INNOVATIVE FUZZY CONTROLLER FOR SEMI-ACTIVE BASE ISOLATION SYSTEMS

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ABSTRACT

Development of the controlling algorithms is one of the most challenging aspects of the structural researchers with the aim of improving the behaviour of the building structures equipped with controllable devices under the seismic hazards. Base isolator of the building structures can be designed for a specific magnitude earthquake level. Obviously, the design is not optimal for all earthquake excitations. In this paper, a semi-active base isolation (SABI) system is employed to enhance the performance of the base isolated structures under the several seismic conditions. A semi-active magneto-rheological (MR) damper works parallel with base isolation system to adjust the damping force of the base isolation. An innovative fuzzy controller is designed to control the applied voltage of the MR damper in accordance to the feedbacks of the structure. To investigate the performance of the controller in reducing the responses of the structure, a fourteen-story building structure is subjected to El Centro, Hachinohe, Kobe, Northridge and Tabas earthquake accelerations. The displacement and acceleration responses of the building's roof story with passive and SABI devices is compared with that of the fixed base structure. Also, to study the influence of the semi-active controller on the lateral displacement responses of the structure, drift stories is compared in the controlled and fixed cases. The results have been showed the efficiency of the fuzzy controller in comparison with the passive base isolation system in reducing the system vibrational responses under the various earthquake excitations.

INTRODUCTION

Base isolation system is one of the beneficial seismic protection devices that in last decades many researchers have been encouraged to investigate and develop various kinds of base isolators. For several years, the technique of rubber bearing insertion between ground and structure has been used as a standard base isolation implementing (Naeim and Kelly 1999). The technique is not profitable to use for the large structures, unless by adding supplemental auxiliary damping devices more robust resistance characteristics can be achieved. Later, a number of experimental and analytical studies have been consummated to evaluate effectiveness of the lead-rubber or sliding bearings with friction and viscous dampers for isolating the structural systems (Chang et al. 2002). Recently to improve the efficiency of isolators, active controlling devices have been employed to suppress all disadvantages of the passive isolation among large motion of the bearings (Kelly et al. 1987, Chang and Spencer 2010). Active devices have their own disadvantageous as large power consumption and decreasing the reliability of the system due to the active force applying on the structure. Since then, several practical devices with adjustable properties named semi-active devices introduced to improve the passive tools. The semi-active instrument consume only a small power, besides can have high reliability, adaptability and a fail-safe mechanism. Semi-active magneto-rheological (MR) dampers is one of the semi-active devices widely used to enhance the structural behavior in the seismic conditions. In this paper, a large scale 1000 KN MR damper is introduced to work parallel with base isolator, as an actuator to control the vibration of a multistory building structure. The damping of the MR damper is adjusted by the command voltage that computed by a fuzzy logic controller based on the real-time feedbacks of the structure.

Zadeh (1965) introduced the fuzzy set theory. Mamdani (1974), by applying Zadeh's theories and linguistic variables along with fuzzy inference, successfully used the 'IF–THEN' rules on automatic operating control of a steam generator considering uncertainties in system parameters. In civil engineering, the fuzzy set theory was applied by various researchers to control the structural external excitations (Teng et al. 2000, Kim and Kang 2012). Fuzzy logic controller is preferred in this study because of its robust character and superior use effectively and easily in the semi-active controlling system. The supervisor of the fuzzy controller design the fuzzy inference rules by the appropriate input(s) defined based on proper fuzzy sets, according to the physical operation of the observed system.

In this paper, an innovative fuzzy logic controller with is designed for a multi-degree-of-freedom building structure equipped with a semi-active base isolator (SABI) by MR damper, to suppress earthquake-induced vibrations. MR damper uses a small amount of external power to modulate the damping. Fuzzy controller inference rules are presented on three inputs of the system that are displacement and velocity of the top floor of the building and velocity of the based level of the structure and the output is the command voltage of the MR damper. A fourteen-story building structure (14 DOFs) model has been used to evaluate the fuzzy controller efficiency in improving the SABI behavior and reducing the structural responses under the various earthquake excitations. Time histories of the top floor displacement of the SABI system and the passive BI and the fixed based structure are plotted and compared. Also, the maximum drifts of the stories of the building with and without the isolators are computed and illustrated. The results show the effectiveness of the fuzzy logic controller of the SABI system in comparison with the structure by passive BI and fixed base building under the earthquake disturbances.

