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HYBRID CONTROL SYSTEMS FOR RIGID BUILDINGS STRUCTURES UNDER STRONG EARTHQUAKES

N. Djedoui[1*], A. Ounis[1], JP. Pinelli[2] and M. Abdeddaim[1]
[1]Larghyde Laboratory, Department of Civil Engineering and Hydraulics, Faculty of Sciences and Technology Mohamed Khider University, BP 145 RP, 07000 Biskra, Algeria
[2]Department of Civil Engineering, Florida Institute of Technology, 32901 Melbourne, Florida, United States

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ABSTRACT

This paper deals with the efficiency of a hybrid vibration control for rigid buildings structures under earthquakes. The hybrid control consists of a base isolator and tuned mass damper (TMD) or active tuned mass damper (ATMD). The active control force is calculated within a feedback loop by the mean of the linear quadratic controller (LQR) designed to penalize the displacement and the velocity of the floor on which the ATMD is installed. A total of four cases are studied based on the placement and the type of the control system either passive TMD or active TMD. The lower and top floor alternatively carries the TMD control system. The case of a rigid six-degree of freedom base isolated frame structure illustrates the effectiveness of the hybrid control through simulations. Simulation results, obtained from real time-history data of three earthquakes (El Centro, Northridge and Loma Prieta) show that the proposed control is effective. The hybrid control system is able to reduce the vibration amplitudes especially the base isolator displacement and acceleration without affecting the super-structure response regardless of the placement of the TMD control system. Such a hybrid control system can protect high importance buildings containing sensitive equipment.

Keywords: Hybrid control; active tuned mass damper; linear quadratic regulator; base isolated structure; vibration control.

1. INTRODUCTION

Vibration control has become a very attractive research field, especially in the last two decades. The objective is to design more efficient structures, less susceptible to natural hazards, especially strong earthquakes or wind forces, and to reach a maximum security

[*]E-mail address of the corresponding author: nassim_ingg@hotmail.fr (N. Djedoui)

level for both human lives and buildings. The resulting control systems fall within three categories: passive control systems, active control systems and semi-active control systems [1, 2].

Base isolators, installed between the foundation and the superstructure, are some of the most widely used devices for vibration control. The base isolator can be mounted on different types of structures: habitation buildings, hospitals and even on bridges. Base isolators are designed to have a very large horizontal deformability and very high vertical stiffness. These devices are able to uncouple the movements of the structure from those of the ground resulting in a reduction of the forces transmitted to the superstructure keeping the super structure's frequency away from the frequencies at which the disturbances energy is concentrated. One of the most widely used systems are the Laminated rubber bearings (LRB) [3].

In base isolator design process, several parameters should be taken in consideration including: the type of soil and location of the structure [4, 5]. High performance of the base isolator is obtained when appropriate characteristics such as isolator stiffness and isolator damping rate are chosen carefully. Increasing the damping in the isolation system results in a reduction in the isolator displacement and structural base shear, however the floor acceleration and the inter-story drift are increased resulting in negative effect on the structure [6].

The efficiency of the base isolator depends on the type of excitation. Large magnitude earthquakes can push the base isolator into critical conditions which result in large displacement with high velocity and high acceleration. Near-fault earthquakes lead to pulse-type displacements [7]. The combinations of many parameters such as isolator yield displacement, superstructure's flexibility, isolation time period and number of stories can have a negative influence on the response behavior of a base-isolated structures [8]. [9] Investigated the sensitivity of base-isolated structures equipped with different base isolators like: LRB, high damping lead rubber HD-LRB, and the resilient-friction R-FBI against wind loadings. Results show that the base-isolated structures are not sensitive to wind loading during common storms.

The coupling of the base isolated structures with passive, active and semi-active devices can make the base isolator more efficient. The result can be a reduction in structural response in the base isolator structures, without increasing the super structure response.

In [10] researchers, combined a class of passive nonlinear base isolator with an active control system in aim to reduce the absolute base displacement. The adaptive control law is used to control the active force. Moreover, the sliding-mode control can also be used to control the active force as [11] and [12]. One step forward, the efficiency of passive devices coupled with the base isolator is studied as in [13], where the authors proposed a supplement elastic stiffness device and viscous damper as in [14].

Many researchers investigated the effect of semi-active devices including magneto rheological fluids damper (MR damper) [14-16] and some other smart materials able to change their parameters in a controlled manner. The need of a small source of energy is the advantage of this sort of devices.

Other authors used a MR damper to control base isolator displacement [17]. Some used different control algorithms for the semi-active control strategy such as the modified clipped-optimal control, the maximum energy dissipation, the modulated homogeneous friction, and fuzzy logic, or even genetic algorithms, with the aim of reducing the response of a base isolated structure using MR damper [18-22].

