MODELLING OF REINFORCE CONCRETE BUILDING WITH ASYMMETRIC PLAN EQUIPPED BY SEMI-ACTIVE TUNED MASS DAMPER USING FUZZY CONTROLLER

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ABSTRACT

In this paper, a fifteen-story reinforced concrete (RC) building with asymmetric plan equipped by semi-active tuned mass damper (STMD) is modelled to evaluate the seismic responses under the earthquake acceleration. Modelling of the structure is done by considering members connected with a rigid floor diaphragm such that has three degrees-of-freedom at each floor, i.e., lateral displacements in two perpendicular directions and a rotation about the vertical axis of the third dimension. A MATLAB program has been developed to calculate the building structural mass, stiffness and damping matrices based on the number of stories, the plans' geometry and loadings, each column's location and specifications and the damping ratio of the structure. A fuzzy controller is employed to control the applied voltage of a semi-active magneto-rheological (MR) damper working parallel with the tuned mass damper attached on the top floor of the building, based on the feedbacks of the structure. The responses of the structure equipped by STMD are compared with those of the building with passive tuned mass damper (TMD) and the uncontrolled structure. The results showed an appropriate performance of the fuzzy controller in reducing the both translational and torsional responses of the RC building structure under the earthquake excitation.

INTRODUCTION

Nowadays modelling of structures with or without controller devices based on appropriate methods is one of the major concerns of the building designers to predict the behavior of the structures precisely. The location of the columns and other members bearing the shear forces of the stories e.g. shear walls or braces and the non-uniform loadings on the story can cause asymmetrical problem in the planar of the building stories due to the divergence of the mass center from the stiffness center of the structure. As this divergence is increased, the torsional responses of the structure cannot be ignored because of the undesirable effects on the members. Many researchers investigated the asymmetrical problems in the buildings and represented and developed various methods to analyze the structure responses over the torsional displacements (Tso and Dempsey 1980, Hejal and Chopra 1989, Ueng et al. 2000, Rafezy and Howsonb 2009, Yiu et. al 2014). In such situations the members have to design with considering the torsional stresses that can be lead to use sizable cross sections and increasing consumption of materials. In this paper a semi-active tuned mass damper with fuzzy controller is presented to control the building structure system with asymmetric plan to reduce the lateral and torsional responses under the earthquake excitation applied on the building base level in both East-West (EW) and North-South (NS) directions.

Tuned mass damper (TMD) was first used to reduce the rolling motion of ships (Frahm 1911). Later, tuned mass damper is developed to restrain the amplitude of single degree-of-freedom systems vibration (Ormondroyd and Den Hartog 1928, Brock 1946 and Den Hartog 1947). Since then TMDs have been used to control the vibration level of different mechanical and structural systems. Warburton (1982) found closed forms for the optimum parameters of TMD subjected to different excitations. Using a numerical searching technique, Tsai and Lin (1993) obtained the optimum parameters of TMDs for damped systems subjected to steady-state support excitations. In a seismic vibration with high stochastic variation a passive TMD system may be has undesirable effect on the structural responses. In order to avoid disadvantages of the passive devices, a new class of adjustable instruments has been introduced with variable controllable damping or stiffness properties (Hrovat et al. 1983) such as magneto-rheological (MR) dampers (Koo 2003).

In this study, a TMD equipped by a MR damper device (so-called semi-active TMD) has been employed to suppress the responses of building structure excited by earthquake acceleration. A fuzzy controller is designed to calculate appropriate input voltage of the MR damper based on the feedbacks of the system. A MATLAB code has been written and developed to compute the structural mass, stiffness and damping matrices on the basis of 3D conception of each story has two lateral and one rotational DOFs. Structural matrices of a fifteen-story RC building with asymmetric plan is obtained by the MATLAB code. The model of the structure equipped by STMD is modelled in the SIMULINK environment of the MATLAB. Two earthquake excitations El Centro E-W and N-S are used and applied simultaneously on the perpendicular lateral directions of the building. The performance of the STMD in reducing the structural responses has been evaluated by comparison of the responses with those of the passive TMD and uncontrolled structure. The time history of stories' drift and accelerations responses of the building with STMD, passive TMD and uncontrolled building, in lateral and torsional directions, have been calculated and plotted. The results showed the efficiency of the STMD by fuzzy controller in reducing all responses of the asymmetric building structure under the earthquake excitation applying in both directions simultaneously.

