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Semi-active structural fuzzy control with MR dampers subjected to near-fault ground motions having forward directivity and fling step

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Abstract. Semi-active control equipments are used to effectually enhance the seismic behavior of structures. Magneto-rheological (MR) dampers are semi-active devices that can be utilized to control the response of structures during seismic loads and have received voracious attention for response suppression. They supply the adaptability of active devices and stability and reliability of passive devices. This paper presents an optimal fuzzy logic control scheme for vibration mitigation of buildings using magneto-rheological dampers subjected to near-fault ground motions. Near-fault features including a directivity pulse in the fault-normal direction and a fling step in the fault-parallel direction are considered in the requisite ground motion records. The membership functions and fuzzy rules of fuzzy controller were optimized by genetic algorithm (GA). Numerical study is performed to analyze the influences of near-fault ground motions on a building that is equipped with MR dampers. Considering the uncontrolled system response as the base line, the proposed method is scrutinized by analogy with that of a conventional maximum dissipation energy (MED) controller to accentuate the effectiveness of the fuzzy logic algorithm. Results reveal that the fuzzy logic controllers can efficiently improve the structural responses and MR dampers are quite promising for reducing seismic responses during near-fault earthquakes.

Keywords: near-fault ground motions; semi-active control; magneto-rheological damper; fuzzy logic controller; genetic algorithm

1. Introduction

Catastrophic structural disasters due to serious seismic occurrences particularly near-fault ground motions, has made the response mitigation, a complicated and assiduous task in civil engineering profession. This attempt is of paramount importance for escalation of safety and ameliorating buildings performance. With remarkable superiority over other methods, control of structures has been one of the promising solutions for suppressing structural vibrations and dissipating vibration energy to preserve buildings and limit damage (Hurlebaus and Gaul 2006). For this purpose, numerous vibration control technologies have been developed. The three major classes of control systems encompass active, passive and semi-active vibration control systems. In passive control system, control forces are provided utilizing the motion of the structure and an

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extrinsic power is not required. On the other hand, a large power origin is required for function of actuators which provide control forces to the structure in an active system (Kerber *et al*. 2007). Semi-active control systems advantageously offer salient benefits of the passive and active systems and have acquired great attention in recent years. In fact, combination of passive and active approaches eventuates in a compromise solution since they provide the reliability of passive control systems along with the versatility of active control systems while much less power supply is needed (Gaul *et al*. 2008).

A variety of disparate semi-active devices such as variable orifice dampers, variable friction devices, adjustable tuned liquid dampers, variable stiffness dampers and controllable fluid dampers have been presented and successfully applied to diverse civil structures (Casciati *et al*. 2006). Among these devices, magneto-rheological (MR) damper has been recognized as one of the most efficient semi-active devices for seismic protection.

The stable state of the structures is well provided when MR dampers are utilized because these systems do not apply the control force directly to the structure. The resistance of the damper is adjusted in order to obtain close performance. Additionally, MR dampers are simply manufactured and blistering in response time. Moreover, enormous force capacity and robustness and permanently modulation of damping force have led to being introduced as ideal semi-active systems. MR dampers typically comprise of a hydraulic cylinder consisting of MR fluids with changing rheological properties in the presence of a magnetic field. Actually, yield strength of these fluids can be controlled during instantaneous variation from a free-flowing liquid to a semi-solid state (Dyke *et al*. 1996, Spencer *et al*. 1997).

Devising effective and viable control algorithms is one of the challenges in the application of the MR dampers to determine the command voltage of the MR damper. A variety of semi-active control algorithms have been extended for control of MR dampers and can be separated into two categories. The first category includes mathematical based methods such as the clipped-optimal algorithm (Dyke *et al*. 1996), optimal controllers (Yoshida *et al*. 2002), Lyapunov stability theory (McClamroch and Gavin 1995), skyhook controllers and continuous sliding mode controllers (Hiemenz *et al*. 2002), decentralized bang-bang, maximum energy dissipation (MED). Jansen and Dyke (2000) used bang–bang control for a building model with absolute acceleration and control force feedback. A similar approach to develop a decentralized bang–bang controller was used by McClamroch and Gavin (1995). In this scheme, the total energy is minimized in the structure. The maximum energy dissipation algorithm was developed by Jansen and Dyke (2000) due to alterations to decentralized bang–bang approach proposed by McClamroch and Gavin (1995). Although these model-based strategies have been successful in suppression of structural vibrations, their performance is strongly affected by the accuracy of the model selected. There have been a vast amount of research on the development and modeling of MR dampers experimentally and theoretically with different control algorithms (Hiemenz *et al*. 2002, Xu *et al*. 2005, Yoshida and Dyke 2005, Loh *et al*. 2007, Ying *et al*. 2009, Saban *et al*. 2011, Huang *et al*. 2012, Guan *et al*. 2012). The second category consists of methods which are independent of a system model. They depend on the actual measured responses of the structure. This category encompasses neural network and fuzzy control methods (Zhou *et al*. 2002, Choi *et al*. 2004, Zhou *et al*. 2012).

Fuzzy logic control (FLC) theory for vibration control of structural systems has attracted the attention of researchers due to intrinsic robustness, simplicity in dealing with the vagueness, nonlinearities and heuristic knowledge (Battaini *et al*. 1998, Casciati *et al*. 1996). Although fuzzy logic provides simple control algorithms, the tuning of the fuzzy controller is a procedure replete with considerable complexity (Casciati *et al*. 1996). Fuzzy control systems have been successfully applied to wide assortment of control problems. A semi-active fuzzy control strategy for seismic response mitigation using a magnetorheological (MR) damper has been proposed by Choi et al (2004). An adaptive fuzzy-logic control strategy for saving structures against drastic earthquakes and powerful winds using magnetorheological (MR) dampers was proposed by Zhou *et al.* (2003). Battaini et al (2004) investigated the wind response control of a tall building through a fuzzy controller. Wilson and Abdullah (2005) extended a fuzzy controller to modulate the damping properties of the MR damper. Having used fuzzifier and defuzzifier factors, they converted the inputs into fuzzy variables and then fuzzy variables into outputs, respectively. Ok *et al.* (2007) proposed a semi-active fuzzy controller that directly determines the input voltage of an MR damper from the response of the MR damper. Das *et al*. (2011) presented a fuzzy-logic control algorithm, based on the fuzzification of the MR damper characteristics. The results revealed that the proposed scheme led to almost the same amount of response reduction similar to that captured by the clipped-optimal control with much less control force and much less command voltage. Fuzzy membership functions play an important role in FLC design and selection of these functions is time-consuming part.

Some laudable efforts were achieved in the application of a genetic algorithm (GA) to the design of an FLC (Kima and Roschke 2006, Pourzeynali 2007). In this manner, the GA optimized FLC is used to modify the parameters of the fuzzy membership functions and finding appropriate fuzzy control rules. As an optimization technique, GAs has attracted the attention of researchers because of their simplicity, ease of functioning, limited requirements, and parallel and global perspective. Kim and Ghaboussi (2001) applied GA to design an optimal FLC controller for response reduction of a 76story tall building excited with severe wind. A design approach based on genetic algorithms (GA) to find the optimum voltage for MR dampers has been presented by Yan and Zhou (2006). Bitaraf *et al*. (2010) developed a fuzzy control strategy based on genetic optimization and concluded that the developed controllers can effectually control structural response.