Recently, researchers proposed a new optimal proportional-derivative (PD) and proportional-integral-derivative (PID) controller to control the base movement for an isolated structure using a piezoelectric friction damper [23]. With the objective of reducing seismic response while preserving the high performance of the isolated building, other researchers proposed a passive hybrid control which consists of coupling a base isolator and a tuned mass damper [24, 25]. They showed that adding a tuned mass damper to the system enhanced the performance of the structure, while a small reduction in the peak base isolator displacement and acceleration were obtained. To overcome the coupling issues of the TMD to the base isolated structure [26] proposed to attach the TMD directly to the base by the mean of a a spring, and a damper. Others proposed a seismic hybrid control systems for a flexible and rigid structures using a modified linear quadratic controller developed by [27].

To overcome limitations of the passive TMD, especially the detuning phenomena and the large space needed, many efforts have been made to enhance the system performance by incorporating an active [15] or semi-active control to the purely passive TMD device. [28, 29] Tested the performance of using an active tuned mass damper on the top of the building where the force is controlled using fuzzy logic and genetic algorithm.

The main purpose of this paper is to study the effect of different hybrid control systems using a base isolator combined with a passive tuned mass damper or an active tuned mass damper. In aim to overcome the negative effect of the base isolator and the TMD cited previously. In this research, the active tuned mass damper is controlled by means of the linear quadratic regulator (LQR) within a feedback loop. This controller is widely used in control problems of civil engineering projects [30-32].

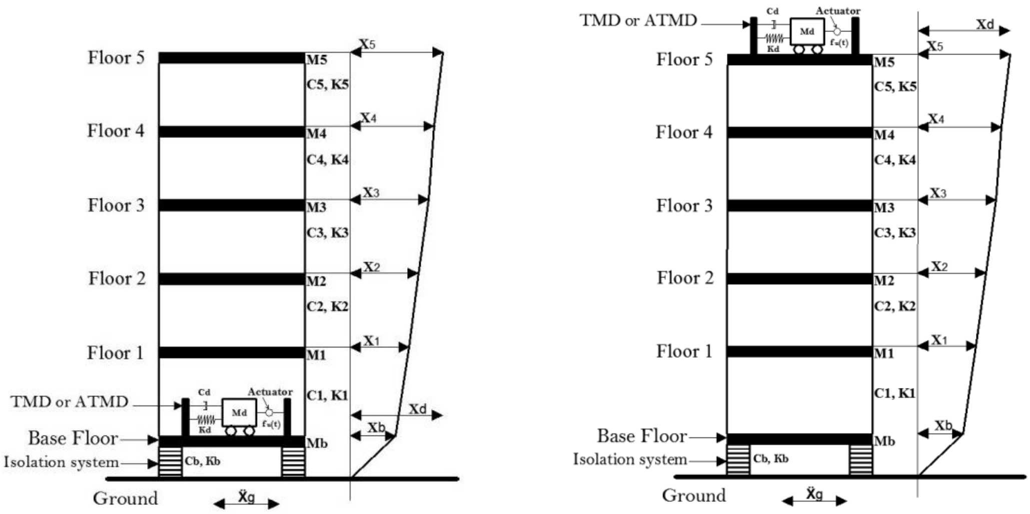
In the case of isolated structures, the behavior of the super structure is affected mainly by the movement of the isolator, since the superstructure behaves like a rigid body, such that the control of the base isolator movement leads to the control of the superstructure response. The existing literature shows that the efficiency of the control device placed on the top floor has not been thoroughly considered. In this paper it is shown that the placement of a passive or an active tuned mass damper on the top floor of the base isolated rigid structure is also an effective strategy to protect structures against earthquakes.

In this work, the performance of four hybrid seismic control strategies were evaluated and compared to the base isolator system alone. A six (6) degrees of freedom rigid isolated frame structure, equipped with LRB isolator combined with passive or active tuned mass damper in the lowest or on the top floor was used in the simulation. Three strong earthquakes were used to evaluate the performance of the hybrid control strategies. It is demonstrated that all hybrid control systems are more effective than a base isolator alone.

The paper is organized as follows. Section 2 presents a description of the analytical model used to represent the base isolated structure equipped with a TMD or an ATMD. Section 3 describes and illustrates the numerical study as well as the implementation and the choice of parameters for the LQR controller. Results and performance of the proposed hybrid system are discussed in Section 4, followed by the conclusions.

2. MDOF BASE ISOLATED FRAME STRUCTURE EQUIPPED WITH HYBRID CONTROL

In this study four hybrid control systems against earthquake are considered: passive hybrid control and active hybrid control, in which the passive hybrid control consists of a base isolated shear building structure equipped with a passive tuned mass damper installed on the lowest floor as shown in Fig. 1.a or on the top floor as depicted Fig. 1.b. However the active hybrid control consists of base isolated shear building structure equipped with an active tuned mass damper installed on the lowest floor as in Fig. 1.c or on the top floor as in Fig. 1.d.



a: Structure (1) The TMD on the lowest floor, c: Structure (3) The ATMD on the lowest floor

b: Structure (2) The TMD on the top floor, d: Structure (4) The ATMD on the top floor

Figure 1. Structural configurations investigated in the numerical study

The n structural hybrid system is idealized by $(n+2)$ degrees of freedom including the base isolation system and the mass damper; subjected to one-dimensional earthquake ground acceleration $\ddot{x}_g$.

