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Effect of Time Delay on Semi-Active Seismic Control of a Nonlinear 11-Story Building Using Floating and Predictive Fuzzy Logic Algorithm

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Abstract: In control systems where sensors and receivers of sensor recorded data are used, there is a possibility of time delay in transferring recorded data of structural motion, which is a factor to reduce the efficiency of control system and even destabilization of structure. In this paper, the effect of time delay on performance of semi-active seismic control of an 11-story building with Magnetorheological (MR) damper is studied using predictive and floating fuzzy logic algorithm. Fuzzy decision-making system and linear and nonlinear model of structure are implemented in MATLAB and OpenSEES, respectively using TCP/IP connection. According to the results of incremental dynamic analysis for seven earthquakes with maximum acceleration of 0.1 to 1.0g and incremental step of 0.1g, floating fuzzy control system has improved roof displacement response of the structure by 38.75% compared to the uncontrolled system, despite time delay of 0.1s in control process and improvement roof response of the structure with linear behavior by no time delay in fuzzy control system based on velocity. In the case of time delay in control system and application of fuzzy decision making system based on roof velocity of the structure and predictive control, the average improvement of structure displacement response is 24.91% compared to uncontrolled system and it is 27.51% in the case of using floating fuzzy system. The same values in nonlinear structure are 30.81, 20.19, and 22.84%, respectively.
Keywords: Semi-active control; Time delay; Nonlinear behavior of structure; Floating fuzzy logic algorithm; Predictive control.

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1. Introduction

In recent years, researchers have been considering the use of semi-active control approach and fuzzy logic algorithm for structural vibration control. One of the semi-active control methods is the application of MR dampers. In the control systems that are using sensors and receivers of structure recorded data, there is a time delay in control process, which is a factor for reduction of control system performance or instability of the structure. To overcome these problems, application of fuzzy controllers along with predictive control is considered, providing a simple and powerful framework for nonlinear control rules that can adapt to uncertainties, time delay and complexities. In recent years, due to the inherent power and ability to deal with nonlinear issues and uncertainties, fuzzy control system has been taken into consideration by researchers. Despite the advantages of using fuzzy controllers, there are also some problems. For making decision and adjustment, fuzzy system requires a thorough understanding of dynamic system which must be determined in advance. Dyke and Spencer (1996) used MR damper to control a 3-story building under the El-Centro earthquake of 1940 [1]. MR damper was installed between the ground and first floor, the analysis results of which implied a reduction in displacement response and acceleration of structure. Gordaninejad and Liu (2000) also controlled the vibrations of two-span bridge using MR dampers [2]. Xu and Shen [3] (2002) used the neural network algorithm in semi-active control of structure using MR dampers. Jung and Kawashima (2002) studied semi-active control of double-deck bridges under the Northridge earthquake of 1994 and Kobe earthquake of 1995, using MR dampers [4]. Jung et al (2003) used MR dampers to semi-active control a suspension cable bridge under the seismic loads [5]. Dyke and Caicedo (2003) modeled the cable bridge of ASCE regulation [6]. In this bridge, 24 MR dampers with production capacity of 1000 kN have been installed in four different parts of the bridge between deck and the base. Sodeyama et al. (2003) built two MR dampers with production capacity of 20 kN and 200 kN respectively, determining damping characteristics of the dampers through experimental and analytical methods [7]. Renzi and Serino (2004) tested a model of four-story structure equipped with MR damper on a shaking table [8]. Zhou and Chang (2003) studied semi-active control of structural vibration using MR damper and adaptive fuzzy control against earthquake excitation [9]. Bing and Zhi (2004) studied semi-active control of cable-stayed bridge constructed by Dyke (2000) using four MR dampers with production capacity of 1000 kN under multiple excitations [10]. Liu et al. (2005) tested semi-active control of 1:12 scaled bridge with two MR dampers on the shaking table [11]. Xu et al. (2005) put the 12-story building model equipped with MR damper under the effect of El-Centro earthquake and reported the appropriate performance of semi-active control system compared to passive control system [12]. Yoshida and Dyke (2005) used MR dampers to control the behavior of two irregular 3D buildings under seismic loads [13].

Pourzeynali and Datta (2005) used semi-active tunable mass dampers and fuzzy algorithm to control the vibrations of suspension bridge [14]. Kim and Roschke (2006) studied the combined control of passive seismic isolators and semi-active MR damper [15]. Yan and Zhou (2006) controlled the vibrations of 3-story building using fuzzy controllers and MR damper along with genetic optimization algorithm subjected to seismic load [16]. Kim and Kang (2012) studied semi-active control of tall building vibrations (a 76-story structure) under wind excitation using semi-active tuned mass damper system and multi-objective fuzzy optimal control system [17]. Zahrai and Salehi (2014) studied the application of MR dampers in various structures [18]. Shariatmadar et al. (2015, 2014) studied active vibration control of buildings using tuned mass dampers and fuzzy logic algorithm considering soil-structure interaction [19, 20]. Bathaei et al. (2017) studied seismic vibration control of College bridge of Tehran-Iran using six MR dampers and fuzzy logic algorithm [21]. Ramezani et al. (2017) studied the design of fuzzy control parameters for semi-active control of tall buildings along with tuned mass dampers [22]. Bathaei et al. (2018) investigated semi-active seismic control of an 11-story building with MR damper and tuned mass damper using type 1 and type 2 fuzzy logic algorithms [23]. Ramezani et al. (2019) compared the fuzzy performance of types 1 and 2 using tuned mass damper and considering uncertainties [24].

In most of the systems, time delay leads to system performance reduction or even system instability; therefore, it should be considered in the control system process. Time delay is particularly important in semi-active and active control systems, as well as any other control system that utilizes sensors and data processing systems. Time delay in control system can occur in receiving, processing and applying force to the structure. The total time delay of a control system can be divided in two parts: first, accessing online information, processing and sending it from decision system to control actuators; secondly, time delay due to activation of electromechanical actuators, which leads to time delay in control process. The combination of these two time delays may have detrimental effect on the stability and performance of control system. Krasovskii (1963) was the first person to study the optimal control considering time delay [25]. Ross and Flugge-Lotz (1969) and Ross (1971) presented the optimal control rules for linear systems [26, 27]. In 1973, Nazaroff and Hewer investigated stabilization of time delays in systems [28]. Hammarstrom and Gros (1980) adapted different optimal control theories to systems with time delays [29]. Abdel-Rohman (1987) considered the effect of time delay in control system with direct feedback of velocity and instability of these control systems [30]. In their experiments, McGreevy et al. (1988) indicated the importance of time delays compensation [31], where the time delay of control system was recorded with active tendon of 40 milliseconds. Abdel-Rohman et al. (1993) studied the identification and vibration control of flexible structures [32]. In their studies, the maximum time delay was 4-step difference (sampling) between input and output data. Chung et al. (1995) studied time delay of structures with multi degrees of freedom using optimal control system and the quadratic objective function of Riccati equation [33]. Chu et al. (2002) investigated the effect of time delay on sustainability of a one degree of freedom system using an optimal feedback control system [34]. Ahmadizadeh et al. (2008) reviewed the common methods used to compensate time delays in combined control systems and proposed an improved method for overcoming time delays [35]. Alhazza et al. (2009) proposed a multi-mode delay feedback control method for single input and single-output systems to reduce free vibrations of cantilever beams [36]. Dong et al. (2009) used neural network to compensate time delay of magnetic dampers in car suspension system [37]. Abdel-Rohman et al. (2010) investigated the compensation of time delay effect in semi-active control system on a suspension bridge with simple supports equipped with tuned mass dampers at the middle of span [38]. Liu (2010) investigated time-fixed and time-variable time delays for linear systems using optimization algorithm of their stability [39]. Song et al. (2010) studied time delay in nonlinear systems using iterative heuristic algorithm to deal with time delays and damper saturation [40]. Mirafzal et al. (2015) studied active vibration control of a cantilever beam, despite time delay, using piezoelectric and genetic algorithms [41]. Bathaei et al. (2016) investigated seismic vibration control of College bridge using genetic algorithm and multiple tuned mass dampers [42]. Bathaei et al. (2022, 2024) presented floating fuzzy in semi-active control system and used predictive control algorithm to overcome time delays. [43-45].

According to the previous studies, optimal design or type 2 fuzzy logic algorithm are used to enhance the performance of fuzzy control systems in structural vibration control. Since the membership functions of fuzzy decision making systems are fixed, in the case of structural behavior change, adaptability of this type of controllers with structural behavior will be less during applied external loads, and the performance of control system will decline. Additionally, time delays in recording and sending structural motion data to decision system can lead to instability of the structure. In this study, to enhance fuzzy control system performance and to deal with complexities of nonlinear behavior of structures and time delay, the fuzzy logic algorithm is used with floating membership functions and structural behavior prediction. In this applied floating fuzzy system, the range of the input membership functions is variable and the fuzzy system is able to redesign at different moments. Changing the structural response will also change and redesign the membership function input range.

The structural behavior is predicted using structural dynamic equations and Diophantine prediction equation to achieve the desired goal. An 11 degrees of freedom structure is used here, considering its linear and nonlinear behavior under seven earthquakes with a maximum acceleration ranging from 0.1g to 1.0g in incremental steps of 0.1g. Two different types of decision-making system are used for the fuzzy control system: one based on roof velocity and another based on roof velocity and displacement of the structure. In the floating fuzzy, the range of definition and adjustment of membership functions is adjusted based on instantaneous input, to make the fuzzy decision making system more adaptable to the structural behavior and to produce the appropriate control force. In fuzzy decision making system with fixed membership functions for the whole seismic range, the input membership functions of fuzzy system are fixed; for the input data, a membership function is fuzzified and the output is determined based on it. In floating fuzzy, however, for each input, fuzzification is done based on the instantaneous membership function. The structural behavior is also predicted for the next 0.1s to asses the effect of 0.1s time delay on the vibration control process and evaluate the ability of predictive control to deal with these possible delays.

