Challenge Journal of Structural Mechanics

Research Article

Investigation of optimum tuned mass damper parameter according to stroke capacity

Aylin Ece Kayabekir [a]

[a] Department of Civil Engineering, İstanbul Gelişim University, 34310 İstanbul, Türkiye

ABSTRACT

During major earthquakes, civil structures may collapse due to vibration that has a frequency close to the frequency content of the structure. Because of this, control systems have also been proposed for building structures. These systems can be active ones that are controlled by electronic devices or passive ones that are tuned mechanical systems. Passive tuned mass dampers (TMDs) include mass, stiffness element and damping element and these are tuned around the frequency of the structure. For optimum tuning and the complex nature of the mathematics under random vibrations, metaheuristic algorithms are needed to be used. In the presented study, TMDs are optimized via Jaya algorithm. The control system was optimized for displacement minimization of the structure. Additionally, the stroke amount of the system was limited. The stroke capacity factor was investigated for wide limits between 0.5 and 4 for normalized stroke according to the maximum displacement of the structure. The investigation was done for a single degree of freedom structure for a general conclusion. It is observed that the stroke limit did not affect performance and optimum parameters after 2.75. The small values of the stroke limit have significantly different optimum period.

ARTICLE INFO

Article history:
Received 23 June 2023
Revised 11 August 2023
Accepted 14 September 2023

Keywords:
Tuned mass damper
Stroke
Control
Jaya algorithm
Vibration
Earthquake

1. Introduction

Numerous control systems have been developed to mitigate the dynamic effects caused by undesirable external factors. Advances in technology and computing have made the implementation of these systems more accessible, and they are widely employed in various mechanical systems, including structures.

In modern cities, buildings have been constructed taller to accommodate growing populations, and long bridges facilitate transportation. Given various factors, notably earthquakes, control systems have become essential for these structures. Merely ensuring safety and reliability is insufficient; these buildings must withstand minimal vibration during earthquakes and strong winds.

In general, two main types of control systems exist: active and passive. Active control systems use an external power source to exert force on the building, either augmenting or dissipating energy within the structure. Active feedback control systems transmit the system's response, measured by physical sensors, as a signal to the control actuator. These systems regulate responses affected by both internal and external influences, with a focus on safety and comfort.

On the other hand, passive control systems do not rely on an external power source but utilize mechanical forces. The effectiveness of passive control depends on the building's design and incorporation of viscoelastic materials to achieve optimal efficiency. Passive systems are more widely used and can be added to existing structures.

Additionally, semi-active and hybrid systems are also present. Passive-tuned mass dampers, composed of mass, spring-like stiffness elements, and viscous dampers, take the form of pendulums or series of isolation systems. Viscoelastic dampers convert kinetic energy into heat energy, effectively damping wind-induced loads in multi-story buildings since the 1980s.

* *Corresponding author.* Tel.: +90-212-422-7000 ; E-mail address: aekayabekir@gelisim.edu.tr (A. E. Kayabekir)
ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2023.04.001

Tuned mass dampers have been successfully applied in various structures since 1971, such as the Citicorp Center, John Hancock Tower, and Fukuoka Tower. Taipei 101 boasts a remarkable example of a mass damper, the tallest and heaviest worldwide, weighing 730 tons and spanning five floors.

