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Implementation of Uniform Deformation Theory in semi-active control of structures using fuzzy controller

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Abstract. Protection of structures against natural hazards such as earthquakes has always been a major concern. Semi-active control combines the reliability of passive control and versatility and adaptability of active control. So it has recently become a preferred control method. This paper proposes an algorithm based on Uniform Deformation Theory to mitigate vulnerable buildings using magneto-rheological (MR) damper. Due to the successful performance of fuzzy logic in control of systems and its simplicity and intrinsically robustness, it is used here to regulate MR dampers. The particle swarm optimization (PSO) algorithm is also used as an adaptive method to develop a fuzzy control algorithm that is able to create uniform inter-story drifts. Results show that the proposed algorithm exhibited a desirable performance in reducing both linear and nonlinear seismic responses of structures. Performance of the presented method is indicated in compare with passive-on and passive-off control algorithms.

Keywords: semi-active control; fuzzy system; MR damper; Uniform Deformation Theory; particle swarm optimization algorithm

1. Introduction

Structural control is essentially the adjustment of the properties of a structure to attain a structurally desirable response to an external load. Although the concept of structural control is attractive and exciting, the basic concepts themselves are not new. They have been the crucial of electrical and control engineering for decades, and have been applied successfully in a variety of other disciplines, such as aerospace and mechanical engineering. However, structural control of civil engineering structures has a more recent origin. Its application to civil engineering structures is unique and presents a host of new challenges. This is especially true for reducing earthquake structural responses, because of the uncertainties and the high power of earthquake forces (Chen and Scawthorn 2005). Yao (1972) first applied control theory for structural control. Todays, many constructors are using this technology in new and retrofit projects. Structural control methods include passive, active, semi-active and hybrid control. The advantages and disadvantages of each method have been well documented. The choice of which approach to use has depended on engineering preference, type of structure, location, nature of the dynamic load, and project commissioning (Mousaad Aly 2013).

In recent years, significant attention has been directed to semi-active control devices because of their reliability and adaptability. Magnetorheological (MR) dampers are one of the innovative devices which are suitable for semi active control. MR dampers offer reliable operation for response reduction at modest cost, and can be categorized as fail-safe devices (Yan and Zhou 2006). They also work even in the situation of control hardware malfunction. MR fluids which are used in MR dampers to offer controllable devices, belong to the category of controllable fluids. The basic characteristic of these fluids include the ability to change in rheological behavior when exposed to a magnetic field. Furthermore, MR damper can give controllable force just working on a battery power. Due to their low-power requirements and fail safe property, MR dampers have been intensively studied by many researchers as control devices for civil engineering structures (Cha *et al.* 2014, Khanmohammadi *et al.* 2014, Bitaraf *et al.* 2014, Shaikh Faruque 2008, Das *et al.* 2012, Wilson and Abdullah 2010, Das *et al.* 2012, Mohajer Rahbari *et al.* 2013, Hung *et al.* 2010, Mohajer Rahbari and Talatahari 2014).

One principal concern in using semi-active method is developing nonlinear control algorithms suitable for implementation in full-scale structures. Many control algorithms have been adopted for semi-active systems, some of them are: decentralized bang-bang approach (Brogan 1991), the controllers based on Lyapunov stability theory (McClamroch and Gavin 1995), maximum energy dissipation algorithm (Johnson and Erkus 2007), Clipped-Optimal (Dyke and Spencer 1996) and Modulated homogeneous friction algorithm (Inaudi 1997). However, these model-based controllers have proper performance in reducing structural vibrations, their performance is affected by the accuracy of the model selected. By increasing the

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height of building, providing an exact mathematical model for structures is more complicated. Intelligent control strategies, can be proper alternatives. Intelligent controllers proposed for use with MR dampers insclude: neural network-based controllers (Shiraishi *et al.* 2002, Ni *et al.* 2002, Xu *et al.* 2003, Karamodin and Kazemi 2010), neuro-fuzzy based controllers (Schurter and Roschke 2001, Das *et al.* 2012) and fuzzy logic-based controllers (Das *et al.* 2012).

In recent years, fuzzy-logic theory (Zadeh 1965), has been preferred to use in intelligent controllers for its simplicity and its way of handling uncertainties. Several researchers show the effectiveness and superiority of fuzzy algorithms to mitigate structural vibration (Brown and Yao 1983, Juang and Elton 1986, Battaini *et al.* 1998, Casciati *et al.* 1996) and specially to control MR dampers as highly nonlinear devices (Bitaraf *et al.* 2014, Shaikh Faruque 2008, Das *et al.* 2012, Kim 2013, Kim and Kang 2012, Kim *et al.* 2010).

However, using fuzzy logic in controller design is rather simple, tuning the limits used to define the membership functions and the inference mechanisms is a sophisticated procedure (Zhao 2001). Many methods have been developed for this purpose. Change of the scaling factors is the most popular strategy, which maps the inputs and outputs to their respective universes of discourses and effects on controller performance (Wilson and Abdullah 2010).

Different methodologies have been proposed for adjusting the scaling factors (Wilson and Abdullah 2010, Dariankov *et al.* 1993, Faravelli and Yao 1996, Nishimori *et al.* 1994, Chao and Teng 1997, Zhao *et al.* 2003). In this research, the Particle Swarm Optimization (PSO) algorithm (Kennedy *et al.* 2001), is used for tuning the scaling factors of fuzzy controllers. This algorithm was inspired by social behavior of bird flocking or fish schooling. There are many particles that constitute a swarm and each one traverses the multidimensional search space looking for the global optima. During flight, each particle adjusts its position according to its own experience, and the experience of neighboring particles, using the most proper position encountered by itself and its neighbors (Faruque and Ramaswamy 2009).