2. System model and disturbance model in predictive control

For a system with $u(t)$ input and $y(t)$ output, discrete transformation function can be considered as $G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})}$, therefore, for the system, equation (1) in the discrete time space can be indicated as:

$$y(t) = G(z^{-1})\,u(t) \quad \Leftrightarrow \quad A(z^{-1})\,y(t) = B(z^{-1})\,u(t) \tag{1}$$

In which,

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \ldots + a_{na} z^{-na}$$
$$B(z^{-1}) = b_1 z^{-1} + b_2 z^{-2} + \ldots + b_{nb} z^{-nb}$$

where, z^{-1} is the operator of discrete transformation function of z, and$a_1, a_2, \ldots, a_{na}$ and $b_1, b_2, \ldots, b_{na}$ are constant coefficients. The system prediction equation for the next k steps will be equal to:

$$\hat{y}(t+k|t) = \frac{B(z^{-1})}{A(z^{-1})} u(t+k|t) \tag{2}$$

In all structures and systems, disturbance is an integral part of the process model; therefore, selecting a disturbance model to display disturbance is as important as choosing a system model. A common model for considering disturbance is controlled auto-regressive integrated moving average (CARIMA); where the disturbance is difference between the measured output and the output calculated by the model. The disturbance model in CARIMA method is considered as equation (3):

$$n(t) = \frac{C(z^{-1})e(t)}{D(z^{-1})} \tag{3}$$

Polynomial $D(z^{-1})$ include $\Delta = 1 - z^{-1}$ integrator, defined as equation (4):

$$D(z^{-1}) = \Delta * A(z^{-1}) = (1 - z^{-1})A(z^{-1}) \tag{4}$$

$e(t)$ is white noise with zero mean, and the polynomial $C(z^{-1})$ is usually considered equal to one.

$$C(z^{-1}) = 1 \tag{5}$$

Hence, equation (3) is shown as follows (Eq. 6):

$$n(t) = \frac{1e(t)}{D(z^{-1})} \tag{6}$$

However, using the following Diophantine equation (Eq. 7) and replacement in Eq. (5), the disturbance model can be shown according to Eq. 8.

$$1 = E_k(z^{-1})\, D(z^{-1}) + z^{-k} F_k(z^{-1}) \tag{7}$$

$$n(t) = \frac{1e(t)}{D(z^{-1})} = \frac{[E_k(z^{-1})D(z^{-1}) + z^{-k}F_k(z^{-1})]\, e(t)}{D(z^{-1})} = E_k(z^{-1})\, e(t) + \frac{z^{-k}F_k(z^{-1})\, e(t)}{D(z^{-1})} \tag{8}$$

Prediction of k steps ahead the disturbance will be equal to:

$$n(t+k) = E_k(z^{-1})\, e(t+k) + \frac{z^{-k}F_k(z^{-1})\, e(t+k)}{D(z^{-1})} \tag{9}$$

where, $E_k(z^{-1})$ and $F_k(z^{-1})$ are polynomial expressions based on z^{-1}, calculated by solving Diophantine equation. $E_k(z^{-1})$is of $k-1$ degree and $F_k(z^{-1})$ of system order.

Using the property of the z transformation function (Eq. 10), and considering $e(t)$ as white noise and unpredictable, $e(t+k)$is also unpredictable and $E_k(z^{-1})\, e(t+k)$ is considered equal to zero. Finally, equation (11) is obtained.

$$z^{-k} e(t+k) = e(t) \tag{10}$$

$$n(t+k) = F_k(z^{-1})\, n(t) \tag{11}$$

Therefore, if the system model and disturbance model are combined, equation (12) is obtained, and prediction of k steps ahead the system even with disturbance model is expressed as eq. (13):

$$y(t) = \frac{B(z^{-1})}{A(z^{-1})} u(t) + n(t) \tag{12}$$

$$y(t+k) = \frac{B(z^{-1})}{A(z^{-1})} u(t+k) + n(t+k \mid t) = \frac{B(z^{-1})}{A(z^{-1})} u(t+k) + F_k(z^{-1})\, n(t) \tag{13}$$

In CARIMA model, $n(t)$ is equal to difference between measured output and the output calculated by the model (Eq. 14):

$$n(t) = y_M(t) - \frac{B(z^{-1})}{A(z^{-1})} u(t) \tag{14}$$

Replacing Eq. (14) in Eq. (13), and using the Diophantine equation and z transformation function properties, Eq. (15) is obtained, which represents the output prediction of system up to k steps ahead:

$$\hat{y}(t+k|t) = F_k(z^{-1})\, y_M(t) \tag{15}$$

Given that input $u(t+k)$ is k steps ahead of the system, and is not available, the expression is assumed to be zero.

Determining $F_k(z^{-1})$, the system output prediction can be obtained up to k steps ahead.

To predict displacement of 11 degrees of freedom structure, linear combination and superposition principle of non-involved degrees of freedom are used.

$$\{U^i_{t+k|t}\} = [\Phi]\{\hat{y}^i_{t+k|t}\} \tag{16}$$

Where, $U^i_{t+k|t}$ is displacement of i^{th} floor, $[\Phi]$ the mode shape matrix, and $\hat{y}^i_{t+k|t}$ is k steps ahead predicted displacement of i-th degree of freedom.

3. Modeling of an 11 degrees of freedom structure

Pourzeinali et al. (2007) presented the 11-story building used in this study (Fig. 1) [46]. Table 1 indicates its characteristics. The linear and nonlinear models of the structure are created in OpenSEES software. The natural period of the structure is equal to 0.89s, and structural damping is considered to be 2% according to the Rayleigh damping. The material of the nonlinear model of structure is considered as bilinear behavior in MATLAB, as shown in Fig. 2. The slope of nonlinear area of stress-strain curve is 0.02 times that of linear area. An equivalent cross-section is used in OpenSEES to model the stiffness of the structural elements. As indicated in Fig. 3, nonlinear beam-column element and the fiber section are used for modeling.

Table 1. Characteristics of the structure

Floor	Floor mass (kg)	Stiffness of floors (kN/m)
1st	215370	4.68E+5
2nd	201750	4.76E+5
3rd	201750	4.68E+5
4th	200930	4.5E+5
5th	200930	4.5E+5
6th	200930	4.5E+5
7th	203180	4.5E+5
8th	202910	4.37E+5
9th	202910	4.37E+5
10th	176100	4.37E+5
11th	66230	3.12E+5

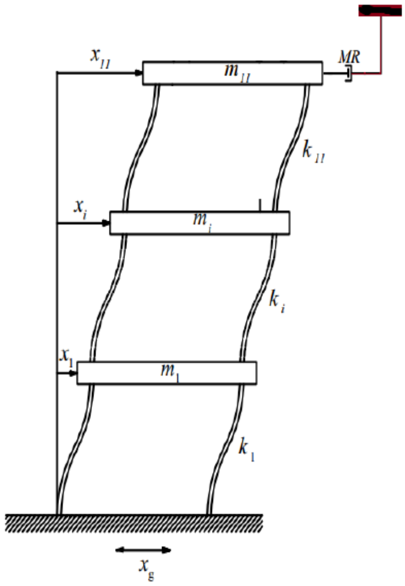

Fig. 1. Lumped mass simplified 11-DOF model of the structure.

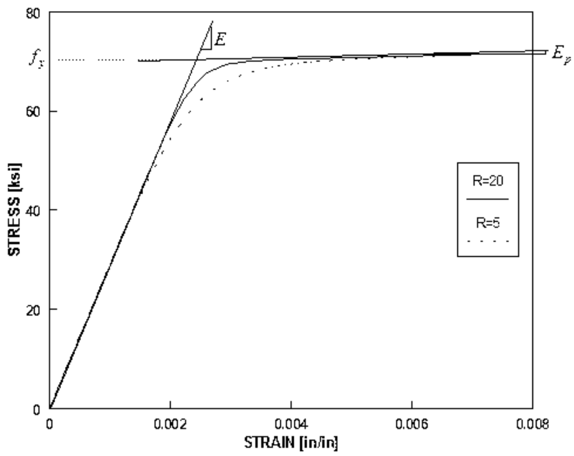

Fig. 2. Stress- strain curve for steel 02 material in OpenSEES.

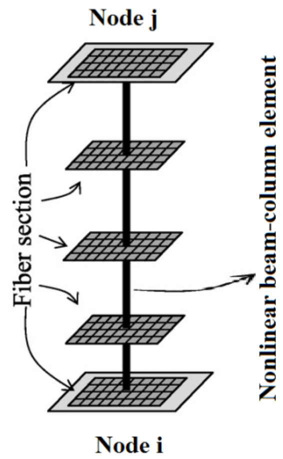

Fig. 3. Schematic of fiber section in OpenSEES.

The best place to install an MR damper is usually the first floor of the structure, between the roof and the foundation of structure, or between floors of the structure. In some studies, an MR damper has been installed between two adjacent structures with different dynamic behaviors. In this study, considering that roof of the structure experiences more displacement and velocity than other floors, an MR damper has been installed at the roof as a Sky Hook to show performance of the proposed control system.

4. Modeling of MR damper

The dampers used in this study are taken from dampers presented by Ok et al. (2007) with capacity of 100 tons [47]. To ensure the correct behavior of MR dampers in the numerical model, the two ends of dampers are subjected to a cyclic deformation, and the diagram of generated force is drawn for zero, 5, and 10 V voltages (Fig. 4). To model the MR damper behavior, its behavioral equations are solved as:

$$f = F = C_0\dot{x} + \alpha z \tag{17}$$

$$\dot{z} = -\gamma|x|z|\dot{z}|^{n-1} - \beta\dot{x}|z|^n + A_m\dot{x} \tag{18}$$

Where, F is damping force, x damping displacement, z evolutionary variable, and parameters n, γ, β and A_m are constant values obtained by testing on each damper. Parameters C_0 and α are determined using the following equations.

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \tag{19}$$

$$C_0 = C_0(u) = C_{0_a} + C_{0_b} u \tag{20}$$

where u is the applied control voltage and parameters α_a, α_b, C_{0_a} and C_{0_b} are constant values. Table 2 indicates the applied parameters and their values.

