SEISMIC CONTROL OF BUILDING FRAMES USING MR DAMPER

Diptesh Das[1], T. K. Datta[2] and Alok Madan[3]

[1]Research Scholar, [2]Professor and [3]Associate Professor, Dept. of Civil Engineering, Indian Institute of Technology Delhi, New Delhi-110016, India. E-mail: tkdatta@civil.iitd.ernet.in ([2] corresponding author)

ABSTRACT :

A fuzzy logic control algorithm, which includes the MR damper dynamics, has been developed by fuzzification of force-velocity curve of the MR damper. The method does not require any analytical model of MR damper characteristics, such as Bouc-Wen model, to be incorporated in the control algorithm. The control algorithm has the feedback structure and is implemented by using the Fuzzy Logic and Simulink toolboxes of MATLAB. In order to study the performance of the algorithm, the control scheme is used to control the responses of an example three storey model building frame taken from the literature. The results indicate that the proposed scheme provides nearly the same percentage reduction of responses as that obtained by clipped optimal control with much less control force and much less command voltage. Position of the damper is found to significantly affect the controlled responses of the structure. It is observed that there is a saturation level of the capacity of the damper for optimum control and any increase in the damper capacity beyond this level does not improve the performance of the controller.

KEYWORDS: Semiactive control, Damper, Fuzzy control, Building, Backbone curve.

1. INTRODUCTION

In recent years, MR damper is identified as a potential device for semiactive control for building frames because of its mechanical simplicity, low power requirement, high dynamic range, large force capacity and robustness. Being an energy dissipation device that cannot add mechanical energy to the structural system, an MR damper is also very stable and fail-safe. Recently, a phenomenological model of a typical MR damper, based on Bouc–Wen hysteresis model (Spencer et. al., 1997) is proposed in connection with the control of responses of structures like building frames and bridges. The proposed model is shown to effectively depict a wide variety of hysteretic behaviour. The model was upgraded in a consequent study in order to consider the MR fluid stiction phenomenon, as well as inertial and shear thinning effects (Yang et. al., 2004). A comprehensive study of the adequacy of various types of dynamic models of MR damper has been done by Jung et. al. (2003).

Two control algorithms, which have been widely used and tested for semiactive control of structures using MR damper are clipped optimal control and bang-bang control. Clipped optimal control uses linear optimal controller and includes MR damper dynamics in developing the control algorithm. Clipped-optimal control strategy, based on acceleration feedback (Dyke et. al., 1996), was found to be effective in controlling structures using MR dampers. The results were verified by laboratory model experiments. Bang-bang control uses Lyapunov's stability theory in developing the control theory and controls MR damper by on-off states of voltage regulator. Jansen and Dyke (2000) used bang-bang control for controlling a building model with absolute acceleration and control force feedback.

The fuzzy logic controller has been widely used in structural control of building frames, both in active control (Battaini et. al., 1998; Al-Dawod et. al., 2003) and hybrid control (Ahlawat et. al., 2002a,b). In the field of semiactive control, Symans and Kelly (1999) developed a control algorithm to modulate the damping coefficient of MR damper. The control algorithm was implemented to regulate the semiactive isolation system in a bridge structure model. Zhou et. al. (2003) proposed an adaptive fuzzy logic control strategy to minimize the difference between a target response and the response of the combined building frame-damper system by adaptively adjusting the MR damper. In another study, a fuzzy controller to regulate the current supplied to the MR damper, based on displacement and velocity, was developed to control the responses of a single storey building. Bhardwaj and Datta (2006) developed a fuzzy controller to control the seismic response of building frame using semiactive hydraulic damper. Neuro-fuzzy techniques, using ANFIS (Adaptive-Network-based Fuzzy Inference System), were applied in semiactive structural control of building frames by Schurter and Roschke (2001). The fuzzy logic controller has not been particularly used for semiactive control of building frames by direct fuzzification of actual MR damper characteristics which are obtained from experiment.

