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Vibrations Control of a SODF Structure Using TMD and MR Damper with Fuzzy Logic Algorithm Based on Velocity

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Abstract: In this study, the effects of using a passive tuned mass damper (TMD) with optimal parameters and a semi-active magnetorheological damper (MR damper) have been evaluated separately and simultaneously to control seismic vibrations of a linear single degree of freedom system, which was a simple "mass-spring-damper" model. OpenSEES software was used to model the single degree of freedom system and TMD, and MATLAB software was used to model MR damper. Fuzzy logic algorithm was used by MATLAB to determine the appropriate voltage for MR damper. By solving the dynamic equation of the damper, its force was calculated and this force was applied to the single degree of freedom system by OpenSEES. In the following, incremental dynamic analysis (IDA) has been performed using 7 earthquake records with maximum acceleration of 0.1g to1.0g with incremental step of 0.1g. Earthquakes are applied to four models without dampers, equipped with optimized TMD, equipped with MR damper, and equipped with both TMD and MR damper. The results showed that the simultaneous use of TMD and MR damper had the greatest effect on controlling the vibration of the system and reduced the maximum displacement by 22.36% and the maximum base shear by 21.85% compared to the case without dampers. Also, using only MR damper had a greater effect than using only TMD on reducing the seismic responses of the single degree of freedom system.

Keywords: Single degree of freedom system; Vibration control; Tuned mass damper; Magnetorheological damper; Incremental dynamic analysis.

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1. Introduction

Many ideas have been proposed for active, passive, semi-active and hybrid structural control systems. The idea of using energy dampers in structures to reduce seismic vibrations was proposed in the analytical and in-vitro studies by Kelly et al. (1972) [1]. Today, vibration control in structures is done by energy consuming systems. This leads to a reduction in the displacement response, base shear, and structure velocity against the lateral forces of the earthquake. The idea of controlling the vibration input to the structure and its response has made fundamental changes in the usual process of strengthening structures against earthquakes. In this viewpoint, instead of strengthening the structure as the only way, additional equipment such as dampers are installed to resist earthquakes together with the structure as a whole. The equipment improve the response of the structure to earthquakes with their special behavior. The study of the equipment creates a new design philosophy that emphasizes on increasing the capacity of energy dissipation in the structure and instead of resisting the earthquake, the structure is controlled against it [2, 3].

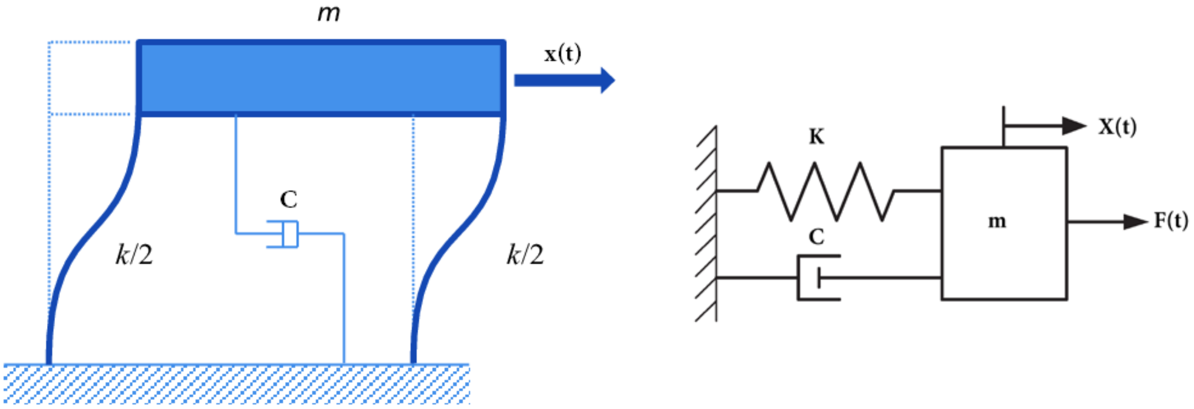
TMD is one of passive control systems that was proposed by Frahm (1909) for the first time to reduce the vibration of ships due to sea waves in the United States [4]. This damper consisted a "mass, spring and damper" system that is placed at a height of the structure to reduce its respo. For this purpose, an additional mass of about 1-2% of the first mode mass of the structure was installed at a suitable height of the structure and its frequency was tuned with the first mode frequency of the structure to control the vibrations of the structure. When this frequency is stimulated, the mass damper absorbs and dissipates the earthquake energy by moving opposite in phase with respect to the structure [5]. The maximum capacity of passive TMD can be used when the parameters are optimal [6]. Guo et al. (2012) proposed an optimization method for a non-linear mass damper and investigated the effectiveness of the non-linear mass damper at different damping ratios of the structure and excitations with different intensity [7]. Salvi and Rizzi (2017) addressed the optimization of mass dampers that are tuned using the active mass balance of the structure and the effect of this damper on the seismic performance of bending frames with linear behavior [8]. Bui and Tran (2022) studied the optimal and multi-objective design of a TMD to control the vibration of bridges against high wind speed. The study results showed that the use of the proposed method increased the critical wind speed of the system to start the vibration of the bridge significantly [9]. Gao et al. (2023) designed the parameters and evaluated the performance of TMD for the seismic control of the structure by considering the interaction between the soil and the structure. The study results showed that the mass damper designed by the proposed method can show proper performance and stability [10]. Shams al-din Lu et al. (2023) investigated an efficient design method using two strategies "meta-heuristic-based optimization" and "reliability-based design optimization" for the optimal design of TMD and multiple TMD in nonlinear structures under uncertainty. They discussed the mechanical parameters of the control system. The study results showed that the "reliability-based design optimization" strategy can optimally design TMD and multiple TMD with proper performance to reduce the seismic responses of nonlinear structures [11].