Table 2. Parameters of the MR damper model

Parameter	Value	Parameter	Value	Parameter	Value
α_a	0872.1×10^7 (N/m)	C_{0_b}	4400 (Ns/m/V)	β	300 (m^{-1})
a_b	9616.4×10^7 (N/m/V)	A_m	2.1	γ	300 (m^{-1})
C_{0_a}	440 (Ns/m)	n	1	η	50 (s^{-1})

According to the internal mechanism of MR dampers, these dampers cannot instantaneously apply command voltage; therefore, it always takes a short time for the applied voltage to equal the command voltage. Hence, the following equation is used to model this negligible time delay in the system.

$$\dot{u} = -\eta(u - v) \tag{21}$$

where, v is command voltage and η is a constant value.

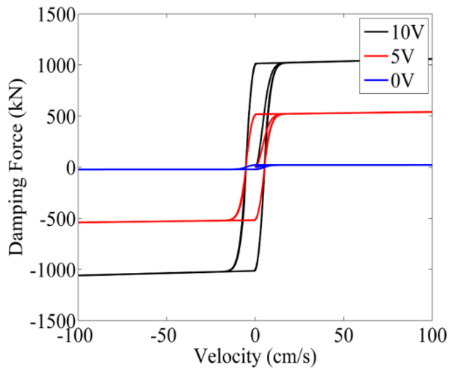

Fig. 4. Hysteretic behavior of an MR damper.

5. Fuzzy logic control algorithm

So far, a large number of control algorithms have been proposed for semi-active control systems, such as Skyhook or Lyapunov control algorithm, etc. These algorithms apply zero or maximum voltage to the structure and do not consider average levels. On the other hand, rapid voltage changes versus instantaneous loads increase the response of structure and possibility of local failure in parts of the structure. Therefore, there is a need for a control algorithm that gradually changes the required voltage. Fuzzy logic control system is an effective method to control the structural vibrations, which provides a simple and powerful framework for making decision despite uncertainties in complex nonlinear systems. Instead of complex mathematic equations, fuzzy control uses linguistic variables to express the relationship between input and output values. The inherent power and simplicity of fuzzy controllers have attracted most of the researchers. In this study, a fuzzy control algorithm with fixed and floating membership functions is used to adjust the voltage required to generate MR damping force. The main flowchart of the floating fuzzy controller is shown in Fig. 5. The fuzzy controller function depends on various design parameters, such as choice of membership function, the range of membership function, and definition of fuzzy rules. It is also important to have effective and reliable fuzzy rules to create a desired level. In this research, an MR damper is installed on the roof of 11-story building, and two decision-making systems are used to produce appropriate control force for different earthquake. First, making decision based on velocity, and second, making decision based on velocity-displacement of structure roof. The values of structure roof velocity and the velocity and displacement of structure roof are considered as input for fuzzy decision making system in the first and second control system, respectively. The outputs are generated based on the rules defined in fuzzy inference system. This output is the voltage required for generating control force by the damper. In a floating fuzzy system, the input membership functions are continuously updated and redesigned by comparing real-time structural responses with recorded responses up until time t (maximum velocity and displacement responses). The range of input membership functions is adjusted according to these maximum recorded responses.

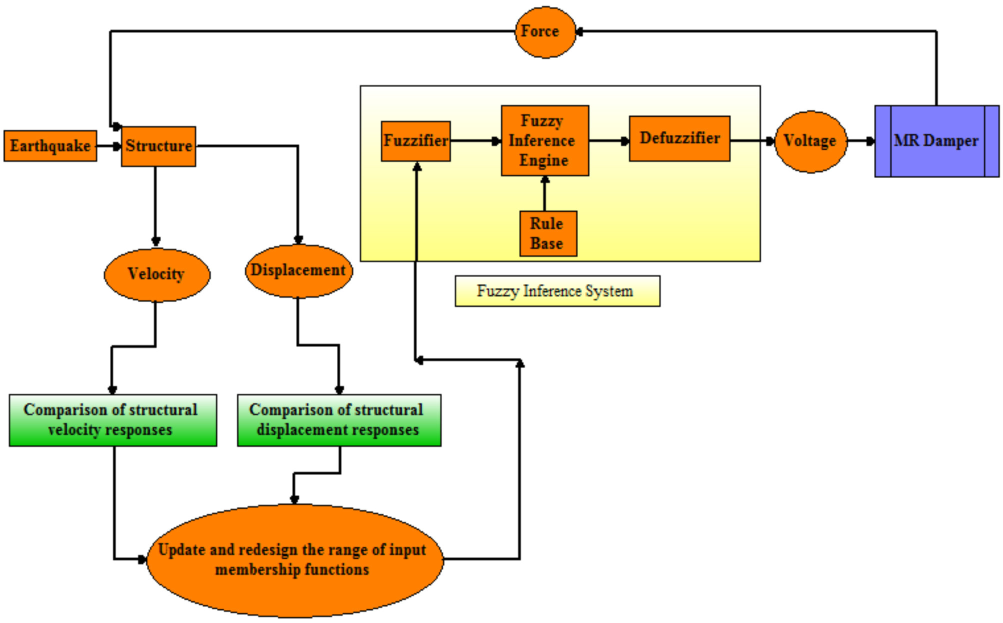

Fig. 5. Floating fuzzy inference system.

In the fuzzy logic algorithm, eleven different linguistic variables are used as the fuzzy decision making system inputs. These linguistic variables are named NVL, NL, NM, NS, NVS, ZO, PVS, PS, PM, PL and PVL, which represent the values described in Table 3.

Table 3. Description of fuzzy linguistic variables considered for input membership functions

Linguistic variable	PVL	PL	PM	PS	PVS	ZO	NVS	NS	NM	NL	NVL
Velocity and displacement values	Positive very large	Positive large	Positive medium	Positive small	Positive very small	Zero	Negative very small	Negative small	Negative medium	Negative large	Negative very large

In this fuzzy system, the output parameter is the same as the voltage applied to MR dampers. For the output parameter, six different fuzzy sets are considered. These sets are shown in Table 4.

Table 4. Description of fuzzy linguistic variables considered for output membership functions

Linguistic variable	VL	L	M	S	VS	ZO
Voltage values	Very large	Large	Medium	Small	Very small	Zero

The dynamic analysis cycle of fuzzy system and semi-active control is indicated in Fig. 6.

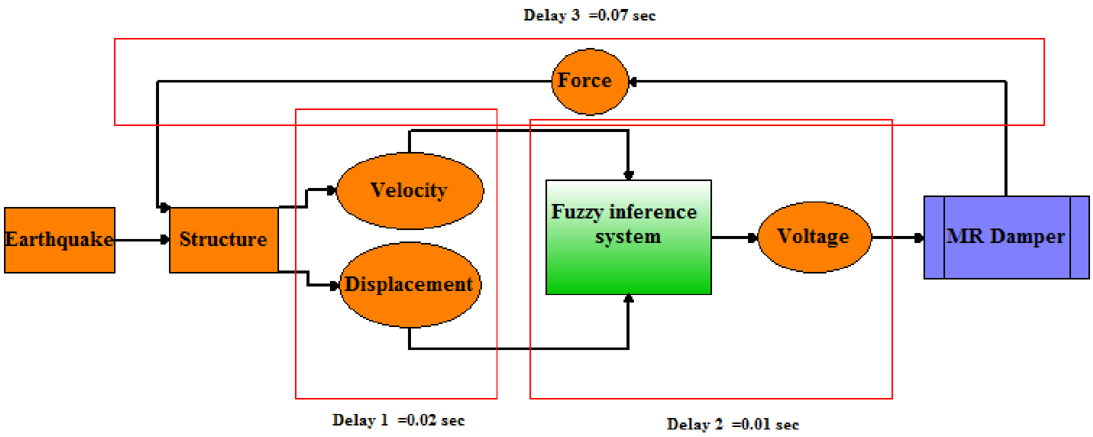

Fig. 6. Dynamic analysis cycle of fuzzy system and time delay in the control process.

Input parameters for the fuzzy inference system (FIS) are the relative velocity and relative displacement of the two ends of MR damper, indicated by RelVel and Disp, respectively. The output is voltage. Figs. 7 and 8 indicate the input and output membership functions defined for the fuzzy system and making decision based on roof velocity of the structure, respectively. For a fuzzy control system with making decision based on roof velocity-displacement of the structure, the membership function of input velocity and output voltage are as in Figs. 7 and 8, and the input membership function of displacement is shown in Fig. 9.

The linear and nonlinear model of the structure used in this study have been created in OpenSEES, and MATLAB is used to implement the fuzzy logic algorithm. These two software programs are connected by TCP/IP method [23], which establishes a connection network where server can communicate with the client using a special channel. This connection continues until the end of applied earthquake.

Tables 5 and 6 represent the rule bases (RB) of the fuzzy inference system based on velocity and velocity-displacement, respectively. The graphic forms of these sets of rules are shown in Figs. 10 and 11, respectively.

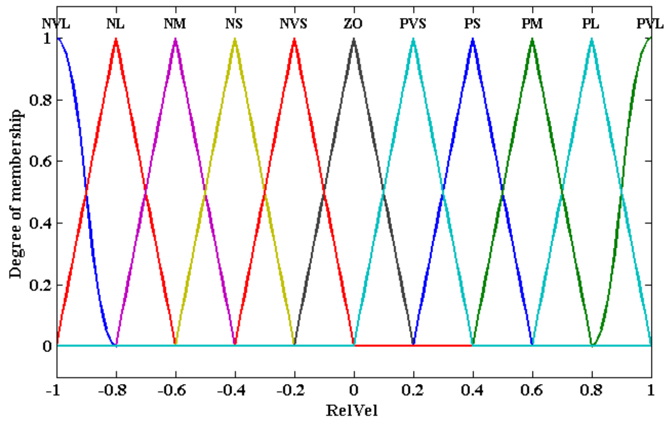

Fig. 7. Input membership function of the fuzzy system.