In the present work, an attempt is made to develop a fuzzy logic controlled algorithm, which includes the MR dynamics. The method is developed by fuzzifying a given backbone curve for force-velocity behaviour of an MR damper and then by also fuzzyfying the appropriate shifts and the interpolation weights, required for the development of the desired hysteresis curve traced by the MR damper during its actuation under earthquake excitation. The control algorithm developed is tested by applying it to control a three storey frame, whose controlled responses obtained by other algorithms are available in the literature. Also, a detailed parametric study is conducted to investigate the efficiency of the control algorithm. The entire computation has been done using the Fuzzy Logic and SIMULINK toolboxes in MATLAB (MATLAB, 2004).

2. DYNAMIC BEHAVIOUR OF MR DAMPER

2.1 Fuzzification of MR Damper Dynamic Behaviour

Instead of using the dynamic behaviour of MR damper represented by Bouc-Wen model, an attempt has been made here to fuzzify the force-velocity characteristics of an MR damper (for controlled sinusoidal experiment) in order to capture the MR dynamics fully in the control algorithm. The fuzzification is done by generating the parent backbone curve of the force-velocity behaviour of MR damper with the help of a set of fuzzy if-then rules. The simulation of the damper force-velocity hysteresis curve consists of four steps.

First, using the Fuzzy Logic Toolbox of SIMULINK, elastic-perfectly plastic backbone curves are generated with the help of fuzzy if-then rules. In order to do that, membership functions were chosen to represent the relative velocity between the two ends of the damper, which is the input variable and also to represent the damper force, which is the output variable. Seventeen bell shaped membership functions, ranging from the minimum to the maximum variable values as shown in the figure 1, are chosen for each of the input and the output variables.

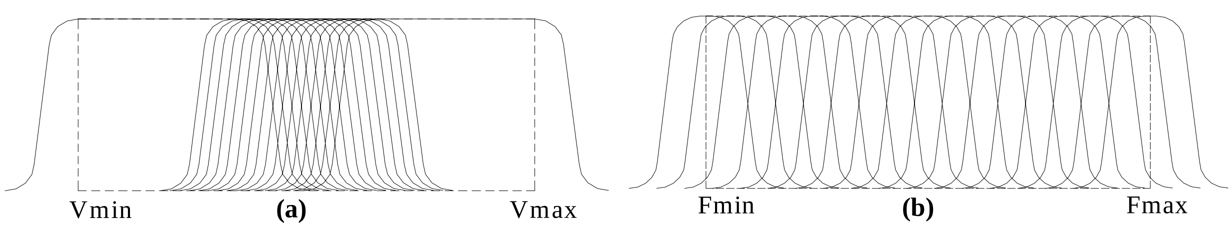

Figure 1 Membership functions for (a) input variable and (b) output variable

In the second step, appropriate shifts are applied to each of the above curves to simulate the hysteretic behaviour of the damper. The shifts are calculated from the yield point P of the elasto-plastic backbone curve. When the input relative velocity value exceeds the yield value v_y, shift is calculated at each time-step as $shift = v - v_y$, where v is the relative velocity at the current time-step. The shift values are cumulatively added till there is a change in the direction of velocity (*i.e.*, when unloading starts after initial loading phase) and a total shift value is obtained (figure 2a). Taking appropriate values from experimental curve, a limiting value is prescribed for the shift. The backbone curve is then horizontally shifted by the total amount of calculated shift to obtain the resultant backbone curves (figure 2b). In the third step, a vertical shift is similarly applied to the backbone curve such as a shift from F_2 to F_3 as shown in the figure 2c.

