CONTROL OF ASYMMETRIC PLAN BUILDINGS WITH ACTIVE TUNED MASS DAMPER USING GENETIC ALGORITHM

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ABSTRACT

The application of active tuned mass damper (ATMD) for the reduction of both the translational and torsional responses of asymmetric building in plan is discussed in the present paper. In the reality, most of the buildings with asymmetrical plan under earthquake have torsion that it will induced to increase the structural response. A multi-objective genetic algorithm to find the optimal control forces and other characteristics of active tuned mass damper. To analytically study, an eight story three-dimensional structure is considered as an example with an ATMD in two direction of the building on the roof. An LQR control algorithm is implemented to reduce the seismic responses of structures. The aim of the multi-objective function is to minimize the response of 8th story and the force of ATMD. Also, input variables are mass, damping and stiffness of the ATMD and the weighting matrix of LQR algorithm. The building is modeled as a structure composed of members connected by a rigid floor diaphragm such that it has three degrees of freedom at each floor, i.e., lateral displacements in two perpendicular directions and a rotation with respect to a vertical axis for the third dimension. The results show that by using ATMD in both directions, in addition to reduction of structural response in the earthquake direction, there are a reduction in the perpendicular to the earthquake direction and torsion.

INTRODUCTION

Protection of large civil structures and human occupants from natural hazards like an earthquake and wind is very important and challenging. In order to protect buildings, a passive or active control is added to the system. Vibration control of civil engineering structures has drawn much attention during the last three decades. The various vibration control strategies, used to prevent structural damage in structure subjected to dynamic loads can be classified as active, passive, hybrid and semi-active control. To mitigate undesirable building motion under strong earthquakes and wind gusts, different structural control systems have been proposed and investigated (Soong, 1990; Connor &Laflamme, 2014). Active control methods are effective for a wide frequency range as well as for transient vibrations. Active control devices are always integrated with a power supply, real time controllers and sensors placed on the structure. The most commonly used active control device for civil engineering structures is the active tuned mass damper (ATMD). As (Li et al, 1992) commented, the high efficiency is the major advantage of ATMD, in which a relatively small mass can be used to reduce structural response. Meanwhile an active control force is applied to move this small mass efficiently in order to achieve further response reduction. Thus, a relatively small active control force can significantly reduce structural response by 40–50% or more. On the other hand, unlike some other active control devices, ATMD can be installed in many kinds of structures: buildings, towers and bridges. Extensive reviews on using ATMD can be found in civil engineering literature (Chang and Soong, 1980; Amini and Tavassoli, 2005; Ankireddiand Yang, 1996). Comprehensive studies have been done to determine the optimal actuator force for the active vibration control systems. The most widespread methods are linear quadratic regulator (LQR), LQG, H2, H∞, sliding mode control, pole assignment, Clippes Optimal Control and Bang-Bang control. Most control methods are based on the optimization technique of maximizing the performance using less control energy under certain constraint and most optimization algorithms used in control design are traditional methods. Unlike traditional optimization methods, evolutionary algorithms such as genetic algorithm (GA) find an optimal solution from the complex and possibly discontinuous solution space. In the field of structural control, GAs have been applied to obtain gains for the optimal controller (Kundu and Kawata, 1996; Jiang and Adeli, 2008b), reduced order feedback control (Kim and Ghaboussi, 1999), optimal damper distribution (Wongprasert and Symans, 2004), and design and optimize the different parameters of the ATMD control scheme (Pourzeynali et al., 2007). Aldemir (2010) introduced a simple integral type quadratic functional as the performance index to suppress the seismic vibrations of buildings. He used the method of calculus of variations to minimize the proposed performance index and obtain the optimal control force. Also, Aldemir et al. (2012) proposed simple methods to obtain the suboptimal passive damping and stiffness parameters from the optimal control gain matrix to control structural response under earthquake excitation.

Although there is some promising development, research efforts regarding active control, usually consider two-dimensional plane frame structures or shear frames. Therefore, it limits the applicability of this method into simple and symmetrical structures. Some researchers have considered three-dimensional structures as building models in structural control and dynamics studies. They mentioned the benefits of using three-dimensional buildings as example structures. (Yanik et al, 2014) have proposed a new active control performance index for vibration mitigation of 3D structures. The proposed active control performance index considers the minimization of the mechanical energy of the three-dimensional structure, control and seismic energies. The implementation of the resulting control scheme does not require the solution of the nonlinear matrix Riccati equation and a priori knowledge of the seismic excitation.

