Structural Engineering and Mechanics, Vol. 36, No. 2 (2010) 181-195 181
DOI: http://dx.doi.org/10.12989/sem.2010.36.2.181

Control of a building complex with Magneto-Rheological Dampers and Tuned Mass Damper

F. Amini* and R. Doroudi

Department of Civil Engineering, Science and Technology University, Tehran 16844, Iran

(Received November 9, 2009, Accepted June 4, 2010)

Abstract. Coupled building control is a viable method to protect tall buildings from seismic excitation. In this study, the semi-active control of a building complex is investigated for mitigating seismic responses. The building complex is formed of one main building and one podium structure connected through Magneto-Rheological (MR) Dampers and Tuned Mass Damper. The conventional semi-active control techniques require a primary controller as a reference to determine the desired control force, and modulate the input voltage of the MR damper by comparing the desired control force. The fuzzy logic directly determines the input voltage of an MR damper from the response of the MR damper. The control performance of the proposed fuzzy control technique for the MR damper is evaluated for the control problem of a seismically-excited building complex. In this paper, a building complex that include a 14-story main building and an 8-story podium structure is applied as a numerical example to demonstrate the effectiveness of semi-active control with Magneto-Rheological dampers and its comparison with the passive control with the Tuned Mass Damper and two uncoupled buildings and hybrid semi-active control including the Tuned Mass Damper and Magneto-Rheological dampers while they are subject to the earthquake excitation. The numerical results show that semi-active control and hybrid semi-active control can significantly mitigate the seismic responses of both buildings, such as displacement and shear force responses, and fuzzy control technique can effectively mitigate the seismic response of the building complex.

Keywords: semi-active control; MR damper; Tuned Mass Damper; building complex.

1. Introduction

Due to increasing population, shortage of supply in land, and centralized service requirements, tall buildings are much needed in modern cities. Some tall buildings are built as a tower (main) structure with a large podium structure to provide a large space for parking, shops, restaurants and hotel. The main structure and podium structure are usually built together on either a common box foundation or a common raft foundation. There are no settlement joints or anti- earthquake joints between the main structure and podium structure. In most cases, the lateral stiffness of the podium structure is more than that of main structure creating the whipping effect. The coupled building control uses dissimilar adjacent structures to impart forces upon one another in such a manner that critical responses are mitigated. This concept was initially introduced by Klein (1972) and following

*Corresponding author, Ph.D., E-mail: Famini@iust.ac.ir

him, Kunieda (1976) proposed the coupling multiple structures in Japan. Over the past three decades, the coupled building research has steadily gained momentum from proposed research concepts to actual implementation. A decade later Klein and Healy (1987) proposed a rudimentary semi-active approach, coupling two buildings with cables that could be released and tightened. Based on their study, it would be appropriate for buildings to be connected near the top, since it is a region where the vibratory modes will have non-zero shorter amplitudes. Numerous passive, active and semi-active control strategies have been considered for low- to high-rise buildings. Yamada *et al*. (1994) connected a pair of 2-story and 3-story building models at the second story with a negative stiffness active control device, and as a result they could significantly mitigate the displacements of these low-rise building models. Graham (1994) connected single-degree-of-freedom building models using both passive and active control strategies, and concluded that both control strategies have significant effect in the reduction of the building's responses. Seto (2000) has applied active strategy to control a flexible structure. Luco *et al.* (1998) joined two buildings with passive damper in the highest region of the structure, and obtained optimum damping value. Zhu *et al*. (2001) have also proposed semi active coupled building control. They considered coupling two single-degree-of freedom masses with a semi-active connector with positive results. Passive friction dampers linking a podium structure to a main building are used by Ng and Xu (2004), and they have been effective in mitigating seismic responses of the building complex. Ng and Xu (2007) have also performed the active control of semi-active building complex with the help of variable friction damper, and LQR method. Amini and Tahernia (2004) have conducted the semi-active control of coupled buildings using semi-active dampers, and pole assignment method. Christenson *et al.* (2006) applied the control force for both active and passive control systems and compared them for varying buildings and connector configurations.

The first application of coupled building control appeared in the Kajima Intelligent Building Complex in Tokyo, Japan. This building complex consists of 5-story and 9-story buildings, and is coupled with passive yielding elements at the 5th floor. Another application was Konoike Headquarters in Osaka, Japan that included one 12-story and three 9-story buildings with passive visco-elastic dampers and the more recent one is Harumi Triton Square buildings complex in Japan that included three high-rise buildings and the building were linked by two 35-ton active control actuators for protection from wind and seismic excitation. In this paper, semi-active control of a building complex is investigated using Magneto-Rheological (MR) Dampers and Tuned Mass Damper for mitigating seismic responses.

Four structural forms are studied in this paper: (1) Hybrid control system using TMD and MR damper; (2) Semi-active control system using MR damper; (3) Passive control system using TMD; (4) State of uncoupled buildings where podium structure is completely separated from main building. The podium structure and main building are subject to earthquake excitation and the seismic responses of both buildings such as displacement, and shear force for all four forms are compared.