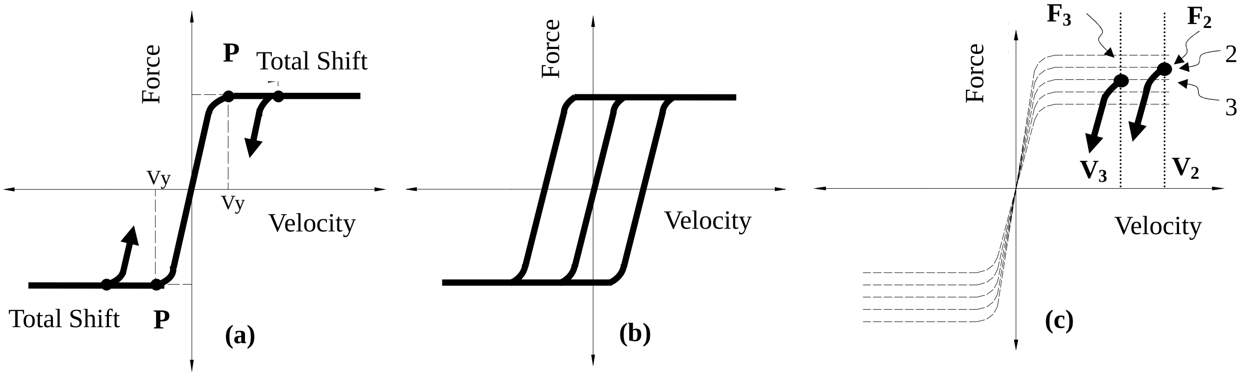

Figure 2 (a) Horizontal shift; (b) Elastoplastic curve with shift and (c) Vertical shift

In the fourth step, the post-yield portion of the backbone curve is generated by interpolating the five different curves obtained from the first two steps. For this purpose, the input relative velocity is mapped to the output consisting of five shape functions ($w_1, w_2, \ldots\ w_5$) with the help of a fuzzy logic toolbox using triangular membership functions both for the input and output variables. The shape function value ranges between 0 and 1 depending on the value of the input variable. Interpolation is done by taking the weighted sum of the output force values to get the damper force as

$$F = w_1 f_1 + w_2 f_2 + w_3 f_3 + w_4 f_4 + w_5 f_5; \quad \text{where} \quad \sum w_i = 1, \qquad i = 1, 2, ...5. \tag{2.1}$$

The parent backbone curve, with post-yield slope, generated by interpolation is shown in the figure 3a. Thus, corresponding to a particular voltage, the MR damper traces out a force-velocity curve as shown in the figure 3b. Different such curves are generated corresponding to different desired constant voltage values by scaling. For the entire procedure of generation of backbone, model of the MR damper has been developed with the help of SIMULINK of MATLAB.

3. DEVELOPMENT OF THE FUZZY LOGIC CONTROL ALGORITHM

Consider a MDOF structure with n degrees of freedom, subjected to an earthquake ground acceleration $\ddot{x}_g(t)$. Assuming that the control forces $\boldsymbol{f}$ are adequate to keep the entire structure within the elastic range, the equation of motion

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \Gamma \boldsymbol{f} - \boldsymbol{M}\Lambda\ddot{x}_g \tag{3.1}$$

where $\boldsymbol{x}$ is vector of relative displacement, $\boldsymbol{f}$ is a vector of control force corresponding to n_c number of dampers and $\ddot{x}_g$ is ground acceleration. $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are mass, damping and stiffness matrices of appropriate size. Γ represents an $n \times n_c$ matrix denoting the control force actuation on the structure due to the location of dampers and Λ is a vector of unity. Eqn 3.1 can be transformed into the state space form as,

$$\dot{\boldsymbol{z}} = \boldsymbol{A}\boldsymbol{z} + \boldsymbol{B}\boldsymbol{f} + \boldsymbol{E}\,\ddot{x}_g; \quad \boldsymbol{y} = \boldsymbol{C}\boldsymbol{z} + \boldsymbol{D}\boldsymbol{f} + \nu \tag{3.2}$$

where $\boldsymbol{A}$ is a $2n\times 2n$ system matrix, $\boldsymbol{B}$ is a $2n\times n_c$ control matrix, $\boldsymbol{E}$ is a $2n\times 1$ disturbance matrix, $\boldsymbol{C}$ is a $p\times 2n$ measurement matrix and $\boldsymbol{D}$ is a $p\times n_c$ matrix. $\boldsymbol{z}$ is a $2n\times 1$ state vector, $\boldsymbol{y}$ is a $p\times 1$ vector of measured outputs, $\boldsymbol{\nu}$ is a $p\times 1$ measurement noise vector.

