Structural Engineering and Mechanics, Vol. 17, No. 3-4 (2004) 493-526
DOI: http://dx.doi.org/10.12989/sem.2004.17.3_4.493

State-of-the-art of semiactive control systems using MR fluid dampers in civil engineering applications

H.-J. Jung†

Department of Civil and Environmental Engineering, Sejong University, Seoul 143-747, Korea

B. F. Spencer, Jr.‡

Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

Y. Q. Ni†

Department of Civil and Structural Engineering, Hong Kong Polytechnic University, Hong Hum, Kowloon, Hong Kong

I.-W. Lee‡†

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea

(Received January 10, 2003, Accepted December 25, 2003)

Abstract. Semiactive control systems have received considerable attention for protecting structures against natural hazards such as strong earthquakes and high winds, because they not only offer the reliability of passive control systems but also maintain the versatility and adaptability of fully active control systems. Among the many semiactive control devices, magnetorheological (MR) fluid dampers comprise one particularly promising class. In the field of civil engineering, much research and development on MR fluid damper-based control systems has been conducted since this unique semiactive device was first introduced to civil engineering applications in mid 1990s. In 2001, MR fluid dampers were applied to the full-scale in-service civil engineering structures for the first time. This state-of-the-art paper includes a detailed literature review of dynamic models of MR fluid dampers for describing their complex dynamic behavior and control algorithms considering the characteristics of MR fluid dampers. This extensive review provides references to semiactive control systems using MR fluid dampers. The MR fluid damper-based semiactive control systems are shown to have the potential for mitigating the responses of full-scale civil engineering structures under natural hazards.

Key words: semiactive control; MR fluid damper; dynamic models; control algorithms; full-scale applications.

† Assistant Professor
‡ Nathan M. Newmark Professor
‡† Professor

1. Introduction

In the field of civil engineering, the control of excessive structural responses produced by natural hazards such as earthquakes and strong winds represents one of the main challenges. In recent years, semiactive control systems have received considerable attention among the various response control strategies, because they not only offer the reliability of passive control systems, but also maintain the versatility and adaptability of fully active control systems. A semiactive control system has the basic configuration as shown schematically in Fig. 1 (Soong and Spencer 2002), where the control actuators do not add mechanical energy directly to the structure, hence bounded input/bounded output stability is guaranteed (Spencer and Sain 1997). Symans and Constantinou (1999) provided a detailed literature review of semiactive control systems for seismic protection and also demonstrated that semiactive control devices such as stiffness control devices, electrorheological (ER) fluid dampers, magnetorheological (MR) fluid dampers, friction control devices, fluid viscous dampers, and tuned mass/liquid dampers have the potential for improving the seismic behavior of full-scale civil engineering structures. Spencer and Sain (1997), Soong and Spencer (2002), and Spencer and Nagarajaiah (2003) also reviewed the recent and rapid developments in structural control in the field of civil engineering, focusing on semiactive control and its implementation in full-scale structures.

Among many semiactive control devices, MR fluid dampers are one particularly promising class because of its mechanical simplicity, high dynamic range, low operating power requirements, large force capacity, and environmental robustness. MR fluid dampers utilize MR fluids, which typically consist of micron-sized, magnetically polarizable dispersed in a carrier medium such as mineral or

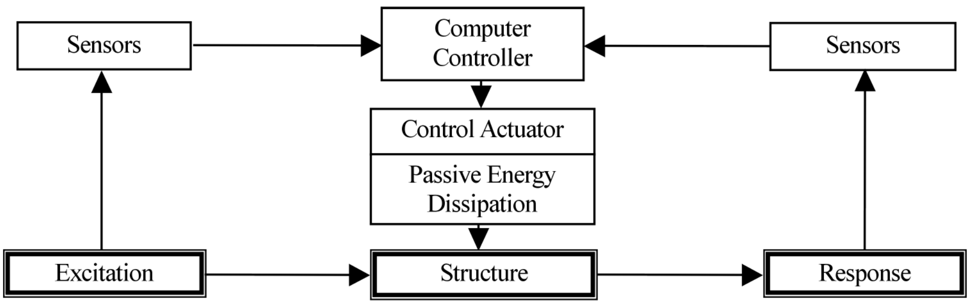
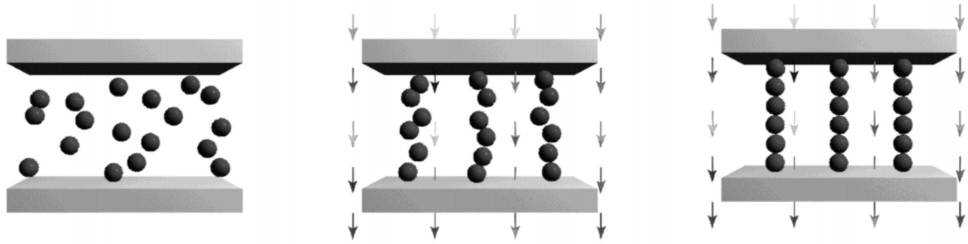


Fig. 1 Blcok diagram of semiactive control system (Soong and Spencer 2002)



(a) without magnetic field (b) with magnetic field

Fig. 2 Behavior mechanism of MR fluids (http://www.rheonetic.com/)

silicone oil, to provide controllable damping forces. When a magnetic field is applied to the fluids, particle chains form, and the fluid becomes a semi-solid and exhibits viscoplastic behavior in a few milliseconds (see Fig. 2).

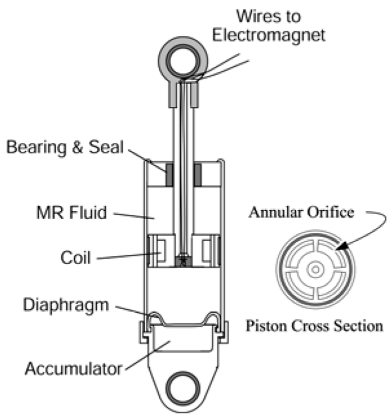
Although MR and ER fluids discovered in the late 1940s (Rabinow 1948, Winslow 1949), researches on ER fluids have primarily carried out for the past four decades. Since recently developed MR fluids appear to be an attractive alternative to ER fluids for use in controllable fluid dampers (Carlson and Weiss 1994, Carlson *et al*. 1995), strong research efforts have been shifted towards the development of MR fluid damper-based control systems. In the civil engineering community, much research and development on MR fluid damper-based control systems has been conducted since this unique semiactive control device was first introduced to civil engineering applications in mid 1990s (Dyke *et al*. 1996a,b, Spencer *et al*. 1997). In 2001, MR fluid dampers were applied to the full-scale structures for alleviation of wind and seismic responses. The cable-stayed Dongting Lake Bridge in China and the Nihon-Kagaku-Miraikan building in Japan constitute the world's first full-scale implementations of MR fluid damper-based semiactive control technology in civil engineering structures.

This state-of-the-art paper presents a comprehensive literature review of dynamic models of MR fluid dampers for describing their complex behavior, as well as control algorithms considering the characteristics of MR fluid dampers in the following two sections. In Section 4, the above referenced full-scale applications of MR fluid dampers to civil engineering structures are also discussed.

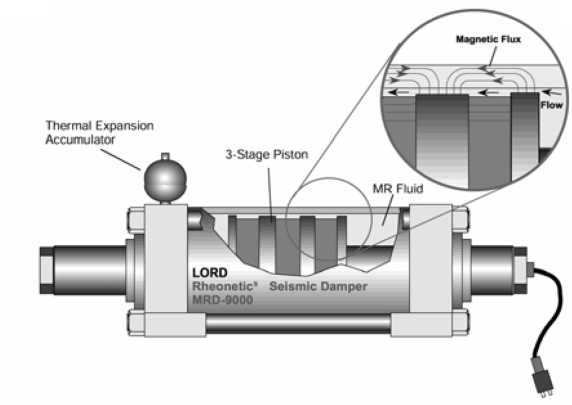
2. Review of dynamic models for MR fluid dampers

Schematics of several MR fluid dampers for civil engineering applications are shown in Fig. 3. Fig. 3(a) shows a small-scale MR fluid damper with the capacity of 3000 N manufactured by the Lord Corporation of Cary, North Carolina, and Fig. 3(b) is a 20-ton prototype large-scale seismic MR fluid damper developed under cooperation between the Lord Corporation and the Structural Dynamics and Control/Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame. Recently, a bypass-type large-scale MR fluid damper was designed by the Sanwa Tekki Corporation in Japan as shown in Fig. 3(c).

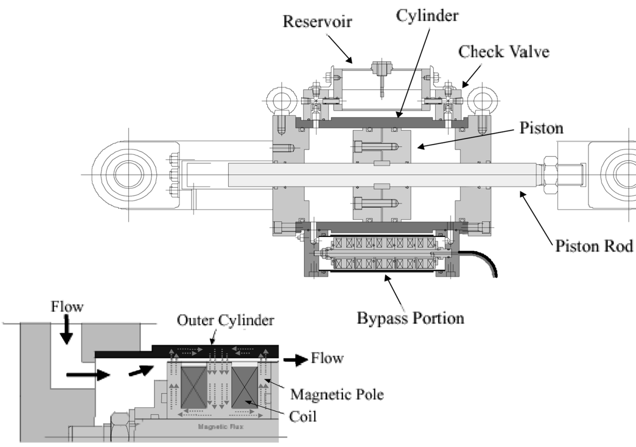
To develop appropriate control algorithms for MR fluid dampers, mathematical and physical models are needed that can accurately reproduce the salient features of the dampers. Two types of dynamic models of MR fluid dampers have been investigated by researchers: (i) *parametric models* which are fitted to experimental results by adjusting few parameters can be described by an arrangement of mechanical elements such as springs and viscous dashpots; (ii) *non-parametric models* which are based entirely on the performance of a specific fluid device and commonly need to an elevated amount of experimental data, obtained by observing the MR fluid response to different excitations under varying operation conditions. Although dynamic models for ER fluid dampers potentially could be used for MR fluid dampers due to the similar behavior between MR and ER fluids, only previous studies on dynamic models for MR fluid dampers are reviewed in this paper. Another review on modeling of ER and MR fluid dampers can be found in Butz and von Stryk (2002).



(a) Small-scale damper



(b) Large-scale damper



(c) Bypass-type large-scale damper

Fig. 3 Schematics of MR fluid dampers (Yang 2001)

2.1 Parametric models

2.1.1 Bingham model and its extended version

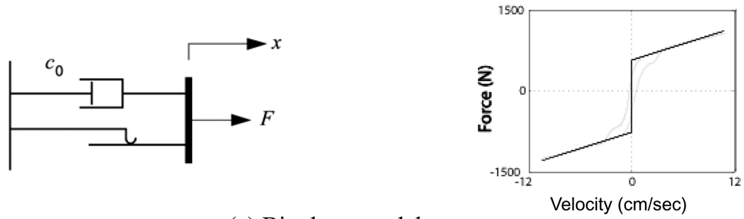
One of the most popular dynamic models that describe the nonlinear behavior of MR fluids is the Bingham model, which was originally developed for portraying the rheological behavior of ER fluids by Stanway *et al*. (1985, 1987) and adopted for the MR fluids by Spencer *et al*. (1997). The model consists of a Coulomb friction element in parallel with a viscous damper as shown in Fig. 4(a). The force generated by the damper is given by

$$f = f_y \mathrm{sgn}(\dot{x}) + c_0 \dot{x} \tag{1}$$

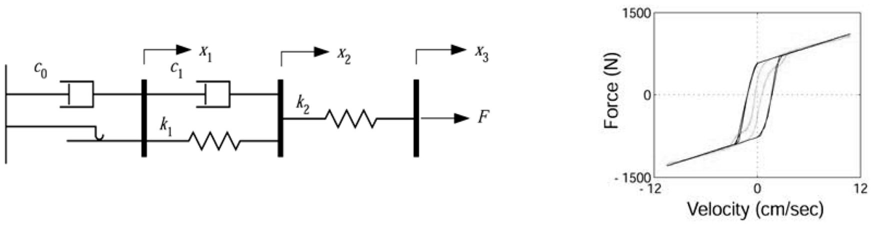
where f_y is the yield force, c_0 is the damping coefficient, and $\dot{x}$ is the velocity of the device. To determine a dynamic model that is valid for fluctuating magnetic fields, the functional dependence of the parameters on the applied voltage u must be determined as follows:

$$f_y = f_{ya} + f_{yb}u, \qquad \text{and} \qquad c_0 = c_{0a} + c_{0b}u. \tag{2}$$

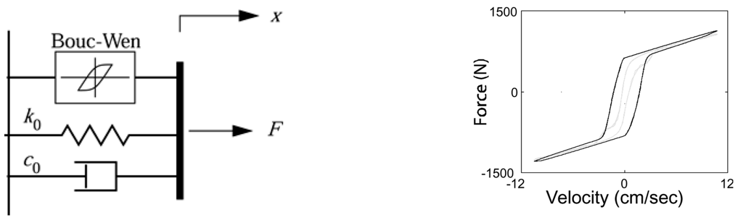
While the Bingham model accounts for MR fluid behavior beyond the yield point, i.e., for fully developed fluid flow or sufficiently high shear rates, it cannot describe the fluid's elastic properties at small deformations and low shear rates, which is necessary for dynamic applications, because it assumes that the fluid remains rigid in the pre-yield region (see Fig. 4a). However, the model is still used mainly in the preliminary studies for an MR fluid damper based control system, owing to its simplicity and easiness for implementation (Dyke 1998, Ren and Xu 2001, Ni *et al.* 2002b).



