Science in China Series E: Technological Sciences

© 2008 SCIENCE IN CHINA PRESS

Springer

www.scichina.com
tech.scichina.com
www.springerlink.com

Integrated intelligent control analysis on semi-active structures by using magnetorheological dampers

XU ZhaoDong[1†] & GUO YingQing[2]

[1]Civil Engineering College, Southeast University, Nanjing 210096, China;
[2] Automation College, Southeast University, Nanjing 210096, China

The control strategy is very important for semi-active control or active control systems. An integrated intelligent control strategy for building structures incorporated with magnetorheological (MR) dampers subjected to earthquake excitation is proposed. In this strategy, the time-delay problem is solved by a neural network and the control currents of the MR dampers are determined quickly by a fuzzy controller. Through a numerical example of a three-storey structure with one MR damper installed in the first floor, the seismic responses of the uncontrolled, the intelligently controlled, the passive-on controlled, and the passive-off controlled structures under different earthquake excitations are analyzed. Based on the numerical results, it can be found that the time domain and the frequency domain responses are reduced effectively when the MR damper is added in the structure, and the integrated intelligent control strategy has a better earthquake mitigation effect.

magnetorheological damper, semi-active control, intelligent

1 Introduction

Semi-active structural control has received considerable attention in recent years because it offers adaptability of active control devices without requiring the associated large power sources, while potentially it can also offer the reliability of passive devices. Various semi-active control devices have been developed, such as magnetorheological (MR) dampers, electrorheological dampers, variable orifice dampers, variable-friction dampers, controllable tuned liquid dampers, semi-active impact dampers, controllable-fluid dampers, etc. Among these dampers, MR dampers are particularly attractive due to the merits of milliseconds responses, simple conformation, low cost, and

---

Received July 6, 2007; accepted March 13, 2008
doi: 10.1007/s11431-008-0209-3

[†]Corresponding author (email: xuzhdgyq@seu.edu.cn)

Supported by the National Natural Science Foundation of China (Grant No. 50508010), the Program for New Century Excellent in the Education Ministry of China, the Program for Jiangsu Province 333 Talents and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, Education Ministry.of China

excellent control effect.

MR dampers are usually installed on the deformation position, such as the braces between columns. When structures deform because of vibration, MR dampers will adjust their characteristic parameters in accordance with the given control law and will absorb vibration energy. Therefore, the control effectiveness of structural systems is highly dependent on the control strategy used for designing semi-active control law. The traditional control strategy for MR semi-active control systems is the bi-state control approach, while inherent time-delay and coarse control precision exist in this strategy. In order to solve these problems, neural network and fuzzy controller techniques are combined to precisely control the structures of MR dampers. In recent years, neural network and fuzzy control techniques are widely used for the vibration control in civil engineering. Back-propagation through time neural controller for active control of structure was developed[1]. Results from computer-simulation studies have shown great promise for the control of civil-engineering structures under dynamic loadings using the artificial neural-network controller. A new neural-network-based control algorithm for active control of a three-story frame structure was developed[2]. Results of that initial study indicated that the neural-network-based control algorithms have the promise of evolving into powerful adaptive controllers after further research. The potential of fuzzy control strategies for active control in civil engineering applications was investigated[3]. The advantage of this approach is its inherent robustness and its ability to handle the nonlinear behavior of the structure. An experimental study of identification and control of structures using neural network was carried out[4], which described the test setup, the experimental validation of the identified model in the time and frequency domains, and experimentally demonstrated the performance of the multiple emulator neural networks. Bridge seismic isolation systems were controlled by using fuzzy controller[5]. A hybrid fuzzy logic and neural network controller was proposed to improve the control performance of multiple-input multiple-output control systems[6]. Its control strategy could not only simplify the implementation problem of fuzzy control but also improve the control performance. A neuron-control method for semi-active vibration control of stay cables using MR dampers was proposed[7], and the analysis showed that the proposed control strategies could effectively implement semi-active vibration control of stay cables with the use of MR dampers. Fuzzy supervisory technique for the active control of earthquake excited building structures was looked into[8]. The improved seismic control performance can be achieved by converting a simply designed static gain into a real-time variable dynamic gain through a fuzzy tuning process. A fuzzy sliding mode control algorithm for structures subjected to seismic activity was also presented[9]. Recently, fuzzy control technique was proposed to evaluate the benchmark control problem of a seismically excited cable-stayed bridge, and the simulated results showed that the proposed semi-active fuzzy control technique could effectively mitigate the seismic response of cable-stayed bridges and successfully enhance the robust performance of the MR damper system[10].

The previous studies made full use of the advantages of the neural network and the fuzzy logic controller, and dealt with the different problems in civil engineering structures. However, few researches have adopted both tools to resolve the time-delay and instantaneous choosing of control parameters in semi-active control or active control. In this paper, a fuzzy controller was used to determine the control currents of MR dampers, with inputs being the earthquake acceleration excitation and predicted displacement of the first floor. When predicting the first floor displacement, a four-layer feed-forward neural network, trained on-line with the Levenberg-Marquardt (LM) algorithm, was adopted. In order to verify effectiveness of the proposed integrated intelligent control strategy, the uncontrolled structure, the passive-on controlled structure and the passive-off controlled structure were compared with the intelligent controlled structure. Through a numerical example of a three-story reinforced concrete structure under different earthquake inputs, it can be concluded that this control strategy is very important for semi-active control, and that the integrated intelligent control strategy can determine currents of MR dampers quickly and accurately and has a better earthquake mitigation effect.

2 Mathematical model of the semi-active structure

2.1 Mathematical model of MR dampers

MR dampers typically consist 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 fluid 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[11].