SYSTEM MODELLING AND SIMULATING

To predict the behavior of the controlled structure accurately, an adequate modeling of the control device is essential. A phenomenological 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 1, has been used to simulate the semi-active behavior of the device.

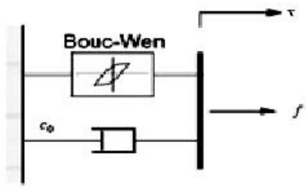

Figure 1. Mechanical model of the MR damper (Yi et al. 2001)

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:

$$f = c_0\dot{x} + \alpha z \tag{1}$$

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

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:

$$\alpha = \alpha(u_c) = \alpha_a + \alpha_b u_c \tag{3}$$

$$c_0 = c_0(u_c) = c_{0a} + c_{0b}u_c \tag{4}$$

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

$$\dot{u}_c = -\eta\,(u_c - u_a) \tag{5}$$

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

TMD is a passive control device that includes a mass, a spring and a viscous damper, tuned to a specific mode of the structure to defect the resonance of the building under the periodic external loading. The equation of motion of a multi-degree-of-freedom system subjected to a seismic excitation $\ddot{u}_g$ and a controlling force $\{f\}$ acting on the tuned mass damper system (Figure 2) can be written as:

$$[M]\{\ddot{d}\} + [C]\{\dot{d}\} + [K]\{d\} = -[M]\{\Lambda\}\ddot{x}_g + \Gamma(k_d d_d + f) \tag{6}$$

and the equation of motion of the auxiliary mass is:

$$m_d \ddot{d}_d + k_d d_d = -m_d(\ddot{d}_n + \ddot{x}_g) - f \tag{7}$$

where the vector $\{d\}$ is the displacement in perpendicular directions and rotation of each story, vector $\{\Lambda\}$ is the influence vector representing the displacement of each degree of freedom resulting from static application of a unit ground displacement; and the [M], [C] and [K] represent the structural mass, damping and stiffness matrices, respectively. f is the force of MR damper. m_d and k_d are the mass and stiffness of tuned mass damper respectively, d_d and d_n are the relative displacement of the auxiliary mass to the structure and story displacement, respectively. Γ is the vector shows where the force of actuator is applied on the building.

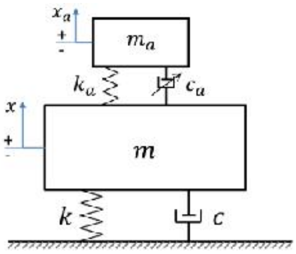

Figure 2. Model of the semi-active tuned mass damper by adjustable damping property

The equation of motion can be rewritten in standard state-space form as follows:

$$\begin{cases} \dot{Z} = A_s Z + B_s u \\ Y = C_s Z + D_s u \end{cases} \tag{8}$$

in which the state vector Z is defined as:

$$Z = \begin{Bmatrix} \{d\} \\ \{\dot{d}\} \end{Bmatrix} \tag{9}$$

According to the structure's equation of motion the state-space matrices are:

$$A_s = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \qquad B_s = \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{10}$$

$$C_s = \begin{bmatrix} I & 0 \\ 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \qquad D_s = \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix} \tag{11}$$

and the input vector u is defined as:

$$u = -\{\Lambda\}\ddot{x}_g + M^{-1}\Gamma(k_d d_d + f) \tag{12}$$

A MATLAB code is developed in this study to calculate the structural mass, stiffness and damping properties, appropriately. Concerning the eccentric of the mass center from the stiffness center in the building floors, the torsional effect cannot be ignored when the acentric distance is large enough (larger than 5% of the floor plan dimensions). Mass of each floor and stiffness of columns is calculated, and then by estimating the mass and stiffness centers of the story, the mass and stiffness of the building in each floor can be achieved. The mass and stiffness matrices are:

$$M_i = \begin{bmatrix} m_i & 0 & 0 \\ 0 & m_i & 0 \\ 0 & 0 & I_{io} \end{bmatrix} \qquad K_i = \begin{bmatrix} k_{xx} & k_{xy} & k_{x\theta} \\ k_{yx} & k_{yy} & k_{y\theta} \\ k_{\theta x} & k_{\theta y} & k_{\theta\theta} \end{bmatrix} \qquad i=1,2,\ldots,n \tag{13}$$

that n is the number of stories. m_i and I_{io} are total mass and torsional mass of the ith floor. In stiffness matrix x, y and θ are indicating the perpendicular displacements and the torsion of the floor respectively. By calculating all matrices of the each story of the building, total mass M and stiffness K matrices of the structure can be assembled using each floor's matrices.