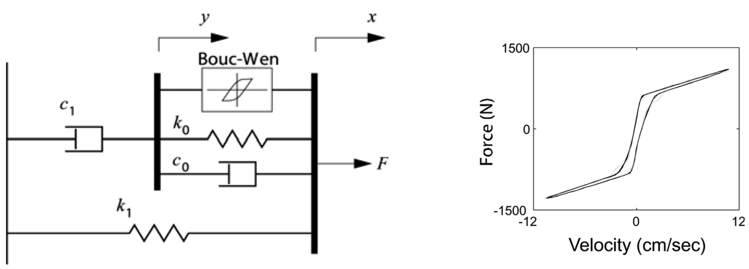
(a) Bingham model



(b) Extended Bingham model



(c) Bouc-Wen model



(d) Modified Bouc-Wen model

Fig. 4 Dynamic models of MR dampers and comparison between the predicted and experimentally obtained responses (Spencer *et al.* 1997)

Also, Spencer *et al.* (1997) investigated the applicability of the extended Bingham model developed by Gamota and Filisko (1991) to describe the behavior of MR fluids. This viscoelastic-plastic model consists of the Bingham model in series with the three-parameter element of a linear solid as shown in Fig. 4(b). The model qualitatively describes the hysteretic response of the MR fluid damper (Fig. 4b). However, the governing equations of the model are extremely stiff due to the nonlinear Coulomb friction element, making them difficult to deal with numerically.

2.1.2 Bouc-Wen model and its modified version

It is well known that the Bouc-Wen hysteresis model is numerically tractable and has been used extensively for modeling hysteretic system (Wen 1976). Thus, Spencer *et al.* (1997) introduced the Bouc-Wen model in order to characterize the behavior of an MR fluid damper. The mechanical analogue of the model is shown in Fig. 4(c). The force generated by the damper is given by

$$f = c_0\dot{x} + k_0(x - x_0) + \alpha z \tag{3}$$

where the evolutionary variable z satisfies

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^n + A\dot{x}. \tag{4}$$

By adjusting the parameters of the model γ, β, n, and A, the degree of linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region can be controlled. Some of the model parameters depend on the command voltage u to the current driver as follows:

$$\alpha = \alpha_a + \alpha_b u, \quad \text{and} \quad c_0 = c_{0a} + c_{0b}u. \tag{5}$$

The Bouc-Wen model predicts the force-displacement behavior of the damper well, and it possesses force-velocity behavior that more closely resembles the experimental data, However, similar to the Bingham model, the nonlinear force-velocity response of the model does not roll-off in the region where the acceleration and velocity have opposite signs and the magnitude of the velocities are small (see Fig. 4c). Recently, another Bouc-Wen model removing the spring in Fig. 4(c) has been developed for a shear-mode MR fluid damper (Yi *et al.* 1998, 2001) and a sponge-type MR fluid damper (Yoshioka *et al.* 2002) by the extensive characteristic test for each damper.

To better predict the damper response in the region where the simple Bouc-Wen model could not describe the behavior of the MR fluid damper, a modified version of the model was proposed as shown in Fig. 4(d) (Spencer *et al.* 1997). The equation governing the force predicted by this model is

$$f = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) = c_1\dot{y} + k_1(x - x_0) \tag{6}$$

where x is the displacement of the damper, and the evolutionary variable z is governed by

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}), \tag{7}$$

and

$$\dot{y} = \frac{1}{c_0 + c_1}\{\alpha z + c_0\dot{x} + k_0(x - y)\}. \tag{8}$$

In this model, the following three parameters depend on the command voltage u to the current driver:

$$\alpha = \alpha_a + \alpha_b u, \quad c_0 = c_{0a} + c_{0b} u, \quad \text{and} \quad c_1 = c_{1a} + c_{1b} u. \tag{9}$$

In addition, the dynamics involved in the MR fluid reaching rheological equilibrium are accounted for through the first order filter

$$\dot{u} = -\eta(u - v) \tag{10}$$

where v is the command voltage applied to the current driver.

Since the modified Bouc-Wen model can well capture the force roll-off in the low velocity region due to bleed or blow-by of fluid between the piston and cylinder, it is capable of predicting response of the MR fluid damper over a wide range of loading while under a constant or variable voltage signal as shown in Fig. 4(d). In semiactive control problems using MR fluid dampers, thus, the modified Bouc-Wen model has been most widely used for describing an MR fluid damper behavior recently (Koh *et al*. 2001, Jung *et al*. 2002, 2003, Chang and Zhou 2002, Erkus *et al*. 2002, Li and Samali 2002, Ribakov and Gluck 2002a, *etc*.)

The modified Bouc-Wen model is governed by seven simultaneous differential equations containing 14 parameters that are obtained according to a constrained nonlinear optimization technique such that the model closely emulates the experimental data on the nonlinear behavior of the damper. Although the accuracy of the numerical model is high enough to enable its use in control simulations, the solution of the seven differential equations is computationally expensive. Vavreck (2002) presented a new technique of parameter estimation for the modified Bouc-Wen model to obtain a cost function using only predetermined time series values. The technique has some advantages such as reduced constraint manipulation through global optimization, single-stage estimation and rapid convergence, owing to the lack of a need to solve differential equations during optimization iterations.

2.1.3 Dynamic models based on experimental results of 20-ton MR fluid damper

All the parametric models mentioned above were developed by considering a small-scale MR fluid damper as shown in Fig. 3(a). Yang *et al*. (2002) tried to estimate the optimized parameters for the modified Bouc-Wen model based on experimental data of a 20-ton prototype large-scale MR fluid damper (Fig. 3b). According to the intensive investigation by Yang (2001), however, the characteristics of the large-scale 20-ton MR fluid damper are quite different from those of the small-scale damper. In the large-scale damper, especially, the stiction phenomenon as well as fluid inertial and shear-thinning effects in the low velocity region becomes quite significant. Thus, an appropriate model that can accurately emulate the complicated behavior of large-scale MR fluid dampers is needed. Yang *et al*. (2001) and Yang (2001) proposed a new phenomenological model based on the response analysis of the 20-ton MR fluid damper as depicted in Fig. 5. The damper resisting force is given by

$$f = \alpha z + kx + c(\dot{x})\dot{x} + m\ddot{x} + f_0 \tag{11}$$

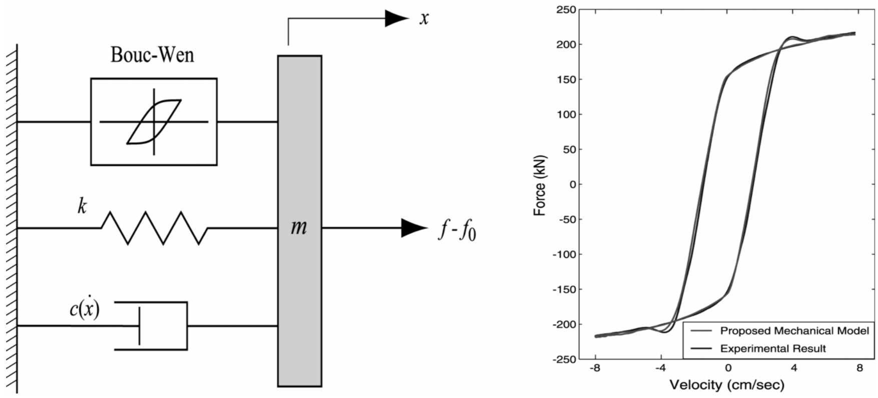


Fig. 5 Dynamic model of MR damper considering stiction phenomenon and fluid inertial effect (Yang *et al.* 2001)

where the evolutionary variable z is governed by

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^{n} + A\dot{x} \tag{12}$$

In this model, the fluid inertial effect is represented by an equivalent mass m; the accumulator stiffness is represented by k; friction force due to the damper seals as well as measurement bias are represented by f_0; and the post-yield plastic damping coefficient is represented by $c(\dot{x})$. To describe the shear-thinning effect on damper resisting force at low velocities as observed in the experimental data, $c(\dot{x})$ is defined as a mono-decreasing function with respect to the absolute velocity $|\dot{x}|$. In this paper, the post-yield damping coefficient is assumed to have a form of

$$c(\dot{x}) = a_1 e^{-(a_2|\dot{x}|)^{p}} \tag{13}$$

where a_1, a_2 and p are positive constants. They compared the predicted results from the new model with experimentally obtained data, and observed the excellent matches as shown in Fig. 5. To be the more reliable candidate of the dynamic model for MR fluid dampers, however, it is needed the extensive validation tests under various excitation conditions.

2.1.4 Nonlinear hysteretic bi-viscous model

The nonlinear bi-viscous model having an improved representation of the pre-yield hysteresis in ER fluid dampers was developed by Kamath and Wereley (1997). Li *et al*. (2000) extended the model to describing the behavior of MR fluid dampers and developed a nonlinear hysteretic bi-viscous model under sinusoidal excitation by experimentally investigating the effects of magnetic field, displacement amplitude and driving frequency on the response forces. Their experimental results offer a new viscoelastic-plastic model to describe the overall behavior of the MR fluid damper as shown in Fig. 6. The governing equation for this model can be expressed as

$$f = f_{ve} + F_s \qquad |f| \le F_c \tag{14}$$

$$f = C_v\dot{x} + R\ddot{x} + F_c\,\mathrm{sgn}(\dot{x}) \qquad |f| > F_c \tag{15}$$

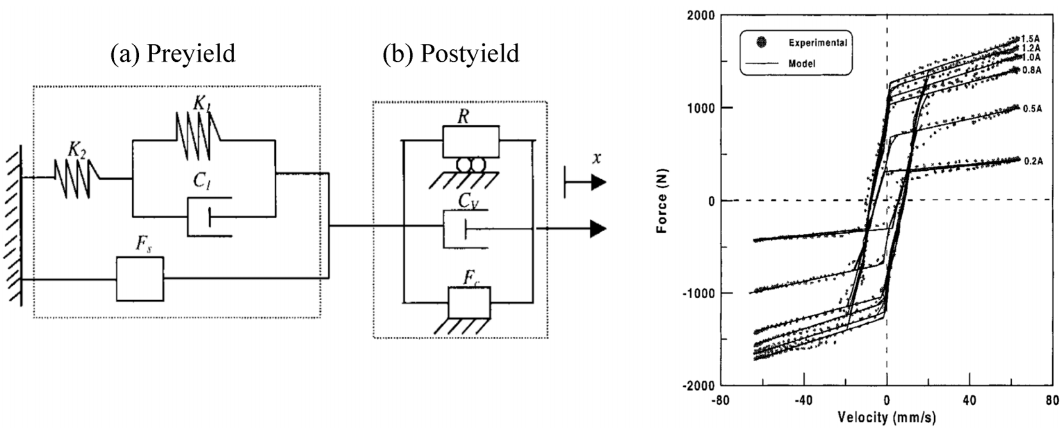


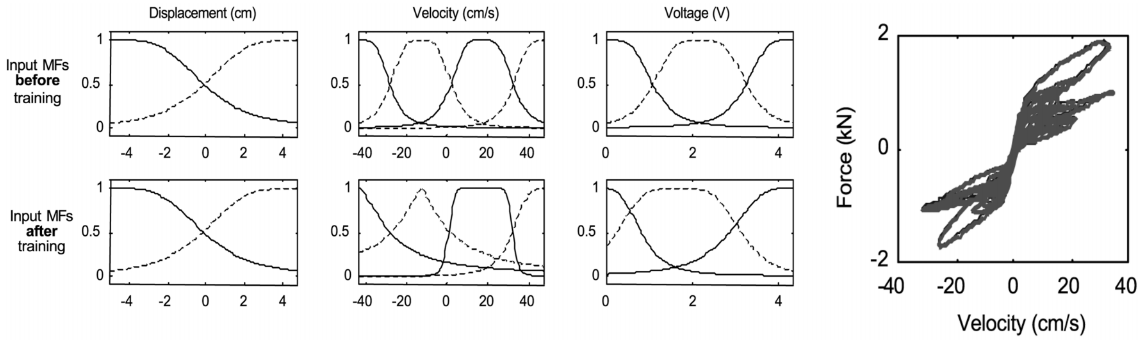
Fig. 6 Viscoelastic-plastic model of MR fluid damper (Li *et al.* 2000)

where f_{ve} is the viscoelastic force, which is represented as $\dot{f}_{ve} + \{(K_1 + K_2)/C_1\}f_{ve} = \{(K_1 + K_2)/C_1\}x + K_2\dot{x}$ (Weiss *et al.* 1994), F_s is the stiction effect, F_c is the damper yield force, C_v is the viscous damping coefficient, and R is the equivalent inertial mass, which depends on displacement amplitude and oscillatory frequency. They showed that the damping effect did not depend on oscillation frequency so much in the very low range of the frequency (below 2.0 Hz), and there is almost no inertial effect on the damping force, whereas when the oscillatory frequency is above 4.0 Hz, there exists distinct obvious nonlinearity due to fluid inertial effect. They also demonstrated that the model could predict the MR fluid damper behavior very well. However, they only considered the sinusoidal excitation and the experimental data from the small-scale damper. Thus, the extensive validation tests under random excitations and considering the large-scale MR fluid damper, which are important for practical use of the damper in civil engineering applications, should be accomplished.

2.2 Non-parametric models

2.2.1 Neural network-based models

A neural network, which can be used to match any nonlinearity through learning, could be an alternative means for the model of MR fluid dampers. Chang and Roschke (1998) developed a neural network model, in which a feedforward network is used and the network training/prediction are relied on all the input and output information of dampers, to emulate the dynamic behavior of MR fluid dampers. Also, Wang and Liao (2001) proposed the model by using a recurrent neural network, in which the output of the network was delayed and fed back to its input layer. In this way, the damping force of the MR fluid damper is needed only during the training stage of the neural network. However, the results presented in their papers are still preliminary for modeling the MR fluid damper using neural networks, so more research work is needed. Moreover, the effectiveness of the their models was only verified by numerically comparing with the modified Bouc-Wen model developed by Spencer *et al.* (1997). Therefore, it is necessary to intensively carry out experimental validations for their models.



