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ORIGINAL RESEARCH PAPER

Structural vibration reduction using self-tuning fuzzy control of magnetorheological dampers

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Abstract Among the control devices considered for dissipating seismic energy and reducing structural vibrations is the magnetorheological (MR) damper which consists of a hydraulic cylinder filled with a suspension of micron-sized, magnetically polarizable iron particles capable of reversibly changing from free-flowing, linear viscous fluid to semi-solid with the application of a magnetic field. Several algorithms have been proposed for regulating the amount of damping provided by MR dampers. An attractive option is the use of fuzzy controllers because they are simple, intrinsically robust, and they do not depend on a model of the system. Tuning of these controllers, however, has shown to be a difficult task because of the large number of parameters involved. This paper proposes a self-tuning fuzzy controller to regulate MR dampers' properties and reduce structural responses of single degree-of-freedom seismically excited structures. Robustness to changes in seismic motions and structural characteristics was assessed by subjecting a rigid and a flexible building to different earthquake records. Results show that the self-tuning controller proposed effectively reduced responses of both structures to all earthquakes considered. In addition, results were compared to those of a fuzzy controller with constant scaling factors and to those of two passive strategies: "passive on" and "passive off", where the current to the MR dampers was set to its maximum allowable value, and zero, respectively.

Keywords Fuzzy control · Fuzzy logic · MR damper · Semi-active control · Structural control · Vibration control

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Abbreviations

CSM Continuous sliding mode
LQG Linear-quadratic-Gaussian
MR Magnetorheological
RMS Root mean square
SDOF Single degree-of-freedom

1 Introduction

In an attempt to reduce injuries, property damage, and most importantly, human losses, different types of structural control devices have been used for reducing structural vibrations. Among the devices proposed for dissipating seismic energy is the magnetorheological (MR) damper. This semi-active device consists of a hydraulic cylinder filled with a suspension of micron-sized, magnetically polarizable iron particles capable of reversibly changing from a free-flowing, linear viscous fluid to a semi-solid, with the application of a magnetic field. This is a highly nonlinear device; therefore, developing control algorithms that are effective, practical, and that fully take advantage of its characteristics has been challenging.

Proposed control strategies for this device can be categorized as model-based control, that is, algorithms that require an accurate mathematical system model; or intelligent control. In the model-based category, the most established control strategy is the clipped-optimal algorithm (Dyke et al. 1996a,b) whose effectiveness has been demonstrated numerically and experimentally in several studies (Dyke et al. 1996a,b; Dyke and Spencer 1997; Dyke 1998; Jansen and Dyke 2000; Yi et al. 2001; Yoshida et al. 2002). This control strategy determines the "ideal" control force through H_2/Linear-Quadratic-Gaussian (LQG), and uses bang-bang (on-off) control to emulate it. Other model-based strategies include the optimal controllers (Zhang and Roschke 1999; Xu et al. 2000; Chang and Zhou 2002; Zhou et al. 2002), the controllers based on Lyapunov stability theory (McClamroch and Gavin 1995; Dyke and Spencer 1997; Jansen and Dyke 2000; Yi et al. 2001), skyhook controllers, and continuous sliding mode (CSM) controllers (Hiemenz et al. 2000). Although these model-based strategies have been successful in reducing structural vibrations, their performance is strongly affected by the accuracy of the model selected. In addition, because models are based on assumptions and uncertainties, it is important to ensure that controllers in this category will be robust enough to control the real life structure (Sreenatha and Pradhan 2002). The nonlinearity and complexity of devices such as the MR dampers render difficult the development of accurate and practical models. In these cases, models developed are often very sophisticated and computationally intensive and often impractical for control applications. Therefore, intelligent control strategies, which do not rely on a system model, seem to be attractive alternatives. Intelligent controllers proposed for use with MR dampers can be divided in the following three categories: neural network-based control (Shiraishi et al. 2002; Dalei and Jianqiang 2002; Ni et al. 2002; Xu et al. 2003), neuro-fuzzy based control (Schurter and Roschke 2001a,b), and fuzzy logic-based control (Zhou and Chang 2000; Zhou et al. 2002; Liu et al. 2001; Choi et al. 2004; Wilson 2005; Wilson and Abdullah 2005a,b).

Fuzzy-based controllers are simple and robust algorithms that use intuitive knowledge instead of differential equations to describe the system. They are suitable for real-time control and do not require information on structural and vibration characteristics of the system to be controlled (Wong et al. 1999). These control strategies consist in the implementation of rules in the format of IF-THEN statements that relate the input variables to the desired output. The process can be summarized by the following steps: (1) Fuzzyfication, where membership functions are used to convert crisp input values to fuzzy linguistic values. (2) Decision Making, where "IF-THEN" rules, created based on control knowledge of the system, are used to relate the linguistic input variables to linguistic output variables. (3) Defuzzification, where the fuzzy linguistic output variable is converted to a crisp control value (Marazzi and Magonette 2001).

Although controllers designed using fuzzy logic are rather simple, the number of parameters used to define the membership functions and the inference mechanisms render their tuning a sophisticated and difficult procedure (Zheng 1992; Yager and Filev 1994; Li and Gatland 1996). Among the methods developed for tuning fuzzy controllers, adjustment of the scaling factors is the most popular strategy because of the large effect these variables have on controller performance (Yager and Filev 1994; Li and Gatland 1996). This is because they are responsible for mapping the inputs and outputs to their respective universes of discourses. Adjustment of these factors may be achieved using heuristic approaches (Daugherity et al. 1992; Driankov et al. 1993; Faravelli and Yao 1996; Li and Gatland 1996), neuro-like approaches (Nishimori et al. 1994; Chao and Teng 1997), genetic algorithms (Arslan and Kaya 2001; Zhao et al. 2003), gain scheduling (Jang and Gulley 1994; Zhao 2001) and self-tuning (Maeda et al. 1990; Woo et al. 2000; Zhao 2001). The latter consists in using a fuzzy decision making system to vary the values of one or more of the scaling factors according to changes in the input variables to the fuzzy controller or the input excitation to the system. Although this strategy has been proposed to tune scaling factors of some fuzzy-controlled devices, it has not yet been employed with MR dampers, where all fuzzy control applications to date consist in selecting fixed values for all scaling factors and maintaining these values constant at all times.

