Intelligent Bi-state Control for the Structure with Magnetorheological Dampers

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ABSTRACT: Magnetorheological (MR) damper is a kind of intelligent control device, which can be used to reduce earthquake responses of building structures. In this paper, a mathematical model of MR dampers is introduced, and the relation between the yielding shear stress and the control current of MR dampers is formulated. Then the bi-state control strategy of the structure with MR dampers is studied. Results show that the control strategy easily leads to overrun of the parameters and the control force of MR dampers under the minor earthquake, which results in amplification of acceleration responses of the structure. For this reason, a modified bi-state control strategy is proposed. In this method, the neural network technique is used to predict the seismic responses of the structure, whilst the intelligent bi-state control strategy on the smart structure with MR dampers is applied to solve the time-delay problem of semiactive control. Numerical simulation of a three-story reinforced concrete frame structure with MR dampers and without MR dampers are performed using the bi-state control method, the modified bi-state control method and the intelligent bi-state control method. Results show that the intelligent control strategy solves the time-delay problem of semiactive control and overrun of control forces under the minor earthquake, and the control force is most veritable and the earthquake mitigation effect is the best.

Key Words: magnetorheological dampers, semiactive control, seismic response, neural network, intelligent bi-state control

INTRODUCTION

In recent years, semiactive control of buildings and structures with magnetorheological (MR) dampers for earthquake hazard mitigation has received considerable attention, because of its excellent performance in the response control of structures without requiring the input of extensive power and energy (Carlson and Weiss, 1994; Carlson and Spencer, 1996a; Dyke and Spencer, 1996; Kamath and Werely, 1997; Spencer and Sain, 1997; Jansen and Dyke, 2000). MR damper is a new kind of semiactive control device by using rheological property of MR fluids under the alternating magnetic fields. This type of damper has many attractive advantages, including inexpensive cost, controllable force, rapid responds, small power requirements, reliability and stability, which allows for the development of this device with a very high bandwidth (Fujita et al, 1999; Li et al. 2000).

In real applications, MR dampers are usually attached in the braces between columns. The sensors would measure and feed back the response quantities to a control unit, which creates through manipulation of the magnetic fields and the yielding strengths in MR dampers during the control process. Obviously, one key step in such a task of seismic hazard mitigation is the development of a control strategy, that can make full use of the capabilities of the smart control device. As we know, in the semiactive or active control, measurement of structure state, transmission and calculation of signal and infliction of control force are time consuming procedures. Moreover, control force is generated based on feedback from sensors that measure the excitation and/or the responses of the structure (Vicken and Celal, 1997). Since the control forces are calculated according to the last responses of the structure in the traditional time-history analysis method, an inherent time-delay problem exists in the traditional method. Time-delay usually leads to instability of control systems (Nikzad et al., 1996; Liu and Daley, 1999). Therefore, one important challenge in the study of semiactive control of the structure is to find a control method, that can dispose of the time-delay problem.

In this paper, a mathematical model on the relation between the yielding shear stress and the control current of the MR damper is first introduced. Then the bi-state control strategy of the structure with MR dampers

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1045-389X/03/01 0035–8 $10.00/0 DOI: 10.1177/104538903033642

(Kamagata and Kobori, 1994) is studied. Results show that the control strategy easily leads to overrun of the parameters and the control force of MR dampers under the minor earthquake, which results in amplification of acceleration responses of the structure. In order to solve this problem, a modified bi-state control strategy is proposed. At the same time, the neural network technique is used to predict the seismic responses of the structure, and the intelligent bi-state control strategy on the smart structure with MR dampers is proposed to solve the time-delay problem of semiactive control. Numerical simulation of a three-story reinforced concrete frame structure with MR dampers and without MR dampers are performed using the bi-state control method, the modified bi-state control method and the intelligent bi-state control method. It is shown that the intelligent control strategy proposed by authors provides the most precise control among the three control strategies.

THE MATHEMATICAL MODEL FOR MR DAMPERS

Magnetorheological dampers can be classified as pressure driven flow mode, direct-shear mode and squeeze-film mode, according to their poles motion form (Jolly et al., 1999). The MR damper used for the seismic mitigation of structure usually belongs to the pressure driven flow mode, which typically consists of a hydraulic cylinder containing micrometer-sized magnetically polarizable particles dispersed in hydrocarbon oil, as shown in Figure 1. In the presence of strong magnetic field, the particles polarize and offer an increased resistance to flow. By varying the magnetic field, the mechanical behavior of MR dampers can be modulated. Since MR fluids can be changed from a viscous fluid to a yielding solid within milliseconds and the resulting control force can be considerably large with a low-power requirement. MR dampers are applicable to large civil engineering structures (Xu et al., 2000).

