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Type-1 and Type-2 Fuzzy Logic Control Algorithms for Semi-Active Seismic Vibration Control of the College Urban Bridge Using MR Dampers

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ABSTRACT: In this study, the application of type-1 and type-2 fuzzy inference system (FIS) in semi-active seismic vibration control of the College Bridge using magnetorheological (MR) dampers is investigated. For this purpose, a detailed 3D finite element model of the bridge fitted with MR dampers is created in OpenSees. The command voltage of MR dampers is determined by employing both types of FISs in Matlab environment and making connection between both software. The results show the higher performance of the type-2 FIS for reducing the undesirable vibrations than that of type-1. This is because of the fact that the type-2 FIS considers interval membership functions for inputs in order to obtain the command voltage of MR dampers. Moreover, type-2 FIS effectively includes the effect of uncertainties and time delay. The results demonstrate that type-2 fuzzy controller is capable of reducing further the maximum displacement, base shear, and moment of the bridge by 24.6, 22.8, and 39.25%, respectively, compared to the type-1 fuzzy controller.

Keywords: College Bridge, MR Damper, Semi-Active Control, Type-1 and Type-2 Fuzzy Logic Controllers.

INTRODUCTION

One of the challenging tasks in civil engineering is to mitigate the vibration due to dynamic loads like earthquake, strong wind, traffic and etc. As a result, vibration control of structures has received remarkable interest in the past decades. Many control devices and algorithms have been proposed each of which has its own advantages and disadvantages. Vibration control is classified into passive, active, and semi-active. In two recent decades, considerable research efforts have been devoted to the semi-active vibration control method because of its exclusive advantages like low energy consumption, having reliability of passive control, and versatility and adaptability of active control. Furthermore, the semi-active control does not have the potential of making system unstable. Among semi-active devices, magneto-rheological (MR) damper is a typical

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example of a smart damper. MR damper is filled with MR fluid and is capable of producing adaptive damping forces that is controlled by magnetic field in real time. It should be noted that MR damper acts like a passive control device in presence of constant magnetic field or its absence. Furthermore, MR dampers are reliable semi-active devices for controlling vibrations of large structures like bridges. One of the challenges in utilizing MR dampers is to develop efficient control algorithms to achieve the maximum performance. Some of these algorithms, like Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian (LQG) algorithms, calculate the control force based on structural response and optimization procedures. For this purpose, an accurate mathematical model of MR damper should be created in order to calculate the control forces under dynamic forces. Moreover, non-linear behavior of MR damper is a limitation to use LQR and LQG. In order to overcome these limitations, Fuzzy Logic Controllers (FLCs) have been utilized, which provide a simple and robust framework to handle non-linear behavior of the system as well as system uncertainties. The advantages of MR dampers and FLCs have been investigated in many studies. Liu et al. (2000) studied the performance of semi-active control of a two-span bridge with MR damper and FLCs. Jung et al. (2002) used MR dampers to protect the non-linear coupled bridge systems under earthquake excitations. Dyke et al. (2003) evaluated the performance of MR dampers to control ASCE benchmark bridge vibration due to earthquake. Zhou et al. (2003) proposed an adaptive FLC strategy with MR damper that involves the design of fuzzy controller and optimization laws. Dai et al. (2004) used MR dampers, in order to control a cable-stayed bridge under multiple-support excitations. Yan and Zhou (2006) used FLCs to make decisions about the appropriate voltage of the MR damper. Kim and Roschke (2006) studied the hybrid control of structures with base isolation system and MR damper. They used FLCs, in order to adjust the command voltage of an MR damper. Kim and Kang (2012) used FLCs to reduce the response of a 76-story benchmark building under wind excitations. For this purpose, they used a semi-active tuned mass damper with an MR damper (MR-STMD) and multi-objective genetic algorithm to optimize fuzzy logic rules. Fayezioghani and Moharrami (2015) conducted a research on optimal vibration control by integrating equations of motion of the structure and MR dampers.

The type-1 and 2 of the fuzzy algorithm were presented in 1965 and 1975, respectively (John and Coupland, 2007). Both of these fuzzy based decision algorithms are able to make appropriate decision and function to solve the complex and non-linear problems. The difference between these two types of algorithms is that the type-2 fuzzy logic algorithm has more versatility and the ability to decide complex issues with uncertainty. The type-1 FLCs have limited performance and membership functions. Moreover, it cannot properly reduce the structural response because of the uncertainties due to noise in sensors' signals and time delay in signal transmission process. As a result, there are some limitations for proper adjustment of command voltage of MR damper using this type of FLCs. In order to overcome these limitations, type-2 FLCs have been proposed. The type-2 FLCs have interval membership functions that adjust the command voltage more accurately compared to type-1 FLCs. Type-2 FLCs are studied in various scientific fields like electrical engineering, biomedical engineering, robotic engineering, etc. The results of researches indicate that the performance of type-2 FLCs are higher than that of type-1. For example, Liang and Mendel (2000) used type-2 fuzzy adaptive filters to overcome time varying co-channel. Moreover, type-2 FLCs are used for the connection admission control in Asynchronous Transfer Mode (ATM) networks (Liang et al., 2000). John et al. (2000) studied the application of type-2 FLCs for image processing in order to classify the crus injuries in sport competitions. Liang and Mendel (2001) applied type-2 FLCs to MPEG variable bit rate video modeling and classification. Moreover, in order to control mobile robots, Hagras (2004) used type-2 FLCs and showed that they are more effective than type-1 FLCs. Shu et al. (2008) used type-2 FLCs to analyze and estimate the network lifetimes for wireless sensor's networks. Jammeh et al. (2009) used type-2 FLCs for congestion control using video streaming across IP networks. Using these controllers, they improved video streaming to receive video frame with minimum pocket loss.

Shariatmadar et al. (2014) used interval type-2 FLC for seismic vibration control of a structure modeled as an SDOF system utilizing active tuned mass damper. In their study, the optimal parameters of Tuned Mass Damper (TMD) have been determined through Genetic Algorithm. Bathaei et al. (2017b) focused on semi-active seismic control of an 11-DOF building model via an idea based on upward and downward trend of motion using type-1 and type-2 fuzzy logic algorithms. The results showed the high performance of proposed control system.

This paper addresses the utilization, evaluation and comparison of type-1 and type-2 FLCs for seismic vibration control of the College Urban Bridge, located in Tehran, using MR dampers. It should be noted that the authors recently have studied the vibration control of the bridge using multiple tuned mass dampers (Bathaei et al., 2017a). In present study, a computer model of the bridge, fitted with MR dampers is created in OpenSees environment. Type-1 and type-2 FLCs are designed in Matlab and TCL/TK programming is employed to connect these two software. The bridge is subjected to earthquake excitations and the effectiveness of type-2 FLCs in vibration control of the bridge is compared with that of type-1 FLCs.

BRIDGE DESCRIPTION AND MODELING

The steel bridge studied herein is the College Bridge in Tehran, Iran (Figure 1). With the length of 372 m, and the width of 10.5 m, this bridge is composed of thirteen spans of 24 m and one end span of 12 m. The type of steel used in bridge construction is ST52. This bridge is more than 40 years old and needs to be retrofitted against seismic hazard. For this purpose, six MR dampers, each having the capacity of 1000 kN, were assumed to be installed between the deck and the last pier. Both of the first and end bridge spans are connected to abutments. The main geometrical properties of the bridge are presented in Tables 1 and 2 and the details of a typical pier of the bridge are demonstrated in Figure 2.

