorded and the transfer function determined (Bendat and Persol 2000). The transfer function between the output and input of the PWM amplifier are curve-fittted. The resulting second-order model of the PWM amplifier is determined to be

$$H(s) = \frac{I_{\mathrm{PWM}}}{I_{\mathrm{com}}} \frac{231s + 51881}{s^2 + 314s + 51881}, \tag{1}$$

where I_{PWM} is the measured current and I_{com} is the command current. The magnitude and phase of the PWM model is compared to the experimentally measured transfer function in figure 3. While the magnitude matches well, it is observed that the phase for the system in equation (1) has an increasing error with larger frequencies. The phase difference is effectively eliminated by including a constant time delay of 0.55 ms in series with the second-order transfer function. The resulting PWM model with delay is shown in figure 3 to accurately capture both the magnitude and phase of the PWM amplifier over the frequency range of interest.

3.2. Dynamics in the magnetic coils and surrounding MR fluid of the damper

To identify the dynamics in the magnetic coils and surrounding MR fluid of the damper, the rise time of the force is examined. Being consistent with the previous literature on MR dampers, the response time of the force is defined as the time required to transition from the initial state to the 95% of the final state (Yang 2001). The response time of the current produced by the PWM amplifier, I_{PWM}, for a step function of 0–2.5 A, is measured in figure 4 to be 20 ms. The corresponding rise time of the MR damper force during this same test when subjected to a constant velocity of 317 mm s^{-1}, also shown in figure 4, is measured to be 550 ms. While the response time of the MR fluid itself is less than 10 ms (www.lord.com) and the response time of the PWM amplifier is around 20–30 ms, research has commonly reported that the response time of the MR damper is much larger (Yang 2001, An and Kwon 2003, Nam and Park 2009).

This discrepancy is due to the inductance of the electromagnetic coil of the MR damper (Koo *et al* 2006). Within the MR damper, the current output from the PWM amplifier is passed through an electromagnetic coil, which generates a magnetomotive force. The magnetic flux produced by the magnetomotive force magnetizes the MR fluid and changes its viscosity. The change in MR fluid viscosity results in a change in the damping force. When the input current varies, the magnetic field changes accordingly. According to Faraday's law, the change of the magnetic field induces a counter electromotive force (Hayt and Buck 2006). The electromotive force opposes the change in magnetic field producing it, thus creating an eddy current. The existence of eddy currents changes the inductance of the electromagnetic system, thus altering the current which is used to effectively magnetize the MR fluid, as shown in figure 2.

The MR damper electromagnetic circuit is modeled using an electrical network in which a resistor and inductor are connected in series (Yang 2001). The dynamic of the model of the electromagnetic circuit is

$$G(s) = \frac{I}{I_{\mathrm{PWM}}} = \frac{1}{1 + \frac{L}{R}s}, \tag{2}$$

where R is resistance of the damper and L is the inductance of the coil. The prior work by Yang (2001) assumed the inductance, L, remains constant. It is observed in recent tests (Jiang 2012) that using constant inductance does not fully capture the behavior of MR damper. To fully capture the time-varying effective current, a time-varying inductance function is proposed here for the large-scale MR dampers as

$$L(t) = L_0 + L_{\mathrm{eddy}}(t), \tag{3}$$

where L_0 is the inductance constant of the damper, which is 1 H, and L_{eddy} is the inductance variation due to the eddy current. The response of the electromagnetic system can be

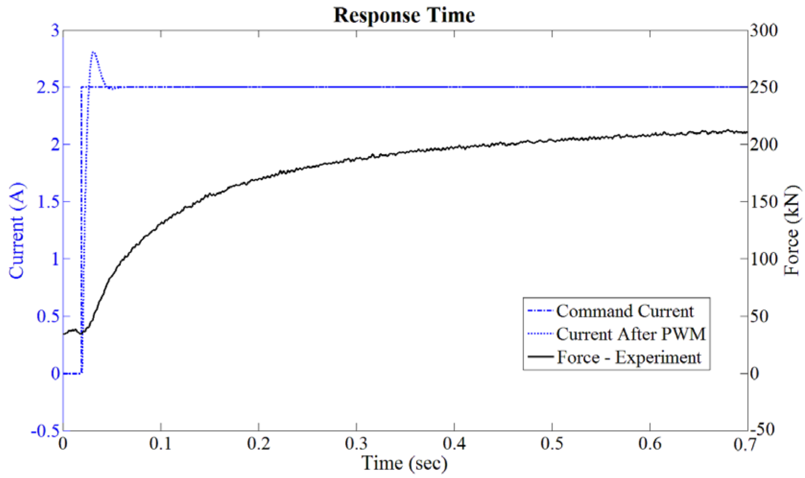

Figure 4. Response time of the command current and MR damper force for step input.