(a) Input membership functions before and after training (b) Comparison between fuzzy and mathematical models subjected to random displacement and random voltage

Fig. 7 Fuzzy modeling of MR fluid dampers (Schurter and Roschke 2000)

2.2.2 Fuzzy logic-based models

One of the advantages of fuzzy logic-based models over other parametric models is that they could substantially reduce the computational requirements for predicting a damper behavior. Schurter and Roschke (2000) developed a fuzzy model of an MR fluid damper with the aid of ANFIS (adaptive neuro-fuzzy inference systems). ANFIS uses a learning algorithm that combines the back-propagation gradient descent and least square methods to create a fuzzy inference system whose membership functions (MFs) are iteratively adjusted according to a given set of input and output data. MF is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Initial and final input MFs for fuzzy modeling to emulate a nonlinear behavior of the damper are shown in Fig. 7. They showed that their model satisfactorily represented behavior of the MR fluid damper while greatly reducing computational requirements (see Fig. 7), and the use of the model increased the feasibility of real-time simulation. Oh *et al*. (2002) applied the neuro-fuzzy modeling technique to the 30-ton MR fluid damper that has been recently manufactured in Japan and tested in Taiwan. They showed that the neuro-fuzzy model could provide a good representation of the MR fluid damper behavior. Excellent agreement was found between the experimental and model responses when experimental data used for training include all of the parameters that influence the behavior of the MR fluid damper in the case of random excitation. However, the model cannot accurately predict the damper behavior in the case of the sinusoidal excitation and constant voltage.

2.2.3 Other non-parametric models

Jin *et al*. (2001, 2002) proposed a non-parametric model by wavelets-based identification techniques, including the ridgelet network to construct the nonlinear mapping. They demonstrated that their algorithm was able to capture a wide range of damping behaviors by comparing the simulation results with measurement data in the constant and variable control current cases. Leva and Piroddi (2002) presented an MR damper-modeling technique based on the nonlinear ARX models and of a suitable identification algorithm. They showed the simplicity, accuracy and robustness of their models compared with a literature reference model. Therefore, they have to carry out the consecutive research including a full experimental verification of the technique and a control implementation of the obtained models.

3. Review of control algorithms for MR fluid damper-based semiactive systems

Development of suitable control strategies that are practically implementable and can fully utilize the capabilities of MR fluid dampers is an important and challenging task, because MR fluid dampers have intrinsically nonlinear nature. Various nonlinear control strategies have been developed to take advantage of the particular characteristics of the MR fluid dampers. The control algorithms for MR fluid damper-structural system can be divided into model-based control, which requires an accurate explicit mathematical model of the dynamics of the structure to be controlled, and intelligent technology-based control (i.e., non-model-based control).

3.1 Model-based control

3.1.1 Optimal control-based algorithms

To date, a clipped-optimal control algorithm has been most widely used for MR fluid damper-based control problems. The strategy of the algorithm is as follows: first, an "ideal" active control device is assumed and an appropriate primary controller for this device is designed by various optimal control algorithms such as a linear quadratic Gaussian (LQG), and then a secondary bang-

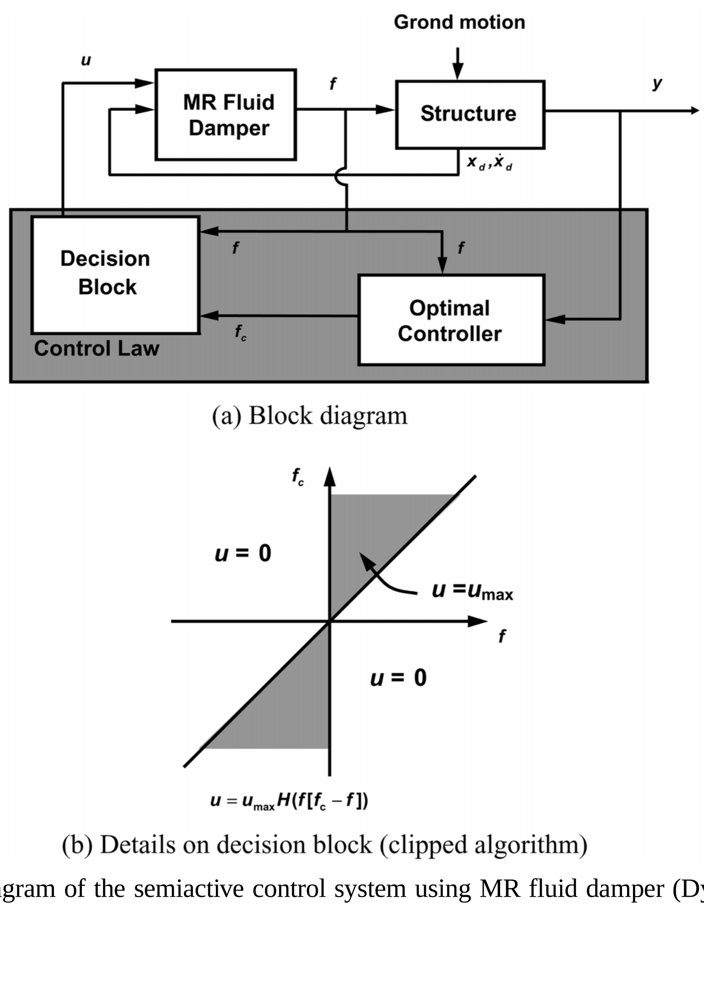
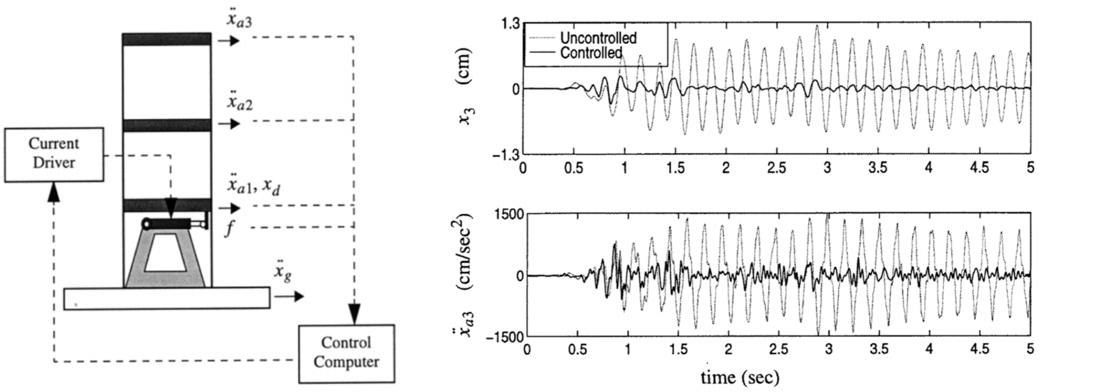


Fig. 8 Block diagram of the semiactive control system using MR fluid damper (Dyke *et al.* 1996a)

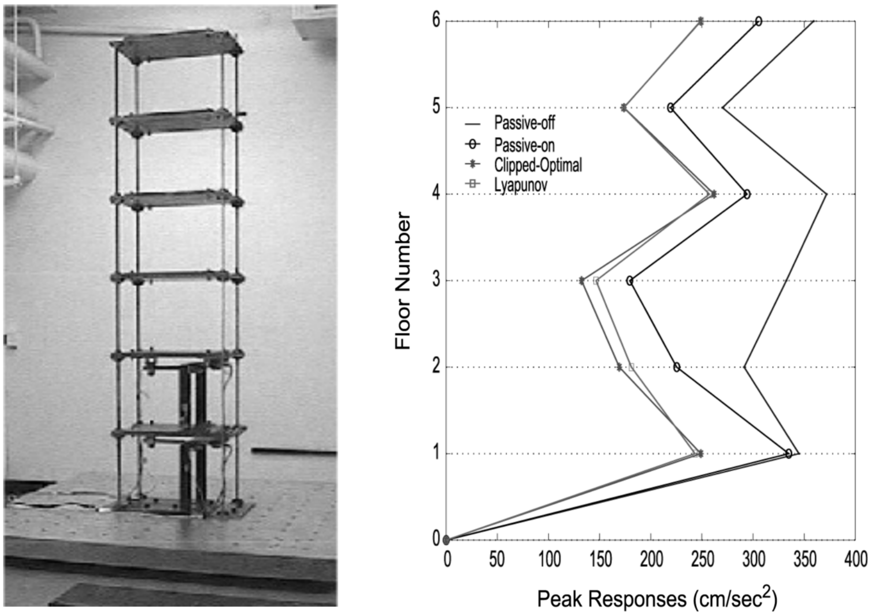
bang-type (i.e., *on-off*-type) controller causes the MR fluid damper to generate the desired control force, so long as this force is dissipative. The block diagram of the MR fluid damper-based control system using the clipped-optimal algorithm is shown in Fig. 8. In the figure, u is a command signal, f_c, is a desired control force, f is a measured control force, y is measured responses, x_d and x_d' are relative structural displacement and velocity at the attachment point of the damper, and $H(\cdot)$ is the Heaviside step function.

Dyke *et al*. (1996a) first proposed the clipped-optimal control algorithm based on acceleration feedback for the structure employing an MR fluid damper. In their approach, a linear quadratic Gaussian (LQG) optimal output feedback controller, combined with a force feedback loop, was designed to adjust the command voltage of the MR fluid damper. They numerically obtained good results when the strategy was applied to control a model of a seismically excited three-story scaled building model. The efficacy of their control system was experimentally verified by conducting a series of experiments as shown in Fig. 9 (Dyke *et al*. 1996b, 1998). In the figure, $\ddot{x}_g$ is a ground acceleration, $\ddot{x}_{ai}(i = 1, 2, 3)$ is an absolute acceleration at each floor, x_d is a relative displacement at the first floor, and f is a measured control force. In addition, Dyke and Spencer (1996) extended the algorithm to the multiple MR fluid damper case in which two MR fluid dampers are used to control a five-story scaled structure, and the results of the study demonstrated that the MR fluid damper was able to reduce the absolute accelerations of the floors of the structure more effectively compared with the passive systems while maintaining approximately the same reduction in maximum inter-story displacements as in the best passive case. Yi *et al*. (1998, 2001) verified experimentally the effectiveness of the clipped optimal control algorithm for the case of multiple MR fluid dampers by considering a six-story test structure employing four parallel-plate, shear-mode MR fluid dampers. They proposed and verified a phenomenological model of the shear-mode MR fluid damper, and then developed a model of the integrated structural system by a nonlinear system identification method. Finally, as depicted in Fig. 10, they demonstrated from shaking table tests considering the El Centro earthquake with three different amplitude levels that the performance of the MR fluid damper-based control system can surpass that of the comparable passive system in a variety of situations. In the “passive-off” case, the command voltage to the MR fluid damper is



(a) Experimental setup (b) Experimental response due to scaled El Centro NS earthquake

Fig. 9 Base isolation system employing MR fluid damper (Dyke *et al.* 1998)

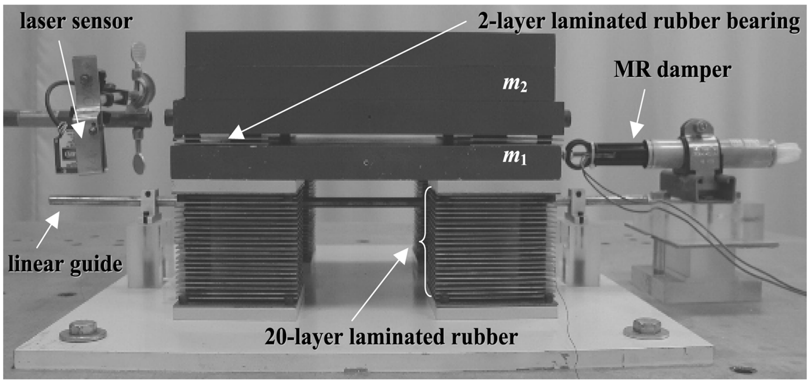


(a) Test structure (b) Peak acceleration response profile

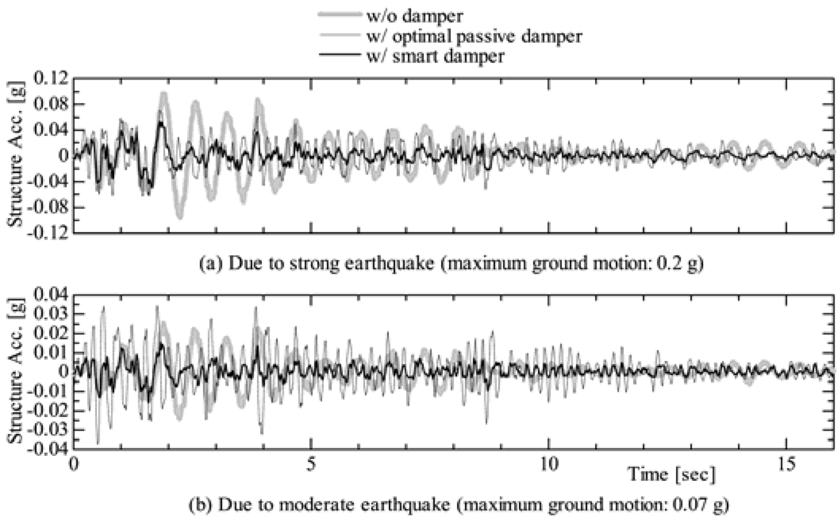
Fig. 10 Experimental verification of control based on Lyapunov stability theory (Yi *et al.* 2001)

held at 0 V, while the voltage to the damper is held at the maximum level in the “passive-on” case. The “Lyapunov” case represents that the control algorithm based on Lyapunov stability theory is employed and this case is discussed in the next section. Dyke (1998) also applied the clipped-optimal control algorithm to mitigate seismic responses of a full-scale 20-story building designed for Los Angeles, California, by employing a total of 30 large-scale MR fluid dampers with a capacity of 900 kN. The preliminary results indicated that MR fluid dampers could effectively be used for the control of seismically excited full-scale buildings.