It is noted that significant progress has been achieved during the past few years in the study of the mathematical model for MR dampers. Most research work (Carlson and Spencer, 1996b; Dyke et al., 1996; Spencer et al., 1997; Werely et al., 1998) has focused on establishing appropriate mathematical models from analysis and experimental studies of MR dampers. One of the most frequently referred model for MR dampers is the Bingham model (Gavin et al., 1996), which is modeled as having a friction component augmented by a Newtonian viscosity component as shown in Figure 2, and gives a relation between the stress and strain rate as

$$\tau = \eta\dot{\gamma} + \tau_y \mathrm{sgn}(\dot{\gamma}) \tag{1}$$

where τ is the shear stress in fluid, η is the Newtonian viscosity, independent of the applied magnetic field, $\dot{\gamma}$ is the shear strain rate and τ_y is the yielding shear stress controlled by the applied field. Based on Equation (1) Phillips et al. (1969) derived the force–displacement relationship for MR dampers,

$$F = \frac{12\eta L_d A_p^2}{\pi D h_d^3}\dot{u}(t) + \frac{3L_d\tau_y}{h_d}A_p \mathrm{sgn}[\dot{u}(t)] \tag{2}$$

where L_d is the length of the piston, A_p is the cross-sectional area of the piston, D is the inner diameter of the vat, h_d is the gap between the piston and the vat, $u(t)$ is the relative displacement of the piston to the vat. The yielding shear stress τ_y is the function of the applied field, which means τ_y is the function of the control current I. Based on the experimental data about MR dampers (Ou and Guan, 1999), dependence of the yielding shear stress τ_y upon the applied current I can be calculated. It is found (Xu, 2002) that the yielding shear stress τ_y is related to the control current I through

$$\tau_y = A_1 e^{-I} + A_2 \ln(I + e) + A_3 I \tag{3}$$

where A_1, A_2 and A_3 are coefficients relative to the property of the MR fluid in the MR damper, and e is the natural constant. Data fitting to experimental results (Ou and Guan, 1999), gives $A_1 = -11374$, $A_2 = 14580$, $A_3 = 1281$. Study (Xu, 2002) shows that the numerical results of the modified Bingham model fit well with the experimental results.

CONTROL STRATEGIES

For frame structures, MR dampers are usually placed between the chevron brace as shown in Figure 3. When considering the stiffness of chevron brace, smart damper-chevron brace system can be seen as a damper and a spring being connected in series. In order to ensure that MR dampers play in role fully, the stiffness

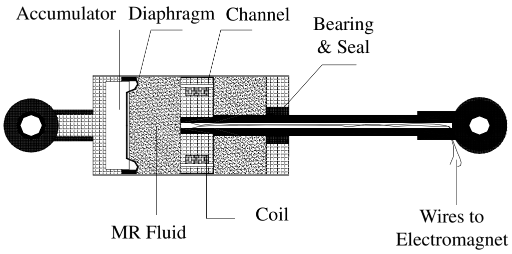

Figure 1. *Schematic of MR damper.*

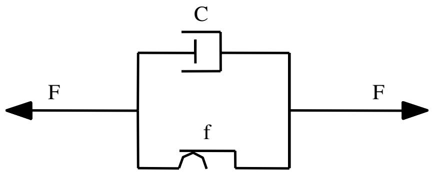

Figure 2. *Bingham Model.*

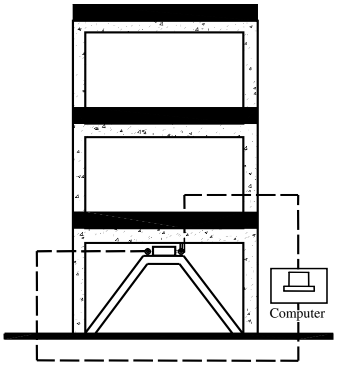

Figure 3. Schematic of smart structure.

of chevron brace is usually strong. So the stiffness of chevron brace can be neglected for simplified calculation, and the equations of motion for the structure with MR dampers can be written as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = -\mathbf{M}\Gamma\ddot{x}_g - \mathbf{B}\mathbf{f}_d \tag{4}$$

where **M**, **C** and **K** are the mass, damping and stiffness matrixes of the structure, respectively, **x** is the vector of the relative displacements of the floors of the structure, Γ is the column vector of ones, $\ddot{x}_g$ is the earthquake acceleration excitation, **B** is the matrix determined by the placement of MR dampers in the structure, $\mathbf{f}_d = [f_{d1}, f_{d2}, \ldots, f_{dn}]^T$ is the vector of control forces produced by MR dampers, and f_{dn} is the control force of the nth floor.