expressed according to Faraday's law as:

$$\varepsilon_{\mathrm{inv}} = -\frac{\mathrm{d}\phi}{\mathrm{d}t}, \tag{4}$$

where $\varepsilon_{\mathrm{inv}}$ is the electromotive force and ϕ is the magnetic flux passing through the magnetic circuit. According to the definition of self-induction of an electromagnetic system, the inductance induced by the eddy current is:

$$\varepsilon_{\mathrm{inv}} = L_{\mathrm{eddy}}\frac{\mathrm{d}i_{\mathrm{eddy}}}{\mathrm{d}t}, \tag{5}$$

where i_{eddy} is the eddy current generated in the magnetic circuit. Further, according to Ohm's law:

$$\varepsilon_{\mathrm{inv}} = Ri_{\mathrm{eddy}}. \tag{6}$$

By setting equal the right hand of equations (5) and (6) and solving for L_{eddy}:

$$L_{\mathrm{eddy}} = \frac{Ri_{\mathrm{eddy}}}{\mathrm{d}i_{\mathrm{eddy}}/\mathrm{d}t}. \tag{7}$$

Substituting equation (7) into (3), the inductance function $L(t)$ can be found as:

$$L(t) = L_0 + \frac{Ri_{\mathrm{eddy}}}{\mathrm{d}i_{\mathrm{eddy}}/\mathrm{d}t}. \tag{8}$$

3.3. Hyperbolic tangent MR damper model

The proposed dynamic models of the PWM amplifier and the inductance dynamics of the coil and surrounding MR fluid can be placed in series with any of the traditional MR damper models. The hyperbolic tangent model, due to its numerical stability during severe nonlinear damper behavior, is adopted in this study to characterize the dynamic response of 200 kN MR dampers.

The hyperbolic tangent model was proposed by Gavin *et al* (2001) for an 8 kN electro-rheological fluid damper. Gavin's model is a simplified version of a system proposed by Gamato and Filisko (1991). The hyperbolic tangent model used in this research is based on the model proposed by Bass and Christenson (2007). A schematic of this model is shown in figure 5.

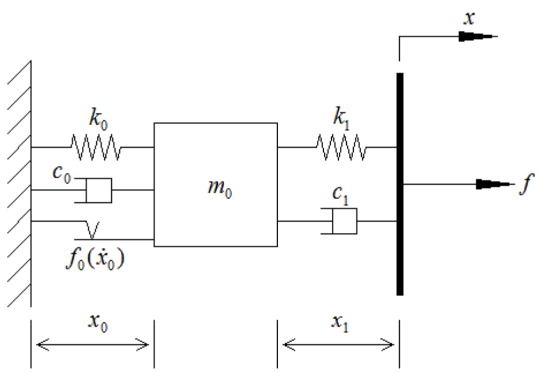

Figure 5. Schematic of the MR damper hyperbolic tangent model.

As shown in figure 5, the hyperbolic tangent model is composed of two sets of spring-dashpot elements, which are connected by an inertial mass element. The inertial mass element resists motion by means of a Coulomb friction element. The displacement and velocity of the inertial mass relative to a fixed base, x_0 and $\dot{x}_0$, and displacement and velocity of damper piston end relative to the inertial mass, x and $\dot{x}_1$, are summed together, resulting in the displacement and velocity across the damper, x and $\dot{x}$. The pre-yield visco-elastic behavior is modeled by k_1 and c_1. The post-yield visco-elastic behavior is modeled by k_0 and c_0. The m_0 term represents the inertia of both fluid and the moving piston. The Coulomb friction is a function of the velocity across the element such that $f_0(\dot{x}_0) = f_0 \tanh(\dot{x}_0/V_{\mathrm{ref}})$, where the parameter f_0 is the yield force and V_{ref} is a reference velocity. The dynamics of the system and force output can be described in state space form as

$$\begin{bmatrix}\dot{x}_0\\ \ddot{x}_0\end{bmatrix} = \begin{bmatrix}0 & 1\\ (-k_0-k_1)/m_0 & (-c_0-c_1)/m_0\end{bmatrix}\begin{bmatrix}x_0\\ \dot{x}_0\end{bmatrix} + \begin{bmatrix}0 & 1\\ k_1/m_0 & c_1/m_0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\end{bmatrix} + \begin{bmatrix}0\\ -1/m_0\end{bmatrix} f_0\tanh(\dot{x}_0/V_{\mathrm{ref}}) \tag{9}$$

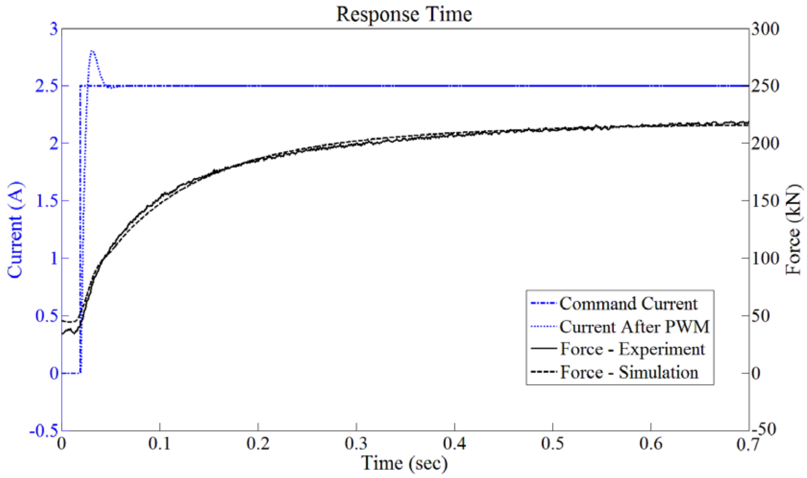

Figure 6. Response time of command current and MR damper force for step input with comparison to proposed MR damper model.