Another class of MR fluid damper-based control systems that has been investigated by a number of researchers is found in the semiactive base isolation system, consisting of a passive base isolation system combined with an MR fluid damper to supplement the effects of the base isolation system. First, Johnson *et al*. (1998) performed a feasibility study on the applicability of semiactive control using the clipped-optimal control algorithm and an MR fluid damper to a base isolated building system, and then Ramallo *et al.* (2000, 2002) conducted an extensive comparison between traditional seismic isolation systems using lead rubber bearings (LRB), one of the most widely used base isolation devices, and the MR fluid damper-based system. Yoshioka *et al*. (2002) verified experimentally the effectiveness of the MR damper-based seismic isolation system. As shown in Fig. 11(a), the experimental structure is a base-isolated two-degree-of-freedom building model subjected to simulated ground motion, and a sponge-type MR fluid damper is installed between the base and the ground to provide controllable damping for the system. Their extensive experimental results indicated that the smart base isolation system employing MR fluid dampers could be effective over a wide range of ground motion intensities and characteristics as shown in Fig. 11(b). Ribakov and Gluck (2002a, b) proposed a selective control base isolation system with MR fluid dampers. They demonstrated from the numerical simulations of five- and eight-story building



(a) Experimental setup

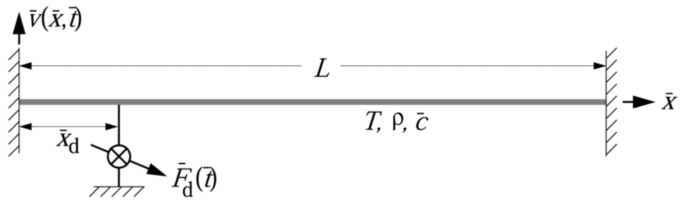


(b) Experimental acceleration response duet to scaled El Centro NS earthquake

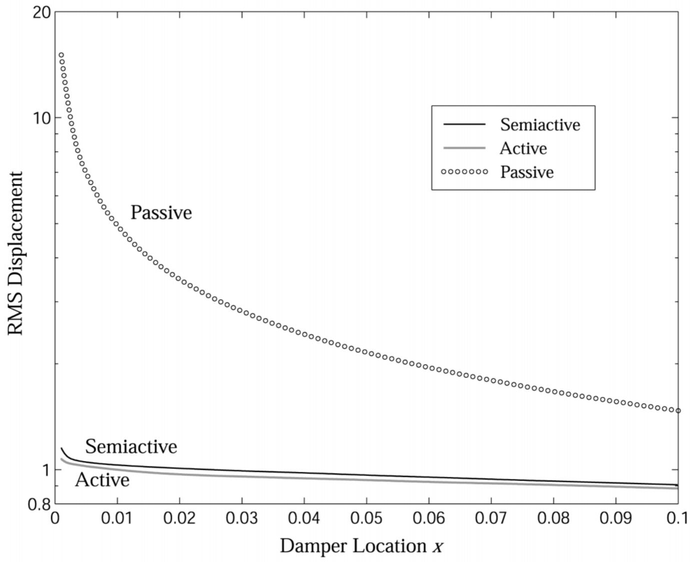
Fig. 11 Base isolation system employing MR fluid damper (Yoshioka *et al.* 2002)

models that the selective control improved the efficiency of the system and reduced the control forces required for optimal structural behavior.

Some researchers also applied the clipped-optimal algorithm to reducing cable vibrations under wind load. Johnson *et al*. (1999, 2000a, 2002) and Baker *et al.* (1999) conducted analytical studies on the mitigation of the wind-induced cable vibration by using the clipped-optimal control algorithm and MR fluid dampers. They numerically demonstrated that the response with a semiactive MR fluid damper could be dramatically reduced compared to the optimal passive linear viscous damper for typical damper configurations as shown in Fig. 12. In the figure, L is the length of the cable, T is the cable tension, ρ is the cable mass per unit length, $\bar{c}$ is the viscous damping per unit length, $\bar{v}(\bar{x}, \bar{t})$ is the transverse deflection of the cable, and $\bar{F}_d(\bar{t})$ is a transverse damper force at location $\bar{x} = \bar{x}_d$. Moreover, Johnson *et al*. (2000b, 2001) extended the previous work by adding sag, inclination, and axial flexibility to the cable model, and showed that the cable response was



(a) Cable with attached damper



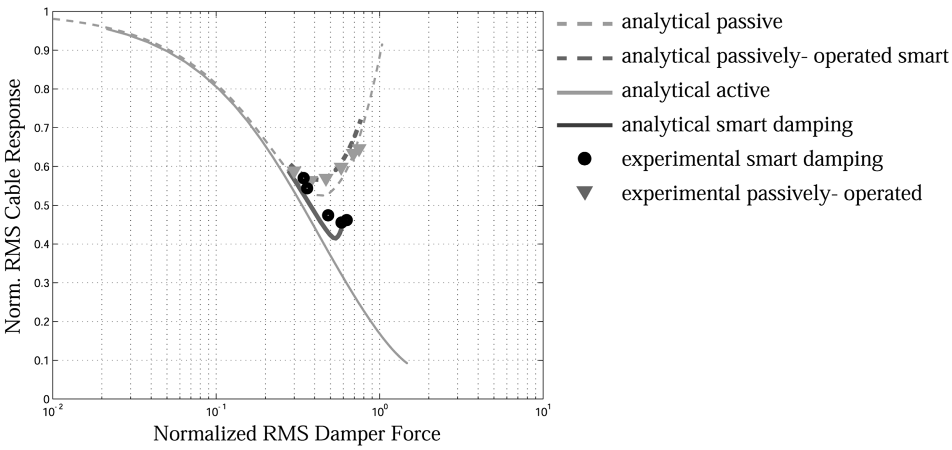
(b) Comparison of passive, active, and semiactive damping strategies for various damping locations

Fig. 12 Semiactive damping system for vibration reduction of stay cables (Johnson *et al*. 2002)

significantly reduced by semiactive dampers for a wide range of cable sag and damper location. Therefore, their analytical works demonstrated the potential benefits using a semiactive damper for absorbing cable vibratory energy. Also, Christenson *et al*. (2001, 2002) and Christenson (2001) experimentally verified the effectiveness of the MR fluid damper-based semiactive control method. As shown in Fig. 13(a), the test structure was a 12.65 m inclined cable, which was dynamically similar to a typical stay cable on a cable-stayed bridge, attaching a shear-mode MR fluid damper. The experimental results showed that semiactive control is able to reduce the cable displacement an additional 20% beyond the performance of passive control (see Fig. 13b).

The applicability of the MR fluid damper-based control system employing the clipped-optimal algorithm to other building problems having special configurations such as a coupled building system and an irregular building system. First, a coupled building control problem, which is a developing method of structural control for mitigating structural responses of a building due to wind and seismic excitations, has been analytically studied by Christenson *et al*. (1999a,b, 2000) and Christenson (2001). They have examined the efficacy of semiactive control using the clipped-optimal control algorithm and MR fluid dampers for the problem. Also, Yoshida *et al*. (2002)

(a) Flat-sag cable experimental setup

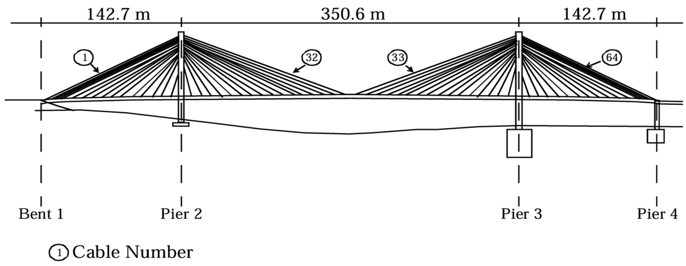


(b) Controller performance at evaluation point and over length of cable

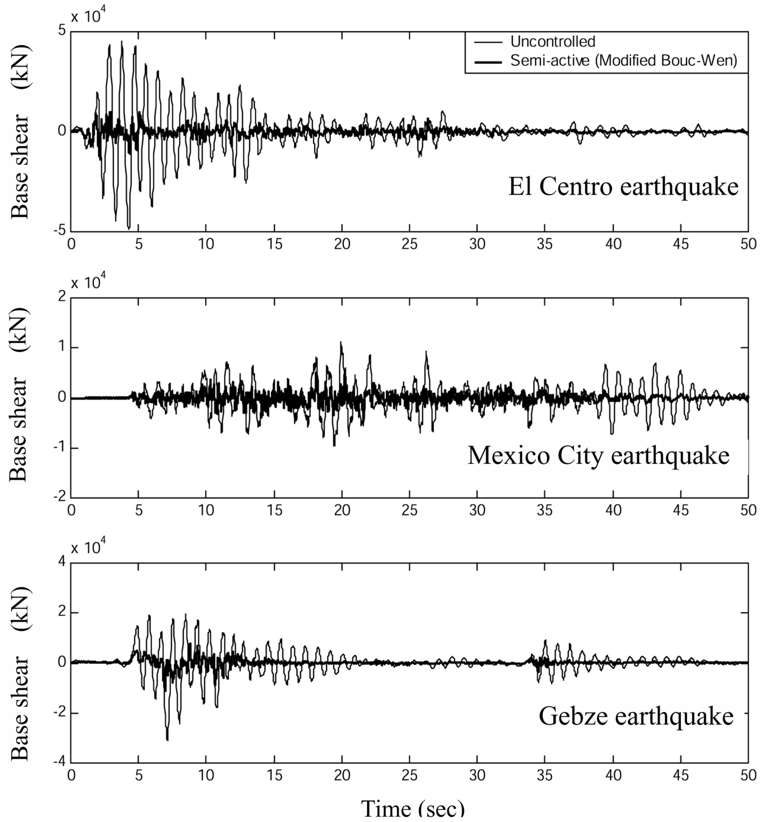
Fig. 13 Experimental study of cable attaching MR fluid damper (Christenson 2001)

applied the clipped-optimal algorithm to control torsional-lateral responses in irregular buildings under lateral seismic excitations. They demonstrated from the experimental studies conducted using a two-story asymmetric building model that the performance of a semiactive controller using MR fluid dampers is significantly better than passive control system.

MR fluid damper-based control systems have been investigated for vibration reduction of bridge structures such as cable-stayed bridges (Jung *et al*. 2001, 2002, 2003, Koh *et al*. 2001) and elevated highway bridges (Ruangrassamee *et al*. 2001, Ruangrassamee and Kawashima 2001, Erkus *et al*.



(a) Schematic of the cable-stayed bridge

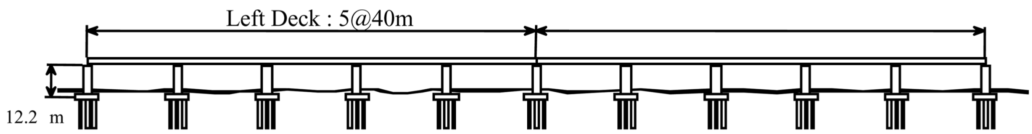


(b) Base shear forces at the pier 2 under the three historical earthquake

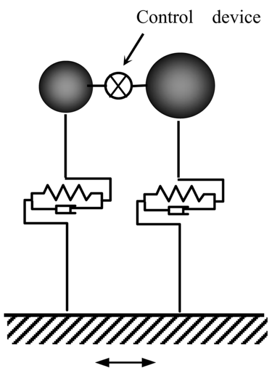
Fig. 14 Cable-stayed bridge employing MR fluid damper (Jung *et al.* 2003)

2002). Jung *et al.* (2001, 2002, 2003) and Koh *et al.* (2001) performed the numerical verification of a semiactive control method combining large-scale MR fluid dampers and the clipped optimal control algorithm for the application of the seismic protection of cable-stayed bridges by examining the ASCE first generation benchmark control problem (Dyke *et al.* 2003) as shown in Fig. 14. Especially, Jung *et al.* (2003) verified the better performance of the MR fluid damper-based control system over the passive control system with decreasing the magnitudes of the earthquake motions by the results considering the several historic earthquakes scaled to various magnitudes.