Various control approaches have been proposed in the literature (McClamroch and Gavin, 1995; Nikzad et al., 1996; Shahram et al., 1999) for semiactive control of the structure with MR dampers, such as the bi-state control (Kamagata and Kobori, 1994), bang-bang control (McClamroch and Gavin, 1995), clipped-optimal control (Dyke et al., 1996), and energy balance control (Shahram et al., 1999). In these control strategies, the bi-state control is the simplest strategy and is realized most easily in practical applications.

Bi-state control

In this control strategy, the current of MR dampers can be switched on or off at any time. If the structure is moving away from its equilibrium position, the current of MR dampers is switched on. If the structure is returning to its equilibrium position, the current of MR dampers is turned off. Mathematically the bi-state control strategy can be expressed as

$$\begin{cases} F_{d2} = (F_{d2})_{\max}, & I = I_{\max} \text{ when } x \cdot \dot{x} \geq 0 \\ F_{d2} = (F_{d2})_{\min}, & I = 0 \text{ when } x \cdot \dot{x} < 0 \end{cases} \tag{5}$$

where F_{d2} is the second item of the right hand side of Equation (2) , which is the main of the control force, and I is the current of MR dampers. This control strategy is simple and easy to realize, but it easily leads to overrun of the parameters and the control force of MR dampers during the initial and the final stages of the earthquake or under the minor earthquake, resulting in amplification of acceleration responses of the structure. This will be demonstrated in the following example.

Modified Bi-state Control

In the bi-state control, when the structure moving away from its equilibrium position, MR dampers will produce the larger control forces, even when the displacement is minor. Consequently, a minor disturbance can lead to un-necessary large change in the parameters of MR dampers. Under the minor earthquake, for example, the displacements of the structure are small, and the structure lies in elastic process and can resist the earthquake even without MR dampers. Therefore the current of MR dampers should be turned off and MR dampers provide the minor control forces. Accordingly, the bi-state control strategy can be modified as

$$\begin{cases} F_{d2} = (F_{d2})_{\max}, & I = I_{\max} \text{ when } x \cdot \dot{x} \geq 0 \text{ and } |x| \geq [x] \\ F_{d2} = (F_{d2})_{\min}, & I = 0 \text{ others} \end{cases} \tag{6}$$

where $[x]$ is the minor displacement limiting value, determined by experience. According to the modified bi-state control strategy, MR dampers provide the minor control forces to the structure under the minor earthquake or during the initial and the final periods of earthquake, avoiding amplifying the acceleration responses of the structure.

Intelligent Bi-state Control

When the control forces produced by MR dampers are determined according to Equations (5) or (6), the seismic responses of the structure with MR dampers expressed as Equation (4) can be calculated by the time-history analysis method (Ray and Josoph, 1975). As discussed above, the inherent time-delay issue exists in the semiactive control and the time-history analysis method, which may lead to inexact control forces and the worse control effect, even the instability of the control system (Nikzad et al., 1996; Liu and Daley, 1999). Therefore, reducing time-delay is very important for the semiactive control. This paper adopts the neural network technique to predict future responses of the structure and control the structure on-line. The neural network technique has some advantages, such as identification and prediction, which is considered as the better method to solve the time-delay problem.