In this study, an eight story three-dimensional structure with an ATMD in two direction of the building on the roof is considered as an example. An LQR control algorithm is implemented to reduce the seismic responses of structures. The aim of the multi-objective function is to minimize the response of 8th story and the force of ATMD. Also, input variables are mass, damping and stiffness of the ATMD and the weighting matrix of LQR algorithm. The building is modeled as a structure composed of members connected by a rigid floor diaphragm such that it has three degrees of freedom at each floor, i.e., lateral displacements in two perpendicular directions and a rotation with respect to a vertical axis for the third dimension.

MATHEMATICAL MODEL OF THE BUILDING

A 3D building is one in which each story is treated as a rigid body with 3 degrees of freedom (DOF) per floor. In this study a 3D with n story building is used to evaluate of dynamics response. 3D building formulation is defined by (Chopra A.K, 2012). The three-dimensional building model is given in Fig. 1 under one horizontal components earthquake ground motion and two dimensional control force. This three-dimensional building is idealized by a 3n-degree of freedom system. The equation of motion of the structure can be described as

$$M^*\ddot{u}(t) + C^*\dot{u}(t) + K^*u(t) = -\eta f(t) + \Gamma U(t) \quad [1]$$

where$\mathbf{M}^*$, $\mathbf{C}^*$, and $\mathbf{K}^*$are ((3n+2)*(3n+2))-dimensional matrix of mass, damping and stiffness that define as Eq.(5,12,15). $\mathbf{u}(t)=\{x_1,y_1,\theta_1,\ldots,x_n,y_n,\theta_n,x_d,y_d\}^T$is the 3n-dimensional response vector denoting the relative displacements in two directions and rotation (θ_1,...,θ_n) of each story unit (with respect to the ground); $\dot{\mathbf{u}}(t)$ and $\ddot{\mathbf{u}}(t)$ are the horizontal, vertical and rotational velocity and acceleration of each story unit respectively. $\mathbf{\Gamma}$ is the ((3n+2)*2)-dimensional location matrix of controllers that define as Eq.(2). We suppose that there are the ATMDonthe roof of building; **U**(t) is the (2x1)-dimensional active control force vector and is described as Eq. (3)

$$\Gamma=\begin{bmatrix}0 & 0\\ -1 & -1\\ 1 & 1\end{bmatrix} \quad [2]$$

where**0**is the zeros matrix with (3n)*1 dimension.

$$\mathbf{U}(t)=\{u_{dx}u_{dy}\}^T \quad [3]$$

In this study control forces are applied to the structure in two direction (x and y direction).

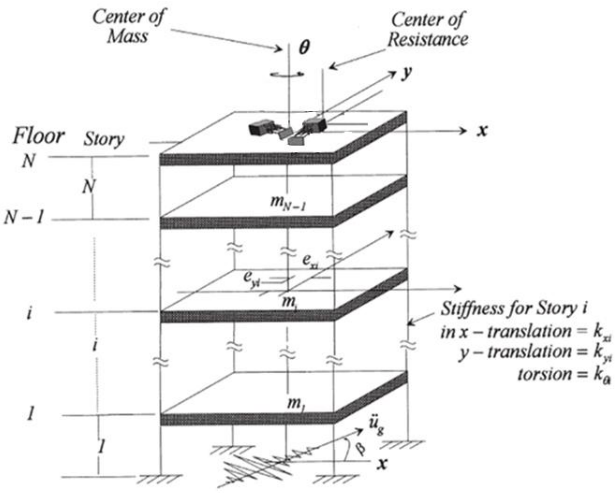

Figure 1. Plan view of floor of torsionally coupled building with ATMD device on the roof

f(t)is the vector of the ground acceleration in terms of the time. $\boldsymbol{\eta}=\{m_1, m_2, \ldots m_n, m_{tx}, m_{ty}\}^T$is ((n+2)*1)-dimensional matrix. The earthquake can excite the structure only in a single direction or in two directions. The building is modeled as a structure composed of members connected by a rigid floor diaphragm such that it has three degrees of freedom at each floor, i.e., lateral displacements in two perpendicular directions and a rotation with respect to a vertical axis for the third dimension. According to this model, the mass matrix of an n-story three-dimensional building without ATMD can be expressed as

$$M=\begin{bmatrix}m_1 & 0 & 0 & \ldots & 0 & 0 & 0\\ 0 & m_1 & 0 & \ldots & 0 & 0 & 0\\ 0 & 0 & I_{01} & \ldots & 0 & 0 & 0\\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots\\ 0 & 0 & 0 & \ldots & m_n & 0 & 0\\ 0 & 0 & 0 & \ldots & 0 & m_n & 0\\ 0 & 0 & 0 & \ldots & 0 & 0 & I_{0n}\end{bmatrix} \quad [4]$$

