Enhancing Seismic Performance of Structures through Hybrid Control: Integrating Tuned Mass Dampers and Actuators

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ABSTRACT

This study analyzes the seismic performance of steel framed structure integrated with hybrid vibration control system. In this study, 10 storey single bay steel framed structure was modeled, and analyzed for vibration control systems viz. a Tuned Mass Damper (TMD) as a passive control at the top, an active control system with actuators, and coaction of active and passive control. The effectiveness of all the vibration control systems was determined by a numerical simulation using MATLAB Simulink. The simulation results demonstrate promising outcomes, with all responses of interest obtained and analyzed. In case of passive control system, 2% mass ratio showed maximum response control among 0.2%, 2%, 3%, and 5% mass ratio. The active case utilizing actuators positioned at storey 1, 3, 4, and 8 achieves optimal control with values of 59.34%, 44.30%, and 44.09% for top floor displacement, storey drift, and base shear, respectively. The hybrid control system employing actuators positioned at storey 1, 2, 3, and 10 and 2% mass ratio attains the most effective control, with respective values of 61.94%, 53.51%, and 68.26% for top floor displacement, storey drift, and base shear, respectively. In general, hybrid control system is the best choice keeping in view the response reduction required and the economy . The future scope of this study includes exploring velocity feedback, robust control using LQG, and implementing Genetic Algorithm in MATLAB for further investigation.

KEYWORDS

Vibration control, TMD, Actuators, Matlab, Steel Structure

INTRODUCTION

The primary concern of earthquake engineering is the design of building structures that are able to withstand the forces and accommodate the deformations that are induced during a seismic event. The seismic response of the system can always be controlled by providing stronger structural members however, that would lead to an uneconomical design. Hence, providing the means for adequate energy dissipation through the yielding of individual members and the generation of localized plastic hinges to enhance global ductility leads to unavoidable damage during a seismic event. The flaw in this approach is the permanent deformations in the structure surviving the seismic event which may seriously affect its service life, leading to the need for expensive repairs. Therefore, alternative approaches are constantly developed and investigated to produce structural designs that satisfy both seismic safety and economic requirements.

Recently, the attention of researchers has focused on reducing forces and deformations in structures through the methods of structural control to generate safer as well as economical structural designs. In their study seismic upgrade of steel frame buildings by using damped braces, Eleonora Bruschi et al. showed that the suggested method was a practical way to balance the damped braces of the low- and mid-rise steel frames. Sugumar et al., performed numerical simulations with MATLAB and SIMULINK to compare the performance of three different algorithms: the linear quadratic regulator (LQR) with reduced order state observer, the linear quadratic Gaussian regulator (LQG), and the stochastic control algorithm with the Kalman filter. It was found that using ATMD will prevent the failure of the control system due to power loss during earthquakes because it uses less power than active control devices and can operate in a more flexible manner. Schmitendorf et. al presented the effects of actuator dynamics and a method to incorporate these dynamics into the overall design, simulation results for seismic-excited building structures demonstrate that the control method is very effective. Jiang et al developed a hybrid control system for reducing seismic response that comprises of hydraulic actuators with servo valve control and viscous fluid dampers on a seismic-resistant structure supported by K-braces. The results demonstrate that this hybrid system outperforms active and passive systems. Rather Faisal studied that in comparison to near field earthquakes, far field earthquakes exhibit a greater reduction in reactions, according to results of a studied active seismic control technique.

Structural control strategies are materialized by special devices that are added to the system to reduce structural response. These methods of response reduction can address not only the prevention of total failure or the limitation of damage but also provide comfort to the occupants of the structure. Depending on the mode of operation of these special devices, the structural response control methods can be broadly classified as passive, active and semi-active control approaches.

RESEARCH SIGNIFICANCE

In present study, the application of Passive control device namely Tuned Mass Dampers, active control devices namely actuators and hybrid device containing passive as well as active control devices to mitigate seismic responses were analysed. The paper aims to analyze the intricacies of these systems, including their real-time response and adaptability. This paper seeks to contribute to the advancement of vibration control methodologies, offering valuable insights into the selection, design, and implementation of suitable control strategies for vibration control of structures.