MODELLING OF SABI AND FUZZY CONTROLLER

The schematic model of the structure with semi-active base isolation system at its base level is shown in Figure 1. By formulating the equations of stories' motion, the reduced matrix equation of the structure is:

$$[M][I + a_1 a_2^T]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\Lambda \ddot{x}_g - \Gamma f_{MR} \tag{1}$$

where, $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices of the base isolated structure by the dimensions of $(n+1)\times(n+1)$, respectively (n is the number of degrees-of-freedom of the fixed based structure). The matrices are obtained in accordance to the relative displacement illustrated in Figure 1.

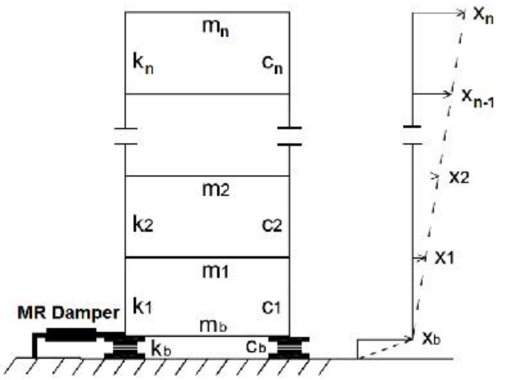

Figure 1. Schematic model of the structure with semi-active base isolator

λ_1 and λ_2 are the influence matrices of the structure's base level acceleration to the building floors that as follows:

$$\lambda_1 = [0 \quad 1 \quad 1\cdots1 \quad 1]^T_{1\times(n+1)} \quad \lambda_2 = [1 \quad 0 \quad 0\cdots0 \quad 0]_{1\times(n+1)} \tag{2}$$

and vector $\{\Lambda\}_{n+1\times1}$ is the influence vector representing the displacement of each degree of freedom resulting from static application of a unit ground displacement and Γ is the vector shows where the force of MR damper (f_{MR}) is applied on the building. To simulate the model of the system in the SIMULINK environment the equations are rewritten in the standard state-space form:

$$\begin{cases} \dot{Z} = A_s Z + B_s u \\ Y = C_s Z + D_s u \end{cases} \tag{3}$$

where Z is the state vector defined as:

$$Z = \begin{Bmatrix} \{x\} \\ \{\dot{x}\} \end{Bmatrix} \tag{4}$$

and the state-space matrices are:

$$A_s = \begin{bmatrix} 0 & I \\ -P^{-1}K & -P^{-1}C \end{bmatrix} \qquad B_s = \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{5}$$

$$C_s = \begin{bmatrix} I & 0 \\ 0 & I \\ -P^{-1}K & -P^{-1}C \end{bmatrix} \qquad D_s = \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix} \tag{6}$$

where the matrix P is:

$$P = [M][I + \lambda_1 \lambda_2^T] \tag{7}$$

I is the unit matrix, and the input vector of the state-space is:

$$u = -P^{-1} M \Lambda \ddot{x}_g - P^{-1} \Gamma f_{MR} \tag{8}$$

A model of MR damper based on the Bouc–Wen hysteretic model in parallel with a dashpot added for a nonlinear 'roll-off' effect as shown in Figure 2, has been used to simulate the semi-active behavior of the device.

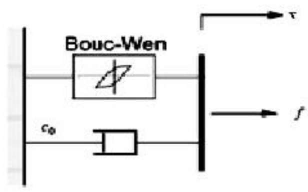

Figure 2. Mechanical model of the MR damper (Yi et al. 2001)

This simple mechanical model has been shown to predict well the behavior of the MR damper over a wide range of inputs in a set of experiments (Yi et al. 2001). The equations governing the force produced by this model of MR damper are given as:

$$f = c_0 \dot{x} + \alpha z \tag{9}$$

$$\dot{z} = -\gamma |\dot{x}| z |z|^{n-1} - \quad \dot{x} |z|^{n} + A\dot{x} \tag{10}$$

where x is the displacement of the device, z is the evolutionary variable and γ, , n, A are parameters controlling the linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region. The functional dependence of the device parameters on the command voltage is expressed as:

$$\alpha = \alpha(u_c) = \alpha_a + \alpha_b u_c \tag{11}$$

$$c_0 = c_0(u_c) = c_{0a} + c_{0b} u_c \tag{12}$$

Moreover, a first-order filter is also used to accommodate the dynamics involved in the MR fluid reaching rheological equilibrium:

$$\dot{u}_c = -\eta (u_c - u_a) \tag{13}$$

where η is the time constant associated with the first-order filter and u_a is the command voltage applied to the current driver.