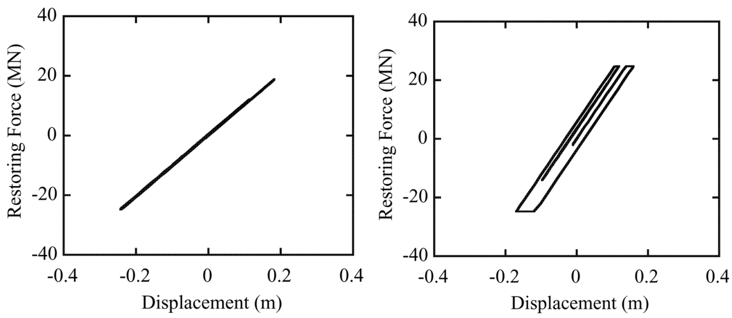
Ruangrassamee *et al.* (2001) and Ruangrassamee and Kawashima (2001) performed a feasibility study of MR fluid damper-based control systems for highway bridges considering the pounding effect and nonlinearity of piers. They simplified a bridge consisting of two five-span continuous decks as two single-degree-of-freedom systems shown in Fig. 15(a)-(b), and considered the nonlinearity of piers caused by plastic deformation under strong ground motion. They demonstrated from numerical simulations that the semiactive control system using the MR fluid damper could be effective to the coupled bridge system considering nonlinear behavior of piers as depicted in Fig. 15(c). Also, Erkus *et al.* (2002) investigated the applicability of semiactive control for seismic protection of elevated highway bridges through comparison with active and passive systems. A bridge pier-



(a) Two five-span continuous bridge



(b) Simplfied bridge model



(c) Restoring force vs. displacement

Fig. 15 Coupled bridge system employing MR fluid damper (Ruangrassamee *et al.* 2001)

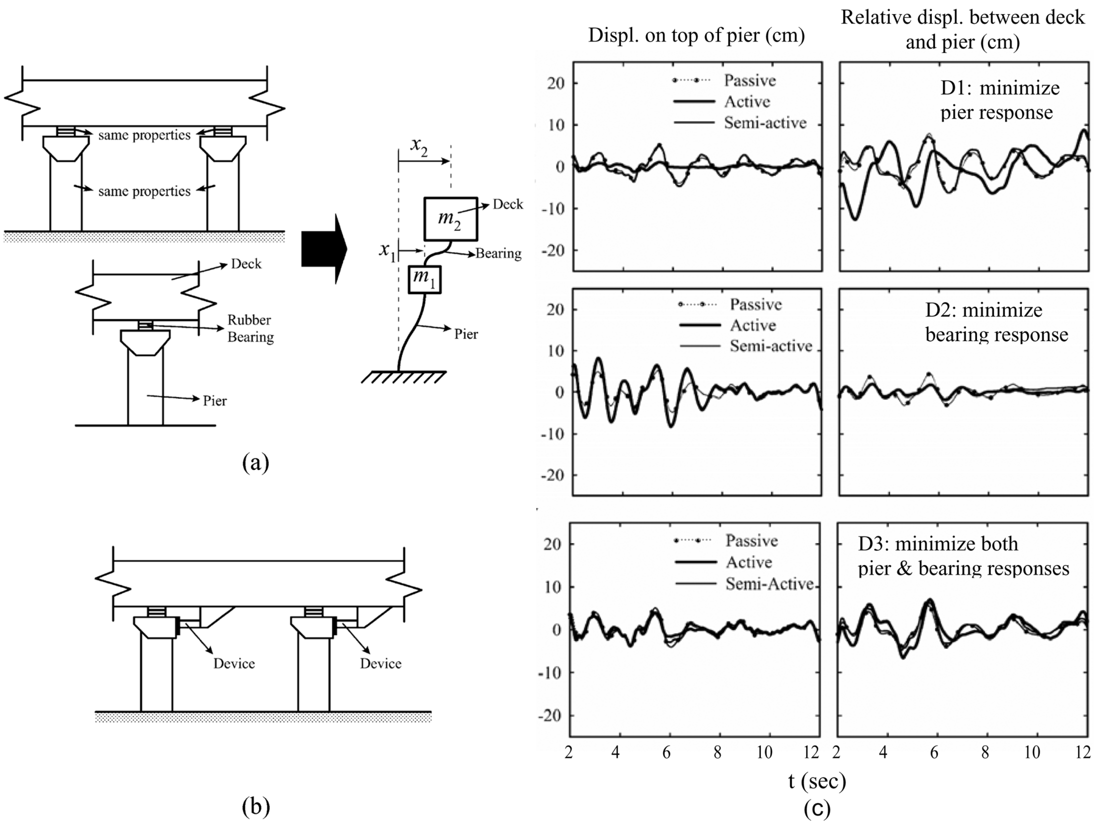
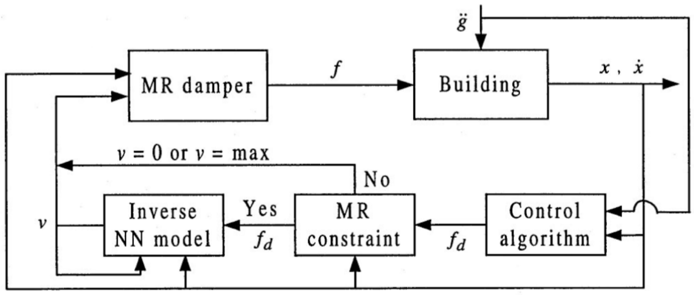


Fig. 16 Elevated highway bridge employing MR fluid dampers: (a) simplified two-degree-of-freedom model; (b) placement of MR fluid dampers (c) response time-histories under the El Centro earthquake (Erkus *et al.* 2002)

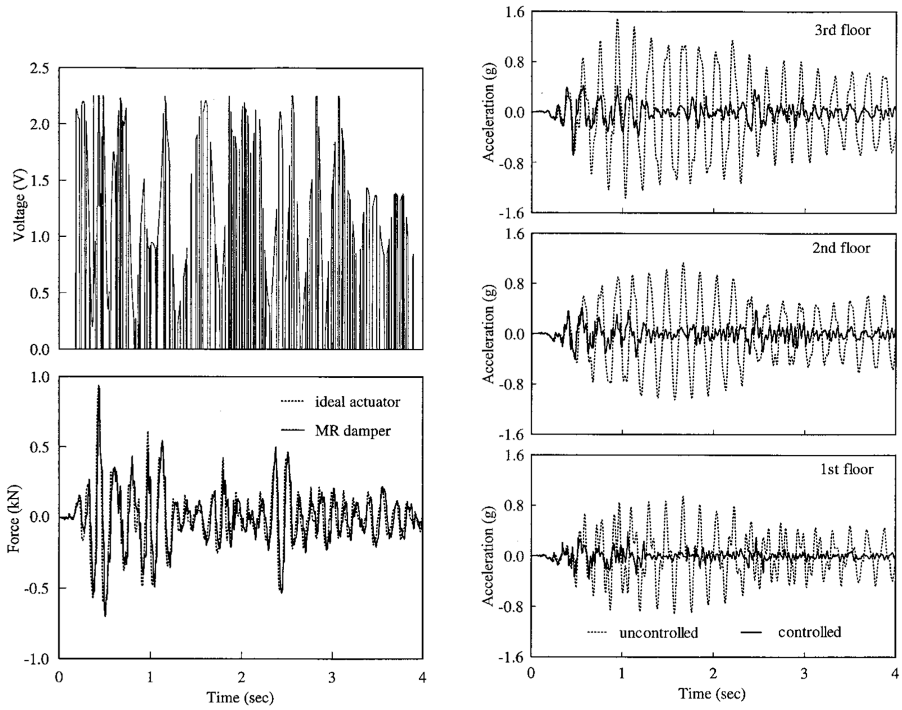
bearing-deck structure was modeled as a linear two-degree-freedom system as shown in Fig. 16(a) and the placement of MR fluid dampers is illustrated in Fig. 16(b). It is verified from the numerical simulation results such as Fig. 16(c) that the semiactive control system shows similar performance to the passive system when the design goal is to reduce pier response (i.e., D1), while it reaches the performance of the active system when the design goal is to reduce deck response (i.e., D2). In the third design (i.e., D3: minimize both pier and bearing responses), all the three control systems have similar performances under the El Centro earthquake.

Xu *et al.* (2000) proposed the sub-optimal displacement control algorithm for the MR fluid-damper control system. The test structure was a four-story building model employing MR fluid dampers between floors. The stiffness of brace system supporting the MR fluid damper was taken into consideration. They numerically showed that installation of MR fluid dampers with the proper parameters obtained through the extensive parametric study and the appropriate control strategy could significantly reduce the seismic response of the building structure. Their algorithm was also applied to seismic response control of a tall building with podium structure and a large-span machinery building on top of ship lift towers (Qu and Xu 2001, Qu *et al.* 2002).

Zhou and Chang (2000a) and Chang and Zhou (2002) presented a linear quadratic regulator



(a) Control strategy



(b) Command voltage and control force (c) Absolute floor accelerations

Fig. 17 Three-story building model employing MR fluid damper (Chang and Zhou 2002)

(LQR) algorithm employing inverse neural network models of MR fluid dampers to provide direct estimation of the voltage that is required to produce a target control force calculated from the LQR algorithm as shown in Fig. 17(a). In the figure, $\ddot{g}$ is a ground acceleration, v is a command signal, f_d is a desired control force, f is a measured control force, and x and $\dot{x}$ are relative displacement and velocity at the location of the damper. As depicted in Fig. 17(b), the force generated by the MR fluid damper could follow those calculated from the optimal control algorithms quite well as long as these optimal control forces are within the damper's capacity. They verified the efficacy of their algorithm analytically by using a three-story building model (see Fig. 17c).

3.1.2 Lyapunov function-based control

Various Lyapunov function-based control algorithms such as control based on Lyapunov stability theory, decentralized bang-bang control, and maximum energy dissipation have been investigated for MR fluid damper-based control systems. Dyke and Spencer (1997) and Jansen and Dyke (1999, 2000) demonstrated from the numerical simulations using a six story structure controlled with MR fluid dampers on the lower two floors that these Lyapunov function-based algorithms have the effective performance in reducing seismic response. Yi *et al*. (2001) experimentally verified the effectiveness of control based on Lyapunov stability theory by testing a scaled six-story building model attached four parallel-plate shear-mode MR fluid dampers under the 1940 El Centro earthquake with three different excitation amplitudes.

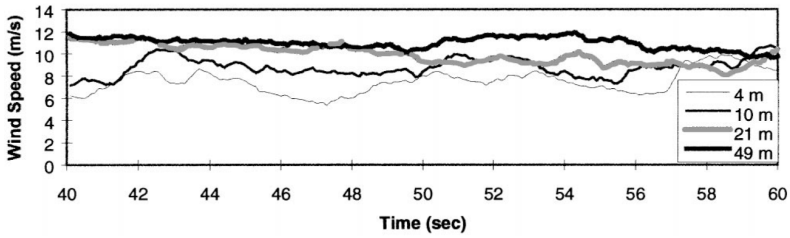
Experimental studies on the control performance of the MR fluid damper-based system using shaking table tests have been carried out. Sahasrabudhe and Nagarajaiah (2001) studied the response of sliding isolated buildings with MR fluid dampers subjected to near fault earthquake ground motion. A 1:5 scale two-story sliding isolated building model with an MR fluid damper and a new Lyapunov controller developed and implemented in real time were used to analytically and experimentally demonstrate the effectiveness of an MR fluid damper. They also demonstrated that while the displacement reductions could be achieved by increasing the passive damping further, it could only be done at the expense of greater force. Wang and Gordaninejad (2001, 2002) also performed the experimental study on Lyapunov-based control of a bridge using MR fluid dampers. They carried out the experiments on a system consisting of a 1/12 scaled, two-span bridge and two MR fluid dampers. They showed that the Lyapunov-based control systems using a feedback bang-bang control law could effectively reduce the bridge relative displacement between the deck and the abutment when subjected to various input motions.

3.1.3 Stochastic control-based algorithms

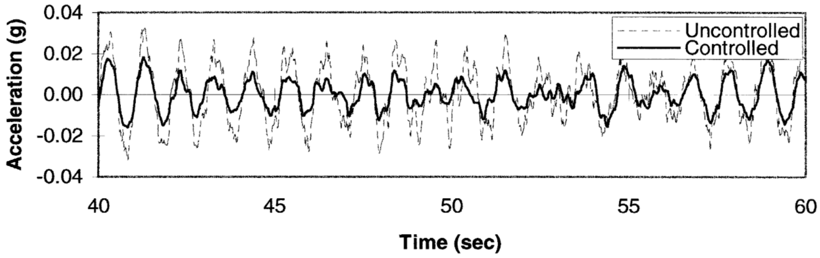
Since the seismic or wind excitation acting on structures is random in nature, some researches on the application of the stochastic dynamical programming principle (Stengel 1986) have been investigated. Ying *et al*. (2002a) developed a one-stage non-clipping stochastic optimal control method, based on the stochastic averaging method, stochastic dynamical programming principle and variational principle, for semiactive control of randomly excited nonlinear systems using MR fluid dampers. They demonstrated from numerical results of vibration control in terms of semiactive MR fluid dampers for a nonlinear single-degree-of-freedom system subjected to Gaussian white noise that the non-clipping optimal control method was more effective and efficient than the clipped LQG control method. In addition, Ni *et al*. (2002a) experimentally investigated a stochastic optimal control strategy to control the seismic response of a 1:15 scaled adjacent building structural system consisting of a 12-story building model and an 8-story model employing MR fluid dampers between the two structures. The control experiments were carried out by installing the MR fluid damper at different stories and subjecting the structural system to sweep sine excitation and the scaled El Centro earthquake excitation. For all the testing cases, the semiactive control system provides greater structural response reduction than the passive control system, indicating the efficacy of the semiactive MR fluid damper for mitigating structural seismic response of adjacent building structures.

3.1.4 Robust control-based algorithms

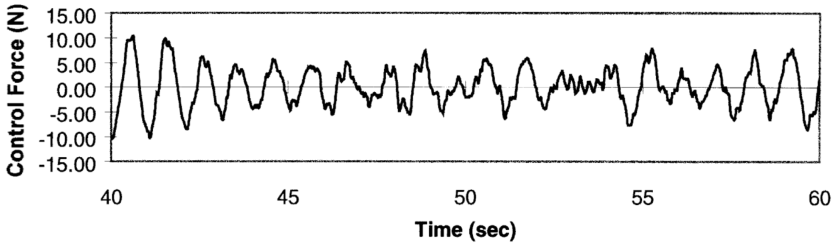
Recently, continuous sliding mode (CSM) control, which was originally developed for robust control of uncertain nonlinear systems (Utkin 1992), has been studied for the application to MR fluid damper-based control systems. Moon *et al*. (2002, 2003) applied the combination of the CSM control algorithm and MR fluid dampers to the ASCE first generation benchmark control problem for seismically excited cable-stayed bridges. A series of numerical simulations showed that the MR damper-based semiactive control system using sliding mode control could improve the control effect as well as enhance the robustness of the system to uncertainties in stiffness of the bridge model. Li



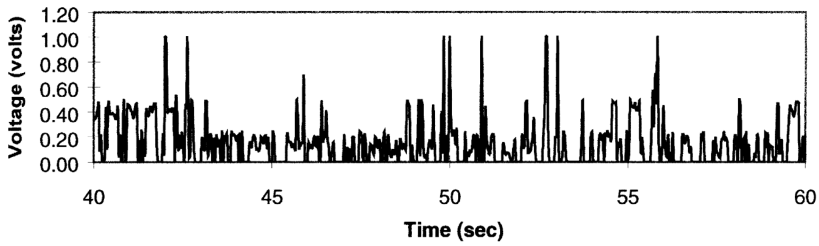
(a) Wind speed set (m/s)



(b) Fourth floor accelerations (g)



(c) Control force (N)



(d) Voltage required for MR fluid damper (volts)

Fig. 18 Four-story building model employing MR fluid damper excited by wind (Zhang and Roschke 1999) and Samali (2002) also used the same combination, i.e., CSM control and MR fluid dampers, to control vibrations of the five-story building model, designed and manufactured at the University of Technology, Sydney, due to the strong ground motion. They showed from numerical simulation that MR fluid dampers with the new control law could compete with some of active control systems in terms of vibration reductions. In Hiemenz *et al.* (2003), the three control laws, such as skyhook control, LQR control, and CSM control, were designed and applied numerically as well as experimentally to a three-story building model. They demonstrated that CSM controller outperformed the LQR and skyhook controllers, consuming the most amount of energy.