Vibration control of structures by MR dampers is a semi-active control system. Using the magnetic liquid in this type of dampers, a lot of force is created by the piston and cylinder system. The semi-active control system of these dampers is provided by tunning a small energy source, which is usually an electric current with a voltage of 12-24 volts. The mechanical properties of the liquid used in these dampers change rapidly with the input voltage change. Without applying an external energy source to the damper and changing its characteristics, this damper works passively [12]. Uz and Hadi (2014) discussed the optimal design of semi-active control system for adjacent buildings connected to MR damper based on integrated fuzzy logic and multi-objective genetic algorithm; The study results showed that reducing the number of dampers to control the dynamic response of the system can help more than increasing the number of dampers in reasonably controlling the seismic response and at the same time reducing the cost [13]. Bathaei et al. (2016) investigated seismic vibration control of College bridge using genetic algorithm and multiple tuned mass dampers [14]. Bathaei et al. (2017) studied seismic vibration control of College Bridge of Tehran-Iran using six MR dampers and fuzzy logic algorithm [15]. Ramezani et al. (2017) studied the design of fuzzy control parameters for semi-active control of tall buildings along with tuned mass dampers [16]. Bathaei et al. (2018) investigated the semi-active control of an eleven-degree-of-freedom building model by combining TMD and MR damper using type I and II fuzzy algorithms. The study results showed that the type II fuzzy controller has a better performance in reducing the seismic responses of the structure than the type I fuzzy controller [17]. Ramezani et al. (2019) compared the fuzzy performance of types 1 and 2 using tuned mass damper and considering uncertainties [18]. Hashemi and Zahrai (2019) studied the fuzzy semi-active control of the nonlinear 9-story structure using the combination of a series of TMD and MR damper placed on the roof of the structure. The study results showed that the series combination of these dampers has reduced the maximum displacement of the roof, the maximum relative displacement and the maximum shear of the base of the structure [19]. Bui et al. (2021) proposed a new parametric dynamic model based on a quasi-static model and a hysteresis coefficient to accurately and significantly predict the hysteresis behavior of magnetic dampers. The study results showed the appropriate efficiency of the proposed model on predicting the hysteresis behavior of MR damper [20]. Bathaei and Zahrai (2022) investigated the effect of time delay on the semi-active fuzzy control of a single degree of freedom structure equipped with MR damper and overcoming it using a predictive control system. The study results showed that equipping the structure with a predictive control system has reduced the difference between the results without time delay and with time delay, and the accuracy of response prediction has increased [21]. Tang et al. (2023) investigated the vibration control of steel-concrete composite railway bridges considering the effects of slip and shear delay by proposing a hybrid model of TMD and MR damper. The study results showed that the use of the combined model of these dampers is associated with reducing the dynamic responses of the vertical vibration of the bridge when the train passes, and it also has good reliability, stability and strength [22]. Bathaei et al. (2022, 2024) presented floating fuzzy in semi-active control system and used predictive control algorithm to overcome time delays. [23- 26].

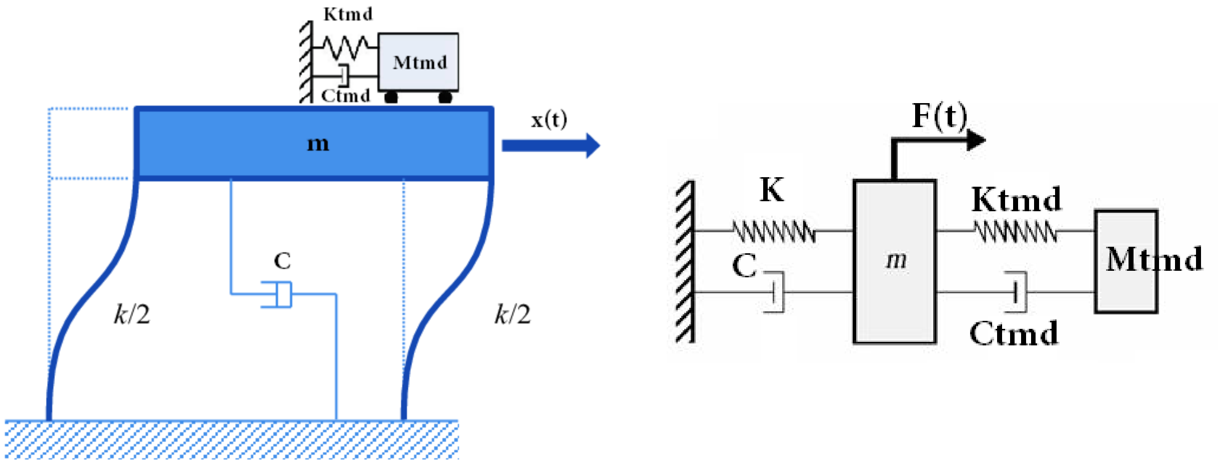
In this paper, the effects of using optimal TMD and semi-active MR damper individually and combined on controlling the seismic vibrations of a linear single degree of freedom structure model have been evaluated and compared. For this purpose, the seismic responses of four single degree of freedom system models were investigated and compared, including: uncontrolled model, model equipped with optimal TMD, model equipped with MR damper and model equipped with both TMD and MR damper under IDA analysis with maximum acceleration of 0.1g to 1.0g and an incremental step of 0.1g. OpenSEES and MATLAB have been used for modeling, and TCP/IP has been used for connection between two software. In order to calculate the appropriate control voltage for MR damper, fuzzy logic has been used. Also, the stability of TMD and MR damper by increasing earthquake velocity has been investigated.