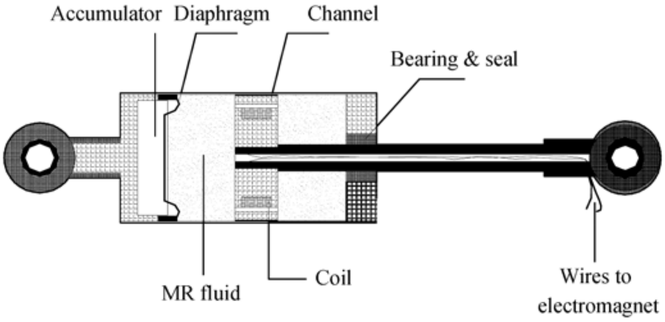

Figure 1 Schematic of MR damper.

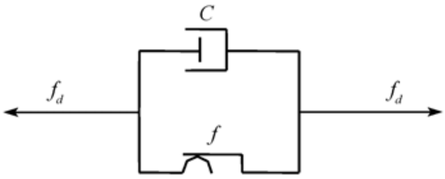

Figure 2 Bingham model.

Most research work[12,13] has focused on establishing appropriate mathematical models from analysis and experimental studies of MR dampers. The most common mathematical model of MR dampers is the Bingham model[14], which is modeled as having a friction component augmented by a Newtonian viscosity component as shown in Figure 2, and the relationship between stress and strain can be expressed as follows:

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

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 dynamic yielding shear stress controlled by the applied field. The force-displacement relationship of MR dampers was derived[15] in terms of eq. (1) as

$$f_d = \frac{12\eta L A_p^2}{\pi D D_h^3}\dot{u}(t) + \frac{3L\tau_y}{D_h} A_p \operatorname{sgn}[\dot{u}(t)], \tag{2}$$

where L is the length of the piston, A_p is the cross-sectional area of the piston, D is the inner diameter of the vat, D_h is the diameter of the small gap in the piston, and $u(t)$ is the relative displacement of the piston to the vat. The dynamic yielding shear stress τ_y is the function of the applied field, which means the dynamic yielding shear stress τ_y is the function of the control current I. This mathematical model, namely the modified Bingham model, was proposed by Xu[16]. The relationship between the dynamic yielding shear stress τ_y and the applied field is determined by experiments, which is relative to the property of the MR fluid. In the model, the relationship between τ_y and I about the MR fluid is as follows:

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

where A_1, A_2 and A_3 are the coefficients related to the property of the MR fluid in the MR damper, and are determined by experimental results, e is the Euler's number. Ref. [16] showed that the numerical results of the modified Bingham model fit well with the experimental results.

2.2 Equations of motion of the controlled structure

For frame structures, MR dampers are usually placed between the chevron brace as shown in Figure 3. In consideration of the stiffness of chevron brace, the mathematical model for smart damper-chevron brace system can be seen as a damper and a spring being connected in series. In order to be sure that MR dampers are in full play, the stiffness of chevron brace is usually strong. So the stiffness of chevron brace can be neglected for simplifying calculation, and the equation of motion of the structure with MR dampers can be written as

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

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are the mass, damping and stiffness matrixes of the structure, respectively, $\boldsymbol{x}$ is the vector of the relative displacements of the floors of the structure, $\boldsymbol{\Gamma}$ is the column vector of ones, $\ddot{x}_g$ is the earthquake acceleration excitation, $\boldsymbol{B}$ is the matrix determined by the position of MR dampers in the structure, $\boldsymbol{f}_d = [f_{d1}, f_{d2}, \cdots, f_{dn}]^{\mathrm{T}}$ is the vector of control forces produced by MR dampers, and f_{di} is the control force of the i-th floor, $i = 1, \cdots, n$.

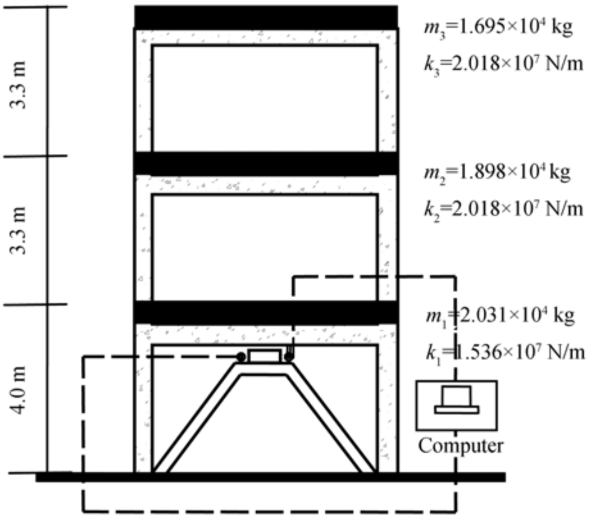

Figure 3 Schematic of smart structure.

3 Integrated intelligent control strategy

3.1 Theoretical description

The basic idea of the proposed integrated intelligent control strategy is that the current of the MR damper is determined by a fuzzy controller, whose inputs are the measured earthquake acceleration and the predicted first floor displacement response provided by a neural network. The architecture of this strategy is shown in Figure 4, which consists of four parts to perform different tasks. The first part is the neural network to be trained on-line. When the number of the sample data pairs is less than 200, the training data pairs will increase step-by-step during the earthquake. When the number of the sample data pairs is more than 200, the oldest data pair will be abandoned in every training step, so that the number of the training data pairs keeps to be 200. The neural network is trained to generate the one-step ahead prediction of displacement $\hat{x}_{k+1}$. Inputs to this network are the delayed outputs (x_{k-2}, x_{k-1}, x_k), the delayed control forces (f_{dk-1}, f_{dk}) and the delayed earthquake inputs ($\ddot{x}_{g_{k-1}}$, $\ddot{x}_{g_k}$). At the initial time, the delayed inputs of the network are taken as zero in accordance with the actual initial circumstance. The second part is the fuzzy controller, whose inputs are the measured earthquake acceleration $\ddot{x}_{g_{k+1}}$ and the predicted displacement $\hat{x}_{k+1}$. The earthquake acceleration $\ddot{x}_{g_{k+1}}$ can be measured by the earthquake accelerometer installed in the foundation of buildings. It is no doubt that the output of the fuzzy controller is control currents of MR dampers. The main aim of this part is to determine control current of MR dampers quickly in accordance with the measured earthquake acceleration $\ddot{x}_{g_{k+1}}$ and the predicted displacement $\hat{x}_{k+1}$. How to design the fuzzy controller and determine the current will be described in detail in the following section. The third part is to calculate the control force in accordance with the control current determined by the fuzzy controller. When the control current of MR dampers is determined by the fuzzy controller, the dynamic yielding shear stress can be calculated by eq. (3), and then the control force of MR dampers can be got by eq. (2), in which the velocity of the piston of MR dampers $\dot{u}(t)$ is the inter-storey relative velocity of this floor. The fourth part is to measure the actual responses of structures with MR dampers. When the earthquake excitation of the time-step k+1 happens but it does not lead to the responses of structures, it is hopeful that the optimum control current of MR dampers of this step is determined simultaneously and quickly. In order to