According to the complex mathematical formulation of the physical behaviour of the MR damper, one cannot easily calculate the appropriate voltage to generate the demanding force of the controller. Hence, in this paper a fuzzy controller is designed and employed to estimate the applied voltage of the MR damper directly using linguistic fuzzy rules. The strategy of the fuzzy controlling is to define the applying voltage of the MR damper attached to the auxiliary tuned mass and the building, with respect to specific feedbacks of the structure. In both horizontal x and y directions of the story, auxiliary mass attached on the top floor of the building can move to suppress the excitations, so two MR dampers are used by the auxiliary mass in both directions. The SIMULINK diagram of the system is illustrated in Figure 3. The inputs of the fuzzy controllers are displacement and velocity of the structure's top story and velocity of the auxiliary mass and the output of fuzzy controller is applying voltage of the MR damper. The membership functions of inputs and output of the fuzzy controller are displayed in Figure 4, and fuzzy rules are presented in Table 1. The abbreviations used in the membership functions of variables are as follows: Z=zero, NE=negative, PO=positive.

Based on the groundhook controller laws (Koo 2003):

$$\begin{aligned} v_{a_{rel}} x \le 0 &\rightarrow c_a = c_{a_{max}} \\ v_{a_{rel}} x > 0 &\rightarrow c_a = 0 \end{aligned} \tag{14}$$

that x is the displacement of the floor and $v_{a_{rel}}$ is the relative velocity of the auxiliary mass to the primary structure. According to the displacement based groundhook laws, the damping of the semi-active damper is set to zero in inappropriate situations. This simple law is implemented in parallel with the fuzzy controller in this model, as can be seen in Figure 3.

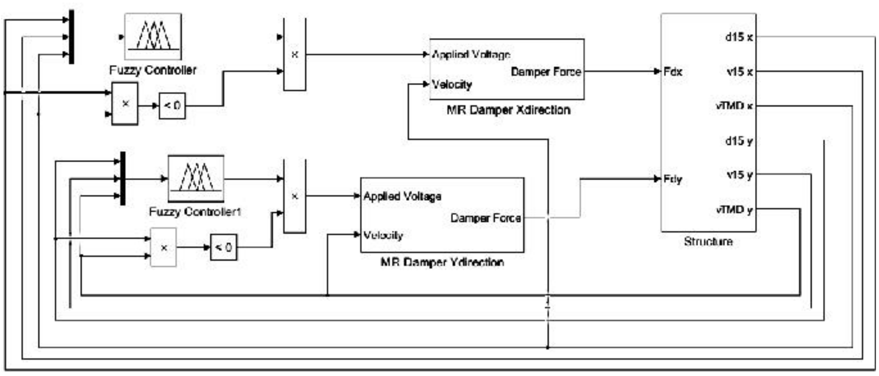

Figure 3. Control diagram for fuzzy control of the MR dampers

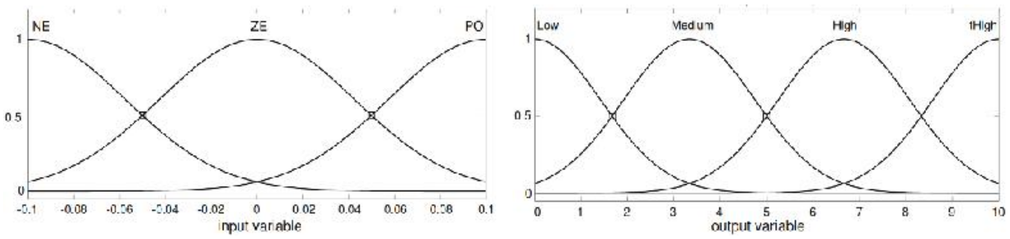

Figure 4. Membership function plots of the inputs and output variables of the fuzzy controller