2. Modeling of a building complex with Magneto-Rheological Dampers and Tuned Mass Damper

Fig. 1 illustrates the analytical model of a building complex which consists of a main building (building 1) and a podium structure (building 2) having m and n stories $(m > n)$ respectively and are connected by $P(n > P)$ MR damper, and one Tuned Mass Damper at different floors. Only one

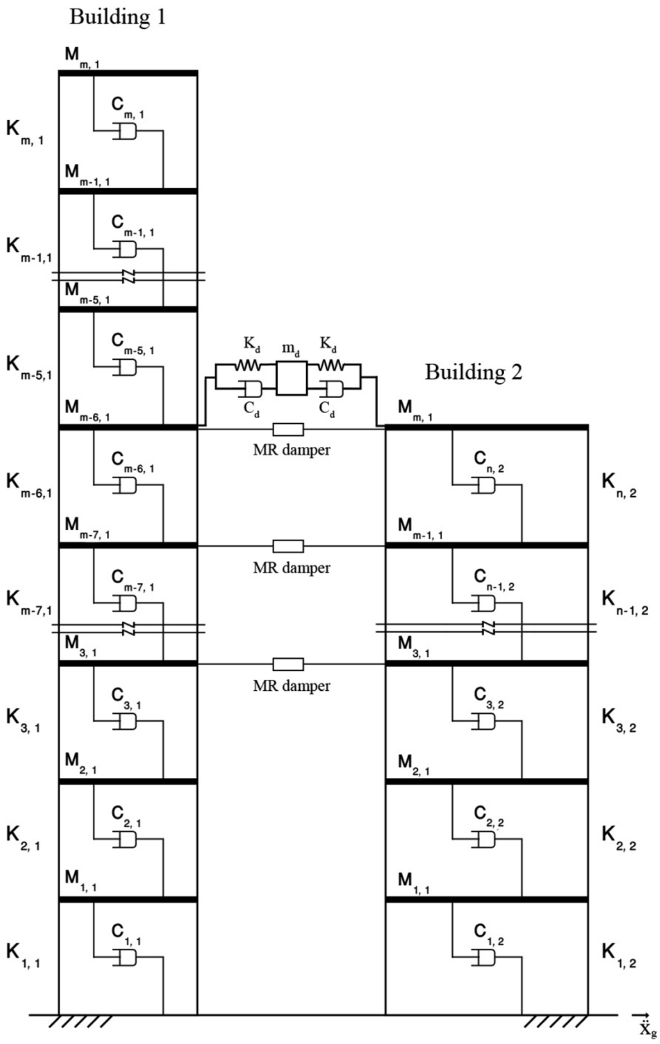

Fig. 1 Schematic diagram of a building complex with Magneto-Rheological Dampers and Tuned Mass Damper

lateral degree-of-freedom (DOF) is considered for each mass concentrated at each floor of the buildings under unidirectional horizontal earthquake excitation. This study does not take any soil-structure interaction into account.

In this study, modeling has been conducted through one of the four following ways.

2.1 Model 1

Two coupled structures are connected by some MR dampers (control system in semi-active state) The equations of motion for coupled structures are as follow

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -Mr\ddot{x}_g(t) + Hf(t) \tag{1}$$

where $x(t), \dot{x}(t), \ddot{x}(t)$ are the vectors of structure displacement, velocity, acceleration relative to ground respectively, and $\ddot{x}_g(t)$ is vector of ground acceleration, and for the building 1 with dimensions $m \times 1$, and building 2 with dimensions $n \times 1$ where m and n are freedom degrees of buildings 1 and 2 respectively. The $N \times N (N = m + n)$ dimension of mass, damping and stiffness matrices are respectively represented by

$$M = \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} C = \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \quad K = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix} \tag{2}$$

where M_k, C_k and K_k are the matrices of mass, damping and stiffness for k-th building (k = 1, 2) respectively.

r is vector loading for ground acceleration $\ddot{x}_g(t)$ and H is load effect for the coupling link control force $f(t)$, are in the form of

$$H = \begin{bmatrix} H_1 \\ -H_2 \end{bmatrix} \qquad r = [1 \ 1 \ \dots \ 1]^T \tag{3}$$

in which dimension of the unit vector r is $N \times 1$, the dimensions of matrices H_1 and H_2 are $m \times p$ and $n \times p$ respectively, and the entries of the matrices will be 1 if the control force $f(t)$ is exerted by control device in the relevant floors, and they will be zero otherwise.

2.2 Model 2

Coupled structures are connected by some MR dampers, and one Tuned Mass Damper (Hybrid control system in semi-active and passive state).

The equations of motion for structures are as follow

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -Mr\ddot{x}_g(t) + Hf(t) \tag{4}$$

The dimension of mass, damping and stiffness matrices are shown as $N \times N (N = m + n + 1)$ respectively, and the dimensions of matrices H_1 and H_2 and vector r are $(m+1) \times p$ and $(n+1) \times p$, $N \times 1$ respectively.

2.3 Model 3

Coupled structures are connected through one Tuned Mass Damper (control system in passive state).

The equation of motion for coupled structure is

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -Mr\ddot{x}_g(t) \tag{5}$$

The dimension of mass, damping and stiffness matrices are represented as $N \times N (N = m + n + 1)$ respectively, and the dimension of vector r is $N \times 1$.

2.4 Model 4

Uncoupled Systems

The uncoupled systems lack any link and they work independently. For such structures two sets of motion equations are provided while degree-of-freedom of structures 1 and 2 are m and n respectively.

$$M_1\ddot{x}_1(t)+C_1\dot{x}_1(t)+K_1x_1(t) = -M_1r_1\ddot{x}_g(t) \tag{6}$$

$$M_2\ddot{x}_2(t)+C_2\dot{x}_2(t)+K_2x_2(t) = -M_2r_2\ddot{x}_g(t) \tag{7}$$

where M_k, C_k and K_k are the matrices of mass, damping and stiffness for k-th building ($k = 1, 2$) respectively.

Also the unit vector r_k has dimension $m \times 1$ for building 1 and $n \times 1$ for building 2.