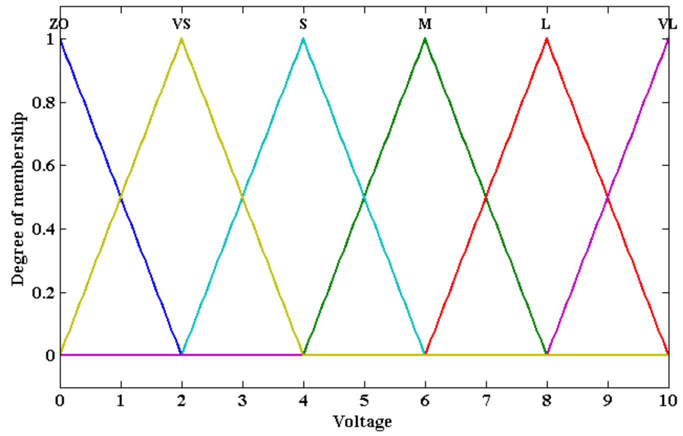

Fig. 8. Output membership function of the fuzzy system.

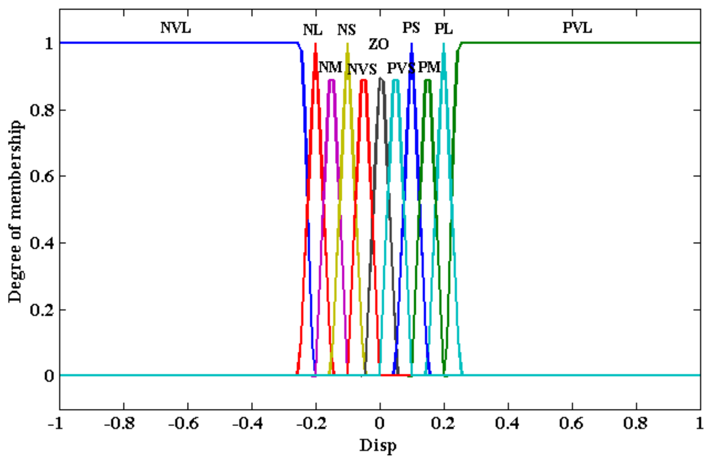

Fig. 9. Input membership function of the fuzzy system.

Table 5. Matrix representation of set of rules based on velocity

	Relative velocity of two ends of damper (RelVel)										
	NVL	NL	NM	NS	NVS	ZO	PVS	PS	PM	PL	PVL
Voltage	VL	L	M	S	VS	ZO	VS	S	M	L	VL

Table 6. Matrix representation of set of rules based on velocity-displacement

		Relative displacement of two ends of damper (Disp)										
		NVL	NL	NM	NS	NVS	ZO	PVS	PS	PM	PL	PVL
Relative velocity of two ends of damper (RelVel)	PVL	L	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
	PL	M	L	VL	VL	VL	VL	VL	VL	VL	VL	VL
	PM	S	M	L	VL	VL	VL	VL	VL	VL	VL	VL
	PS	VS	S	M	L	VL	VL	VL	VL	VL	VL	VL
	PVS	ZO	VS	S	M	L	VL	VL	VL	VL	VL	VL
	ZO	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
	NVS	VL	VL	VL	VL	VL	VL	L	M	S	VS	ZO
	NS	VL	VL	VL	VL	VL	VL	VL	L	M	S	VS
	NM	VL	VL	VL	VL	VL	VL	VL	VL	L	M	S
	NL	VL	VL	VL	VL	VL	VL	VL	VL	VL	L	M
	NVL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	L

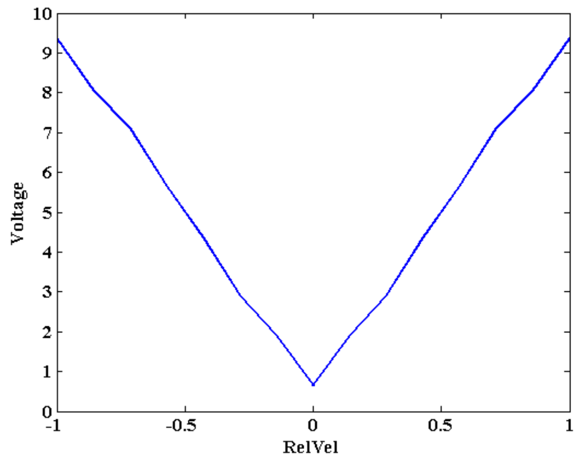

Fig. 10. Graphical representation of the fuzzy inference system with making decision based on velocity.

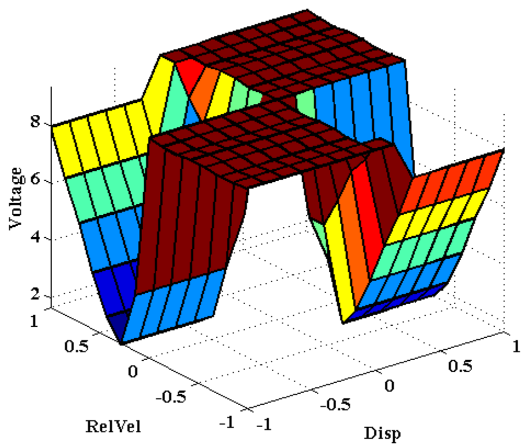

Fig. 11. Graphical representation of the fuzzy inference system with making decision based on velocity and displacement.

6. Time delay in fuzzy control system

Time delays in control systems may occur at different levels of control process. In this study, time delay in the fuzzy control system is considered as a flowchart in Fig. 6.

The first time delay occurs during data recording and sending to the fuzzy control system, while the second one is related to data processing by the fuzzy decision making system and selection of appropriate control voltage. The third time delay happens after receiving control voltage by damper and converting it to the force applied to the structure. In order to overcome time delays considered in the control process of linear and nonlinear structural vibrations, the actions are taken according to the flowchart presented in Fig. 12. The linearity and nonlinearity of element in different stories are examined by recording structural motion in different stories and calculating the inter-story drift. If any element of the structure under the applied seismic force converts to nonlinear and enters the plastic area, the stiffness amount of that element in prediction model changes to 2% of the initial stiffness and response of the structure is predicted by the updated model. The predicted values for structural displacement and velocity in the 11th story of structure are sent to fuzzy inference system, to calculate the appropriate control voltage by covering time delay, and send it to the MR damper.

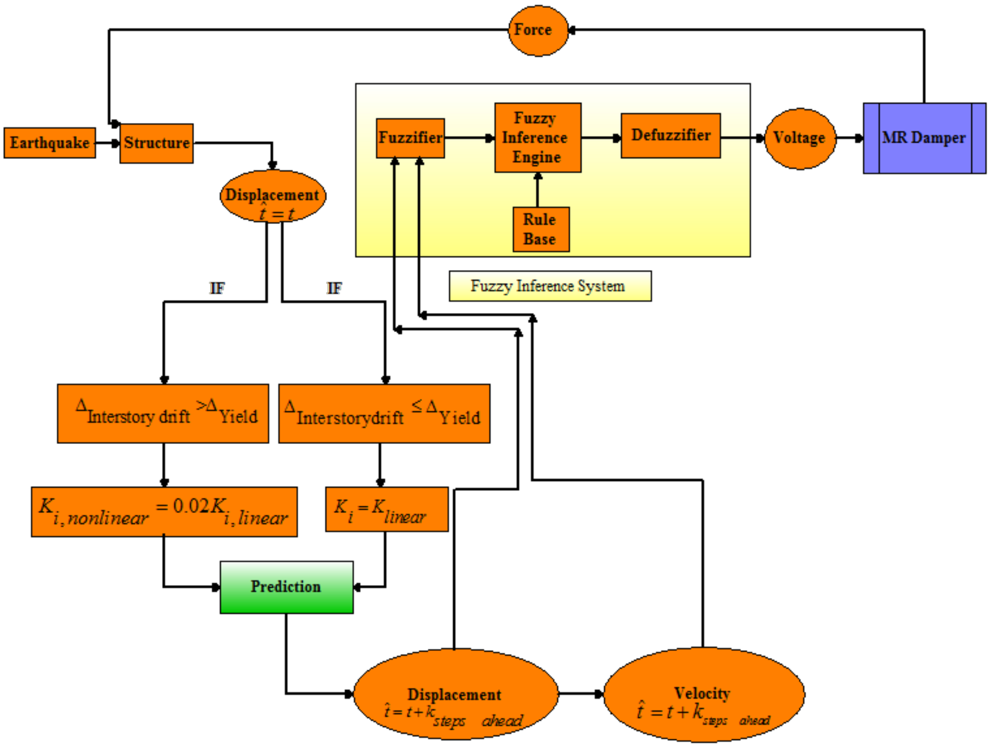

Fig. 12. Vibration control process with time delay and prediction.

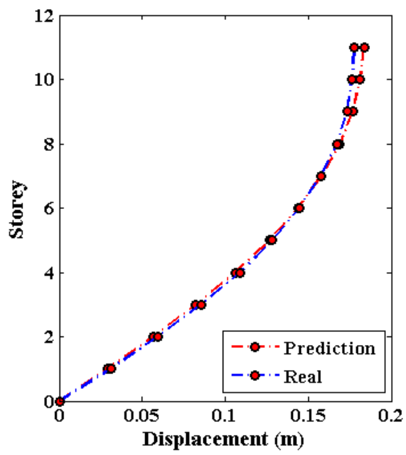

Fig. 13. Inter-story drift of the structure subjected to the Northridge earthquake with maximum acceleration of 0.5g.

Fig. 13 compares the inter-story drift of the structure in real time and prediction of 10 steps ahead, subjected to the Northridge earthquake with maximum acceleration of 0.5g. The maximum prediction error is 5.54% which occurred in the first floor of the structure. Prediction error values are shown in Table 7.