And with ATMD can be expressed as

$$M^*=\begin{bmatrix}m_1 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0\\ 0 & m_1 & 0 & \ldots & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & I_{01} & \ldots & 0 & 0 & 0 & 0 & 0\\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots\\ 0 & 0 & 0 & \ldots & m_n & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & \ldots & 0 & m_n & 0 & 0 & 0\\ 0 & 0 & 0 & \ldots & 0 & 0 & I_{0n} & 0 & 0\\ 0 & 0 & 0 & \ldots & 0 & m_{tx} & 0 & m_{tx} & 0\\ 0 & 0 & 0 & \ldots & 0 & 0 & m_{ty} & 0 & m_{ty}\end{bmatrix} \quad [5]$$

Where m_i and I_{0i} are the mass and the moment of inertia of the diaphragm of ithstory.I_{0i}can be expressed as

$$I_{0i}=\sum[\frac{m_{ij}}{12}(a^2+b^2)+m_{ij}[(\bar{x}-\bar{X})^2+(\bar{y}-\bar{Y})^2] \quad [6]$$

Where a and b arethe length and width of each panel slab in diaphragm. Also $\bar{x}$ and $\bar{y}$ are center of mass and j is the label of eachpanel slab in diaphragm. So$\bar{X}$ and $\bar{Y}$that are center of mass of the whole diaphragm, can be expressed as

$$\bar{X}=\frac{\sum m_{ij}.\bar{x}}{\sum m_{ij}} \quad , \quad \bar{Y}=\frac{\sum m_{ij}.\bar{y}}{\sum m_{ij}} \quad [7]$$

In the Eq. 5, m_{tx} and m_{ty} are the mass of ATMD in x and y direction, respectively. Also, the stiffness matrix of each story of three-dimensional building can be expressed as 3*3 dimensional matrix according to Eq.(8).

$$\mathbf{k_i}=\begin{bmatrix} k_{xx} & 0 & k_{x\theta} \\ 0 & k_{yy} & k_{y\theta} \\ k_{\theta x} & k_{\theta y} & k_{\theta\theta} \end{bmatrix} \quad [8]$$

where the indices of the matrix can be expressed asEqs.(9)

$$k_{xx}=\sum_{j=1}^{sizek} k_{xj} \quad , \quad k_{yy}=\sum_{j=1}^{sizek} k_{yj} \quad , \quad k_{x\theta}=k_{\theta x}=\sum_{j=1}^{sizek} k_{xj}\,(\bar{Y}-\bar{y}_k)$$
$$k_{y\theta}=k_{\theta y}=\sum_{j=1}^{sizek} k_{yj}\,(\bar{X}-\bar{x}_k) \quad , \quad k_{\theta\theta}=\sum_{j=1}^{sizek} (k_{xj}\,(\bar{Y}-\bar{y}_k)^2+k_{yj}(\bar{X}-\bar{x}_k)^2) \quad [9]$$

k_{xj}andk_{yj} are lateral stiffness of each resistant elements (i.e., columns) in x and y direction, respectively and, $\bar{x}_k$ and $\bar{y}_k$ are coordinate of resistant elements in x and y direction, respectively. Index j is the label of resistant elements in each story and sizek is number of whole resistant elements in each story. The center of stiffness of each story in x and y directioncan be expressed as

$$\bar{X}_k=\frac{\sum k_{xj}.\bar{x}_k}{\sum k_{xj}} \quad , \quad \bar{Y}_k=\frac{\sum k_{yj}.\bar{y}_k}{\sum k_{yj}} \quad [10]$$