Table 1. Parameters of the hyperbolic tangent model.

Parameters as a function of damper current (A)	Units
$k_0 = (0.10i^4 - 1.00i^3 + 1.30i^2 + 2.30i + 6.20) \times 10^{-4}$	kN mm^{-1}
$k_1 = -2.43i^4 + 23.76i^3 - 80.70i^2 + 110.62i + 55.08$	kN mm^{-1}
$c_0 = (-0.98i^4 + 9.33i^3 - 29.96i^2 + 35.80i + 12.64) \times 10^{-2}$	kN s mm^{-1}
$c_1 = (0.62i^4 - 6.73i^3 + 26.69i^2 - 46.06i + 35.67) \times 10^{-2}$	kN s mm^{-1}
$m_0 = (0.16i^4 - 1.62i^3 + 5.48i^2 - 7.05i + 4.85) \times 10^{-3}$	kg
$f_0 = 1.52i^4 - 10.27i^3 + 2.79i^2 + 94.56i + 6.19$	kN
$V_{\mathrm{ref}} = -0.12i^4 + 1.36i^3 - 6.19i^2 + 13.12i + 0.76$	mm s^{-1}

and the MR damper force, f, is a function of the state of equation (9) and the displacement and velocity across the damper as

$$f = [-k_1 \ \ -c_1] \begin{bmatrix} x_0 \\ \dot{x}_0 \end{bmatrix} + [k_1 \ \ c_1] \begin{bmatrix} x \\ \dot{x} \end{bmatrix}. \qquad (10)$$

The hyperbolic tangent model requires seven parameters ($k_0, k_1, c_0, c_1, m_0, f_0, V_{\mathrm{ref}}$) to fully characterize the dynamic behavior of the MR damper. The hyperbolic tangent model parameters are determined for fixed sinusoidal displacements and frequency combinations and constant current using a multidimensional unconstrained nonlinear minimization Nelder–Mead direct search simplex method (MathWorks 2007, Lagarias *et al* 1998). The function minimized in this direct search method is the root mean square (RMS) error between the measured and simulated forces over sinusoidal excitations. The values of each model parameter are averaged over the frequency and amplitude for each of the constant current levels identified. Polynomials are fit to the averaged data points for each model parameter as a function of current. Further details on how these parameters are determined can be found in Bass and Christenson (2007). The parameters proposed in Bass and Christenson (2007) are further modified and refined to accommodate over-driven and back-driven control strategies. The parameters of the hyperbolic tangent model used in this study are shown in table 1.

4. Validation

4.1. Step-up test

Using the proposed updated hyperbolic tangent MR damper model with the updated PWM model and newly proposed dynamic model of inductance, the comparison between the simulation and experimental data for a constant damper velocity and step current input from figure 4 is presented in figure 6. The model used in the simulation is able to accurately predict the force rise time of the MR damper for a step input.

4.2. Back-driven test

One common challenge in controlling MR dampers is that when the damper current is turned off the control force does not return to a low force for an extended period of time (Yang 2001). For the 200 kN MR dampers the time required for the damper force to return to the off state is over 500 ms. To achieve a faster response time of the desired force, a ±7.5 A current may be used instead of ±2.5 A in the controller in an over-driven/back-driven approach, thus giving better control performance of the MR damper (Yang 2001, Phillips *et al* 2010). Figure 7 shows the comparison between the proposed MR damper model and the experimental data for a back-driven control approach where the back-driven command current is pulsed on for 0.2 ms and the damper is moved at a constant velocity of 50 mm s^{-1}. The response time for the damper force to return to low damper force, even in this aggressive control strategy, is predicted well by the model.

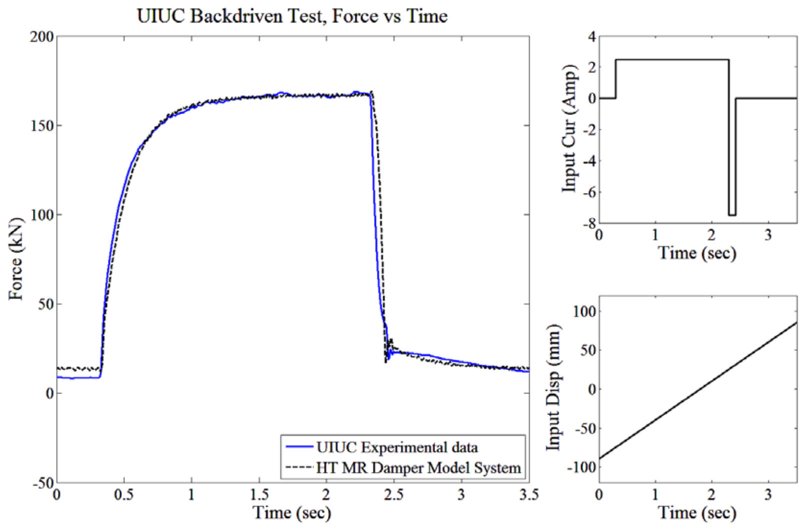

Figure 7. Back-driven—force time history.