The equation of motion of the entire structural system can be written as:

(a) Hybrid control installed on the lowest floor

In case of passive tuned mass damper installed on the lowest floor as in Fig. 1.a, the equation of motion can be written as follows:

$$[M]\{\ddot{x}\}+[C_1]\{\dot{x}\}+[K_1]\{x\}=-[M]\{r\}\{\ddot{x}_g\} \quad (1)$$

In case of active tuned mass damper installed on the lowest floor as in Fig. 1.b, the equation of motion will be written as follows:

$$[M]\{\ddot{x}\}+[C_1]\{\dot{x}\}+[K_1]\{x\}=-[M]\{r\}\{\ddot{x}_g\}+\{d_1\}(f_u) \tag{2}$$

(b) Hybrid control installed on the top floor

If a passive tuned mass damper is installed on the top floor as shown in Fig. 1.c, the equation of motion can be written as follows:

$$[M]\{\ddot{x}\}+[C_2]\{\dot{x}\}+[K_2]\{x\}=-[M]\{r\}\{\ddot{x}_g\} \tag{3}$$

In case of an active tuned mass damper installed on the top floor as in Fig. 1.d, the equation of motion is written as follows:

$$[M]\{\ddot{x}\}+[C_2]\{\dot{x}\}+[K_2]\{x\}=-[M]\{r\}\{\ddot{x}_g\}+\{d_2\}(f_u) \tag{4}$$

In the previous equations, $[M]=(n+2)\times(n+2)$ is the mass matrix with diagonal elements $M=[m_b, m_1, m_2 ... m_{n-1}, m_n, m_d]$, where m_b and m_d are the base and the tuned mass damper masses respectively, and m_i is the mass of the ith floor for $(i=1,2,...,n)$. $[C_1]=(n+2)\times(n+2)$ and $[C_2]=(n+2)\times(n+2)$ are the related damping matrices, $[K_1]=(n+2)\times(n+2)$ and $[K_2]=(n+2)\times(n+2)$ are the related stiffness matrices, where c_b, c_d and k_b, k_d are the base isolator and the tuned mass damper damping and stiffness respectively.

$$C_1=\begin{bmatrix} c_b+c_1+c_{tmd} & -c_1 & & & & & -c_{tmd} \\ -c_1 & c_1+c_2 & -c_2 & & & & \\ & -c_2 & \ddots & \ddots & & & \\ & & \ddots & \ddots & -c_{n-1} & & \\ & & & -c_{n-1} & c_{n-1}+c_n & -c_n & \\ & & & & -c_n & c_n & \\ -c_{tmd} & & & & & & c_{tmd} \end{bmatrix} \tag{5}$$

$$K_1=\begin{bmatrix} k_b+k_1+k_{tmd} & -k_1 & & & & & -k_{tmd} \\ -k_1 & k_1+k_2 & -k_2 & & & & \\ & -k_2 & \ddots & \ddots & & & \\ & & \ddots & \ddots & -k_{n-1} & & \\ & & & -k_{n-1} & k_{n-1}+k_n & -k_n & \\ & & & & -k_n & k_n & \\ -k_{tmd} & & & & & & k_{tmd} \end{bmatrix} \tag{6}$$

And

$$C_2 = \begin{bmatrix} c_b + c_1 & -c_1 & & & & & \\ -c_1 & c_1 + c_2 & -c_2 & & & & \\ & -c_2 & \ddots & \ddots & & & \\ & & \ddots & \ddots & -c_{n-1} & & \\ & & & -c_{n-1} & c_{n-1} + c_n & -c_n & \\ & & & & -c_n & c_n + c_{tmd} & -c_{tmd} \\ & & & & & -c_{tmd} & c_{tmd} \end{bmatrix} \tag{7}$$

$$K_2 = \begin{bmatrix} k_b + k_1 & -k_1 & & & & & \\ -k_1 & k_1 + k_2 & -k_2 & & & & \\ & -k_2 & \ddots & \ddots & & & \\ & & \ddots & \ddots & -k_{n-1} & & \\ & & & -k_{n-1} & k_{n-1} + k_n & -k_n & \\ & & & & -k_n & k_n + k_{tmd} & -k_{tmd} \\ & & & & & -k_{tmd} & k_{tmd} \end{bmatrix} \tag{8}$$

$\{x\} = [x_b, x_1, ..., x_n, x_d]^T$, $\{\dot{x}\} = [\dot{x}_b, \dot{x}_1, ..., \dot{x}_n, \dot{x}_d]^T$ and $\{\ddot{x}\} = [\ddot{x}_b, \ddot{x}_1, ..., \ddot{x}_n, \ddot{x}_d]^T$ $(n+2)$ are the displacement, velocity and acceleration response vectors respectively, all the responses are relative to the ground, also x_b and x_d are the displacements of the base and the mass damper respectively. $\{r\} = [1,1,...,1]^T$ $(n+2)$ is the unit influence vector. $\{d_1\} = [-1,0,...,0,1]^T$ $(n+2)$ and $\{d_2\} = [0,0,...0,-1,1]^T$ $(n+2)$ are the active control force f_u vectors location.