In this study, according to the physical attributes of the semi-active base isolated building structure and the phase of the responses, fuzzy controller has been designed to reduce the responses under the earthquake excitations applied to the system. In conventional base isolation controlling algorithms the demanding force of the system is calculated according to the feedbacks and the applying voltage of the MR damper estimated by a filter (Yoshioka et al. 2002 and Bo Chen et al. 2014). An innovative fuzzy controller is proposed that can directly apply the appropriate voltage to the MR damper to reduce the responses of the structure equipped by semi-active base isolation system. Inputs of the fuzzy controller are the velocity of the base story and the displacement and velocity responses of the top floor and the output is the command voltage of the MR damper. The membership functions of the inputs and output are shown in Figure 3. The abbreviations used in the membership functions of variables are as follows: Z=zero, NE=negative, PO=positive.

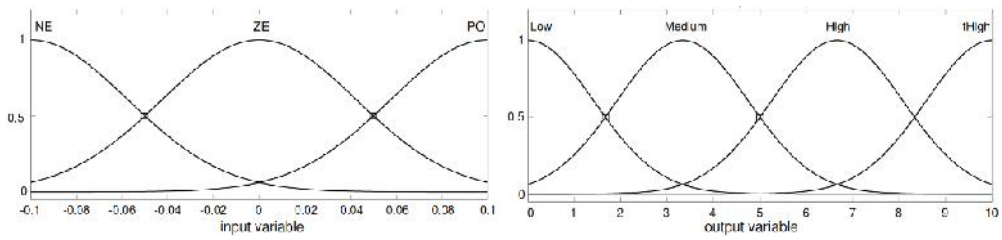

Figure 3. Fuzzy membership functions of the inputs and output

According to the physical influence of the passive base isolator on the building structure, by lengthening the period of the structure the shear force of the stories could be reduced based on the natural frequency of the fixed structure (without base isolator). However, in high-rise buildings with high natural period the base isolator may be ineffective, semi-active system is proposed in this study to suppress the inefficiency of the base isolation system on the high-rise structures. By simulating the semi-active base isolation system and running the model experimentally with several times, to investigate the influence of several feedbacks of the structure as displacement and velocity of the top story and base level equipped by semi-active damper two laws has been found to be reduced the responses of the structure as follows:

$$\begin{cases} x\,\dot{x}_b \le 0 \rightarrow c_b \ne 0 \\ x\,\dot{x}_b > 0 \rightarrow c_b = 0 \end{cases} \tag{14}$$

$$\begin{cases} \dot{x}\,\dot{x}_b \le 0 \rightarrow c_b \ne 0 \\ \dot{x}\,\dot{x}_b > 0 \rightarrow c_b = 0 \end{cases} \tag{15}$$

according to these laws, the damping force is applicable on the system while the velocity direction of the base level is being opposed the displacement or velocity direction of the structure. The fuzzy controller inference rules designed based on these laws by the inputs were chosen to be displacement and velocity of the structure and the velocity of the base level. The fuzzy inference rules are presented in the Table 1.

Table 1. Fuzzy inference rules

Rule	$\dot{x}$	x	$\dot{x}_b$	v	Rule	$\dot{x}$	x	$\dot{x}_b$	v	Rule	$\dot{x}$	x	$\dot{x}_b$	v
1	NE	NE	NE	Low	10	ZE	NE	NE	Low	19	PO	NE	NE	Low
2	NE	NE	ZE	Medium	11	ZE	NE	ZE	Medium	20	PO	NE	ZE	Medium
3	NE	NE	PO	tHigh	12	ZE	NE	PO	tHigh	21	PO	NE	PO	tHigh
4	NE	ZE	NE	Low	13	ZE	ZE	NE	Medium	22	PO	ZE	NE	Medium
5	NE	ZE	ZE	Medium	14	ZE	ZE	ZE	Low	23	PO	ZE	ZE	Low
6	NE	ZE	PO	High	15	ZE	ZE	PO	Medium	24	PO	ZE	PO	Low
7	NE	PO	NE	tHigh	16	ZE	PO	NE	tHigh	25	PO	PO	NE	tHigh
8	NE	PO	ZE	Medium	17	ZE	PO	ZE	High	26	PO	PO	ZE	Medium
9	NE	PO	PO	Low	18	ZE	PO	PO	Low	27	PO	PO	PO	Low