Table 7. Accuracy of inter-story drift prediction subjected to the Northridge earthquake with maximum acceleration of 0.5g

Story	Drift (Real)	Drift (Prediction)	Difference of inter-story drift (%)
1	0.0098	0.0103	5.54
2	0.0189	0.0198	4.82
3	0.0274	0.0285	3.95
4	0.0353	0.0364	2.85
5	0.0422	0.0428	1.40
6	0.0480	0.0482	0.34
7	0.0526	0.0525	0.23
8	0.0564	0.0557	1.14
9	0.0590	0.0578	2.01
10	0.0604	0.0589	2.63
11	0.0612	0.0592	3.16

7. Earthquakes applied to the structure for dynamic analysis

In order to study the behavior of structure and proposed control system, the structure has been exposed to seven earthquakes. The applied earthquakes are selected from FEMA P695 guideline and their characteristics are presented in Table 8. The maximum acceleration of earthquakes applied to the structure ranges from 0.1 g to 1.0 g with incremental step of 0.1g.

Table 8. Earthquakes applied to the structures

No	Earthquake	Station	M	Year	PGA
1	Northridge	Canyon Country-WLC	6.7	1994	0.48
2	Duzce, Turkey	Bolu	7.1	1999	0.82
3	Hector Mine	Hector	7.1	1999	0.34
4	Imperial Valley	El Centro Array #11	6.5	1979	0.38
5	Kobe, Japan	Nishi-Akashi	6.9	1995	0.51
6	Kocaeli, Turkey	Duzce	7.5	1999	0.36
7	Loma Prieta	Capitola	6.9	1989	0.53

8. Numerical results and discussion

In order to evaluate the performance of considered control systems, the earthquakes presented in Table 8 are applied to the structure with maximum acceleration of 0.1g to 1.0 g. As an example, roof displacement responses of the structure with linear and nonlinear behavior are shown in Figs. 14-17 subjected to the Kocaeli earthquake in Turkey with maximum acceleration of 0.5g. Figs. 14 and 15 indicate the results of a fuzzy making decision system based on roof velocity and displacement of the structure, where the maximum displacement is recorded on the roof in the absence of MR damper and control system. In absence of time delay in the control system, floating and fixed fuzzy systems have almost the same responses. With time delay, the response of structure increases while the performance of control system decreases. In Fig. 15, where the control system is installed in the nonlinear structure, the structure without MR damper exhibits significant response; furthermore, as it enters to nonlinear area, the vibrations of the structure are around the plastic hinge and the residual displacement in the structure is evident.

Despite the time delay in control system and the use of the predictive control system, the structural response is closer to that without time delay state. The considered time delay is covered with prediction of structural behavior. The predictive control system in nonlinear behavior mode updates the nonlinear model of the structure at each step of dynamic analysis and predicts 10 steps ahead.

Making decision system in Figs. 16 and 17 is based on the roof velocity of the structure. In the linear structure (Fig. 16), there is no residual displacement because the structure returns to zero displacement (stationary state) after the end of the seismic load. The better performance of the fuzzy prediction system is understandable with a time delay in the control system (Fig. 16). In the linear structure, where there are no changes in dynamic equations and structural seismic behavior, predictions are more accurate than in nonlinear structure. Prediction of structural behavior when it enters to the nonlinear area, requires updating the structure model and its dynamic equations, which reduces the accuracy of prediction and overcoming time delays in the control system. Although it is difficult to predict nonlinear behavior of the structure, and more analysis time is required, it is possible to control structural vibrations along with time delay and improve the structural response.

The average maximum roof displacement responses of the structure subjected to the effect of seven earthquakes applied to the structure are shown in Figs. 18 and 19 for the linear and nonlinear models of the structure, respectively. As the maximum acceleration applied to the structure increases, so does its response. The structure response figure for no damper in the model is completely linear and ascending, but for the structure with the fuzzy control system, the acquired responses are not necessarily linear due to the nonlinearity of the fuzzy decision-making system. According to Fig. 18, the best performance of the control system is in the absence of time delay and use of floating fuzzy. Time delay at low accelerations has greater effect on performance of the control system; by increasing the maximum acceleration applied to the structure and increasing structural response, time delay has less effect on performance of the control system. In the nonlinear model of the structure, the best performance is also achieved with a floating fuzzy making decision system without time delay. Diagrams of Figs. 20 and 21 are similar to Figs. 18 and 19 except that their fuzzy making decision system is based on roof velocity of the structure.

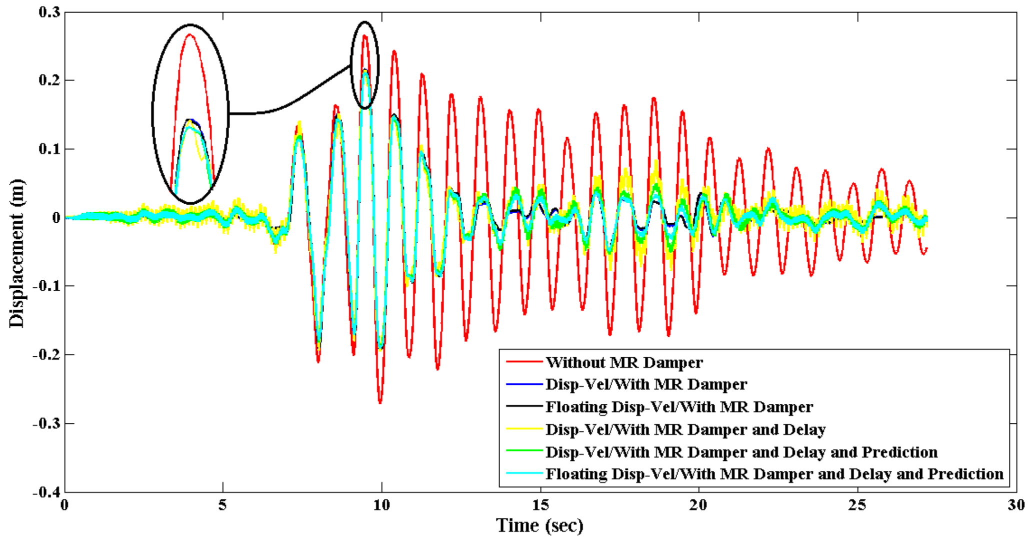

Fig. 14. Roof displacement response of the structure with linear behavior under the Kocaeli earthquake, by maximum acceleration of 0.5g and fuzzy inference system based on velocity-displacement.

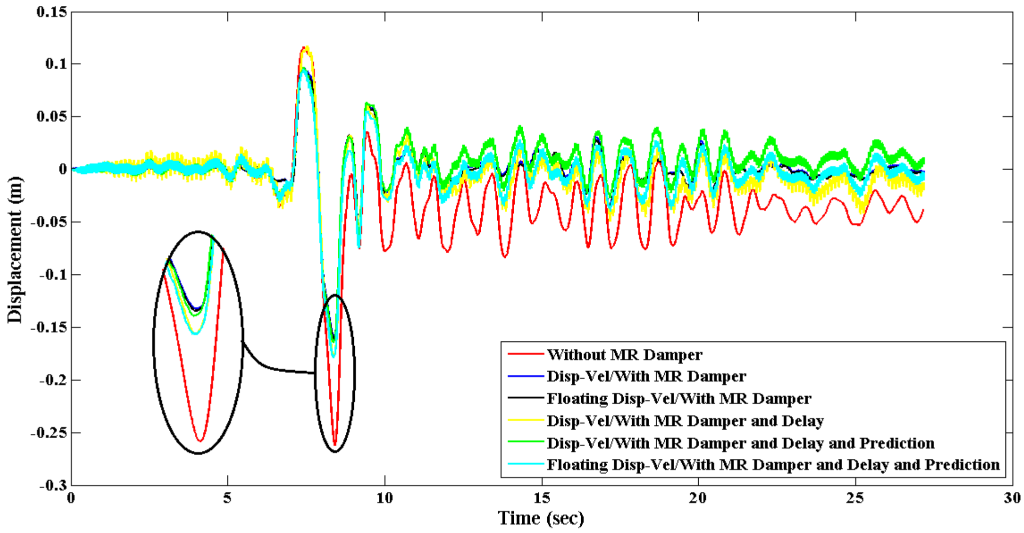

Fig. 15. Roof displacement response of the structure with nonlinear behavior under the Kocaeli earthquake, by maximum acceleration of 0.5g and fuzzy inference system based on velocity-displacement.

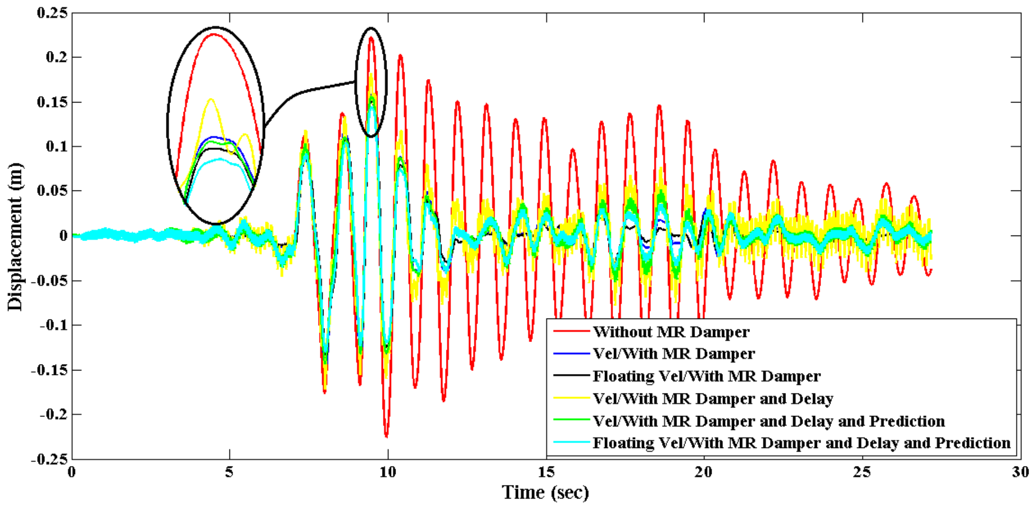

Fig. 16. Roof displacement response of the structure with linear behavior under the Kocaeli earthquake, by maximum acceleration of 0.5g and fuzzy inference system based on velocity.