4.3. RTHS test

Real-time hybrid simulation is a powerful and cost-effective alternative for testing rate-dependent structural components, such as advanced energy dissipation devices, and serves as the state-of-the-art method to experimentally test MR dampers. High-fidelity models of the physical components, the MR dampers, are very important for pre-testing of the RTHS system (Jiang and Christenson 2011) and to move toward model-based simulation. In this section, the performance of the proposed MR damper model will be validated to RTHS test results. To demonstrate the inherent variability in RTHS testing from the dampers themselves and the experimental facilities as a comparison to the purely simulated results using the proposed model, the RTHS tests are conducted on two different large-scale MR dampers located at the University of Illinois at Urbana-Champaign and the Lehigh University NEES facility.

At the Lehigh facility, the MR damper is connected to the hydraulic actuator through a stiff horizontal steel section. This section extends the reach of the actuator to accommodate the spacing of anchor locations that secure the damper and the actuator to the laboratory strong floor. A 534 kN load cell is installed between the horizontal steel section and the damper piston to directly measure the force developed in the damper. An actuators with 1700 kN force capacity which can generate up to about 500 kN at a piston velocity of 1.0 m s^{-1} with 3 servo-valves is used for this real-time hybrid testing. An inverse compensation procedure is used at the Lehigh University to minimize actuator delay in the real-time hybrid simulation (Chen *et al* 2008).

At the University of Illinois, a 556 kN actuator with a stroke of ±152.4 mm is used. A 445 kN load cell in line with the actuator measures the restoring force of the attached specimen. The actuator and MR damper are both mounted on a 7.62 mm-thick steel plate. Steel blocks and wedges are used to prevent lateral translation of the actuator and specimen. The steel plate is tied down to the strong floor using threaded rods to prevent flexing of the plate and shear keys are used to prevent lateral translation of the plate. Illinois uses a model-based feedforward–feedback delay compensation technique (Carrion and Spencer 2007). Pictures of the experimental setups for the large-scale MR damper at the University of Illinois and Lehigh University are shown in figures 8 and 9, respectively.

Two error evaluation criteria are used to evaluate the performance of the MR damper model: normalized RMS error of the damper force, as calculated using equation (11), and normalized absorbed energy error, as calculated using equation (12).

$$Err_f^{\rm rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[f^{\exp}(t_i) - f^{\rm sim}(t_i)]^2} \Big/ f_{\max}^{\exp}, \qquad (11)$$

where $f^{\exp}$ and $f^{\rm sim}$ are the damper forces from the physical experiment and from the damper model at time t_i, respectively. $f_{\max}^{\exp}$ is the maximum damper force from the physical experiment.

The energy absorbed by the damper during the seismic event is introduced and used as a means to evaluate the performance of the damper models in this study. The absorbed energy is calculated by summing up the areas under the damper force–displacement curve during an event.

$$Err^{\rm energy} = |E^{\exp} - E^{\rm sim}|/E^{\exp}, \qquad (12)$$

where $E^{\exp}$ and $E^{\rm sim}$ the total energy absorbed by the damper in the physical experiment and by the damper model in the pure numerical simulation during an event, respectively.

The simulated component of the hybrid test in this study is a benchmark structure proposed by Phillips *et al* (2010). The structure is a three-story one-bay steel frame building, with total weight of 596 kN. The structure is a linear, in-plane, three degrees-of-freedom model with an MR damper attached between the ground and first story. The MR damper is controlled using a semiactive controlled strategy. A primary

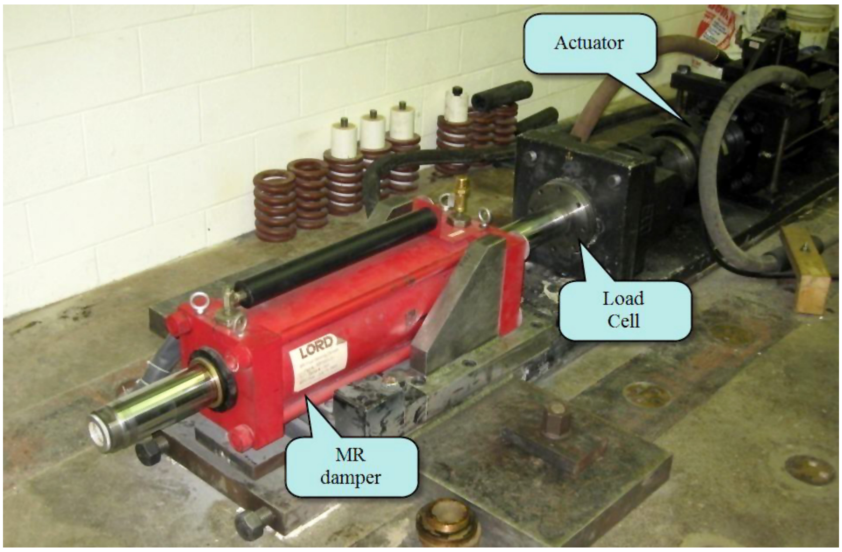

Figure 8. MR damper test setup at University of Illinois.