After determining stiffness matrix for each story, we can assemble total stiffness matrix for the whole structure without ATMD as

$$K=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & -k_3 & \dots & -k_n \\ 0 & 0 & -k_n & k_n \end{bmatrix} \quad [11]$$

and with ATMD as

$$K^*=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 & 0 \\ 0 & -k_3 & \dots & -k_n & \dots \\ 0 & 0 & -k_n & k_n & k_{t2} \\ 0 & 0 & 0 & \dots & k_{t1} \end{bmatrix} \quad [12]$$

where matrix of $\mathbf{k_{t1}}$ and $\mathbf{k_{t2}}$can be expressed as

$$k_{t1} = \begin{bmatrix} k_{tx} & 0 \\ 0 & k_{ty} \end{bmatrix} k_{t2} = \begin{bmatrix} -k_{tx} & 0 \\ 0 & -k_{ty} \\ 0 & 0 \end{bmatrix} \quad [13]$$

The damping matrix of an n-story three-dimensional building without ATMD can be expressed as

$$C=\alpha.M+\beta.K \text{where} \quad \alpha=\frac{2\xi.\omega_1.\omega_{3n\text{-}2}}{\omega_1+\omega_{3n\text{-}2}} \quad \text{and} \quad \beta=\frac{2\xi}{\omega_1+\omega_{3n\text{-}2}} \quad [14]$$

ω_1 and ω_{3n-2} are natural frequencies of the building in x direction of first and eight story, respectively, that can be determined from $|\mathbf{K}\text{-}\boldsymbol{\omega}^2\mathbf{M}|\boldsymbol{\varphi}=\mathbf{0}$. Also, ξ is damping ratio. The damping matrix of a building with ATMD can be expressed as

$$\mathbf{C}^{*}=\begin{bmatrix} & & & & \mathbf{0} \\ & \mathbf{C} & & & \mathbf{0} \\ & & & & \dots \\ & & & & \mathbf{c}_{t2} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \dots & \mathbf{c}_{t1} \end{bmatrix} \quad [15]$$

where matrix of $\mathbf{c}_{t1}$ and $\mathbf{c}_{t2}$can be expressed as

$$C_{t1} = \begin{bmatrix} C_{tx} & 0 \\ 0 & C_{ty} \end{bmatrix} C_{t2} = \begin{bmatrix} -C_{tx} & 0 \\ 0 & -C_{ty} \\ 0 & 0 \end{bmatrix} \quad [16]$$

CLASSICAL LINEAR OPTIMAL CONTROL LAW

In control theory, Eq. (1) can be conveniently rewritten in state-space form as

$$\dot{Z}(t) = AZ(t) + B_uU(t) + B_rf(t) \quad [17]$$

Where **A** is ((6n+4)*(6n+4))-dimensional matrix that can be expressed as

$$A=\begin{bmatrix} 0 & I \\ \text{-}M^{*-1}K^{*} & \text{-}M^{*-1}C^{*} \end{bmatrix} \quad [18]$$

where**0**and**I** are the zero and Identity matrix with ((3n+2)*(3n+2)) dimension, respectively. $\mathbf{B_u}$is((6n+4)*2)-dimensional matrix that can be expressed as

$$B_u=\begin{bmatrix} 0 \\ M^{*-1}\Gamma \end{bmatrix} \quad [19]$$

where**0**is the zeros matrix with ((3n+2)*2) dimension. $\mathbf{B_r}$is((6n+4)*1)-dimensional matrix that can be expressed as

$$B_r=\begin{bmatrix} 0 \\ \text{-}M^{*-1}\eta \end{bmatrix} \quad [20]$$

where**0**is the zeros matrix with (3n+2)*1 dimension. $\mathbf{Z(t)}$and$\mathbf{\dot{Z}(t)}$ are ((6n+4)*1)-dimensional matrices that can be expressed as

$$Z(t)=\begin{bmatrix} u(t) \\ \dot{u}(t) \end{bmatrix} \dot{Z}(t)=\begin{bmatrix} \dot{u}(t) \\ \ddot{u}(t) \end{bmatrix} \quad [21]$$