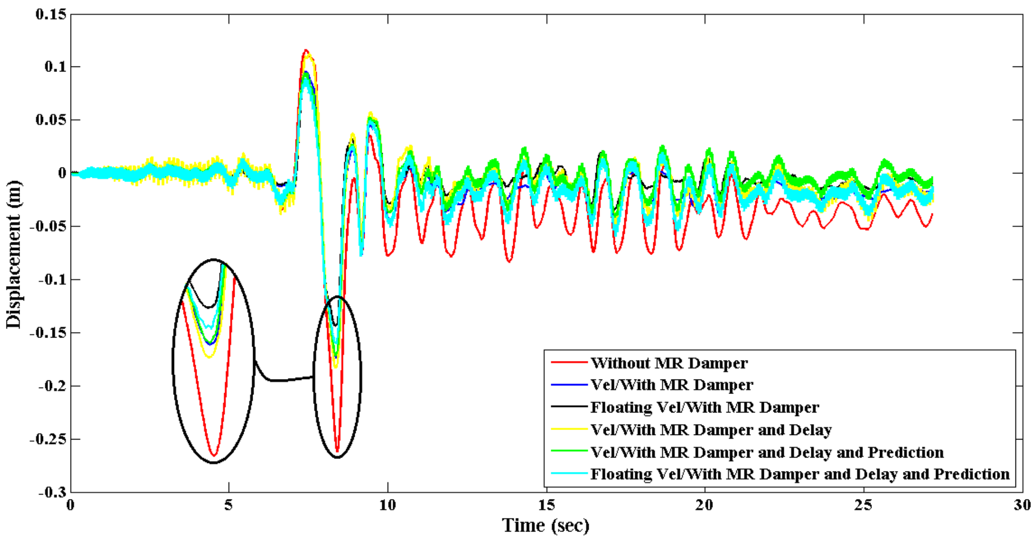

Fig. 17. Roof displacement response of the structure with nonlinear behavior under the Kocaeli earthquake, by maximum acceleration of 0.5g and fuzzy inference system based on velocity.

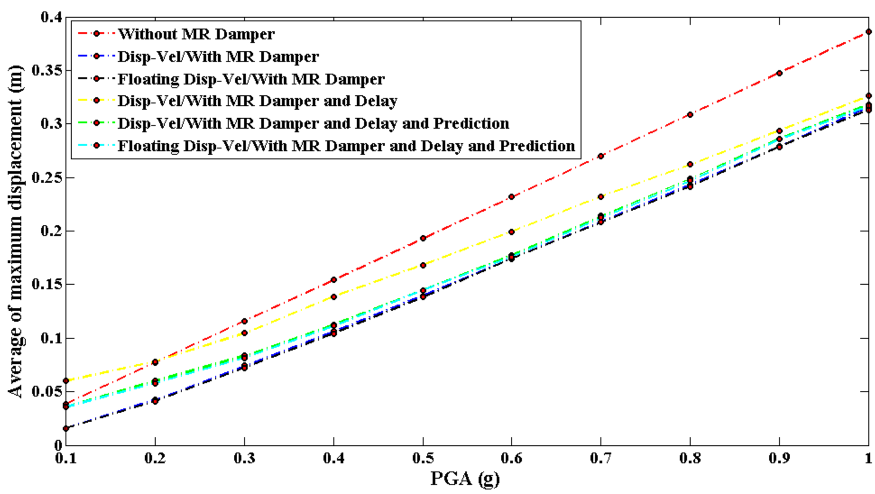

Fig. 18. Average of maximum roof displacement for structure with linear behavior under the applied earthquakes with fuzzy making decision system based on velocity-displacement.

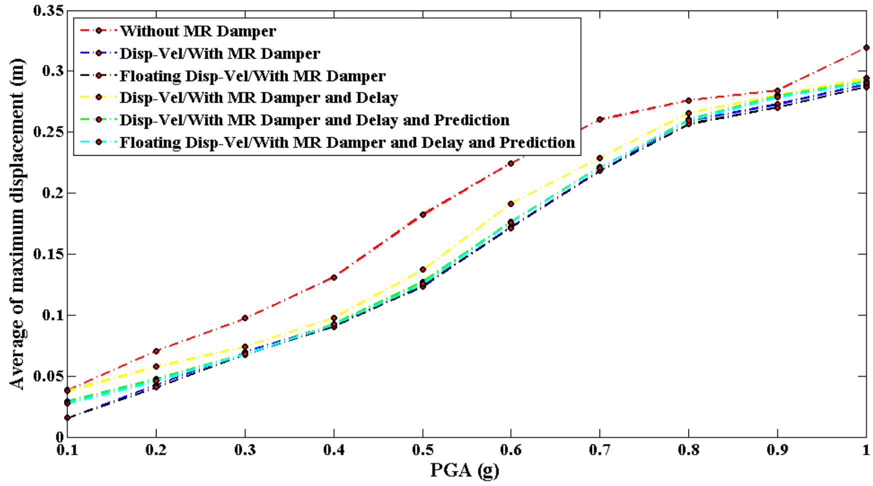

Fig. 19. Average of maximum roof displacement for structure with nonlinear behavior under the applied earthquakes with fuzzy making decision system based on velocity-displacement.

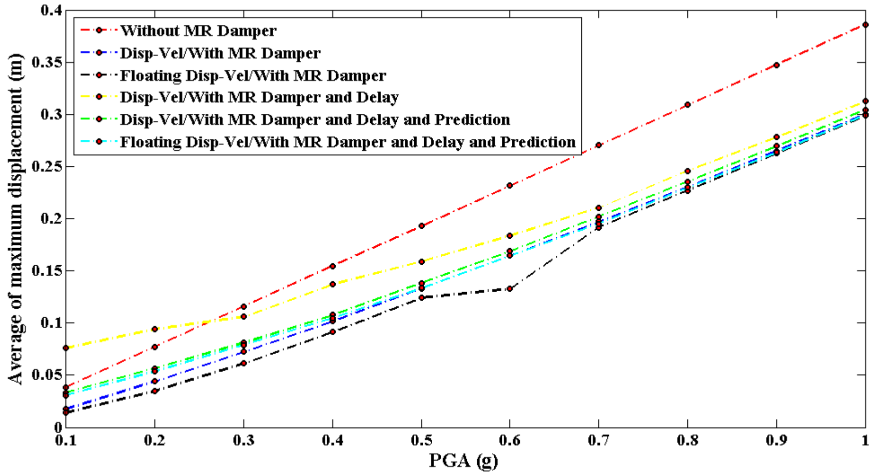

Fig. 20. Average of maximum roof displacement for structure with linear behavior under the applied earthquakes with fuzzy making decision system based on velocity.

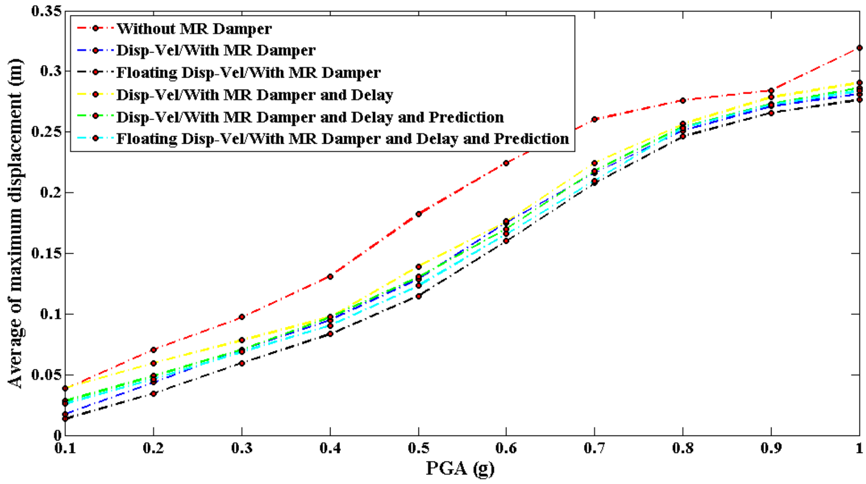

Fig. 21. Average of maximum roof displacement for structure with nonlinear behavior under the applied earthquakes with fuzzy making decision system based on velocity.

Diagrams of Figs. 22 and 23 show the average base shear versus maximum earthquake accelerations applied to the structure with nonlinear behavior. In both making decision systems, the base shear has almost no increases after reaching a maximum acceleration of 0.5g, while the structural elements flow in nonlinear area or plastic range and result in increased displacement responses of the structure. Time delay in the control system not only increases the structural response but leads to faster entry into the nonlinear area and material yielding.

Tables 9 and 10 represent the average improvement percentage of roof displacement response in structures with linear and nonlinear behavior using a fuzzy making decision system based on roof velocity and displacement of the structure. Tables 11 and 12 represent the average improvement of roof displacement response in structures with linear and nonlinear behavior using a fuzzy making decision system based on roof velocity of the structure. With increase maximum acceleration of applied earthquakes, improvement percentage decreases in results. By employing floating and predictive fuzzy, time delays considered in control process are covered. The main factor in the appropriate performance of a floating fuzzy system compared to a fixed fuzzy system is its variability at any time relative to the input data and its instantaneous redesign. In a floating fuzzy making decision system, the input membership functions are constantly changing, and with each new input, the range of input membership function changes to be able to apply the most appropriate control force to the structure; while, in the fuzzy making decision system with fixed membership function, the membership functions are fixed for the entire during of the applied earthquakes and the range of fuzzy inputs do not change, so fixed fuzzy adaptability is less than the floating fuzzy and its performance is reduced. With the increase of maximum seismic acceleration, the improvement percentage of performance in considered control systems has decreased, the main reason of which is increase of force applied to the structure and the constant capacity of MR damper.