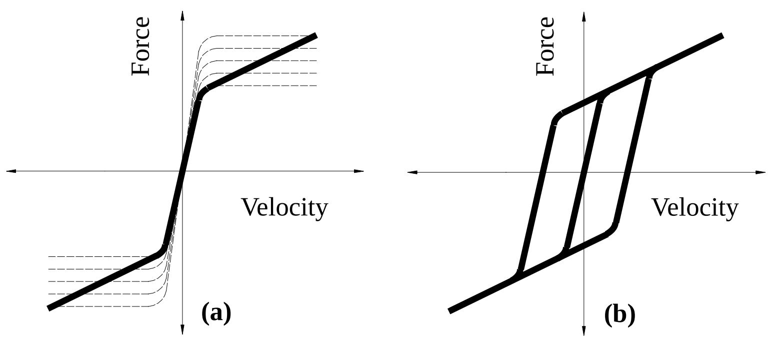

Figure 3 (a) Backbone curve; (b) Idealized hysteresis curve

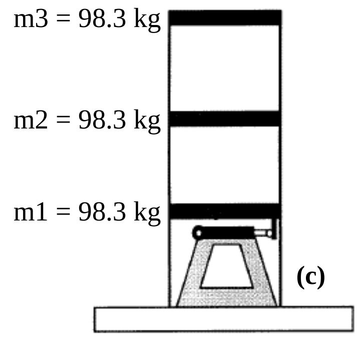

Figure 4 Example building frame

The fuzzy Logic Control algorithm has been implemented in the SIMULINK model of MATLAB using an integration time-step of 0.001 seconds. The structural model is incorporated with the help of the state-space block of SIMULINK. For the present study, $\boldsymbol{D}$ and $\boldsymbol{\nu}$ are set to zero in the SIMULINK block. From the floor displacements and floor velocities, relative displacements and relative velocities between two floors are computed and are provided as input to the MR damper. Based on the input velocity, the damper adopts any of the force-velocity hysteretic curves corresponding to the desired (n) values of supplied voltages. For developing the control algorithm, the entire range of input relative floor velocity is divided equally into n parts. When the lowest voltage range is chosen, the input velocity is in the lowest range and the damper produces an output control force corresponding to the force-velocity hysteretic curve of that voltage. The same correspondence between the velocity and voltage, and hence, the control force is maintained when the input velocity lies in the higher ranges and other intermediate ranges. Thus, the control algorithm can be said to maintain a high-high, low-low relationship between the input and output.

4. NUMERICAL SOLUTION AND DISCUSSIONS

The method of fuzzy semiactive control using MR dampers as described above is used to control the response of a three storey example problem taken from the existing literature (Dyke et. al., 1996). The required properties of the frame shown in the figure 4 for solving Eqn 3.2 are given below

$$\boldsymbol{K} = 10^5\begin{bmatrix} 12.0 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix}\frac{\mathrm{N}}{\mathrm{m}};\quad \boldsymbol{C} = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix}\frac{\mathrm{Ns}}{\mathrm{m}};\quad \begin{array}{l} \Gamma^T = \begin{bmatrix} -1 & 0 & 0 \end{bmatrix} \text{(1st storey damper only)} \\ \Gamma^T = \begin{bmatrix} 1 & -1 & 0 \end{bmatrix} \text{(2nd storey damper only)} \\ \Gamma^T = \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} \text{(3rd storey damper only)} \end{array}$$

The control of response is achieved by using dampers of different capacities and characteristics. The efficiency of the method in controlling the response is investigated under a number of parametric variations. The parameters include capacity of the damper, its characteristics (backbone curve), its location on the structure and fuzzy rule base.

In the absence of actual experimental curves of MR dampers of different capacities, depicting their force-displacement and force-velocity characteristics under cyclic loading at different voltages, damper characteristics of a 3000 N capacity damper available in the literature is scaled to obtain different variations as desired. This has been done for demonstration purpose only and to bring out the effect of different parameters on the efficiency of the control scheme.