The bridge model is created in OpenSees software. The piers and the deck are modeled as nonlinear and elastic elements, respectively. Each pier includes a column and a capital and the deck is composed of six built-up girders braced by truss elements. The model is fully fixed to the ground at the piers and also the deck is pinned to the piers at the bents. In addition, the bridge design loads are calculated in accordance with AASHTO (1992) and DIN 1072 (1985) codes. Each 24 m long span weighs about 77.5 tons and the total weight of the bridge is approximately 1194 tons. Four earthquake records, including two far-filed and two near-field records, are considered to be applied to the bridge: 1940 El Centro, 1956 Kern-County, 1994 Northridge, and 1995 Kobe. The characteristics of these ground motions are presented in Table 3.

Table 1. Geometrical properties of the College Bridge spans

Span	Length (m)
x_0	24
x_1	12
x_2	24

Table 2. Geometrical properties of the College Bridge piers

Pier	Height (m)
h_1	0.85
h_2	2.08
h_3	3.42
h_4	4.4
h_5	5.24
h_6	5.72
h_7	5.84
h_8	5.84
h_9	5.38
h_{10}	4.68
h_{11}	3.85
h_{12}	2.64
h_{13}	1.55
h_{14}	0.85

For verification, the bridge is also modeled in SAP2000. The value of fundamental period of the bridge in OpenSees is 0.44 sec while SAP2000 gives a fundamental period of 0.43 sec. Moreover, the displacement response of the bridge subjected to aforementioned earthquake records for both models are obtained. The maximum longitudinal displacement response of the longest pier, i.e. pier 9, using both software is reported in Table 4. Figure 3 shows the time history of longitudinal displacement of the pier 9 subjected to Kern-County earthquake. The results reveal the accuracy of the modeling.

MR DAMPER

There are several models for MR damper. In present study, the Bouc-Wen (Ok et al., 2007) model is used to simulate the mechanical behavior of MR dampers (Figure 4). Since such element is not available in OpenSees library, the equivalent force generated by the damper is included in the model instead of modelling the damper. The Bouc-Wen model includes a Bouc-Wen element and a dashpot connected in parallel. Full scale tests on MR dampers have proven that Bouc-Wen model can effectively simulate the real behavior of these dampers (Spencer and Dyke, 1996).

Table 3. Characteristics of earthquake records used

Earthquake	Station	PGA (g)	Type
El Centro	El Centro	0.35	Far-field
Kern-County	1095 Taft Lincoln School	0.23	Far-field
Kobe	KJM	0.83	Near-field
Northridge	Sylmar-Olive	0.84	Near-field

Table 4. Maximum longitudinal displacement of the tallest pier (pier 9) for different earthquakes

Earthquake	Maximum Displacement OpenSees (cm)	Maximum Displacement SAP2000 (cm)	Difference (%)
El Centro	3.8	3.55	6.58
Kern-County	3.94	3.75	4.82
Kobe	12.83	12.38	3.51
Northridge	12.43	11.45	7.88

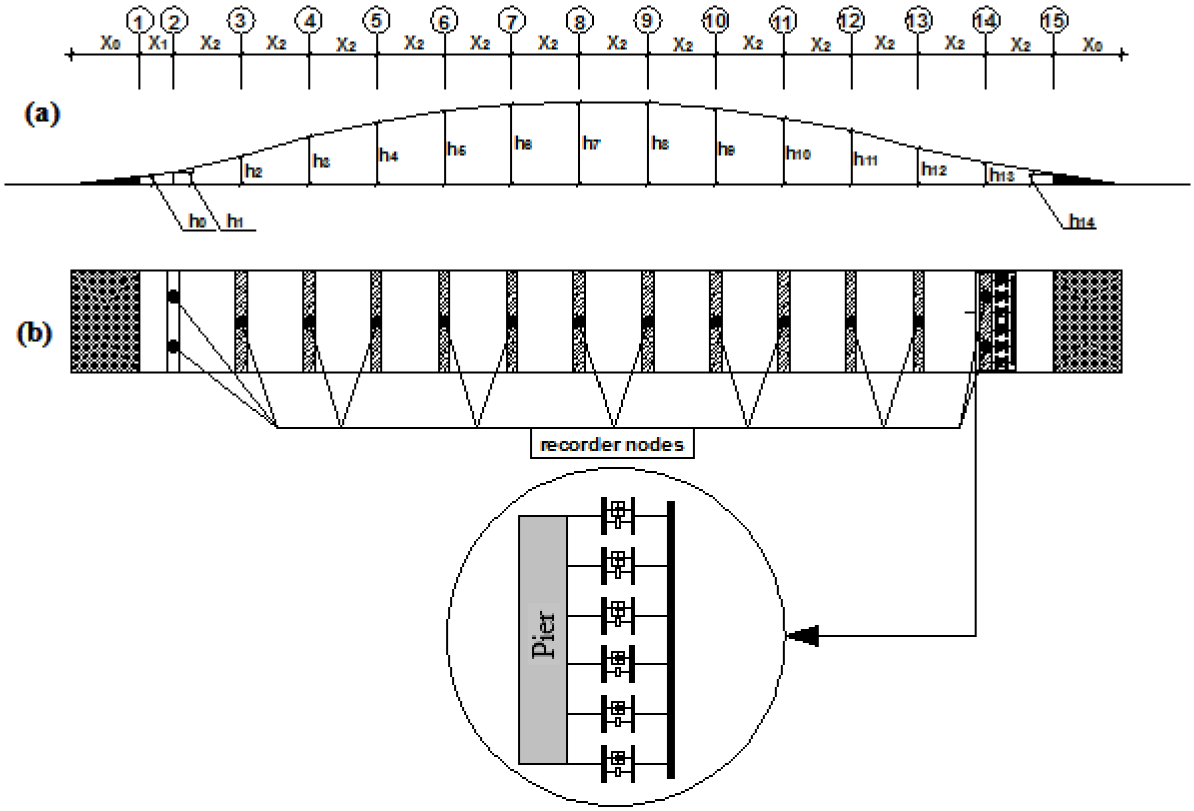
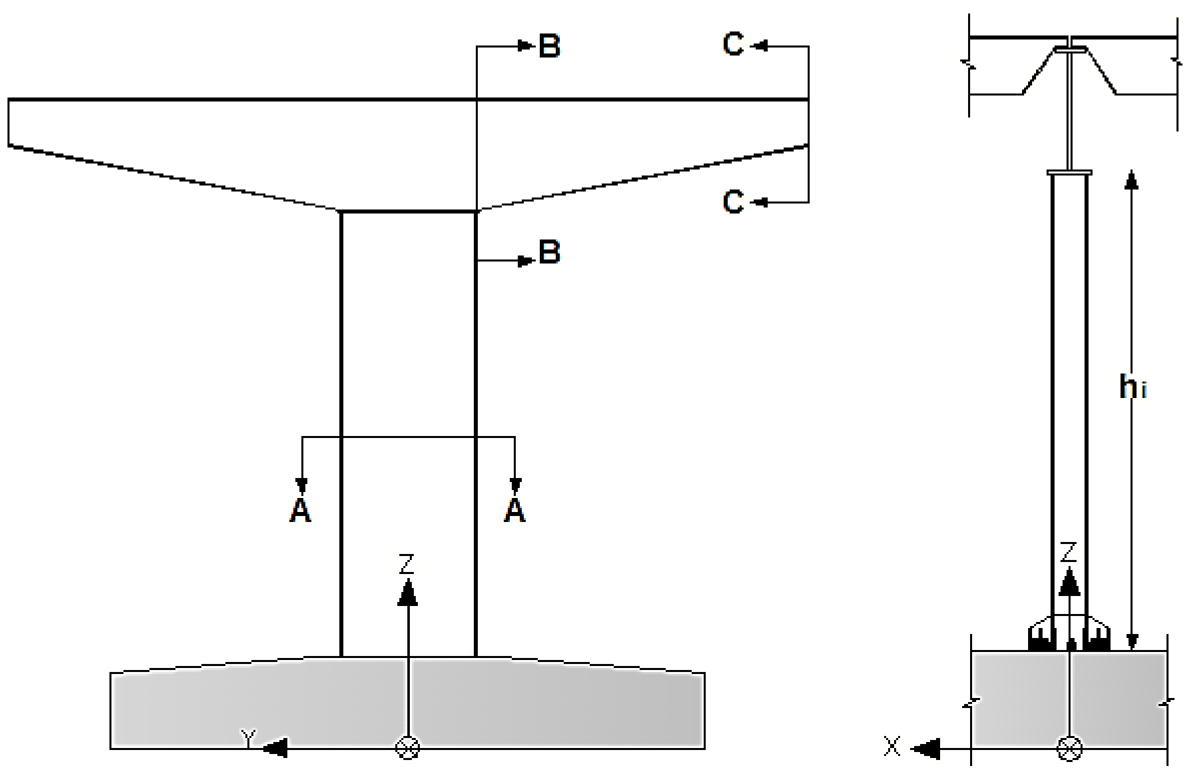
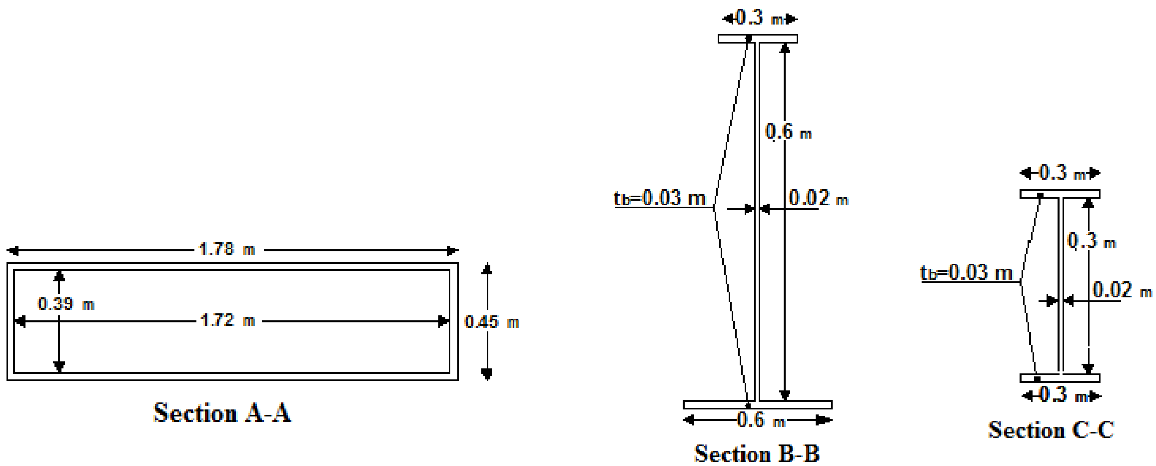


