

ACTIVE CONTROL OF BUILDING STRUCTURES BY USING ACTIVE MASS DAMPERS WITH LINEAR QUADRATIC REGULATOR CONTROL LAW**Tri Maryono Rusadi**Program Studi Matematika, Fakultas MIPA, Universitas Mataram, Indonesia
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e-mail siska_aprilia3@poliwangi.ac.id**Abstract**

This paper presents a theory of optimal control of building structures that are experienced in the earthquake load excitation by using an active mass damper. Control mechanism is done using active mass exerts a force on the control structure based on structural response is continuously measured. The concept of the Linear Quadratic Regulator (*LQR*) is used to calculate the required control force structure based on the input acceleration response that is measured using the accelerometer. *LQR* optimal control system reliability was tested using shear building model is given Active Tuned Mass Damper (ATMD) five stories above the structure to provide the base acceleration excitation of disturbances in the form of a data record from the accelerogram. Test results for various load acceleration theory base, such as acceleration simulation of El-Centro N-S earthquake, Kobe earthquake, earthquake Pacoima, Northridge earthquake, Kern-County earthquake, and the Chichi earthquake showed optimal *LQR* control is able to give good results. From the analysis and simulation results concluded that the optimal weighting matrix on the value of $Q = 1000$ and the weighting matrix $R = 0.1$ are able to reduce on the structural displacement of the top floor ranged from 19.80% – 58.90%, while for the reduction of the displacement velocity structure in the top floor between 18.24% – 54.18%

Keyword: Control Structure, Active Control, Earthquake, Active Mass Damper, Linear Quadratic Regulator (*LQR*).

INTRODUCTION

The construction and design of buildings, bridges, and other infrastructure buildings so far have been in the form of passive structures that only rely on their mass and stiffness to withstand dynamic external loads and static loads caused by their own weight, so that the safety and reliability of the structure are often directly related to the stiffness and massiveness of the structure. Conservative conventional design will produce a rigid and massive structure.

Structural rigidity has created many vibrational problems in structures that were previously of little concern. Meanwhile, building regulations and standards require increasingly higher safety and comfort requirements, so it is necessary to develop a building construction design concept that is able to actively adapt to dynamic loads. In this case, the

response of the structure in the form of movement of each floor, speed, and acceleration that occurs due to dynamic external loads can be controlled by a control system that works actively and is able to adapt to external disturbances acting on the structure, so that the dynamic characteristics and behavior of building construction can be improved (Herlien, 2008).

Device similar to the tuned mass damper (TMD) was patented by Frahm in 1911. This device was later modified with a viscous damper to control structures exposed to vibrations with varying frequencies. In order to use these devices efficiently, optimization became necessary (Ormondroyd, 1928). It is important to understand the need for optimization. This is based on the fundamental equations by Den Hartog (1947).

With an active control system, it is expected to reduce the excessive structural response caused by

dynamic external loads such as wind, sea waves or earthquakes forces (Sergio Pastor Ontiveros-Pérez, 2022). The optimal control system was chosen as the method used for the controller as a regulator of external energy supply to an actuator. The actuator functions as a mechanical device for generating external forces on the structure (Lanlan Xu, 2018). Information on the magnitude of the control force is obtained from the sensor measuring the acceleration of the structure located on each floor of the building structure. Dampers with this method are often called active mass dampers or Active Tuned Mass Dampers (ATMD). The most commonly used controller for ATMD systems is the Proportional-Integral-Derivative (PID) controller (Kayabekir et al., 2020).

In this research, the problem refers to the article by Kayabekir (2022), where the effectiveness of the ATMD was able to reduce the maximum structural displacement is between 0.99% and 12.23%. To optimize the reduction provided by the ATMD, its parameters will be adjusted according to the equations of Den Hartog (1947), and for the building structure, it will be aligned with the SNI 1726-2012 regulations.