Throughout history, numerous advancements have been made in the field of tuned mass dampers (TMDs) to address the dynamic effects caused by external factors. The foundations of TMDs were laid by Herman Frahm in 1909 when he invented a device to prevent vibrations in ship machinery. His subsequent study on vibration control served as the basis for TMDs. By 1911, Frahm (1909) obtained a patent for his invention, which he called a tuned vibration damper. In 1928, Ormondroyd and Den Hartog initiated theoretical studies on modulated mass dampers. Den Hartog's work in 1949 led to a system where the mass lacked natural damping. However, later studies revealed that TMDs with damping are more effective due to enhanced energy conversion. Over the years, researchers like Bishop and Welbourn (1952) and Hartog (1956) further contributed to TMD research, exploring the damping parameters and optimizing their efficiency under different excitation conditions. From 1971 onwards, TMDs started being applied in various structures, with researchers continuously seeking to enhance their performance. Studies by Falcon et al. (1967), Ioi and Ikeda (1978), and Warburton and Ayorinde (1980) proposed methods to optimize TMD parameters. Subsequent research by various authors, including Xu and Igusa (1992), Tsai and Lin (1993), and Villaverde and Koyoama (1993), delved into optimizing TMD design for different types of structures and excitations. In the 21st century, researchers explored novel concepts, such as tuned mass damper-inerter (TMDI) devices (Marian and Giaralis 2014) and variable-tuned mass damping inerter (VTMDI) models (Li et al., 2020), to improve TMD performance and adaptability. In recent years, efforts have been made to optimize TMDs' performance in different scenarios, considering nonlinear behavior (Domenico and Ricciardi 2018) and integrating electromechanical components for energy conversion (Petrini et al. 2020). Advanced metaheuristic techniques like particle swarm optimization (PSO) (Leung and Zhang, 2009), harmony search, bat algorithm (Bekdaş and Nigdeli 2017) and genetic algorithms (Frans and Arfiadi 2015) have been applied to optimize TMD design.

Zucca et al. (2021) proposed a methodology for the TMD-controlled design of a historic masonry chimney, including a two-step optimization procedure. Caicedo et al (2021) developed a differential evolution method based optimization process for tuned mass dampers (TMDs) and tuned mass dampers inerter (TMDIs) placed on the upper floors of high-rise buildings exposed to seismic effects. Ant colony optimization was employed by Soheili et al. (2021) in order to minimize of the story drifts of a 40-story building considering soil structure interaction. Yücel et al (2022) introduced flower pollination algorithm for the reduction of critical displacements in the time-history domain Different TMD configurations including single and multiple TMD attached to nonlinear structures was optimized by Domizio et al. (2022) via PSO to increase effectiveness of seismic response control. Araz et al. (2023) investigated the optimum TMD design for a high-rise building to reduce the structural response under various embedment depths and soil properties. Mohsen Khatibinia et al. (2023) proposed an approach based on passive ensemble particle swarm and gray wolf optimization techniques in order to design optimum TMDs by considering seismic damage representing structural responses.

The optimum design parameters for tuned mass dampers must be also suitable for practical applications. For that reason, the stroke capacity of TMD must be considered in the optimum design which includes optimization of period and damping ratio of TMD for minimization of structural displacement. The stroke capacity was included as a design constraint by Bekdaş and Nigdeli 2017) using harmony search and bat algorithm. In the present study, stroke factor was investigated for a wide range that have maximum limit ($st_{\max}$) between 0.5 and 4.0 for normalized stroke. The normalized stroke is the ratio of drift of TMD and maximum displacement of the structure without TMD. Jaya algorithm that is developed by Rao (2016) was used in the methodology since it is a parameter free algorithm.

2. Methodology

In this study, software has been developed that analyzes the tuned mass dampers placed on a single degree of freedom system. The equation of motion of damped free vibration of structural systems under dynamic effects is given below.

$$\boldsymbol{M}\ddot{x}(t) + \boldsymbol{C}\dot{x}(t) + \boldsymbol{K}x(t) = -\boldsymbol{M}\{\boldsymbol{1}\}\ddot{x}_g(t) \tag{1}$$

The Matlab Simulink block diagram that provides the solution of this Eq. (1) for the developed software is given in Fig. 1.