In spite of ordinary ground motions, near-fault ground motions eventuate in large demands on structures. The damaging effects of near-field motions on structures have necessarily corroborated the need of contemporary design strategies (Hsu and Fu 2004, Qiang *et al*. 2009). A number of researches have investigated the effects of near-field ground motions on the dynamic response of structures (MacRae *et al*. 2001, Jangid and Kelly 2001). The ground motions possess long-duration pulses with high velocity that may cause serious damage to structures located in the near-field regions. Due to different characteristics of ground motions, an optimal controller should be developed to drive a semi-active damper for both far-field and near-field earthquakes. Forward rupture directivity effects which are commonly typified by a long-period velocity pulse present normal component of the near-field motions that cause strong dynamic motions. Fling step effects, the parallel component the near-fault ground motions, are characterized with the long-period nature of the static displacement and cause restricted inertial demands. Ghaffarzadeh *et al*. (2012) proposed a fuzzy controller strategy in application and investigated effects of near-fault ground motions on semi-active control of building frames using semi-active variable orifice dampers. Lu *et al*. (2012) investigated semi-active friction isolation systems and proposed a solution to excessive isolator displacement when subjected to near fault ground motions.

In this paper, fuzzy logic control technique, which is widely accepted as an effective tool for constructing input–output mapping relationships, is adopted for seismic protection subjected to near-fault ground motions with semi-active MR dampers to assess the effects of earthquake intensity on the seismic performance of structures in relation to the characteristics of the near-fault ground motions. Displacement and velocity responses are considered as the feedback to the fuzzy logic controller. Genetic algorithm technique was utilized to design an accurate fuzzy controller by optimization of the membership functions and fuzzy rules of fuzzy controller. In a numerical example, the developed FLC is applied to a ten storey building and time history analyses are conducted to evaluate the performance under characteristics of near-fault ground motions. The results obtained using the developed controller in this study are compared with those of Maximum energy dissipation control algorithm to demonstrate the efficiency of fuzzy logic controllers.

2. MR Dampers

An MR damper typically comprises of a piston rod, electromagnet, accumulator, bearing, seal, and damper cylinder filled with MR fluid. As noted earlier, by modulating the magnetic field, damping properties of MR damper and its stiffness can be adjusted. The first application of MR dampers to protect structures has been conducted by Spencer *et al*. (1996). Numerous methods have been proposed to depict the behavior of MR dampers (Spencer *et al*. 1997). Due to the nonlinear properties of these dampers their behavior is not simply modeled based on mathematical approaches. In this paper, to characterize the dynamic behavior of the MR damper, a modified Bouc–Wen model developed by Spencer and coworkers (Spencer *et al*. 1997) that demonstrate the nonlinear behavior of the MR damper in response to cyclic excitations is used as shown in Fig. 1. The equations of the force '*F*' in this model are given by

$$F = c_1\dot{y} + k_1(x - x_0) \tag{1}$$

$$\dot{y} = \frac{1}{(c_0 + c_1)}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \tag{2}$$

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

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \tag{4}$$

$$c_1 = c_1(u) = c_{1a} + c_{1b}u \tag{5}$$

$$c_0 = c_0(u) = c_{0a} + c_{0b}u \tag{6}$$

$$\dot{u} = -\eta(u - v) \tag{7}$$

where z and α, called volutionary variables, is related to the hysteretic behavior of the MR damper;$c_0$is the viscous damping parameter at high velocities;$c_1$is the viscous damping parameter for force roll-off at low velocities; α_a, α_b,c_{0a}, c_{0b}, c_{1a} and c_{1b} are parameters that portray the dependence of the MR damper force on the voltage;$k_0$controls the stiffness at large velocities;k_1 represents the accumulator stiffness;$x_0$is the incipient displacement of spring with stiffness k_1; α, β and A are modifiable shape parameters of the hysteresis loops, i.e., the linearity in the unloading and the transition between pre-yielding and post-yielding regions; v and u are input and output voltages of a first-order filter, respectively; and η is the time constant of the first-order filter.

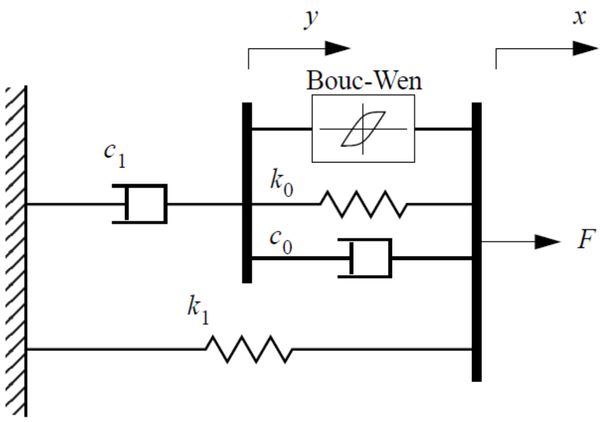

Fig. 1 Modified Bouc-Wen model of MR damper

3. Semi-active MED control algorithm

In the design of a feedback controller, the MED control algorithm applies Lyapunov's direct approach (McClamroch and Gavin 1995) to perform stability analysis. In the states of the system, Lyapunov function, V(z), must be a positive definite function, z, assuming that the origin is a stable equilibrium point. In this theory, negative semi-definite variation of the Lyapunov function,$\dot{V}$ (z), proves the stability of the origin. Thus, the main attempts must be done to make $\dot{V}$ as negative as feasible in this control method. Leitmann (1994) applied Lyapunov's direct approach for the design of a semi-active controller. In this approach, a Lyapunov function is stated in the following form

$$V(z) = \frac{1}{2}\|z\|_P^2 \tag{8}$$

where $\|z\|_P$ is the P-norm of the states

$$\|z\|_P = [z^T P z]^{1/2} \tag{9}$$

and P is a real, symmetric, positive definite matrix. In the case of a linear system, to ensure $\dot{V}$ is negative definite, the matrix P is determined using the Lyapunov equation

$$A^T P + PA = -Q_P \tag{10}$$

for a positive definite matrix Q_P. The equations of motion of a structure controlled with n MR dampers can be written as

$$M_S \ddot{X} + C_S \dot{X} + K_S X = \Lambda f - M_S \Gamma \ddot{x}_g \tag{11}$$

where M_s, K_s and C_s are mass, stiffness and damping matrices of appropriate size, X is a vector of the relative displacements of the floors of the structure, $\ddot{x}_g$ is a one dimensional ground acceleration, $f = [\ f_1\ ,\ f_2\ ,\ \dots\ f_n\ ]^T$ is the vector of measured control forces corresponding to n number of dampers, defined by Eqs. (1)-(7), generated by the n MR dampers, Γ is a column vector of ones, and Λ is a vector determined by the placement of the MR dampers in the structure. In this paper MR control device is installed in all stories. State-space form of the equation is as follows

$$\dot{z} = Az + Bf + E\ddot{x}_g \tag{12}$$

where z is the state vector, A is system matrix, B and E are force location matrices. The derivative of the Lyapunov function for a solution of Eq. (12) is

$$\dot{V} = -\frac{1}{2} z^T Q_P z + z^T PBf + z^T PE\ddot{x}_g \tag{13}$$

McClamroch and Gavin (1995) extended a similar approach to develop the decentralized bang-bang control scheme to utilize with an electrorheological damper. In this approach, the Lyapunov function was chosen to represent the total vibratory energy in the structure, as in

$$V = \frac{1}{2} X^T K_S X + \frac{1}{2}(\dot{X} + \Gamma \dot{x}_g)^T M_S (\dot{X} + \Gamma \dot{x}_g) \tag{14}$$