The governing equations (1), (2), (3) and (4) can be written in state-space in general form as:

$$\dot{z}(t) = Az(t) + E\ddot{x}_g(t) + Bf_u(t) \tag{9}$$

$$y(t) = Hz(t) \tag{10}$$

where:

$$z(t) = \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix}_{(2n+4)} \tag{11}$$

$$A = \begin{bmatrix} O_{(n+2)\times(n+2)} & I_{(n+2)\times(n+2)} \\ -M^{-1}K_{(n+2)\times(n+2)} & -M^{-1}C_{(n+2)\times(n+2)} \end{bmatrix} \tag{12}$$

$$E = \begin{bmatrix} O_{(n+2)\times 1} \\ -r_{(n+2)\times 1} \end{bmatrix} \tag{13}$$

$$B = \begin{bmatrix} I_{(n+2)\times 1} \\ \\ M^{-1} d_{(n+2)\times 1} \end{bmatrix} \tag{14}$$

$$H = \left[I_{(n+2)\times(n+2)} \right] \tag{15}$$

To simplify the representation, the general form of the state-space is used. However for each case the appropriate $[K]$ $[C]$ and $\{d\}$ are chosen.

In the active hybrid control and in aim to achieve the best performance the needed control force is calculated using the classical linear quadratic optimal controller LQR is used [33]. The active control force f_u is obtained by minimizing the performance index J assuming the earthquake excitation is neglected.

$$J = \int_0^{t_f} \{Z\}^T [Q]\{Z\} + \{f_u\}^T [R]\{f_u\} \tag{16}$$

$$\text{And } f_u = -\frac{1}{2} R^{-1} B^T P \{Z\} \tag{17}$$

$$PA + A^T P + Q - PBR^{-1} B^T P = 0 \tag{18}$$

With t_f defined as duration of the earthquake, Q is a diagonal positive semi-definite weighting matrix and P $(2n+4)\times(2n+4)$ is a matrix obtained by the resolution of the Riccati equation Eq. (17). R is a positive definite weighting matrix, in this study only one active force is applied then $R = a$ (1×1), Q and R are to be chosen appropriately.

In this paper MATLAB program is used for the simulation and the resolution of Riccati equation, Simulation model using SIMULINK is schematized in Fig. 2.

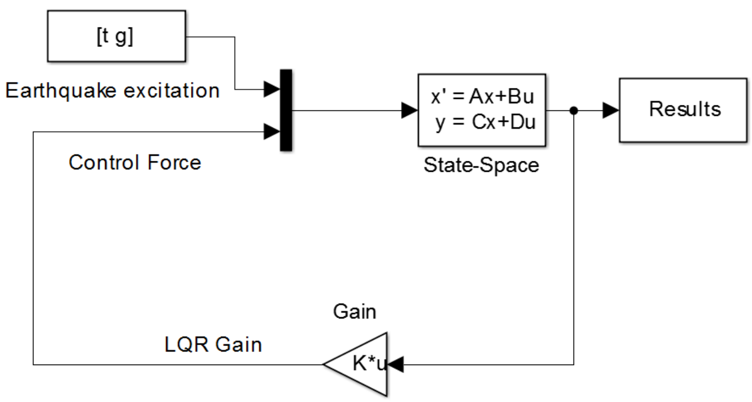


Figure 2. Simulation model using LQR controller with feedback

3. NUMERICAL STUDY

In this study four cases of a hybrid control system are investigated. The following notations are used throughout the paper:

- Structure (1): base isolated structure equipped with a passive tuned mass damper installed on the lowest floor, Fig. 1. a.
- Structure (2): base isolated structure equipped with a passive tuned mass damper installed on top floor, Fig. 1. B.
- Structure (3): base isolated structure equipped with an active tuned mass damper installed on lowest floor, Fig. 1. C.
- Structure (4): base isolated structure equipped with an active tuned mass damper installed on top floor, Fig. 1. d.

Each of the four previous structures in Fig. 1 was subjected to three earthquakes; El-Centro, Northridge and Loma Prieta with maximum peak acceleration PGA of 0.34, 0.56 and 0.36g respectively as shown in Fig. 3. The chosen earthquakes are classified as fare field case of El Centro and near field case of Northridge and Loma Prieta, and have different frequencies so the performance of the structure can be tested under different seismic excitations as multiple tests.

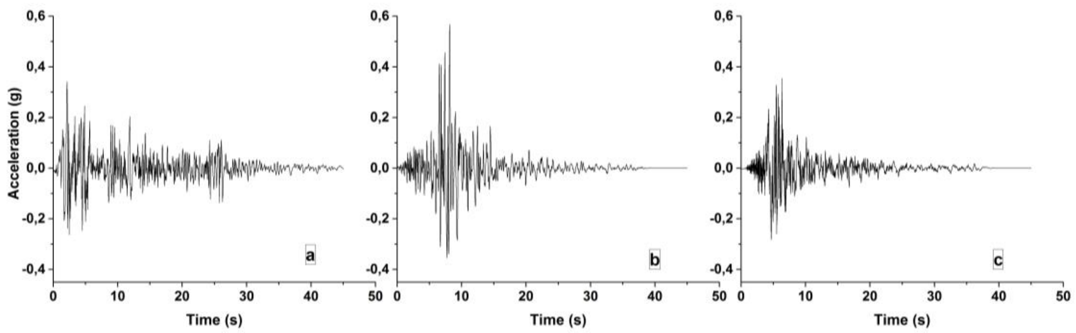


Figure 3. Earthquakes records used in simulation a: El Centro, b: Northridge and c:Loma Prieta

In order to compare the results a two dimensional model 2D for a six story building 6-story with $(n+1)$ degrees of freedom, this structure is considered as a base isolated lumped structure with an elastic behavior proposed by [24], where his work is used to check the performance of the hybrid control.