2. Vibration of a single degree of freedom system subjected to dynamic force

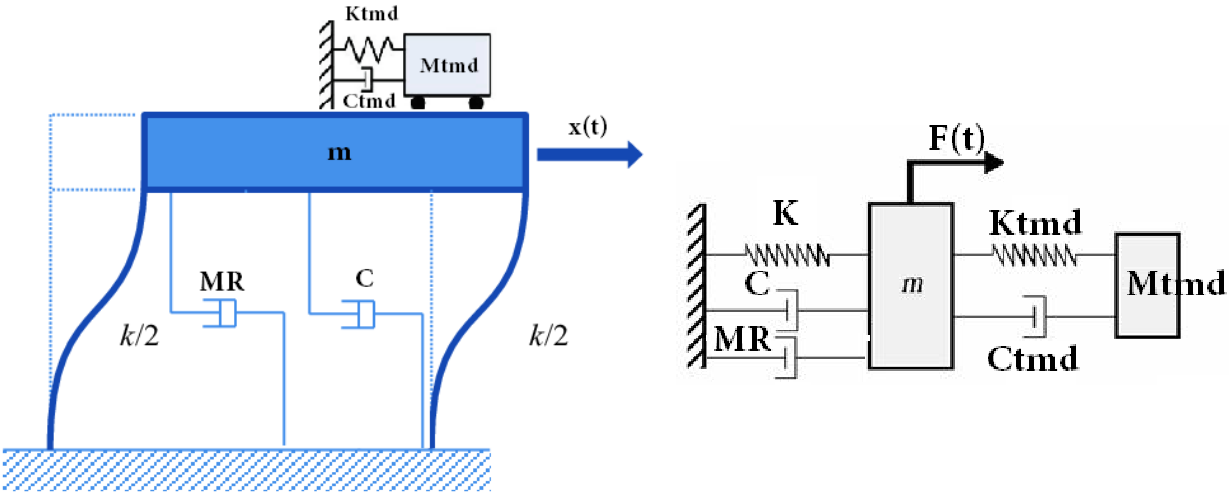
The simplest model to explain the vibration of a single-degree-of-freedom system is the simple mass, spring, and damper model. Figure 1 shows the single-degree-of-freedom system. In this simple model, m is the mass, k is the stiffness of the spring and c is the damping of the damper, and f(t) is a dynamic external force. In general, oscillation is performed in two forms: free vibration and forced vibration. Free vibration occurs when no external force acts on the vibrating system and the vibration is caused by an initial displacement and release or an initial velocity in the system. When the single degree of freedom system is subjected to an external dynamic force and begins to oscillate, forced vibration occurs. Dynamic external force can be caused by impact, blast wave, harmonic forces, non-harmonic excitation forces or seismic excitation.



A: SODF system



B: SODF system & TMD



C: SODF system & TMD & MR

Figure 1. A simple model for the single degree of freedom system

Equation (1) shows the movement of the single degree of freedom system under the dynamic force *f(t)*. Where the parameters m, k and c are the mass, stiffness and damping of the system, respectively. The parameter *x(t)* is the displacement of the system. $\dot{x}(t)$ and $\ddot{x}(t)$ are the first and second derivatives of the displacement with respect to time, or the velocity and acceleration of the system at each moment of excitation.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \tag{1}$$

There are several mathematical methods to obtain the solution of the equation of the single degree of freedom system. Laplace transform is a suitable method to solve this equation. By applying the Laplace transform under the initial conditions, the following solution will be obtained:

$$X(s) = \frac{F(s)}{ms^2+cs+k} + \frac{(ms+c)x(0)+m\dot{x}(0)}{ms^2+cs+k} \tag{2}$$

where *X(s)* and *F(s)* are the Laplace transforms of time functions *x(t)* and *f(t)*, respectively. Given zero initial conditions, the equation will be simplified as Equation (3). Equation (3) is a familiar equation for a linear dynamic system, where *G(s)* is the transformation function of the system. The vibration time signal *x(t)* is obtained from the inverse Laplace transform *X(s)*.

$$X(s) = \frac{F(s)}{ms^2+cs+k} = G(s)F(s) \tag{3}$$

3. Modeling

In order to model the single degree of freedom system and TMD, OpenSEES has been used, and for modeling MR damper, MATLAB has been used. In fact, there was no MR damper element in OpenSEES. Therefore, by MATLAB, the appropriate control voltage for MR damper during IDA analysis was determined by implementing the fuzzy logic algorithm. By solving the dynamic equation of MR damper, its force was calculated and applied to the single degree of freedom structure model by OpenSEES. TCP/IP was used for connection between two software.

3.1 Modeling of the single degree of freedom model equipped with TMD

In this section of the paper, the studied model equipped with TMD and its related parameters are discussed in order to achieve the optimal frequency and damping of the damper. Figure 2 shows the single degree of freedom model studied as the simple "mass, spring and damper" model, on which TMD is also installed. In the proposed model, the parameters m, k and c are the mass, stiffness and damping of the single degree of freedom system, the parameters m_d, k_d and c_d are the mass, stiffness and damping of TMD, *p(t)* is the dynamic external stimulating force, u is the displacement of the system and u_d is the displacement of the tuned mass damper.

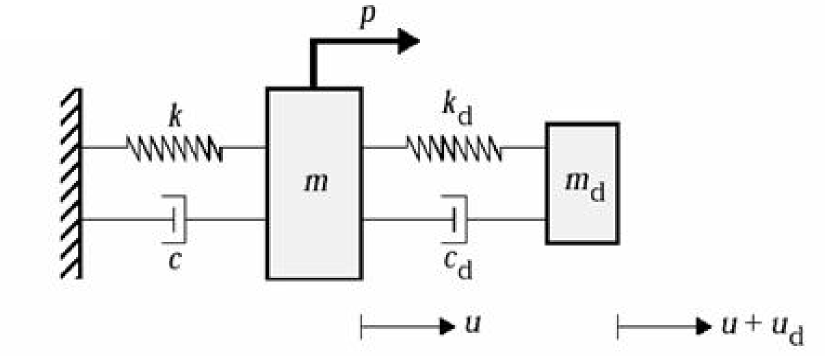


Figure 2. Single degree of freedom system model by TMD

In this article, the mass ratio of TMD equal to 0.02 of the mass of the single degree of freedom system has been considered. In order to calculate the frequency and the optimal damping percentage of TMD, equations (4) and (5) proposed by Pastia and Luca have been used, respectively [27].