In this study, the main idea of uniform deformation theory has been applied for choice of cost function in PSO. Many studies have been carried out to investigate the effectiveness of this theory in seismic design of structures (Karami 2001, Moghaddam and Karami 2003, Karami Mohammadi *et al.* 2004, Moghaddam and Hajirasouliha 2006). Results of these researches confirm the success of this theory in optimum seismic design. According to this theory, assigning structural capacities in such a way that leads to uniform distributed demand to capacity ratios usually generates a safer design and a more light-weighted structure.

The aim of this paper is to propose a fuzzy controller based on uniform deformation theory to control structures equipped with MR dampers. Here, the effectiveness and efficiency of the suggested algorithm to mitigate structural responses under different earthquakes has been investigated. To test the robustness of the algorithm, numerical simulations were conducted on two structures equipped with MR dampers. Results were compared to “passive on" and “passive off” systems.

2. Fuzzy control system

A fuzzy control system combines “IF-THEN” statements, as fuzzy rules, to relate the controller inputs to desired outputs. A fuzzy controller comprises four fundamental components, including: fuzzification, inference system, rule base and defuzzification.

Membership functions in fuzzy logic controllers convert the measured variables into linguistic terms (fuzzification interface). The shape and characteristics of membership functions define the way they are converted to linguistic terms and are generally selected by engineers’ judgment depending on given problems. A rule base is formed for the fuzzy controller by an expert, which will decide the actions of the controller based on the inputs. Fuzzy logic rules is of the form “IF-THEN” that convert inputs to outputs. The output obtained is again in linguistic term and will be fuzzy in nature. So, a defuzzification unit is required to convert this fuzzy linguistic term into discreet values that is mapped on to the actuator command (Edalath 2007).

Since a fuzzy rule base combines different rules, fuzzy reasoning is needed to derive conclusions from a family of IF-THEN rules. So fuzzy reasoning is a method to organize a set of rules and get a unique output. Two types of reasoning mechanisms that have been extensively applied to a variety of engineering fields are Mamdani and Takagi-Sugeno (TS) fuzzy models. Since Mamdani model, unlike the TS one, takes advantage of all features of fuzzy systems, this model is mainly used in control of structures (Chen and Pham 2000).

2.1 Design of Fuzzy controller

The aim of this study is to propose a fuzzy control algorithm to mitigate structural responses of buildings equipped with MR dampers, subjected to earthquakes. PSO algorithm is used to find proper scaling factors for inputs. The input variables to the fuzzy controller were chosen as floor displacement (x) and floor velocity ($\dot{x}$), while the output is the current (or voltage) applied to the MR damper (i).

2.2 Input fuzzification

The design of fuzzy controller begins with dividing the input space into fuzzy regions and definition of membership functions. In this research, 5 triangle membership functions with 50 percent overlap are used for inputs. Input and output functions, as shown in Figs. 1-2, were labeled ZO for Zero, S for Small, M for Medium, L for Large, NS for Negative Small, PS for Positive Small, NL for Negative Large and PL for Positive Large. As shown in Fig. 2, the input membership functions are defined in the range of -1 to +1. So, the crisp input values must be normalized to be mapped to proper output utilizing membership functions.

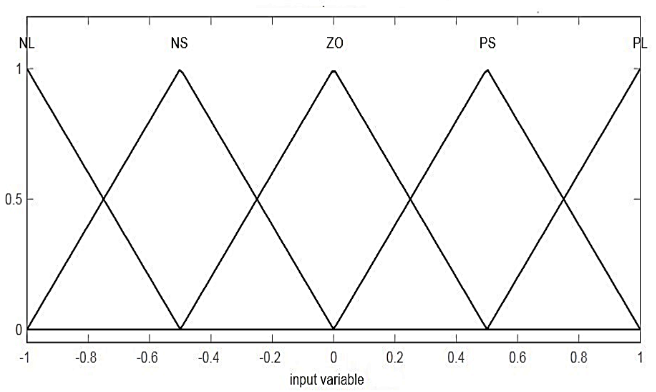


Fig. 1 Input membership functions

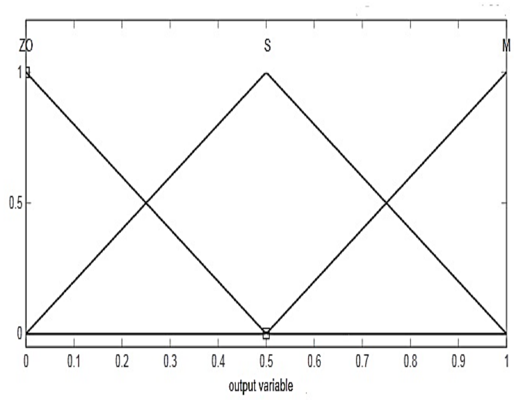


Fig. 2 Output membership functions

2.3 Input values normalization

In this paper, the scaling factors of displacement and velocity are considered as functions of input acceleration and are obtained in independent ranges by employing PSO optimization algorithm. The first step is choosing proper range of acceleration, which might occur in lifetime of structure, and calculating the logarithm of this range, as shown below

$$Log\_ACC = [\log(A_{\min}) \quad \log(A_{\max})] \tag{1}$$

where A_{min} and A_{max} are, respectively, probabilistic minimum and maximum values of input ground acceleration in mentioned interval of time. In this paper the range of ground acceleration is considered between 0.000001 g to 2 g and the corresponding range for scaling factor is optimized by PSO.