Fig. 1. a) Side view, b) Top view of the College bridge and details of the MR dampers' placement



(a) (b)



(c)

Fig. 2. a) Front view, b) Side view, c) Cross sections of a typical pier of the bridge

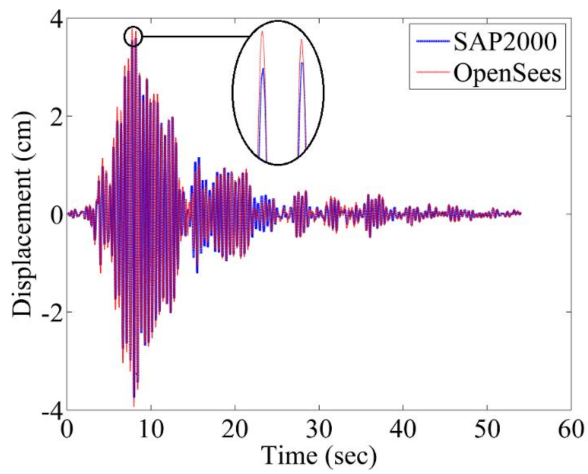


Fig. 3. Longitudinal displacement of the tallest pier (pier 9) subjected to Kern-County earthquake

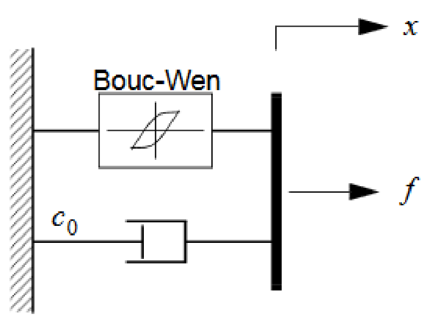


Fig. 4. Mechanical Model of the MR Damper

To verify the correctness of damper modelling, the variations of damping force for 0, 5, and 10 volts versus damper velocity are obtained. The dampers used in this study are identical to the ones used by Ok et al. (2007). The force generated by the MR damper is calculated by

$$f = F = C_0 \dot{x} + \alpha z \tag{1}$$

$$\dot{z} = -\gamma |\dot{x}| z |\dot{z}|^{n-1} - \beta \dot{x} |z|^n + A_m \dot{x} \tag{2}$$

where x: is the relative displacement of both ends of the damper and z: is the evolutionary variable. The parameters γ, β, n, and A_m: are determined based on test data; C_0 and α: are determined based on the control voltage u through the following equations

$$\alpha = \alpha(u) = \alpha_a + a_b u \tag{3}$$

$$C_0 = C_0(u) = C_{0_a} + C_{0_b} u \tag{4}$$

where u: is the applied control voltage and parameters α_a , α_b , C_{0a} , and C_{0b}: are presented in Table 5.

The graphs presented by Ok et al. (2007) and those obtained in present study are shown in Figures 5 and 6, respectively. Comparing the graphs for all voltage values, it is understood that the mechanical model of MR dampers effectively simulates the real behavior of this damper.

Since the dampers employed are not capable of exerting the required control force instantaneously, a time delay always occurs in control system. The amount of time delay depends on the type of the damper. In general, the time delay for MR dampers varies between 0.02 and 0.1 sec. However, a time delay of 0.02 sec is considered in present study.

Considering the internal mechanism of an MR damper, this damper cannot immediately apply the command voltage. Therefore, it takes a brief moment for the applied voltage to meet the command voltage. For taking this delay into consideration, a first-order filter is utilized as follows

$$\dot{u} = -\eta(u - v) \tag{5}$$

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

TYPE-1 AND TYPE-2 FUZZY CONTROL

Numerous control algorithms have been proposed; in order to adjust semi-active control systems. For example, skyhook control algorithm, direct Laypunov based control algorithms, modified homogeneous friction algorithm and clipped optimal strategy, etc. In the past few decades or so, the main area of success with fuzzy logic was in industry (Ślaski and Maciejewski, 2011; Anand et al., 2015; Varga and Bogdan, 2009; Tanaka et al., 2001; Achour-Olivier and Afra, 2016).