The base of the isolated structure is assumed as a rigid mass m_b, and its displacement relative to the ground is denoted as x_b. The isolation system is assumed linear with a lateral stiffness k_b and a damping c_b. The superstructure has five (5) degrees of freedom; each degree of freedom has a lumped mass m_i. The corresponding displacement component x_i which represents the super-structural deformation relative to the ground. The computed natural frequencies of the isolated structure are 0.501, 8.267, 15.927, 22.513, 27.568 and 30.746 Hz.

The total mass is $m_T = m_b + \sum_{i=1}^{5} m_i$ (19)

The tuned mass damper is tuned to the first frequency of the base isolated structure, parameters of the TMD are chosen according to [34], for a minimum displacement response of the primary structure and a mass ration $\mu = 5\%$ is chosen.

$$m_{tmd} = \mu \times m_T \tag{20}$$

$$f_{tmd} = \frac{f_{S1}}{(\mu+1)^2} \tag{21}$$

$$k_{tmd} = f_{tmd} \times m_{tmd} \tag{22}$$

$$c_{tmd} = \sqrt{\frac{3\mu}{8(\mu+1)^3}} \tag{23}$$

where m_{tmd} is the mass of the TMD, f_{S1} is the first frequency of the structure and f_{tmd} is the frequency of the TMD. k_{tmd} and c_{tmd} are respectively the stiffness and the damping of the TMD device. Parameters of the isolated structure are illustrated in Table 1.

Table 1: Parameters of the structure and the base isolator

Floor	Mass (kg)	Stiffness (kN/m)	Damping (kN.s/m)
Base and isolator	3500	210	2.66
1	3500	$35x10^3$	35
2	3500	$35x10^3$	35
3	3500	$35x10^3$	35
4	3500	$35x10^3$	35
5	3500	$35x10^3$	35
Tuned mass damper	1050	8.55	0.763

As mentioned previously, the control force in the case of an active hybrid control in structure (2) and structure (4) was calculated using an LQR controller in a closed loop form with a feedback. A simple schema of the used model is illustrated in Fig. 2. With the application of an active control and the instantaneous optimal control law of the equation (16), the structural response depends on the weighing matrices Q and R. In the present study the R is chosen to be 10^{-3}. The matrix Q $(2n+4)\times(2n+4)$ is chosen to be diagonal matrix as follows:

$$Q = \begin{bmatrix} q_1 & & & \\ & q_1 & & \\ & & \ddots & \\ & & & q_{2n+4} \end{bmatrix} \tag{24}$$

Assuming all floors are equipped with sensors, displacements and velocities are used to feed the LQR controller. Furthermore the ATMD movement (displacement and velocity) should be free, in other words $Q(7,7)=0$, $Q(14,14)=0$ (no penalization on the ATMD displacement and velocity) and all other diagonal elements are chosen to be 10^6 for both of the structure (3) and the structure (4). However, it interesting to mention that many algorithms can be used to optimize the parameters of the controller and to minimize the power source capacity like the iterative method [35], Wavelet PSO-Based LQR [36] and the multi-objective genetic algorithm [26].

4. RESULT AND DISCUSSION

To illustrate the effectiveness of the proposed hybrid systems, the behavioral responses of structures (1), (2), (3) and (4) are obtained and compared with the same isolated structure equipped just with base isolator.

Table 1, Table 2 and Table 3 illustrate the comparison the peak displacement and the peak acceleration in the base under El Centro, Northridge and Loma Prieta respectively.

From Table 1, Table 2 and Table 3 it is observed that: a reduction of 20% and 25% in the base peak displacement is obtained for both of structures (1) and (2) (passive hybrid control) compared to the isolated structure equipped with just the base isolator,, under the aforementioned excitations.

However, a reduction in the base peak displacement can reach 77% in the case of structures (3) and (4) (active hybrid control) under El Centro and 85% for both of Northridge and Loma Prieta.

In the other side, a neglected or a slight reduction in the peak acceleration is obtained; 0% in the case of structures (1) and (2) under El Centro, 2% under Northridge and 4% under Loma Prieta. This reduction can reach 8% under El Centro, 10% under Northridge and 40% under Loma Prieta in the case of structures (3) and (4).

Table 1, Table 2 and Table 3 show also the comparison where we used another important measurement of the vibration intensity that is called the mean-square absolute acceleration responses. Mean square response is particularly important for evaluating accumulative structural damage and low cycle fatigue. No soil structure interaction is considered in this study, the absolute base floor displacement and acceleration are the same as the relative displacement and acceleration.