Using Eq. (11), the rate of change of the Lyapunov function is then

$$\dot{V} = -\frac{1}{2} x^T K\dot{x} + (\dot{x} + \Gamma \dot{x}_g)^T (-C\dot{x} - Kx + \Lambda f) \tag{15}$$

The MED control algorithm is developed as a variation of the decentralized bang-bang approach in such a way that the velocity of the ground in the kinetic energy term is eliminated from Lyapunov function

$$V = \frac{1}{2} x^T Kx + \frac{1}{2} x^T M\dot{x} \tag{16}$$

The term which can be directly affected by alterations in the control voltage is identified and the following control law is obtained:

$$v_i = V_{\max} H(-\dot{x}^T \Lambda_i f_{iMR}) \tag{17}$$

$H(.)$ is the Heaviside step function, f_{iMR} is the measured force produced by the ith MR damper, and Λ_i is ith column of the Λ matrix. When the measured force and relative velocity are dissipating energy, the resulting control law will command the maximum voltage. In the case of the minimum voltage energy is not being dissipated.

4. Fuzzy logic control

One of the promising methods to deal with complex nonlinear systems is fuzzy logic approach. Actually, fuzzy logic control is independent of the precise mathematical-based models to modify the dynamical response, including vibration control. Despite using elaborate mathematical terms, fuzzy logic uses simple verbose statements to determine relationships between inputs and outputs of a controller. FLC is a knowledge-based control strategy and enables the use of linguistic directions as rudiments for control. In other words, it provides an algorithm which can convert the linguistic control scheme according to an expert's knowledge into a control strategy. Due to its simplicity and effectiveness, several researchers have used fuzzy logic theory to develop controllers for semi-active devices (Zhou *et al*. 2003, Choi *et al*. 2004, Wilson and Abdullah 2005, Ok *et al*. 2007, Kim *et al*. 2010, Das and Datta 2011).

A general architecture of an FLC is given in Fig. 2. The design of a fuzzy controller consists of three fundamental sections. The first step is fuzzification. After defining input and output variables, input variables are transformed into linguistic variables in such a way that membership functions are dedicated to each input and output variable. In the next step, the defined inputs and outputs are related by a fuzzy rule base. The assessment of rules are operated in the form of IF-THEN rules to specify the output for a given input set based on fuzzy inference mechanism.

Various design parameters such as discretization of the universes of discourse, selection of membership functions and definition of rule base may have influence on the performance of an FLC. An effective rule base to perform at the desired level is more significant in FLC. As stated before, the nonlinear behavior of the MR damper which should be incorporated in the dynamic response of the structure including these dampers is significantly effective in design of fuzzy control rules to drive the MR damper voltage.

The last step is defuzzification in which the output variable that is a fuzzy quantity is converted into interpretable non-fuzzy discrete values according to fuzzy rule and membership functions. This step is accomplished using a defuzzification method. In fact, the defuzzification module combines a set of fuzzified outputs for all the rules in order to reach a single conclusion. This paper adopts the center-of-gravity (COG) method among the defuzzification methods. For the *j*th rule of the *i*th MR damper, the COG method computes the command voltage v_i output to be

$$v_i = \frac{\sum_{j=1}^{N_R} b_i^{(j)} \int \mu_i^{(j)}}{\sum_{j=1}^{N_R} \int \mu_i^{(j)}} \tag{18}$$

where N_R is the number of rules applied to the given input, $\mu_i^{(j)}$ is the output membership function corresponding to the fuzzy variable defined in the consequent statement of the *j*th rule for the *i*th input, $b_i^{(j)}$ is the center of the output membership function $\mu_i^{(j)}$, and $\int \mu_i^{(j)}$ represents the area of the output membership function $\mu_i^{(j)}$.

4.1 Genetic algorithm technique

Genetic Algorithms (GAs) are a kind of evolutionary search algorithms based on concepts inspired by natural genetics to find solutions to problems. The rudiment of the theory is to retain a population of chromosomes during process of finding singular solutions to the problem. These solutions evolve competitively and their variations are controlled over the process. In fact, A GA commences with a population of indiscriminately produced chromosomes, and makes progress toward better chromosomes by means of genetic operators. During consecutive generations, the adaptability of the chromosomes in the population is investigated to determine if they can be considered as solutions to proceed to the next stage. According to these assessments, a new generation, population of chromosomes, is produced by means of a selection mechanism and specific genetic operators such as crossover and mutation.

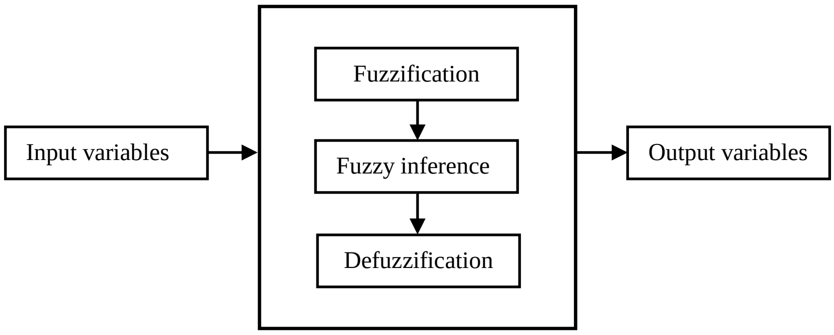

Fig. 2 The algorithm of fuzzy control inference.

A fitness function must be concocted for each problem. Consequently, to design the GA-FLC, the fuzzy membership functions and rule base in fuzzy system are modulated in such a way that the optimum solution is achieved. Scaling functions applied to the input and output variables of a fuzzy system normalize the universes of discourse in which the fuzzy membership functions are defined. These functions are parameterized through a single scaling factor or a lower and upper bound in the case of linear scaling. An individual represents the entire fuzzy rules as its chromosome encodes the parameterized membership functions associated with the linguistic terms.

5. Near-fault ground motions

The proximity of the fault rupture surface is defined as the regions in which the near-fault of an earthquake exists since ground motions near a ruptured fault can be remarkably different than those located further away from the seismic source. These earthquakes are affected by the rupture mechanism and slip direction relative to the site. Because of tectonic movements, near-fault ground motions are characterized with the permanent ground displacement at the site. They actually present both severe dynamic motions and strict static displacements.

Forward directivity effects are a special sort of ground motions that are particularly challenging to characterize for seismic performance assessment. These normal component of near-fault motions cause severe dynamic motions and are generally typified by a long-period velocity pulse. This effect occurs through propagation of fault rupture towards the site at a velocity almost similar to the velocity of the shear waves and the slip direction is parallel to the site. The period of a directivity pulse escalates with the magnitude of the earthquake (Somerville 2002, Somerville

2003) and they averagely present larger elastic spectral acceleration values at medium to long periods. Scrutiny of the velocity and displacement time histories of these motions characterized with forward directivity reveals the special feature of the pulse-like motion. These effects eventuate in large-amplitude pulses with early occurrence in the velocity time history (Somerville *et al*. 1997).Furthermore, the greater PGV of the near-fault motions in comparison with ordinary strong ground motions causes considerable influence on the loading of the structural system. Forward directivity effects can be resulted due to both strike-slip faults and dip-slip faults. In strike-slip faulting, the rupture present horizontal movement parallel to strike, and horizontal orientation of the slip direction is parallel to the strike of the fault. The general location and orientation of a dip-slip fault is around the surface exposure of the fault (Orozco and Ashford 2002). For both cases, forward directivity takes place nearly along with normal direction of the fault.