The next step is definition of two ranges for scaling factors of velocity and displacement, corresponding to defined ground acceleration range

$$SFD_i = [D_{i,\min} \quad D_{i,\max}] \tag{2}$$

$$SFV_i = [V_{i,\min} \quad V_{i,\max}] \tag{3}$$

Where SFD_i is the Scaling Factor of Displacement of ith floor and SFV_i is the Scaling Factor of Velocity of ith floor.

In every moment, scaling factors are calculated by linear interpolation based on the input acceleration at that moment. For instance, if the displacement and velocity of ith floor are $D(t)$ and $V(t)$ at a certain moment and input ground acceleration is $A(t)$, normalized values of displacement and velocity, $\overline{D}(t)$ and $\overline{V}(t)$, could be calculated as follow

$$\overline{D_i}(t) = D_i(t)(D_{i,\min} + \frac{\log(A(t)) - \log(A_{\min})}{\log(A_{\max}) - \log(A_{\min})}(D_{i,\max} - D_{i,\min})) \tag{4}$$

$$\overline{V_i}(t) = V_i(t)(V_{i,\min} + \frac{\log(A(t)) - \log(A_{\min})}{\log(A_{\max}) - \log(A_{\min})}(V_{i,\max} - V_{i,\min})) \tag{5}$$

2.4 Optimization of scaling factor

Particle Swarm optimization (PSO) as a heuristic global optimization method, shares many similarities with Evolutionary Computation (EC) techniques in general and genetic algorithm (GA) in particular. The main difference between the PSO approach compared to EC and GA is that PSO does not have genetic operators such as crossover and mutation and does not change the population from generation to generation, but keep the same population, iteratively updating the positions of the members of the population. Also, PSO is really two populations - best positions and current positions. This allows greater diversity and exploration over a single population (which with elitism would only be a population of best positions). Moreover, the momentum effects on particle movement can allow faster convergence (e.g., when a particle is moving in the direction of a gradient) and more variety in search trajectories.

Due to its many advantages including its simplicity, easy implementation and the other features mentioned above, PSO was selected as the optimization approach in this study.

PSO approach utilizes a cooperative swarm of particles, where each particle represents a candidate solution, to explore the space of possible solutions to an optimization problem. Each particle is randomly initialized and then allowed to ‘fly’. At each step of the optimization, each particle is allowed to evaluate its own cost function and the cost of its neighboring particles. Each particle can keep track of its own solution, which resulted in the best cost (minimum cost), as well as see the candidate solution for the best performing particle in its neighborhood. In this paper, PSO algorithm is used with 20 particles and the termination criterion is the number of iterations performed (50 iteration).

The process of optimizing the ranges of scaling factors is classified in the following five steps:

(a) Random choice of first ranges for scaling factors.

(b) Analysis of structure under considered earthquake utilizing selected ranges for scaling factors. (Note that, at every time step, the normalized inputs are calculated according to ground acceleration in that step.)

(c) Calculating the cost function of PSO algorithm.

(d) Updating the scaling factors’ ranges by PSO algorithm.

(e) Repetition of two last steps until satisfaction of termination criterion.

2.4.1 Cost function of PSO

Choosing a proper cost function is an important consideration in using a meta-heuristic algorithm. It must be able to represent the algorithm's targets. In recent studies, the cost functions used were mainly multi-objective (Yan and Zhou 2006, Faruque and Ramaswamy 2009). They include sentences with different weights. Each sentence may reflect an important structural response (displacement, velocity and/or acceleration). The cost function in this paper is defined as follows

$$CF. = \sum_{i=1}^{N} abs(D_i - D_{target}) \qquad (6)$$

where N denotes the number of stories and D_i and D_{target} are, respectively, the maximum drift of ith floor and the target drift. According to this definition, minimum CF. corresponds to the smallest deviation of inter-story drifts, D_is, from a fixed target drift, D_{target}, which resembles the most uniform distribution of drifts.

The target drift values for two and four story frames were selected as 1.4 cm, and 2.1 cm, respectively. These measures were determined based on the following information: the result of uncontrolled structure analysis, maximum allowable drift in the considered performance level of structure, and also the structural responses using passive-on and passive-off control methods. While the considered values for target drift in this study lead to attainment the acceptable results, the best values could be determined based on the optimization studies.

Variation of cost functions with respect to the iteration steps at the example studies are shown below in Fig. 3 and Fig. 4. We can see that the cost functions are gradually improved during the iterations.