In Eq. (1), x is the displacement vector. The equivalent of x in the block diagram is expressed as Y. Each point on the x vector has its derivative, the first derivative corresponds to velocity and the second derivative to acceleration. The equivalent of these values in the block diagram are defined as $Y1$ and $Y2$, respectively. In the diagram, E is the earthquake record, Etime corresponds to the earthquake time vector with 0.005 steps, and Y3 is earthquake acceleration ($\ddot{x}_g(t)$). In the equation of motion, M, C, K are mass, damping and stiffness matrices, respectively, given in Eqs. (2-4). In the block diagram, these matrices are seen as Mmatrix, Cmatrix and Kmatrix.

$$\boldsymbol{M} = \begin{bmatrix} m & \\ & m_d \end{bmatrix} \tag{2}$$

$$\boldsymbol{K} = \begin{bmatrix} k + k_d & -k_d \\ k_d & k_d \end{bmatrix} \tag{3}$$

$$\boldsymbol{C} = \begin{bmatrix} c + c_d & -c_d \\ c_d & c_d \end{bmatrix} \tag{4}$$

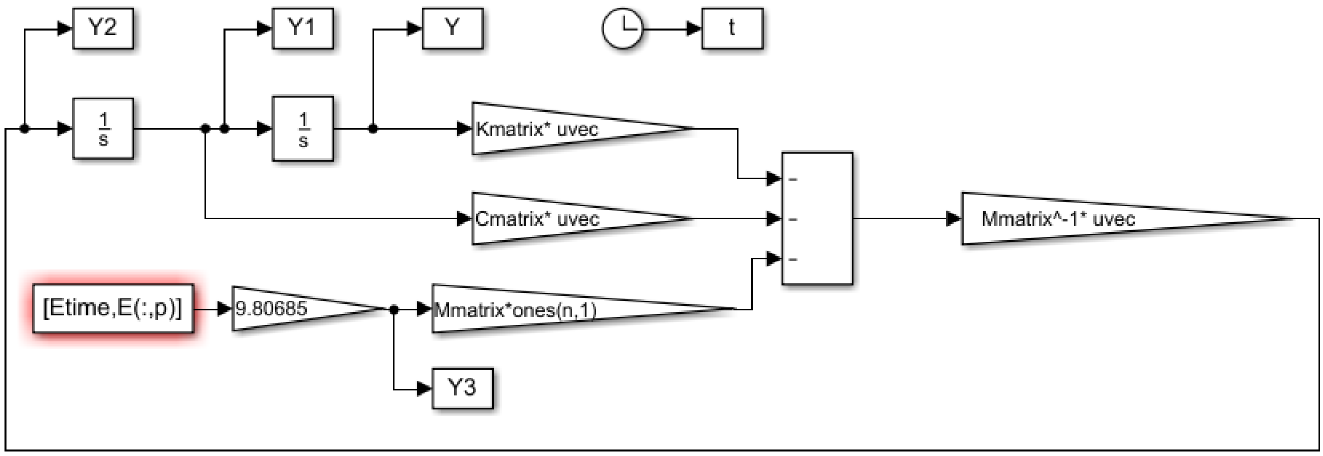

Fig. 1. The Matlab Simulink block diagram for dynamic analysis.

In the equations, m, c, k are the mass, damping and rigidity of the structure, respectively. Values with d subscript are the parameters used for TMD.

Dynamic analyzes were made under a total of 44 different earthquake records, 22 earthquakes and bidirectional ones given in FEMA P-695 as far-fault ground motions. The aim is to apply all earthquake records of the building in the design and to consider even the most unfavorable situation in terms of structural reactions under these records. What is meant by the most favorable situation is the analysis of the earthquake that causes the greatest displacement in the structure. This earthquake is defined as a critical earthquake in the study.

In order to apply the effects of these 44 earthquakes and compare their structural responses, the time step interval of the earthquake record is arranged equally. The Simulink block diagram that performs this editing process in the code is presented in Fig. 2.

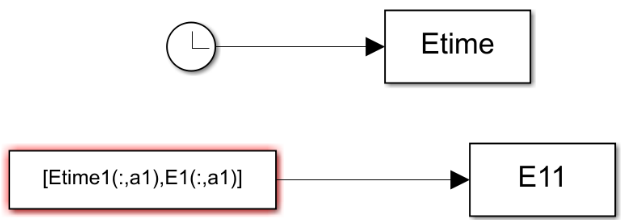

Fig. 2. The Matlab Simulink block diagram for earthquake data.