3. Determination of maximum displacement and shear force for each floor

3.1 State space

The state space representation provides a convenient and compact way to model and analyze systems with multiple inputs and outputs. The state space representation is a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations. The representation of any dynamic system in state space representation explains the extent of a multi degree of freedom system (MDFS) subjected to the external control force and the external disturbance force shown as below

$$\dot{q}(t) = Aq(t)+Bf(t)+C\ddot{x}_g(t) \tag{8}$$

Where A, B and C are constant matrices as follows

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ -M^{-1}H \end{bmatrix}, \quad C = \begin{bmatrix} 0 \\ r \end{bmatrix}$$

And $q(t) = [x(t), \dot{x}(t)]^T$, $\ddot{x}_g(t)$ and $f(t)$ are vectors of ground acceleration and control force respectively.

The resultant from solution Eq. (8) is

$$q(t) = e^{A(t-t_0)}x(t_0) + \int_{t_0}^{t} e^{A(t-\tau)}[Bf(\tau) + C\ddot{x}_g(\tau)]d\tau \tag{9}$$

The maximum displacement of each story is determined by numerical solving Eq. (9).

3.2 Determination of maximum shear force for each story

The total shear force at any story equals the product of the story stiffness and the drift of that story. The value of shear force at each story is determined as follows

$$V(t)_i = K_i\Delta(t)_i \tag{10}$$

$$\Delta(t)_i = x(t)_i - x(t)_{i-1} \tag{11}$$

Where $V(t)_i, K_i$ and $\Delta(t)_i$ are shear force, story stiffness and drift of story for i-th story respectively. Also $x(t)_i$ and $x(t)_{i-1}$ are displacement of i-th story and (i-1)-th story.

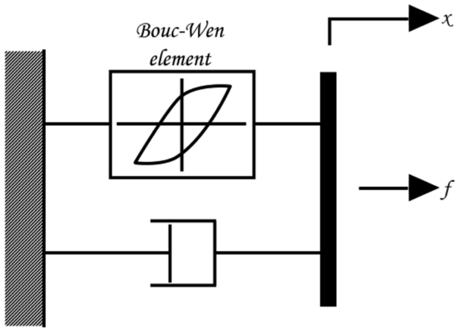

Fig. 2 Mechanical model of a shear mode type MR damper

4. Modeling of Magneto-Rheological damper and Tuned Mass Damper

4.1 Modeling of magneto-rheological damper

A Magneto-Rheological (MR) damper consists of a hydraulic cylinder containing a solution that, in the presence of a magnetic field, can be changed from a free flowing, linear viscous fluid to a semi-solid with controllable yield strength. This solution is called MR fluid and is composed of micron-sized magnetically polarizable particles dispersed in a carrier medium such as water, mineral or synthetic oil. MR fluid is normally a free flowing viscous fluid, but polarisation may be influenced by an external magnetic field. Hence, the control input variable of MR dampers is either current or voltage. A number of phenomenological MR damper models have been presented by many researchers (Spencer *et al.* 1997, Wen *et al.* 1976, Stanway *et al.* 1985). Most models are based on the so-called Bouc-Wen model. This approach models the MR damper behavior by combining linear spring elements, linear dash-pot elements, nonlinear damping elements, friction elements with the Bouc-Wen element that describes the hysteresis phenomenon of MR dampers, for example, the simple Bouc-Wen model proposed by Spencer Jr. *et al.* (1997). In this study, a simple mechanical model is used which includes a Bouc-Wen element in parallel with a viscous damper. This model is reported to accurately predict the behavior of a prototype shear-mode MR damper over a number of inputs in a set of experiments (Yi *et al.* 2001, Jansen *et al.* 2000, Dyke *et al.* 1999), and it is appropriate for modeling a full-scale MR damper (Ramallo *et al.* 2002). Likewise, Ok *et al.* (2007) applied this model MR damper for controlling the cable-stayed bridge. A schematic of such model is presented in Fig. 2. Eq. (8) describes the force generated by the device

$$f = C_0\dot{X} + \alpha Z \tag{12}$$

where C_0 is the damping coefficient, $\dot{X}$ is velocity of the device, α is the Bouc-Wen parameter associated with the yield stress of the MR fluid, and Z is an evolutionary variable that accounts for the history dependence of the response and satisfies the following equation

$$\dot{Z} = \gamma|\dot{X}|Z|\dot{Z}|^{n-1} - \beta\dot{X}|\dot{Z}|^{n} + A_m\dot{X} \tag{13}$$

The adjustment of hysteresis parameters β, γ and A_m, determines the linearity in the unloading region as well as the transition smoothness from the pre-yield to the post-yield regions. α and c_0 are

Table 1 Parameters for the MR damper mode

Parameter	Value	Parameter	Value	Parameter	Value
α_a	1.0872×10^5 (N/cm)	C_{0b}	44.0 (N sec/cm·V)	β	3 (cm^{-1})
α_b	4.9616×10^5 (N/(cm·V))	A_m	1.2	γ	3 (cm^{-1})
C_{0a}	4.40 (N sec/cm)	n	1	η	50 (s^{-1})

the model parameters depending on the voltage u as the current driver is represented below

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \tag{14}$$

$$c_0 = c_0(u) = c_{0a} + c_{0b} u \tag{15}$$

In addition, the current driver circuit of the MR damper brings dynamics into the system. These dynamics are usually considered to be a first order time lag in the response of the device to changes in the command input. These dynamics are explained with the first order filter on the control input provided by

$$\dot{u} = -\eta(u - v) \tag{16}$$

where v is command voltage applied to the control circuit, and η represents the time constant of the first-order filter.