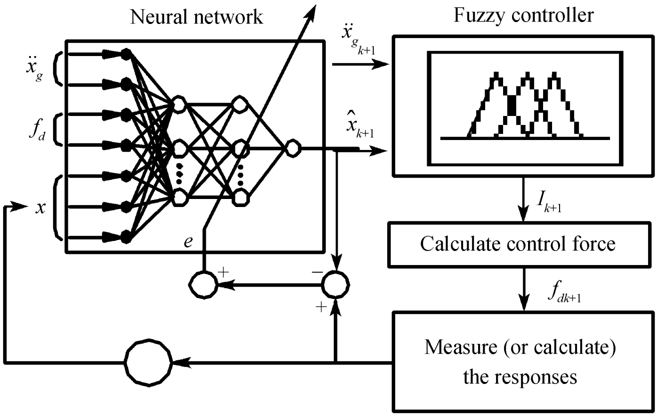

Figure 4 Architecture of the intelligent control strategy.

reach this hope, it is required to predict the forthcoming responses of structures in accordance with the actual responses of the time-step k. At the same time, the actual responses will be fed back to the neural network and the weights and bias will be revised in real-time. In this paper, the calculated results 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 of the neural network on-line.

3.2 Design of the neural network

Neural network is a simplified model consisting of elementary processing units (also called neurons). It is the large amount of interconnections between these neurons, whose capability to learn from data enables the neural network to become a strong predicting and classification tool. In this study, a four-layer feed-forward neural network, which consists of an input layer, two hidden layers and an output layer (as shown in Figure 4), is selected to predict the seismic responses of structures with MR dampers.

The net input value net_k of the neuron k in a layer and the output value O_k of the same neuron can be calculated by

$$net_k = \sum w_{jk} O_j, \tag{5}$$

$$O_k = f(net_k + \theta_k), \tag{6}$$

where w_{jk} is the weight between the j-th neuron in the previous layer and the k-th neuron in the current layer, O_j is the output of the j-th neuron in the previous layer, $f(\cdot)$ is the neuron's activation function which can be a linear function, radial basis function and sigmoid function, and θ_k is the bias of the k-th neuron. In the neural network architecture as shown in Figure 4, the logarithmic sigmoid transfer function is chosen as the activation function of the first hidden layer, i.e.

$$O_k = f(net_k + \theta_k) = \frac{1}{1 + e^{-(net_k + \theta_k)}}. \tag{7}$$

The tangent sigmoid transfer function is chosen as the activation function of the second hidden layer, i.e.

$$O_k = f(net_k + \theta_k) = \frac{1 - e^{-2(net_k + \theta_k)}}{1 + e^{-2(net_k + \theta_k)}}. \tag{8}$$

The linear transfer function is chosen as the activation function of the output layer. i.e.

$$O_k = f(net_k + \theta_k) = net_k + \theta_k. \tag{9}$$

It must be noted that neural network needs to be trained before predicting seismic responses. As the inputs are applied to the neural network, the network outputs $\hat{\boldsymbol{y}}$ are compared with the targets $\boldsymbol{y}$. The difference between them, or error, is processed back through the network to update the weights and biases of the neural network so that the network outputs may match closer the targets. The input and output data are usually 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 converged to a threshold minimum defined by a corresponding performance function. In this paper, the mean square error (MSE) function is adopted, and Levenberg-Marquardt (LM) algorithm[17] is adopted to train the neural network, which can be written as

$$\boldsymbol{w}^{i+1} = \boldsymbol{w}^i - \left[\frac{\partial^2 E}{\partial \boldsymbol{w}^{i2}} + \mu \boldsymbol{I}\right]^{-1} \frac{\partial E}{\partial \boldsymbol{w}^i}, \tag{10}$$

where i is the iteration index, $\partial E / \partial \boldsymbol{w}^i$ is the gradient descent of the performance function E with respect to the parameter matrix $\boldsymbol{w}^i$, $\mu \geqslant 0$ is the learning factor, $\boldsymbol{I}$ is the unity matrix.

During the vibration process, the neural network updates the weights and bias of neurons in real-time in accordance with sampling pairs until the objective error is satisfied, i.e. the property of the structure is acquired. As we know, the main aim of the neural network is to predict the dynamic responses of the structure, and to provide inputs to the fuzzy controller and data for calculating control force of MR dampers. Thus the output of the neural network is the prediction of displacement $\hat{x}_{k+1}$. In order to predict the dynamic responses of the structure accurately, the most directly and important factors affecting the predicted dynamic responses are considered, i.e. the delayed outputs (x_{k-2}, x_{k-1}, x_k), the delayed control forces (f_{dk-1}, f_{dk}) and the delayed earthquake inputs ($\ddot{x}_{g_{k-1}}$, $\ddot{x}_{g_k}$).