Therefore, the objective of this paper is to develop a self-tuning fuzzy controller to regulate the damping properties of MR dampers and reduce structural responses of single degree-of-freedom (SDOF) seismically excited structures. To test the robustness of the algorithm to changes in seismic motions and structural characteristics, numerical simulations were conducted where two single-story structures: one rigid and one flexible, were subjected to a wide range of earthquake records.

2 System description

The buildings were modeled as lumped masses, that is, the entire structural mass (m) was assumed to be located at the top of the building. In addition, stiffness (k) and damping (c) were assumed to be constant. The equation of motion for a SDOF system equipped with a damper is:

$$m\ddot{x} + c\dot{x} + kx = -f - m\ddot{x}_g \tag{1}$$

where $x, \dot{x}, \ddot{x}$ are the floor displacement, velocity, and acceleration, respectively, f is the control force, and $\ddot{x}_g$ is the ground acceleration.

2.1 Structural parameters

The controller was designed for the SDOF building described in Yeh et al. (1994), which has a mass of 345,600 kg, a stiffness of 3.4×10^7 N/m and a damping ratio of 0.02. Since its natural frequency is 9.92 rad/s and its period is 0.63 s, it is classified as a rigid structure according to Sadek and Mohraz (1998). Because structures tend to loose stiffness as they are damaged during earthquakes, the controller designed needs to be robust enough to reduce responses of a more flexible structure. Therefore, the second structure was selected such that it had the same mass and damping coefficient as the original building, but a reduced stiffness of 5.3×10^6 N/m. The resulting natural frequency was 3.92 rad/s and the period was 1.6 s, classifying it as a flexible structure according to Sadek and Mohraz (1998).

2.2 MR damper model

Two 20-ton MR dampers were used to reduce vibration of each of the buildings considered. Structural responses were simulated in Matlab and Simulink. For this purpose, the phenomenological model proposed by Spencer et al. (1997) was selected to relate the current applied to the MR dampers to the damping forces obtained:

$$f = \alpha z + c_o(\dot{x} - \dot{y}) + k_o(x - y) + k_1(x - x_o) = c_1\dot{y} + k_1(x - x_o) \quad (2)$$

$$\dot{z} = -\gamma\,|\dot{x} - \dot{y}|\,z\,|z|^{n-1} - \beta\,(\dot{x} - \dot{y})\,|z|^n + A\,(\dot{x} - \dot{y}) \quad (3)$$

$$\dot{y} = \frac{1}{c_o + c_1}\left\{\alpha z + c_o\dot{x} + k_o\,(x - y)\right\} \quad (4)$$

f is the control force of each MR damper, x, the damper displacement, y, an internal displacement of the damper, α, the Bouc-Wen parameter describing the MR fluid yield stress, c_o represents the viscous damping at large velocities, k_o the stiffness at large velocities, k_1 models the damper force due to the accumulator, and c_1 reproduces the roll-off occurring in the experimental data when velocities are close to zero. Evolutionary variable z is defined as the integral of Eq. (3). Values for the parameters of the 20-ton MR dampers were obtained experimentally by Yang and colleagues to fit the experimental data (Yang 2001; Yang et al. 2002): $A = 2679.0\,\text{m}^{-1}$, γ and $\beta = 647.46\,\text{m}^{-1}$, $k_o = 137,810$ N/m, $n = 10$, $x_o = 0.18$ m, and $k_1 = 617.31$ N/m. Variables α, c_o, c_1 are functions of the input current to the damper (i):

$$\alpha(i) = 16566i^3 - 87071i^2 + 168326i + 15114 \quad (5)$$

$$c_o(i) = 437097i^3 - 1545407i^2 + 1641376i + 457741 \quad (6)$$

$$c_1(i) = -9363108i^3 + 5334183i^2 + 48788640i - 2791630 \quad (7)$$

To accommodate the dynamics of the MR fluid reaching rheological equilibrium, the following first order filter is also provided by Yang and his colleagues (Yang 2001; Yang et al. 2002):

$$H(s) = \frac{31.4}{s + 31.4} \quad (8)$$

It is important to note that the numerical model of the MR damper is used solely to simulate the building responses and not to design or run the self-tuning fuzzy controller proposed.

2.3 Seismic motions

Design of the self-tuning fuzzy controller was performed considering the north-south acceleration of the following four earthquakes: El Centro, Hachinohe (Takochi-oki), Northridge, and Kobe (Hyogo-ken Nanbu). Magnitude, peak acceleration, and root mean square (RMS) acceleration of these four seismic excitations are presented on Table 1. The robustness of the controller to changes in seismic excitations was evaluated by subjecting the structures to the twenty earthquakes selected by Sadek and Mohraz (1998) to include a wide range of magnitudes, epicentral distances, peak ground accelerations and soil conditions (Table 2).

Table 1 Earthquake records used in the design of the self-tuning fuzzy controller

Earthquake	Date	Magnitude	Component	Peak acceleration (m/s^2)	RMS acceleration (m/s^2)
El Centro, CA	May 18, 1940	7.1	N–S	3.4170	0.4764
Hachinohe, Japan	May 16, 1968	7.9	N–S	2.2500	0.3956
Northridge, CA	January 17, 1994	6.8	N–S	8.2676	0.7219
Kobe, Japan	January 17, 1995	6.9	N–S	8.1782	0.5909

3 Self-tuning fuzzy controller

The schematic of the system presented in Fig. 1 shows that the input variables to the self-tuning fuzzy controller were selected as floor displacement (x) and floor velocity ($\dot{x}$), while the output was chosen as the current applied to the MR dampers (i). Figure 2a presents the membership functions for both input variables. They consist of seven identical triangles with 50% overlap, defined on the normalized universe of discourse $[-1, 1]$. Membership functions for the output are shown in Fig. 2b, and consist of four identical triangles, also with 50% overlap, defined on the normalized universe of discourse [0,1]. Labels used to define the membership functions are as follows: NL refers to negative large, NM to negative medium, NS to negative small, ZO to zero, PS to positive small, PM to positive medium, and PL to positive large. The defuzzification process selected was the centroid method, which defines the crisp output as the centroid of the area under the membership functions resultant from the union of the fuzzy outputs.