$$f_{TMD} = \frac{f_1}{1+\mu} \tag{4}$$

$$\xi_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)^3}} \tag{5}$$

where f_{TMD} and f_1 are the frequency of the tuned mass damper and the frequency of the structure, μ is the mass ratio and ξ_{opt} is the optimal damping percentage of the tuned mass damper, respectively. The total mass of the single degree of freedom system is considered equal to 1500000 kg and the damper mass is equal to 30000 kg. The frequency of the single degree of freedom system is 0.8197 Hz and the frequency of the TMD is 0.8036 Hz. The optimal damping percentage of the damper is also calculated to be 8.4%. Table 1 shows the parameters related to the linear single degree of freedom system model, and TMD.

Table 1. Parameters of the single degree of freedom system and optimized TMD

SDOF	TMD
m= 1500000 kg	m_d= 30000 kg
k= 39.4784×10^6 N/m	k_d= 7.7026×10^5 N/m
c= 6.2832×10^5 N.sec/m	c_d= 2.5583×10^4 N.sec/m
ξ= 4 %	ξ_{opt}= 8.4 %
f_1= 0.8197 Hz	f_{TMD}= 0.8036 Hz

By OpenSEES, in order to model the stiffness of the single degree of freedom system and the stiffness of the tuned mass damper, elastic material is used, and to model the damping of the single degree of freedom system and the mass damper, viscous material is used. Both materials are modeled with uniaxial behavior. Also, to model the elements of the single degree of freedom system and TMD, the zero-length element has been used. Figure 3 shows the behavior of uniaxial elastic material used for modeling by OpenSEES.

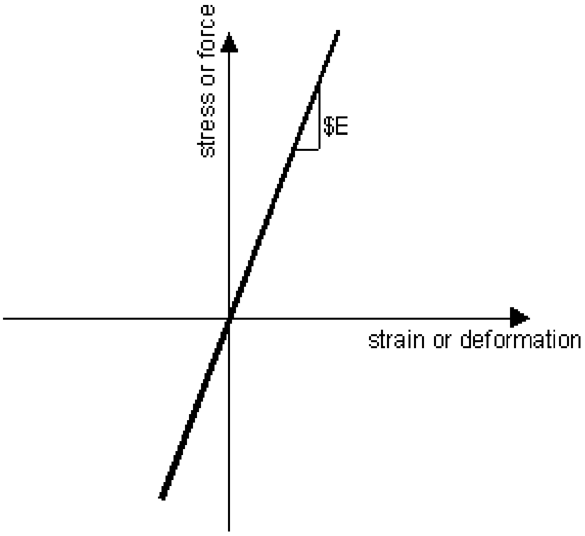


Figure 3. Uniaxial-Material Elastic behavior by OpenSEES [28]

3.2 Verification of MR damper behavior

To ensure the accuracy of the behavior of MR damper in the model, this damper has been subjected to a cyclic deformation and the graph of the force produced has been drawn for zero, 5 and 10 volts. The dampers used in this study are taken from the dampers used in an article by Ok et al. (2007) [29]. The graphs drawn are also compared with the graphs presented by these researchers. To model the behavior of MR damper, its behavioral equations have been solved in the equations (6) and (7).

$$F = C_0\dot{x} + \alpha z \tag{6}$$

$$\dot{z} = -\gamma|x|z|\dot{z}|^{n-1} - \beta\dot{x}|z|^n + A_m\dot{x} \tag{7}$$

where F is the MR damper force, x is the displacement of the damper, z is the evolutionary variable, and the parameters n, γ, β, and Am are constants that are obtained from testing each damper. The parameters C_0 and α are also determined using equations (8) and (9) in which u is the applied control voltage and parameters α_a,a_b,$C_{0_a}$and $C_{0_b}$are constants. Table 2 also shows the used parameters and their values [29].

$$\alpha = \alpha(u) = \alpha_a + a_b u \tag{8}$$

$$C_0 = C_0(u) = C_{0_a} + C_{0_b} u \tag{9}$$

Table 2. Parameters used in MR damper

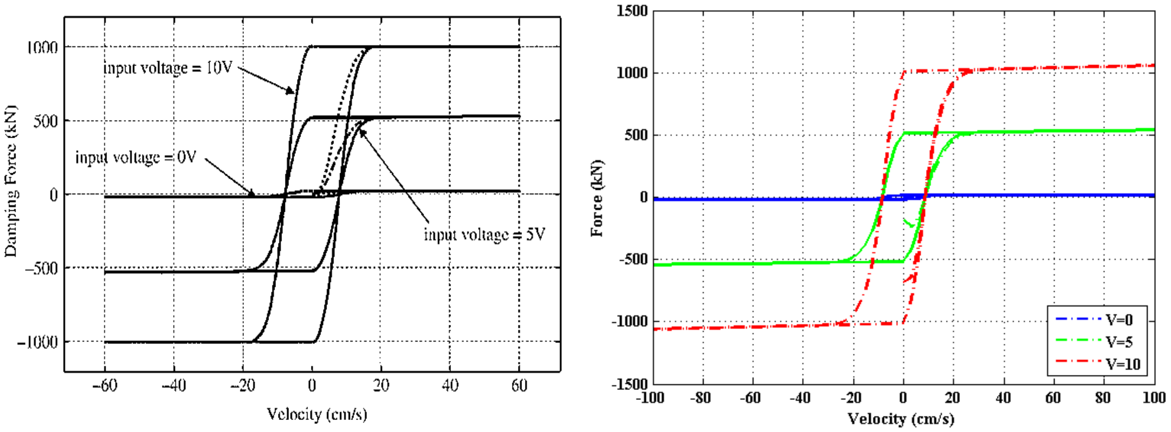
parameter	value	parameter	value	parameter	value
α_a	1.0872 × 10^7 (N/m)	C_{0_b}	4400 (Ns/m/v)	β	300 (m^{-1})
a_b	4.9616 × 10^7 (N/m/V)	A_m	1/2	γ	300 (m^{-1})
C_{0_a}	440 (Ns/m)	n	1	η	50 (s^{-1})