In the analysis process, the best combination of TMD parameters (m_d, c_d and k_d) for the structure is investigated. The definition of the best combination refers to the parameters that give the lowest displacement (x) under the dynamic effects of the structure. In the search process, Jaya algorithm, one of the metaheuristic algorithms, was used.

The optimization process with metaheuristic algorithms can be summarized in 3 stages, namely pre-optimization, analysis and optimization stage. In the pre optimization step, the problem is defined via entering data of earthquake records, design constants, limit values of design variables and population (solution vector) number. There are 4 design constants for the problem. These are the mass of the structure, the stiffness coefficient and damping ratio, and the TMD stroke limit ($st_{\max}$). TMD optimization was done for constant mass ratio that 5%. The design variable of TMD that are optimized are period (T_d) (as seen in Eq. (5)), and damping ratio (ξ_d) (as seen in Eq. (6)). Then an initial solution matrix including candidate solution vectors as much as population number is generated. A candidate solution vector consists of randomly generated values within ultimate limits of each design variables.

$$T_d = 2\pi\sqrt{\frac{m_d}{k_d}} \tag{5}$$

$$\xi_d = \frac{c_d}{2m_d\sqrt{\frac{k_d}{m_d}}} \tag{6}$$

In the analysis stage, the objective function is calculated and the design constraints are checked. The goal of optimization is to find the TMD design that provide the minimum displacement. Accordingly, the objective function is defined as follows.

$$f(x) = \text{minimize}(|x|) \tag{7}$$

As the design constraint the normalized stroke must be lower or equal to stroke limit ($st_{\max}$) as given in Eq. (8).

$$\frac{\max[|x_d - x|]_{\text{with}TMD}}{\max[|x|]_{\text{without}TMD}} \leq st_{\max} \tag{8}$$

In the last stage, using the existing solutions (X_{old}) stored in the initial solution matrix new solutions (X_{new}) are generated according to the algorithm equations. Algorithm have one equation as follow.

$$X_{\text{new}} = X_{\text{old}} + \text{rand} \cdot (g^* - |X_{\text{old}}|) - \text{rand} \cdot (g^w - |X_{\text{old}}|) \quad (9)$$

where g^* and g^w are best and worst solutions respectively. "rand" is a function that produce random values between 0 and 1.

The pseudocode of the search process performed as iterative is shown below. The stages of methodology are given in Table 1.

Table 1. Methodology stages

An example of stages in metaheuristic-based optimization
Data entering stage
Initial stage:
Generation of initial solution with random design variables
Structural analyses without TMD
Structural analyses with TMD
Iterative stage begins
New solution generation stage
Structural analysis with TMD
Selection and elimination stage
Save and output results

3. Numerical Examples

The numerical example includes a single degree of freedom structure that has 1 s period and 5% inherent damping. In optimization, the period limits of TMD are taken between 0.5s and 1.5s. The damping ratio of TMD was searched between 0.01 and 0.5. All optimum results and the objective function which is the maximum displacement of TMD are given in Table 2.

Table 2. Results of design variables for different stroke capacity

$st_{\max}$	T_d (s)	ξ_d	X (m)
0.50	0.694	0.500	0.272
0.75	0.894	0.500	0.265
1.00	0.907	0.351	0.258
1.25	0.902	0.246	0.252
1.50	0.932	0.196	0.247
1.75	0.912	0.131	0.242
2.00	0.910	0.088	0.237
2.25	0.943	0.080	0.233
2.50	0.955	0.065	0.231
2.75	0.948	0.047	0.231
3.00	0.944	0.033	0.230
3.25	0.941	0.023	0.229
3.50	0.939	0.014	0.228
3.75	0.938	0.010	0.228
4.00	0.938	0.010	0.228

As seen in Fig. 3, the optimum period remains the same after 2.75 stroke limit. By the decrease of TMD mobility, the optimum period decreases. All optimum periods are below the natural period of the structure.