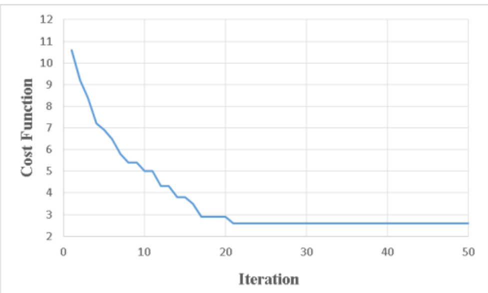


Fig. 3 Variation of Cost Function in 2 story Frame

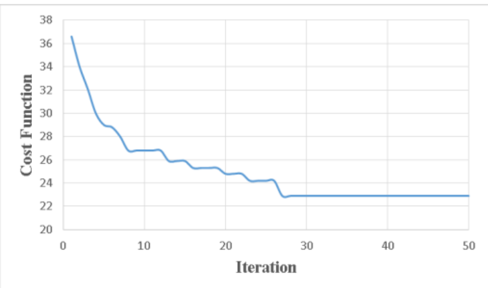


Fig. 4 Variation of Cost Function in 4story Frame

2.4.2 ET excitation functions

As explained in the above sections, optimizing the scaling factors depends on the applied earthquake record. In this paper, ET records are used to find the optimized scaling factors. These records are the acceleration functions introduced in Endurance Time (ET) method (Estekanchi *et al*. 2004). They are generated to be compatible with a design acceleration spectrum by using numerical optimization methods. They have been introduced to assess the seismic performance of structures at different intensity levels by a single time history analysis. In this study, an ET record that is compatible with Iranian standard response spectrum at t=10 sec is used (Fig. 5). The optimized scaling factors for two considered structures are presented in Tables 1-2. It is assumed in this study that the same scaling factors could be used for any other earthquake.

2.5 Rule base

The inference rules for the fuzzy control system (Table 3) were inspired by the rule base described by Liu *et al.* (2001). The logical base of designing this rule base is explained by the following examples. If the structure is moving away from its original position, floor displacement is positive large (PL), and floor velocity is also positive

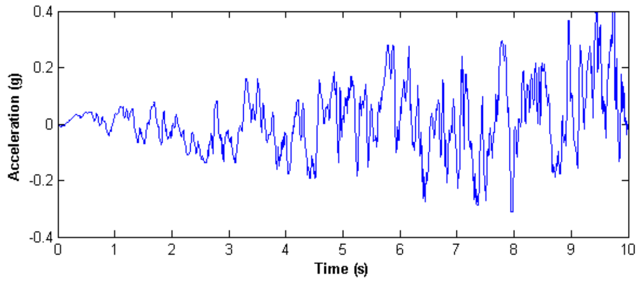


Fig. 5 ET excitation function (calibrated with 2800 standard response spectrum)

Table 1 Scaling factors of two story shear frame

	Story	Range
Scaling factor of displacement	1	[120 130]
Scaling factor of velocity	1	[4.2 15.5]
Scaling factor of displacement	2	[251 245]
Scaling factor of velocity	2	[4.3 18]

Table 2 Scaling factors of four story shear frame

	Story	Range
Scaling factor of displacement	1	[79 186]
Scaling factor of velocity	1	[8 19.5]
Scaling factor of displacement	2	[180 246]
Scaling factor of velocity	2	[13 11]
Scaling factor of displacement	3	[65 246]
Scaling factor of velocity	3	[12 7]
Scaling factor of displacement	4	[140 270]
Scaling factor of velocity	4	[11 15]

Table 3 Rule base

Velocity \ Displacement	NL	NS	ZO	PS	PL
NL	L	L	S	ZO	L
NS	L	S	S	ZO	S
ZO	L	ZO	ZO	ZO	L
PS	S	ZO	S	S	L
PL	L	ZO	S	L	L

large (PL), then the rules will result in large (L) current which increases the viscosity of the MR fluid and discourages structural motion. On the other hand, if the structure is returning to its original position, floor displacement is positive large (PL), and floor velocity is negative large (NL), the current is set to zero to decrease the amount of damping provided and allow the structure to return to its original position (Wilson and Abdullah 2010).

2.6 Defuzzification

As was mentioned before, defuzzification is a way of extracting definite values from fuzzy sets. In this paper, three triangle membership functions with 50 percent overlap, as shown in Fig. 2, have been defined for outputs. Although there are many defuzzification methodologies, a commonly used method by the name of centroid of area is used here. Since the minimum and maximum voltage of MR dampers are 0 and 10 Volt, the final output must be 0 to 10. Because the output value of fuzzy system is in the range of 0 to 1, the results must be multiplied by 10 (Fig. 2).

3. System description

To evaluate the proposed semi-active nonlinear fuzzy control system, a two-story and a four-story shear frames are modeled. Each frame is equipped with two MR dampers in the first story and one MR damper in other stories. Their properties are presented in Tables 4-5. Nonlinear dynamic analyses are conducted to investigate the effectiveness of controller. Eight ground motion records as introduced in Table 6 are used for the above mentioned analyses.

Table 4 Two story frame Structural properties

Story	Mass (ton)	Stiffness(N/m)
1	345.6	1.8405e+08
2	345.6	1.8405e+08

Table 5 Four story frame Structural properties

Story	Mass (ton)	Stiffness(N/m)
1	276.48	1.3788e+08
2	276.48	1.3788e+08
3	276.48	7.4233e+07
4	276.48	7.4233e+07

Table 6 Properties of considered earthquakes

Earthquake	PGA(g)	Date	Duration(s)	Step time
El centro	0.3483	1940	53.76	0.02
Northridge	0.6169	1994	40	0.02
Parkfield	0.3574	1966	40.95	0.01
San Fernando	0.3658	1971	36	0.02
Victoria	0.6212	1980	30.3	0.01
Cape Mendocino	0.5125	1806	24.45	0.01
Kobe	0.5027	1995	36.6	0.01
Duzce	0.5353	1999	25.87	0.005

4. MR damper modeling

Bouc (1967) introduced an adaptable mathematical model to describe hysteresis behavior of a single degree of freedom structure under the forced vibrations. Then, Wen (1976) generalized this model for random vibrations and proposed an approximate solution procedure (Mohajer Rahbari 2013).