Table 1. Fuzzy controller rules

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

NUMERICAL SIMULATION

In this study, a structure with fifteen degrees of freedom equipped by STMD is analyzed under earthquake excitation to evaluate performance of the fuzzy controller in reducing the vibrational responses. The plan of the building's typical story is shown in Figure 5. The height of all stories is considered equal to 3.2 *m*. As can be seen the geometry of the plan and loadings (the stair case has higher weight and openings are weightless) are asymmetric. The total gravity surface load on the floors is 1150 kg/m^2 in the staircase area and 745 kg/m^2 on the rest of the floor. The eccentric distances of the mass and stiffness centers calculated by the written MATLAB code are 1.98 meters in x direction and 0.49 meters in y direction, that these values exceeded the 5% of the plan's dimensions. The structure subjected to El Centro EW and NS earthquake records (Figure 6) in x and y directions, respectively.

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}. These parameters are based on the identified experimented model of a prototype MR damper (Yi et al. 2001).

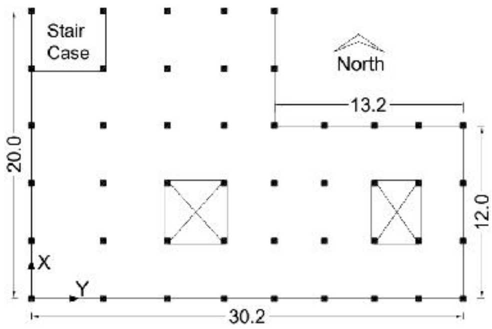

Figure 5. The plan of typical story of the building

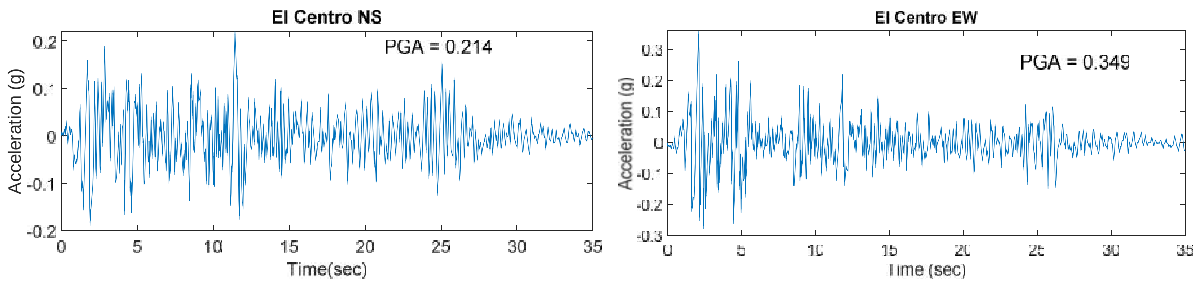

Figure 6. The earthquake excitation records

The mass ratio of TMD is considered 5% of the first modal mass of the structure. Also, damping ratio of the TMD is considered 5% of the critical damping value of the first mode of the structure. The responses of the structure coupled with semi-active tuned mass damper system under El Centro earthquake excitation in both EW and NS components, calculated and compared with the responses of the uncontrolled structure. The top floor displacement responses of the uncontrolled and controlled structures by STMD and TMD are shown in Figure 7. Peak and RMS displacement and acceleration responses of the top floor of the uncontrolled structure and the reduction percentages of the structure responses by STMD and TMD are presented in Table 2. The responses in both displacement directions and rotation of the top floor are reduced by semi-active tuned mass damper fuzzy controlling device, distinctively. The results of TMD and STMD can be comprised in Table 2 with of the uncontrolled structure. In the displacement *x* and *y* and rotational directions, STMD controller has improved the efficiency of the TMD by 64%, 34% and 23% in peak responses, and 86%, 226%, 118% in RMS responses, respectively. According to the results, besides the STMD has efficiency in reducing all responses of the structure, by adjustable damping property the semi-active TMD showed better performance in reducing the structural responses in comparison with passive TMD.