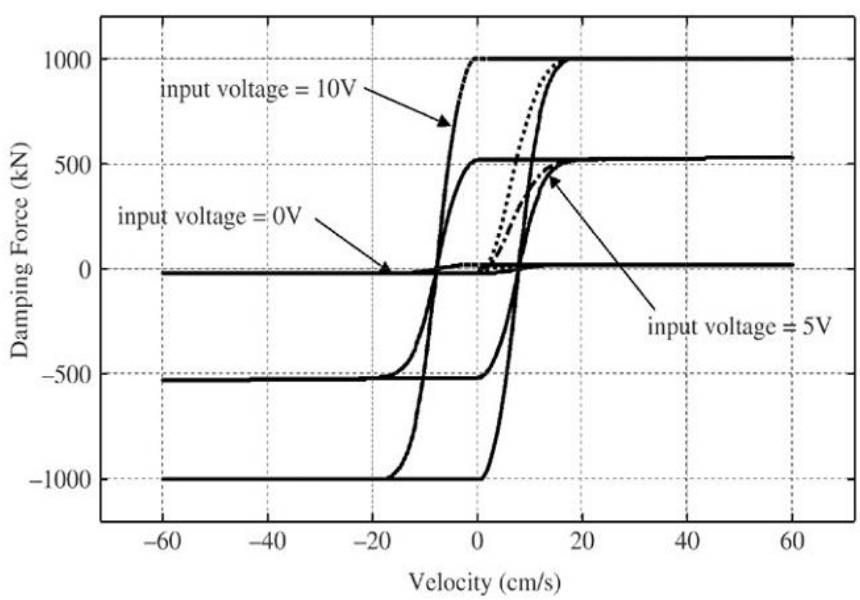


Fig. 5. Mechanical behavior of MR damper, presented by Ok et al. (2007)

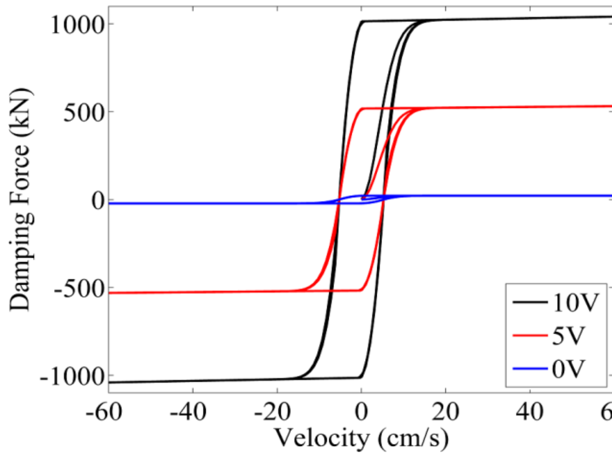


Fig. 6. Mechanical behavior of MR damper; used in present study

Table 5. Parameters for the MR damper model (Ok et al., 2007)

Parameter	Value (Unit)	Parameter	Value (Unit)	Parameter	Value (Unit)
α_a	$1.0872\times10^7\ (\mathrm{N/m})$	c_{0b}	$4400\,(\mathrm{Ns/m/V})$	β	$300\,(\mathrm{m^{-1}})$
α_b	$4.9616\times10^7\ (\mathrm{N/m/V})$	A_m	1.2	γ	$300\,(\mathrm{m^{-1}})$
c_{0a}	$440\,(\mathrm{Ns/m})$	n	1	η	$50\,(\mathrm{s^{-1}})$

The application of fuzzy logic allows researchers to specify the relationship between sensor inputs and actuator outputs using “If...Then...” type of linguistic rules. A fuzzy logic algorithm would be able to translate or interpolate these rules into a nonlinear mapping between sensor input signals and actuator outputs for feedback control. For these reasons, there is a need for control algorithms that can change the voltage between zero and the maximum voltage level using input data. In this study, FLCs are used to calculate the command voltage of MR damper.

Fuzzy control is an effective approach which offers a simple and robust framework to deal with uncertainties and complex nonlinear systems. Moreover, fuzzy controllers use simple verbose statements instead of complicated mathematical terms to make a relation between inputs and outputs of the system. For the aforementioned reasons, many researchers used FLCs for semi-active systems (Yan and Zhou, 2006; Zhou et al., 2003; Ok et al., 2007).

In order to configure FIS in present study, a rule-base proposed by Symans and Kelly (1999) is considered and adjusted to be employed. This rule-base is represented by rule-base number 5 in their study.

The schematic diagram of the FIS is shown in Figure 7. Fuzzy logic process consists of several steps. At first, input and output variables are defined. Then, fuzzification of variables, which includes the process of converting crisp values to linguistic fuzzy values, is performed by assigning membership functions to each variable. To define variables as fuzzy sets, a fuzzy rule-base is used to relate the inputs and outputs. By fuzzy logic mechanism, the rules are evaluated to specify the output for a given input set. As a final step, the fuzzy variables transform to non-fuzzy discrete values by defuzzification step. The abovementioned steps form the process take place in type-1 FLC. There are some limitations to control the vibrations using these controllers. For example, when different people have different perceptions of an issue, linguistic uncertainties arise and type-1 FLCs are not able to express them. Furthermore, type-1 FLCs have low adaptation with time delay. In this study, the time delay is due to three factors: the first factor is caused by recording and transmitting structural response to FIS; the second factor is caused by the processing time in FIS and calculating the command voltage, and the third factor is caused by the MR damper mechanism to apply control force after receiving the command voltage. Meantime, the noise of sensors can also affect the performance of the control system. It should be noted that type-1 FLCs cannot consider these effects.

According to abovementioned limitations, there is a need for employing a controller that can consider these issues. For this purpose, type-2 FLCs have been used herein. Type-2 fuzzy sets and systems generalize type-1 to handle more uncertainties. Type-2 FLCs have several steps like type-1 FLCs, but there is a difference between them in the output process. In type-2 FLCs, the output process consists of type-reducer and defuzzification steps. The type-reducer converts the type-2 FLCs to type-1 FLCs. The schematic diagram of the type-2 FLC is shown in Figure 8. In this study, the toolbox provided by Wu and Mendel (2007) is used in order to apply the type-2 fuzzy procedure.

The performance of fuzzy systems depends on various design parameters such as discretization of the universes of discourse, choice of membership functions and definition of rule bases. It is especially important for a fuzzy logic system to have an effective and reliable rule-base to perform at desired level. However, the design of fuzzy logic control rules to derive the MR damper voltage is challenging since it requires a proper understanding of dynamic response of the structure with the MR damper which shows a highly nonlinear behavior.

The membership functions of type-1 FISs are triangle functions for input and triangle-Gaussian functions for output variables. In addition, the membership functions of type-2 FISs are triangular for both input and output variables. Relative displacement and velocity of the MR damper are employed as input variables, and the command voltage of MR damper is defined as a single output. The inputs and output membership functions of type-1 and type-2 FLCs are shown in Figures 9 and 10, respectively. The membership functions for voltage as an output in type-2 fuzzy system are identical to those defined for type-1 fuzzy system.

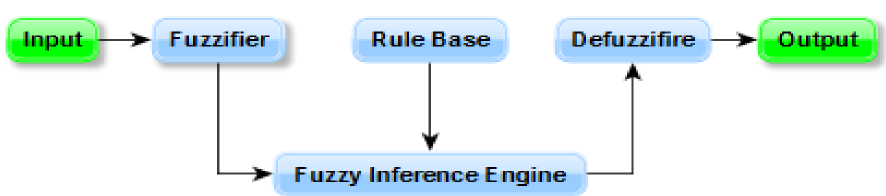


Fig. 7. The schematic diagram of the type-1 FLC

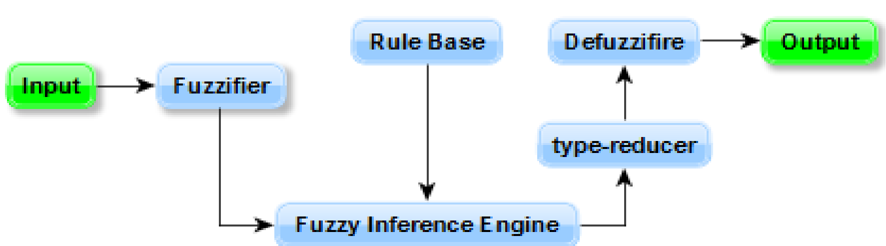


Fig. 8. The schematic diagram of the type-2 FLC

The fuzzy sets for input variables include: NVL = negative very large; NL = negative large; NM = negative medium; NS = negative small; NVS = negative very small; ZO = zero; PVS = positive very large; PS = positive small; PM = positive medium; PL = positive large; and PVL = positive very large. The fuzzy sets for output variables also include: ZO = zero; VS = very small; S = small; M = medium; L = large; and VL = very large. The rule-bases adopted for FLC are given in Table 6.