3.3 Design of fuzzy controller

The first step of designing the fuzzy controller is to determine the basic domains of inputs and outputs. Earthquake acceleration excitation and displacement responses are chosen as inputs of the fuzzy controller, because earthquake acceleration excitation influences seismic responses directly, and displacement responses are usually limited in seismic code and used to evaluate effect of earthquake mitigation. The domain of earthquake wave is determined in accordance with the amplitude of the input acceleration. For an unknown earthquake wave beforehand, the domain can usually be determined to be 0—10 m/s^2. In order to get accurate results, a smaller domain can be adopted. If the building is in the lower earthquake intensity area, the domain can be reduced accordingly, such as 0—4 m/s^2 for the area with 7 degree intensity, 0—6 m/s^2 for the area with 8 degree intensity. During the calculation process, it is found that the resulting difference is very small if the domain is changed from 0—10 m/s^2 to 0—4 m/s^2 [18]. In this paper, the 0.2g El Centro earthquake wave is adopted as the earthquake input, the basic domain is determined to be 0—4 m/s^2. In order to reduce the number of inputs of the fuzzy controller and outputs of the neural network, the displacement of the first floor where one MR damper is installed is considered as the other input to the fuzzy controller. The elastic limit of storey drift is h/550 and the elastoplastic limit of storey drift is h/50 for frame structures according to the seismic code in China, where h is the storey height. In accordance with these limits and designing experience, the basic domain of the first floor displacement response is 0—h_1/200, where h_1 is the height of the first floor. The output of the fuzzy controller is the control current of the MR damper, whose basic domain is 0—2 A, the same as the working current of the MR damper. According to the basic domains of the earthquake acceleration excitation, the first floor displacement and the control current of the MR damper, the fuzzy domains are determined to be 0—4, 0—6 and 0—2, respectively. So the corresponding quantification factors or proportion factors are determined as: the quantification factor of earthquake wave is K_{djsd} =2, the quantification factor of the first floor displacement of structure is K_{wy}=300, and the proportion factor of the control current of the MR damper is K_{dl}=1.

The membership functions are usually chosen in accordance with the characters of the membership functions and designing experience. Generally speaking, the shape of the membership functions must be like the steamed bread shape with one kurtosis. For simplifying calculation, triangle or trapeziform functions are usually adopted as the membership functions. In this paper, triangle and trapeziform membership functions are adopted as the membership functions of the earthquake acceleration and the first floor displacement of the structure. The triangle membership function is adopted as the membership functions of control current of MR dampers[18]. The membership function curves of the earthquake acceleration, the first floor displacement of structure and the control current of the MR damper are plotted in Figure 5.

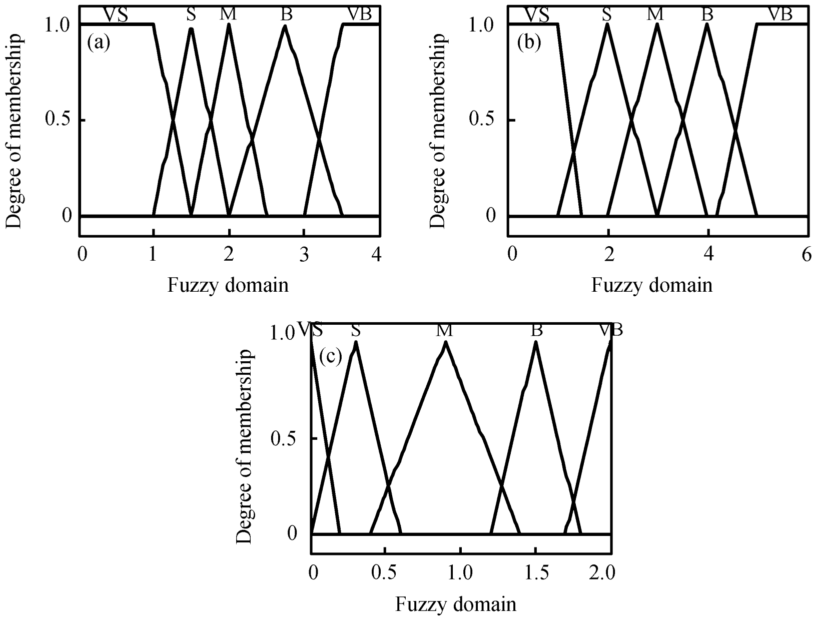

Figure 5 The membership function curves of the inputs and output of the fuzzy controller. (a) The earthquake acceleration; (b) the first floor displacement; (c) the input current of MR dampers.

The earthquake acceleration, the first floor displacement of structure and the control current of the MR damper will be divided into five grades, i.e. {VS (very small), S (small), M (middle), B (big), VB (very big)}. The fuzzy rules of fuzzy controller are made according to the experience, as listed in Table 1. The design ideas of the fuzzy rules are as follows. During the initial stages of earthquake and the course of small earthquakes, the control forces produced by MR damper should be very small, and too strong control forces may result in the magnification of acceleration responses of the structure. Under the stronger earthquake excitations, in order to prevent destruction due to large displacement, middle or big control forces should be provided.

Table 1 Fuzzy rules of determination of currents in fuzzy controller

Displacement	Acceleration				
	VS	S	M	B	VB
VS	VS	VS	VS	S	M
S	VS	VS	S	S	M
M	VS	S	M	M	B
B	S	S	M	B	VB
VB	M	B	B	VB	VB

In this paper, the centroid method is chosen as the defuzzification method, namely the value of the output variable is computed by finding the variable value of the center of gravity of the membership function for the fuzzy value. This method is very accurate and is the most common method for defuzzification[19].

4 Numerical simulations

To illustrate the effectiveness of the proposed integrated intelligent control strategy for the semi-active control structure, numerical simulations are given. A model of a three-storey 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 $\boldsymbol{m}$=[2.031 1.898 1.695]×10^4 kg, the initial stiffness vector $\boldsymbol{k}$=[1.536 2.018 2.018]×10^7 N/m, and the storey height $\boldsymbol{h}$=[4.0 3.3 3.3] m. The common MR damper as shown in Figure 1 is adopted in this study. The MR fluid tested in ref. [20] is used in the MR damper, the coefficients in eq. (3) for this damper are A_1=–11374, A_2=14580 and A_3=1281, and the viscosity η is 0.9 Pa · s[16]. The effective length of the piston L is 400 mm, the gap D_h is 2 mm, and the inner diameter of the vat D is 100 mm.