On the other hand, fling step effects are associated with consistent ground displacements due to surface fault rupture. Pulses related to this effect portray disparate properties. While lack of permanent ground displacement leads to two sided velocity pulses in forward directivity, fling step effects generally present a single sided velocity peak because of permanent ground displacement. Although this permanent displacement could be significant for structural design, it is less important compared to forward directivity effects. A distinct step in a displacement–time history of fling step is noticed which occurs along with the strike of the fault and in the dip exposure for strike-slip and dip-slip, respectively.

5.1 Selection of ground motions

In current study, nine near-fault ground motions are considered to specifically study the MR damper performance in relation to the characteristics of the near-fault ground motion. In order to consider ground motions with manifold characteristics, ordinary far-fault records and near-fault ground motions having forward directivity and fling step effects were used. Three near-fault ground motion records with forward directivity and three near-fault ground motions with fling step were selected. In contrast, another set of earthquake records at the same site was selected to illustrate far-field ground motion characteristics and was used for comparison purposes. Table 1 lists basic properties of the recorded motions. Figs.3 and 4 illustrate ground acceleration time histories for the selected fault-normal

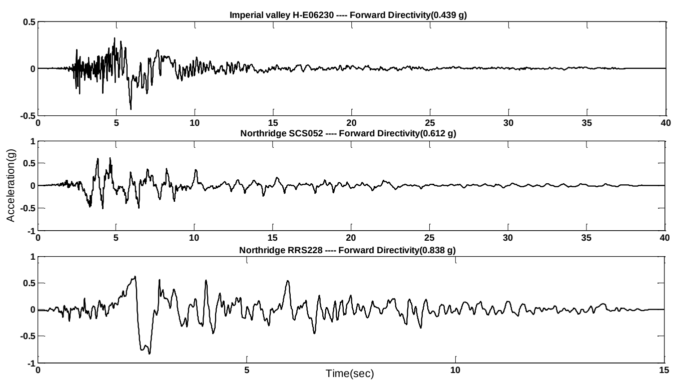

Fig. 3 Near fault ground motions with Forward directivity effects

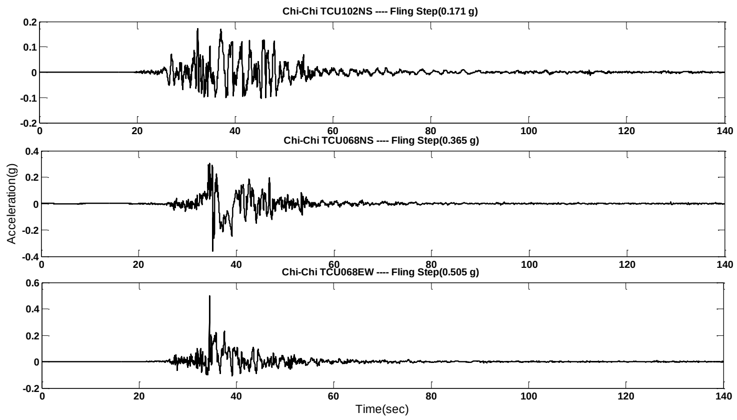

Fig. 4 Near fault ground motions with Fling step effects

Component of near-fault ground motions with forward directivity and ground acceleration time histories of fault-parallel component with fling step, respectively. It can be seen that these typical near-fault records have an obvious acceleration pulse that causes very large displacement. Ground acceleration time histories of ordinary far-fault ground motions without pulse are plotted in Fig. 5. As noted in the previous section, evaluation of the velocity time histories and displacement time histories of near-fault motions reveals their special features. Ground acceleration, velocity and displacement time history traces of the Imperial Valley record associated with forward directivity effect and Chi-Chi (TCU068NS) record having fling step effect are illustrated in Figs. 6 and 7, respectively. It is clearly seen the records contain large-amplitude pulses particularly by the velocity and displacement traces. The fling step effect exhibits obvious tectonic deformation at the end of the displacement time history. Such pulses do not appear in a typical far-fault ground motion as shown for the Northridge (WST 270) record in Fig. 8.

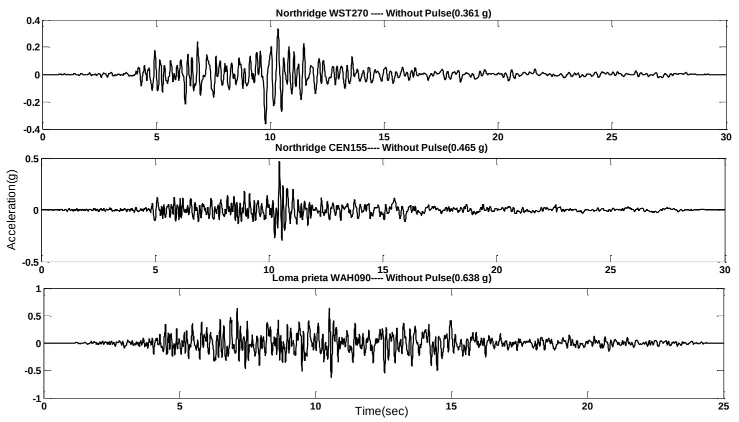

Fig. 5 Far- faultground motions without pulse.

Table 1 Properties of selected ground motions

Type	*Earthquake*	*Station*	$d(km)$	$PGA(g)$	$PGV(cm/s)$	$PGD(cm)$
Forward Directivity Pulses	Imperial Valley	H-E0230	0.6	0.439	109.8	44.74
	Northridge	SCS052	6.2	0.612	117.4	52.47
	Northridge	TCU102NS	1.19	0.838	71.5	107.2
Fling Step Pulses	Chi-Chi	TCU102NS	1.19	0.171	71.5	107.2
	Chi-Chi	TCU068NS	3.01	0.365	292.2	867.7
	Chi-Chi	TCU068EW	3.01	0.505	280.5	709.5
Without Pulse	Northridge	WST270	29.0	0.361	20.9	4.27
	Northridge	CEN155	30.9	0.465	19.3	3.48
	Loma Prieta	WAH090	16.9	0.638	38.0	5.85

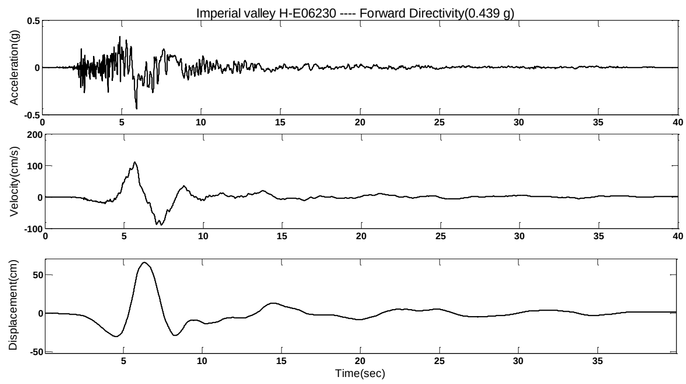

Fig. 6 Ground acceleration, velocity and displacement time histories of typical near-fault ground motions having forward directivity