Neural networks are simplified models of the biological structure found in human brains. These models consist of elementary processing units (also called neurons). It is the large amount of interconnections

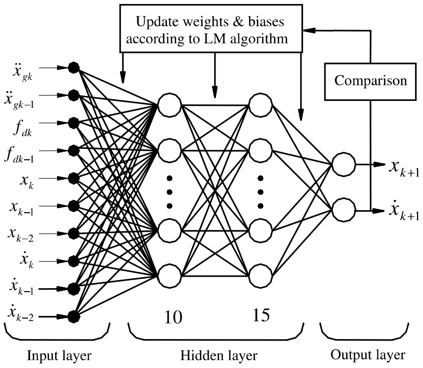

Figure 4. *The neural network architecture.*

between these neurons and their capability to learn from data, that provide a strong predicting and classification tool. Here, the neural network approach is selected to predict the seismic responses of the structure. A four-layer feedforward neural network, consisting of an input layer, two hidden layers and an output layer (as shown in Figure 4), is adopted. The inputs of the neural network are the delayed earthquake accelerations, the delayed control forces and the delayed seismic responses, and the outputs of the neural network are the predicting seismic responses.

The net input net_k of neuron k in some a layer and the output O_k of the same neuron are calculated by

$$\mathrm{net}_k = \sum w_{jk} O_j \tag{7}$$

$$O_k = f(\mathrm{net}_k + \theta_k) \tag{8}$$

where, w_{jk} is the weight between the jth neuron in the previous layer and the kth neuron in the current layer, O_j is the output of the jth neuron in the previous layer, $f(\cdot)$ is the neuron's activation function which can be linear function, radial basis function and sigmoid function, and θ_k is the bias of the kth neuron. If the bias θ_k is regarded as an additional input whose weight and input are θ_k and 1, respectively, the adjustment for the bias θ_k can be considered as the adjustment for a weight.

In the neural network architecture as shown in Figure 4, the logarithmic sigmoid transfer function is chosen as the activation function for the first hidden layer,

$$O_k = f(\mathrm{net}_k + \theta_k) = \frac{1}{1 + e^{-(\mathrm{net}_k + \theta_k)}} \tag{9}$$

the tangent sigmoid transfer function is chosen as the activation function of the second hidden layer,

$$O_k = f(\mathrm{net}_k + \theta_k) = \frac{1 - e^{-2(\mathrm{net}_k + \theta_k)}}{1 + e^{-2(\mathrm{net}_k + \theta_k)}} \tag{10}$$

and the linear transfer function is chosen as the activation function of the output layer,

$$O_k = f(\mathrm{net}_k + \theta_k) = \mathrm{net}_k + \theta_k \tag{11}$$

Neural networks need to be trained before it is used to predict seismic responses. When the inputs are applied to the neural network, the network outputs $\hat{\mathbf{y}}$ are compared to the targets $\mathbf{y}$. The error between both is processed back through the network to update the weights and biases of the neural network in order that the network outputs approach the targets as closely as possible. The input and output data are mostly represented by vectors called training pairs. The process as mentioned above is repeated for all the training pairs in the data set, until the network error converges to a threshold minimum defined by a corresponding performance function. In this paper, the mean square error (MSE) function is adopted as the performance function, it can be written as

$$E = \frac{1}{2} \sum_{p=1}^{P} \sum_{l=1}^{L} [y_p(l) - \hat{y}_p(l)]^2 \tag{12}$$

where $p(p = 1, 2, \ldots, P)$ are the training pairs, and L is the number of neurons in the output layer.

In order to make the network outputs $\hat{\mathbf{y}}$ approach the targets $\mathbf{y}$, the weights are moved in the opposite direction of the gradient of the performance function (Zeidenberg, 1990). The most popular algorithm used for training neural networks is the so-called back-propagation (BP) algorithm. The BP algorithm has a simple structure and can be understood and implemented quite easily. However, the algorithm usually suffers from the drawback of slow convergence (Tan and Sain, 2000).

A useful way to improve the BP algorithm is through to use second-order-convergence approaches such as Gauss–Newton method and Levenberg–Marquardt (LM) method. LM method is adopted in this paper to train the neural network, which can be written as

$$\mathbf{w}^{i+1} = \mathbf{w}^i - \left[\frac{\partial^2 E}{\partial \mathbf{w}^{i2}} + \mu \mathbf{I} \right]^{-1} \frac{\partial E}{\partial \mathbf{w}^i} \tag{13}$$

where i is the iteration index, $\partial E / \partial \mathbf{w}^i$ is the gradient descent of criterion E with respect to the parameter matrix $\mathbf{w}^i$, $\mu \geq 0$ is learning factor, and $\mathbf{I}$ is the unity matrix. If the Taylor series expansion is applied to error vector $\mathbf{e}$ ($\mathbf{e} = [e_1, e_2, \ldots, e_L]^T$) around the operating point, the first derivatives result in the Jacobian given by