In order to evaluate the adaptability of the proposed strategy for different excitations, the model of the structure is subjected to El Centro earthquake, Taft earthquake and artificial earthquake wave with 0.2 g acceleration amplitude, and the sampling time is 0.02 s. The simulation procedure is implemented by using MATLAB.

4.1 Case 1: El Centro earthquake wave

Under the 0.2g El Centro earthquake excitation, the responses of the structure with the MR damper controlled by the integrated intelligent control strategy are compared with the responses of the structure without the MR damper. Figures 6(a) and 6(b) show the displacement response comparison and the acceleration response comparison between the intelligently controlled and the uncontrolled structures of the top floor. It can be shown from Figures 6(a) and 6(b) that both the displacement and the acceleration responses of the intelligently controlled structure are reduced effectively compared with those of the uncontrolled structure. In order to further verify the effectiveness, the numerical results of the passive-on controlled structure (i.e. the control currents are kept at the maximum value 2A) and the passive-off controlled structure (i.e. the control currents are kept at the minimum value 0A) are compared with those of the intelligently controled structure, as shown in Figures 7 and 8, respectively. As the figures show, the displacement responses of the intelligent controlled structure are a little worse than those of the passive-on controlled structure, while the acceleration responses of the intelligently controlled structure are better than those of the passive-on controlled structure. Moreover, the dynamic responses of the passive-on controlled structure are magnified in the initial period of the earthquake excitation. For the passive-off controlled structure, the control currents and forces become the minimum values, the acceleration responses are almost the same as those of the intelligently controlled structure, the displacement responses are worse than those of the intelligently controlled structure. These results can be seen clearly from Figure 9, i.e. comparison of the maximum displacement and acceleration responses of each floor. The maximum displacement responses of the first, the second and the third floors of the uncontrolled structure are 17.5, 26.9 and 31.4 mm, respectively, while those of the intelligently controlled structure are 9.1, 15.3 and 18.5 mm, which are reduced by 48.0%, 43.1% and 41.1% compared with those of the uncontrolled structure, respectively. Similarly, the maximum acceleration responses are reduced from 4.15, 5.07, 5.97 m/s^2 for the uncontrolled structure to 3.03, 3.62, 4.66 m/s^2 for the intelligently controlled structure by 27.0%, 28.5% and 21.9%, respectively. Compared with the results of the passive-on controlled structure with the maximum displacement responses 7.8, 12.5, 15.0 mm and the maximum acceleration responses 9.61, 3.98, 5.14m/s^2, the displacement responses of the intelligently controlled structure are not better than those of the passive-on controlled structure, while the acceleration responses are superior to those of the passive-on controlled structure, especially for the first floor. This is due to that the passive-on control strategy provides the maximum control forces during the earthquake excitation. Improper control forces will lead to magnification of the dynamic responses, especially for the acceleration responses.

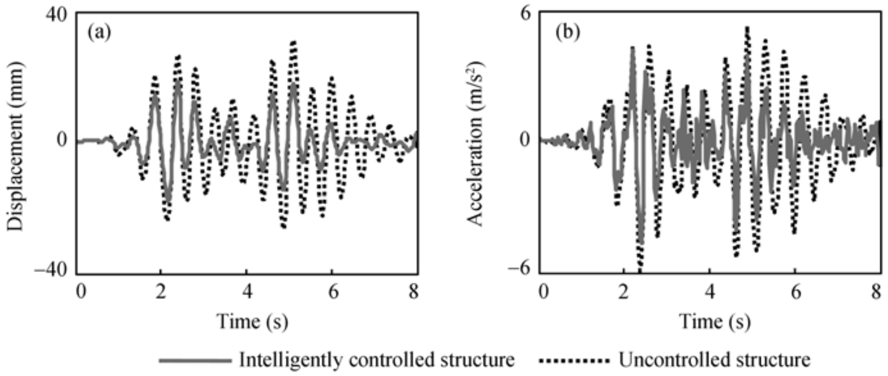

Figure 6 The top floor responses comparison between the intelligently controlled and uncontrolled structures. (a) The displacement responses; (b) the acceleration responses.

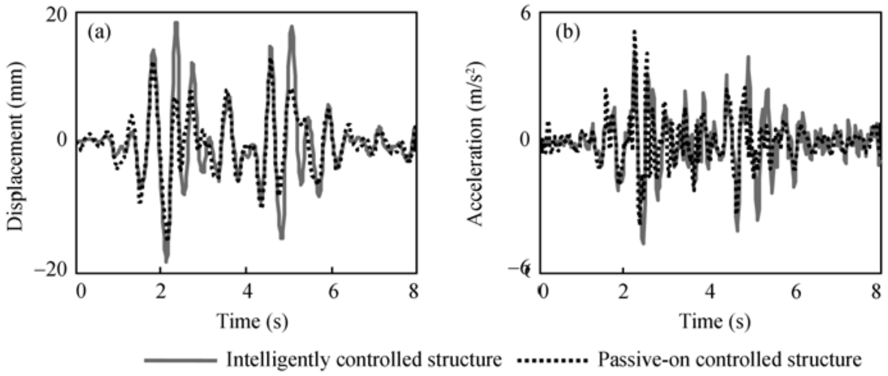

Figure 7 The top floor responses comparison between the intelligently controlled and passive-on controlled structures. (a) The displacement responses; (b) the acceleration responses.