Because there is no methodical approach for the development of rule-bases for fuzzy controllers, standard rule-bases are often used as a starting point (Yager and Filev 1994) and modified, as needed, to better attain the control objectives. In this paper, the standard rules developed by MacVicar-Whelan (1976) and a modified version of this set developed by Liu et al. (2001) were selected as bases because they reflected the desired control actions. For instance: if floor displacement is positive large, and floor velocity is also positive large, indicating that the structure is moving away from its original position, then the rules require the current to be applied to the dampers to be positive large in order to increase the viscosity of the MR fluid, therefore increasing the amount of damping provided and discouraging structural motion. On the other hand, if floor displacement is positive large, and floor velocity is negative large, indicating that the structure is returning to its original position, then the current is set to zero to decrease the amount of damping provided and allow the structure to return to its original position. Because variations to these standards did not noticeably improve the results obtained, the rule-base described in Liu et al. (2001) was ultimately selected and is presented in Table 3.

Since normalized universes of discourse were used for both inputs and for the output to the fuzzy controller, scaling factors were required to map the variables to these domains. As shown in Fig. 1, the input scaling factors were labeled K_d and K_v, for displacement and velocity, respectively, and the output scaling factor was labeled K_u. Although fuzzy controllers are simple algorithms, their tuning is a challenging task because of the flexibility the designer has in selecting the rules, the number of membership functions, their shapes and overlap, and the values for the input and output scaling factors. To date, fuzzy controllers designed for MR dampers have used fixed values for all scaling factors and maintained these values constant throughout the seismic motion. This paper analyzes the effect of varying at least one of the

Table 2 Earthquake records used to evaluate the effectiveness of the self-tuning fuzzy controller

Earthquake	Station name	Magnitude	Component	Peak acceleration (m/s^2)	RMS acceleration (m/s^2)
San Fernando, California 02/09/1971	Pacoima Dam	6.4	S 16 E	11.4806	1.5954
	Pacoima Dam	6.4	S 74 W	10.5495	1.0744
	250 E. First Street Basement, Los Angeles	6.4	N 36 E	0.9781	0.1592
	250 E. First Street Basement, Los Angeles	6.4	N 54 W	1.2273	0.1584
Loma Prieta, California 10/17/1989	Corralitos Eureka Canyon Road	7.1	0°	6.1770	0.7126
	Corralitos Eureka Canyon Road	7.1	90°	4.6938	0.6333
	Capitola Fire Station	7.1	0°	4.6292	0.8267
	Capitola Fire Station	7.1	90°	3.9079	0.6084
Northridge, California 01/17/1994	Arleta Nordhoff Ave. Fire Station	6.7	90°	3.3732	0.3985
	Arleta Nordhoff Ave. Fire Station	6.7	360°	3.0205	0.3496
	Pacoima Dam Down Stream	6.7	175°	4.0711	0.4406
	Pacoima Dam Down Stream	6.7	265°	4.2555	0.3908
Northwest, California 10/07/1951	Ferndale City Hall	5.8	S 44 W	1.0200	0.1001
	Ferndale City Hall	5.8	N 46 W	1.0950	0.1122
San Francisco, California 03/22/1957	San Francisco Golden Gate Park	5.3	N10 E	0.8180	0.0663
	San Francisco Golden Gate Park	5.3	S 80 E	1.0280	0.0885
Helena, Montana 10/31/1935	Helena Montana Carrol College	6.0	S 00 W	1.4350	0.0947
	Helena Montana Carrol College	6.0	S 90 W	1.4250	0.1190
Parkfield, California 06/27/1966	Temblor, California # 2	5.6	N 65 W	2.6430	0.2504
	Temblor, California # 2	5.6	S 25 W	3.4080	0.3043

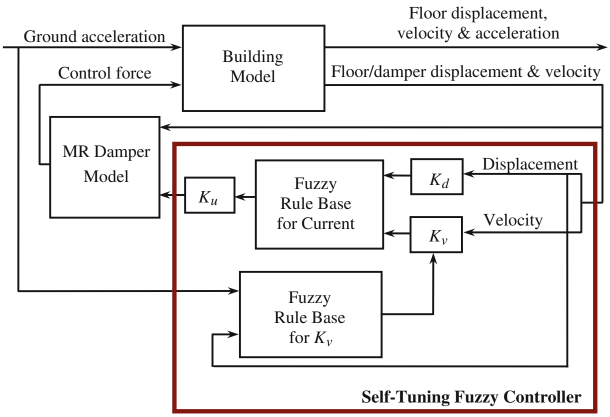

Fig. 1 System diagram

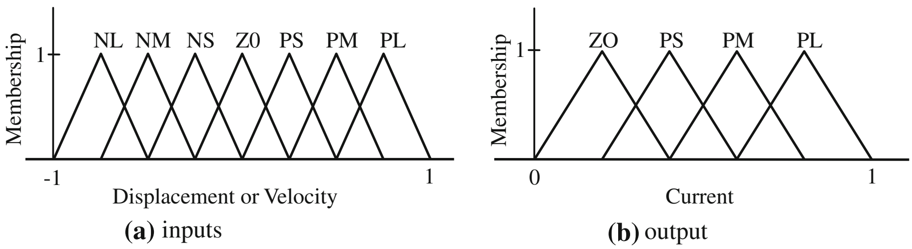

Fig. 2 Membership functions

Table 3 Control rule base (Liu et al. 2001)