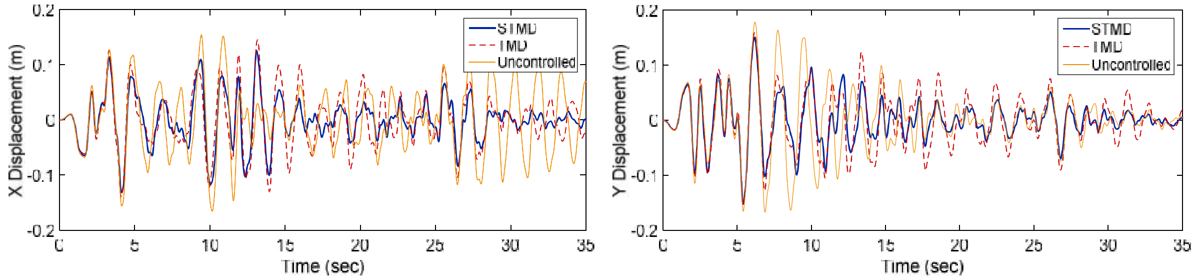

Figure 7. Displacement response in *x* and *y* directions

Table 2. Response reduction percentages of the tuned mass damper systems

Direction		Uncontrolled		Reduction percentage: TMD		Reduction percentage: STMD	
		X	Y	X	Y	X	Y
Acceleration (m/s^2)	Peak	7.206	7.308	5.6	3.1	14.9	7.1
	RMS	2.08	1.911	5.8	4.5	18.1	13.4
Displacement (m)	Peak	0.166	0.178	12.6	10.8	20.7	14.3
	RMS	0.062	0.055	18.1	8.5	33.6	27.7
Rotation (radian)	Peak	0.0116		32.7		40.1	
	RMS	0.00296		15.3		33.4	

One of the major criteria of the building structural design is the drifts of stories under the lateral loadings. By decreasing the drift responses, a controlling auxiliary device can be significantly effective on the design of the structure. The story peak and RMS drift responses under the earthquake in both directions of *x* and *y*, computed for semi-active TMD, passive TMD and uncontrolled structure. The results for all stories are plotted in Figure 8 (the values are without dividing to the story height). As can be seen, the STMD decreased the drift of the all stories of the structure in comparison with of the uncontrolled results. The semi-active controller improved the efficiency of the passive TMD in all drift responses. However, TMD has negative effect on the first four stories of the structure in peak drifts of direction *x* excitation, STMD enhanced the inefficiency of the passive tuned mass damper and decreased the responses.

The maximum peak drifts of the uncontrolled structure in *x* and *y* directions are 0.0238 m and 0.0252 m (by dividing to the story height are equal to 0.00744 and 0.00787), respectively. The maximum drift results of the TMD in *x* and *y* directions are decreased by 11% and 7%, and of the STMD are 15% in both directions. The maximum RMS drifts of the uncontrolled structure are 0.00734 m and 0.00708 m, in *x* and *y* directions, respectively. The maximum RMS drift results of TMD in *x* and *y* directions are decreased by 14% and 8%, and so for the STMD's are 30% and 24%. The drifts results have been shown the efficiency of the STMD in reducing all the story drift responses.

The building structure used for this study has an asymmetric plan due to the geometry and loadings of the floors (Figure 5). So under the earthquake excitation, undesirable rotation responses can be occur in the structure stories. According to the results, STMD has an effective manner in reducing the structural responses of the structure in lateral perpendicular directions of the floors in comparison with passive TMD and uncontrolled building. In addition to these results, the building peak and RMS rotational responses with

STMD are computed and compared with of the passive TMD and uncontrolled structure in Figure 9. The maximum peak and RMS rotations of the uncontrolled structure are equal to 0.0017 and 0.00042 that have been decreased in TMD responses by 5% and 10% and in STMD responses by 9% and 20%, respectively. However, in some cases due to the fixed properties of the TMD, showed undesirable results in comparison with uncontrolled structure responses, STMD increased the efficiency of the passive TMD in all results.