One of the limitations of MR damper is the time delay in applying the control force. Given that the dampers used in control systems cannot apply the required force instantly, there is always an unwanted time delay in applying the control force. The amount of this delay depends on the type of dampers used. In general, for existing dampers, this value is around 0.02-0.1 seconds, and in this study, the value of 0.07 has been used.

Due to the internal mechanism of MR damper, these dampers cannot apply the command voltage instantaneously. Therefore, it always takes a small amount of time for the voltage applied to the system to be equal to the command voltage. Therefore, to model this insignificant time delay in the system, Equation (10) is used, where V is the command voltage and η is constant [29].

$$\dot{u} = -\eta(u - v) \tag{10}$$

Figure 4 shows the graphs provided by Ok et al. compared to the graphs obtained from this study. As shown, for all three voltages of zero, 5 and 10 volts, the behavior of MR damper is modeled well and close to reality.



(1) (2)

Figure 4. MR damper behavior: 1) Ok et al. [29], 2) present study

3.3 Fuzzy logic algorithm

Given that there is no MR damper element by OpenSEES, in order to model the force of this damper, MATLAB was used. In this way, the dynamic equation of MR damper was calculated by MATLAB and this force was sent to OpenSEES using the connection between the software. By OpenSEES, the force calculated by MATLAB was applied to the single degree of freedom structure. As mentioned earlier, to calculate the appropriate control force of MR damper, it is necessary to calculate the appropriate control voltage, so the fuzzy logic algorithm has been used to determine the appropriate voltage. In the following, the fuzzy logic algorithm used are discussed.

In the fuzzy algorithm used in this study, eleven different fuzzy sets have been considered for the system input parameters. These sets were NVL, NL, NM, NS, NVS, ZO, PVS, PS, PM, PL and PVL. Table 3 shows each of these eleven fuzzy sets. In all the phase systems used in this study, the output parameter is the voltage applied to MR damper. For the output parameter, six different fuzzy sets have been considered. Table 4 shows each of these six fuzzy sets.

Figure 5 shows the cycle of performing semi-active control analysis using a fuzzy system with velocity decision making system. The input parameter for the fuzzy inference system (FIS) is the relative velocity of the two ends of MR damper, which is denoted by RelVel. For FIS, the rule base (RB) is used as shown in Table 5. Figure shows the set of RB. As shown, the diagram is drawn in two dimensions. Because one input and one output are defined in FIS. Figure 6 shows the two-dimensional diagram of the fuzzy inference system based on the relative velocity of the two heads of the MR damper.

Table 3. Description of the considered fuzzy sets for the input parameters

fuzzy sets	PVL	PL	PM	PS	PVS	ZO	NVS	NS	NM	NL	NVL
values	Very large positive values	Large positive values	Average positive values	Small positive values	Very small positive values	Values close to zero	Very small negative values	Small negative values	Average negative values	Large negative values	Very large negative values

Table 4. Description of the considered fuzzy sets for the output parameters

fuzzy sets	VL	L	M	S	VS	ZO
values	Very large values	Large values	Average values	Small values	Vary small values	Values close to zero

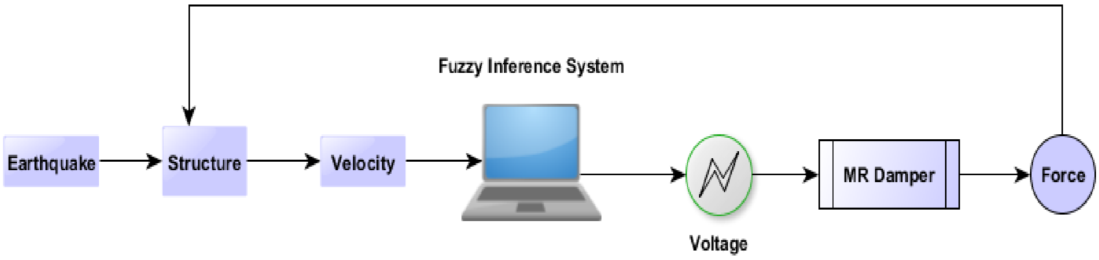


Figure 5. Semi-active control analysis cycle using FIS with velocity making decision system

Table 5. Fuzzy rule base

	RelVel of dampers										
	NVL	NL	NM	NS	NVS	ZO	PVS	PS	PM	PL	PVL
voltage	VL	L	M	S	VS	ZO	VS	S	M	L	VL

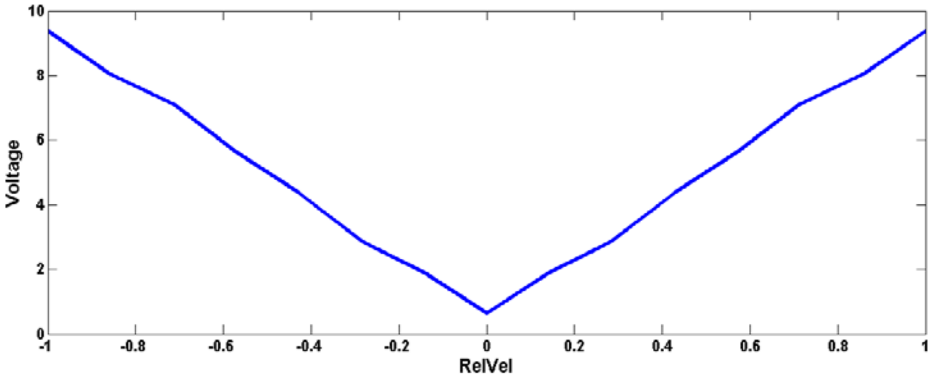


Figure 6. 2D RB1

As mentioned earlier, the single degree of freedom system and the element of TMD were modeled by OpenSEES and MR damper and its force calculation have been modeled by implementing fuzzy logic using MATLAB. For the connection between the software, TCP/IP has been used. To use TCP/IP, the possibility of creating a network connection between the server and the client, which is a feature of TCL, has been used.