THEORY STUDY

ANALYSIS DYNAMIC SYSTEM

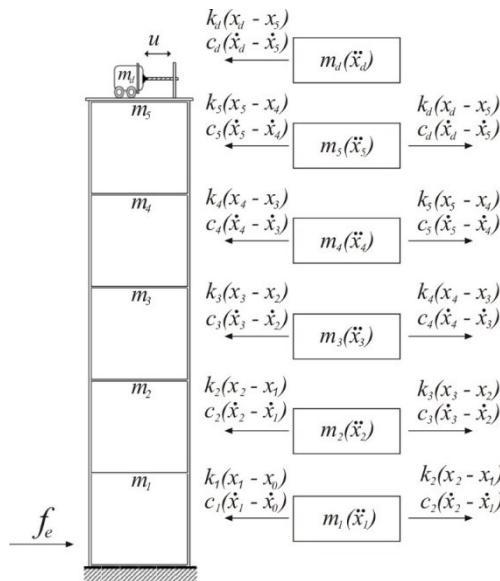


Figure 1. Modeling of 5-Story Structure

The one-story building has a single degree of freedom (SDOF) and the n-story building has a multi-degree of freedom (MDOF), so that in each story there is only one degree of freedom. This model is called a

sliding building. In this model, several assumptions are used, including the mass of the structure centered on each floor, the stiffness of the beam is considered to be infinite, and the axial deformation of the column is neglected. The equation of motion of a dynamic system with n degrees of freedom with control forces is (Song, 1990):

$$M \ddot{x}(t) + C \dot{x}(t) + K x(t) = H u(t) + E f_e(t) \quad (1)$$

The M , C , and K matrices are the mass, damping, and stiffness matrices of the structure, respectively. While $\ddot{x}(t)$, $\dot{x}(t)$, $x(t)$ denote the respective vectors that are acceleration, relative velocity and relative movement of the structure. H is the location matrix of the control force, E is the location matrix of the external excitation force. $u(t)$ is the control force vector and $f_e(t)$ is the external excitation force vector.

STRUCTURE VIBRATION CONTROL

The control system on the structure can be divided into 3 major parts, namely passive control system, active control, and hybrid control. Passive control does not require external energy, while active control requires the addition of external energy. Hybrid control is a combination of the two control systems mentioned above. The discussion in this section will focus on an active control mechanism by using an additional mass that actively responds to external disturbances.

There are several types of active structural control as follows (Herlien, 2008).

- Closed-Loop Control.
- Open-Loop Control (feed-forward control)
- Closed-Open Loop Control.

For closed-loop active control, in the structural control problem, the input control is defined as u . View the state-space as the following equation (Song, 1990):

$$\dot{z}(t) = A z(t) + B u(t) + W f_e \quad (2)$$

$$\text{With : } z(t) = \begin{bmatrix} x(t) \\ v(t) \end{bmatrix}; \quad A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix};$$

$$z(t_0) = z_0 \quad ; \quad B = \begin{bmatrix} 0 \\ M^{-1}H_c \end{bmatrix} \quad ; \quad W = \begin{bmatrix} 0 \\ M^{-1}E \end{bmatrix};$$

$$f_e = \ddot{x}_g$$

For the closed-loop control case, the control force can be calculated using the formula:

$$u(t) = -R^{-1}B^T S z(t) \quad (3)$$

with

$$G = R^{-1}B^T S \quad (4)$$

So that the state-feedback control can be written as follows:

$$u(t) = -G z(t) \quad (5)$$

The S matrix is the Riccati matrix calculated from the equation:

$$A^T S + SA - SBR^{-1}B^T S + Q = 0 \quad (6)$$

To determine the optimal performance index, it is necessary to use the state-feedback control law. The optimal value is as follows (Lewis, 1992):

$$J(t_0) = \frac{1}{2} z^T(t_0) S(t_0) z(t_0) \quad (7)$$

By substituting equation (5) into equation (2) where the solution is to reduce the response. Equation (2) can be modified to:

$$\dot{z}(t) = (A - BG)z(t) + Wf_e \quad (8)$$

METHOD

Literature study is utilized in this research and is employed a secondary data obtained from the U.S. Geological Survey (USGS) and Pacific Earthquake Engineering Research Center (PEER). The data includes accelerogram recordings of earthquakes that occurred in several areas. While the structural parameters obtained from the design according to the rules of SNI 1726-2012.