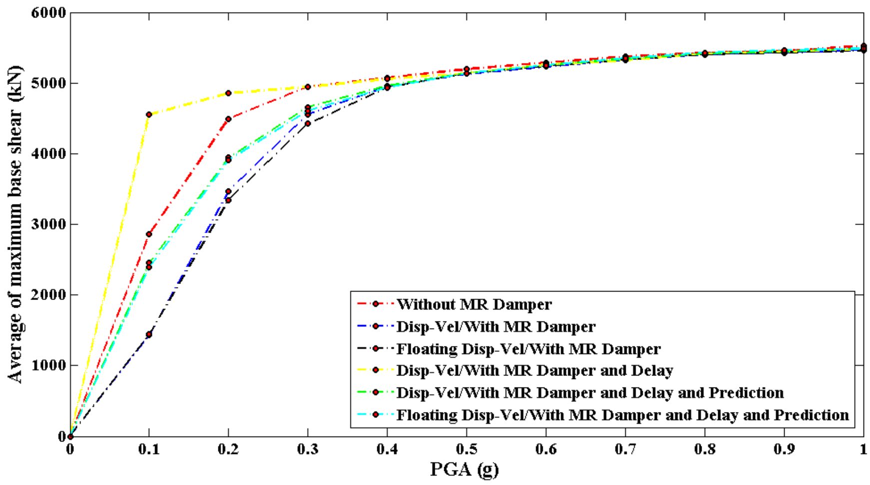

Fig. 22. Average of maximum base shear for the structure with nonlinear behavior under the applied earthquakes with fuzzy making decision system based on velocity-displacement.

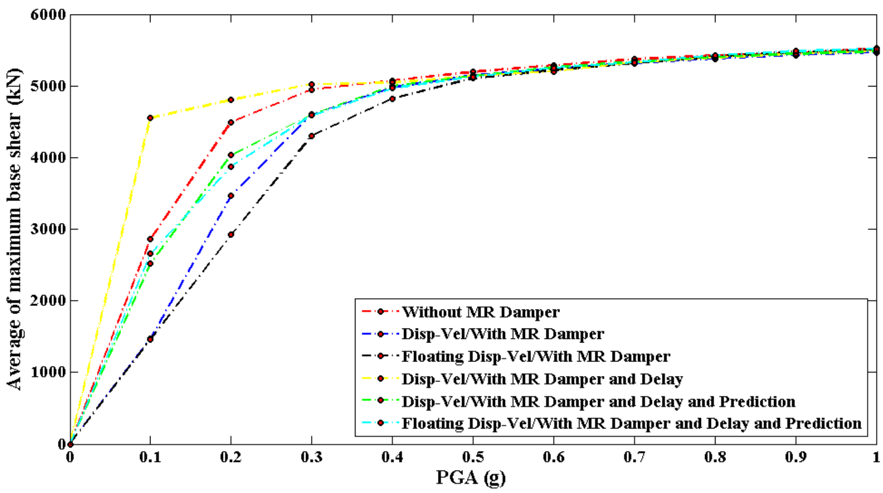

Fig. 23. Average of maximum base shear for the structure with nonlinear behavior under the applied earthquakes with fuzzy making decision system based on velocity.

Table 9. Average improvement percentage for displacement response in linear structure with fuzzy making decision system based on roof velocity and displacement of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	59.01	59.50	-55.68	6.24	8.17
0.2	44.99	46.59	-0.96	22.17	25.06
0.3	35.81	37.78	9.58	27.72	29.74
0.4	31.21	32.62	10.14	26.98	27.77
0.5	27.60	28.27	12.85	25.00	25.12
0.6	24.81	24.92	13.99	23.36	24.19
0.7	22.86	23.01	14.09	20.74	21.43
0.8	21.25	21.83	15.16	19.43	20.03
0.9	19.67	19.79	15.52	17.59	17.83
1.0	18.21	18.88	15.57	17.55	17.95

Table 10. Average improvement percentage for displacement response in nonlinear structure with fuzzy making decision system based on roof velocity and displacement of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	58.96	59.65	1.94	23.59	28.91
0.2	39.89	42.32	18.28	32.63	35.08
0.3	28.80	30.69	23.86	30.11	30.18
0.4	29.88	30.96	25.17	29.28	29.63
0.5	32.32	32.09	24.73	30.06	31.18
0.6	23.25	23.65	14.71	21.47	21.59
0.7	16.08	16.21	11.98	15.03	15.13
0.8	6.19	7.02	3.74	5.76	5.99
0.9	3.94	4.84	1.35	1.48	1.83
1.0	9.44	10.03	7.91	8.80	8.94

Tables 13-16 indicate the average improvement in base shear of the structure in different control systems. Time delay increases the base shear. With a time delay in control system, the damper applies force to the structure in the same direction of structure motion, which is a factor in increasing base shear and rapid entry of structure to nonlinear area. The results of base shear in linear structure (Tables 13 and 15) show a greater increase with time delay in control process than nonlinear structure (Tables 14 and 16). In nonlinear structure with increasing the maximum acceleration of applied earthquakes, the elements of structure enter to nonlinear area and the base shear remains almost constant.

The average improvement percentage of the roof displacement RMS and base shear is indicated in Figs. 24 and 25, respectively. Since dispersion and the amount of responses in linear structures are more than nonlinear structures, therefore, RMS of displacement and base shear in linear structure is more than nonlinear structure.

Table 11. Average improvement percentage for displacement response in linear structure with fuzzy making decision system based on roof velocity of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	55.32	63.27	-96.34	14.05	20.80
0.2	42.97	55.20	-21.52	26.67	30.45
0.3	37.32	47.18	8.32	29.88	31.87
0.4	34.01	40.76	11.33	30.34	32.16
0.5	31.10	35.77	17.62	28.35	30.91
0.6	29.00	42.76	20.79	27.15	29.03
0.7	27.08	29.02	22.17	25.25	27.74
0.8	25.38	26.53	20.43	23.80	25.53
0.9	23.78	24.42	20.01	22.47	24.14
1.0	22.32	22.62	19.03	21.18	22.51

Table 12. Average improvement percentage for displacement response in nonlinear structure with fuzzy making decision system based on roof velocity of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	54.54	64.68	-1.11	26.49	32.22
0.2	38.03	51.38	15.62	30.85	34.54
0.3	27.80	39.11	19.87	27.70	29.44
0.4	27.65	36.29	25.64	25.61	30.79
0.5	29.40	37.09	23.77	28.36	32.32
0.6	22.08	28.80	21.55	24.23	26.18
0.7	16.93	20.16	13.76	16.35	19.45
0.8	9.04	10.80	7.02	8.04	8.32
0.9	4.49	6.37	1.85	4.01	4.09
1.0	11.90	13.43	9.09	10.27	11.11

The roof displacement response of the structure with fuzzy control system subjected to the Duzce earthquake in Turkey with a maximum acceleration of 0.4g is indicated in Fig. 26. Figures of the floating fuzzy rules in making decision based on velocity for the Duzce earthquake in Turkey, Bolu station, with maximum acceleration of 0.4g at t=2.35 sec, t=5.06 sec, t=7.47 sec, t=7.71 sec and t=7.89 sec, and for making decision system based on velocity-displacement at t=7.71 sec are represented in Figs. 27 and 28, respectively.

9. Conclusion

In this study, two different making decision systems are used to investigate the effect of time delay on semi-active vibration control of 11-story building using MR damper. Roof velocity and roof velocity and displacement of the structure are used in the first and second making decision systems, respectively. A floating fuzzy control system is used to enhance performance of fuzzy control system. In this floating fuzzy control system, the range of input membership functions for velocity and displacement is considered variable, and the floating fuzzy has the ability to redesign and update the range of membership functions. To overcome time delay in the vibration control process, predictive control system has been used from the time of recording structure motion data until applying the force to the structure. The time delay considered in the vibration control process is 0.1 sec, which requires 10 prediction steps with a time step of 0.01sec to cover it. Both fixed and floating fuzzy control system have been implemented on an 11-story structure with linear and nonlinear behavior, subjected to 7 earthquakes with maximum acceleration of 0.1-1.0g.

Table 13. Average improvement percentage of maximum base shear in linear structure with fuzzy making decision system based on roof velocity and displacement of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	50.13	49.22	-264.05	1.62	3.21
0.2	37.55	41.31	-93.20	4.38	19.91
0.3	29.12	33.32	-45.30	9.66	25.24
0.4	22.61	25.60	-32.51	16.55	20.42
0.5	20.17	21.45	-12.46	14.91	19.45
0.6	18.61	19.02	-2.31	13.61	16.00
0.7	17.21	17.41	0.22	15.22	15.92
0.8	16.41	16.14	2.79	12.66	15.08
0.9	15.86	15.02	5.68	12.78	13.76
1.0	15.03	14.29	9.15	12.61	13.89

Table 14. Average improvement percentage of maximum base shear in nonlinear structure with fuzzy making decision system based on roof velocity and displacement of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	49.97	49.51	-58.92	14.30	16.45
0.2	22.84	25.70	-8.00	12.32	13.07
0.3	7.88	10.51	0.06	5.82	6.83
0.4	2.43	2.69	0.35	2.25	2.80
0.5	1.15	1.07	1.08	1.06	1.08
0.6	1.15	1.00	0.67	0.75	0.79
0.7	0.75	0.78	0.83	0.44	0.28
0.8	0.36	0.29	0.06	0.09	-0.19
0.9	0.49	0.32	0.31	0.21	-0.21
1.0	1.06	1.10	0.75	0.63	0.69

Based on the results of incremental dynamic analysis for the linear structure without time delay in the fuzzy control system based on roof velocity and displacement of the structure, on average, the floating fuzzy control system has reduced roof displacement response by 31.31% compared to the uncontrolled system. With time delay in the control system and using a fuzzy making decision system based on roof velocity and displacement of the structure, as well as predictive control, there is an average improvement of 20.67% in roof displacement response compared to uncontrolled case, and with floating fuzzy it is about 21.72%. The same values for a nonlinear structure are 25.74, 19.82 and 20.84%, respectively. In vibration control of structures with linear behavior and without time delay in the control system based on roof velocity of the structure, on average, the floating fuzzy control system has improved roof displacement response of the structure by 38.75% compared to the uncontrolled system. Compared to the uncontrolled system, the average improvement percentage of roof displacement response of the structure with time delay and using fuzzy making decision system based on roof velocity and predictive control is about 24.91%, and 27.51% when using floating fuzzy. The same values for a nonlinear structure are 30.81, 20.19, and 22.84%, respectively.

