

A Comparative Study on Hybrid Vibration Control of Base-isolated Buildings Equipped with ATMD

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Abstract-The vibration control for building structures using hybrid control (base isolators BI and Active Tuned Mass Dampers-ATMDs) has attracted the attention of researchers. This paper establishes a hybrid vibration control system of structure and compares structural response and active tuned mass damper performance among the structure using two different control algorithms (PID and LQR). Through simulation research, from the comparative analysis of performance indexes of structural response and ATMD performance, it is concluded that the LQR controller outperforms the PID controller in reducing the structural responses.

Keywords-PID control; LQR control; hybrid control; base isolation; ATMD

I. INTRODUCTION

One of the biggest challenges in structural engineering is the development of structural vibration control techniques [1]. With those techniques, structures can be better protected from the damaging effect of destructive environmental forces such as earthquakes, winds, and other external loads [2]. Structural control has been investigated and has shown great results in reducing the vibrations in different civil structures under the effect of dynamic loads [3, 4].

The structural vibration control system can be divided by its method, or the types of devices being used, into four general types: passive control, active control, semi-active control, and hybrid control. A passive system can reduce the vibration energy without the need for external power. It uses a passive mechanism to reduce the response of the structure. This type of control utilizes two methods: seismic base isolation and supplemental damping [5]. Passive control mechanisms include tuned mass (or liquid) damper (TMD/TLD), viscoelastic

damper, base isolation systems, etc. [5-7]. Although the usage of a passive control system is very simple and affordable, it has significant disadvantages, such as being less adaptable to external environmental actions such as earthquakes and winds. The active structural control system uses actuators, sensors mounted at different locations on the structure to measure external excitations and the structural response, and a computer to calculate the appropriate force control. An external power source also is needed for actuators to apply forces to control or to modify the motion of the structure. Active control devices include Active Tendon Systems (ATS), Active Mass Dampers (AMD), active brace systems, etc. [8]. Hybrid structural control systems are excellent vibration control systems, because they combine the reliability of the passive system and the adaptability of the active system [9, 10]. To get the optimal control force, many methods and algorithms have been created. An analytical model for the entire system and a dynamic model of the system are needed, including all its objects such as the structure, sensor, actuators, and controller [11, 12].

In a building structure equipped with an ATMD, a motor based device called actuator applies a force known as control force. One or more actuators apply these forces to a structure according to the control law and use an external energy source for their operation. These forces can be used to add or dissipate energy from the structure to be controlled. To build such a system, there are two radically different approaches: The first is to identify the seismic excitation which creates the vibrations to cancel it out by superimposing an "inverse" excitation on it. This active control strategy is called feedforward. It is mainly developed in acoustics [13, 14], but it is also very useful for the control of vibration of structures. The second is to identify the structure's response rather than the excitement that makes it

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vibrate. It, therefore, requires the modeling of the structure to evaluate its dynamic behavior. The vibration control work that goes into this type of strategy is called feedback loop control. [15].

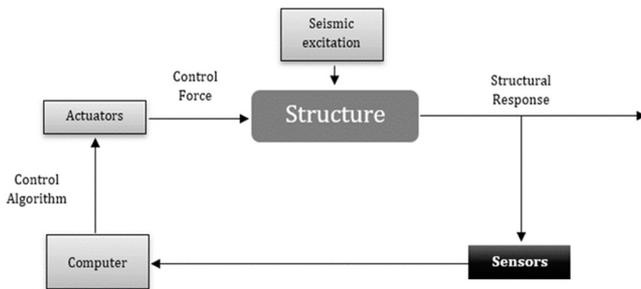


Fig. 1. Structural vibration control.

Base isolation systems are a well-known application of the passive control approach. These base isolators are placed between the foundations and the superstructure, these devices make it possible to decouple the movement from the ground to the superstructure, the aim of which is to reduce the forces transmitted from the ground. The isolators absorb the ground's shaking energy and filter high-frequency accelerations so that the isolated superstructure moves essentially in a rigid mode undergoing low accelerations and almost no deformations [16]. For this reason, the base isolation system is an effective tool to ensure the seismic protection of rigid structures. To design the appropriate base isolator and to have its optimum performance many parameters should be considered, like the different characteristics of the soil and the location of the structure [17]. LRB (Laminated Rubber Bearings) base isolators are known as one of the most used systems in isolating structures. And therefore, this type was chosen in the current study.

The main purpose of this work is to compare and evaluate two different types of control algorithms (PID and LQR), that control and drive the ATMD. The ATMD will be placed on the top floor because it has been proven that putting it there is a very effective strategy to reduce the structural responses. Our structure will be equipped with base isolators in both cases and the performance of the two systems will be evaluated under the effect of three strong earthquakes (El Centro, Kobe, and Northridge).