4. Applied earthquakes to the model

In this article, 7 earthquakes have been used in order to perform IDA analysis on the studied models. The earthquakes were selected based on FEMA P-695 [30], whose characteristics are shown in Table 6.

Table 6. Earthquakes applied to the studied models [30]

EQ No	Earthquake	Station	M	Year	PGA (g)
1	Northridge	Beverly Hills	6.7	1994	0.52
2	Northridge	Canyon Country-WLC	6.7	1994	0.48
3	Duzce, turkey	Bolu	7.1	1999	0.82
4	Hector Mine	Hector	7.1	1999	0.34
5	Imperial Valley	Delta	6.5	1979	0.35
6	Imperial Valley	El Centro Array #11	6.5	1979	0.38
7	Kobe, Japan	Nishi-Akashi	6.9	1995	0.51

5. Incremental dynamic analysis

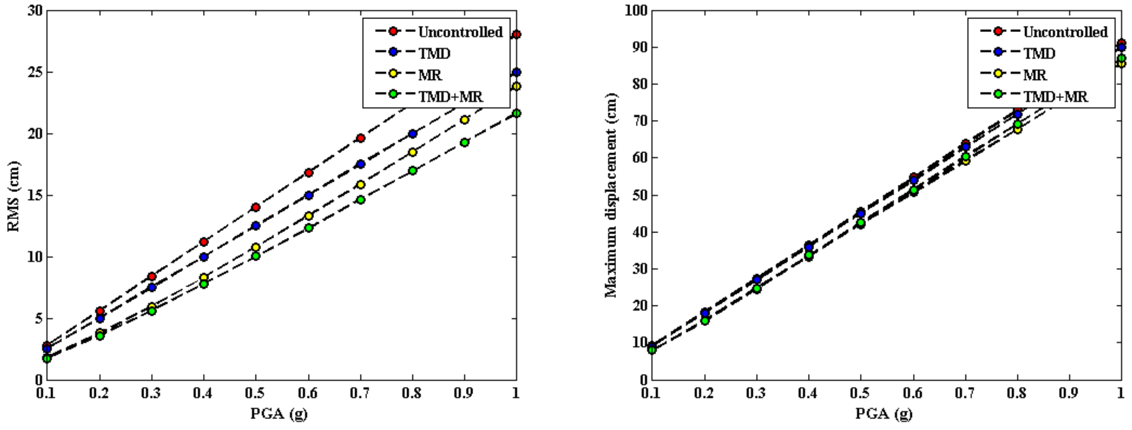
In this study, on each of the single degree of freedom system models without dampers, equipped with TMD, equipped with semi-active MR damper, and equipped with both TMD and MR damper, IDA analysis was done under the effect of 7 earthquakes as shown in Table 6 with the maximum acceleration of 0.1g to1.0g with incremental step of 0.1g. After performing IDA, the responses of displacement and base shear of the studied models and the dispersion of the responses have been investigated. According to the valid seismic regulations of the world as well as Iran's 2800 standard [31], whenever at least 7 accelerometers are used for IDA, the final response can be considered equal to the average response of all earthquakes, which is also considered as the average response in this article. One of the most important and widely used outputs obtained from IDA, which can be used for the interpretation of analysis results, is the calculation of the dispersion of responses. The concept of "index of dispersion" or "root mean squared (RMS)" is the dispersion of the responses compared to the stationary state during earthquakes. RMS solution is calculated using Equation (11), where x_i is the solution and n is the number of solutions.

$$\text{RMS}\ (x) = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}} \tag{11}$$

6. Analysis results

After performing IDA and given that the number of earthquakes and the number of analyzes performed are large, a sample of applied earthquakes was presented, for which the Northridge-EQ2 earthquake was selected. Figure 7 shows the responses of maximum displacement and RMS displacement of all studied models for the mentioned earthquake compared for maximum acceleration of 0.1g to1.0g. As shown, based on the response of the maximum displacement, the responses of models without dampers and equipped with TMD, as well as models equipped with MR damper and equipped with both dampers are almost identical, and the judgment about which control damper plays a role effective in controlling the displacement of the single degree of freedom structure is somewhat difficult. Therefore, based on the comparison of the displacement dispersion responses, it can be clearly concluded that the models equipped with both TMD and MR damper, equipped with MR damper, and equipped with TMD had the greatest and least effect on reducing the structural displacement response of the linear single degree of freedom structure, to the model without dampers during earthquakes, respectively.