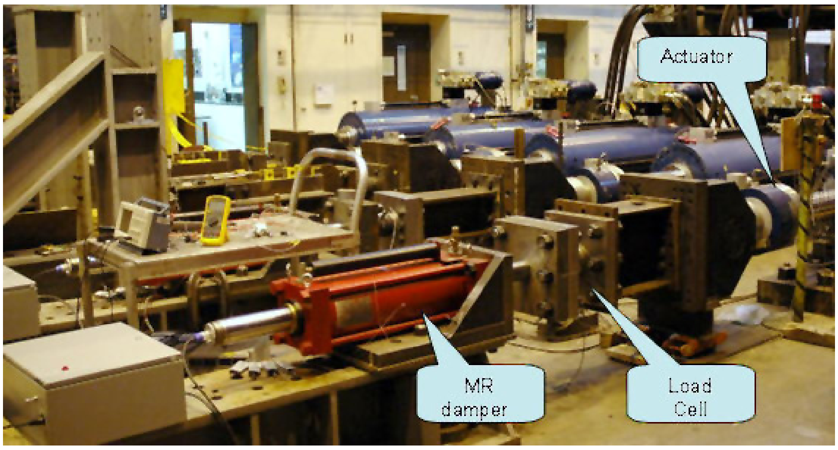

Figure 9. MR damper test setup at Lehigh NEES facility.

Linear Quadratic Gaussian (LQG) controller together with a secondary clipped optimal controller is used to provide the proper current level to the damper. This controller uses the clipped optimal control algorithm with a maximum current of 2.5 A. The LQR gains are selected to achieve optimal response action on force-tracking with $R = 1500$ and $Q = 1$. Further details regarding the building structure and the control strategy are presented in Phillips *et al* (2010).

The N–S component of the El Centro earthquake recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of 18 May 1940 is utilized as the excitation in this study.

The pure numerical simulation results with a hyperbolic tangent MR damper model are compared against the RTHS results to evaluate the performance of the model. Figure 10 shows the force comparison between the MR damper model and the RTHS results. To highlight the differences more closely, a 18 s portion of the force response is shown in figure 11. The comparison of the response of the structure for the first-story displacement is shown in figures 12 and 13. The first-story displacement response represents the response with the greatest disparity between experimental and simulated responses.

As observed from figure 11, there is a small discrepancy between the forces from the hyperbolic tangent MR damper model and those from physical specimens, which causes the small discrepancy in story displacement shown in figure 13. The discrepancy may be due to the model not being designed and calibrated for the high velocities (>300 mm s^{-1}) experienced during the testing and the fact that the semiactive control specifies command currents based on the simulated building response and any difference can amplify the discrepancy. The comparison of energy absorbed by the damper model and the physical dampers is shown in figure 14.

In addition to the normalized RMS error of the damper force, the normalized displacement RMS error is calculated

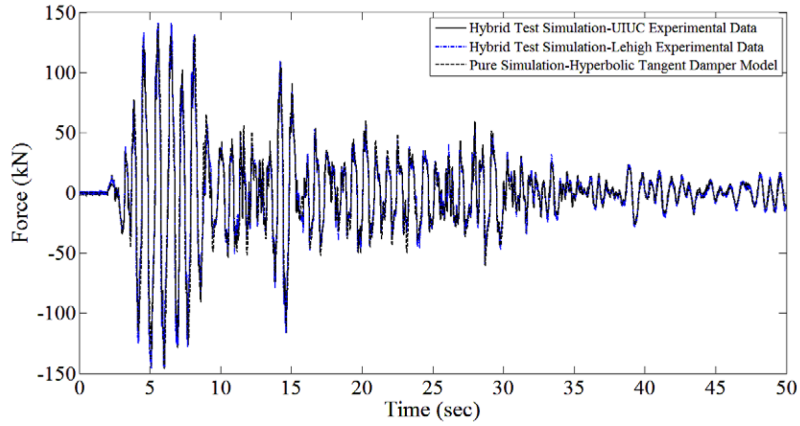

Figure 10. Real-time hybrid test comparison, clipped optimal control, force time history.

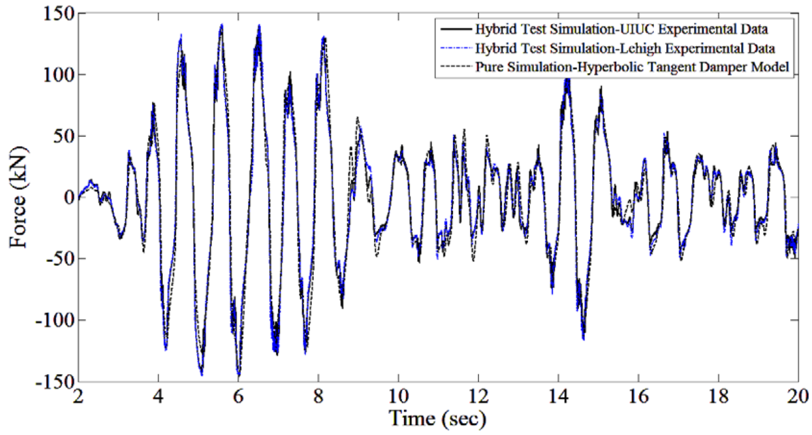

Figure 11. Real-time hybrid test comparison, clipped optimal control, force time history (zoom-in).