In order to arrive at a dynamic model of an MR damper with a capacity of 1000 kN, the parameters of a shear-mode prototype MR damper were recognized from test results achieved in Washington University, and scaled up so as to have the maximum capacity of 1000 kN with the maximum command voltage V_{max} = 10 V (Yoshida *et al.* 2004). These parameters are listed in Table 1. In this study two buildings are connected by three MR dampers at stories 8, 7, and 3.

4.2 Modeling of Tuned Mass Damper

A Tuned Mass damper (TMD) is a device consisting of mass, spring and a damper that is attached to the structure in order to reduce dynamic response of structure that is subject to wind and seismic loads. The frequency of damper is tuned to a particular structural frequency so that when frequency is excited, the damper resonates due to the structural motion. The concept of TMD was introduced by Frahm (1909) to reduce the rolling motion of ship sand. Years later the theory of TMD was presented by Ormondroyd and DenHartog (1928). They used the fixed-points method to arrive at an accurate approximate solution of the optimal parameters such as natural frequency f_d and damping ratio ξ_d of a TMD that minimizes the displacement of the primary structure where the latter has vanishing structural damping. Much work has been done on damping systems based on TMD, and optimization of TMD parameters. (Warburton *et al.* 1980, Rana *et al.* 1998, Asami and Nishihara 2003). In addition, f and μ are the two most important parameters of TMD whereas f is (tuning ratio) the frequency of the TMD to that of the structure and μ is the TMD mass to the mass of the main structure.

Tsai and Lin (1993) suggest equations for the optimal tuning parameters f and ξ_d determined by curve fitting schemes. The equations are listed below for completeness.

$$f = ((\sqrt{1-.5\mu}/(1+\mu)) + \sqrt{1-2\xi^2} - 1) - (2.375 - 1.034\sqrt{\mu} - .426\mu)\xi\sqrt{\mu}$$
$$- (3.730 - 16.903\sqrt{\mu} + 20.496\mu)\xi^2\sqrt{\mu} \quad (17)$$

$$\xi_d = \sqrt{3\mu/(8(1+\mu)(1-\mu))} + (.151\xi - .171\xi^2) + (.163\xi + 4.980\xi^2)\mu \quad (18)$$

ξ is the damping ratio of main building (bulding 1).

Dynamic parameters of TMD including m_d, k_d, c_d, ω_d are as follow

$$m_d = \mu m_{e1} \quad (19)$$

$$\omega_d = f\omega \quad (20)$$

$$k_d = m_d \omega_d^2 \quad (21)$$

$$c_d = 2 m_d \xi_d \omega_d \quad (22)$$

m_d, ω_d, k_d and c_d are mass, frequency, stiffness, and damping of TMD respectively. ω and m_{e1} are the frequency of first mode of main building and the mass of main building in first mode of frequency respectively.

In this study two buildings are connected by one TMD at 8th story level.

4. Semi-active fuzzy controller

This part describes the semi-active fuzzy system for modulating the MR damper. Fuzzy Logic was introduced by Lotfi A. Zadeh (1965). Fuzzy control uses expert knowledge instead of differential equations to describe a system. It is a process that uses fuzzy information to determine desirable control actions and is used in complex systems in which there are no simple mathematical models, systems with inexact models, nonlinear systems, or systems with ambiguity or vagueness.

Furthermore, fuzzy control is also a very useful application in civil engineering which consists of formulating fuzzy rules to determine actions to be taken, based on the sensed structure's responses. Developed mainly in the fields of transportation and structures, the research was initially conducted in active control, and more recently the study has included semi-active control too.

In active structural vibration control, fuzzy theory has been used to determine the desired control force to be applied by the actuator. Moreover, in semi-active control, fuzzy logic has been applied to determine the desired voltage or current that a semi-damper can work with.

Fuzzy set theory has been usually employed to vary the amount of damping based on the relative velocity and displacement of the base of the structure.

The fuzzy system model employed in this study has been used by Ok *et al.* (2007) to control the cable-stayed bridges by MR dampers. Fuzzy control is based on if-then rules that connect the input information to desired output. It has three steps (Aldawod 2001): (1) Fuzzification, that the crisp value of the input information is converted to a fuzzy linguistic value using membership functions (2) Decision making that uses "if-then" rules to conclude the linguistic value of the output. (3) Defuzzification, where the fuzzy output is converted to a crisp value.

In this study, fuzzy control directly determines the input voltage to the MR damper from the response information of the MR damper. On the other hand, input information is the velocity of MR damper and output information is the voltage of MR damper. The diagram of the system is illustrated in Fig. 3. To quantify the input information, a fuzzy set is defined using a total of 11 fuzzy variables and selected as 11 identical triangles with 50% overlap: NVL, NL, NM, NS, NVS, Zero, PVS, PS, PM, PL, PVL, refer to the linguistic values, i.e., N (negative), P(positive), S(small), M(medium), L(large), V(very) and Zero. The range of input information is between maximum negative value velocity of MR damper and maximum positive value velocity of MR damper. Input membership functions are shown in Fig. 4. The fuzzy variable for output information always has a