RESEARCH METHODOLOGY

Matlab and Simulink were used to model the passive, active and Hybrid Control of a Ten Storey Steel framed structure, Figure 1, with parameters given in Table 1. A Matlab code was fed to the Simulink to get the required results. In this study, linear quadratic regulator (LQR) control algorithms was considered.The simulations were run for the following three control models.

- Passive Control by Using TMD.
- Active Control by Using Actuators.
- Hybrid control by Using TMD and Actuators

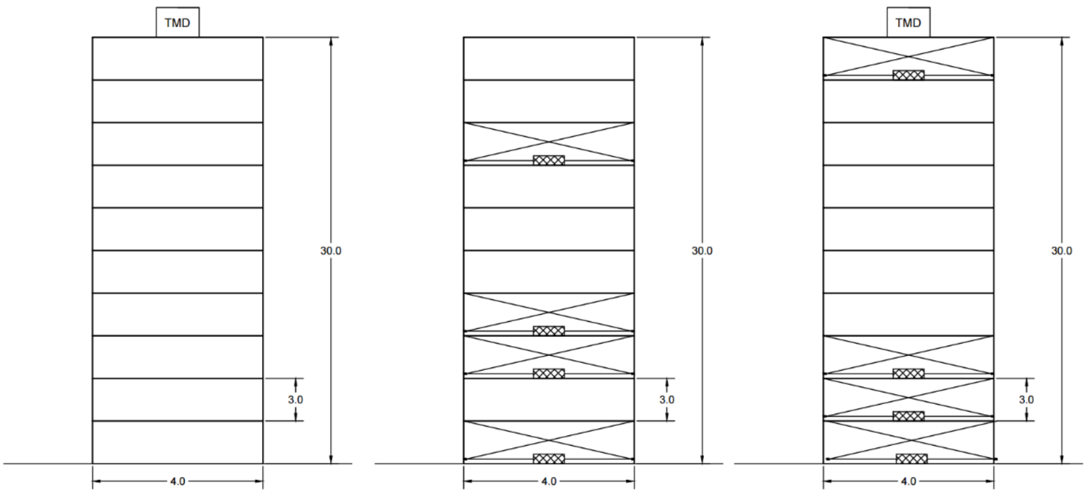

Figure 1 Model for (a) Passive control (b) active control and (c) Hybrid control

All the models were subjected to recorded earthquake induced ground motions (El Centro). The mass and frequency characteristics are chosen similar to those likely to be encountered in a typical medium sized multistoried building. Each storey has the same mass, and stiffness except for the top storey which has mass equal to the half of other storey.

In passive control , tuned mass damper is mounted at the top of the shear building. The mass of the TMD is tuned with the mass of the building using trial and error approach. Linear Quadratic Regulator technique has been used in active control to generate the control force and this control force is delivered to the structure through actuators. The actuators have been placed at various floors under various combinations in order to get a combination where there is sufficient reduction of response at the expense of less control force. Finally, both the TMD and the actuators are used together under hybrid control. In all the cases three basic responses i.e. top storey displacement, base shear, and storey drift were obtained.

Table 1: Basic parameters of a model

S. NO.	Parameters	Value
1	Floor stiffness	400x10^6 N
2	Floor mass	150x10^3 kg
3	Top floor mass	75x10^3 kg
4	Bay width	4m
5	Floor height	3m

RESULTS AND DISCUSSIONS

4.1 Results for Passive control

The author should explain the outcomes of the works carried out and discuss in detail. The figures and tables should be presented in the following manner.

The presented data in Table 1 outlines the effects of different mass ratios on the base shear of a structure under various control strategies. The uncontrolled base shear values at different mass ratios serve as a reference. When passive control using Tuned Mass Dampers (TMDs) is employed, the base shear is consistently reduced. For a mass ratio of 0.2%, the controlled base shear is 4500 KN, resulting in a reduction of 3.846%. At higher mass ratios of 2% and 3%, the controlled base shear values are 3910 KN and 4329 KN, corresponding to reductions of 16.453% and 7.5%, respectively. However, an unexpected trend is observed at a mass ratio of 5%, where the controlled base shear increases to 5040 KN, indicating a increase of -7.692%. These findings underscore the intricate interplay between control strategies, mass ratios, and their impact on structural behavior,suggesting the optimum mass ratio of 2%. Figure 2 shows the Comparison of Top Floor Displacement, Storey Drift, Base Shear Under Passive Control for best Mass Ratio of 2%.