In the classical optimal control law; the classical integral type quadratic performance measure

$$J = \int_0^{t_1} (Z^T QZ + U^T RU)dt \quad [22]$$

is minimized; where t_1 is the duration longer than that of an earthquake.**Q**is positive semi-definite weighting matrix with ((6n+4)*(6n+4))-dimensional matrix and **R** is positive definite weighting matrix with (2*2)-dimensional matrix. In order to adjust the power requirements in the actuators, the numerical values for the elements of **Q** and **R** matrices are assigned according to the relative importance of the state variables and the control forces in the minimization procedure. If we want to achieve a significant decrease in structural response in the time domain, we must assign larger values to the elements of the weighting matrix **Q** than to those of the weighting matrix **R**. The opposite is true when the elements of **R** are large in comparison with those of **Q**. In Eq. (1) and Eq. (17), vector **U**(t) can be expressed as

$$U(t) = -GZ(t) = -R^{-1}{B_u}^T PZ(t) \quad [23]$$

Where**G** is gain matrix and**P** is((6n+4)*(6n+4))-dimensional matrix and determine by solving the following nonlinear matrix Riccati equation as follows:

$$PA + A^T P - PB_u R^{-1}{B_u}^T P + Q = 0 \quad [24]$$

Combining Eq. (23) and Eq. (17), the following equation can be obtained.

$$\dot{Z}(t) = AZ(t) + B_u(-R^{-1}{B_u}^T PZ(t)) + B_r f(t) \quad [25]$$

After simplification, Eq. (26) can be expressed as

$$\dot{Z}(t) = (A - B_u R^{-1}{B_u}^T P)Z(t) + B_r f(t) \quad [26]$$

Considering $\mathbf{A}^* = \mathbf{A} - \mathbf{B_u R^{-1} {B_u}^T P}$, Eq. (27) can be expressed as

$$\dot{Z}(t) = A^* Z(t) + B_r f(t) \quad [27]$$

To analysis of structural response in the state space, in addition to the Eq. (27), also the Eq. (28) should be defined.

$$y = EZ(t) + Lf(t) \quad [28]$$

where**E** and **L** matrices can be expressed as

$$E = \begin{bmatrix} I & 0 \\ 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \quad [29]$$

where**0**and**I** are the zero and Identity matrices with (3n+2)*(3n+2) dimension, respectively.

$$L = \begin{bmatrix} 0 \\ 0 \\ -\Lambda \end{bmatrix} \quad [30]$$

where**0**is the zero matrix with (3n+2)*1 dimension. With theEq. (23) and Eq. (24), we can use state space toolbox of MATLAB for solving response of structure(i.e., lateral displacements in two perpendicular directions and a rotation with respect to a vertical axis for the third dimension).

NUMERICAL EXAMPLE

For our example in the particular application studied in this work we consider an eight story steel structure building. The building is assumed to be as Fig. 2. The floor is consisting of five panel slab and one opening. We assume that only the uniform dead load are applied on panel slab that the value is 2000 Kg/m^2. The mass of the slab is considered in the value. Having dimension of each panel slab and their center of massand using Eq. (4-7), the mass matrix can be obtained. The story heights are 3.2 m and for all of the columns are used box with dimensions 30x30 cm and thickness 2.5 cm, so their moment of inertia will be 3.4948x10^4 m^4. The modulus of elasticity of steel is 2.1x10^{10} MPa. The stiffness of each columns due to rigidity of diaphragm can be expressed as

$$I = \frac{12EI}{L^3} \quad [31]$$

where E, I and L is modulus of elasticity, moment of inertia, and height of each columns, respectively. So the stiffness of each columns is 2687645 Kg/m. Having stiffness of each columns and their coordinateand using Eq. (8-13), the stiffness matrix of whole structure can be obtained.