CASE STUDY OF 5-STORY BUILDING

The building structure reviewed in this study is a building with a concrete structure and has a concentrated mass on each floor of 20 tons. The length of the span in the longitudinal direction of the structure is denoted by $L = 6 \text{ m}$, column height $H = 4 \text{ m}$ with column dimensions for each floor of $400 \text{ mm} \times 400 \text{ mm}$ and Young's modulus $E = 2.1 \times 10^{11} \text{ N/m}^2$. The damping ratio for each variance is set at $\xi = 5\%$ and The ratio of the mass of the ATMD to the total mass of the main system is $\mu = 3\%$. The frequency ratio of the structure is $\omega = 9.1652 \text{ rad/s}$ and the frequency ratio of the ATMD is $\omega_d = 8.8976 \text{ rad/s}$.

Earthquake Accelerogram data used:

1. The El Centro earthquake of 18 May 1940 N-S with a peak ground acceleration (PGA) of 0.35g, where g is the acceleration due to gravity.
2. Kern County Earthquake, 21 July 1952 PGA= 0.16g.
3. Pacoima Dam Earthquake, 9 February 1971 PGA= 1.172g.
4. Kobe Earthquake, 16 January 1995 PGA= 0.836g.
5. Chichi Earthquake, Taiwan, 20 September 1999 PGA= 1.13g
6. Northridge Earthquake, 17 January 1994 PGA= 0.883g

(PEER NGA Strong Motion Database Record & U.S. Geological Survey (USGS))

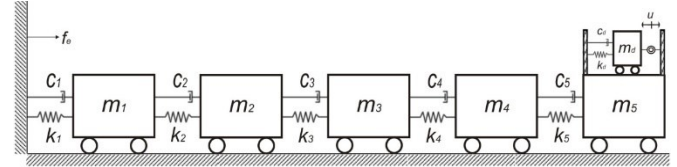


Figure 2. Mass-Damping-Spring Model

SYSTEM SIMULATION

System simulation is carried out using the facilities available in the SCILAB software program. From the simulation results, the system response can be compared with and without the optimal control signal.

RESULT AND DISCUSSION

The structure selected for testing is a five-story regular building structure with a total structure height of 20 m. The building structure is functioned as an office in accordance with the Indonesian National Standard SNI 1726-2012 concerning Earthquake Resistance Planning Standards for Building Structures. The structural model is then idealized as a two-dimensional shear building with five degrees of freedom. The following are some of the parameters used in this simulation.

Below are some comparison charts between Non-TMD (NTMD) building systems, with TMD and with ATMD. The simulation shown is a 5th floor model, because on that floor the greatest movement occurs. The graph showing the displacement of the top floor due to earthquake acceleration is shown in Figure 3 – Figure 8 shows that the maximum movement of the 5th floor given by the controller is smaller than the graph without the controller. The speed of

displacement of the 5th floor due to the acceleration of the time history of the earthquake is shown in Figure 9 - Figure 14 which shows that the controller is able to reduce the response of the structure affected by the earthquake.

Table 1. Structural Parameters

Floor (n)	Column Dimension		K _n (ton/s ²)	C _n (ton/s)	M _n (ton)
	b (mm)	H (mm)			
1	400	400	1680	18.3304	20
2	400	400	1680	18.3304	20
3	400	400	1680	18.3304	20
4	400	400	1680	18.3304	20
5	400	400	1680	18.3304	20
ATMD	-	-	237.5	5.5788	3