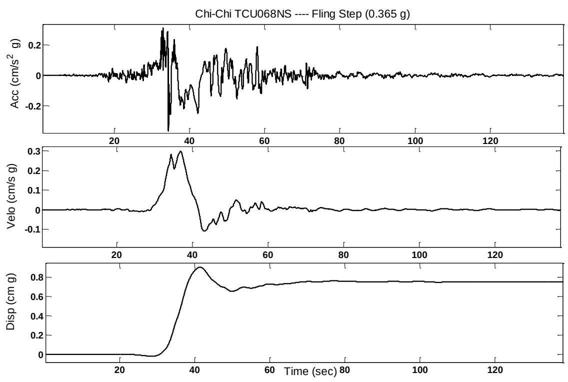

Fig. 7 Ground acceleration, velocity and displacement time histories of typical near-fault ground motions having fling step

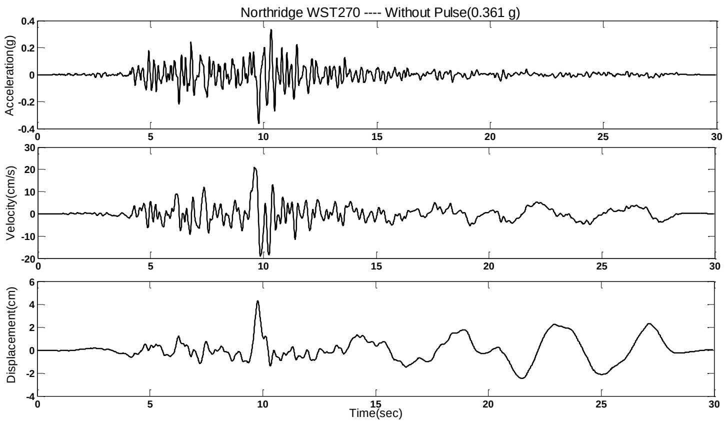

Fig. 8 Ground acceleration, velocity and displacement time histories of typical far-fault ground motions without pulse

Table 2 Mass and stiffness values of test structure

Story	Mass	Stiffness
Story 1-3	95000 kg	1780 x 10^5 N/m
Story 4-6	87500 kg	1655 x 10^5 N/m
Story 7-9	77500 kg	1402 x 10^5 N/m
Story 10	65000 kg	1112 x 10^5 N/m

6. Numerical example and results

To evaluate the performance of the proposed semi-active fuzzy control system using MR dampers and its effectiveness in relation to characteristics of near-fault ground motions, forward directivity and fling step, a ten-story shear building structure is studied. Fig. 9 illustrates the structural model for this study. Response control results of the proposed control system are compared to those of an uncontrolled system and MED control system.

6.1 Ten story shear building structure

A model of a ten story building in which all stories are equipped with a MR damper is considered. The MR damper parameters used in this simulation arec_{0a} = 21 Ns/cm, c_{0b} = 3.5 Ns/cm, k_0 = 46.9 Ns/cm, c_{1a} = 283 Ns/cm, c_{1b} = 2.95 Ns/cmV, k_1= 5.00 Ns/cm, α_a = 14.3 N/cm, α_b = 140 N/cmV, γ = 695 Ns/cm^{-2}, β = 363 cm^{-2}, A = 120, n = 1 and η = 19 s^{-1}. As stated in section 3, the equation of motion of the ten storey shear building model, taken for seismic mitigation analysis is given in the Eq. (11). Mass and stiffness parameters are listed in Table 2 and matrices are formed as follows

$$M=\begin{bmatrix} m_1 & 0 & \cdots & 0 \\ 0 & m_2 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & m_{10} \end{bmatrix} \quad , \quad K=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & \cdots & 0 \\ -k_2 & k_{2+3} & -k_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & & -k_{10} \end{bmatrix} \tag{19}$$

The Rayleigh damping matrix is constructed using 3% modal damping for the first and second modes.

6.2 Design of fuzzy logic controller

This section describes the semi-active fuzzy control strategy for determining the input voltage of the MR damper. The design of the semi-active fuzzy controller involves specification of the response quantities to be used as input to the fuzzy controller and the distribution and type of membership functions to be used for the selected input variables and the definition of the output variables. The developed fuzzy logic controller consists of two input variable (displacement and velocity of stories), defined by seven membership functions on the normalized universe of discourse [−1, 1] and one output variables (command voltage) having five membership functions defined on the normalized universe of discourse [0,1].The input membership functions must have a logical gamut of input values because the outermost member ship functions will hardly or necessarily be usable if the range is too large or too small and hence restrict the variability of the control system. The type of membership functions chosen for the input and output variables are triangular shaped, as illustrated in Fig. 10. The definitions of the fuzzy variables of input membership function are as follows: NL = Negative Large, NM = Negative Medium, NS = Negative Small, ZR =Zero, PS = Positive Small, PM = Positive Medium and PL = Positive Large. The definitions of the fuzzy variables of the output membership function are as follows: ZE =Zero, S = Small, M =Medium, L=Large and VL = Very Large. The voltage is the fuzzy output for the structural control system. Scaling factors were required to map the input and output variables to the domains of normalized universes of discourse. In this paper 20, 2 and 3.5 V were selected as constant scaling factors of displacement, velocity and voltage, respectively. The fuzzy rule base is determined to represent the relationship between input and output fuzzy variables, where the output alters in proportional to the scale of each input. The rule- base module is constructed by specifying a set of if -premise-then-consequent statements. For example, the multiple-input multiple-output IF–THEN rules of the fuzzy control are shown in the form

$$R^j: \quad If\ x_1\ is\ A_1^j\ and \cdots and\ x_p\ is\ A_p^j \quad Then\ \ y_1\ is\ B_1^j\ and \cdots and\ \ y_m\ is\ B_m^j \tag{20}$$

where R^j denotes the *j*-th rule of the fuzzy inference rule, $j=1,2,\ldots,q$, $x_1, x_2, \ldots, x_p$ are the inputs of the fuzzy controller, A_i^j is the linguistic value with respect to x_i of rule j , $y_1, y_2, \ldots, y_m$ are the outputs of the fuzzy controller and B_i^j is a fuzzy singleton function defined by experts. The fuzzy rule-base for all possible if -premise-then-consequent statements can be listed in a tabular form. Table 3 represents the fuzzy rule table used for the semi-active fuzzy controller in this study. The defuzzification module, the final component of the fuzzy logic, operates on the fuzzified outputs obtained from the inference mechanism. As noted earlier, we adopt the center of gravity defuzzification method in this study.

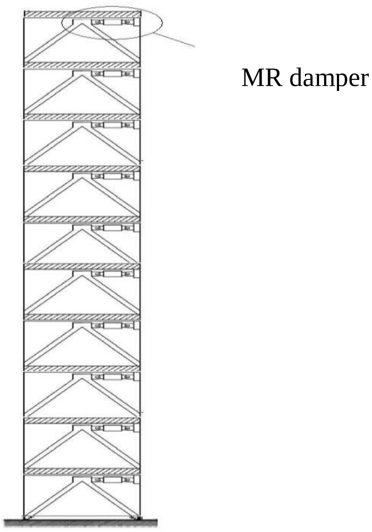

Fig. 9 Controlled test structure with MR dampers.