In present study, Bouc-Wen model is employed to find the dampers' current needed to obtain the specified damping forces. In mathematical expression of the hysteresis Bouc-Wen model, a first-order nonlinear differential equation relates the nonlinear force to the system deformation. The proper adjustment of several parameters in this equation lead to an exact estimation of the actual structural behavior (Mohajer Rahbari 2013). The force produced by this model is calculated using the following equations

$$F = C_0 \dot{x} + k_0 (x - x_0) + \alpha z \tag{7}$$

where α is the MR material yield stress parameter and z denotes the hysteretic deformation of model. k_0 and c_0 are, respectively, the stiffness and damping coefficients. They are given as a linear function of the efficient voltage in the following equations

$$\dot{z} = -\gamma \,|\, \dot{x} \,|\, z \,|\, z \,|^{n-1} - \beta \dot{x} \,|\, z \,|^{n} + A\dot{x} \tag{8}$$

Table 7 Optimal values of the parameters of the Bouc-Wen model for a 1000 kN magnetorheological damper

Parameter	Unit	Value
α_a	KN/m	26
α_b	KN/m/V	29.1
c_{0a}	KN.s/m	105.4
c_{0b}	KN.s/m/V	131.6
x_0	m	0
γ	m^-2	141
β	m^-2	141
A	-	2075
n	-	2
η	s^-1	100

$$\alpha(u) = \alpha_a + \alpha_b u \tag{9}$$

$$k_0(u) = k_{0a} + k_{0b} u \tag{10}$$

$$c_0(u) = c_{0a} + c_{0b} u \tag{11}$$

$$\dot{u} = -\eta(u - v) \tag{12}$$

where v is the applied voltage for the current generation. u is the efficient voltage that can be calculated by the given first-order filter. The Optimized Values of Bouc-wen parameters are presented in Table 7. They are calculated for 1000 KN MR dampers through solving a constrained nonlinear optimization problem (Mohajer Rahbari 2013).

5. The controlling process

In this research, a real-time communication is established between Matlab and Opensees. The main code is written in Matlab and Openness is called as an analysis engine. In each time step, ground acceleration values and structural responses are given to the fuzzy control system. The fuzzy system finds the most proper voltage for the moment. Afterward, the Bouc-wen model is used to determine damping forces from the current. These forces are used by Opensees for the rest of the analysis.

6. Numerical results

6.1 2-story shear frame

In this section, the results of nonlinear dynamic analyses for a 2-story shear frame is presented. Figs. 6-7 contain the time history of inter-story drifts in El-Centro and Northridge Earthquakes, respectively. It can be seen that the proposed algorithm decreases inter-story drifts. The maximum drift in El-Centro earthquake reduced from 5.27 cm in uncontrolled state to 1.6 cm in controlled one. In Northridge earthquake, these values are 6.6 cm and 2.95 cm, respectively.

The results for other 6 earthquakes also show a similar trend. So, the proposed algorithm could control the structural responses in its effort to create an almost uniform drift distribution in every considered earthquakes. Figs. 10-11 present a comparison of structural responses in controlled and uncontrolled structures. As can be seen, the proposed algorithm which attempts to create uniform inter-