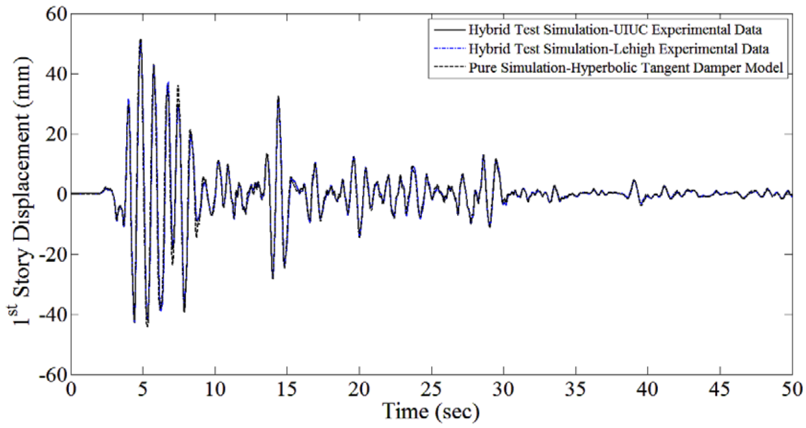

Figure 12. Real-time hybrid test comparison, clipped optimal control, first-story displacement.

to evaluate the performance of the MR damper model.

$$Err_x^{\mathrm{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[x^{\mathrm{exp}}(t_i) - x^{\mathrm{sim}}(t_i)]^2} \Bigg/ x_{\mathrm{max}}^{\mathrm{exp}} \qquad (13)$$

where x^{exp} and x^{sim} are the displacement across the damper from the physical experiment and the damper model at time t_i, respectively. $x_{\mathrm{max}}^{\mathrm{exp}}$ is the maximum displacement across the damper from the physical experiment. Results are provided in table 2. The normalized RMS error for displacement and force are larger for the simulation than for the RTHS experiment, as compared to the University of Illinois RTHS. While the model was developed for different inputs, the force response of the MR damper model is consistent with the physical tests for this particular RTHS.

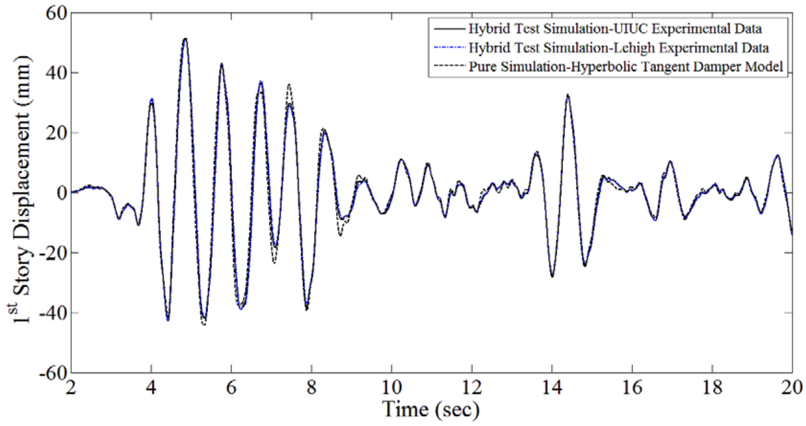

Figure 13. Real-time hybrid test comparison, clipped optimal control, first-story displacement (zoom-in).

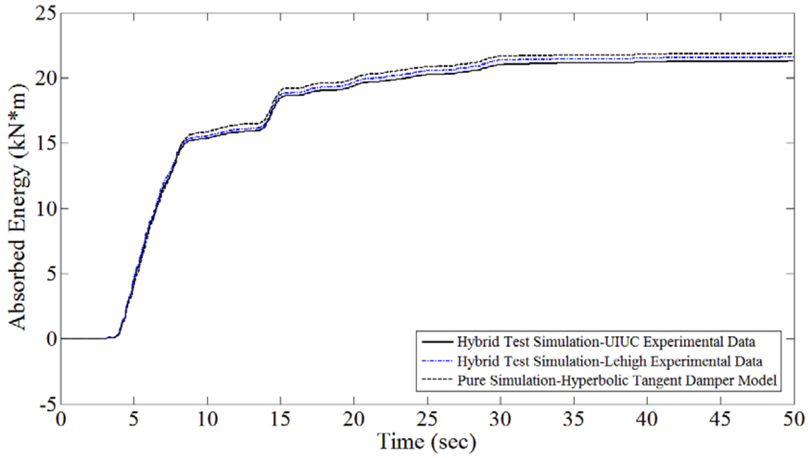

Figure 14. Real-time hybrid test comparison, clipped optimal control, absorbed energy.

Table 2. RTHS—error comparison. (Note: the analytical model and Lehigh experimental results are compared to the University of Illinois experimental results.)