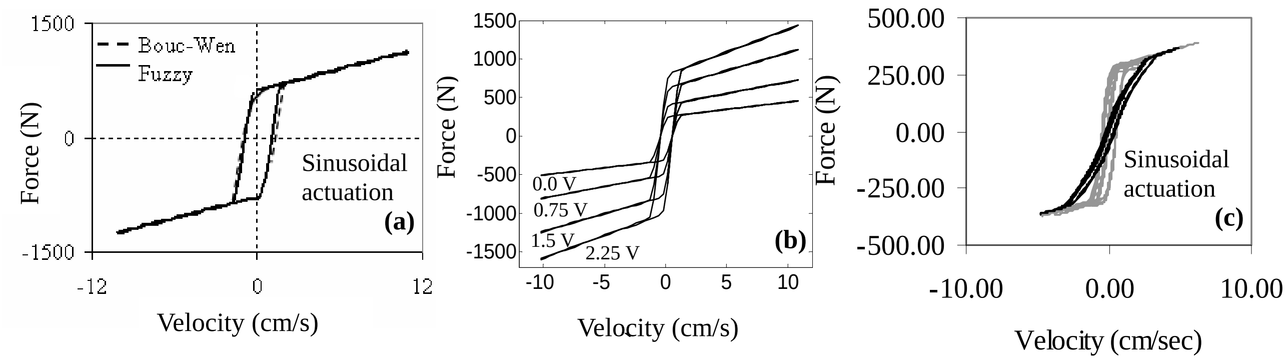

Figure 5 Force vs velocity curves for MR damper (a) Hysteretic curve (b) Backbone curves for different voltages and (c) Hysteretic responses for softer damper

The comparison between the hysteretic curve generated by Bouc-Wen model and fuzzification for a voltage of 1.5 volts, as described before, is shown in the figure 5a for sinusoidal actuation of the damper. Using the prescribed backbone curve obtained from the model, different backbone curves are constructed (by scaling) for different capacities of the damper at different voltages. The backbone curves for different voltages corresponding to 3000 N capacity damper is shown in the figure 5b. Further, the characteristics of the backbone curve of the 3000 N capacity damper is modified to obtain a softer MR damper, having the same capacity but larger yield velocity. This has been done to demonstrate the effect of the yield velocity or a softer system on the efficiency of the control scheme. The force-velocity curves for the controlled response obtained for these softer dampers for sinusoidal actuation are shown in the figure 5c.

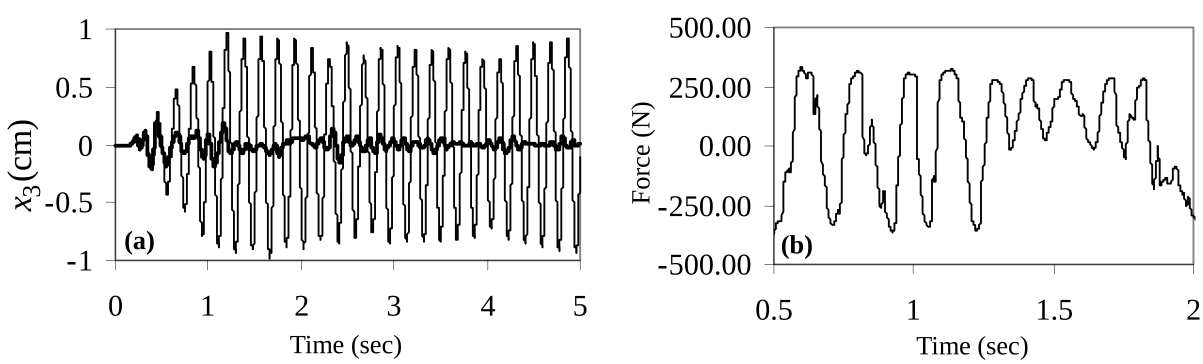

Figure 6 Time histories of (a) Controlled and uncontrolled responses and (b) Control force.