Table 2: Effect of the different control strategies in the base floor under El Centro earthquake

Structure	Peak displacement (cm)	RMS displacement (cm)	Peak acceleration (cm/s^2)	RMS acceleration (cm/s^2)
Isolated structure	22.41	8.13	348.91	94.96
structure (1)	17.95	4.31	349.95	66.80
structure (2)	17.92	4.28	350.12	66.61
structure (3)	8.57	1.94	323.18	51.89
structure (4)	8.52	1.90	324.45	52.71

Table 3: Effect of the different control strategies in the base floor under El Northridge earthquake

Structure	Peak displacement (cm)	RMS displacement (cm)	Peak acceleration (cm/s^2)	RMS acceleration (cm/s^2)
Isolated structure	36.80	11.77	788.71	137.09
structure (1)	27.98	5.46	774.18	89.71
structure (2)	27.73	5.41	774.04	89.39
structure (3)	12.25	1.78	687.31	66.63
structure (4)	12.14	1.75	721.00	67.14

Table 4: Effect of the different control strategies in the base floor under Loma Prieta earthquake

Structure	Peak displacement (cm)	RMS displacement (cm)	Peak acceleration (cm/s^2)	RMS acceleration (cm/s^2)
Isolated structure	36.80	11.77	788.71	137.09
structure (1)	27.98	5.46	774.18	89.71
structure (2)	27.73	5.41	774.04	89.39
structure (3)	12.25	1.78	687.31	66.63
structure (4)	12.14	1.75	721.00	67.14

As can also be seen from Table 1, Table 2 and Table 3 a significant reduction in RMS displacement is obtained for all cases. A reduction of 50%, 55% and 58% in RMS displacement is obtained for the structure (1) and the structure (2) under El Centro, Northridge and Loma Prieta respectively. However the reduction in RMS displacement can reach 77%, 85% and 87 % of structure (3) and structure (4) under same excitations.

In the other side, the passive hybrid control in structures (1) and (2) can reduce the RMS acceleration with 30%, 45% and 50% under El Centro, Northridge and Loma Prieta. A reduction of 45%, 55% and 70% for the same quantity is obtained using an active hybrid control in structure (3) structure (4).

For a base isolated structure it is well known that a significant deformation will occur in the base isolator; As a consequence, a reduction in the floor absolute displacement is obtained. Maximum drifts of all floors are presented in Fig. 4, Fig. 5 and Fig. 6, it is clear that the implementation of either passive or active hybrid systems doesn't affect the absolute displacement of the floors except for the base. All the wanted reductions in response quantities are obtained, just by improving the base isolator behavior and making the structure more safe by reducing the base isolator displacement and, more comfortable by reducing the base isolator acceleration.

Note: in Fig. 4 to Fig. 6 the base floor is noted as floor 1, the ground is noted as floor 0.

Time histories of the base displacement responses of structure (1), (2), (3) and (4) are obtained and compared with the same isolated structure equipped with just a base isolator.

Considering the passive hybrid control alone and as can be observed from Fig. 7, Fig. 8 and Fig. 9, the efficiency of this system results in a slight reduction in term of the peak base floor displacement, particularly in the beginning of the excitations.

The passive hybrid control maximum performance was achieved after a couple of cycles of vibrations; TMD uses the energy stored from the primary structure to oppose the undesired vibration of the primary structure.