$$\mathbf{J}^i = \begin{bmatrix} \dfrac{\partial e_1}{\partial w_1^i} & \dfrac{\partial e_1}{\partial w_2^i} & \cdots & \dfrac{\partial e_1}{\partial w_R^i} \\ \dfrac{\partial e_2}{\partial w_1^i} & \dfrac{\partial e_2}{\partial w_2^i} & \cdots & \dfrac{\partial e_2}{\partial w_R^i} \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{\partial e_L}{\partial w_1^i} & \dfrac{\partial e_L}{\partial w_2^i} & \cdots & \dfrac{\partial e_L}{\partial w_R^i} \end{bmatrix}_{L \times R} \tag{14}$$

where, L is the number of neurons in the output layer, and R is the number of weights. A series of changes are carried for Equation (13) (Hagan and Menhaj, 1994), and the following equation can be obtained.

$$\mathbf{w}^{i+1} = \mathbf{w}^{i} - (\mathbf{J}^{iT}\mathbf{J}^{i} + \mu\mathbf{I})^{-1}\mathbf{J}^{iT}\mathbf{e} \qquad (15)$$

Equation (15) is the iteration formula for the LM method. The basic steps of this method are as follows:

1. Set the initial weights (or bias) $\mathbf{w}^i = \mathbf{w}^0$, and take a large starting value of μ;
2. Calculate the performance of a function $E(\mathbf{w}^i)$ and the Jacobian matrix $\mathbf{J}^i$;
3. Calculate according to $\mathbf{w}^{i+1}$ Equation (13);
4. Is $|E(\mathbf{w}^{i+1})| \le |E(\mathbf{w}^i)|$?
5. Yes: decrease μ, i.e. $\mu^{i+1} = \alpha\mu^i (0 < \alpha < 1)$, where α is the decrease coefficient;
6. No: increase μ by multiplying the increase coefficient β, i.e. $\mu^{i+1} = \beta\mu^i (\beta > 1)$.
7. If the performance index E is less than target or the number of training epochs reaches the fixed number, then stop, else goes to (2).

The proposed intelligent bi-state control architecture can be seen in Figure 5. The architecture consists of three parts to perform different tasks. The first part is the neural network to be trained on-line. The neural network is trained to generate the one step ahead prediction of displacement $\hat{x}_{k+1}$ and velocity $\hat{\dot{x}}_{k+1}$. Inputs to this network are the delayed outputs $(x_{k-2}, x_{k-1}, x_k, \dot{x}_{k-2}, \dot{x}_{k-1}, \dot{x}_k)$, the delayed earthquake inputs $(\ddot{x}_{g_{k-1}}, \ddot{x}_{g_k})$ and the delayed control forces $(f_{d_{k-1}}, f_{d_k})$. The second part is to determine the control currents of MR dampers according to the modified bi-state control strategy. Then the control forces can be calculated in accordance with Equations (2) and (3), and the responses of the structure with MR dampers can be obtained by the time-history analysis method. The third part is to measure the actual responses of the structure with MR dampers. In this paper, the results calculated by the time-history analysis method are used to substitute for the actual measured responses. The errors between the predicted responses and the actual responses are used to update the weights on-line.