Modelling of the system containing the structure and semi-active base isolator with MR damper device and fuzzy controller that estimates the applying voltage of the MR damper is planned by the SIMULINK environment of the MATLAB software (Figure 4). A gaussian noise generator is employed to consider the imperfection of the sensors estimating the system responses. In addition, with a unit delay, the postponed time of the applying MR damper force to the structure can be taken into account.

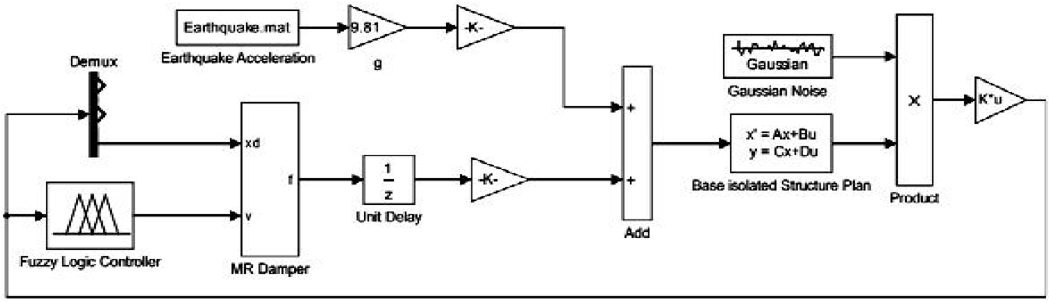

Figure 4. Simulink model of the controlled structure

NUMERICAL SIMULATION

In this paper, to investigate the seismic responses of building structure equipped by semi-active base isolator with the introduced innovative fuzzy controller, a fourteen-story building structure with actual dimensions and loadings has been considered. The plan's geometry of the building is a square with dimensions of 15×15 m^2, has 16 concrete square columns by equal bays of 5 *m* in two perpendicular axis and the height of all stories are 3.2 *m*. The uniform mass loading of the building structure on the base isolation level (m_b in Figure 1) and on the above stories of the building are considered 1100 and 800 kg/m^2, respectively. According to the symmetry of the plan and byassuming the concentrated mass and the rigid floor concepts, the mass and stiffness matrices are calculated, and damping matrix of the building structure, by considering 3% for damping ratio of the structural modes, is obtained. The properties of the building structure and base isolation system are presented in Table 1. The base isolators' properties are of the elastomer natural rubber bearing isolators (Higashino and Okamoto 2006). The building is subjected to El Centro, Hachinohe, two far-field, and Kobe, Northridge and Tabas, three near-field, earthquake accelerations (Figure 5), to evaluate the performance of the SABI, in reducing the seismic responses.

Table 2. Building structure and base isolators properties

Floor	Mass (kg)	Stiffness (N/m)	Damping (N.s/m)
Base isolated level	247500	15800000	14400
1 to 4	180000	762880000	304473
5 to 9	180000	500480000	199746
10 to 14	180000	312480000	124714

The following parameters of the MR damper were selected so that the device has a capacity of 1000 kN with a maximum command voltage of 10 *V*: α_a = 1.0872e5 *N/cm*, α_b= 4.9616e5 *N/(cmV)*, c_{oa}= 4.40 *Ns/cm*, c_{0b}= 44.0 *Ns/(cmV)*, *n*=1, *A*=1.2, γ=3 cm^{-1},   =3 cm^{-1} and η=50 s^{-1}. The parameters are based on the identified model of a shear-mode prototype MR damper tested at Washington University (Yi et al. 2001) and scaled up to have maximum capacity of 1000 *kN* with a maximum command voltage of 10 *V* (Ping and Agrawal 2009).

The responses of the fixed base building structure and the isolated building with passive BI and SABI under the El Centro earthquake excitation have been computed and plotted in Figure 6, for the displacement and acceleration responses of the top story. As can be seen the responses of the building reduced significantly by SABI equipment of the structure, however the passive BI only efficacious in the acceleration responses. The passive BI system reduced the peak displacement response of the structure, but couldn't accommodate the displacements on the latter time of the resonance occurred after the seismic excitation.