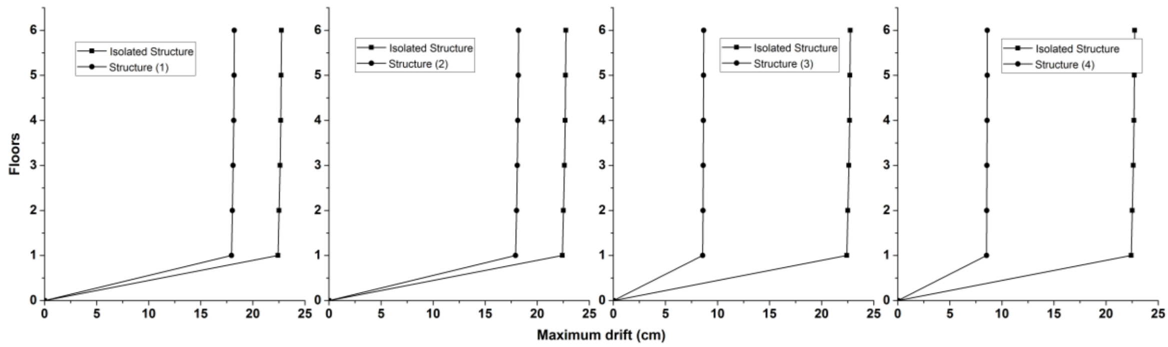


Figure 4. Maximum drifts under El Centro earthquake

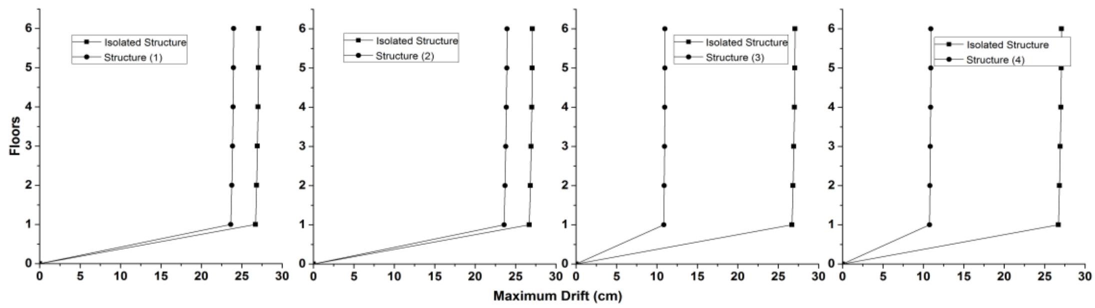


Figure 5. Maximum drifts under Northridge earthquake

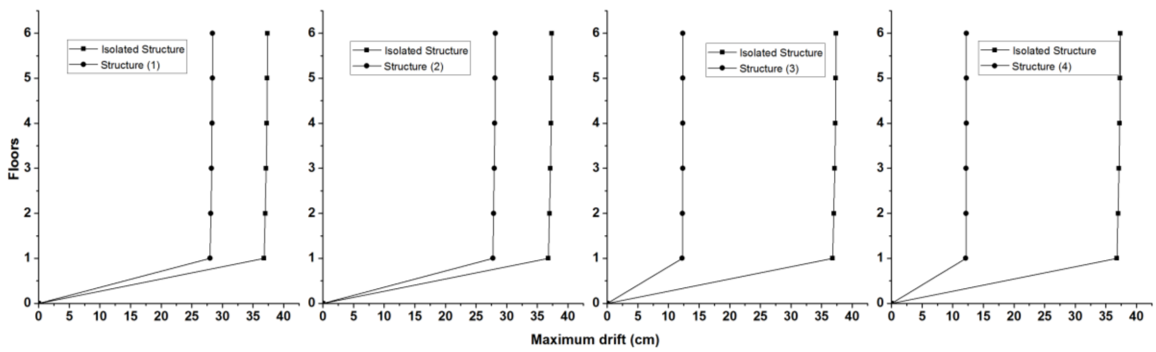


Figure 6. Maximum drifts under Loma Prieta earthquake

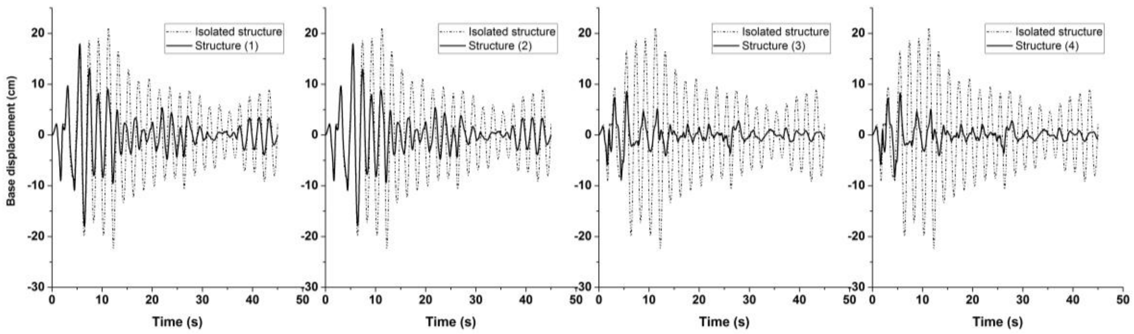


Figure 7. Base displacement under El Centro earthquake

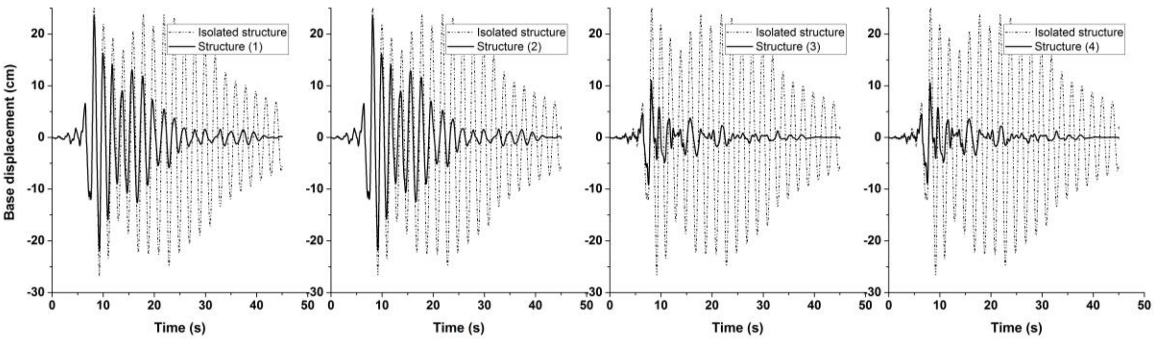


Figure 8. Base displacement under Northridge earthquake

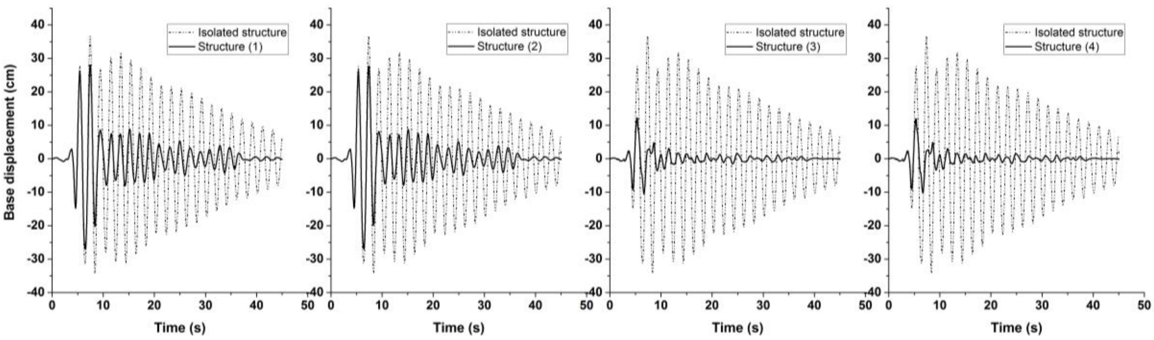


Figure 9. Base displacement under Loma Prieta earthquake

Furthermore, the hybrid active control is more effective than the hybrid passive control, and the above performances are obtained by using an external force. The required patterns of the forces under the different earthquakes are represented in Fig. 12. Due to the rigid behavior of the superstructure, same active force is needed for both of structures (3) and (4). It can be seen that the active control force is totally affected by the form of the earthquake excitation in another term the structural response. Against the aforementioned earthquakes, the peak control force in absolute value for the example of buildings is at the order of

1.3×10^4 kN against El Centro and Loma Prieta, 1.6×10^4 kN against Northridge.

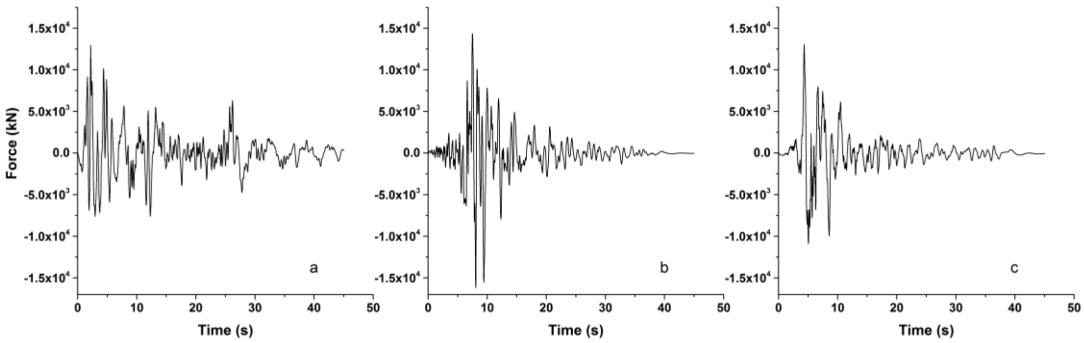


Figure 10. Active control force needed under a. El Centro, b. Northridge and c. Loma Prieta earthquakes

Examination of the above numerical results indicates that both of passive and active hybrid controls are more efficient in controlling vibration of a base isolated structure, in term of reducing the base isolation displacement, and acceleration and also RMS responses.

It is clear that by adding an active force to the passive hybrid system, the active hybrid system is more preferment than the passive hybrid control, firstly. Secondly, numerical results also show that in the case of a rigid structure (model used in this study) the placement of the control device doesn't affect the performance of the system.