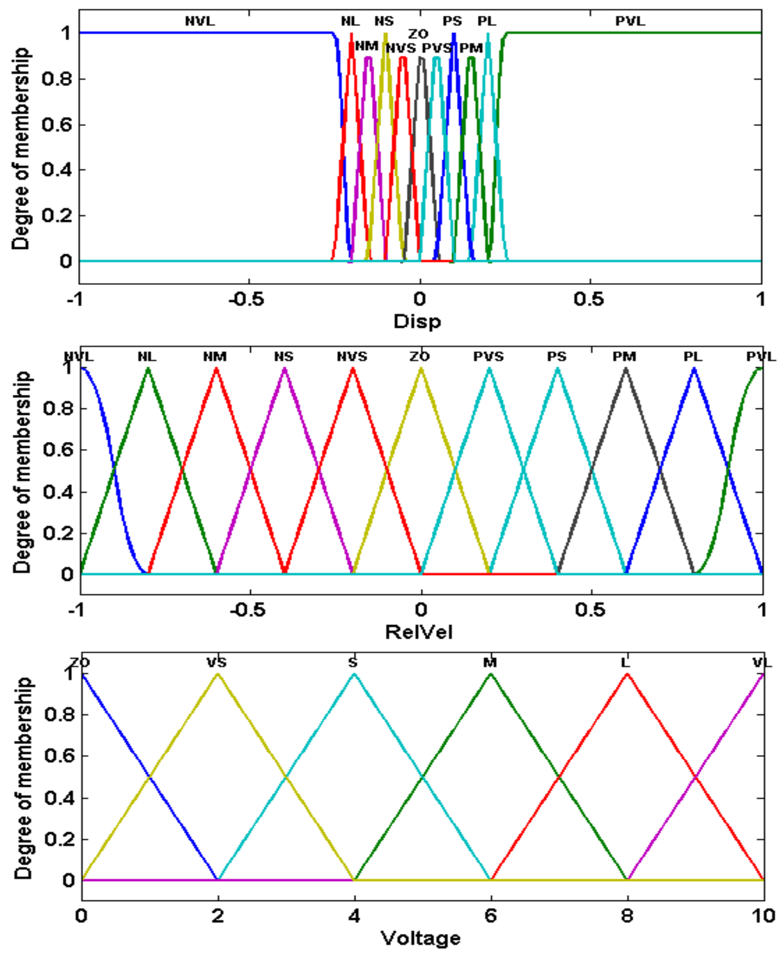


Fig. 9. Input and output membership functions for type-1 FLC

Table 6. Rule base for FISs

		Displacement										
		NVL	NL	NM	NS	NVS	ZO	PVS	PS	PM	PL	PVL
	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
Relative Velocity	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

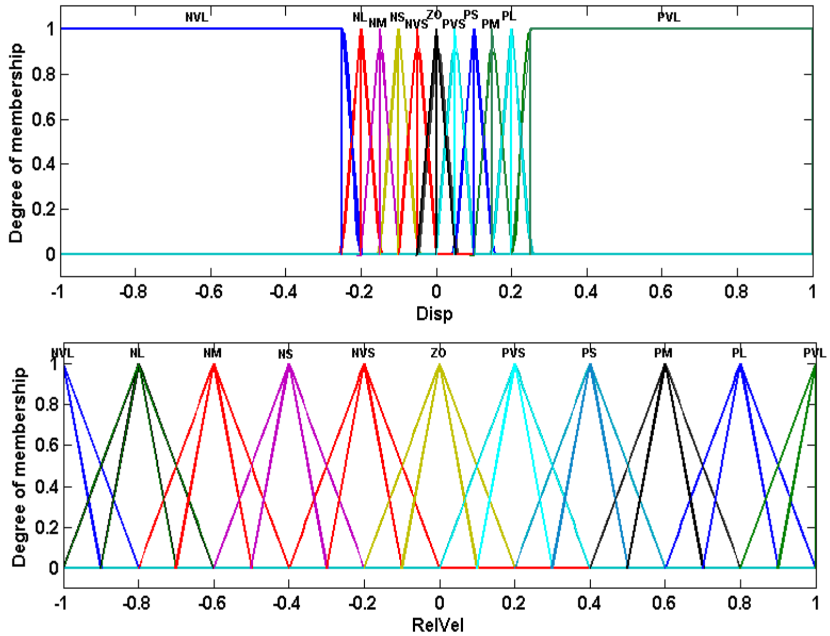


Fig. 10. Input and output membership functions for type-2 FLC

NUMERICAL STUDY

The finite element model of the bridge is created in OpenSees. In order to employ control algorithms to compute the command voltage of MR damper, MATLAB software is used. Since the bridge is modeled in OpenSees and the FLCs are implemented in MATLAB, there is a need for making a connection between these software. One of the features of TCL/TK programming language is to make network connection between server and client. For this purpose, the socket coding is used in TCL editor program. To analyze the bridge structure, at the first time the OpenSees software computes the velocity and displacement of the first step and they are sent to MATLAB. Then, the required voltage to generate MR damper force is calculated using fuzzy logic algorithm by MATLAB. The generated force gained in previous step is sent to OpenSees software as a TCL file and it is used as an input force in the second step. The process is shown in Figure 11.

The sensors record the relative displacement and velocity of MR damper during the earthquake and transmit the data to the FIS. Afterward, the FIS determines the command voltage of MR damper. Finally, the control force is applied to the structure by MR damper.

In this process, the time delay for the system is considered as follows: The time delay due to recording and sending data is 0.02 sec; the time delay in computing the control force by FIS is 0.01 sec which is measured by Tic-Toc code; and the time delay for MR damper to apply the control force to the structure is 0.02 sec.

In order to consider the effect of maximum acceleration of earthquake on the performance of control system, the incremental dynamic analyses (IDA) is conducted. For this purpose, some evaluation criteria are used to evaluate the performance of control systems. The evaluation criteria which are categorized in maximum and the normed values of response, are presented in Table 7. The recording points to compute the evaluation criteria for displacement and acceleration are shown in Figure 1. The evaluation criteria J_1 and J_2 are related to the maximum longitudinal displacement and acceleration at the deck level and J_3 and J_4 consider the maximum shear and moment at the base level, respectively. Furthermore, the evaluation criteria J_5 and J_6 evaluate the root mean square (RMS) of longitudinal displacement and acceleration at the deck level, respectively. J_7 and J_8 also evaluate the RMS of shear and moment at base level in longitudinal direction.

The time history of longitudinal displacement of the largest pier of the bridge is shown in Figure 12 for uncontrolled and controlled cases. A zoomed part of the plots is provided in Figure 13. The structural response with MR damper and FISs, including type-1 and type-2 FLCs, are significantly less than those of the uncontrolled system. As it is observed in Figures 12 and 13, the response of the structure with type-2 FLCs is more favorable than that of the type-1 FLCs.