Table 2: Comparison of Controlled and Uncontrolled Base Shear With Different Mass Ratios

Comparison of Base Shear at Different Mass Ratio			
Base Shear			
% Mass Ratio	Uncontrolled Base Shear (KN)	Controlled Base Shear (KN)	Percentage Reduction
0.2	4680	4500	3.846
2	4680	3910	16.453
3	4680	4329	7.5
5	4680	5040	-7.692

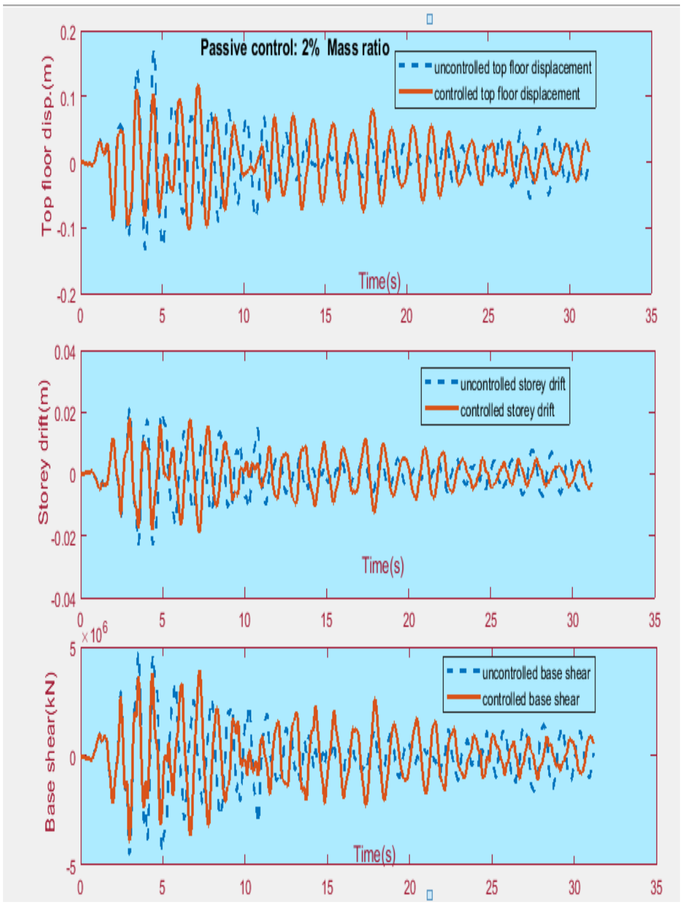

Figure 1 Comparison of Top Floor Displacement,Storey Drift,Base Shear Under Passive Control for best Mass Ratio of 2%

4.2 Results for Active control

Simulations were run for various combination of 4 actuator positions at 10 floors and the optimum results for controlling top floor displacement, storey drift, base shear, and control force were obtaind when actuators were placed at 1st,3rd,4th and 8th floor depicted in Figure 3. Choosing to employ only 4 actuators strikes a balance between achieving a substantial reduction in base shear and avoiding the potential drawbacks associated with adding more actuators, such as increased system complexity, higher costs, and potential maintenance challenges. Therefore, the data provides a strong basis to defend the decision to employ 4 actuators as an effective and efficient choice for achieving a considerable reduction in base shear while optimizing practicality and cost considerations.The data presented Table 2 highlights the influence of the number of actuators on the base shear of a structure, along with the corresponding percentage reduction achieved through active control. The uncontrolled base shear is set as the benchmark for comparison. As the number of actuators increases, the controlled base shear consistently decreases. With a single actuator, the controlled base shear is reduced to 3250 KN, resulting in a reduction of 31.69%. This trend continues as the number of actuators rises, showcasing reductions of 32.74%, 39.05%, 45.99%, 50.82%, 53.34%, 56.49%, 59.44%, 61.96%, and 62.59% for 2 to 10 actuators, respectively. These findings emphasize the significance of selecting an appropriate number of actuators for effective vibration control, indicating a substantial reduction in base shear as the actuator count increases. This underscores the importance of optimizing the actuator layout to achieve the desired level of structural performance improvement.