x	$\dot{x}$ NL	NM	NS	ZO	PS	PM	PL
NL	PL	PL	PL	PM	ZO	ZO	ZO
NM	PL	PL	PL	PS	ZO	ZO	PS
NS	PL	PL	PL	ZO	ZO	PS	PM
ZO	PM	PL	PS	ZO	PS	PM	PL
PS	PS	PM	ZO	ZO	PL	PL	PL
PM	ZO	PS	ZO	PS	PL	PL	PL
PL	ZO	ZO	ZO	PM	PL	PL	PL

scaling factors. Therefore, to determine which parameter (or parameters) should be varied with ground excitation or with floor responses, a parametric analysis was conducted where the rigid structure was subjected to the following four earthquakes: El Centro, Hachinohe, Northridge, and Kobe while the values for K_d and K_v were varied from 0.01 to 50, and the values considered for K_u were 2, 4, and 6. These ranges include the values obtained with equations proposed by Yager and Filev (1994):

Table 4 Uncontrolled responses of rigid structure to four different earthquakes

Earthquake	Maximum displacement (m)	Maximum velocity (m/s)	Maximum acceleration (m/s^2)
El Centro, CA	0.0870	0.8126	10.4105
Hachinohe, Japan	0.0514	0.4968	5.2095
Northridge, CA	0.1436	1.4306	19.8497
Kobe, Japan	0.2204	2.1732	24.5961

$$K_d = \frac{1}{d_{\max}} \tag{9}$$

$$K_v = \frac{1}{v_{\max}} \tag{10}$$

as well as those obtained with equations proposed by Liu et al. (2001):

$$K_d = \frac{3}{d_{\max}} \tag{11}$$

$$K_v = \frac{3}{v_{\max}} \tag{12}$$

$$K_u = \frac{i_{\max} - i_{\min}}{3} \tag{13}$$

where $d_{\max}$ and $v_{\max}$ refer to the maximum structural displacement and velocity, respectively. Values for these variables were selected as the largest uncontrolled responses of the rigid structure to the following four earthquakes: El Centro, Hachinohe, Northridge, and Kobe (Table 4). Additional variables used in the equations above include: $i_{\min}$ which is the minimum current to the MR damper (0 A), and $i_{\max}$ which is the maximum current (6 A) (Yang 2001).

Results of this parametric analysis showed that there might be a relationship between K_v and the ground motion intensity. To further investigate this relationship, a second parametric analysis was conducted where K_v values were varied from 0.01 to 10 and responses of the rigid structure to the following scaled versions of the El Centro earthquake were obtained: 25, 50, and 100%. Values of K_v larger than 10 were not considered in this second analysis because they were found to be less effective, and, in some instances, to lead to inconsistent results. Values for K_d ranged from 2 to 50 and K_u was selected as 2, 4, and 6. Results of this study confirmed that the controller was not sensitive to changes in the magnitude of K_d or K_u. Consequently, these scaling factors were kept constant and equal to the values that yielded the best results for the cases considered, that is: $K_d = 7$, and $K_u = 4$. Results of this study also showed that there was a relationship between the ground acceleration and the velocity scaling factor K_v: the smaller the earthquake acceleration, the smaller the value of K_v that would produce greater structural reductions. Therefore, a fuzzy controller was designed to adjust the values of this parameter at each time step. This strategy is referred to as "self-tuning". As shown in Fig. 1, the inputs to this controller were selected as ground acceleration ($\ddot{x}_g$) and floor displacement (x), while the output was evidently selected as K_v. Three membership functions were used to define each of the inputs; they were labeled S for small, M for medium, and L for large, as shown in Fig. 3. The universes of discourse were selected according to the ranges observed for each of the variables: [0, 0.1] for floor displacement (Fig. 3a), [0, 1.5] for ground excitation (Fig. 3b), and [0, 15] for K_v (Fig. 3c).

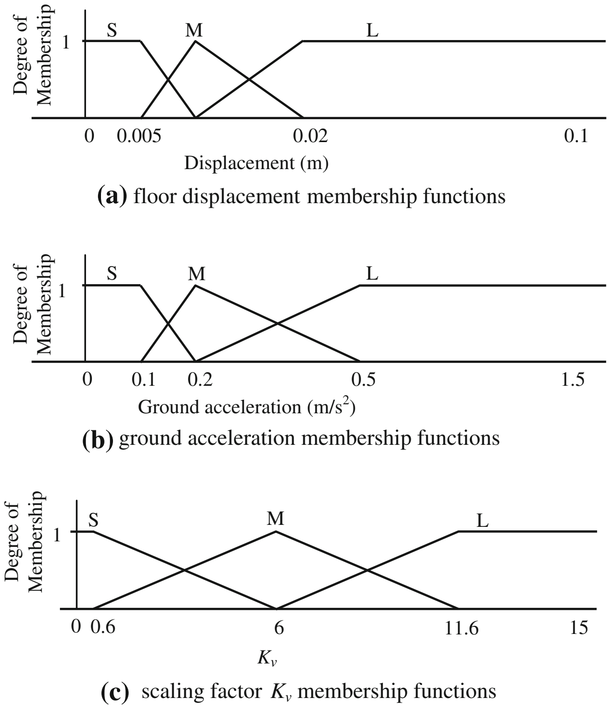

Fig. 3 Membership functions for inputs and output of the fuzzy control strategy used to self-tune scaling factor K_v

Table 5 Fuzzy rules for computation of scaling factor K_v

$\ddot{x}_g$	x		
	S	M	L
S	S	M	L
M	M	M	L
L	L	L	L

The inference rules for this fuzzy control system were based on the results of the second parametric analysis described above, which can be summarized as follows: values of K_v increased with increasing floor displacements and ground accelerations. Small variations of these rules were considered with the El Centro earthquake until the best combination was obtained (Table 5).