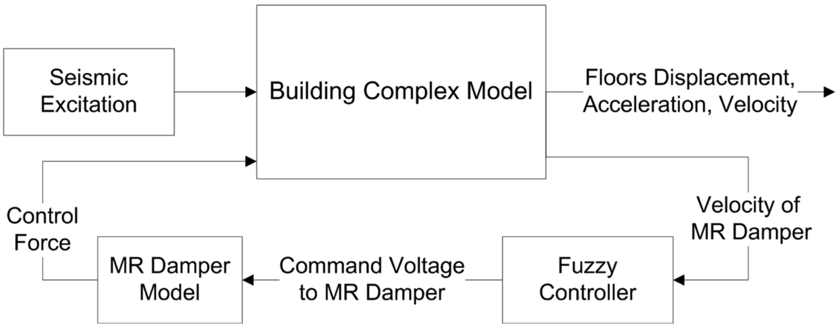

Fig. 3 The diagram of the system

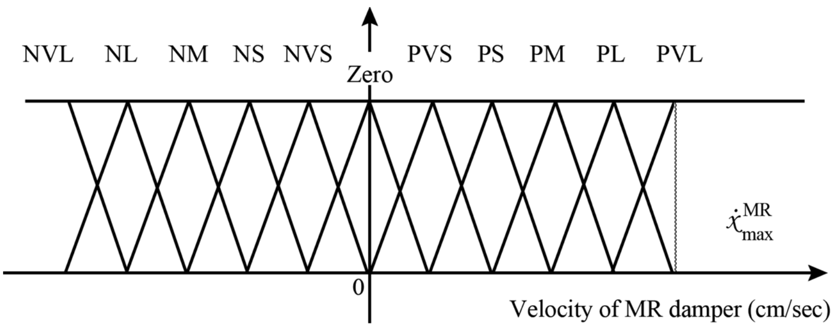

Fig. 4 Input membership functions

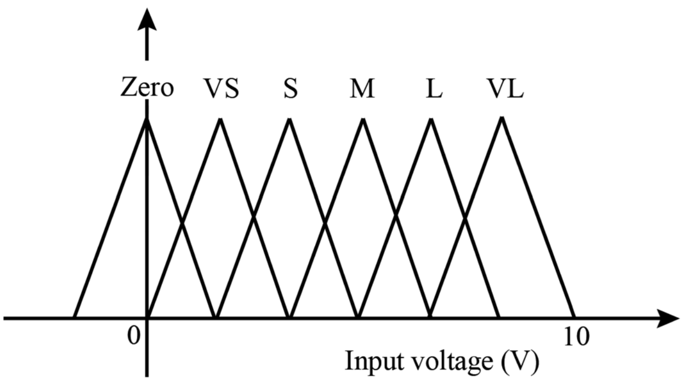

Fig. 5 Output membership functions

Table 2 Fuzzy rule tables

Velocity of MR damper	Input	NVL	NL	NM	NS	NVS	Zero	PVS	PS	PM	PL	PVL
Command voltage to MR damper	Output	VL	L	M	S	VS	Zero	VS	S	M	L	VL

positive value. Thus, the fuzzy set for output information includes 6 fuzzy variables and is selected as six identical triangles with 50% overlap: Zero, VS, S, M, L, and VL, refer to the linguistic values, i.e., S (small), M (medium), L (large), V (very) and Zero. The range of output information is between 0 and 10, namely the range of MR damper's voltage. The output membership functions are shown in Fig. 5.

The rule-based module is built through clear-cut description of a set of if-then statements. In this study, the fuzzy rules applied for the semi-active fuzzy controller are shown in Table 2. The connection between the input and output fuzzy variables is determined by this fuzzy rule table, where the output varies in parallel with the scale of each piece of given input information. For example:

If the velocity of MR damper is PVS, then the input voltage to MR damper is VS.

where the input information is velocity of the MR damper and the fuzzy input variable is PVS and the command voltage to MR damper is the output information, and the fuzzy output variable is VS.

5. Results analysis

The numerical simulations of the seismic responses of the building complex are performed within the MATLAB environment through a SIMULINK block. The fuzzy logic toolbox built on the MATLAB numeric computing environment is integrated into the SIMULINK block to simulate the fuzzy controller.

The basic building complex considered in the numerical study consists of 14 and 8-story buildings which are denoted as building 1 and building 2 respectively. Floor masses of individual buildings are identical and horizontal story stiffness of each building is uniform as well. The structural parameters of the buildings are summarized in Table 3 which also lists the first natural frequencies of individual buildings. Rayleigh damping is assumed for each building and 1% critical damping ratios in the first two modes of an individual building are considered.

Historical earthquake record is selected for comparative evaluation of control performance among control algorithms. The considered one far-field earthquakes is:

El Centro NS (1940, PGA = 3.417 m/s^2). Its corresponding time duration is 53.7 sec.

The ratio μ of the TMD mass to the mass of the structure: $\mu = .05$

Four structural models are investigated in this study: Semi-active control system using MR damper where two buildings are joined by Magneto-Rheological Dampers; Hybrid control system using TMD and MR damper where two buildings are connected by Magneto-Rheological Dampers and Tuned Mass Damper; Passive control system using TMD where two buildings are linked by Tuned Mass Damper; Uncoupled buildings state where building 2 is completely separated from the building 1. Displacement and shear force are investigated as seismic responses to compare each of

Table 3 Structural parameters and dynamic characteristics of individual buildings

Building	Floor mass $\times 10^5$ kg	Floor stiffness $\times 10^8$ N/m	Natural frequency *Hz*
1	5.5	9.25	.708
2	11	37.195	1.71