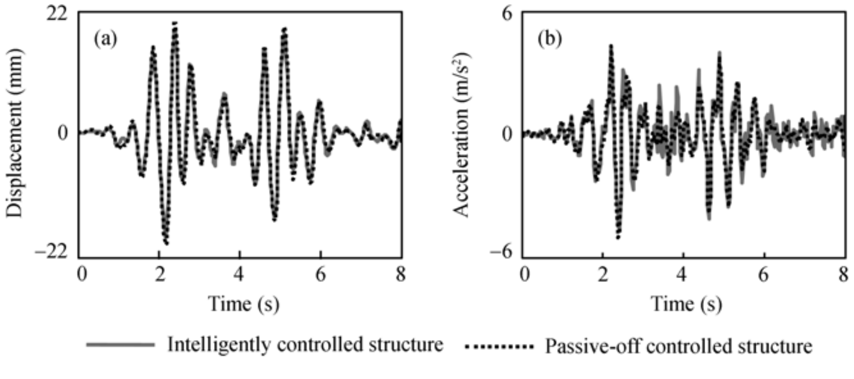

Figure 8 The top floor responses comparison between the intelligently controlled and passive-off controlled structures. (a) The displacement responses; (b) the acceleration responses.

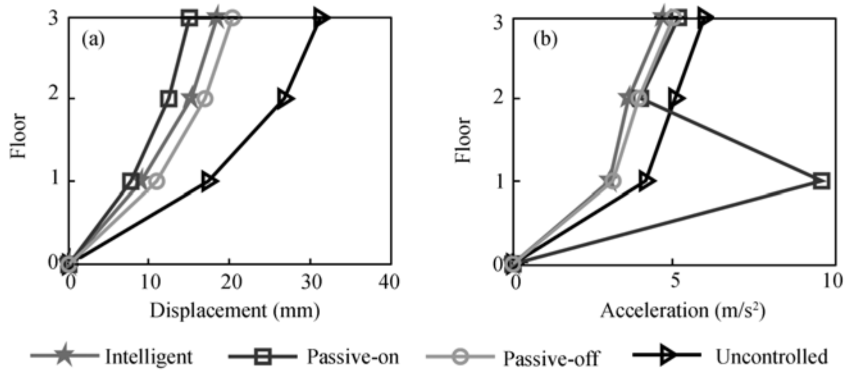

Figure 9 The maximum responses comparison of each floor (El Centro). (a) The displacement response; (b) the acceleration response.

When the passive-off control strategy is adopted, the maximum displacement and acceleration responses are 11.0, 17.0, 20.4 mm and 3.15, 3.94, 5.02 m/s^2, respectively. Obviously, the control results of the passive-off control strategy are not better than those of the intelligent control strategy. It can be concluded that the intelligent control strategy is superior to the passive-on control strategy and the passive-off control strategy, and that it is very effective to choose control currents precisely for reducing the dynamic responses of structures.

In order to evaluate the dynamic responses reduction of the proposed strategy roundly, acceleration frequency domain response spectra of the top floor is analyzed. Figure 10 shows the frequency domain response spectra comparison of the top floor for the uncontrolled, intelligently controlled, passive-on controlled and passive-off controlled structures. The frequency domain responses of the top floor are 432.5, 160.4, 165.0 and 168.1 for the uncontrolled, intelligently controlled, passive-on controlled and passive-off controlled structures at near the basic natural frequency of the structure 2.20 Hz. It can be seen that the frequency domain responses are effectively reduced when the MR damper is added in the structure, and the integrated intelligent control strategy has the best earthquake mitigation effect at near the basic natural frequency of the structure.

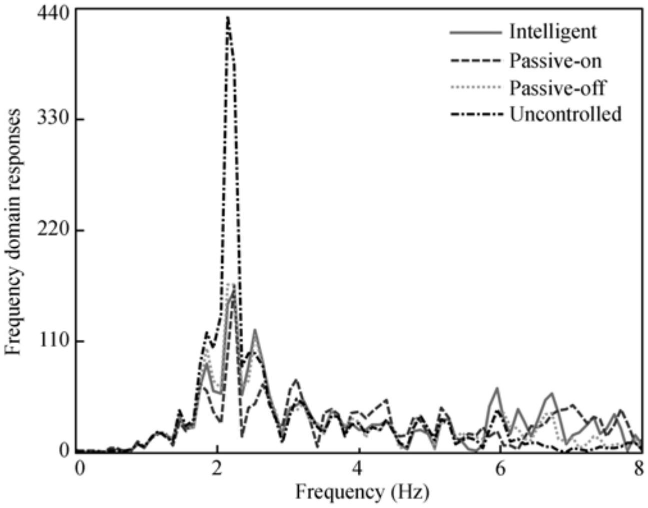

Figure 10 Frequency domain responses of the top floor acceleration (El Centro).

4.2 Case 2: Taft earthquake wave

When Taft earthquake wave is considered as the excitation, the numerical results are plotted in Figures 11 and 12. The maximum displacement and acceleration responses of each floor of the uncontrolled structure are 7.4, 11.8, 13.9 mm and 2.81, 3.44, 4.21 m/s^2, those of the intelligently controlled structure are 4.7, 8.7, 10.5 mm and 2.57, 3.02, 3.24 m/s^2, those of the passive-on controlled structure are 5.1, 8.1, 10.0 mm and 9.08, 3.35, 3.93 m/s^2, and those of the passive-off controlled structure are 5.5, 9.8, 12.0 mm and 2.15, 2.84, 3.29 m/s^2. Though the displacement responses of the passive-on controlled structure are slightly better than those of the intelligently controlled structure, the acceleration responses of the passive-on controlled structure are the worst, especially for the first floor with the MR damper, the improper control forces lead to magnification of the acceleration responses. Obviously, the integrated intelligent control strategy has a better earthquake mitigation effect. Similar conclusions are got from frequency domain analysis, and the frequency domain responses of the top floor are 195.9, 88.4, 112.2 and 93.2 for the uncontrolled, intelligently controlled, passive-on controlled and passive-off controlled structures at near the basic natural frequency of the structure 2.20 Hz. It can be concluded that the time domain and the fre-