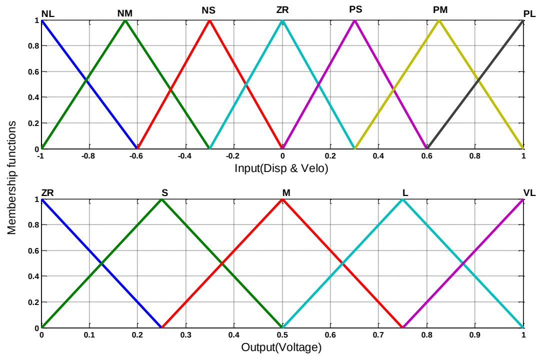

Fig. 10 Input and output membership functions

Table 3 Rule base table of fuzzy controller

Data base		Velocity						
		NL	NM	NS	ZR	PS	PM	PL
Displacement	NL	VL	L	L	M	S	S	ZR
	NM	L	M	M	S	S	ZR	S
	NS	M	S	S	ZR	ZR	S	S
	ZR	S	S	ZR	ZR	ZR	S	S
	PS	S	S	ZR	ZR	S	S	M
	PM	S	ZR	S	S	M	M	L
	PL	ZR	S	S	M	L	L	M

6.2.1 Optimization of FLC

Genetic algorithm is utilized as an effectual method for design of the FLC. It provides a rational fuzzy relation between the selected structural responses and the corresponding voltage of MR damper. The optimization procedure is carried out through a fitness function that specifies the design criteria in a quantitative manner. This function assesses each chromosome to achieve an optimal solution. In this study, the displacement response of the stories is to be minimized as main goal of the optimization problem. The fitness function to be minimized in this study is considered as

$$F = \sum_{i=1}^{n} \left[\max(d_i)\right]^2 \tag{21}$$

where d_i is the controlled response of the building (here, the displacement response of the stories).

The membership functions and fuzzy rules of fuzzy controller were optimized and updated from primary membership functions and fuzzy rules. In order to adjust the membership functions used for input and output variables, 10 parameters (4 parameters for input and 6 parameters for output membership functions) are considered to be optimized. All of the information represented by the FLC parameters is encoded in a chromosome which is made up of 10 genes representing these parameters. Fig. 11 shows the final optimized membership functions for input and output vectors. Reasonable GA operator parameters are very influential in improving the GA performance.

These parameters such as initial population size, crossover rate and mutation rate are chosen according to the problem being studied. In this stage, the number of initial population size is taken to be about 40. The crossover rate and mutation rate are taken as 0.85 and 0.01, respectively. The constraint of convergence is considered as 100 generations of the population.

The parameters of input and output membership functions should be optimized while the rule base remains unchanged. Therefore, after optimization of membership functions, the rules of the fuzzy controller are optimized based on the final membership functions with a chromosome made up of 49 genes according to Table 3. Optimized rule base table of fuzzy controller is tabulated in Table 3. The final rule surface plot after optimization is shown in Fig. 12. The number of initial population size is taken to be about 50. The crossover rate, mutation rate and the constraint of convergence are taken as 0.85, 0.01 and 100, respectively, as the membership functions optimization.

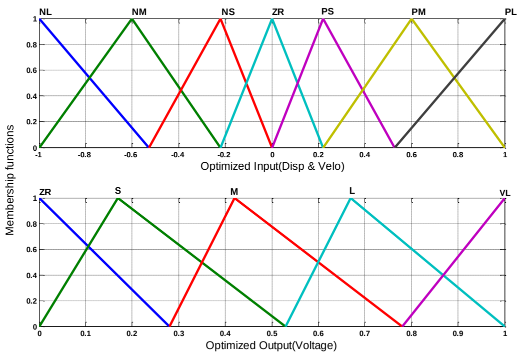

Fig. 11 Optimized Input and output membership functions

6.3 Seismic response mitigation results

To verify the control design validity and the effectiveness of described methods in near-fault ground motions, time histories of roof displacement and profiles of drifts are illustrated. For conciseness, graphic roof displacement and drift of the test structure are presented for only 3of the 9 earthquakes considered. Nevertheless, discussion presented in this section will refer to structural responses to all 9 near-fault and far-fault seismic motions. Figs. 13, 14 and 15 provide time history of the roof displacement and drift for the uncontrolled compared with fuzzy-controlled and fuzzy-controlled compared with MED control algorithm under the Northridge earthquake(SCS052) having forward directivity, Chi-Chi (TCU068EW) having fling step and Northridge (WST270) far-fault ground motion. For simplicity, in this paper, the seismic motion with forward directivity effect and fling step effect will be referred to as “FD” and “FS”, respectively, while the far-fault seismic motion without pulse will simply be called “WP”.

Table 4 Rule base table of fuzzy controller after optimization

Data base		Velocity						
		NL	NM	NS	ZR	PS	PM	PL
Displacement	NL	VL	L	M	S	S	ZR	ZR
	NM	L	M	S	S	ZR	ZR	S
	NS	M	S	S	ZR	ZR	S	S
	ZR	S	S	ZR	ZR	ZR	S	S
	PS	S	S	ZR	ZR	S	S	M
	PM	S	ZR	ZR	S	S	M	L
	PL	ZR	ZR	S	S	M	L	M

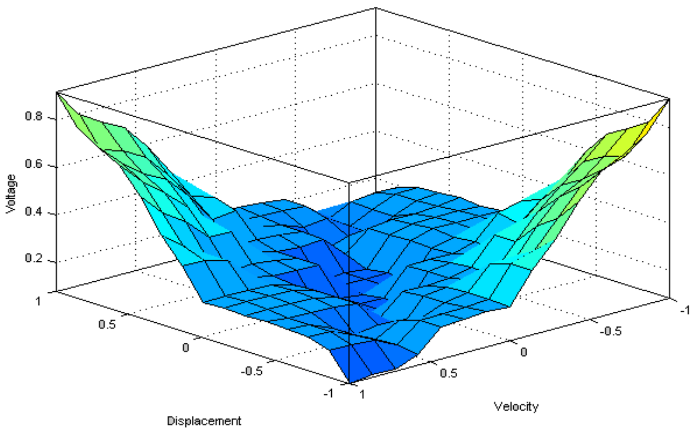

Fig. 12 Final representation of rule surface of fuzzy controller

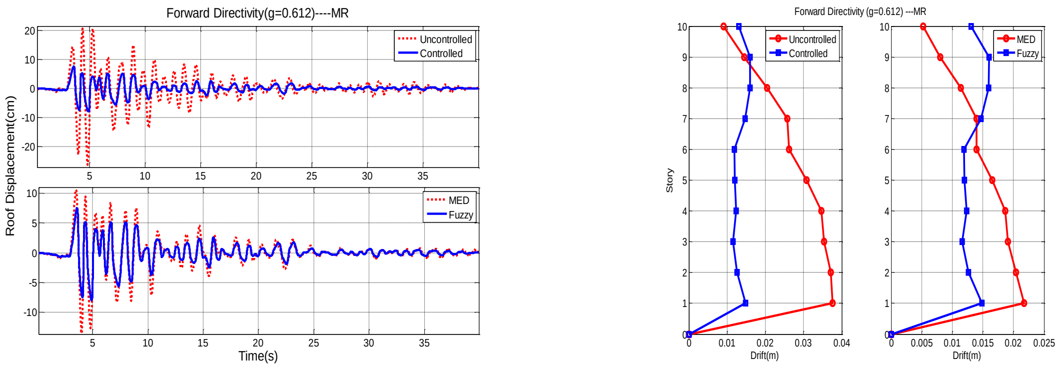

Fig. 13 Results of roof displacement time history and drift in controlled and uncontrolled structure-Forward directivity (g=0.612)

Compared to the uncontrolled system, the fuzzy logic controlled MR damper system greatly reduces the roof displacement in near-fault and far-fault earthquakes. The performance of the system employing the semi-active fuzzy control system surpasses that of MED system in reducing roof displacement, especially for seismic motion with FD and WP effect.