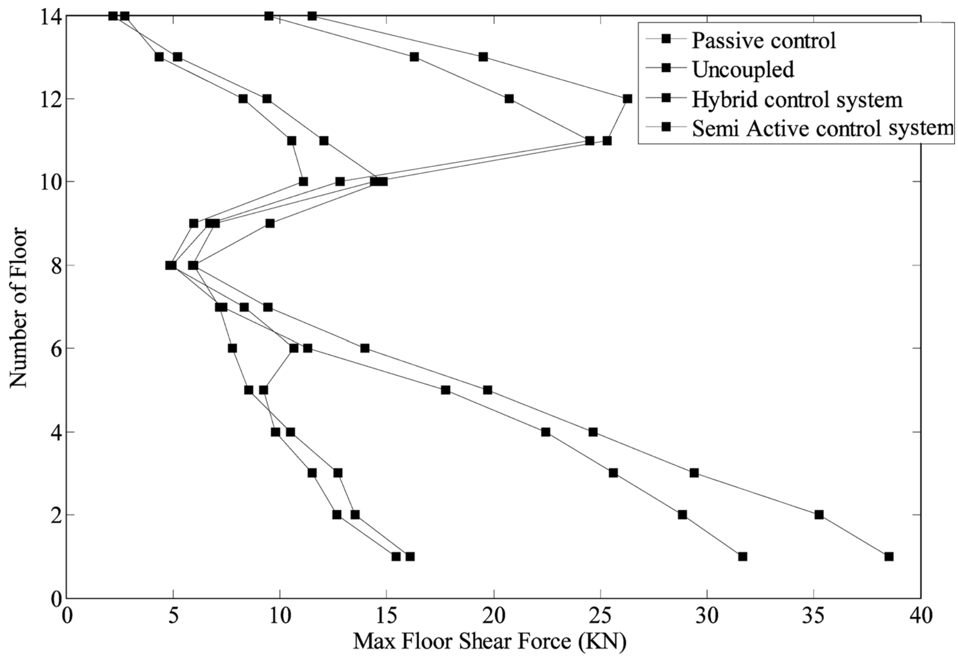

Fig. 6 Maximum shear force in different stories of building 1 in different coupling configurations

the four structural models. Maximum displacement and shear force are determined by solving equations motion numerically calculated by MATLAB software.

Fig. 6 illustrates the maximum shear force in different stories of building 1. As it is shown, Model 1 has the largest effect on decreasing shear force of stories, and hybrid control system has more effect in lowering shear force of stories compared with Model 4.

In Fig. 7, the maximum displacement of building 1 is shown. Model 1 has the largest effect on reduction the maximum displacement of stories and also the hybrid control system has significant effect on reducing the building's displacement.

The maximum displacement and maximum shear force of building 1 in hybrid control system, Model 1, and passive control system compared with Model 4 is decreased by 51.74, 55.32, and 14.34 percent respectively.

Fig. 8 displays the maximum shear force of different stories of building 2. As shown, the hybrid controller system has the largest effect on reducing shear force of stories. And Model 1 has larger effect on lowering shear force of stories compared with passive controller system. In Fig. 9 the maximum displacement of building 2 is illustrated and relevant results of maximum responses of

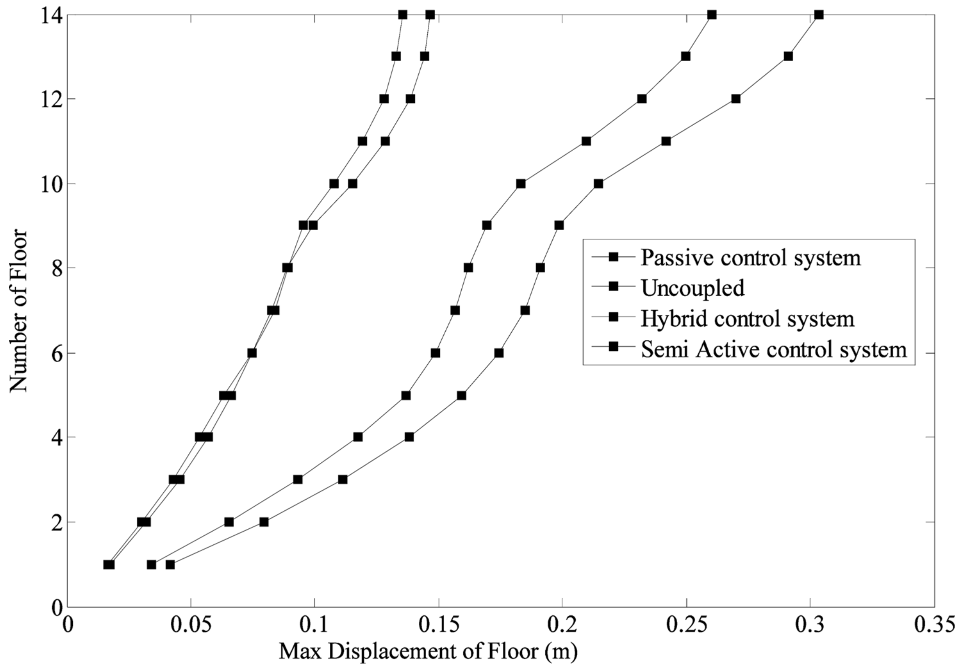

Fig. 7 Maximum displacement of stories of building 1 in different coupling configurations