Table 3: Comparison of Controlled and Uncontrolled Base Shear of various floors for Elcentro earthquake time history by Active Control to Find Optimum Number of Actuators

No. of Actuators	Uncontrolled Base Shear (KN)	Controlled Base Shear (KN)	Percentage Reduction in Base Shear
1	4758	3250	31.69
2	4758	3200	32.74
3	4758	2900	39.05
4	4758	2570	45.99
5	4758	2340	50.82
6	4758	2220	53.34
7	4758	2070	56.49
8	4758	1930	59.44
9	4758	1810	61.96
10	4758	1780	62.59

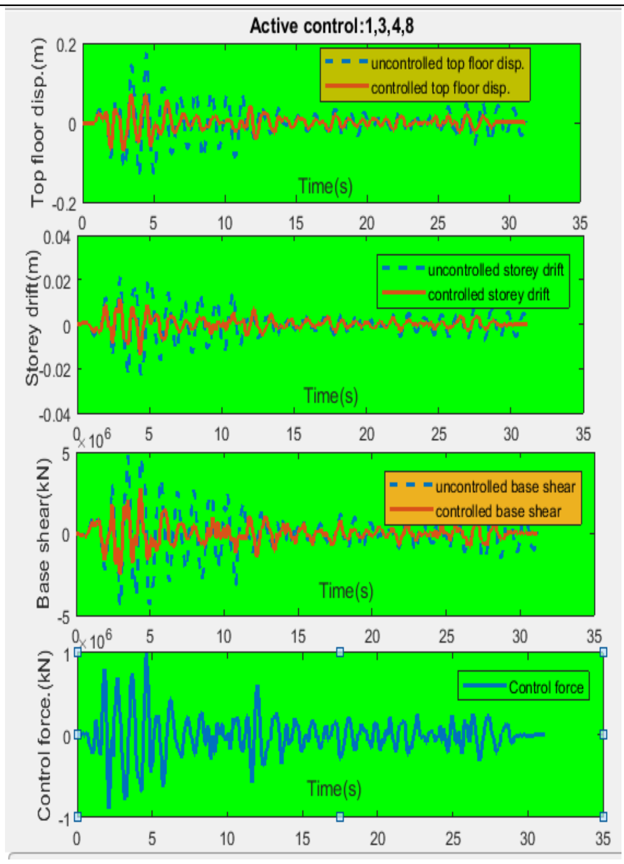

Figure 2 Comparison of Top Floor Displacement,Storey Drift,Base Shear and Control Force Under Active Control for Best Actuator Location 1,3,4,8

4.3 Results for Hybrid control

Using the optimum mass ratio of 2% obtained from passive control simulations and again changing the position of actuators to the best position for actuator placement i.e., 1st, 2nd ,3rd and 10th floor instead of that obtained in active control simulations that is 1st , 3rd, 4th and 8th . All the four parametres that is top floor displacement, storey drift, base shear, and the control force are controlled by adopting hybrid control methodology. Figure 4 shows the seismic response of hybrid vibration control in reference to uncontrolled systems. Figure 5 shows the comparision of the hybrid and active vibration control for the top floor displacement,storey drift , base shear and required control force.