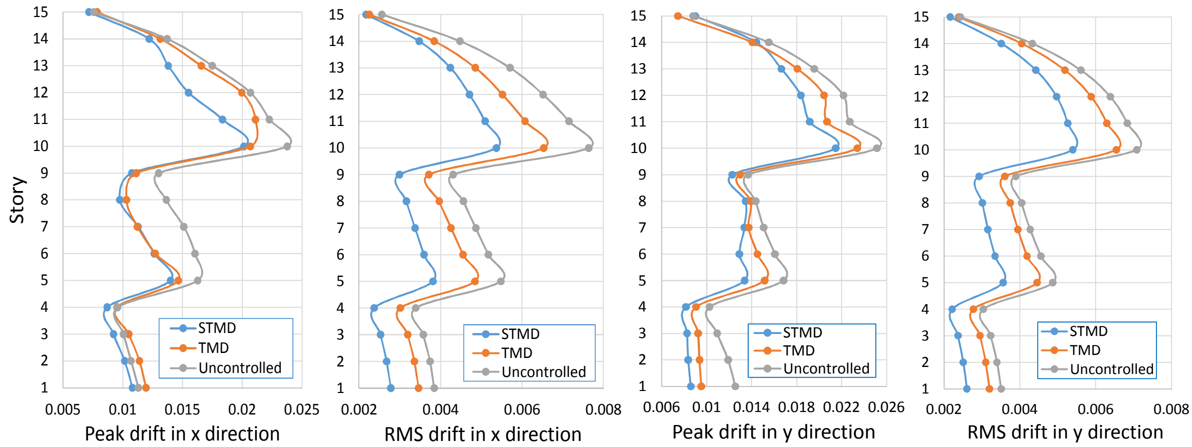

Figure 8. Peak and RMS drifts of structure stories in *x* and *y* directions

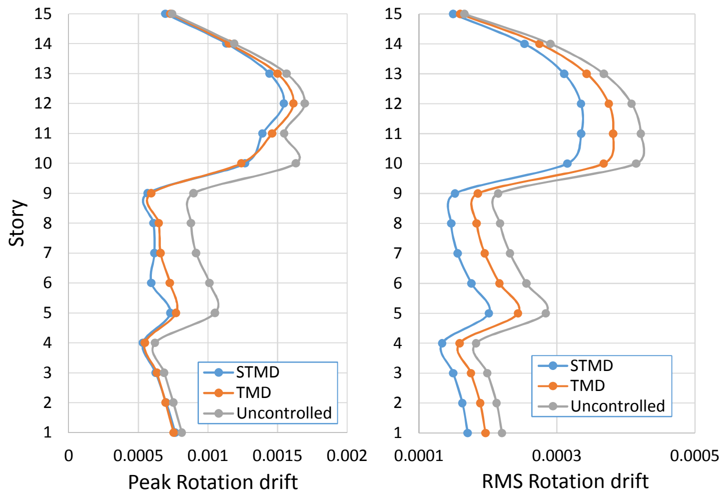

Figure 9. Peak and RMS drifts of structure stories in rotation direction

CONCLUSIONS

A fuzzy controller has been designed and implemented to adjust damping of a semi-active magneto-rheological damper working parallel with an auxiliary tuned mass attached to main RC building structure with asymmetric traits due to the geometry and loadings of the floors. Asymmetric property of the structure can be undesirable on the earthquake excitations that applying external accelerations in both perpendicular directions of the base of the building, due to the rotational responses of the stories. A fifteen-story building structure considered with two perpendicular planar and a rotational degrees-of-freedom in each story (totally 45 DOFs). To evaluate the mass and stiffness and damping matrices of the asymmetric 3-Dimension structure a MATLAB code has been written and developed.

The auxiliary mass damper frequency is considered equal to that of the first mode of the main structure and mass ratio is 5% of the first modal mass of the structure. The model of the structure equipped by STMD and fuzzy controller are simulated in the SIMULINK environment. The system results are computed under two directional earthquake acceleration of the El Centro EW and NS components. By accordance to the results of the building with and without controlling device, STMD has been efficient in reducing the seismic responses of the structure in a robust manner in comparison with passive TMD. However, the asymmetric of the building could be undesirable under the lateral vibrational loadings due to the increasing of the rotational responses of the stories, STMD has been decreased the rotational drifts as well as the horizontal perpendicular displacements of the all structure's floors.

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