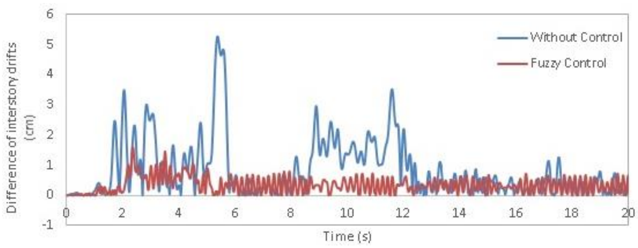


Fig. 6 Difference of inter-story drifts under El-Centro Eq

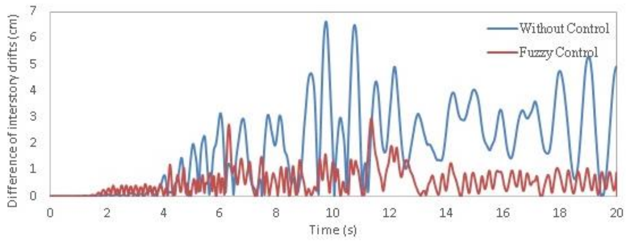


Fig. 7 Difference of inter-story drifts under Northridge Eq

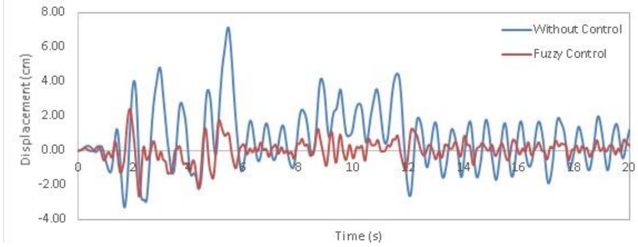
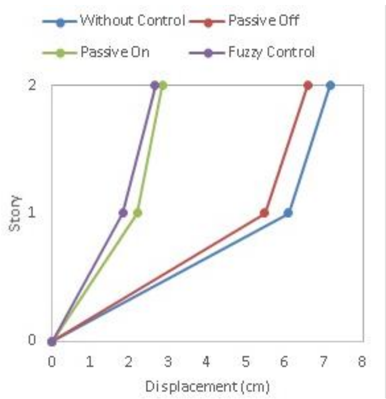
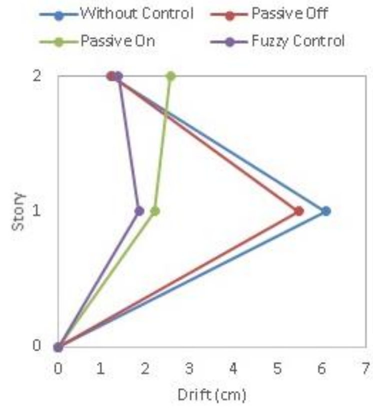


Fig. 8 Time history of roof displacement under El-Centro Eq



(a) Maximum of displacements



(b) Maximum of interstory drifts

Fig. 9 Maximum of displacements and interstory drifts under El-Centro Eq.

story drifts, not only reduce the maximum value of inter-story drifts, but also can reduce the maximum roof displacement.

In average, the maximum drifts and roof displacements in controlled structures have, respectively, 55.5 and 45 percent reduction compared to uncontrolled ones. Figs. 12-13 show the structural responses in uncontrolled and controlled structures under Northridge and Kobe earthquakes.

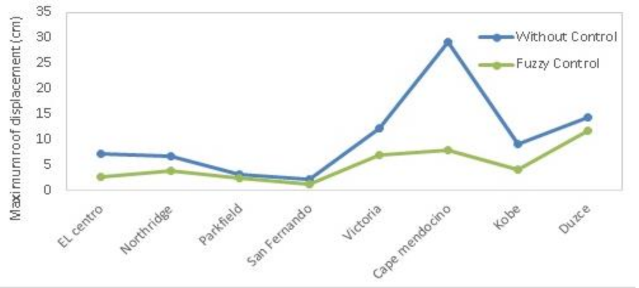


Fig. 10 Maximum value of roof displacements

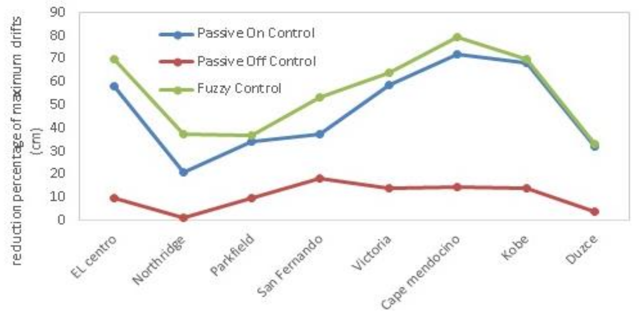
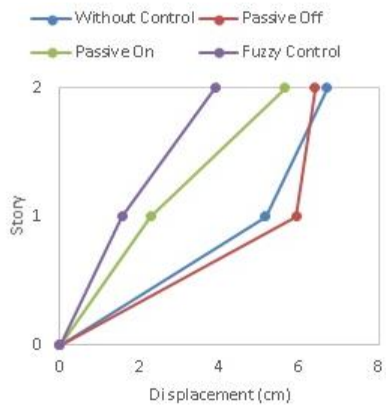
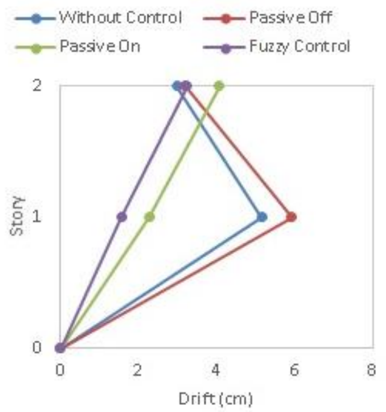


Fig. 11 Reduction percentage of maximum drifts

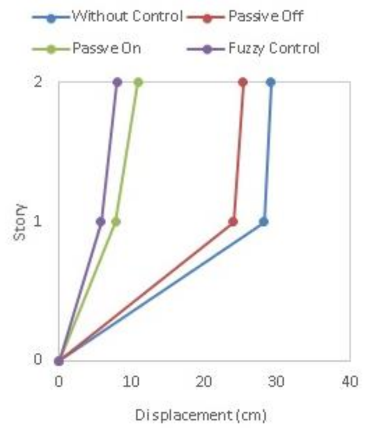


(a) Maximum of displacements

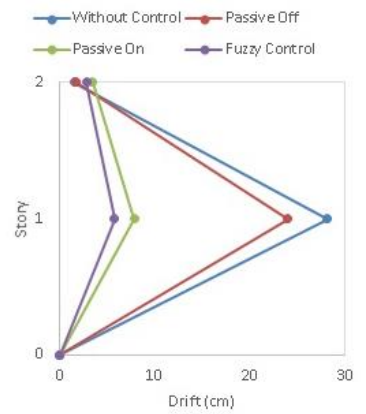


(b) Maximum of interstory drifts

Fig. 12 Maximum of displacements and interstory drifts under Northridge Eq



(a) Maximum of displacements



(b) Maximum of interstory drifts

Fig. 13 Maximum of displacements and interstory drifts under Cap mendocino Eq

6.2 4-story shear frame

In Figs. 14-15, reduction of the standard deviation of story drifts under El-centro and Northridge earthquakes are shown. It can be seen that these values reduced from 5.27 and 2.5 to 1.6 and 1.2 under El-centro and Northridge earthquakes, respectively. Figs. 16-17, show the structural responses after controlling in El-centro and Northridge earthquakes. The maximum drift and roof displacement reduced 48% and 41% relative to the corresponding responses of uncontrolled structure. Comparing the results using a passive-on control algorithm, it is concluded that the maximum drift and roof displacement also reduced 12% and 16% with respect to the corresponding responses in passive-on control system.