Damper model	First-story normalized displacement RMS error (%)	Normalized force RMS error (%)	Absorbed energy (kN m)	Normalized energy error (%)
Proposed MR damper model	2.70	5.61	21.88	2.83
Lehigh physical damper	0.72	2.85	21.59	1.45
Illinois physical damper	—	—	21.28	—

5. Conclusion

This paper presents a new MR damper model that incorporates the dynamics of the inductance. In this paper, an MR damper model that includes a model of the pulse-width modulated (PWM) power amplifier providing current to the damper, the proposed model of the time-varying inductance of the large-scale 200 kN MR dampers coils and surrounding MR fluid—a dynamic behavior that is not typically modeled—and a hyperbolic tangent model of the controllable force behavior of the MR damper is presented. The model is validated using experimental test data conducted on two 200 kN large-scale MR dampers located at the SSTL at the University of Illinois at Urbana-Champaign and the Lehigh University NEES facility. Comparison with experimental test results for both prescribed motion and current and real-time hybrid simulation of semiactive control of the MR damper shows that the proposed MR damper model can accurately predict the force response of the MR damper for constant velocity and a step input of the current, capturing the rise time of the damper force. The damper model is also shown to accurate predict a back-driven current control scheme used to reduce the response time of the force to the off state, illustrating the usefulness of the MR damper model in simulating over-driven and back-driven control strategies. Lastly, the fully dynamic behavior of the large-scale 200 kN MR damper model is compared to a RTHS of actual dampers at Illinois and Lehigh applied to a three-story one-bay steel frame building using semiactive control of the dampers. The model is shown to provide less than a 3% error in the RMS first-story displacement and measure of energy dissipation as compared to the RTHS test. The 200 kN MR damper model presented in this paper is available for public use from the NEES database (NEEShub) at http://nees.org/resources/3479.

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References

Aguirre N, Ikhouane F, Rodellar J and Christenson R E 2008 Modeling and identification of large scale magnetorheological dampers *4th European Conf. on Structural Control (St Petersburg)*

Ali Sk F and Ramaswamy A 2009 Testing and modeling of MR damper and its application to SDOF systems using integral backstepping technique *J. Dyn. Syst. Meas. Control ASME* **131** 021009

Alvarez L and Jimenez R 2002 Real-time identification of magneto-rheological dampers *IFAC'02: 15th Triennial World Congr.*

An J and Kwon D S 2003 Modeling of a magnetorheological actuator including magnetic hysteresis *J. Intell. Mater. Syst. Struct.* **14** 541–50

Bass B J and Christenson R E 2007 System identification of a 200 kN magneto-rheological fluid damper for structural control in large-scale smart structures *Proc. American Control Conf. (New York)* pp 2690–5

Bendat J S and Persol A G 2000 *Random Data Analysis and Measurement Procedures* (New York: Wiley–Interscience)

Canudas de Wit C, Olsson H, Astrom K J and Lischinsky P 1995 A new model for control of systems with friction *IEEE Trans. Autom. Control* **40** 419–25

Carrion J E and Spencer B F 2007 Model-based strategies for real-time hybrid testing *Newmark Structural Engineering Laboratory Report Series* NSEL, University of Illinois, Report 006

Chang C C and Roschke P 1998 Neural network modeling of a magnetorheological damper *J. Intell. Mater. Syst.* **9** 755–64

Chen C, Ricles J M, Marullo T M and Mercan O 2008 Real-time hybrid testing using the unconditionally stable explicit CR integration algorithm *Earthq. Eng. Struct. Dyn. IAEE* **38** 23–44

Chen C, Ricles M J, Sause R and Christenson R E 2010 Experimental evaluation of an adaptive inverse compensation technique for real-time simulation of a large-scale magneto-rheological fluid damper *Smart Mater. Struct.* **19** 025017

Choi S B, Lee S K and Park Y P 2001 A hysteresis model for the field-dependent damping force of a magnetorheological damper *J. Sound Vib.* **245** 375–83

Christenson R E and Lin Y Z 2008 Real-time hybrid simulation of a seismically excited structure with large-scale magneto-rheological fluid dampers *Hybrid Simulation Theory, Implementations and Applications* ed V E Saouma and M V Sivaselvan (London: Taylor and Francis) NL ISBN: 978-0-415-46568-7

Christenson R E, Lin Y Z, Emmons A T and Bass B 2008 Large-scale experimental verification of semiactive control through real-time hybrid simulation *ASCE J. Struct. Eng.* **134** 522–35

Dahl P R 1968 A solid friction model *Technical Report* TOR-0158(3107-18)-1 (El Segundo, CA: the Aerospace Corporation)

Domingez A, Sedaghati R and Stiharu I 2006 A new dynamic hysteresis model for magnetorheological dampers *Smart Mater. Struct.* **15** 1179–89

Du H, Lam J and Zhang N 2006 Modeling of a magneto-rheological damper by evolving radial basis function networks *Eng. Appl. Artif. Intell.* **19** 869–81

Dyke S J, Spencer B F, Sain M K and Carlson J D 1998 An experimental study of MR dampers for seismic protection *Smart Mater. Struct.* **7** 693

Ehrgott R C and Masri S F 1992 Modeling the oscillatory dynamic behavior of electrorheological materials in shear *Smart Mater. Struct.* **1** 275–85

Gamato D and Filisko F E 1991 High frequency dynamic mechanical study of an aluminosilicate electrorheological material *J. Rheol.* **35** 1411–25

Gavin H, Hoagg J and Dobossy M 2001 Optimal design of MR dampers *Proc. US–Japan Workshop on Smart Structures for Improved Seismic Performance in Urban Regions (Seattle)* pp 225–36