The example building frame is controlled for scaled El Centro earthquake excitation with a 3000 N MR damper placed in the first storey. The same problem with the same scaled El Centro excitation was solved by Dyke et. al. (1996) using clipped-optimal control. In the figure 6a, the controlled displacement response obtained by the fuzzy control algorithm is shown. The corresponding time histories of damping force and the applied voltage are shown in figures 6b and 7a. It is seen from the figure that the control of response of the third storey is obtained as 78.85 %. Control of the same response reported by (Dyke et. al., 1996) by clipped optimal control is 77.96 %, nearly the same as that obtained here. However, far less control force is required when fuzzy control is used. In clipped-optimal control, maximum control force is 941 N (Dyke et. al., 1996), whereas fuzzy control requires 391.13 N. Percentage control of displacement, interstorey drift and absolute acceleration for the three stories is shown in Table 1.

The maximum voltage required in fuzzy control is 0.63 volts (figure 7a), much less than that required in clipped-optimal control (2.25 V) reported by Dyke et. al. (1996). The reason for less control force requirement and hence, less voltage in the case of fuzzy control is due to the difference in control law being applied to the two control schemes. In the latter, on-off control law is adopted, i.e., voltage is either kept at maximum or zero. Accordingly, the control forces in the MR damper are generated. In the fuzzy control, a continuous variation of voltage with time is generated with the help of fuzzy controller. The control force, and hence, the voltage at any instance of time, depend directly on the velocity response. The force-velocity plot for the controlled response under El Centro earthquake for the fuzzy control is shown in the figure 7b. Comparing figures 5a and 7b, it is seen that the fuzzy control algorithm provides nearly the same shape of the force-velocity curve as that given in the input backbone curve.

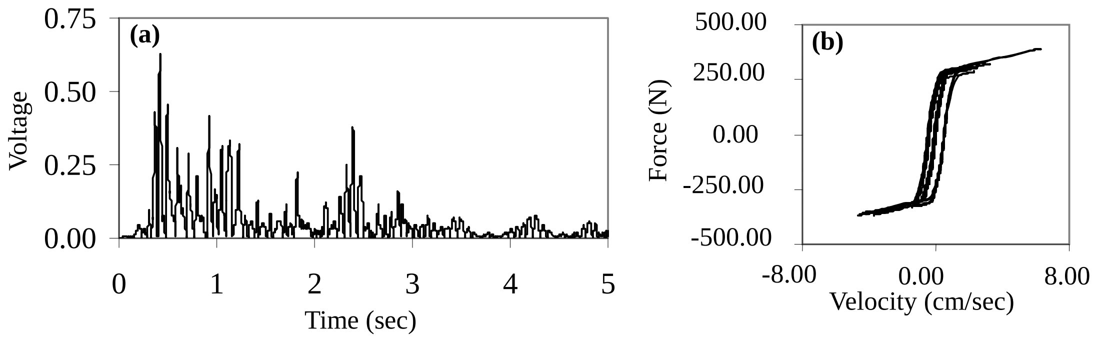

Figure 7 (a) Time history of control force and (b) Force vs. velocity plot of the MR damper.

4.1 Effect of Position of the MR damper

The response of the frame is controlled by MR damper placed at three different positions, namely, first storey, second storey and third storey. Maximum percentage control for different response quantities for each case are compared in the figure 8a. It is seen from the figure that maximum percentage control of the response quantities significantly vary with the position of the damper in the structure. Maximum reduction in response is obtained when the damper is placed at the first storey and the minimum reduction is obtained when it is placed in the third storey (Table 1). The order of difference between the two cases is large; for example, maximum percentage control in the top storey is about 79% when the damper is placed in the first storey, whereas only 29% control in the same response is achieved when the damper is placed in the third storey. However, the maximum control force requirement in all the cases remains nearly the same. Further, it is observed that the maximum percentage control of the relative displacement remains more or less the same for all storeys for each position of the damper, but the maximum percentage control of other response quantities are different for different storeys for each position of the damper placed in the frame.