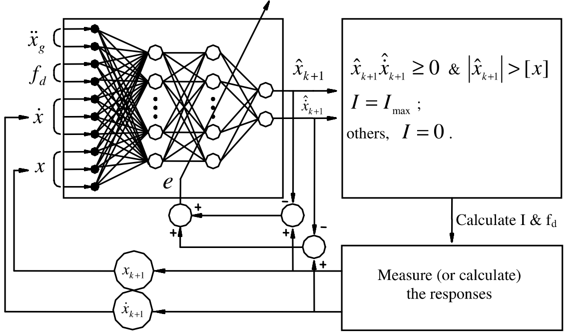

Figure 5. *Structure of the intelligent bi-state control strategy.*

NUMERICAL EXAMPLE

To evaluate the intelligent bi-state control method for the structure with MR dampers, a numerical example is considered in which a model of a three-story reinforced concrete structure is controlled with one MR damper in the first floor, as shown in Figure 3. The model structure parameters are the mass vector $\mathbf{m} = [20310,\ 18980,\ 16950]$ kg, the initial stiffness vector $\mathbf{k} = [1.320,\ 1.856,\ 1.856] \times 10^7$ N/m, the story height $\mathbf{h} = [4.0,\ 3.3,\ 3.3]$ m. The top floor displacement is adopted as the judgement item of the minor displacement limit value in Equation (6). The common MR damper as shown in Figure 1 is adopted in this study, the coefficients of MR fluid in the Equation (3) are $A_1 = -11374$, $A_2 = 14580$ and $A_3 = 1281$, and the viscosity η is 0.9 Pa s. The effective length of the piston L_d is 400 mm, the gap h_d is 2 mm, and the inner diameter of the vat is 100 mm. The maximum current of MR dampers is $I_{\max} = 2.0$ A. The structure is subjected to the North-South component of the 1940 El Centro earthquake with 400 cm/s^2 of acceleration in magnitude.

The responses of the structure with the MR damper under the bi-state control strategy and the structure without the MR damper have been calculated. Figures 6(a) and (b) show displacement and acceleration responses of the top floor of the bi-state controlled and the uncontrolled structure. Figure 6(a) shows that the displacement response of the bi-state controlled structure is reduced considerably compared to the uncontrolled structure. The maximum displacement response of the top floor under bi-state control strategy is 34.35 mm and is reduced by 46.7% compared to the maximum displacement response of the uncontrolled structure 64.47 mm. Figure 6(b) shows that the acceleration response of the bi-state controlled structure is also reduced but the decreasing degree of the amplitude is smaller than that of the displacement. The maximum acceleration response of the top floor under bi-state control strategy is 9.28 m/s^2 and is reduced by 32.4% compared to the maximum acceleration response of the uncontrolled structure 13.73 m/s^2. However, it can be seen from Figure 6(b) that the acceleration response of the bi-state controlled structure is amplified during the initial and the final stages of earthquake. When MR dampers are added into the structure, the stiffness and the damping of the structure are increased. Increasing of the stiffness and the damping will contribute to reducing the displacement responses of the structure. While increasing of the stiffness will bring to increasing of the earthquake shear force of the structure, which leads to the inapparent descent of the acceleration

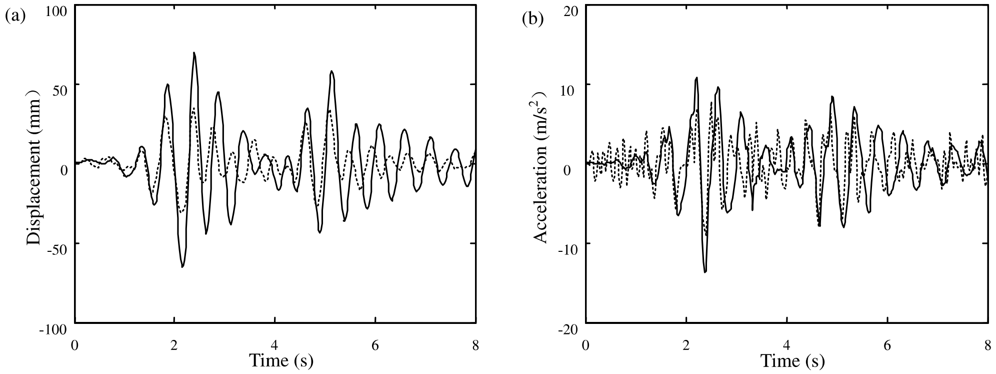

Figure 6. *Comparison about dynamic responses between uncontrolled structure and bi-state controlled structure: (a) The top floor displacements' comparison —— Uncontrolled structure; (b) The top floor accelerations comparison ······ Bi-state controlled structure.*