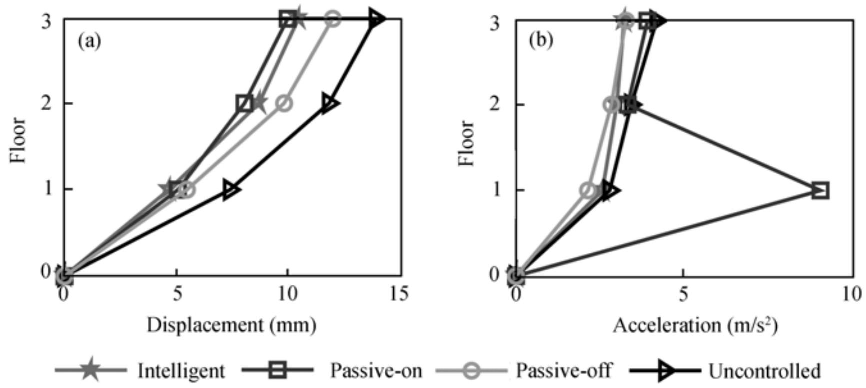

Figure 11 The maximum responses comparison of each floor (Taft). (a) The displacement response; (b) the acceleration response.

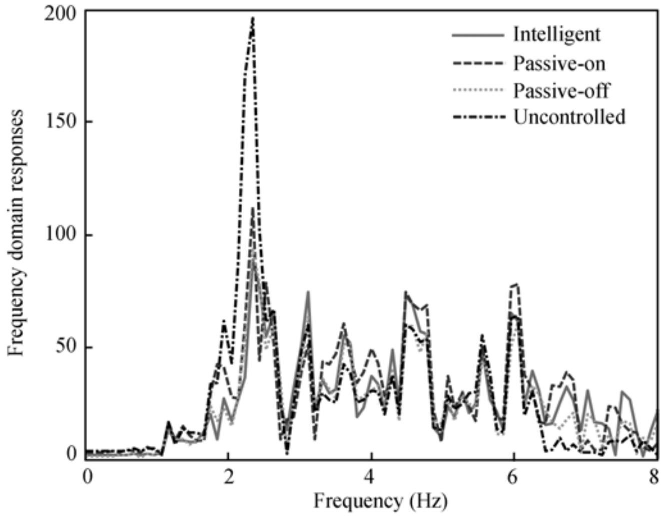

Figure 12 Frequency domain responses of the top floor acceleration (Taft)

quency domain responses are reduced effectively when the MR damper is added in the structure, and the integrated intelligent control strategy has the best earthquake mitigation effect.

4.3 Case 3: Artificial earthquake wave

Artificial earthquake wave generated in accordance with earthquake effect factor spectra in Chinese anti-earthquake code of structures GB50011-2001 is commonly used to check the anti-earthquake ability of structures. Figure 13 shows the maximum displacement and acceleration responses of all floors. Figure 14 shows the frequency domain responses of the top floor. The maximum displacement and acceleration responses of each floor of the uncontrolled structure are 20.8, 32.5, 38.5 mm and 3.77, 5.92, 7.09 m/s^2, those of the intelligently controlled structure are 11.64, 18.78, 22.10 mm and 3.37, 4.90, 5.54 m/s^2, those of the passive-on controlled structure are 8.7, 13.1, 15.2 mm and 9.90, 4.72, 4.20 m/s^2, and those of the passive-off controlled structure are 13.9, 22.3, 26.7 mm and 3.31, 4.76, 5.68 m/s^2. Though the displacement responses of the passive-on controlled structure are slightly better than those of the intelligently controlled structure, the acceleration responses of the first floor of the passive-on controlled structure are not ideal, and magnification of the acceleration response occurs in this floor. Similarly, the integrated intelligent

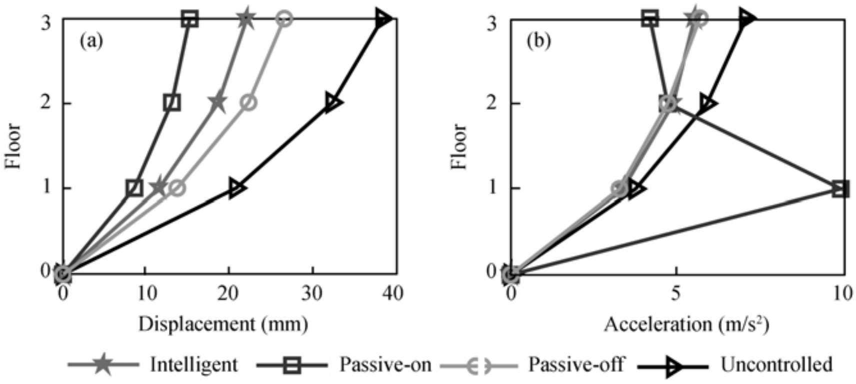

Figure 13 The maximum responses comparison of each floor (artificial). (a) The displacement response; (b) the acceleration response.

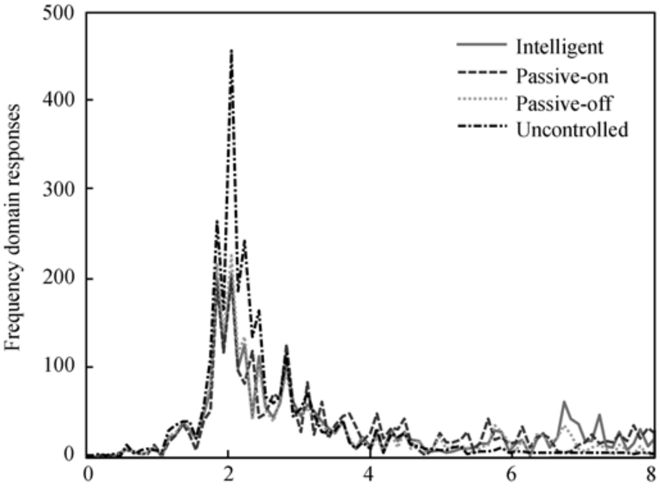

Figure 14 Frequency domain responses of the top floor acceleration (artificial).

control strategy has the better earthquake mitigation effect. It can be seen from the frequency domain analysis results that the frequency domain responses of the top floor are 454.9, 205.0, 200.6 and 226.5 for the uncontrolled, intelligently controlled, passive-on controlled and passive-off controlled structures at near the basic natural frequency of the structure 2.20 Hz. Though the frequency domain response of the top floor of the passive-on controlled structure is slightly less than that of the intelligently controlled structure, it must be noted that the frequency domain response is for the top floor and the frequency domain response of the first floor will be magnified.