Table 7. The evaluation criteria as ratio of the average of maximum and RMS responses of controlled system to that of uncontrolled system

Criterion	Relationship	Criterion	Relationship
J_1	$\dfrac{\text{Average }(\max\lvert x_c(t)\rvert)}{\text{Average }(\max\lvert x_u(t)\rvert)}$	J_5	$\dfrac{\text{Average }(\text{RMS}\lvert x_c(t)\rvert)}{\text{Average }(\text{RMS}\lvert x_u(t)\rvert)}$
J_2	$\dfrac{\text{Average }(\max\lvert \ddot{x}_c(t)\rvert)}{\text{Average }(\max\lvert \ddot{x}_u(t)\rvert)}$	J_6	$\dfrac{\text{Average }(\text{RMS}\lvert \ddot{x}_c(t)\rvert)}{\text{Average }(\text{RMS}\lvert \ddot{x}_u(t)\rvert)}$
J_3	$\dfrac{\text{Average }(\max\lvert V_c(t)\rvert)}{\text{Average }(\max\lvert V_u(t)\rvert)}$	J_7	$\dfrac{\text{Average }(\text{RMS}\lvert V_c(t)\rvert)}{\text{Average }(\text{RMS}\lvert V_u(t)\rvert)}$
J_4	$\dfrac{\text{Average }(\max\lvert M_c(t)\rvert)}{\text{Average }(\max\lvert M_u(t)\rvert)}$	J_8	$\dfrac{\text{Average }(\text{RMS}\lvert M_c(t)\rvert)}{\text{Average }(\text{RMS}\lvert M_u(t)\rvert)}$

Table 8. The values of evaluation criteria

Evaluation criterion		J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8
El Centro	type-1 FLC	0.54	9.61	0.62	0.92	0.40	14.41	0.38	0.69
	type-2 FLC	0.38	1.51	0.46	0.53	0.31	1.67	0.32	0.48
Kern-County	type-1 FLC	0.40	8.15	0.51	0.73	0.36	14.0	0.37	0.64
	type-2 FLC	0.32	1.41	0.41	0.43	0.29	1.82	0.31	0.45
Kobe	type-1 FLC	0.49	6.56	0.58	0.81	0.40	10.68	0.40	0.75
	type-2 FLC	0.35	1.53	0.42	0.47	0.27	1.06	0.29	0.39
Northridge	type-1 FLC	0.69	9.35	0.77	1.0	0.49	21.01	0.46	0.81
	type-2 FLC	0.54	1.38	0.63	0.68	0.37	2.05	0.37	0.49

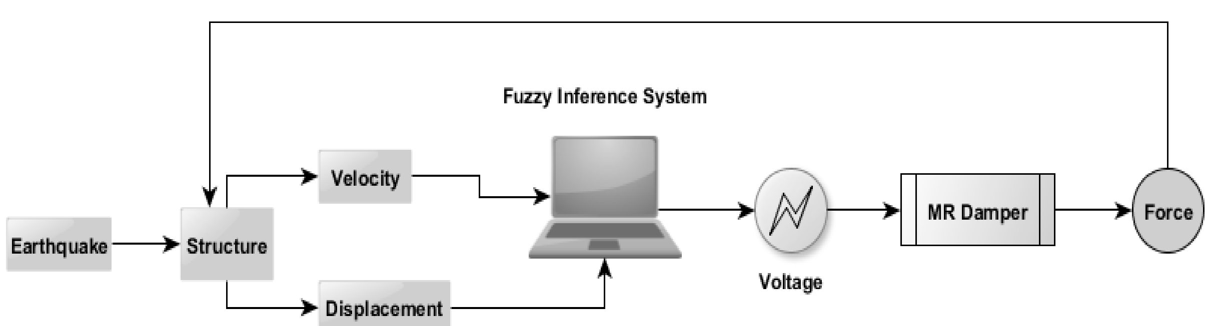


Fig. 11. Process of the devised semi-active control system

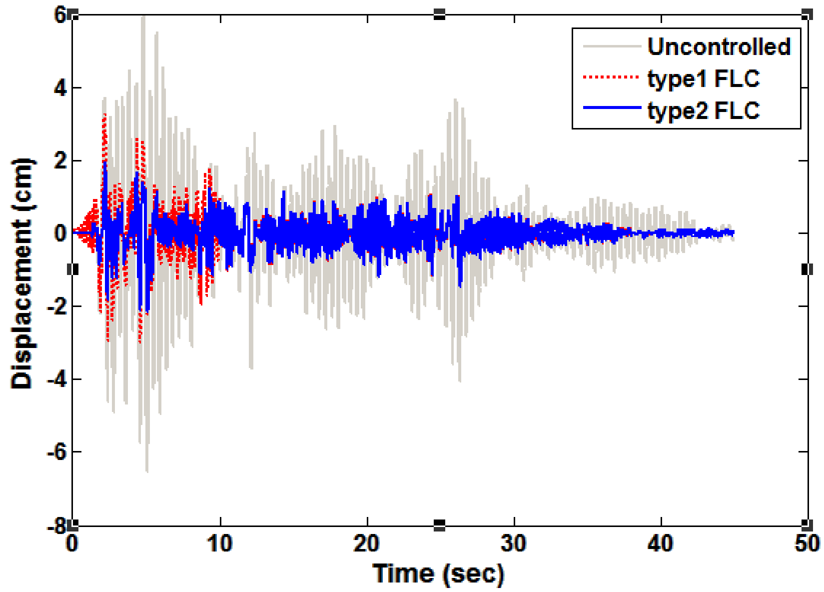


Fig. 12. Displacement time history of the largest pier of bridge

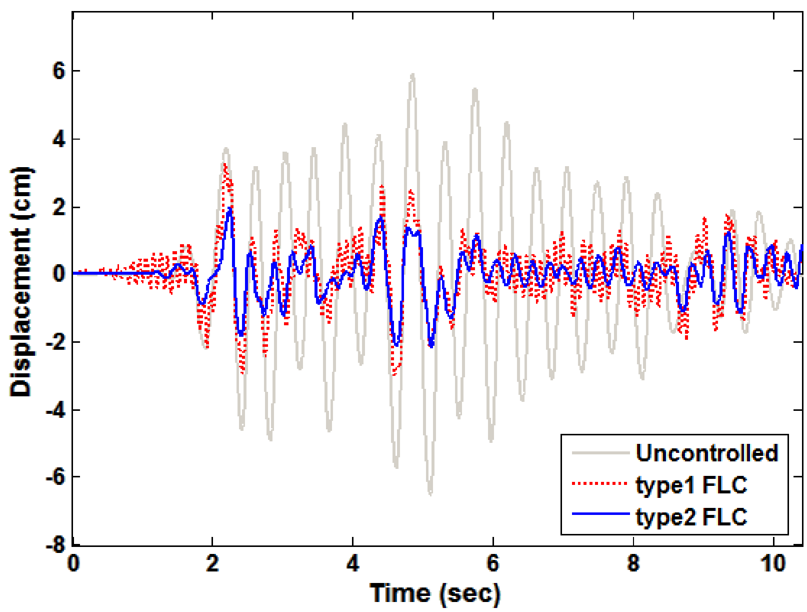


Fig. 13. The zoomed part of displacement time history of the largest pier of bridge

In order to appraise the performance of FISs compared with the uncontrolled case, the values of evaluation criteria are presented in Table 8. These values show excellent control performance for the evaluation criteria J_1, J_3, J_4, J_5, J_7 and J_8, while for J_2 and J_6 it is not so. The high values of evaluation criteria J_2 and J_6 that are related to the acceleration response are due to rigid behavior of the bridge and determination of the MR damper voltage based on displacement and velocity by FISs. It is obvious that the type-2 FISs exhibit higher performance compared to type-1 FLCs for controlling the vibrations due to earthquake excitations. The variations of the evaluation criteria versus different PGA values are presented in Figures 14 to 21 where T1 = type-1 FLC and T2 = type-2 FLC.