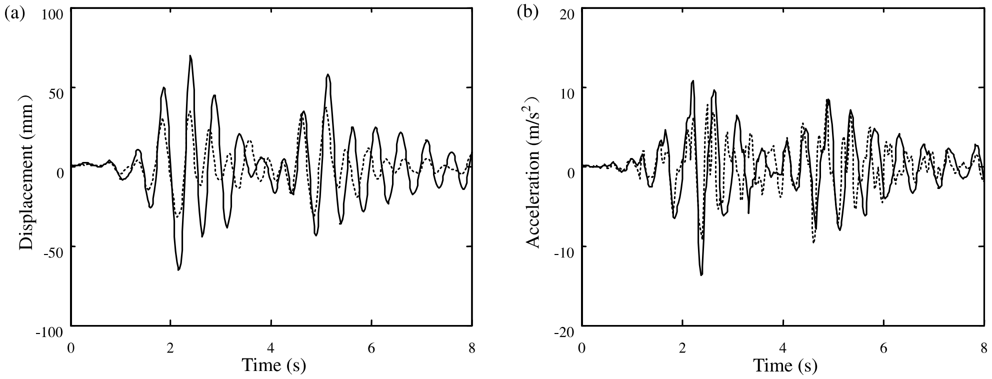

Figure 7. *Comparison about dynamic responses between uncontrolled structure and modified bi-state controlled structure: (a) The top floor displacements' comparison —— Uncontrolled structure; (b) The top floor accelerations comparison ······ Modified bi-state controlled structure.*

response of the structure. Moreover, increasing the stiffness of the structure blindly may lead to the excessive earthquake shear force of the structure, which causes the amplification of the acceleration responses. During the initial and the final stages of earthquake, the MR damper produces the larger control force (see Equation (5)), which may be the main reason of the amplification of the acceleration response.

The responses of the structure with the MR damper under modified bi-state control strategy are also calculated. Figure 7(a) and (b) show the top floor's displacement responses comparison and acceleration responses comparison between the modified bi-state controlled structure and the uncontrolled structure. It can be shown from Figure 7(a) and (b) that the displacement and the acceleration responses of the modified bi-state controlled structure are both reduced. The maximum displacement and acceleration responses of the top floor under the modified bi-state control strategy are 37.27 mm and 9.66 m/s^2, are reduced by 46.4 and 29.7% respectively, compared to those of the uncontrolled structure. It also can be shown from Figure 7(b) that the amplification of the acceleration response is eliminated during the initial and the final stages of earthquake, because the minor displacement do not cause the larger control force of the MR damper according to Equation (6).

The responses of the structure with the MR damper under intelligent bi-state control strategy are also calculated. Figure 8(a) and (b) show the top floor's displacement responses comparison and acceleration responses comparison between the modified bi-state controlled structure and the intelligent bi-state controlled structure. It can be shown from Figure 8(a) and (b) that both the displacement response and the acceleration response of the intelligent controlled structure are smaller than those of the modified bi-state controlled structure. This is because the neural network technique is adopted to predict the dynamic responses of the structure, the control force of the MR damper is determined according to the predicted responses, the time-delay problem of the traditional control strategies is solved, and the dynamic responses calculated by the intelligent control strategy are authentic. Figure 8(a) and (b) also show that the displacement response and the acceleration response of the intelligent controlled structure is amplified slightly in the initial stage of the earthquake comparing with those of the modified bi-state controlled structure. The neural network must be trained enough before it predicts the dynamic

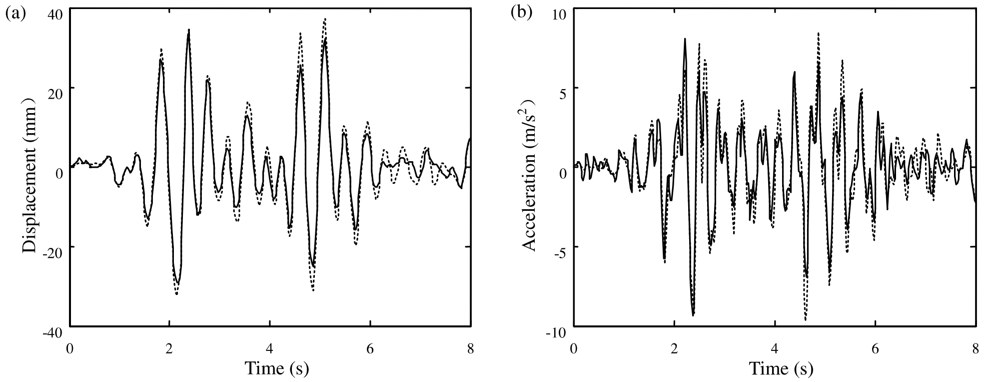

Figure 8. *Comparison about dynamic responses between intelligent bi-state controlled structure and modified bi-state controlled structure: (a) The top floor displacements' comparison —— Intelligent bi-state controlled structure; (b) The top floor accelerations' comparison ······ Modified bi-state controlled structure.*