The LQG/LTR (linear quadratic Gaussian with loop transfer recovery) control strategy based on acceleration feedback in conjunction with an MR fluid damper was also considered to reduce wind-induced response of the four-story building model (Zhang and Roschke 1999). An experimental method of system identification that uses modal analysis was carried out to determine the dynamic and static characteristics of the system for formulating a stat-space representation of the structure. They showed that the control force notably reduced simulated peak floor accelerations when a strong wind loading was applied to the structure as shown in Fig. 18.

3.2 Intelligent technology-based control

3.2.1 Neural network-based control

The applicability of a neural network-based control algorithm to semiactive control systems using MR fluid dampers has been investigated recently. Ni *et al*. (2000, 2002b) proposed two types of neural network-based controllers (i.e., full-order and reduced-order models) for reducing the excessive vibration of sagged stay cables incorporated with MR fluid dampers. A numerical simulation study on a 12 m long testing cable (a 1:12 scale model of a prototype cable in an actual cable structure) was conducted to compare the control effectiveness of the developed neuro-controllers using incomplete observation with that of the LQG and clipped LQG controllers with complete observation and to verify the adaptive ability of off-line trained neuro-controllers under different external excitations. As shown in Fig. 19, the analytical results of their study showed that neuro-controllers could effectively implement semiactive vibration control of stay cables with the use of MR fluid dampers. As shown in Fig. 19(a), the static equilibrium configuration lies in the vertical plane x-y and is described by the function $y(s)$, s being the curvilinear abscissa. The dynamic configuration of the cable under a distributed load is $u(s, t)$ and $v(s, t)$. B_j and α_j are the damper location and the angle between damper and horizontal axes.

Xu *et al*. (2003) proposed an on-line real-time control method employing a four-layer feedforward neural network, trained on-line under the Levenberg-Marquardt algorithm, which is one of the second-order convergence-based approaches for least squares optimization and is used to improve the back-propagation algorithm for training neural networks in this case, for semiactive control of structures with MR fluid dampers. Their on-line real-time learning and control architecture consists of three parts to perform different tasks. The first part is the on-line training neural network, which is trained to generate the one-step-ahead prediction of displacement and velocity by considering inputs including the delayed displacements and velocities, the delayed control forces and the delayed earthquake inputs. The second part is to calculate control currents and control forces. The third part is to measure the actual responses of structures with MR fluid dampers. The errors between the predicted responses and the actual responses are used to update the weights on-line. They demonstrated that the response of the structure with MR fluid dampers calculated by their

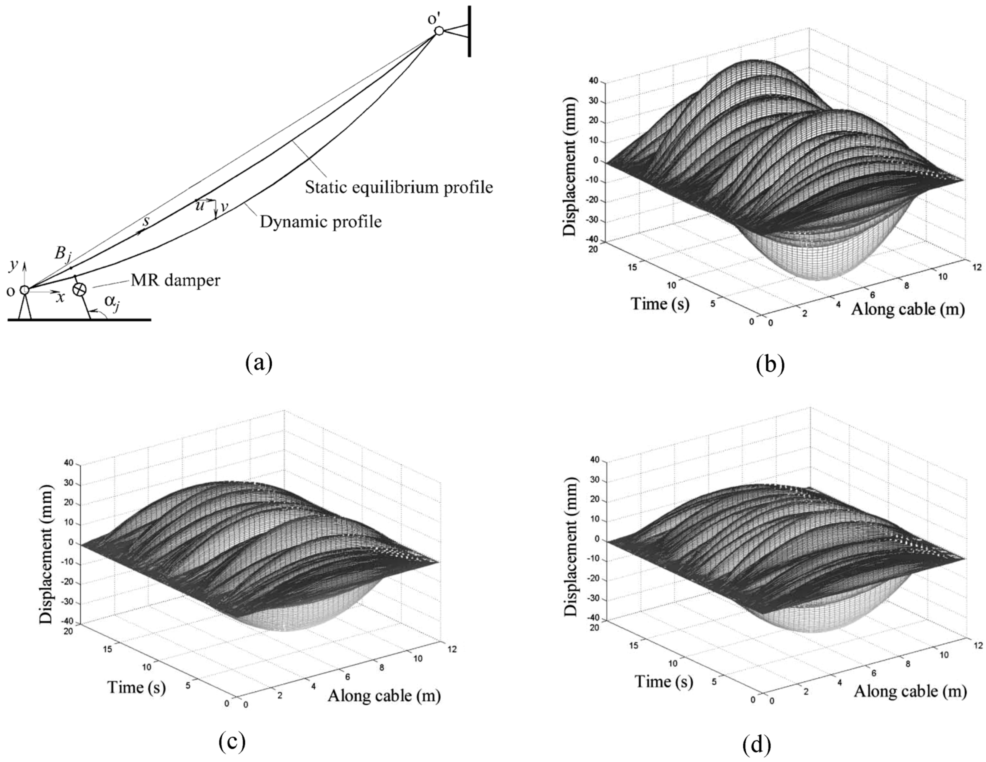


Fig. 19 Cable response without and with neuro-control under testing loading: (a) configuration of the system; (b) without control; (c) full-order model; (d) reduced-order model (Ni *et al.* 2002)

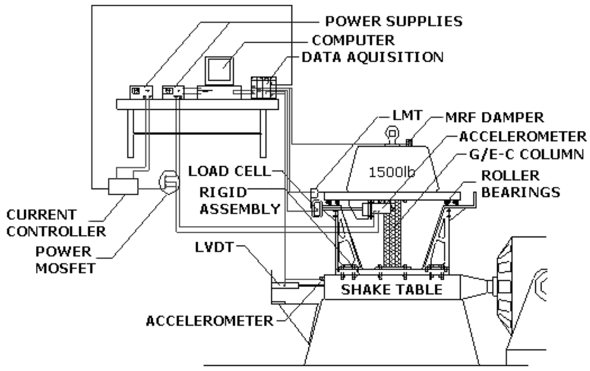
method were smaller than those calculated by the traditional elastoplastic time-history method, especially for the acceleration responses.

3.2.2 Fuzzy logic-based control

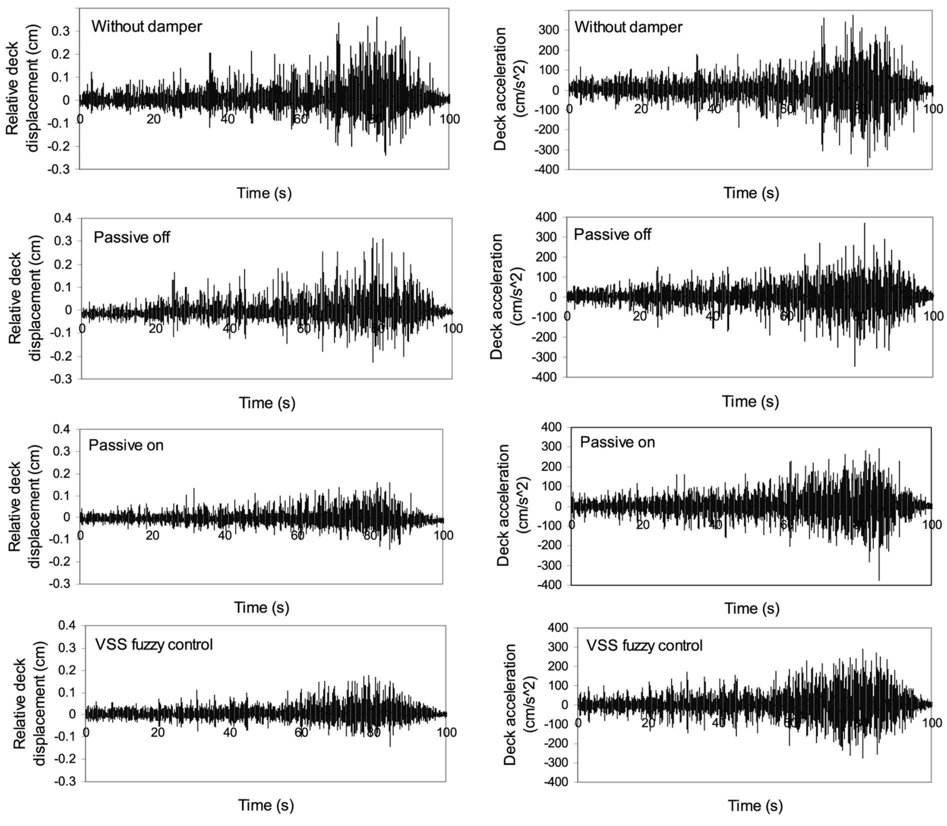
Fuzzy logic-based control algorithms, which influence the behavior of a system by changing inputs to that system according to a set of rules that model how to operate the system, offer a simple and robust framework for the specification of nonlinear control laws that can accommodate uncertainty and imprecision (Subramanian *et al*. 1996). Therefore, many researchers have been studied the possibility of the fuzzy controllers for the MR fluid damper-based control system.

Zhou and Chang (2000b) and Zhou *et al*. (2002) performed the feasibility study of the fuzzy logic-based control to the semiactive control system with MR fluid dampers by considering a nonlinear three-story building model that exhibited bilinear elasto-plastic behavior. They insisted that because the control strategy based on the combination of the fuzzy controller and the adaptation law did not require a prior knowledge of the combined building-damper system, their approach provided a robust control strategy that could be used to protect nonlinear or uncertain structures subjected to random loads. They also demonstrated from the numerical example that their control strategy could be applied to mitigate earthquake-induced response of the nonlinear multi-degree-of-freedom system using an MR fluid damper.

Liu *et al*. (2000, 2001) applied the closed-loop control algorithm based on fuzzy logic to a 1/12 scaled two-span bridge model employing the MR fluid damper. The sufficient condition for the closed-loop stability of the fuzzy control system was derived from the variable structure system



(a) Schematic of the experimental setup



(b) Relative deck displacement (c) Deck acceleration

Fig. 20 Time response of scaled bridge system under random base motion (Liu *et al.* 2002) theory. They experimentally demonstrated the effectiveness of the semiactive MR fluid damper-based control system on the vibration reduction of a scaled bridge model. Also, it was demonstrated that the stable fuzzy control system could significantly reduce the relative deck displacement using about 55% less power compared to passive-on state, while the absolute deck acceleration was relatively unaffected as shown in Fig. 20. In the figure, the "VSS fuzzy control" means the variable structure system-based fuzzy logic control proposed by Liu *et al.*

Schurter and Roschke (2001a,b) proposed a new approach for reduction of earthquake-induced vibration in constructed facilities such as single-degree-of-freedom and four-degree-of-freedom building models by way of a neuro-fuzzy technique. Energy of each building is dissipated through MR fluid dampers whose damping properties are continuously updated by a fuzzy controller. According to numerical simulation, MR fluid dampers are less effective control mechanisms than passive dampers with respect to a single-degree-of-freedom building model. On the other hand, MR fluid dampers are predicted to be superior when used with multi-degree-of-freedom structures for reduction of lateral acceleration.

4. Full-scale applications

In 2001, MR fluid dampers were applied to the full-scale structures for alleviation of wind and seismic responses of the structures. The cable-stayed Dongting Lake Bridge in China and the Nihon-Kagaku-Miraikan building in Japan constitute the world's first full-scale implementations of MR fluid damper-based semiactive control technology in civil engineering structures.

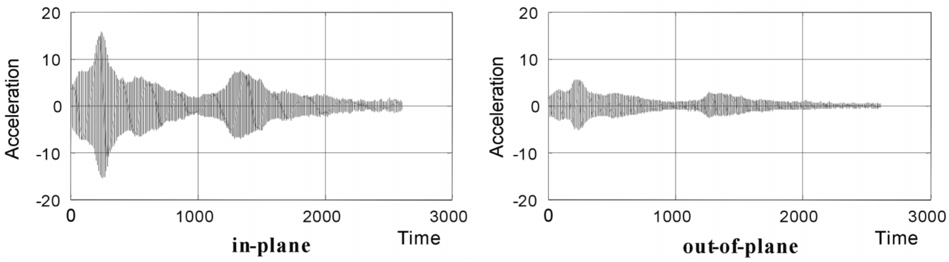
The Dongting Lake Bridge in China constitutes the first full-scale implementation of MR fluid dampers for bridge structures as shown in Fig. 21. Two MR fluid dampers shown in Fig. 3(a) are mounted on each cable to mitigate cable vibration. A total of 312 MR fluid dampers are installed on 156 stayed cables. Fig. 22 shows that MR fluid dampers can significantly suppress wind-rain-induced cable vibration. Extensive field testing, as well as analytical and lab-scale tests (Lou *et al*. 2001, Ko *et al*. 2002a,b, Ni *et al*. 2002c,d, Chen *et al*. 2002a) were conducted. The technical support of this engineering project was provided through a joint venture between the Central South University (Z.Q. Chen), The Hong Kong Polytechnic University (J.M. Ko and Y.Q. Ni), and B.F. Spencer, Jr. Moreover, MR fluid dampers have been chosen for implementation on the Binzhou Yellow River Bridge in China to reduce cable vibration. The installation is expected to be completed in October 2003 (Spencer and Nagarajaiah 2003). Recently, a feasibility study on applicability of MR fluid dampers for cable vibration control of the Stonecutter Bridge with a main span of 1018 m - the world's longest cable-stayed bridge being under construction - has been accomplished (Chen *et al*. 2002b, Ying *et al*. 2002b).