4.4 Neural network analysis

In the integrated intelligent control strategy, time-delay problem is solved by the neural network, and appropriate control currents are determined quickly by fuzzy controller. It is concluded that the control strategy is very important for semi-active control or active control. In order to evaluate the contribution of the incorporation of the neural network response prediction, the neural network part shown in Figure 4 is deleted, the inputs of fuzzy controller are changed into the delayed displacement x_k and the measured earthquake acceleration $\ddot{x}_{g_{k+1}}$, and the control force is calculated by using the delayed velocity $\dot{x}_k$. The maximum displacement and acceleration responses of the top floor are 19.2 mm and 4.78 m/s^2, respectively with a 0.2g El Centro earthquake wave. Those of the intelligently controlled structure with neural network are 18.5 mm and 4.66 m/s^2, respectively. Therefore, when the neural network is adopted, both the displacement and the acceleration responses are improved.

5 Concluding remarks

This study proposes an integrated intelligent control strategy for structures incorporated with MR dampers. In this strategy, the time-delay problem is solved by a neural network and the control currents of the MR dampers are determined quickly by a fuzzy controller. Through a numerical example of a three-storey structure with one MR damper installed in the first floor, the seismic responses of the uncontrolled, the intelligently controlled, the passive-on controlled, and the passive-off controlled structures under different earthquake excitations are analyzed. Based on the numerical results, it can be found that both time domain and frequency domain responses are reduced effectively when the MR damper is added in the structure, and the integrated intelligent control strategy has the best earthquake mitigation effect. The control strategy is very important for semi-active control or active control. The integrated intelligent control strategy is better than the passive-on and the passive-off control strategies obviously because the inherent time-delay problem is solved by the neural network and more appropriate control currents can be chosen by the fuzzy controller in the integrated intelligent control strategy.

1 Chen H M, Tsai K H, et al. Neural network for structural control. J Comp Civil Eng, ASCE, 1995, 9(2): 168－176

2 Ghaboussi J, Joghataie A. Active control of structures using neural network. J Eng Mech, ASCE, 1995, 121(6): 555－567

3 Battaini M, Casciati F, Faravelli L. Fuzzy control of structural vibration: an active mass system driven by a fuzzy controller. Earthq Eng Struct Dyn, 1998, 27(11): 1267－1276

4 Bani-Hani K, Ghaboussi J, Schneider S P. Experimental study of identification and control of structures using neural network. Earthq Eng Struct Dyn, 1999, 28(9): 995－1018

5 Symans M D, Kelly S W. Fuzzy logic control of bridge structures using intelligent semi-active seismic isolation systems. Earthq Eng Struct Dyn, 1999, 28(1): 37－60

6 Huang S J, Lian R J. A combination of fuzzy logic and neural network controller for multiple-input multiple-output systems. Int J Sys Sci, 2000, 31(3): 343－357

7 Ni Y Q, Chen Y, et al. Neuro-control of cable vibration using semi-active magneto-rheological dampers. Eng Struct, 2002, 24(3): 295－307

8 Park K S, Koh H M, Ok S Y. Active control of earthquake excited structures using fuzzy supervisory technique. Adv Eng Software, 2002, 33(6): 761－768

9 Dounis A I, King R E. Optimum fuzzy sliding mode semi-active control of structures subjected to earthquakes. J Intel Fuzzy Sys, 2003, 14(1): 37－47

10 Ok S Y, Kim D S, et al. Semi-active fuzzy control of cable-stayed bridges using magnetorheological dampers. Eng Struct, 2007, 29(6): 776－788

11 Xu Y L, Qu, W L, Ko J M. Seismic response control of frame structure using magnetorheological/electrorheological dampers. Earthq Eng Struct Dyn, 2000, 29(5): 557－57

12 Spencer B F, Dyke S J, et al. Phenomenological model for magnetorheological dampers. J Eng Mech, ASCE, 1997, 123(3): 230－238

13 Werely N M, Pang L, Kamath G M. Idealized hysteresis modeling of electrorheological dampers. J Intel Mater Sys Struct, 1998, 9(8): 642－649

14 Gavin H P, Hanson R D, Filisko F E. Electrorheological dampers, Part I: analysis and design. J Appl Mech, 1996, 63: 669－675

15 Phillips R W. Engineering applications of fluids with a variable yield stress. PhD Dissertation. Berkeley: University of California, 1969

16 Xu Z D. Study on semi-active control of structures incorporated with magnetorheological dampers. Report of Postdoctoral Fellow (in Chinese). Xi'an: Xi'an Jiaotong University, 2002

17 Hagan M T, Menhaj M B. Training feedforward networks with the Marquardt algorithm. IEEE Trans Neural Networks, 1994, 5(6): 989－993

18 Guo Y Q. Study on intelligent earthquake mitigation control of magnetorheological structure. Thesis of Master Degree (in Chinese). Xi'an: Xi'an Architecture and Technology University, 2003

19 Li S Y. Fuzzy Control, Neural Network and Intelligent Control Theory (in Chinese). Harbin: Press of Harbin Industry University, 1998

20 Ou J P, Guan X C. Experimental study of MR damper performance. Earthq Eng Eng Vib (in Chinese), 1999, 19(4): 76－81