With the optimal value of the minimum cost at

$$J(t_0) = \frac{1}{2} z^T(0)S(0)z(0) = 0$$

Top Floor Displacement Simulation

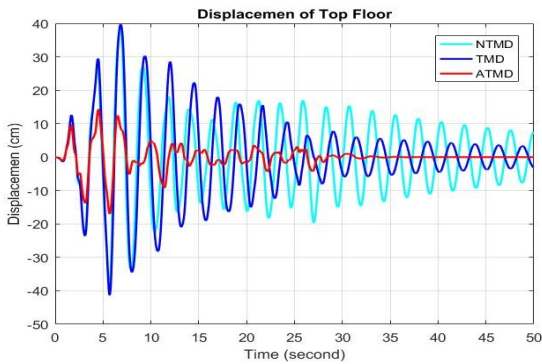


Figure 3. Displacement of the top floor due to the El Centro Earthquake

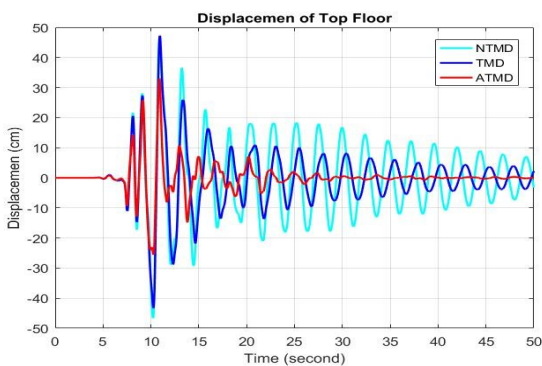


Figure 4. Displacement of the top floor due to the Kobe Earthquake

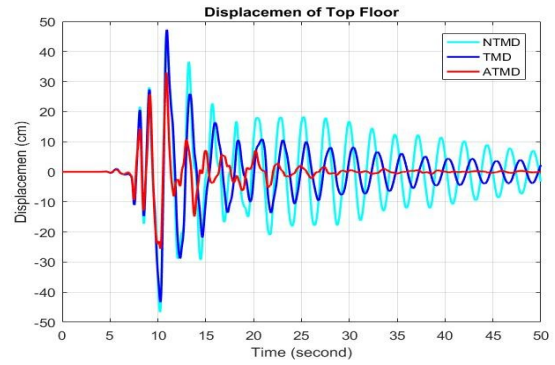


Figure 5. Displacement of the top floor due to the Northridge Earthquake

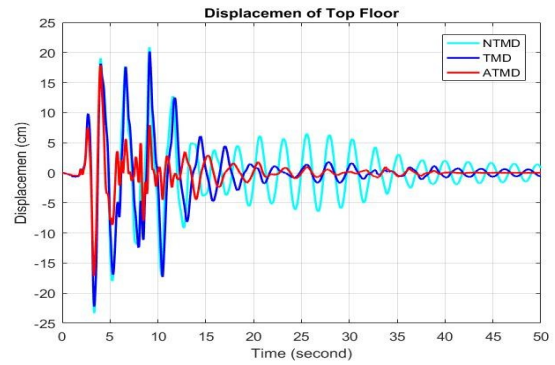


Figure 6. Displacement of the top floor due to the Pacoima Earthquake

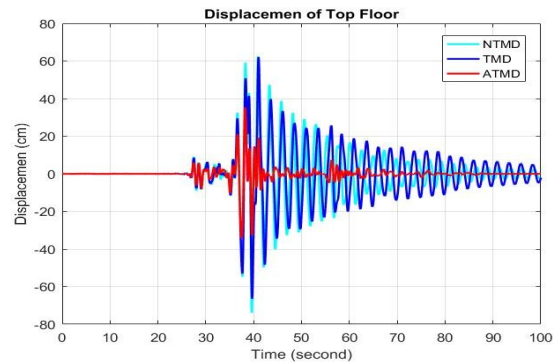


Figure 7. Displacement of the top floor due to the Chichi Earthquake

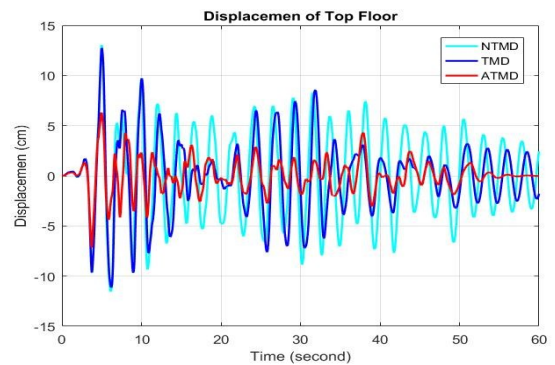


Figure 8. Displacement of the top floor due to the Kern-County Earthquake

Consider Figure 3 - Figure 8, it can be seen that by using a controller, the response of a 5-story building affected by an earthquake can be significantly

reduced. The reduction in the displacement of structures on the top floor ranged from 19.80% - 58.90%.