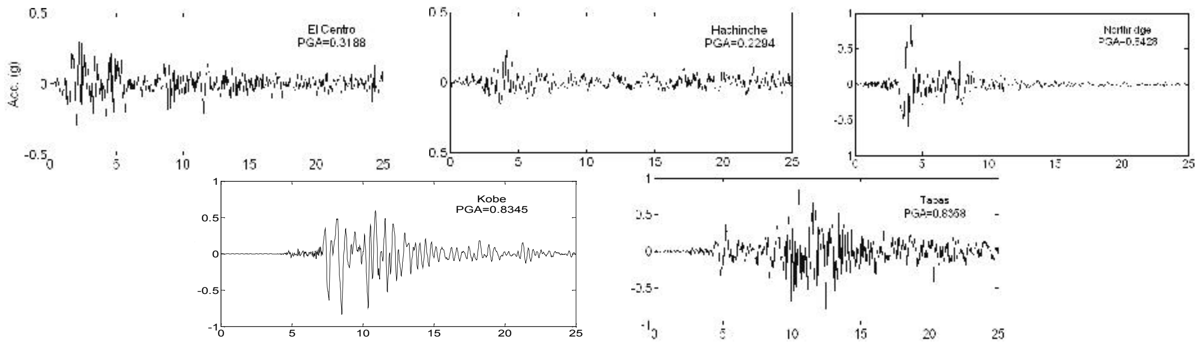

Figure 5. The earthquake accelerations' plots

All results of the SABI performance evaluation of in comparison with passive BI in reducing the building responses under the applied five earthquake vibrations are presented in Table 3. In accordance to the results, the SABI with innovative fuzzy controller, in all displacement responses, has improved the passive base isolator performance and the controller has a significant efficacy in reducing the vibrations of the building in comparison with the fixed base structure. However, the passive BI system decreased the peak responses in comparison with fixed base structure by 33% in far-field and 53% in near-field excitations, the fuzzy controller of the SABI system reduced the fixed base structure responses by 77% and 69% in far-field and near-field earthquakes, respectively. The results showed the SABI increased the performance of the passive BI in reducing the peak displacement responses of the structure by 133% in far-field and 30% in near-field excitations, averagely.

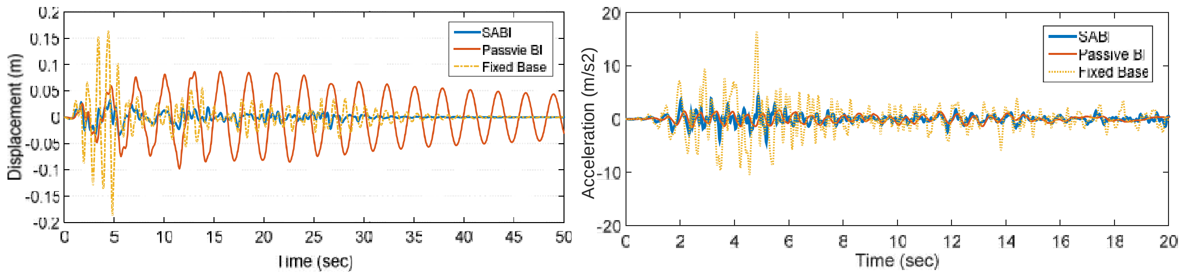

Figure 6. Top story responses under the El Centro earthquake

Table 3. Response reduction percentages of the SABI and passive BI systems

Earthquake	Response	Fixed Base Response	Reduction Percentage	
			Passive BI	SABI
El Centro	Displacement	0.186	47.3	81.2
	Max Inter Story drift	0.0232	57.6	83.8
	Acceleration	16.55	89.9	73.0
Hachinohe	Displacement	0.165	18.8	73.3
	Max Inter Story drift	0.0183	25.6	74.6
	Acceleration	9.33	83.5	68.2
Northridge	Displacement	0.144	48.6	79.9
	Max Inter Story drift	0.0165	53.6	75.0
	Acceleration	10.42	84.1	68.2
Kobe	Displacement	0.341	76.0	76.2
	Max Inter Story drift	0.0340	76.4	76.2
	Acceleration	24.27	86.6	77.1
Tabas	Displacement	0.259	35.9	49.4
	Max Inter Story drift	0.0292	42.8	53.2
	Acceleration	24.3	85.1	71.4

In addition, the SABI results in reducing the max story drift have been showed significant efficacy in comparison with the fixed based structure drifts, by average reducing 79% and 68%, versus that of the passive BI, by average 42% and 58%, in far-field and near-field earthquake excitation, respectively. Hence, the SABI system has increased the performance of the passive BI in both near-field and far-field seismic hazards by averagely reduction percentages of 88% and 17%, respectively. In acceleration responses, the SABI system has decreased the performance of the passive BI by average percentage of 16%, although both semi-active and passive base isolation systems averagely decreased the acceleration response of the fixed base building by 63% in all earthquakes.