Roof displacement reduction due to fuzzy logic control system is slightly better for the motions having FS effect. In near-fault having FD, it can be seen that the FLC decreases the drift significantly except for the ninth and tenth floors. The performance of FLC leads to great reduction in drift in FS and WP ground motions. Maximum drifts obtained from FLC yields in better results in lower stories while MED control system has better performance in upper stories subjected to FD effect. In FS effect, the overall reduction of drift due to FLC is similar to MED. Finally, for far-fault seismic motions, FLC results in drifts less than that of MED. As a result, the MR dampers reduce structural responses and are promising for semi active structural control in relation to characteristics of near fault fields and far fault fields.

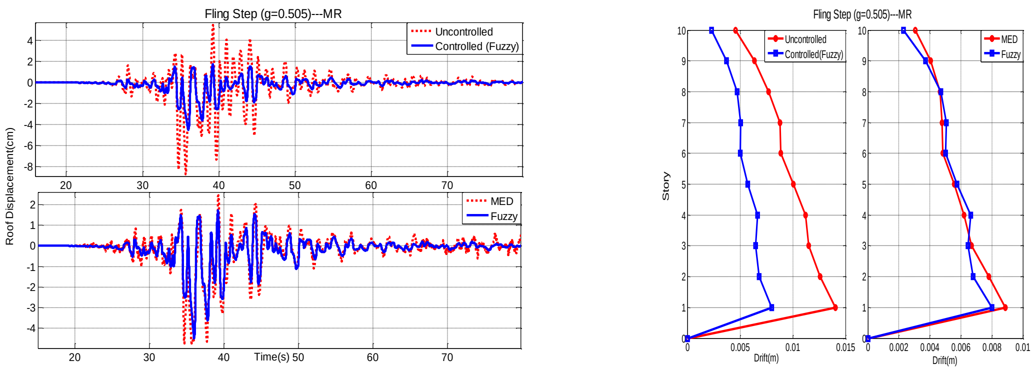

Fig. 14 Results of roof displacement time history and drift in controlled and uncontrolled structure – Fling step (g=0.505)

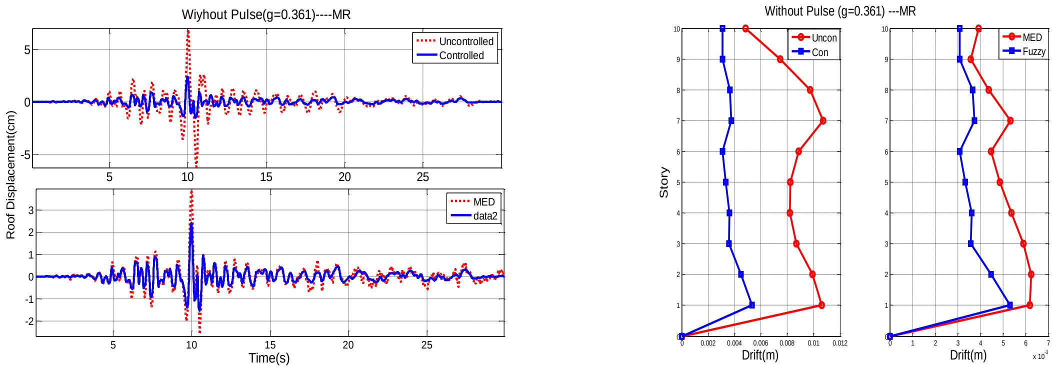

Fig. 15 Results of roof displacement time history and drift in controlled and uncontrolled structure – Far-fault motions (g=0.361)

The effectiveness of methods on response reductions in earthquake vibrations is further evaluated by a set of performance indices comparing the controlled response against the results obtained from the uncontrolled cases. There are different sets of evaluation criteria which are used in structural control to evaluate the performance of the buildings. The set of evaluation criteria, Eqs. (22) to (30), used in this study to compare the performance of the structure are defined based on both maximum and RMS responses(Jansen and Dyke 2000,Ohtori 2004) ($J_1, \ldots, J_9$) where $x_i(t)$ is displacement of i-th story, $d_i(t)$ is drift of i-th story, $\ddot{x}_i(t)$ is acceleration of i-th story, $f_l(t)$ is control force produced by l-th device, m_i is mass of i-th story, h_i is height of i-th story and W is effective seismic weight of building. The term 'c' refers to the controlled system and the term 'u' refers to uncontrolled system.

$$J_1 = \frac{\max\limits_{t,i} \frac{|d_i^c(t)|}{h_i}}{\max\limits_{t,i} \frac{|d_i^u(t)|}{h_i}} \qquad J_2 = \frac{\max\limits_{t,i} |x_i^c(t)|}{\max\limits_{t,i} |x_i^u(t)|} \qquad J_3 = \frac{\max\limits_{t,i} |\ddot{x}_{ai}^c(t)|}{\max\limits_{t,i} |\ddot{x}_{ai}^u(t)|} \qquad J_4 = \frac{\max\limits_{t} \left|\sum_i m_i \ddot{x}_{ai}^c(t)\right|}{\max\limits_{t} \left|\sum_i m_i \ddot{x}_{ai}^u(t)\right|}$$

$$J_5 = \frac{\max\limits_{t,i} \frac{\|d_i^c(t)\|}{h_i}}{\max\limits_{t,i} \frac{\|d_i^u(t)\|}{h_i}} \qquad J_6 = \frac{\max\limits_{t,i} \|x_i^c(t)\|}{\max\limits_{t,i} \|x_i^u(t)\|} \qquad J_7 = \frac{\max\limits_{t,i} \|\ddot{x}_{ai}^c(t)\|}{\max\limits_{t,i} \|\ddot{x}_{ai}^u(t)\|} \qquad J_8 = \frac{\max\limits_{t} \left\|\sum_i m_i \ddot{x}_{ai}^c(t)\right\|}{\max\limits_{t} \left\|\sum_i m_i \ddot{x}_{ai}^u(t)\right\|}$$

$$J_9 = \frac{\max\limits_{t,l} |f_l(t)|}{W} \qquad (22\text{-}30)$$

The performance of the system according to set of evaluation criteria for seismic records characterized with forward directivity is tabulated in Table 5 for both FLC and MED control methods. The overall control performance of the FLC is excellent for most of the evaluation criteria compared to MED. In particular, MED provides better result for J_3 and J_7 in which FLC increases the corresponding structural response. Table 6 provides comparative results of the evaluation criteria for the near-fault ground motions having fling step. Compared to MED, the FLC exhibits excellent control performance for the evaluation criteria J_1,J_2, J_5, J_6, J_7whereas the values for the J8 evaluation criteria still show very competent control performance. Results of J_3 show that both control methods increase corresponding response of the structure. For J_4 evaluation criteria, MED control system results in better performance than that of FLC. In addition, the noticeable control performance of the FLC semi-active control strategy can clearly be observed from the simulation results for the far-fault ground motions listed in Table 7. Considering the overall evaluation criteria, the FLC control system is quite effective for the seismic response control in far-fault seismic motions. The effectiveness of the logic-based semi-active MR damper system is also verified from the average evaluation criteria for the nine earthquakes given in Table 5 through Table 7.