Table 2. Comparison of maximum displacement due to earthquake effects

Earthquake	Maximum Displacement (m)		
	Non-TMD	TMD	ATMD
El Centro	0.3922	0.4133	0.1701
Kobe	0.4665	0.4726	0.3304
Northridge	0.5112	0.4673	0.3093
Pacoima	0.2332	0.2223	0.1787
Chichi	0.7389	0.6647	0.3535
KernCounty	0.1305	0.1274	0.0713

From the Table 2, it can be observed that the Non-TMD condition consistently produces the largest maximum displacement for all earthquake records, indicating the highest structural response when no control system is applied. The implementation of a TMD reduces the maximum displacement, showing that passive control is effective in mitigating earthquake-induced vibrations, although the reduction is relatively moderate in some cases.

The ATMD system provides the most significant reduction in maximum displacement across all earthquakes listed (El Centro, Kobe, Northridge, Pacoima, Chi-Chi, and Kern County). This demonstrates that active control is more effective than passive control in limiting structural displacement under seismic loading.

Top Floor Displacement Speed Simulation

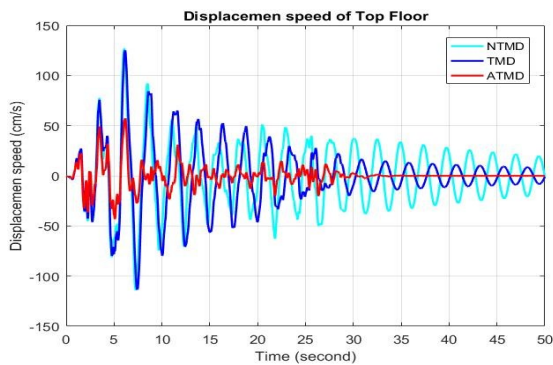


Figure 9. Graph of Top Floor Displacement Speed due to the El Centro Earthquake

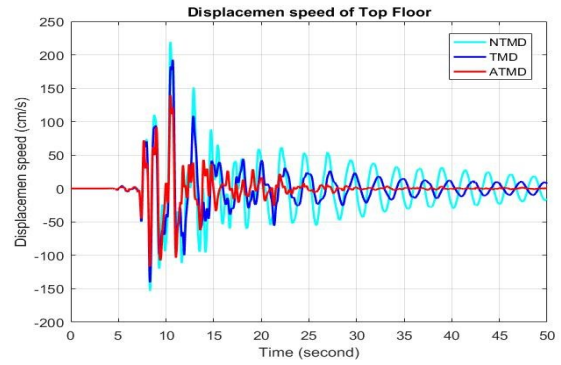


Figure 10. Graph of Top Floor Displacement Speed due to the Kobe Earthquake

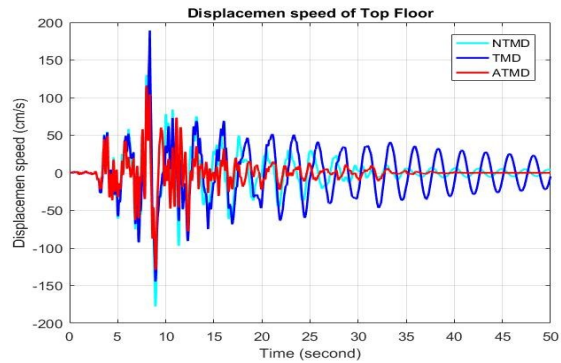


Figure 11. Graph of Top Floor Displacement Speed due to the Northridge Earthquake