Table 15. Average improvement percentage of maximum base shear in linear structure with fuzzy making decision system based on roof velocity of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	49.59	47.81	-396.65	3.59	3.52
0.2	37.63	49.24	-164.60	7.04	7.05
0.3	31.16	40.92	-84.09	17.16	19.01
0.4	28.11	33.99	-51.73	21.17	23.51
0.5	25.62	28.67	-25.70	20.80	22.64
0.6	24.18	35.01	-10.39	20.89	21.90
0.7	22.75	22.08	-4.70	19.91	21.07
0.8	21.53	20.21	-0.96	19.05	20.24
0.9	20.26	18.65	5.55	18.57	19.91
1.0	19.15	17.36	9.18	17.99	19.76

Table 16. Average improvement percentage of maximum base shear in nonlinear structure with fuzzy making decision system based on roof velocity of the structure

PGA(g)	Improvement percentage (%)				
	With MR damper/uncontrolled	With MR damper (floating)/uncontrolled	With MR damper and delay/uncontrolled	With MR damper and delay and prediction/uncontrolled	With MR damper and delay and prediction (floating)/uncontrolled
0.1	48.48	48.87	-58.96	11.90	17.26
0.2	22.83	34.97	-6.88	10.30	13.83
0.3	6.92	13.02	-1.63	6.73	6.80
0.4	1.89	4.96	0.57	1.44	1.51
0.5	0.89	1.69	1.04	1.02	1.27
0.6	0.95	1.32	1.01	1.08	1.15
0.7	0.86	1.05	0.81	0.84	0.85
0.8	0.73	0.89	0.58	0.63	0.65
0.9	0.55	0.62	0.13	0.31	0.35
1.0	1.06	1.38	0.79	0.91	0.99

According to the results of incremental dynamic analysis of structure with linear behavior and without time delay in fuzzy control system based on roof velocity and displacement of the structure, on average, floating fuzzy control system has improved base shear by 25.27% compared to the uncontrolled structure. With time delay in the control system and using fuzzy making decision system based on roof velocity and displacement of the structure and predictive control, the average improvement of base shear is 11.40% compared to the uncontrolled system, which increases to 16.28% when using floating fuzzy. The same values for a nonlinear structure are 9.29, 3.78 and 4.15%, respectively. In vibration control of the structure with linear behavior and without time delay in the control system based on roof velocity of the structure, on average, the floating fuzzy control system has improved base shear by 31.39% compared to the uncontrolled structure. With time delay in the control system and using fuzzy making decision system based on roof velocity of the structure and predictive control, the average improvement of roof displacement response of the structure is 16.16% compared to the uncontrolled systems, ; this further increases to 17.86% when using floating fuzzy. The same values in structure with nonlinear behavior are 10.87, 3.51, and 4.46%, respectively. The average root mean square (RMS) of roof displacement response and base shear increased with time delay in the control system.

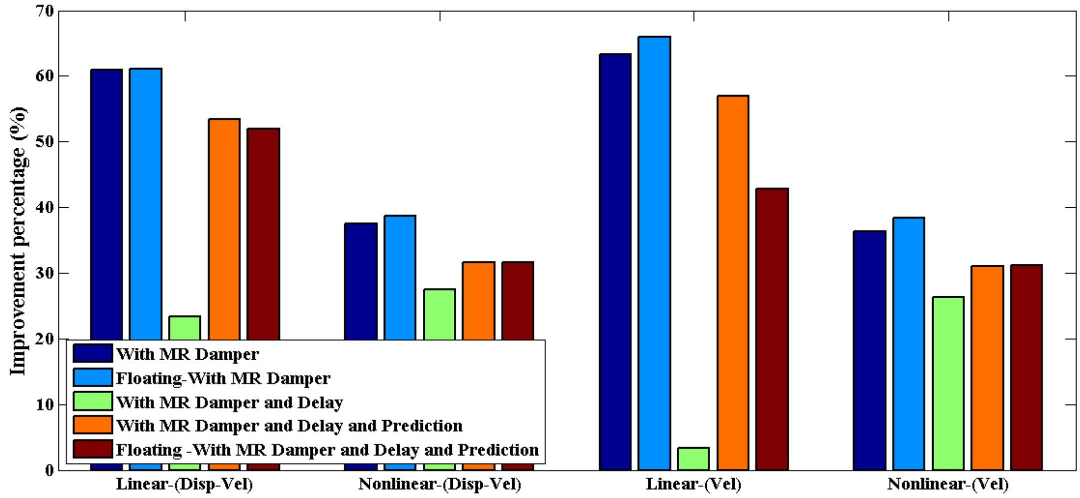

Fig. 24. Average improvement percentage of roof displacement RMS subjected to applied earthquakes.

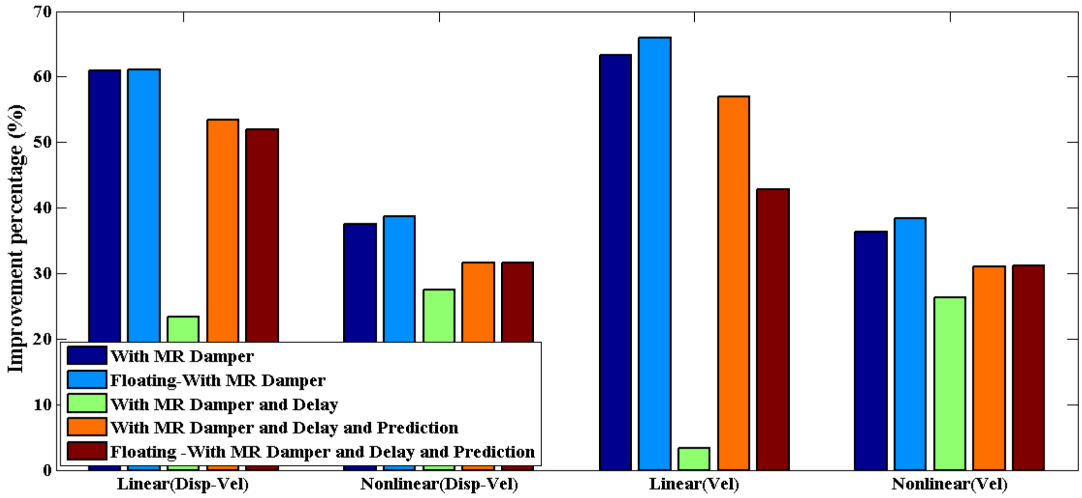

Fig. 25. Average improvement percentage of base shear RMS subjected to applied earthquakes.

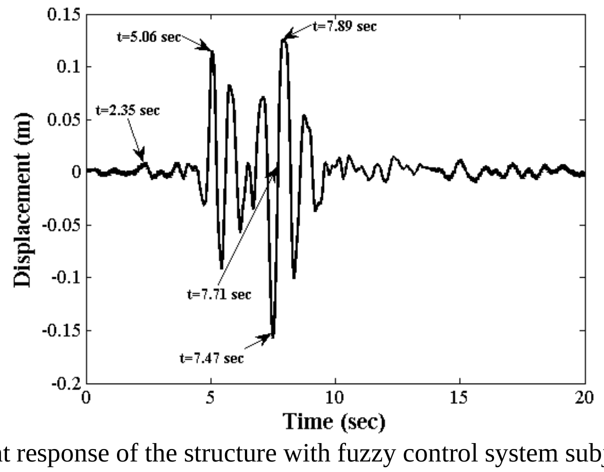

Fig. 26. Roof displacement response of the structure with fuzzy control system subjected to the Duzce earthquake in Turkey with maximum acceleration of 0.4g.

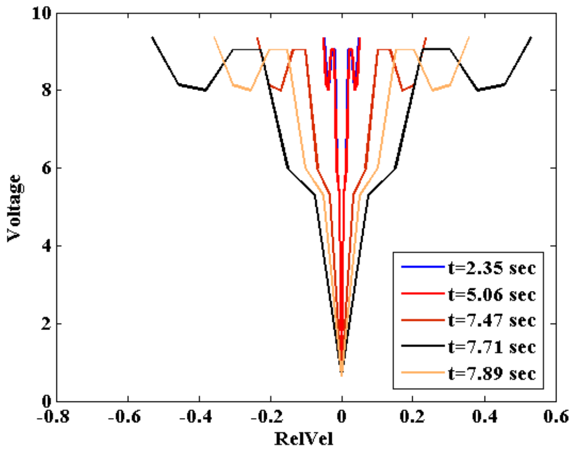

Fig. 27. Graphical representation of fuzzy making decision system rules based on roof velocity at different times.

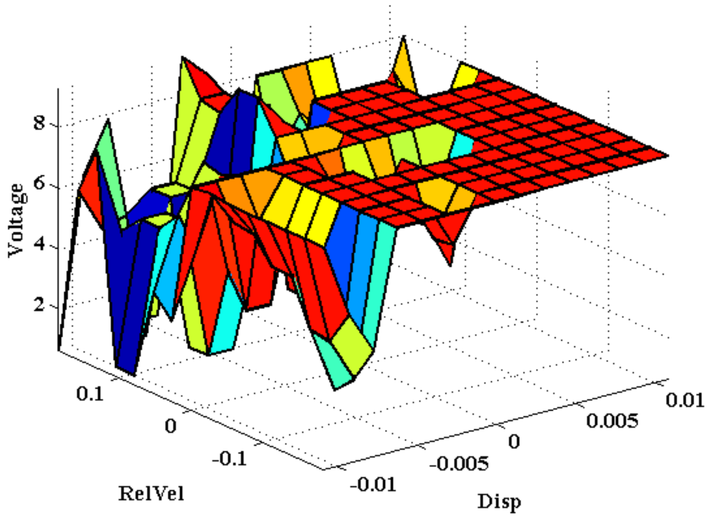

Fig. 28. Graphical representation of fuzzy making decision system rules based on roof velocity-displacement at t=7.71 sec.

10. References

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