Placement of the tuned mass damper or active tuned mass damper in the lowest floor requires a large space and malfunction of this floor. One of the solutions demonstrated in this study, a possible way to save the functionality and usage of the lowest floor is by placing the control device in the top floor which guaranties the same performances.

5. CONCLUSION

This paper focuses on the combined application of base isolator and passive or active tuned mass damper, installed on the lowest floor and on the top of the building, with the objective of reducing the base-isolated building responses when subjected to earthquake excitations using the LQR controller. The LQR controller is designed to evaluate the active control force in the active hybrid systems in a closed loop control approach, based on minimizing the cost function in the LQR controller and responses of the structure.

The results from the numerical study lead to the following observations:

1. The hybrid active control system is more effective than the passive hybrid control system, which in turn is more effective than a base isolator alone, for reducing the building responses.
2. A reduction of more than of 70% in the base isolator displacement is obtained using the hybrid active control while base acceleration is also kept within an acceptable range.
3. A significant reduction in RMS response was reached, for all proposed controls strategies.

4. Installing a hybrid control systems enhance the base isolated structure security and comfort during strong earthquakes.
5. The location of the TMD or ATMD is not critical. First or top floor locations yielded similar rigid body type performance of the structure.
6. Performance of active device depends totally on an external power source. However, optimizations method like the multi objective genetic algorithm method is applicable in aim to reduce the force demand.

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