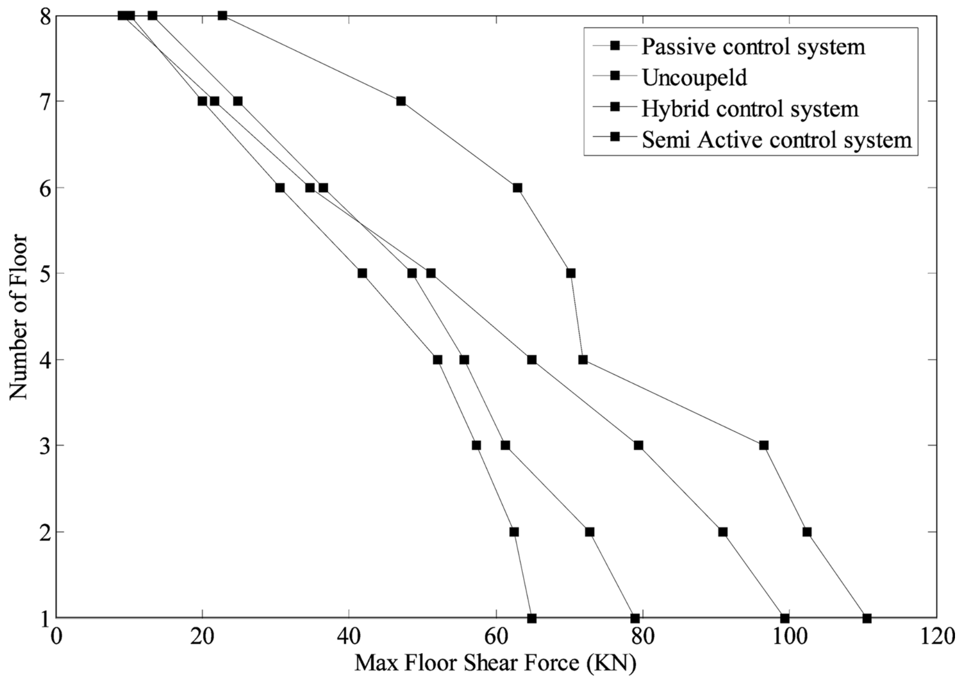

Fig. 8 Maximum shear force in different stories of building 2 in different coupling configurations

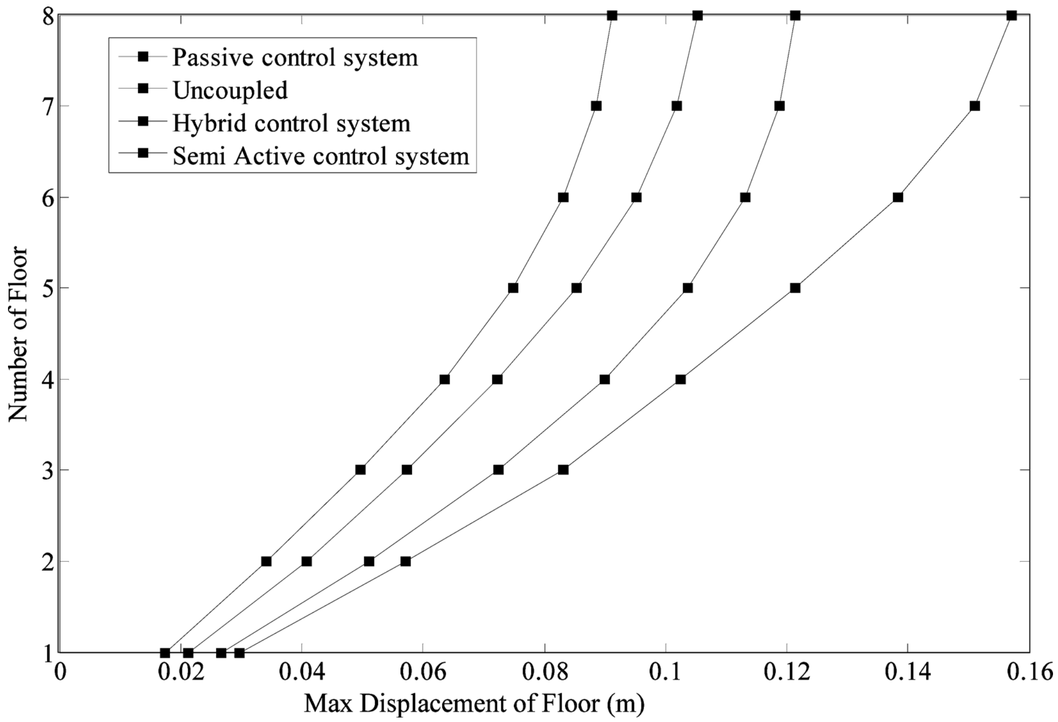

Fig. 9 Maximum displacement of stories of building 2 in different coupling configurations

Table 4 Maximum displacement and Base shear force of 14 and 8-story buildings

		Hybrid control system	Semi-active control system	Passive control system	Uncoupled
Max Displacement (m)	building 1	0.14655	0.13567	0.26014	0.30368
	building 2	0.09127	0.10536	0.12132	0.15705
Max Base Shear Force (kN)	building 1	141377	125494.75	240629.5	280904
	building 2	339486.20	391886.52	451249.74	584147.48

displacement in controller systems is similar to stories shear force.

The maximum base shear force and the maximum displacement of building 2 in hybrid control system, Model 1, and passive control system compared with Model 4 is decreased by 41.88, 32.91, and 22.75 percent respectively.

Larger effect of hybrid control system compared with Model 1 one maybe due to the fact that it is usually installed in the last story for higher efficiency of TMD. For building 2 TMD building in the 8th story (the top story) complex buildings are installed as connectors.

In Table 4 maximum displacement (top story displacement) and Base shear force of building 1and building 2 is shown.

As shown in Table 4, the hybrid control system and Model 1 have the highest effect on reducing two buildings' responses.

6. Conclusions

In this study, the semi-active control of a building complex with Magneto-Rheological Dampers and Tuned Mass Damper under earthquake excitation has been extensively studied through numerical simulation. Performance evaluation of three categories include: semi-active control strategies; hybrid semi-active control with the Tuned Mass Damper and Magneto-Rheological and; passive control with the Tuned Mass Damper. The fuzzy logic is employed to form a controller to exert appropriate voltage to MR damper to provide control force.

Using MR damper semi-active as connector of complex buildings in different stories leads to lowering buildings' responses when they are subject to earthquake excitation. Likewise, MR damper prevents main structure from the whipping effect.