It can be seen that the maximum drift of structure under El-Centro earthquake was reduced to 53 and 23 percent compared to uncontrolled and Passive-on mode, respectively. Trying to create uniform story drifts led to 56 percent reduction in roof displacement with respect to uncontrolled structure. This reduction is about 30 percent in compare with the passive-on mode. In Figs. 18-22, the reduction of standard deviation of drifts and the maximum of seismic responses and reduction percentages under all of considered earthquakes are shown.

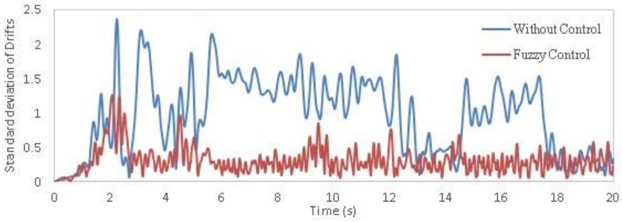


Fig. 14 Standard deviation of Drifts under El-Centro Eq

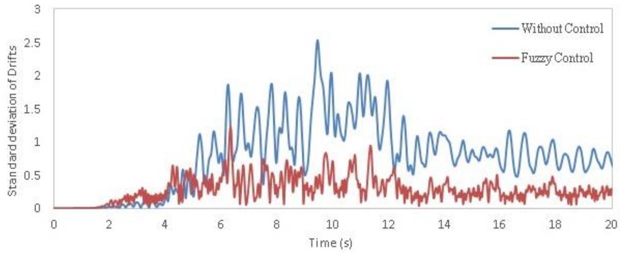


Fig. 15 Standard deviation of Drifts under Northridge Eq

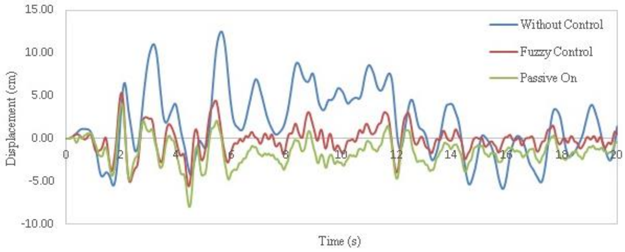
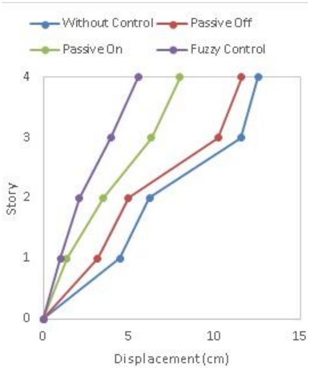
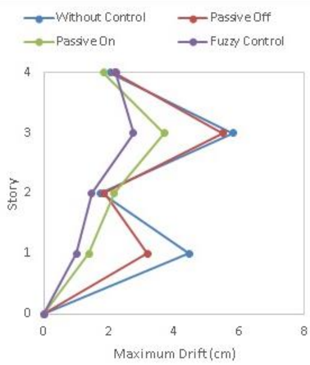


Fig. 16 Time history of roof displacement under El-Centro Eq



(a) Maximum of displacements



(b) Maximum of interstory drifts

Fig. 17 Maximum of displacements and interstory drifts under El-Centro Eq

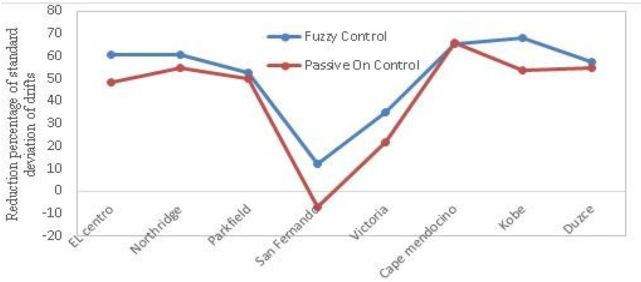


Fig. 18 Reduction percentage of standard deviation of drifts relative to uncontrolled structure