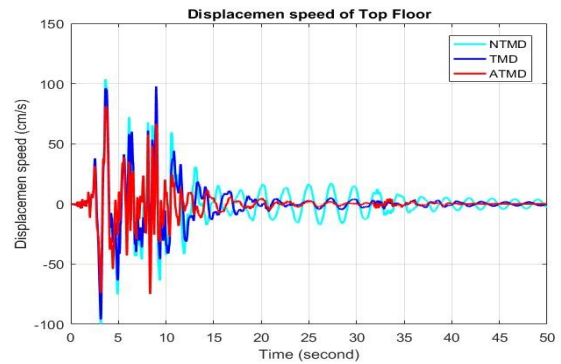


Figure 12. Graph of Top Floor Displacement Speed due to the Pacoima Earthquake

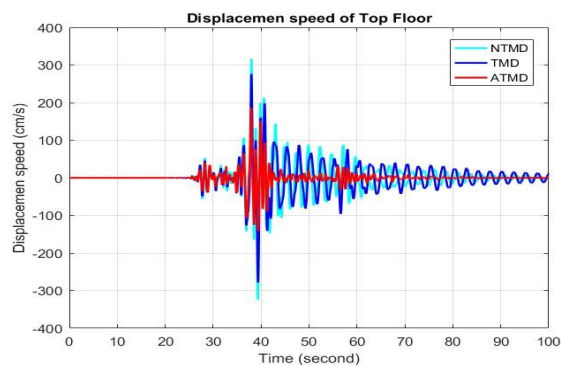


Figure 13. Graph of Top Floor Displacement Speed due to the Chichi Earthquake

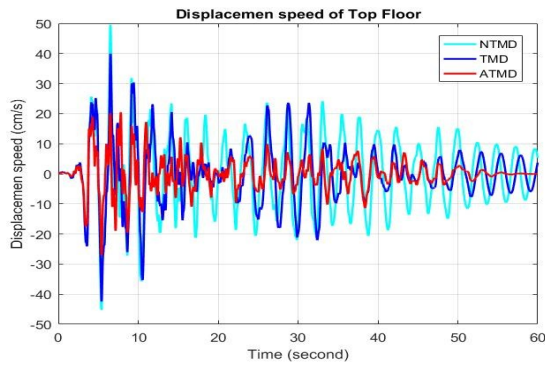


Figure 14. Graph of Top Floor Displacement Speed due to the Kern-County Earthquake

Figure 9 – Figure 14 represents graph of changes in speed that occur in the displacement of the top floor. The reduction in the speed of displacement of the structure on the top floor ranged from 18.24% – 54.18%. The system with a controller (denoting by red graph) has a different graphic image than the system without a controller (denoting by blue graph).

Table 3. Comparison of maximum displacement velocity due to earthquake effects

Earthquake	Maximum Displacement Speed (m/s)		
	Non-TMD	TMD	ATMD
El Centro	1.2723	1.2502	0.5734
Kobe	2.9134	1.9273	1.3986
Northridge	1.8393	1.8932	1.2913
Pacoima	1.0362	0.9602	0.8103
Chichi	3.2396	2.7852	1.8674
KernCounty	0.4954	0.4241	0.2711

Table 3 show that both TMD and ATMD systems are effective in reducing the maximum displacement velocity caused by earthquakes. Compared to the Non-TMD condition, the use of a TMD consistently decreases the response, while the ATMD provides the greatest reduction for all earthquake cases. For strong earthquakes such as Chichi and Kobe, the reduction achieved by ATMD is particularly significant, indicating its superior performance in controlling structural vibrations. Even for moderate events like Pacoima and Kern County, ATMD still yields lower displacement velocities than both Non-TMD and TMD cases.

In summary, the table 3 demonstrates that ATMD is the most effective control strategy in minimizing maximum displacement velocity due to earthquake effects, followed by TMD, while structures without control experience the highest response.

CONCLUSION

From the results of the analysis, it is concluded that from the results of theoretical testing for various basic acceleration loads, such as simulations of the acceleration of the El Centro N-S earthquake, the Kobe earthquake, the Pacoima earthquake, the Northridge earthquake, the Kern-County earthquake, and the Chichi earthquake, it shows that optimal *LQR* control is able to provide sufficient results. good. From the analysis and simulation results, it can be concluded that the most optimal results are on the value of the weight matrix $Q = 1000$ and the weight matrix $R = 0.1$. The reduction in the displacement of the structure on the top floor ranged from 19.80% – 58.90%, while the reduction in the speed of displacement of the structure on the top floor ranged from 18.24% – 54.18%.

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