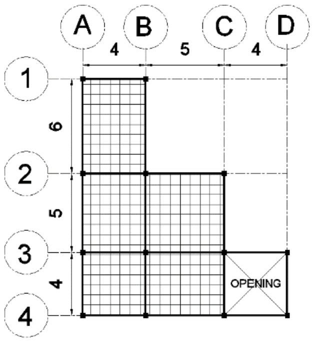

Figure 2. Eight story building with ATMD devices modeled as three dimensionally

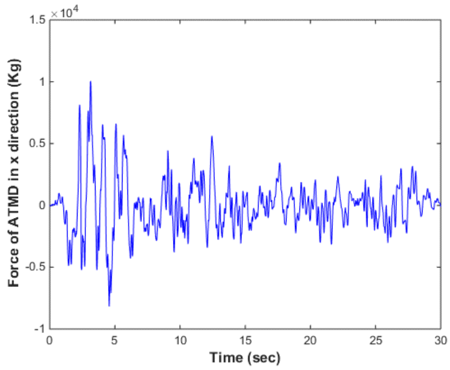

Figure 3. Force of ATMD versus the time in the first story

TheATMD is located in both direction on the roof. The structure is under Elcentro earthquake in x direction. In Riccati equation (Eq. 24) the weighting matrix R is constant and equal to R=I*1x10^{-6} and the weighting matrix Q is equal to Q=αI, where I is Identity matrix. Using multi-objective genetic algorithm, we are trying to minimize the response of 8th story and control force of ATMD. Also, input variables are mass, damping and stiffness of the ATMD and α in the weighting matrix Q. For multi-objective optimization, MATLAB toolbox were used. The only constraint of problem is the maximum control force of ATMD that is 1x10^4 Kg.After run the program, several results can be obtained that one of the best results is observed in Table 1. Also this reduction can be observed in Fig. 3. In the case, the results indicate that the reduction of the displacement of structure in x and y direction are 40% and 45%, respectively. Also, the reduction in torsion is 36%. This shows that the ATMD greatly reduce plan asymmetric effect that causing a displacement in the perpendicular direction to the earthquake and torsion.

Table 1. Optimal variables as input of problems

Variables	m_{tx}	m_{ty}	k_{tx}	k_{ty}	c_{tx}	c_{ty}	α
values	16118	5123	1059554	324972	18674	19202	3.45x10^{11}

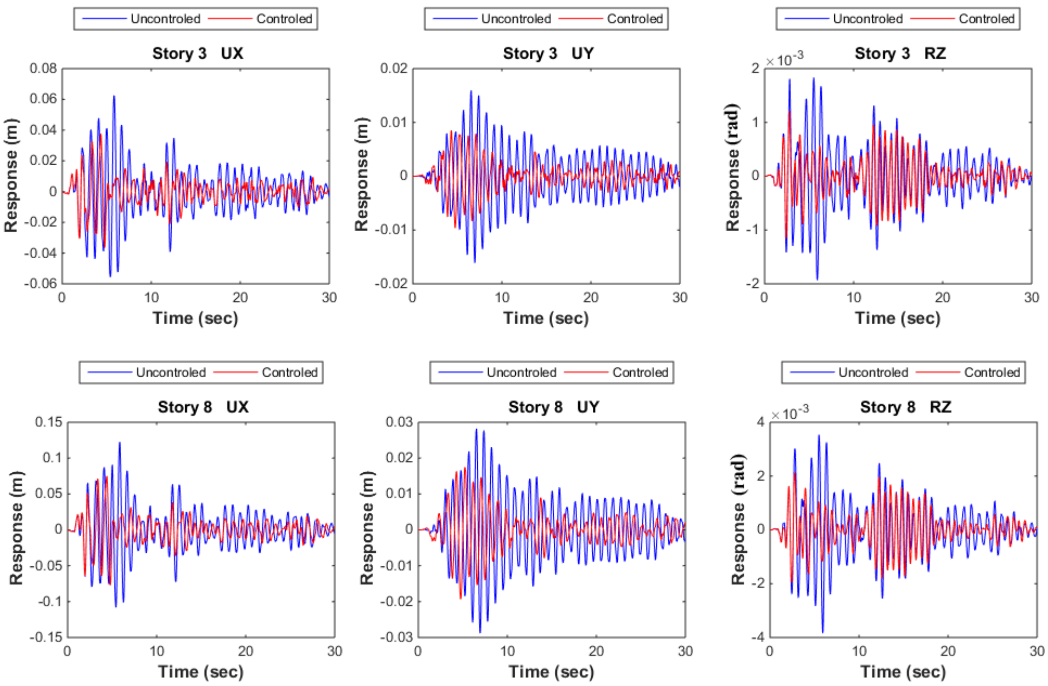

Figure 4. Response of the third and 8th story

CONCLUSIONS

In this paper, an 8 story steel structure building with asymmetric plan under elcentro earthquake has been considered. Using ATMD controller and LQR control algorithm tried to reduction of structural responses. The results indicate that by adjusting the weighting matrices in LQR control algorithm and mass, stiffness and damping in ATMD by multi-objective genetic algorithm, we can minimize response of structure. ATMD in addition to reduction displacement in earthquake direction, greatly reduce plan asymmetric effect that causing a displacement in the perpendicular direction to the earthquake and torsion.

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