As mentioned in an earlier section, to determine the robustness of the self-tuning algorithm to changes in structural characteristics, and more specifically to softening of the structure due to column damage during the earthquakes, responses of a more flexible structure equipped with fuzzy-controlled MR dampers designed for the rigid structure were considered. The effectiveness and the robustness of the proposed self-tuning algorithm to changes in seismic excitations were also evaluated by subjecting both structures to the 24 earthquakes presented previously.

4 Results and discussion

Numerical simulations of structural responses obtained with the self-tuning fuzzy controlled MR dampers were conducted using Matlab and Simulink. Evaluation criteria based on peak and RMS displacements and accelerations were used to assess the effectiveness of the control system. These criteria were obtained by dividing the controlled responses by the respective uncontrolled responses, as shown below:

$$J_1 = \frac{\text{RMS } (x(t))}{\text{RMS } (x_{\text{unc}}(t))} \tag{14}$$

$$J_2 = \frac{\text{RMS } (\ddot{x}(t))}{\text{RMS } (\ddot{x}_{\text{unc}}(t))} \tag{15}$$

$$J_3 = \frac{\max |x(t)|}{\max |(x_{\text{unc}}(t))|} \tag{16}$$

$$J_4 = \frac{\max |\ddot{x}(t)|}{\max |(\ddot{x}_{\text{unc}}(t))|} \tag{17}$$

where x and $\ddot{x}$ are the controlled displacement and acceleration, respectively, whereas x_{unc} and $\ddot{x}_{unc}$ are the uncontrolled displacement and acceleration, also respectively.

For conciseness, graphic displacement and acceleration responses of the rigid structure are presented for only 4 of the 24 earthquakes considered (Figs. 4,5,6,7). Nevertheless, discussion presented in this section will refer to structural responses to all 24 seismic motions. The average values for the evaluation parameters of all 24 earthquakes, along with their respective 95% confidence intervals were found to be: $\bar{J}_1 = 0.290(\pm 0.061)$, $\bar{J}_2 = 0.836(\pm 0.339)$, $\bar{J}_3 = 0.462(\pm 0.092)$, and $\bar{J}_4 = 0.821(\pm 0.120)$, showing that peak and RMS displacements and accelerations were reduced with the self-tuning fuzzy controlled MR dampers for a very wide range of seismic motions. As expected, displacement reductions were larger than those obtained for acceleration because control rules were based on floor displacement.

Values of J_1 ranged from 0.563 for the S80E component of the San Francisco earthquake to 0.078 for the N46W component of the Northwest California earthquake, showing that RMS displacements were reduced for all seismic motions. Peak displacements were also reduced for all of the earthquakes considered, with values for J_3 ranging from 0.938 for one of the components of the Parkfield earthquake to 0.147 for the N36E component of the San Fernando earthquake. RMS accelerations were reduced for almost all of the seismic motions, with the lowest value for J_2 reaching 0.194 for one of the components of the Loma Prieta earthquake measured at the Capitola Fire Station. Finally, peak accelerations were also reduced for most earthquakes, with the lowest value for J_4, 0.380, being observed for the same component of the Loma Prieta earthquake mentioned above.

Results obtained with the proposed self-tuning strategy were compared to those obtained with a fuzzy controller that kept all scaling factors constant throughout the seismic motion: $K_d = 32$, $K_v = 3.3$, and $K_d = 4$ (Wilson 2005; Wilson and Abdullah 2005a). For simplicity, in this paper, the controller with constant scaling factors will be referred to as "fuzzy controller", while the self-tuning fuzzy control system proposed will simply be called "self-tuning". To determine whether the use of semi-active control systems can be justified, the fuzzy control algorithms were compared to two passive strategies: "passive on", where the current to the MR dampers was set at maximum allowable value (6 A), and "passive off", where the current was set to zero. Figure 8 and Table 6 present the average results ($\bar{J}$) for all four control strategies. Paired difference two-tailed t-tests were conducted to compare the