II. PID AND LQR CONTROLLERS

A Proportional Integral Derivative (PID) regulator is a control organ that allows carrying out the closed-loop regulation of an industrial process. The regulator compares a value measured on the process with a setpoint. The difference between these two values (the error signal) is then used to calculate a new input value of the process tending to reduce as much as possible the difference between the measurement and the setpoint (lowest possible error signal).

"PID" represents the abbreviations of the three actions it uses to make its corrections: a Proportional action, an Integral action, and a Derivative action. Adjusting this type of controller is often a matter of experience. Its independence

towards the model of the system is a guarantee of robustness when applied to known, linear, and little-variant systems[18].

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de}{dt} \quad (1)$$

where K_p is the proportional gain, K_i is the integral gain, and K_d is the derivative gain.

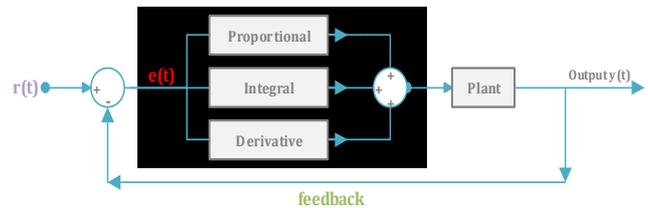


Fig. 2. The PID controller.

Linear Quadratic Regulator (LQR) control belongs to the family of optimal control algorithms. In optimum control, a cost function representing a performance index is chosen and then reduced to provide the optimal input. In the quadratic optimum control problem, the cost function can be designed to be quadratically dependent on the control input and the output state or response [19]:

$$J = \frac{1}{2} \int_{t_0}^{t_f} (x^T Q x + u^T R u) dt \quad (2)$$

where Q is the weighting matrix (output), and R is the control vector (input). The performance index J represents the balance between the structural response and the control energy, the purpose of which is to reduce the response of the structure. The performance index shown in (3) is chosen in such a way, as to minimize the structural response and control energy over the time interval from t_0 to t_f . When the elements of Q are large, the response of the system will be minimized to a large control force. When the elements of R are large, the control force will be small, but the structural response cannot be reduced sufficiently [20, 21].

$$u(t) = -KX(t) \quad (3)$$

K (LQR gain vector) is given by:

$$K = R^{-1} B^T P \quad (4)$$

where P is the solution matrix of Riccati's equation.

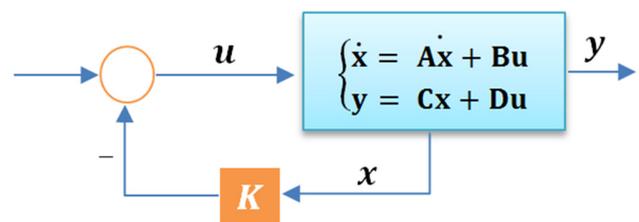


Fig. 3. The LQR controller.

The simulation was done in Matlab/Simulink. Three strong historically known earthquakes were used. El Centro (1940), Northridge (1994), and Kobe (1995) earthquakes.

V. RESULTS AND DISCUSSION

The response results of the isolated, uncontrolled structure were compared to the same structure equipped with an ATMD, using PID and LQR control algorithms. Figures 5-7 show the building's top floor displacement comparison.

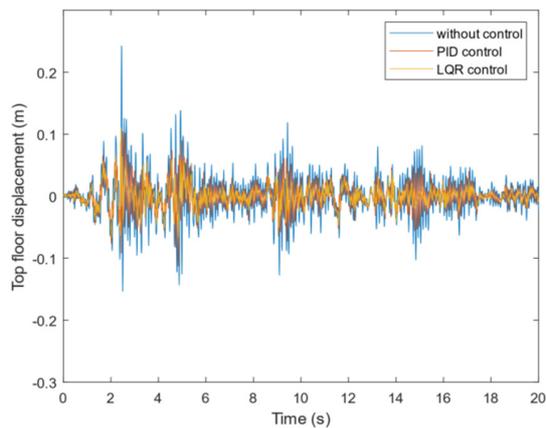


Fig. 5. Structural response under El Centro seismic excitation.

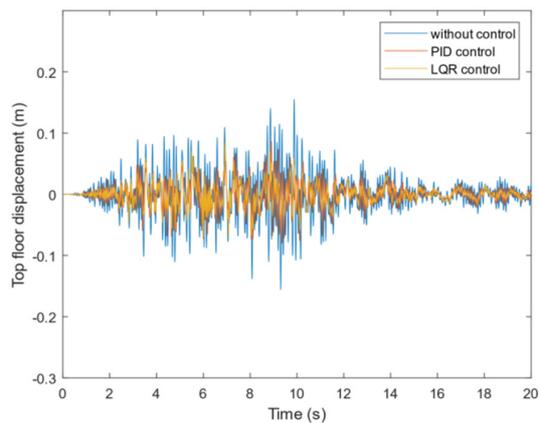


Fig. 6. Structural response under Kobe seismic excitation.