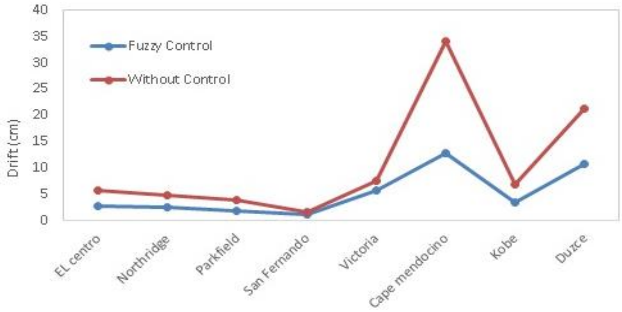


Fig. 19 Maximum Value of interstory drifts

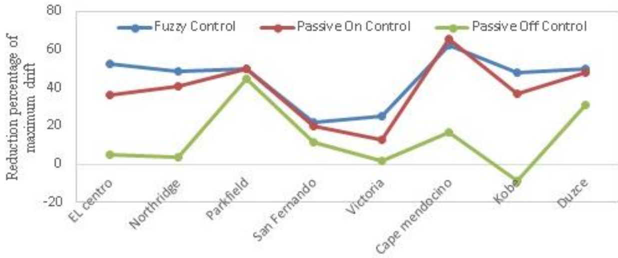


Fig. 20 Reduction percentage of maximum drift relative to uncontrolled structure

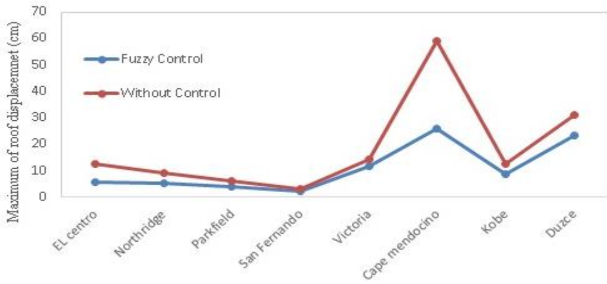


Fig. 21 Maximum Value of roof displacement

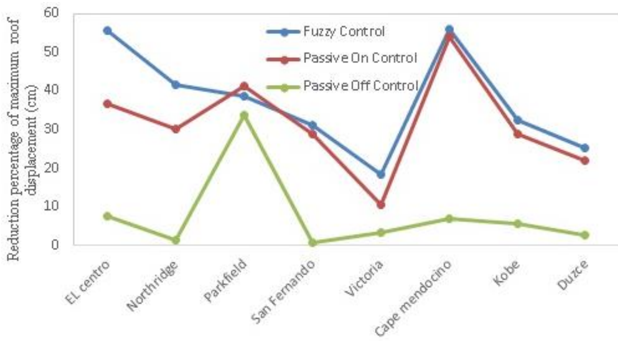
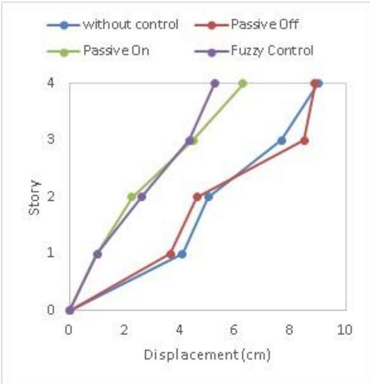
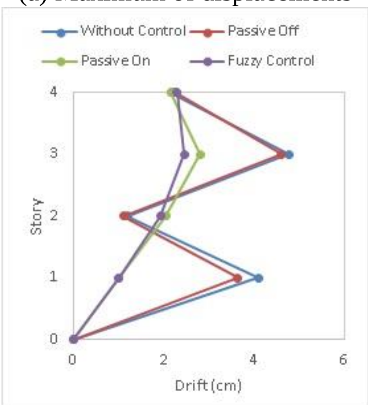


Fig. 22 Reduction percentage of maximum roof displacement

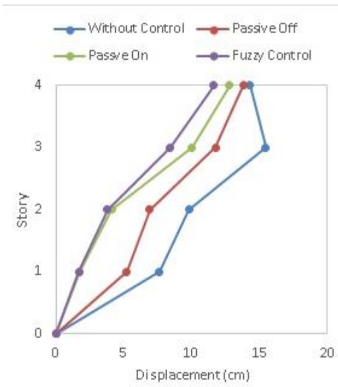


(a) Maximum of displacements

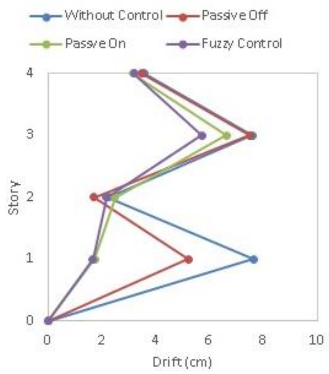


(b) Maximum of interstory drifts

Fig. 23 Maximum of displacements and interstory drifts under Northridge Eq



(a) Maximum of displacements



(b) Maximum of interstory drifts

Fig. 24 Maximum of displacements and interstory drifts under Victoria Eq

To more evaluate the performance of proposed algorithm, the seismic response of mentioned structure under Northridge and Victoria earthquake is also presented in the following figures.

7. Conclusions

In this paper, a fuzzy control algorithm is proposed for semi-active control of structures. PSO algorithm and ET excitation function are used to adjust this fuzzy system. The effectiveness of proposed algorithm was investigated on two considered shear frames equipped with MR dampers under 8 earthquakes. The average of reduction percentage in maximum drifts of 2 and 4-story frames were 55.5% and 38.4%, respectively. These reductions were 45% and 37% for roof displacements. The proposed fuzzy control algorithm which was designed to create uniform inter-story drifts, could decrease the structural responses in most cases. Also, the maximum value of story drifts and roof displacements were more reduced in compare with passive-on control. It can be said that using uniform deformation theory not only has considerable usefulness in seismic design of structures but also can be used as a proper base to design control algorithms.

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