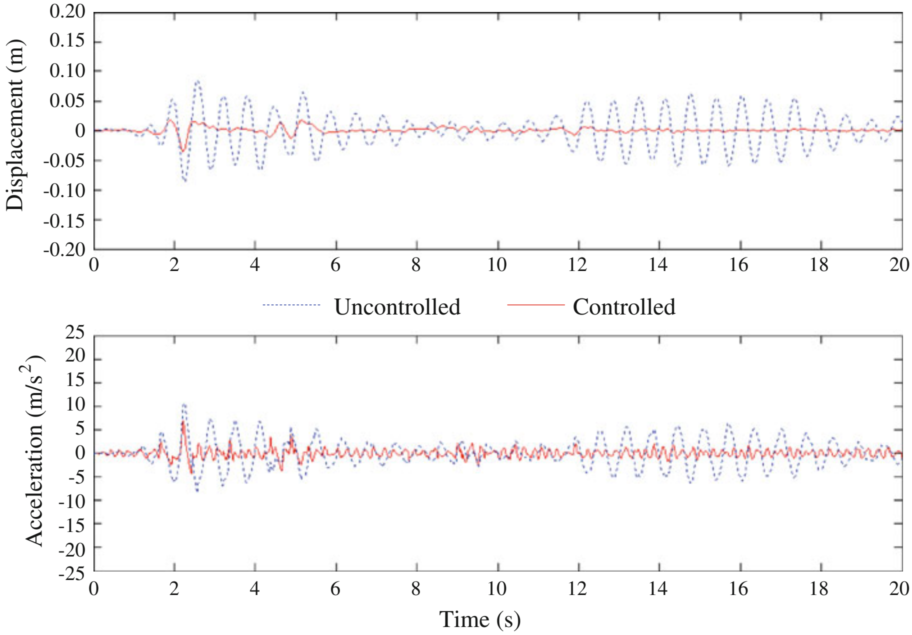

Fig. 4 Rigid building responses to El Centro earthquake

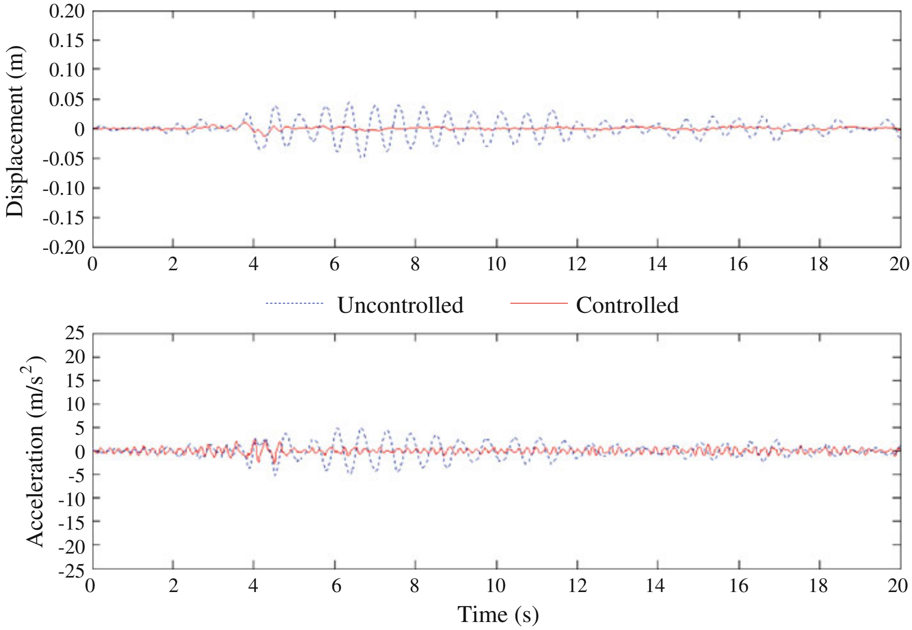

Fig. 5 Rigid building responses to Hachinohe earthquake

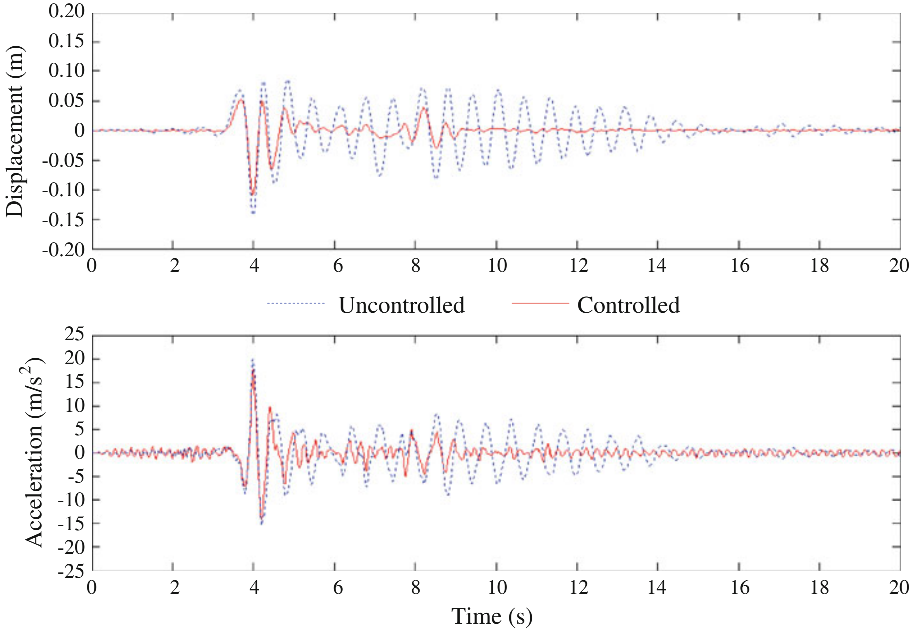

Fig. 6 Rigid building responses to Northridge earthquake

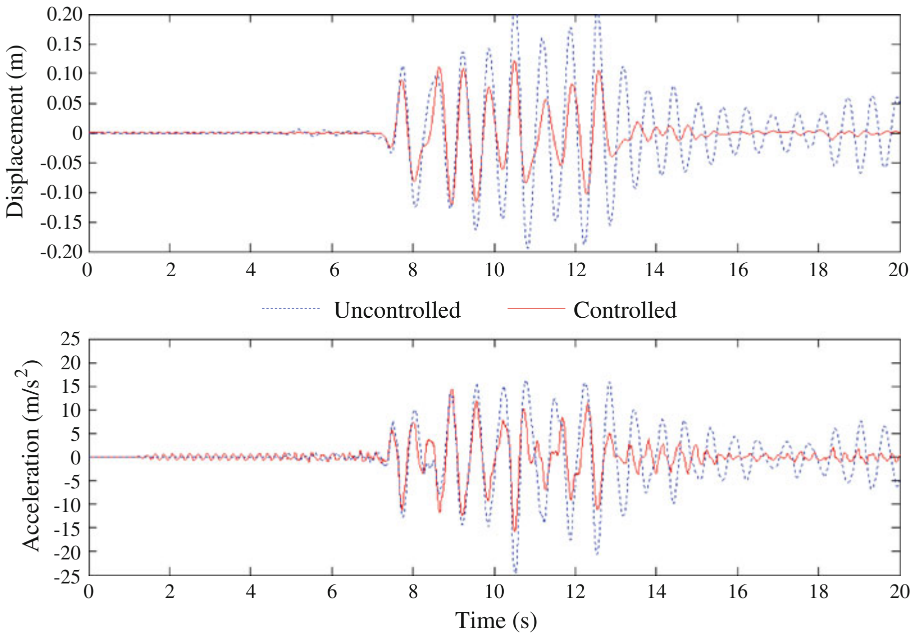

Fig. 7 Rigid building responses to Kobe earthquake

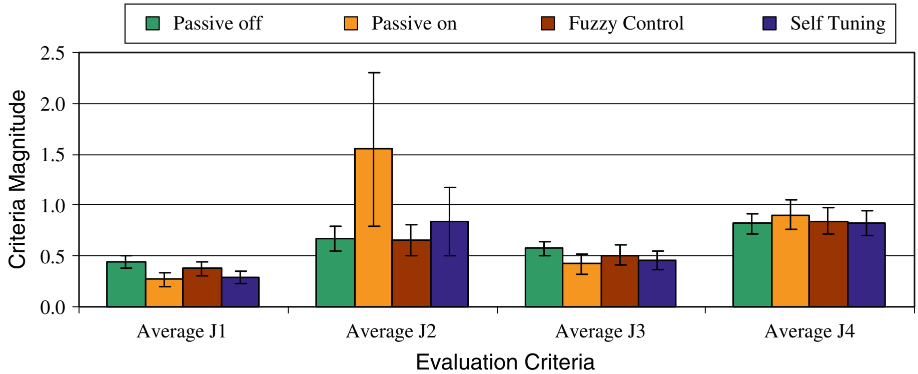

Fig. 8 Comparison of average evaluation criteria values for the rigid structure's responses obtained with different control strategies (*errorbars* indicate 95% intervals)

Table 6 Average values of evaluation criteria for rigid structure's responses obtained with different control strategies (95% intervals presented in parenthesis)

	$\bar{J}_1$	$\bar{J}_2$	$\bar{J}_3$	$\bar{J}_4$
Passive off	0.445(±0.064)	0.667(±0.124)	0.575(±0.068)	0.818(±0.098)
Passive on	0.268(±0.062)	1.548(±0.752)	0.423(±0.101)	0.902(±0.144)
Fuzzy controller	0.374(±0.075)	0.652(±0.151)	0.507(±0.097)	0.843(±0.129)
Self-tuning	0.290(±0.061)	0.836(±0.339)	0.462(±0.092)	0.821(±0.120)

Table 7 Observed significance level (*P*-values) for paired difference two-tailed t-tests obtained for the rigid structure

	$\bar{J}_1$	$\bar{J}_2$	$\bar{J}_3$	$\bar{J}_4$
Passive off vs. passive on	<0.01	0.01	<0.01	0.05
Passive off vs. fuzzy controller	<0.01	0.41	0.01	0.27
Passive off vs. self-tuning	<0.01	0.18	<0.01	0.87
Passive on vs. fuzzy controller	<0.01	0.01	<0.01	0.07
Passive on vs. self-tuning	<0.01	<0.01	<0.01	<0.01
Fuzzy controller vs. self-tuning	<0.01	0.11	<0.01	0.21

average value of the evaluation criteria of each of the controllers against each other. Observed significance levels (P-values) for these tests are presented in Table 7.

These results show that the self-tuning algorithm was more effective in reducing structural responses than the fuzzy controller that maintained constant all scaling factors. Values obtained for evaluation criteria $\bar{J}_1$ and $\bar{J}_3$ with the self-tuning controller were significantly lower than those obtained with the fuzzy controller ($P < 0.01$ for both cases), while for evaluation criteria $\bar{J}_2$ and $\bar{J}_4$, paired difference t-test results ($P = 0.11$ and $P = 0.21$, respectively) indicate that there might be no difference in the values of the parameters obtained with the different fuzzy controllers.