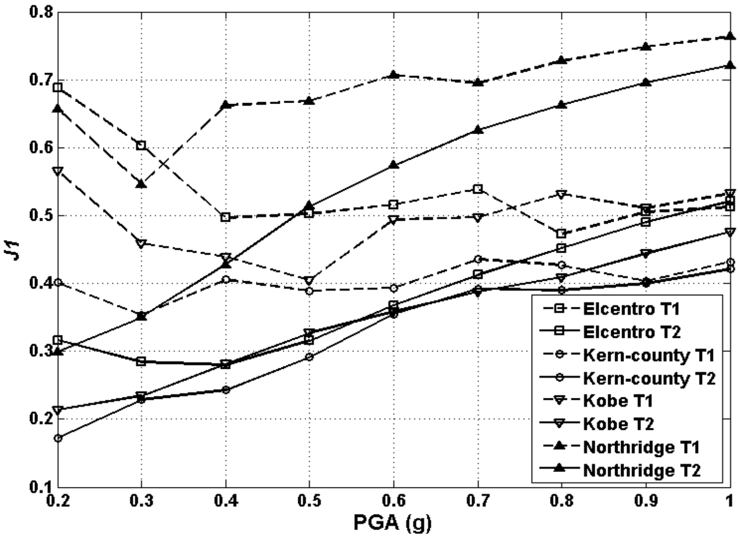


Fig. 14. Variation of J_1 vs. PGA

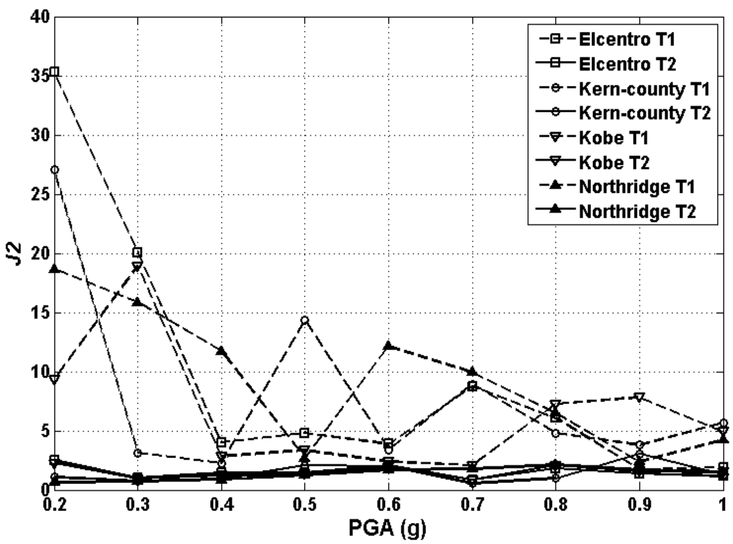


Fig. 15. Variation of J_2 vs. PGA

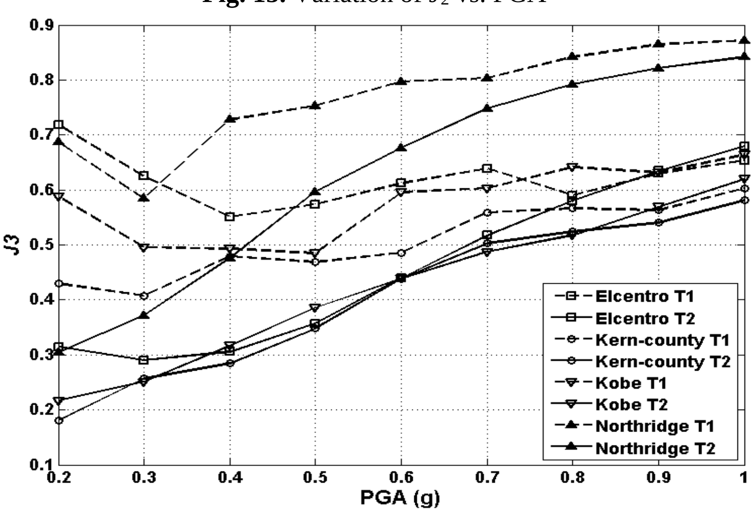


Fig. 16. Variation of J_3 vs. PGA

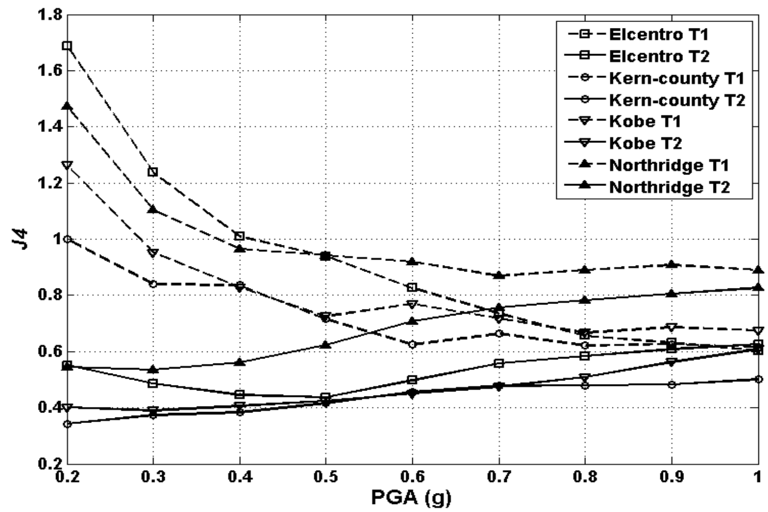


Fig. 17. Variation of J_4 vs. PGA

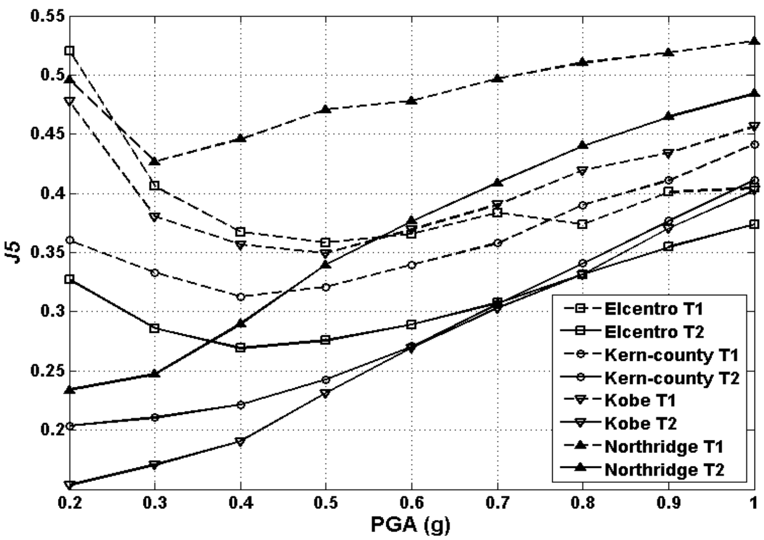


Fig. 18. Variation of J_5 vs. PGA

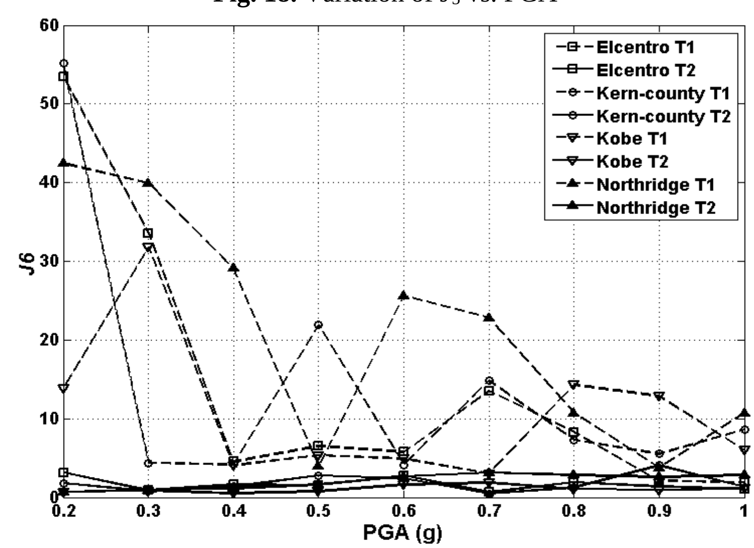


Fig. 19. Variation of J_6 vs. PGA

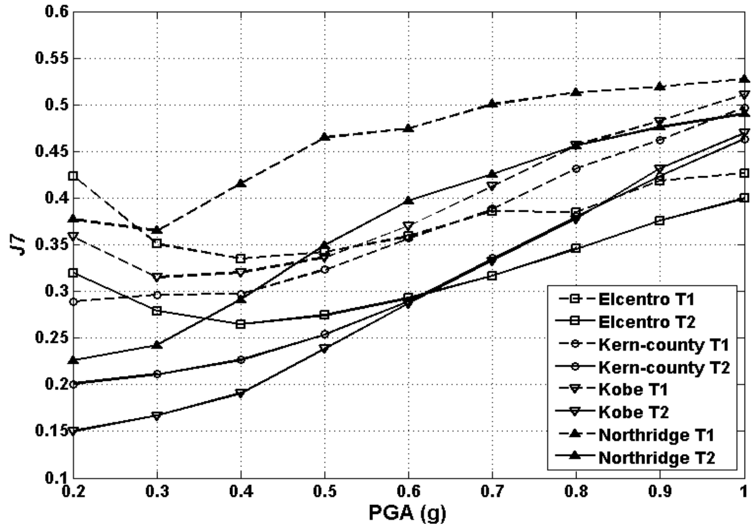


Fig. 20. Variation of J_7 vs. PGA

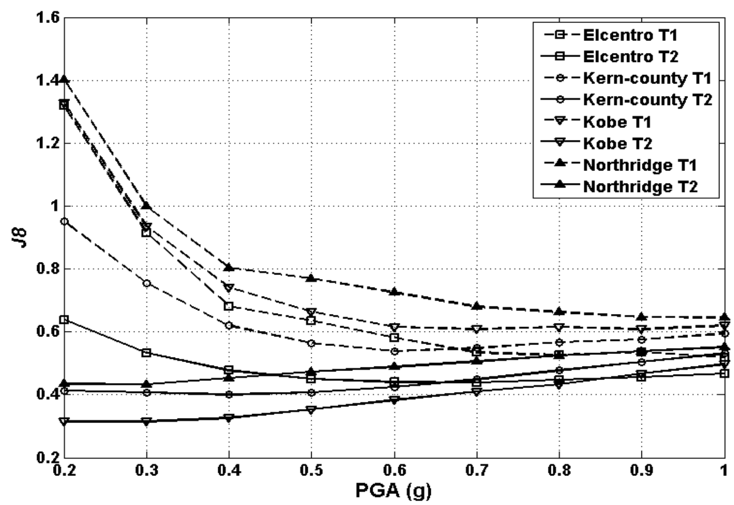


Fig. 21. Variation of J_8 vs. PGA

As seen in the figures, the performance of the type-2 FLC is more appropriate for different evaluation criteria than type-1 FLC. According to the presented figures, the type-2 of the fuzzy control system is less sensitive to PGA than type-1 FLC. The type-2 of the fuzzy decision making is appropriate for different PGAs of the earthquakes. This shows that the versatility of the type-2 FLC is more than type-1 for linear and non-linear behavior of the structure. For control systems having more complicated behavior and for the cases that the accurate values of the input fuzzy data are not available, the type-2 of the control system has more versatility. The type-1 FLCs have lower adjustment with time delay than type-2 FLCs. This advantage of type-2 FLCs is due to their ability to consider time delay by membership functions with interval for the inputs, whereas type-1 FLCs employ linear membership functions for input variables and obtain the command voltage of MR damper using these memberships. Hence, the type-1 FLCs cannot effectively calculate the command voltage of the MR damper in presence of time delay. In some time steps, the control force of MR damper is in phase with the response of the structure. This problem results in a decrease in performance of control system. The schematic diagram of the interval membership of type-2 FLCs was shown in Figure 10. For more explanation, the readers are referred to Figure 22. In this figure, the horizontal axis is the fuzzy variable and the vertical axis is the degree of membership function. The gray area is the uncertainty (footprint of uncertainty). As can be seen, the membership functions of the type-2 FLCs can be nonlinear and for this purpose the type-2 FLCs can obtain the command voltage properly. Therefore, the type-2 FLC system has more appropriate function than the type-1 FLC.

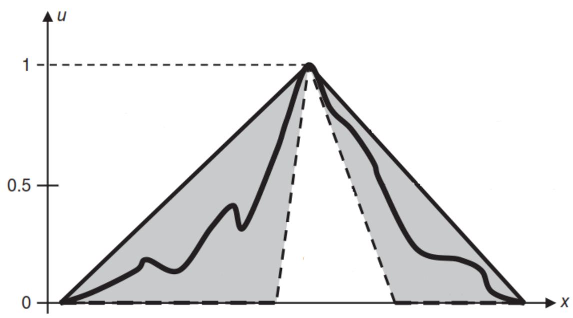


Fig. 22. The membership functions of the type-2 FLCs