In 2001, the Nihon-Kagaku-Miraikan in Japan, the Tokyo National Museum of Emerging Science and Innovation, has two 30-ton, MR fluid dampers installed between third and fifth floors as shown in Fig. 23. This is the first implementation of MR fluid dampers to a building structure. The dampers were built by the Sanwa Tekki Corporation using Lord Corporation MR fluid. Recently, 40-ton MR fluid dampers were installed in a residential building in Japan along with laminated rubber bearings, lead dampers, and oil dampers to provide the best seismic protection (Fujitani *et al*. 2003).

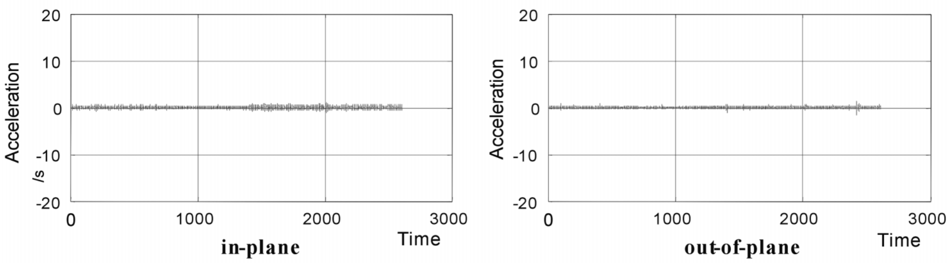
(a) Overview

(b) Full implementation

Fig. 21 Dongting Lake Bridge in China (Ni 2002)



(a)



(b)

Fig. 22 Acceleration time-history response of a cable in the Dongting Lake Bridge: (a) without dampers; (b) with MR dampers (Ni *et al.* 2002b)

(a) Overview

(b) Installation of an MR fluid damper

Fig. 23 Nihon-Kagaku-Miraikan in Japan (Spencer and Nagarajaiah 2003)

5. Conclusions

A detailed literature review has been presented of dynamic models of MR fluid dampers for describing their complex dynamic behavior, as well as control algorithms that consider the characteristics of MR fluid dampers. This extensive review provides references to semiactive control systems using MR fluid dampers. The analytical, lab-scale, and field tests described in this paper clearly demonstrate that MR fluid damper-based semiactive control systems have the potential for mitigating the responses of full-scale civil engineering structures under natural hazards such as earthquakes and strong winds. It should be emphasized that the MR fluid damper-based control technology is still evolving and expanding. Therefore, significant advances and important full-scale applications to civil infrastructures will certainly continue for several years to come. More information regarding MR fluid dampers and their application to civil engineering structures can be found at <http://cee.uiuc.edu/sstl> and at <http://www.rheonetic.com>.

Acknowledgements

This research is supported in part by the Smart Infra-Structure Technology Center (SISTeC) from the Ministry of Science and Technology in Korea, by the US National Science Foundation under grant CMS 99-00234 (Dr. S.C. Liu, Program Director), and by the Lord Corporation.

References

Baker, G.A., Johnson, E.A., Spencer, Jr., B.F. and Fujino, Y. (1999), "Modeling and semiactive damping of stay cables", *Proc. of the 13th ASCE Eng. Mech. Conf.*, Baltimore, Maryland, USA, CD-ROM.

Butz, T. and von Stryk, O. (2002), "Modelling and simulation of electro- and magnetorheological fluid dampers", *ZAMM: Applied Mathematics and Mechanics*, **82**, 3-20.

Carlson, J.D. and Weiss, K.D. (1994), "A growing attraction to magnetic fluids", *Machine Des*., (Aug.), 61-64.

Carlson, J.D., Catanzarite, D.M. and St. Clair, K.A. (1995), "Commercial magneto-rheolgoical fluid devices", *First Int. Conf. on ER Fluids, MR Fluids and Associated Technol*., Sheffield, U.K.

Chang, C.-C. and Roschke, P.N. (1998), "Neural network modeling of a magnetorheological damper", *J. Intelligent Material Systems and Structures*, **9**, 755-764.

Chang, C.-C. and Zhou, L. (2002), "Neural network emulation of inverse dynamics for a MR damper", *J. Struct. Eng*., ASCE, **128**(2), 231-239.

Chen, Z.Q., Wang, X.Y., Ni, Y.Q. and Ko, J.M. (2002a), "Field measurement on wind-rain-induced vibration of bridge cables with and without MR dampers", *Proc. of the 3rd Int. Conf. Structural Control*, Como, Italy.

Chen, Y., Ni, Y.Q. and Ko, J.M. (2002b), "Applicability of passive and active devices for vibration control of long-span bridge cables", Research Report, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong.

Christenson, R.E. (2001), "Semiactive control of civil structures for natural hazard mitigation: analytical and experimental studies", Ph.D dissertation, University of Notre Dame, Indiana, USA.

Christenson, R.E. and Spencer, Jr., B.F. (1999a), "Coupled building control using 'smart' dampers", *Proc. 13th ASCE Engineeing Mechanics Conf.*, Baltimore, Maryland, USA, CD-ROM.

Christenson, R.E., Spencer, Jr., B.F. and Johnson, E.A. (1999b), "Coupled building control using active and smart damping strategies", *Optimization and Control in Civil and Structural Engineering* (B.H.V. Topping and B. Kumar eds.), Civil-Comp Press, 187-195.

Christenson, R.E., Spencer, Jr., B.F. and Johnson, E.A. (2000), "Coupled building control using 'smart' damping strategies", *Proc. of the Smart Systems for Bridges, Structures, and Highways, the 7th SPIE Annual International Smart Structures and NDE Symposia*, Newport Beach, CA, USA.

Christenson, R.E., Spencer, Jr., B.F. and Johnson, E.A. (2001), "Experimental verification of semiactive damping of stay cables", *Proc. of the 2001 American Control Conf.*, Arlington, Virginia, USA, 5058-5063.

Christenson, R.E., Spencer, Jr., B.F. and Johnson, E.A. (2002), "Experimental studies on the smart damping of stay cables", *Proc. of the 2002 Structures Congress*, Denver, Colorado, USA, CD-ROM.

Dyke, S.J. (1998), "Seismic protection of a benchmark building using magnetorheological dampers", *Proc. 2nd World Conf. Structural Control,* Kyoto, Japan, **2**, 1455-1462.

Dyke, S.J. and Spencer, Jr., B.F. (1996), "Seismic response control using multiple MR dampers", *Proc. of the 2nd Int. Workshop on Structural Control*, Hong Kong, 163-173.

Dyke, S.J. and Spencer, Jr., B.F. (1997), "A comparison of semi-active control strategies for the MR damper", *Proc. of the IASTED Int. Conf. Intelligent Information Systems*, The Bahamas.

Dyke, S.J., Spencer, Jr., B.F., Sain, M.K. and Carlson, J.D. (1996a), "Modeling and control of magnetorheological dampers for seismic response reduction", *Smart Materials and Structures*, **5**, 565-575.

Dyke, S.J., Spencer, Jr., B.F., Sain, M.K. and Carlson, J.D. (1996b), "Experimental verification of semi-active structural control strategies using acceleration feedback", *Proc. of the 3rd Int. Conf. Motion and Vibration Control*, Chiba, Japan, **III**, 291-296.

Dyke, S.J., Spencer, Jr., B.F., Sain, M.K. and Carlson, J.D. (1998), "An experimental study of MR dampers for seismic protection", *Smart Materials and Structures: Special Issue on Smart Materials and Structures Technology: Application to Large Civil Infrastructure*, **7**, 693-703.

Dyke, S.J., Caicedo, J.M., Turan, G., Caicedo, J.M., Bergman, L.A. and Hague, S. (2003), "Phase I benchmark control problem for seismic response of cable-stayed bridges", *J. Struct. Eng.*, **129**(7), 857-872.

Erkus, B., Abe, M. and Fujino, Y., (2002), "Investigation of semi-active control for seismic protection of elevated highway bridges", *Eng. Struct.*, **24**, 281-293.

Fujitani, H. *et al*. (2003), "Development of 400 kN magnetorheological damper for a real base-isolated building", *Proc. of SPIE Conf. Smart Structures and Materials*, **5057**.

Gamota, D.R. and Filisko, F.E. (1991), "Dynamic mechanical studies of electrorheological materials: moderate frequencies", *J. of Rheology*, **35**, 399-425.

Hiemenz, G.J., Choi, Y.T. and Wereley, N.M. (2003), "Seismic control of civil structures using semi-active MR braces", *Computer-Aided Civil and Infrastructure Engineering*, **18**, 31-44.

Jansen, L.M. and Dyke, S.J. (1999), "Investigation of nonlinear control strategies for the implementation of multiple magnetorheological dampers", *Proc. of the 1999 ASCE Engineering Mechanics Conf.*, Baltimore, Maryland, USA.

Jansen, L.M. and Dyke, S.J. (2000), "Semi-active control strategies for the MR damper: a comparative study", *J. Eng. Mech.*, ASCE, **126**(8), 795-803.

Jin, G., Sain, M.K., Pham, K.D., Spencer, Jr., B.F. and Ramallo, J.C. (2001), "Modeling MR-dampers: a nonlinear blackbox approach", *Proc. of the American Control Conference*, Arlington, Virginia, USA.

Jin, G., Sain, M.K. and Spencer, Jr., B.F. (2002), "Modeling MR-dampers: the ridgenet estimation approach", *Proc. of the American Control Conference*, Anchorage, Alaska, USA.

Johnson, E.A., Ramallo, J.C., Spencer, Jr., B.F. and Sain, M.K. (1998), "Intelligent base isolation systems", *Proc. of the Second World Conf. on Structural Control (2WCSC)*, Kyoto, Japan, **1**, 367-376.

Johnson, E.A., Spencer, Jr., B.F. and Fujino, Y. (1999), "Semiactive damping of stay cables: a preliminary study", *Proc. of the 17th Int. Modal Analysis Conf.*, Kissimmee, Florida, USA, 417-423.

Johnson, E.A., Baker, G.A., Spencer, Jr., B.F. and Fujino, Y. (2000a), "Mitigating stay cable oscillation using semiactive damping", *Smart Structures and Materials 2000: Smart Systems for Bridges, Structures and Highways* (S.C. Liu ed.), Newport Beach, California, USA, **3988**, 207-216.

Johnson, E.A., Christenson, R.E. and Spencer, Jr., B.F. (2000b), "Semiactive damping of cables with sag", *Proc. of the Int. Conf. on Advances in Structural Dynamics (ASD2000)* (J.M. Ko and Y.L. Xu eds.), Hong Kong, 327-334.

Johnson, E.A., Christenson, R.E. and Spencer, Jr., B.F. (2001), "Smart stay cable damping - effects of sag and inclination (invited)", *Proc. of the 8th Int. Conf. Structural Safety and Reliability (ICOSSAR'01)*, Newport Beach, California, USA, CD-ROM.

Johnson, E.A., Baker, G.A., Spencer, Jr., B.F. and Fujino, Y. (2002), "Semiactive damping of stay cables", *J. Eng. Mech.*, ASCE, in press.

Jung, H.-J., Spencer Jr., B.F. and Lee, I.-W. (2001), "Benchmark control problem of seismically excited cable-stayed bridges using smart damping strategies", *Proc. of the IABSE Conf. on Cable-Supported Bridges - Challenging Technical Limits*, Seoul, Korea, Serial 84, 256-257 (Full paper in CD-ROM).

Jung, H.-J., Spencer, Jr., B.F. and Lee, I.-W. (2002), "Seismic protection of cable-stayed bridges using magnetorheological dampers", *Proc. of the Seventh U.S. Nat. Conf. on Earthquake Engineering*, Boston, Massachusetts, USA, CD-ROM.

Jung, H.-J., Spencer, Jr., B.F. and Lee, I.-W. (2003), "Control of seismically excited cable-stayed bridge employing magnetorheological fluid dampers", *J. Struct. Eng.*, **129**(7), 873-883.

Kamath, G.M. and Wereley, N. (1997), "Nonlinear viscoelastic-plastic mechanism-based model of an electrorheological damper", *J. Guidance, Control Dynamics*, **20**, 1125.

Ko, J.M., Ni, Y.Q., Chen, Z.Q. and Spencer, Jr., B.F. (2002a), "Implementation of MR dampers to donting Lake Bridge for cable vibration control", *Proc. of the 3rd Int. Conf. Structural Control*, Como, Italy.

Ko, J.M., Zheng, G., Chen, Z.Q. and Ni, Y.Q. (2002b), "Field vibration tests of bridge stay cables incorporated with magneto-rheological (MR) dampers", *Smart Structures and Materials 2002: Smart Systems for Bridges, Structures, and Highways* (S.C. Liu and D.J. Pines eds.), SPIE **4696**.

Koh, H.M., Park, W., Park, K.S., Ok, S.Y. and Hahm, D. (2001), "Performance evaluation and cost effectiveness of semi-active vibration control system for cable-stayed bridges under earthquake excitation", *Proc. of the IABSE Conf. on Cable-Supported Bridges - Challenging Technical Limits*, Seoul, Korea, Serial 84, 258-259 (Full paper in CD-ROM).

Leva, A. and Piroddi, L. (2002), "NARX-based technique for the modeling of magneto-rheological damping devices", *Smart Materials and Structures*, **11**, 79-88.

Li, W.H., Yao, G.Z., Chen, G., Yeo, S.H. and Yap, F.F. (2000), "Testing and steady state modeling of a linear MR damper under sinusoidal loading", *Smart Materials and Structures*, **9**, 95-102.

Li, J. and Samali, B. (2001), "Sliding mode control of five story benchmark model with magnetorheological (MR) damper", *Proc. of the eighth Ease Asia-Pacific Conf. on Structural Engineering and Construction*, Singapore, Paper No. 1534, CD-ROM.