As expected, the passive on system was found to be more effective in reducing RMS and peak displacements ($P < 0.01$ for $\bar{J}_1$ and $\bar{J}_3$) than the passive off scheme, while the opposite

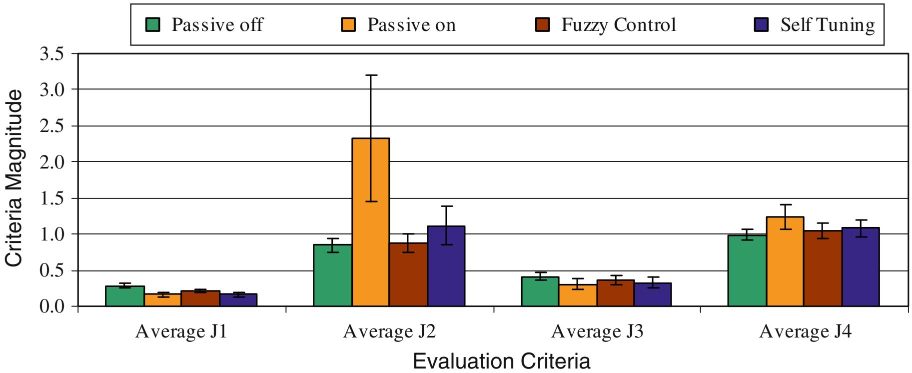

Fig. 9 Comparison of average evaluation criteria values for the flexible structure's responses obtained with different control strategies (*errorbars* indicate 95% intervals)

was observed with respect to RMS and peak accelerations ($P = 0.01$ for $\bar{J}_2$, $P = 0.05$ for $\bar{J}_4$). Like the passive on strategy, both fuzzy controllers were found more effective in reducing RMS and peak displacements than the passive off system ($P \leq 0.01$ for $\bar{J}_2$ and $\bar{J}_4$). However, better results were observed with these fuzzy strategies than with passive on control with respect to RMS and peak acceleration reductions since paired difference t-tests showed that there might not be a difference between reductions obtained with the passive off strategy and either one of the fuzzy controllers, while, as mentioned above, passive on performance was inferior to that of the passive off strategy.

When comparing the passive on system to the fuzzy controller, it was found that the passive set up was more effective in reducing displacements than fuzzy control ($P < 0.01$ for $\bar{J}_1$ and $\bar{J}_3$); there seem to be no difference in performance with respect to reductions in peak acceleration ($P = 0.07$); but the fuzzy controller yielded better results with respect to RMS accelerations ($P = 0.01$ for $\bar{J}_2$). Finally, although reductions in RMS and peak displacements were larger with the passive on strategy than with the self-tuning controller ($P < 0.01$ for $\bar{J}_1$ and $\bar{J}_3$), the opposite was observed with respect to RMS and peak accelerations, where self-tuning control outperformed passive on ($P < 0.01$ for $\bar{J}_2$ and $\bar{J}_4$).