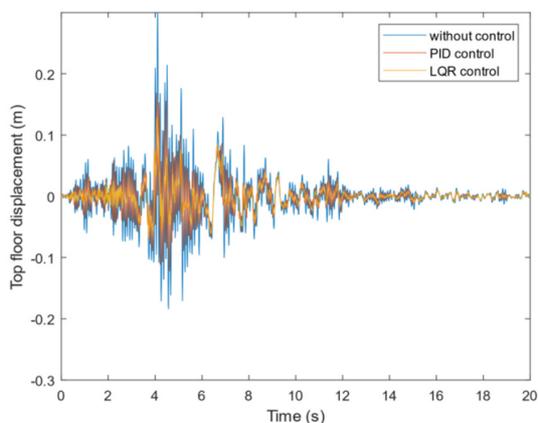


Fig. 7. Structural response under Northridge seismic excitation.

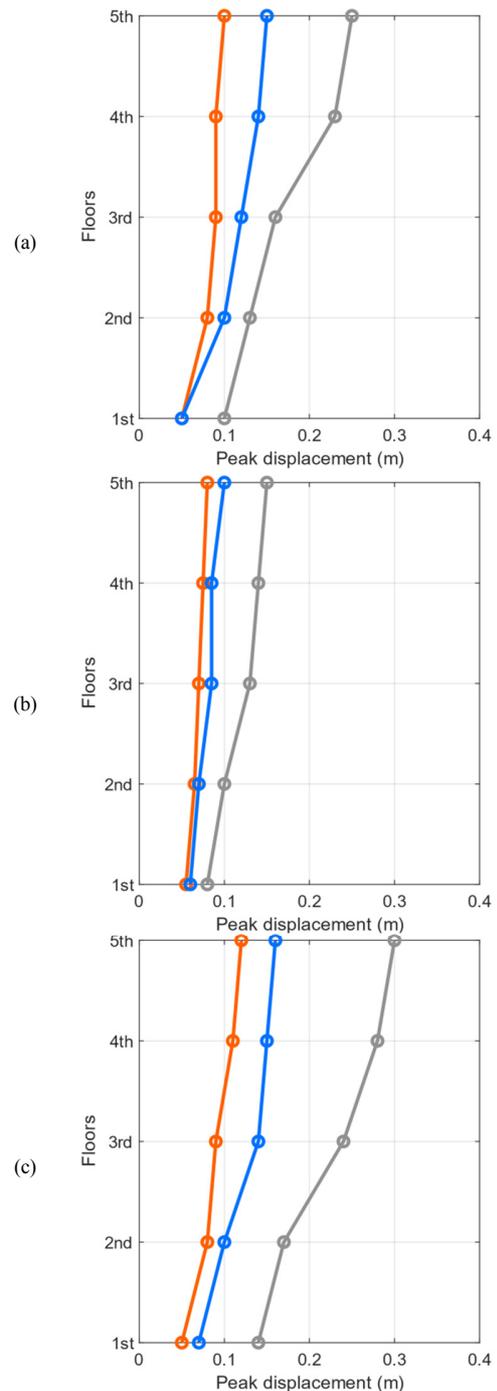


Fig. 8. Maximum story drift for the structure under the different earthquake excitations: (a) El Centro, (b) Kobe, and (c) Northridge.

Figure 5 shows the top floor displacement under El Centro earthquake excitation. It can be seen that the hybrid control system using the LQR controller reduces the peak displacement by almost 60% and the PID controller by 49% in comparison with the uncontrolled structure. Figure 6 shows the top floor displacement under Kobe earthquake excitation. From this Figure, it can be noted that the hybrid control system using the LQR controller outperforms the PID controller and reduces the

peak displacement by almost 57%. The top floor displacement under Northridge earthquake excitation is shown in Figure 7. Again, the hybrid control system using the LQR controller surpasses the PID controller and reduces the peak displacement by almost 62%. As these Figures show, using the LQR controller to control the displacement of the top floor of the structure always gives better results than when using a PID system. It can be seen that the hybrid system designed using an LQR controller is more efficient and effective than PID control in reducing the displacement of this building in the three cases.

VI. CONCLUSION

The objective of this study is to combine the application of base isolators and ATMDs to minimize the structural responses under the influence of seismic excitations using two different controllers, LQR and PID. According to the numerical studies for a 5-story building, and the obtained results, the following conclusions can be drawn:

- The comparison between LQR and PID controllers indicates that the LQR controller is more effective in reducing the displacements and the vibration of the building and surpasses the PID controller by far.
- In this study, the active control system proved to be far more efficient than the passive control systems in reducing the structural response.
- More than 50% of the top floor displacement is reduced by using the hybrid control system.
- Using a hybrid control system to control the vibration of a structure improves its performance in resisting strong earthquake excitations and makes the structure safer and more comfortable during earthquakes.

For future research, we will work in combining LQR and PID controllers in order to get the advantages of each system.

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