4.2 Effect of the Capacity of Dampers

The capacity of the damper is expected to have a significant influence on the control of the response and the maximum control force required. The reason for this is that the nature of the backbone curve changes for different capacity of the damper without the change in the yield velocity. In order to investigate this effect, five different capacities of the damper are used to control the response, namely (1) 450 N; (2) 1500 N; (3) 2250 N; (4) 3000 N; and (5) 4800 N. The maximum percentage control and the corresponding maximum control force for the different capacity dampers mentioned above are shown in the figure 8b for the first storey. It is seen from the figure that for lower capacity damper, the maximum percentage reduction in response is less as it would be expected. However, beyond a certain capacity of the damper namely 500 N, there is no significant change in the percentage control of response. For the first storey response, it is observed that if damper of higher capacity than 500 N is used, the maximum control force required is marginally increased without any significant increase in the percentage control of the response. Thus, it appears that there is a saturation level in terms of the capacity of the damper and therefore, this saturation level needs to be known for optimum control of response.

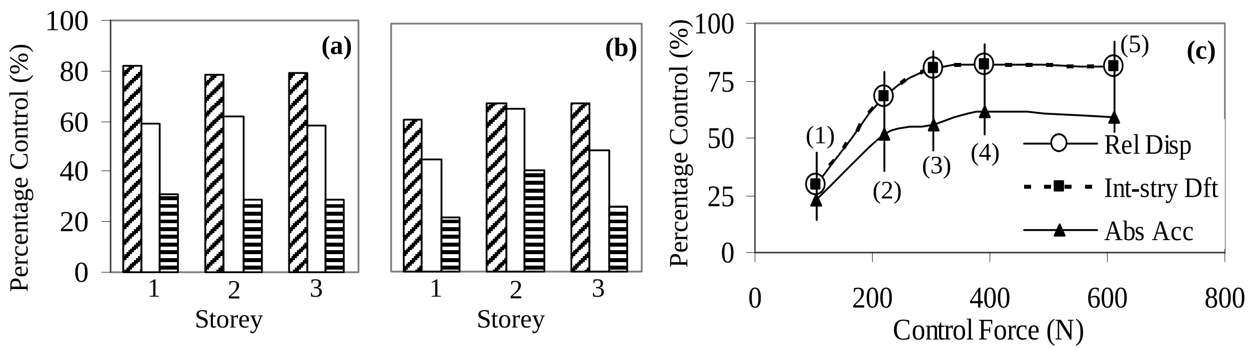

Figure 8 Variation of percentage control with (a) Storey relative displacement; (b) Storey absolute acceleration and (c) Control force (Damper location: 1st Storey 2nd Storey 3rd Storey)

4.3 Effect of Yield Velocity of the Damper

In previous discussions, the different backbone curves of the dampers have the same yield velocity. In order to study the effect of the yield velocity of the damper, the yield velocities of the backbone curve are changed, keeping the capacity of the damper same. Two cases are considered. In one of the cases, the yield velocity is larger, thereby making the damper relatively softer than the other. The maximum percentage control of responses and the corresponding maximum control forces are shown in Table 1. It is seen from the table that there are no significant differences between the maximum percentage control of responses obtained from the two cases. However, the softer damper requires little less control force.

Table 1. Maximum percentage control of different responses and the required maximum control force

Damper Position	Responses Measured at	Damper (Figure 5b)				Softer Damper (Figure 5c)			
		Percentage Control (%)			Maximum Control Force (N)	Percentage Control (%)			Maximum Control Force (N)
		x^{+}	x_d^{++}	$\ddot{x}_a^{\#}$		x	x_d	$\ddot{x}_a$	
First Storey	First Storey	81.76	81.76	61.39	391.13	80.82	80.82	57.39	366.63
	Second Storey	78.77	69.32	68.22		79.61	70.02	74.91	
	Third Storey	78.85	66.85	68.24		77.78	65.56	64.87	

Note: (+) Relative Displacement; (++) Interstorey Drift; (#) Absolute Acceleration.