Table 7 shows the average responses of the maximum displacement and RMS displacement of all studied models for the maximum acceleration from 0.1g to1.0g. The values in Table 7 have been calculated by averaging the responses of 7 earthquake records introduced in Table 6 for each maximum acceleration. For example, for structure without damper, the average response of the maximum displacement at the maximum acceleration of 0.5g is equal to 0.44 m. This value is the average result of the maximum displacement responses of the single degree of freedom system under 7 earthquake records with a maximum acceleration of 0.5g. The last row of the table is also the average displacement values for different maximum acceleration. The average values of the response of the maximum displacement of the linear single degree of freedom system in the model without dampers for different maximum acceleration is equal to 0.483 m, which is equal to 0.43 m for the model equipped with TMD, 0.397 for the model equipped with MR damper and 0.375 m for the model equipped with both TMD and MR damper. As a result, the average improvement percentage of the response of the maximum displacement of the single degree of freedom system in the models equipped with TMD, equipped with MR damper and equipped with both TMD and MR damper compared to the model without dampers is equal to 10.97, 17.80 and 22.36%. In order to better compare the performance of different control systems, the improvement percentage of responses is also reported. The average improvement percentage of the maximum displacement of the structure in the model equipped with MR damper compared to the model equipped with TMD is equal to 7.67%, and 12.79 and 5.54% in the model equipped with both TMD and MR damper compared to the models equipped with TMD and MR damper, respectively.



(2) (1)

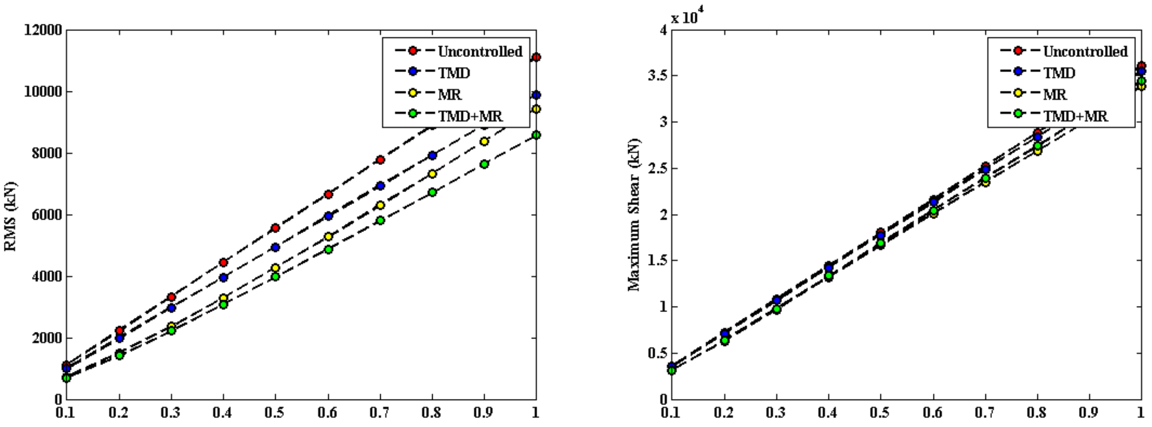
Figure 7. Comparison of displacement responses of models under Northridge-EQ2 earthquake: 1) Max, 2) RMS

Table 7 shows that the average displacement response of the linear single degree of freedom system in the model without dampers for different maximum acceleration is equal to 0.135 m, which is equal to 0.107 m for the model equipped with TMD, 0.095 m for the model equipped with MR damper and 0.083 m for the model equipped with both TMD and MR damper. As a result, the average improvement percentage of RMS displacement of the linear single degree of freedom system in models equipped with TMD, equipped with MR damper and equipped with both TMD and MR damper compared to the model without dampers is equal to 20.74, 29.62 and 38.51%, respectively. The average improvement percentage of RMS displacement in the model equipped with MR damper compared to the model equipped with TMD is 11.21% and, 12.63 and 22.42% in the model equipped with both TMD and MR damper compared to the models equipped with TMD and equipped with MR damper, respectively. By comparing the average improvement of the maximum displacement of the structure and the average improvement of RMS displacement during applied earthquakes, it can be seen that the percentage of the improvement of RMS displacement is higher than the percentage of the improvement of the maximum displacement, indicating that the control systems in addition to reducing the maximum response of the structure to the main pulse of the earthquake can reduce the response of the structure to the effect of weaker pulses and in total reduce the energy input to the structure during earthquakes.

Table 7. Average responses of the maximum displacement and RMS displacement of the studied models under the effect of IDA

PGA (g)	Maximum Displacement (m)				RMS Displacement (m)			
	Uncontrolled	TMD	MR	MR+TMD	Uncontrolled	TMD	MR	MR+TMD
0.1	0.09	0.08	0.06	0.06	0.02	0.02	0.01	0.01
0.2	0.18	0.16	0.13	0.13	0.05	0.04	0.03	0.03
0.3	0.26	0.23	0.20	0.19	0.07	0.06	0.05	0.04
0.4	0.35	0.31	0.28	0.26	0.10	0.08	0.06	0.06
0.5	0.44	0.39	0.35	0.33	0.12	0.10	0.08	0.07
0.6	0.53	0.47	0.43	0.41	0.15	0.12	0.10	0.09
0.7	0.61	0.55	0.51	0.48	0.17	0.14	0.12	0.11
0.8	0.70	0.63	0.59	0.55	0.20	0.15	0.14	0.12
0.9	0.79	0.70	0.67	0.63	0.22	0.17	0.17	0.14
1	0.88	0.78	0.75	0.71	0.25	0.19	0.19	0.16
Average (m)	0.483	0.430	0.397	0.375	0.135	0.107	0.095	0.083

Figure 8 shows the comparison of responses of maximum base shear and RMS base shear of all four studied models for the Northridge-EQ2 earthquake for the maximum acceleration of 0.1g to 1.0g. As shown, based on the response of the maximum base shear, similar to the maximum displacement, the responses of models without dampers and equipped with TMD, as well as models equipped with MR damper and equipped with both dampers, are almost identical, and the judgment about which control system plays a role in reducing the base shear of the single degree of freedom structure seems a bit hard. Therefore, based on the comparison of RMS base shear, it can be easily seen that the models equipped with both TMD and MR damper, equipped with MRD and equipped with TMD had the greatest and least effect on reducing the base shear response of the linear single degree of freedom structure to the model without dampers or uncontrolled during earthquakes, respectively.