Gavin H P, Hanson R D and Filisko F E 1996 Electrorheological dampers, part II: testing and modeling *J. Appl. Mech.* **63** 676–82

Guo D and Hu H 2005 Nonlinear-stiffness of a magnetorheological fluid damper *Nonlinear Dyn.* **40** 241–9

Hakuno M, Shidawara M and Hara T 1969 Dynamic destructive test of a cantilever beam, controlled by an analog-computer *Trans. Japan Soc. Civil Eng.* **171** 1–9 (in Japanese)

Hayt W H Jr and Buck J 2006 *Engineering Electromagnetics* (New York: McGraw-Hill)

Housner G W, Soong T T and Masri S F 1994 Second generation of active structural control in civil engineering *Proc. 1st World Conf. on Structural Control* pp 3–18, Pasadena California Panel

Ikhouane F and Dyke S J 2007 Modeling and identification of a shear mode magnetorheological damper *Smart Mater. Struct.* **16** 605–16

Jiang Z and Christenson R 2011 A comparison of 200 kN magneto-rheological damper models for use in real-time hybrid simulation pretesting *Smart Mater. Struct.* **20** 065011

Jiang Z 2012 Increasing resilience in civil structures using smart damping technology *PhD Dissertation* University of Connecticut, CT

Johnson E A, Ramallo J C, Spencer B F and Sain M K 1998 Intelligent Base Isolation Systems *Proc. 2nd World Conf. on Structural Control (2WCSC)* vol 1 *(Kyoto)* pp 367–76

Koo J H, Goncalves F D and Ahmadian M 2006 A comprehensive analysis of the response time of MR dampers *Smart Mater. Struct.* **15** 351–8

Kwok N M, Ha Q P, Nguyen T H, Li J and Samali B 2006 A novel hysteretic model for magnetorheological fluid dampers and parameter identification using particle swarm optimization *Sensors Actuators* A **132** 441–51

Lagarias J C, Reeds J A, Wright M H and Wright P E 1998 Convergence properties of the Nelder–Meade simplex method in low dimensions *SIAM J. Opt.* **9** 112–47

Mahin S A, Shing P B, Thewalt C R and Hanson R D 1989 Pseudodynamic test method—current status and future directions *J. Struct. Eng.* **115** 2113–28

Nakashima M 2001 Development, potential, and limitations of real-time online (pseudo-dynamic) testing *Phil. Trans. R. Soc. London* A **359** 1851–67

Nam Y J and Park M K 2009 Electromagnetic design of a magnetorheological damper *J. Intell. Mater. Syst. Struct.* **20** 181–91

Park E, Lee S and Lee H 2008 Real-time hybrid testing of a steel-structure equipped with large-scale magneto-rheological dampers applying semi-active control algorithms *Proc. ASME 2008 Conf. on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS 2008)* pp 387–98, Paper no SMASIS2008-488

Phillips B, Chae Y, Jiang Z, Spencer B F, Ricles J, Christenson R, Dyke S J and Agrawal A 2010 Real-time hybrid simulation benchmark study with a large-scale MR damper *Proc. 5th World Conf. on Structural Control and Monitoring (Tokyo)*

Şahin İ, Engin T and Çeşmeci Ş 2010 Comparison of some existing parametric models for magnetorheological fluid dampers *Smart Mater. Struct.* **19** 035012

Schurter K C and Roschke P N 2000 Fuzzy modeling of a magnetorheological damper using Anfis *Proc. IEEE Int. Conf. on Fuzzy Systems* pp 122–7

Shing P B, Nakashima M and Bursi O S 1996 Application of pseudodynamic test method to structural research *Earthq. Spectra* **12** 29–56

Spencer B F, Dyke S J, Sain M K and Carlson J D 1997 Phenomenological model of a magnetorheological damper *J. Eng. Mech. Div. ASCE* **123** 230–8

Spencer B F and Nagarajaiah S 2003 State of the art of structural control *J. Struct. Eng.* **129** 845–56

Stanway R, Sproston J and Stevens N 1987 Non-linear modeling of an electro-rheological vibration damper *J. Electrost.* **20** 167–84

Takanashi K 1975 Non-linear earthquake response analysis of structures by a computer actuator on-line system (part 1: details of the system) *Trans. Archit. Inst. Japan* **229** 77–83 (in Japanese)

Takanashi K and Nakashima M 1987 Japanese activities on on-line testing *J. Eng. Mech.* **113** 1014–32

Wang D H and Liao W H 2004 Modeling and control of magnetorheological fluid dampers using neural networks *Smart Mater. Struct.* **14** 111–26

Wereley N and Pang L 1998 Nondimensional analysis of semi-active electrorheological and magnetorheological dampers using approximate parallel plate models *Smart Mater. Struct.* **7** 732–43

Wilson C M D and Abdullah M 2005 Structural vibration reduction using fuzzy control of magnetorheological dampers *Proc. 2005 Structures Congr. 2005 Forensic Engineering Symp.* doi:10.1061/40753(171)198

Yang G 2001 Large-scale magnetorheological fluid damper for vibration mitigation: modeling, testing and control *PhD Dissertation* University of Notre Dame, Indiana, USA