The overall performance of the semi-active fuzzy control system is much superior to that of the MED control system. For evaluation criteria J_1 and J_5 (peak and RMS drift), FLC provides 57% reduction under FD effects, 40% reduction under FS effects and 50% reduction for WP while MED control system results in 32% reduction for FD effects, 40% reduction for $J_1$and 30% reduction for J_5under FS effects and finally 40% reduction subjected to WP motions. Results of J_2 and J_6 are so similar to the results of J_1 and J_5. For J_3 (peak acceleration), results of MED are much better than FLC during motions having FD and FS effects. FLC results are better than that of MED for J_3 in far-fault fields. Results of J_4 and J_8 (peak and RMS base shear) show that FLC has better performance under FD effect while MED control results are better during FS effects. For far-fault motions FLC is superior to MED control system. For J_7 (RMS of acceleration), in near- fault having FD, FLC results in less decrease than MED while FLC further reduces the response in relation to near-fault having FS and far-fault motions.

Table 5 Evaluation criteria of near-fault ground motions with forward directivity effects

	PGA=0.439		PGA=0.612		PGA=0.838		Average evaluation criteria	
	Fuzzy	MED	Fuzzy	MED	Fuzzy	MED	Fuzzy	MED
J1	0.4183	0.6653	0.4264	0.6653	0.4244	0.6886	0.4230	0.6730
J2	0.3533	0.6935	0.3033	0.6935	0.4068	0.6553	0.3544	0.6807
J3	1.3929	0.9879	0.6054	0.9879	1.6923	0.7006	1.2302	0.8921
J4	0.8455	0.8850	0.8228	0.8850	0.9260	0.7534	0.8647	0.8411
J5	0.5588	0.7406	0.3953	0.7406	0.4085	0.6128	0.4542	0.6980
J6	0.4497	0.6731	0.3509	0.6731	0.3797	0.5629	0.3934	0.6363
J7	0.7527	0.7565	1.1328	0.7565	0.8879	0.6133	0.9244	0.7087
J8	0.7068	0.8240	0.4873	0.8240	0.5559	0.6118	0.5833	0.7532
J9	0.0449	0.0261	0.1067	0.0261	0.1067	0.1220	0.0861	0.0580

Seismic response mitigation of corresponding evaluation criteria, J_1, J_2, J_3, J_5, J_6 and J_7, exhibit less reduction subjected to near-fault motions having FD and FS effects. This point can be seen in which near-fault seismic motions present larger value of evaluation criteria than far-fault motions. One noteworthy point is that near-fault earthquakes investigated in this study require larger control force (J_9), especially for those having FD effect. Consequently, near-fault motions have potentially more influence on the seismic response mitigation and control of structure. Also, it can be seen that FS effect presents large evaluation criteria indicating less response suppression than earthquakes having FD effect. In other words, near-faults motions characterized with FS affect more intensely the control of structure. It should be mentioned that fuzzy logic controller with MR damper demonstrated high efficiency and yielded significant reduction in structural seismic response under various excitations.

Table 6 Evaluation criteria of near-fault ground motions with fling Step effects

	PGA=0.171		PGA=0.365		PGA=0.505		Average evaluation criteria	
	Fuzzy	MED	Fuzzy	MED	Fuzzy	MED	Fuzzy	MED
J1	0.5768	0.6034	0.5166	0.5597	0.6308	0.6313	0.5733	0.5981
J2	0.4854	0.5563	0.4302	0.5529	0.5276	0.5453	0.4810	0.5515
J3	1.5244	1.7324	2.1113	1.3032	0.8659	1.1222	1.5005	1.3859
J4	0.8751	0.6813	1.1659	1.1446	1.0270	0.8561	1.0226	0.8940
J5	0.5656	0.6638	0.6549	0.7495	0.6297	0.7231	0.6167	0.7121
J6	0.4887	0.5944	0.5735	0.6731	0.5580	0.6476	0.5400	0.6383
J7	0.8391	1.6425	0.8184	1.2180	0.8096	1.5884	0.8223	1.4829
J8	0.6492	0.6262	0.6353	0.6691	0.7045	0.7267	0.6630	0.6740
J9	0.0229	0.0237	0.0550	0.0412	0.0311	0.0232	0.0363	0.0293

Table 7 Evaluation criteria of far-fault ground motions without pulse

	PGA=0.361		PGA=0.435		PGA=0.638		Averageevaluation criteria	
	Fuzzy	MED	Fuzzy	MED	Fuzzy	MED	Fuzzy	MED
J1	0.4959	0.5832	0.6748	0.7651	0.4177	0.5717	0.5294	0.6400
J2	0.3465	0.5625	0.3390	0.5260	0.3302	0.4463	0.3385	0.5116
J3	0.9389	1.2107	0.8367	0.9909	0.9505	0.9458	0.9087	1.0491
J4	0.6791	0.9272	0.6717	0.8354	0.9534	0.9552	0.7680	0.9059
J5	0.5008	0.6001	0.4932	0.5712	0.4453	0.5428	0.4797	0.5713
J6	0.3392	0.4966	0.3389	0.4410	0.3350	0.4760	0.3377	0.4712
J7	0.7274	0.8906	0.6746	1.0242	0.6746	0.7511	0.6922	0.8886
J8	0.8626	0.9693	0.8004	0.9949	0.8004	0.9060	0.8211	0.9567
J9	0.0327	0.0421	0.0465	0.0207	0.0465	0.0267	0.0419	0.0298

7. Conclusions

The semi-active fuzzy control of responses of a ten-storey model building frame using an MR damper is presented to evaluate structural control when subjected to near-fault seismic motions characterized with forward directivity and fling step in comparison with far-fault earthquakes. Displacement and velocity responses are considered as two input variables to the fuzzy logic controller. Results showed that the developed semi-active fuzzy controller was capable of effectively reducing the responses of the structure, therefore exhibiting a robust behavior to changes in external excitations. In addition, Results obtained with the fuzzy logic controller were compared to those obtained with maximum energy dissipation algorithm. Fuzzy logic controller was found to be highly effective and yielded better performance. It was shown that Near-fault motions demand larger control force than far-fault motions, especially for records associated with forward directivity. Structural response control resulted in larger reduction under far-fault ground motions compared to near fault earthquakes. In particular, ground motions having fling step effect demonstrated high influence and less response mitigation than forward directivity effect. The results of this investigation indicate the prospective use of MR dampers as semi-active devices in smart structures excited with near-fault motion characteristics.

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