(2) (1)

Figure 8. Comparison of maximum base shear and RMS base shear of models under Northridge-EQ2 earthquake: (1) Max, (2) RMS

Table 8 shows the average responses of maximum base shear and RMS base shear of all models studied for maximum acceleration of 0.1g to 1.0g. The values in Table 7 have been calculated by averaging the responses of 7 earthquake records introduced in Table 6 for each level of maximum acceleration. For example, for the structure without damper, the average response of the maximum base shear at the maximum acceleration of 0.5g is equal to 17340.629 kN. This value has been obtained from averaging the maximum base shear of the linear single degree of freedom system under 7 earthquake records with a maximum acceleration of 0.5g. The last row of the table is also the average values of the base shear response for different maximum acceleration. The average values of the response of the maximum base shear of the linear single degree of freedom system in the uncontrolled model for different maximum acceleration is equal to 19074.688 kN, which for the model equipped with TMD is equal to 17037.146 kN, 15763.178 kN for the model equipped with MR damper and 14906.610 kN for the model equipped with both TMD and MR damper. As a result, the average improvement percentage of the response of the maximum base shear of the single degree of freedom system in models equipped with TMD, equipped with MR damper and equipped with both TMD and MR damper compared to the model without dampers is equal to 10.68, 17.36 and 21.85%, respectively. The average improvement percentage of the maximum shear response of the single degree of freedom structure in the model equipped with MR damper compared to the one equipped with TMD is 7.47% and 12.50 and 5.43% in the model equipped with both TMD and MR damper compared to the models equipped with TMD and MR damper, respectively.

Table 8 shows the average RMS basic shear of the linear single degree of freedom system in the model without a damper for different maximum acceleration is equal to 5444.969 kN, which is equal to 4209.277 kN for the model equipped with TMD, 3808.630 kN for the model equipped with MR damper and 3272.448 kN for the model equipped with both TMD and MR damper. As a result, the average improvement percentage of the base shear dispersion of the linear single degree of freedom system in models equipped with TMD, equipped with MR damper, and equipped with both TMD and MR damper compared to the model without dampers is 22.69, 30.05, and 39.89%, respectively. The average percentage of improvement in the dispersion of the base shear in the model equipped with MR damper compared to the one equipped with TMD is equal to 9.51%, and 22.25 and 14.07% in the model equipped with both TMD and MR damper compared to the models equipped with TMD and equipped with MR damper, respectively. By comparing the average improvement of the maximum base shear and the average improvement of RMS base shear during applied earthquakes of the structure, it can be seen that the percentage of the improvement of RMS base shear is higher than the percentage of the improvement of the maximum base shear.

Table 8. Average responses of the maximum base shear and RMS base shear of the studied models under the effect of IDA

PGA (g)	Maximum Base Shear (N)				RMS Base Shear (N)			
	Uncontrolled	TMD	MR	MR+TMD	Uncontrolled	TMD	MR	MR+TMD
0.1	3468126	3097661	2521909	2440069	989994	765323	536952	485432
0.2	6936247	6195327	5207431	5022411	1979989	1530646	1166061	1040125
0.3	10404371	9292981	7982647	7674267	2969983	2295969	1828718	1623261
0.4	13872496	12390656	10914949	10434399	3959977	3061292	2537133	2239326
0.5	17340629	15488301	13943296	13264180	4949972	3826615	3287481	2877445
0.6	20808757	18585976	17040381	16136413	5939966	4591938	4072449	3531759
0.7	24276871	21683643	20187900	19047714	6929960	5357261	4886242	4199711
0.8	27745014	24781314	23381186	22007786	7919955	6122584	5727409	4881324
0.9	31213114	27878986	26592071	25010129	8909949	6887907	6584885	5573310
1	34681257	30976614	29860014	28028729	9899943	7653230	7458967	6272784
Average (kN)	19074.688	17037.14	15763.17	14906.61	5444.969	4209.27	3808.63	3272.45

7. Conclusion

In this study, the effects of using tuned mass damper with optimal parameters and a semi-active magnetorheological damper have been evaluated separately and simultaneously to control seismic vibrations of a linear single degree of freedom system. IDA was under the effect of 7 earthquakes with maximum acceleration of 0.1g to 1.0g on the single degree of freedom system without a damper, equipped with an optimally TMD, equipped with MR damper and equipped with both TMD and MR damper. OpenSEES and MATLAB were used for modeling, and TCP/IP was used for the connection between the software. Fuzzy logic algorithm was also used to calculate the appropriate control voltage for MR damper. The results showed that the models equipped with both TMD and MR damper, equipped with MR damper and equipped with TMD had the greatest and least effects on reducing the response of displacement and base shear of the linear single degree of freedom structure, compared to the model without dampers during earthquakes, respectively. In the model equipped with both TMD and MR damper, a reduction by 22.36% in maximum displacement and 21.85% in maximum base shear was observed compared to the case without dampers. Also, in this model, a reduction by 38.51% in RMS displacement and 39.89% in RMS base shear was observed compared to the case without dampers. By comparing the average improvement of the maximum displacement and maximum base shear of the structure and the average improvement of RMS displacement and RMS base shear during applied earthquakes, it can be said that the percentage of improvement of dispersion of responses was higher than the percentage of improvement of maximum responses. In other words, in addition to reducing the maximum response of the structure to the main pulse of earthquakes, the control systems can reduce the response of the structure to the effect of weaker pulses and in total reduce the energy input to the structure during earthquakes.

From the results, It can be mentioned that with the MR damper, the performance of the tuned mass damper has also improved. In addition, in case of using fuzzy inference system, the adaptability of dampers with the behavior of the structure increases because the fuzzy system makes decisions non-linearly. With the combination of MR and TMD, the response of the structure subjected to the maximum accelerations of the earthquake has also decreased.

8. References

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