To test the robustness of the self-tuning strategy to changes in structural stiffness due to damage sustained during the earthquakes, the flexible structure described earlier was subjected to all 24 earthquakes. Results showed that even though the self-tuning fuzzy controller was designed for a stiffer structure, it was able to effectively reduce both displacements and accelerations of this flexible structure. RMS and peak displacements were reduced for all earthquakes, with J_1 values ranging from 0.329 to 0.048 and J_3 values ranging from 0.757 to 0.088. Peak and RMS accelerations were reduced for most excitations considered. Average results obtained with the different control strategies are presented in Fig. 9 and Table 8. P-values obtained for paired difference two-tailed t-tests conducted to compare the average evaluation criteria of each of the control strategies against each other are presented in Table 9.

Similar to the results obtained for the rigid structure, the self-tuning controller was more effective in reducing RMS and peak displacements than the fuzzy controller that maintained constant all scaling factors ($P < 0.01$ for $\bar{J}_1$ and $P = 0.03$ for $\bar{J}_3$). Both fuzzy controllers were found to be as effective in reducing peak accelerations ($P = 0.24$), but the fuzzy controller outperformed the self-tuning scheme ($P < 0.01$) with respect to reduction in RMS accelerations ($P = 0.01$). It is however important to remind the reader that the self-tuning

Table 8 Average values of evaluation criteria for flexible structure's responses obtained with different control strategies (95% intervals presented in parenthesis)

	$\bar{J}_1$	$\bar{J}_2$	$\bar{J}_3$	$\bar{J}_4$
Passive off	0.284(±0.027)	0.845(±0.088)	0.413(±0.049)	0.985(±0.072)
Passive on	0.160(±0.033)	2.328(±0.880)	0.308(±0.073)	1.234(±0.173)
Fuzzy controller	0.214(±0.028)	0.876(±0.122)	0.361(±0.066)	1.053(±0.105)
Self-tuning	0.169(±0.032)	1.117(±0.263)	0.324(±0.077)	1.079(±0.112)

Table 9 Observed significance level (P-values) for paired difference two-tailed t-tests obtained for the flexible structure

	$\bar{J}_1$	$\bar{J}_2$	$\bar{J}_3$	$\bar{J}_4$
Passive off vs. passive on	<0.01	<0.01	<0.01	<0.01
Passive off vs. fuzzy controller	<0.01	0.18	0.02	0.03
Passive off vs. self-tuning	<0.01	0.01	<0.01	0.02
Passive on vs. fuzzy controller	<0.01	<0.01	<0.01	<0.01
Passive on vs. self-tuning	0.13	<0.01	0.04	<0.01
Fuzzy controller vs. self-tuning	<0.01	<0.01	0.03	0.24

control strategy was not designed for the flexible structure and that the aim of this exercise is solely to test its robustness to changes in structural stiffness.

Responses of the flexible structure with the passive systems were also compared to those obtained with the fuzzy strategies. As anticipated, the self-tuning controller outperformed the passive off system with respect to RMS and peak displacement reductions ($P < 0.01$ for $\bar{J}_1$ and $\bar{J}_3$), while the inverse was observed with respect to RMS and peak accelerations ($P = 0.01$ for $\bar{J}_2$ and $P = 0.02$ for $\bar{J}_4$). Finally, self-tuning was more effective than the passive on scheme with respect to RMS and peak acceleration reductions ($P < 0.01$ for $\bar{J}_2$ and $\bar{J}_4$), as effective as passive on control for RMS displacement reduction ($P = 0.13$ for $\bar{J}_1$), but less effective for peak displacements ($P = 0.04$ for $\bar{J}_3$).

5 Conclusions

The objective of this paper was to develop a self-tuning fuzzy controller to regulate the damping properties of MR dampers, thus reducing structural responses of SDOF structures subjected to seismic loads. To demonstrate the effectiveness and robustness of the algorithm developed, simulations were conducted in Matlab and Simulink. Results showed that the self-tuning algorithm proposed was capable of effectively reducing the responses of the SDOF structure to a very wide range of earthquakes, therefore exhibiting a robust behavior to changes in external excitations. In addition, the algorithm was shown to be robust to changes in structural stiffness since it was capable of reducing structural responses of a flexible structure subjected to a wide range of earthquakes, even though it was designed for a stiffer one.

Results obtained with the proposed self-tuning algorithm were compared to those obtained with a fuzzy controller that maintained constant all scaling factors. The self-tuning controller was found to be more effective in reducing structural displacements than its fuzzy counterpart, while being just as effective with respect to acceleration reductions. Finally, the effectiveness of the self-tuning algorithm was compared to that of two passive strategies: passive off, where no current was applied to the MR dampers, and passive on, where constant maximum current was applied to the dampers. As expected, the passive on strategy was very effective in reducing structural displacements, but in doing so, it increased accelerations. On the other hand, the passive off strategy was capable of reducing both structural displacements and accelerations, although displacement reductions were not as accentuated as those obtained with its passive counterpart. Responses obtained with the self-tuning fuzzy controller were shown to be a good balance between the behaviors of the passive strategies considered. Results showed that self-tuning outperformed the passive off control with respect to peak and RMS displacement reductions, while similar performances were observed for both controllers with respect to acceleration reduction. In addition, as shown graphically in Fig. 8, although the passive on strategy yielded better results for displacement reductions than self-tuning, the latter was found to be significantly more effective with respect to acceleration reductions.

As an extension to this work, the first author of this paper is currently evaluating the possibility of applying these algorithms to multi-degree-of-freedom structures. Variations in the number, size, and placement of the dampers are being considered. Preliminary results have been promising.

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