5. CONCLUSION

The semiactive fuzzy control of responses of a three-storey model building frame using MR damper is presented. The method does not require Bouc-Wen model to be incorporated in the control algorithm. Instead, the idealized (smooth) force-velocity curve of the MR damper obtained from the experimental test can be directly used and fuzzified to develop the control algorithm using simulink and fuzzy toolbox of MATLAB. The implementation of the control algorithm requires continuous change of voltage, sampled at certain intervals, to be applied to the MR damper in a closed loop control scheme. The efficiency of the proposed control scheme is evaluated by considering an example problem taken from the literature. A parametric study is also conducted to study the effect of the important parameters on the control of response of the structure. The results of the study lead to the following conclusion:

1) The proposed control scheme provides nearly the same maximum percentage reduction of responses as that obtained by clipped-optimal control with a much less control force.
2) The displacement and drift control are better than the absolute acceleration control. Significant control of response can be achieved with small control force, and hence, with small voltage (of the order of 0.75 volt); thus, the control scheme is found to be highly efficient.
3) Position of the damper has significant effect on the control of response. The position of the damper in the lowest storey provides the maximum control of response for all storeys. However, the control force requirement does not change significantly with the change in position of the damper.
4) There is a saturation level for the capacity of the damper used for optimum control; beyond a certain capacity of the damper, there is no significant gain in the control of response with increase in control force.
5) For the same capacity of the damper and the same control of response, the maximum control force is found to be little less for a softer damper.

REFERENCES

Ahlawat, A. S., and Ramaswamy, A. (2002a). "Multi-objective optimal design of FLC driven hybrid mass damper for seismically excited structures." *Earthquake Engrg. and Struct. Dyn.*, **31**, 1459-1479.

Ahlawat, A. S., and Ramaswamy, A. (2002b). "Multiobjective optimal FLC driven hybrid mass damper for torsionally coupled, seismically excited structures." *Earthquake Engrg. and Struct. Dyn.*, **31**, 2121-2139.

Al-Dawod, M., Samali, B., Kwok, K., and Naghdy, F. (2003). "Fuzzy Controller for Seismically Excited Nonlinear Buildings." *J. Engrg. Mech.*, ASCE, **130:4**, 407-415.

Battaini, M., Casiati, F., and Faravelli, L. (1998). "Fuzzy control of structural vibration. An active mass system driven by a fuzzy controller." *Earthquake Engrg. and Struct. Dyn.*, **27**, 1267-1276.

Bhardwaj, M. K., and Datta, T. K. (2006) "Semiactive Fuzzy Control of the Seismic Response of Building Frames." *J. Struct. Engrg.*, ASCE, **132:5**, 791-799.

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

MATLAB. (2004). Version 7.0.0.19920 (R14). The Math Works, Inc., Natick, Mass.

Schurter, K. C., and Roschke, P. N. (2001). "Neuro-Fuzzy Control of Structures using Magnetorheological Dampers." *Proceedings of the American Control Conference*, Arlington, 1097-1102.

Spencer, B. F., Jr., Dyke, S. J., Sain, M. K., and Carlson, J. D. (1997). "Phenomenological Model for Magnetorheological Damper." *J. Engrg. Mech.*, ASCE, **123:3**, 230–238.

Symans, M. D., and Kelly, S. W. (1999). "Fuzzy Logic Control of Bridge Structures using Intelligent Semi-active Seismic Isolation Systems." *Earthquake Engrg. and Struct. Dyn.*, **28**, 37-60.

Wilson, C. M. D., and Abdullah, M. M. (2005). "Structural Vibration Reduction using Fuzzy Control of Magnetorheological Dampers." *ASCE Structures Congress*, New York.

Yang, G., Spencer, B. F., Jr., Jung, H., and Carlson, J. D. (2004). "Dynamic Modeling of Large-Scale Magnetorheological Damper Systems for Civil Engineering Applications." *J. Engrg. Mech.*, ASCE, **130:9**, 1107-1114.

Zhou, L., Chang, C. C., and Wang, L. X. (2003). "Adaptive Fuzzy Control for Nonlinear Building-Magnetorheological Damper System." *J. Struct. Engrg*, ASCE, **129:7**, 905-913.