To assess the performance of type-2 FLC in different natural frequencies of the structure, an SDOF system is considered. The mass and damping ratio of this structure have been considered to be 500 ton and 2 percent, respectively. Figure 23 shows the variations of J_1 versus natural period of the SDOF system. This figure reveals the better performance of type-2 FLC for all period range. However, its performance is much higher for the period range between 0.7 to 2.2 sec. Regarding that the structure behaves near rigid for low periods, the operation of this control system is lower. For the high periods, the displacement of the structure increases and it leads to rather lower performance of the control system because the stroke of MR dampers has been limited to 25 cm. However, on the whole, it can be deduced that the proposed control system is more effective than type-1 FLC.

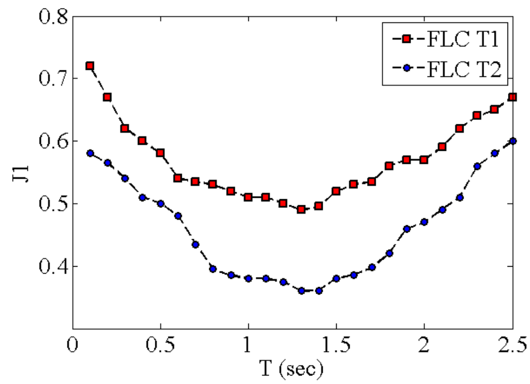


Fig. 23. Variations of J_1 versus natural period of an SDOF structure for type-1 and type-2 FLC

CONCLUSIONS

In this study, application of type-1 and type-2 FLCs for semi-active vibration control of the College Bridge using MR dampers is assessed. To improve the seismic behavior of the structure and consider the uncertainties and time delay of the control process, the type-2 FLCs is utilized, which employs interval membership functions for input variables to improve the performance of system. In order to evaluate the performance of control system, the response of the structure subjected to four different earthquakes (1940 El Centro, 1956 Kern-County, 1994 Northridge, and 1995 Kobe) is obtained. The last pier is connected to the deck using six MR dampers, each with the capacity of 1000 kN. Furthermore, eight evaluation criteria are defined in order to assess the performance of control system. The results for both of type-1 and type-2 FISs are compared with those of the uncontrolled case. According to the obtained results, utilizing type-2 FLC results in more reduction of the structural responses compared to the case that type-1 FLC is used. This reduction for the maximum and normed displacement responses is between 20% to 29.6%, for maximum and normed values of base shear is between 18.2% to 27.6% and for the maximum and normed values of base moment is between 32% to 42.4%. The results show the superior performance for type-2 FLCs in comparison with type-1 for vibration mitigation of the bridge. This predominance is because of the fact that type-2 FLC can model and minimize the effects of uncertainties in rule-base fuzzy logic systems.

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