Due to the boundaries in the site of the building, where adjacent distance between buildings must be observed and outweigh than this, the limitation of horizontal displacement of the rubber bearing base isolators (averagely 35 *cm*), it is important to adjust the moving of the base level. According to the low stiffness of the isolators in comparison with the structure in horizontal movements, the base level of the structure that equipped by base isolators may have large displacements under the seismic loadings, as shown in Figure 7 plotted for the structure with SABI and passive BI systems under the El Centro earthquake. As can be seen, the passive BI has a large peak displacement of 42 *cm* versus the considerable reduced 12 *cm* of the SABI system. In the other earthquakes the base level excitation of the passive BI and SABI are calculated: 64 and 13 *cm* in Hachinohe, 34 and 8 *cm* in Northridge, 36 and 29 *cm* in Kobe, 80 and 50 *cm* in Tabas earthquakes, respectively. According to these results, semi-active base isolators decreased the base level displacement 198% averagely, in comparison with the passive BI.

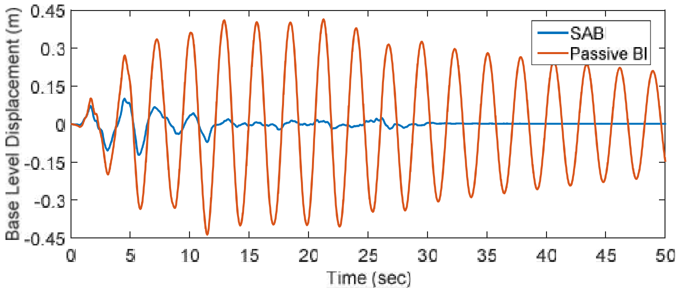

Figure 7. Base level displacement in the isolated structure under the El Centro earthquake

CONCLUSIONS

An innovative fuzzy controller has been presented to regulate the applied voltage of a semi-active magneto-rheological (MR) damper employed as an actuator of base isolation system of building structure under the earthquake excitations. The fuzzy controller inputs are selected to be the velocity and displacement of the infrastructure and the velocity of the base isolated level. The inference rules of the fuzzy logic controller are designed to suppress the both infrastructure and base isolated level vibrations based on the structural feedbacks. The attributes of the fuzzy logic controller are planned according to the physical concept of the observed system.

A building structure with fourteen DOFs (fourteen-story) and symmetric plan and loadings with actual dimensions is considered and the mass, stiffness and damping matrices of the structure are computed. The responses of the building structure with fixed base under the five earthquake excitations are calculated and compared with that of the base isolated structure with the presented semi-active base isolation system controlled by fuzzy controller. In addition, the seismic results of the structure equipped by passive base isolators are calculated and compared with SABI results to investigate the enhancement of the controlling system in reducing the vibration responses. The following results are achieved:

- The SABI performance in reducing the displacement responses of the structure are significant in comparison with the fixed base structure in both far-field and near-field excitations. The results showed that the SABI reduced the responses by average 77% in far-field and 69% in near-field excitations.
- The passive base isolated structure unlike the SABI system couldn't accommodate the resonances under the earthquake motions after the applying time. Also, the SABI system has increased the performance of the passive BI in reducing the structure displacement by average percentages of 133% in far-field and 30% in far-field excitations.

- The maximum drift responses has been reduced significantly by SABI fuzzy controller. In comparison with fixed base structure the peak story drift decreased 79% and 68% by SABI system and 42% and 58% by passive BI, in far-field and near-field excitations, respectively. Obviously, the SABI enhanced the passive base isolation performance.
- In acceleration responses, the SABI system has decreased the performance of the passive BI by average percentage of 16%, although both semi-active and passive base isolation systems averagely decreased the acceleration response of the fixed base building by 63% in all earthquakes.

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