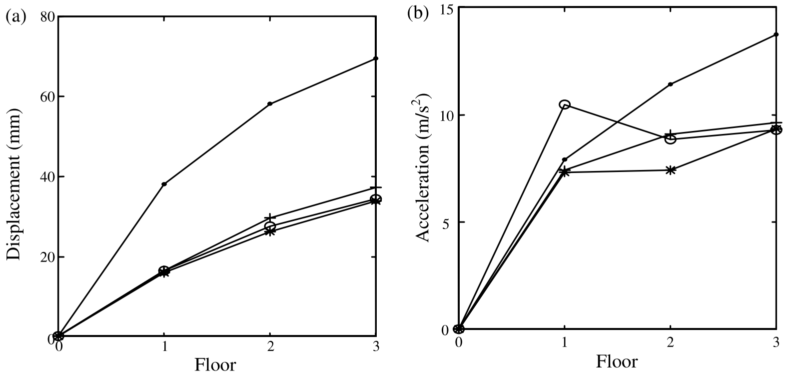

Figure 9. *Comparison about the maximum dynamic responses of each floor among the four structure: (a) Comparison about displacement; (b) Comparison about acceleration. —●— Uncontrolled structure; —|— modified bi-state controlled structure; —○— Bi-state controlled structure; —*—Intelligent bi-state controlled structure.*

responses veritably. The neural network of the intelligent control strategy is trained on-line, while in the initial stage of the earthquake, the neural network is not trained enough, the predicted responses have large errors and the control force is distorted. So the dynamic response calculated by the intelligent control strategy is amplified slightly in the initial stage of the earthquake. But this slight amplification do not affect the total calculation of the structure because the neural network can predict the dynamic responses veritably only after about 20 earthquake samples (0.4 s earthquake time).

Figure 9(a) and (b) show the comparison of the maximum displacements and the maximum accelerations of each floor for the uncontrolled structure, the bi-state controlled structure, the modified bi-state controlled structure and the intelligent bi-state controlled structure. It can be seen from Figure 9(a) that the MR damper can reduce the displacement responses of the structure effectively. For the top floor, the maximum displacement of the uncontrolled structure is 69.47 mm, those of the bi-state controlled structure, the modified bi-state controlled structure and the intelligent controlled structure are 34.35, 37.27 and 33.90 mm, and are reduced by 50.6, 46.4, and 52.2%, respectively. Figure 9(b) shows that the acceleration responses of the structure with the MR damper are also reduced except the first floor's acceleration of the bi-state controlled structure. For the top floor, the maximum acceleration of the uncontrolled structure is 13.73 m/s^2, those of the bi-state controlled structure, the modified bi-state controlled structure and the intelligent controlled structure are 9.28, 9.66 and 9.30 m/s^2, and are reduced by 32.4, 29.7, and 32.3%, respectively. While the first floor's maximum acceleration of the bi-state controlled structure (10.46 m/s^2) increase 32.23% compared to that of the uncontrolled structure (7.91 m/s^2). This amplification is due to overrun of the control force of the MR damper during the initial stage of earthquake. It has also been verified from Figure 5(a) and (b) that the intelligent control strategy is the best strategy among all the control strategies considered here. Both displacement responses and acceleration responses of the intelligent controlled structure are reduced more effectively than others. The intelligent control strategy solves the time-delay problem of semiactive control and overrun of control forces under the minor earthquake. The corresponding control force is most veritable and the earthquake mitigation effect is best.

CONCLUSIONS

We have investigated the application of the bi-state control strategy, the modified bi-state control strategy and the intelligent control strategy to suppress the vibration of building structures with MR dampers. Comparison of the three control strategies suggests:

1. The MR damper is a kind of excellent semiactive control device, and it can reduce the dynamic responses of building structure effectively.
2. The bi-state control strategy easily leads to overrun of the parameters and the damping forces of MR dampers during the initial and the final stages of earthquake or under the minor earthquake, which results in acceleration response's amplification of the structure.
3. The modified bi-state control strategy dispose of the problem of overrun of the control force, which avoid acceleration response's amplification of the structure.
4. The intelligent control strategy solves the time-delay problem of semiactive control and overrun of control forces under the minor earthquake. The obtained control force is most veritable and the earthquake mitigation effect is the best.

ACKNOWLEDGMENT

This research is financially supported by the National Postdoctoral Science Foundation, People Republic of China, Grant No.CP2001014 and the National Natural Science Foundation, People Republic of China, Grant No.50135030. These supports are gratefully acknowledged.

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