Combining MR damper semi-active and Tuned Mass Damper as connector of two buildings, the buildings' responses are lowered significantly. Furthermore, combining these two dampers implies less required control force in one story.

Using Tuned Mass Damper (TMD) as a connector of two coupled buildings causes the following:

Lowering buildings' responses if the first natural frequency of the podium building is larger than natural frequency of the main building. TMD has larger effect on lowering two coupled buildings (podium building stiffness is higher than the main building)

The nearer TMD location to the top of building 1, the more significant effect in the reduction of the main building's responses would be.

Achieving the control force by fuzzy theory has quite desired results, and furthermore simplification of problems of building control is one of its advantages.

References

Aldawod, M., Samali, B., Naghdy, F. and Kwok, K.C.S. (2001), "Active control of along wind response of tall building using a fuzzy controller", *J. Eng. Struct.*, **23**, 1512-1522.

Amini, F. and Tahernia, I. (2004), "Semi active control of seismic response of tall building with podium structure using semi active dampers by pole assignment method", *Proceedings of Third European Conference on Structural Control*, Vienna Austria, July.

Asami, T. and Nishihara, O. (2003), "Closed-form exact solution to H-infinity optimization of dynamic vibration absorbers (Application to different transfer functions and damping systems)", *J. Vib. Acoust-Trans. ASME*, **125**(3), 398-405.

Christenson, R.E., Spencer, B.F., JR, Johnson, E.A. and Seto, K. (2006), "Coupled building control considering the effects of building/connector configuration", *J. Struct. Eng.,* **132**, 853-863.

Dyke, S.J., Yi, F. and Carlson, J.D. (1999), "Application of magneto-rheological dampers to seismically excited structures", *Proceedings of International Modal Analysis Conference*.

Frahm, H. (1909), *Device for Damped Vibrations of Bodies,* U. S. Patent No. 989958.

Graham, M.C. (1994), "Design strategies for coupling buildings", Master's Thesis at the Massachusetts Institute of Technology.

Jansen, L.M. and Dyke, S.J. (2000), "Semi active control strategies for MR dampers Comparative study", *J. Eng. Mech.*, **126**(8), 795-803.

Luco, J.E. and Barros, F.C.P.D. (1998), "Optimal damping between two adjacent elastic structures", *Earthq. Eng. Struct. D.*, **27**, 649-659.

Klein, R.E., Cusano, C. and Stukel, J. (1972), "Investigation of a method to stabilize wind induced oscillations in large structures", *Presented at 1972 ASME Winter Annual Meeting*, Paper No. 72-WA/AUT-H, New York.

Klein, R.E. and Healy, M.D. (1987), "Semi-active control of wind induced oscillations in structures", *Proceedings of 2nd International Conference on Structural Control, University of Waterloo*, Ontario, Canada, Martinus Nijhoff Publishers, Dordrecht, July.

Kunieda, M. (1976), "Earthquake prevent design and earthquake proof design for structures", *J. JSME*, **79**(689), 86-91.

Ng, C.L. and Xu, Y.L. (2004), "Seismic vibration control of medium-rise building and podium structure linked in parallel by passive friction dampers", *Proceedings of 10th Anniversary Symposium on Performance of Response Controlled Buildings*.

Ng, C.L. and Xu, Y.L. (2007), "Semi-active control of a building complex with variable friction dampers", *Int. J. Eng. Struct.*, **29**, 1209-1225.

Ok, S.Y., Kim, D.S., Park, K.S. and Koh, H.M. (2007), "Semi-active fuzzy control of cable-stayed bridges using magneto-rheological dampers", *J. Eng. Struct.*, **29**, 776-788.

Ormondroyd, J. and Den Hartog, J.P. (1928), "The theory of the dynamic vibration absorber", *Proceedings of the ASME*, APM-50-7.

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

Rana, R. and Soong, T.T. (1998), "Parametric study and simplified design of tuned mass dampers", *J. Eng. Struct.*, **20**, 193-204.

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

Seto, K. and Watanabe, T. (2000), "Vibration control of multiple buildings connected with active controlled bridges for improving reliability under the large seismic excitation", *Proceedings of 8th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability,* Notre Dame, Indiana, USA.

Spencer, Jr., B.F., Dyke, S.J., Sain, M.K. and Carlson, J.D. (1997), "Phenomenological model of magneto rheological damper", *J. Eng. Mech.*-ASCE, **123**(3), 230-238.

Tasi, K.C. and Lin, G.C. (1993), "Optimum tuned-mass damper for minimizing steady-state response of support-excited and damped system", *J. Earthq. Eng. Struct. D.*, **22**, 957-973.

Warburton, G.B. and Ayorinde, E.O. (1980), "Optimum absorber parameters for simple systems", *Int. J. Earthq. Eng. Struct.. D.*, **8**, 197-217.

Wen, Y.K. (1976), "Method of random vibration of hysteretic systems", *J. Eng. Mech. Div.-ASCE*, **102**(2), 249-263.

Yamada, Y., Ikawa, N., Yokoyama, H. and Tachibana, E. (1994), "Active control of structures using the joining member with negative stiffness", *Proceedings of First World Conference on Structural Control*, Pasadena, CA, 2, TP2-41-49, August.

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

Yoshida, O. and Dyke, S.J. (2004), "Seismic control of a nonlinear benchmark building using smart dampers", *Int. J. Eng. Mech.*, **130**(4), 386-392.

Zade, A.L. (1965), "Fuzzy Sets", *J. Inform. Control*, **8**, 338-353.

Zhu, H., Wen, Y. and Iemura, H.A. (2001), "Study on interaction control for seismic response of parallel structures", *J. Comput. Struct.*, **79**, 231-242.