Liu, Y., Gordaninejad, F., Evrensel, C.A. and Wang, X. (2000), "Semi-active control of a bridge using controllable magneto-rheological dampers", *Smart Systems for Bridges, Structures, and Highways, Proc. of SPIE Conf. on Smart Materials and Structures* (S.C. Liu ed), Newport Beach, California, USA, **3988**, 199-206.

Liu, Y., Gordaninejad, F., Evrensel, C.A. and Hitchcock, G. (2001), "Experimental study on fuzzy logic vibration control of a bridge using fail-safe magnetorheological fluid dampers", *Smart Systems for Bridges, Structures, and Highways, Proc. of SPIE Conf. on Smart Materials and Structures* (S.C. Liu ed), Newport Beach, California, USA, **4330**, 281-288.

Lou, W.J., Ni, Y.Q. and Ko, J.M. (2001), "Modal damping and stepping-switch control of stay cables with magnetorheological fluid dampers", *Smart Structures and Materials 2001: Smart Systems for Bridges, Structures, and Highways* (S.C. Liu ed.), SPIE **4330**, 354-365.

Moon, S.J., Bergman, L.A. and Voulgaris, P.G. (2002), "Sliding mode control of a cable-stayed bridge subjected to seismic excitation", *Proc. of the 7th US Nat. Conf. Earthquake Engineering*, Boston, Massachusetts, USA, CD-ROM.

Moon, S.J., Bergman, L.A. and Voulgaris, P.G. (2003), "Sliding mode control of cable-stayed bridge subjected to seismic excitation", *J. Eng. Mech.*, ASCE, **129**(1), 71-78.

Ni, Y.Q. (2002), "Implementation of magneto-rheological dampers to cable-stayed bridges for wind-rain-induced vibration control", *Seminar at KAIST*, Daejeon, Korea.

Ni, Y.Q., Cao, D.Q., Ko, J.M. and Chen, Y. (2000), "Neuro-control of inclined sagged cables using semi-active MR dampers", *Proc. of the Int. Conf. on Advances in Structural Dynamics (ASD2000)* (J.M. Ko and Y.L. Xu eds.), Hong Kong, **II**, 1373-1380.

Ni, Y.Q., Liu, H.J. and Ko, J.M. (2002a), "Experimental investigation on seismic response control of adjacent buildings using semi-active MR dampers", *Smart Structures and Materials 2002: Smart Systems for Bridges, Structures, and Highways* (S.C. Liu and D.J. Pines eds.), SPIE **4696**.

Ni, Y.Q., Chen, Y., Ko, J.M. and Cao, D.Q. (2002b), "Neuro-control of cable vibration using semi-active magneto-rheological dampers", *Eng. Struct.*, **24**, 295-307.

Ni, Y.Q., Chen, Y., Ko, J.M. and Zheng, G. (2002c), "Optimal voltage/current input to ER/MR dampers for multi-switch control of stay cable vibration", *Proc. of the 3rd World Conf. Structural Control*, Como, Italy.

Ni, Y.Q., Duan, Y.F., Chen, Z.Q. and Ko, J.M. (2002d), "Damping identification of MR-damped bridge cables from in-situ monitoring under wind-rain-excited conditions", *Smart Structures and Materials 2002: Smart Systems for Bridges, Structures, and Highways*, S.-C. Liu and D.J. Pines (eds.), SPIE **4696**.

Ni, Y.Q., Ying Z.G., Wang, J.Y., Ko, J.M. and Spencer, Jr., B.F. (2003), "Semi-active control of randomly wind-excited tall building structures using MR-TLCDs", accepted to *Proc. of the 5th Int. Conf. on Stochastic Structural Dynamics*, Hangzhou, China.

Oh, J.W., Roschke, P.N., Lin, P.Y., Carlson, J.D. and Sunakoda, K. (2002), "Neuro-fuzzy modeling of a 30-ton magnetorheological damper", *Proc. of the 2nd Int. Sym. Advances in Structural Engineering and Mechanics*, Busan, Korea, CD-ROM.

Qu, W.L. and Xu, Y.L. (2001), "Semi-active control of seismic response of tall buildings with podium structure using ER/MR dampers", *The Structural Design of Tall Buildings*, **10**, 179-192.

Qu, W.L., Xu, Y.L. and Lv, M.Y. (2002), "Seismic response control of large-span machinery building on top of ship lift towers using ER/MR moment controllers", *Eng. Struct.*, **24**, 517-527.

Rabinow, J. (1948), "The magnetic fluid clutch", *AIEE Transaction*, **67**, 1308-1315.

Ramallo, J.C., Johnson, E.A., Spencer, Jr., B.F. and Sain, M.K. (2000), "'Smart' base isolation systems", *Proc. of the Advanced Technology in Structural Engineering, Structures Congress*, Philadelphia, Pennsylvania, USA, CD-ROM.

Ramallo, J.C., Johnson, E.A. and Spencer, Jr., B.F. (2002), ""Smart" base isolation systems", *J. Eng. Mech.*, ASCE, **128**(10), 1088-1099.

Ribakov, Y. and Gluck, J. (2002a), "Selective controlled base isolation system with magnetorheological dampers", *Earthq. Eng. Struct. Dyn.*, **31**, 1301-1324.

Ribakov, Y. and Gluck, J. (2002b), "Selective combined control stiffness and magneto-rheological damping system in nonlinear multistory structures", *The Structural Design of Tall Buildings*, **11**, 171-195.

Ruangrassamee, A. and Kawashima, K. (2001), "Semi-active control of bridges by using MR dampers", *Proc. of the US-Japan Workshop on Smart Structures for Improved Seismic Performance in Urban Region,* Seattle, Washington, USA, 199-212.

Ruangrassamee, A., Jung, H.-J., Kawashima, K. and Spencer, Jr., B.F. (2001), "Semi-active control of a nonlinear coupled bridge system by the clipped optimal control algorithm", *Proc. of the US-Japan Workshop on Smart Structures for Improved Seismic Performance in Urban Region*, Seattle, Washington, USA, 183-198.

Sahasrabudhe, S. and Nagarajaiah, S. (2001), "Semiactive control of sliding isolated buildings with MR dampers", *Proc. of 2001 Mechanics and Materials Conf.*, San Diego, California, USA.

Schurter, K. and Roschke, P.N. (2000), "Fuzzy modeling of a magnetorheological damper using ANFIS", *Proc. of the IEEE Fuzzy 2000 Conf.,* San Antonio, Texas, USA.

Schurter, K. and Roschke, P.N. (2001a), "Neuro-fuzzy control of structures using acceleration feedback", *Smart Materials and Structures*, **10**, 770-779.

Schurter, K. and Roschke, P.N. (2001b), "Neuro-fuzzy control of structures using magnetorheological dampers", *Proc. of the 2001 American Control Conf.* Washington, D.C., USA.

Soong, T.T. and Spencer Jr., B.F. (2002), "Supplemental energy dissipation: state-of-the-art and state-of-the-practice", *Eng. Struct.*, **24**, 243-259.

Spencer Jr., B.F. and Sain, M.K. (1997) "Controlling buildings: a new frontier in feedback", *IEEE Control Systems Magazine*: Special Issue on Emerging Technologies (Tariq Samad, Guest Ed.), **17**(6), 19-35.

Spencer Jr., B.F. and Nagarajaiah, S. (2003) "State of the art of structural control", *J. Struct. Control,* ASCE, **129**(7), 845-856.

Spencer Jr., B.F., Dyke, S.J., Sain, M.K. and Carlson, J.D. (1997), "Phenomenological model of a magnetorheological damper", *J. Eng. Mech.*, ASCE, **123**, 230-238.

Stanway, R., Sproston, J.L. and Stevens, N.G. (1985), "Non-linear identification of an electro-rheological vibration damper", *IFAC Identification and System Parameter Estimation*, 195-200.

Stanway, R., Sproston, J.L. and Stevens, N.G. (1987), "Non-linear identification of an electro-rheological vibration damper", *J. of Electrostatics*, **20**, 167-184.

Stengel, R.F. (1986), *Stochastic Optimal Control: Theory and Application*, John Wiley & Sons, New York, NY.

Subramanian, R.S., Reinhorn, A.M., Nagarajaiah, S. and Ryley, M.A. (1996), "Hybrid control of structures using fuzzy logic", *Microcomput. Civ. Eng*., **11**, 1-18.

Symans, M.D. and Constantinou, M.C. (1999), "Semi-active control systems for seismic protection of structures: a state-of-the-art review", *Eng. Struct.*, **21**, 469-487.

Utkin, V.I. (1992), *Sliding Modes in Control Optimization*, Springer, New York, NY.

Vavreck, A.N. (2002), "Single-stage magnetorheological damper parameter estimation", *Smart Materials and Structures*, **11**, 596-598.

Wang, D.-H. and Liao, W.-H. (2001), "Neural network modeling and controllers for magnetorheological fluid dampers", *Proc. of the 2001 IEEE Int. Fuzzy Conf.* 1323-1326.

Wang, X. and Gordaninejad, F. (2001), "Lyapunov-based control of a bridge using magneto-rheological fluid dampers", *Proc. of the 8th Int. Conf. on ER/MR Fluids.*

Wang, X. and Gordaninejad, F. (2002), "Lyapunov-based control of a bridge using magneto-rheological fluid dampers", *J. Intelligent Material System and Structures*, **13**(7), 415-419.

Wang, J.Y., Ni, Y.Q., Ko, J.M. and Spencer, Jr., B.F. (2002), "Semi-active TLCDs using magneto-rheological fluids for vibration mitigation of tall buildings", *Proc. of the Int. Conf. on Advances in Building Tech.*, Hong Kong.

Wen, Y. (1976), "Method for random vibration of hysteretic systems", *J. Eng. Mech. Div.*, **102**, 249-263.

Weiss, K.D., Carlson, J.D. and Nixon, D.A. (1994), "Viscoelastic properties of magneto- and electro-rheological fluids", *J. Intelligent Material System and Structures*, **5**, 772.

Winslow, W.M. (1949), "Induced vibration of suspensions", *J. of Applied Physics*, **20**, 1137-1140.

Xu, Y.L., Qu, W.L. and Ko, J.M. (2000), "Seismic response control of frame structures using magnetorheological/electrorheological dampers", *Earthq. Eng. Struct. Dyn.*, **29**, 557-575.

Xu, Z.-D., Shen, Y.P. and Guo, Y.-Q. (2003), "Semi-active control of structures incorporated with magnetorheological dampers using neural networks", *Smart Materials and Structures*, **12**, 80-87.

Yang, G. (2001), "Large-scale magnetorheological fluid damper for vibration mitigation: modeling, testing and control", Ph.D dissertation, University of Notre Dame, Indiana, USA.

Yang, G., Jung, H.-J. and Spencer, Jr., B.F. (2001), "Dynamic modeling of full-scale MR dampers for civil engineering applications", *Proc. of the US-Japan Workshop on Smart Structures for Improved Seismic Performance in Urban Region*, Seattle, Washington, USA, 213-224.

Yang, G., Spencer, Jr., B.F., Carlson, J.D. and Sain, M.K. (2002), "Large-scale MR fluid dampers: modeling and dynamic performance considerations", *Eng. Struct.*, **24**, 309-323.

Yi, F., Dyke, S.J., Frech, S. and Carlson, J.D. (1998), "Investigation of magnetorheological dampers for earthquake hazard mitigation", *Proc. of the 2nd World Conf. Structural Control*, Kyoto, Japan, **1**, 349-358.

Yi, F., Dyke, S.J., Caicedo, J.M. and Carlson, J.D. (2001), "Experimental verification of multi-input seismic control strategies for smart dampers", *J. Eng. Mech.*, ASCE, **127**(11), 1152-1164.

Ying Z.G., Ni, Y.Q. and Ko, J.M. (2002a), "Non-clipping optimal control of randomly excited nonlinear systems using semi-active ER/MR dampers", *Smart Structures and Materials 2002: Smart Systems for Bridges, Structures, and Highways* (S.C. Liu and D.J. Pines eds.), SPIE **4696**.

Ying, Z.G., Ni, Y.Q. and Ko, J.M. (2002b), "Analysis and control of dynamic stability of bridge stay cables induced by parametrically excited oscillation", Research Report, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong.

Yoshida, O., Dyke, S.J., Giacosa, L.M. and Truman, K.Z. (2002), "Torsional response control of asymmetric buildings using smart dampers", *Proc. of the 15th ASCE Engineering Mechanics Conf.*, New York, NY, USA, CD-ROM.

Yoshioka, H., Ramallo, J.C. and Spencer, Jr., B.F. (2002), ""Smart" base isolation strategies employing magnetorheological dampers", *J. Eng. Mech.*, ASCE, **128**(5), 540-551.

Zhang, J. and Roschke, P.N. (1998), "Neural network simulation of magnetorheological damper behavior", *Proc. of the Int. Conf. on Vibration Engineering '98*, Dalian, China.

Zhang, J. and Roschke, P.N. (1999), "Active control of a tall structure excited by wind", *J. Wind Engineering and Industrial Aerodynamics*, **83**, 209-223.

Zhou, L. and Chang, C.C. (2000a), "A recurrent neural network emulator for the inverse dynamics of an MR damper", *Proc. of the Int. Conf. on Advances in Structural Dynamics (ASD2000)* (J.M. Ko and Y.L. Xu eds.), Hong Kong, 365-372.

Zhou, L. and Chang, C.C. (2000b), “Adaptive fuzzy control for a structure-MR damper system”, *Smart Systems for Bridges, Structures, and Highways*, *SPIE's 7th Annual Int. Symp. on Smart Structures and Materials*, Newport Beach, California, USA.

Zhou, L., Chang, C.C. and Spencer, Jr., B.F. (2002), “Intelligent technology-based control of motion and vibration using MR dampers”, *Earthq. Eng. Eng. Vib.*, **1**(1), 100-110.