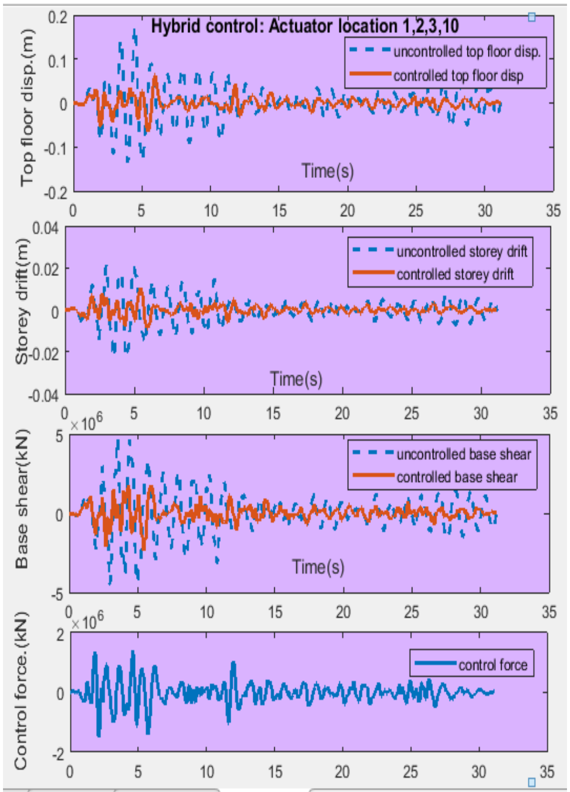

Figure 3 Comparison of Top Floor Displacement,Storey Drift,Base Shear and Control Force Under Hybrid Control for 2% Mass Ratio and Best Actuator Location 1,2,3,10

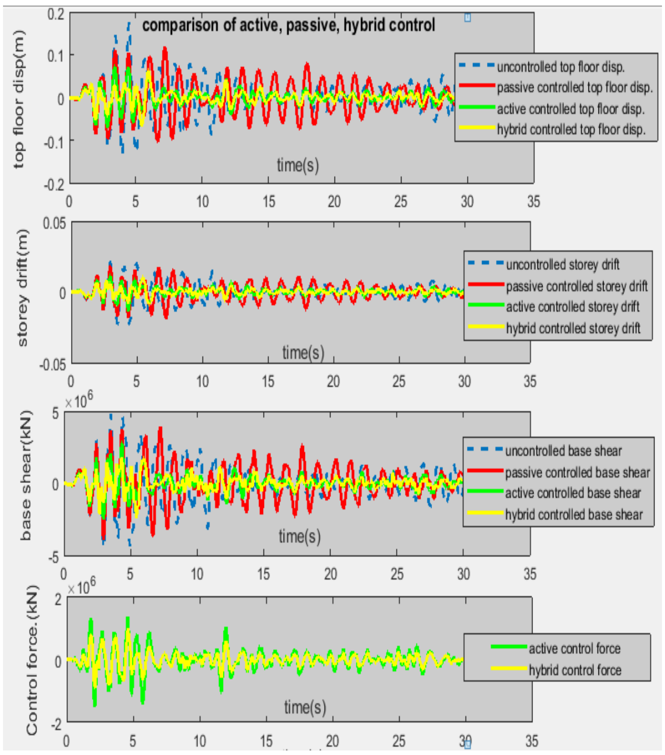

Figure 4 Comparison of Top Floor Top Floor Displacement,Storey Drift,Base Shear and Control Force for Active,Passive And Hybrid Control

CONCLUSIONS

This paper has investigated the two most important problems of active vibration control, modeling and control design. The main conclusions that were drawn from this study are as follows:

1. In case of passive vibration control, 2% mass ratio showed maximum reduction in top floor displacement, storey drift, and base shear signifying 2% mass ratio to be optimum for vibration control among 0.2%, 2%, 3% and 5%. Moreover, 5% mass ratio resulted in reverse effect, that is controlled base shear is more than uncontrolled base shear, so the mass ratio less than 5% shall be used in passive control.

2. The reduction of 59.34%, 44.30%, 44.09 % in Top floor displacement, Storey drift, and Base shear respectively is achieved in Active case by using actuators at 1st, 3rd, 4th, 8th storey in reference to uncontrolled response.

3. The Hybrid vibration control results in a reduction of 61.94%, 53.51% and 68.26% in Top floor displacement, Storey drift, and Base shear, respectively. In case of hyrid vibration control, position of actuators changed from 1st, 3rd, 4th, 8th storey to 1st,2nd ,3rd and 10th storey to achieve best results.

4. Among passive ,active and hybrid vibration control systems hybrid system resulted in maximum reduction in seismic responses. Hence, hybrid system appears to be promising vibration control approach while designing or retrofitting structures in earthquake prone areas.

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