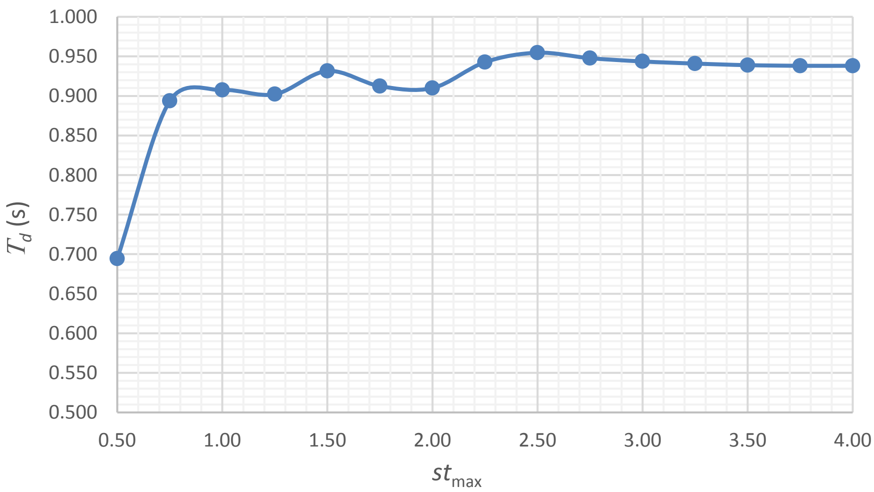

Fig. 3. Relationship of period according to $st_{\max}$.

According to Fig. 4, the optimum damping ratio is at the maximum limit for $st_{\max}$ 0.75 and 0.5 values. If the stroke limit is very big, damping is not important in optimum design.

As seen in Fig. 5, the maximum displacement is highly reduced up to 2.5 stroke limit, but there are no critical change if the stroke limit is higher than 2.5.

Time history graphs were also drawn for the 4 cases ($st_{\max}$ 0.5, 1, 2 and 3 cases) selected as examples to demonstrate the performance of TMD on structural displacement. Component1 of Imperial Valley (IMPVALL/H-E11140) earthquake record is a critical earthquake for all cases. Time history graphs for this earthquake are presented in Figs. 6- 9 for different $st_{\max}$ cases in comparison with TMD.

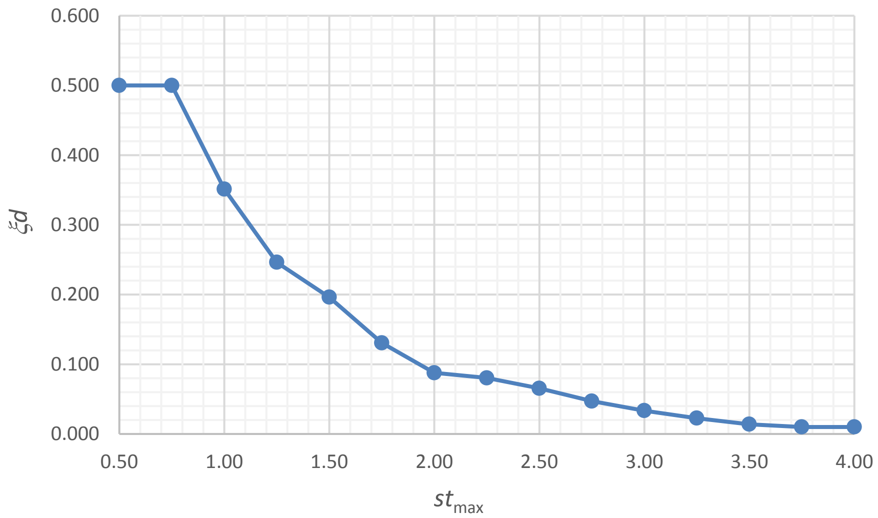

Fig. 4. Relationship of damping ratio according to st_{max}.

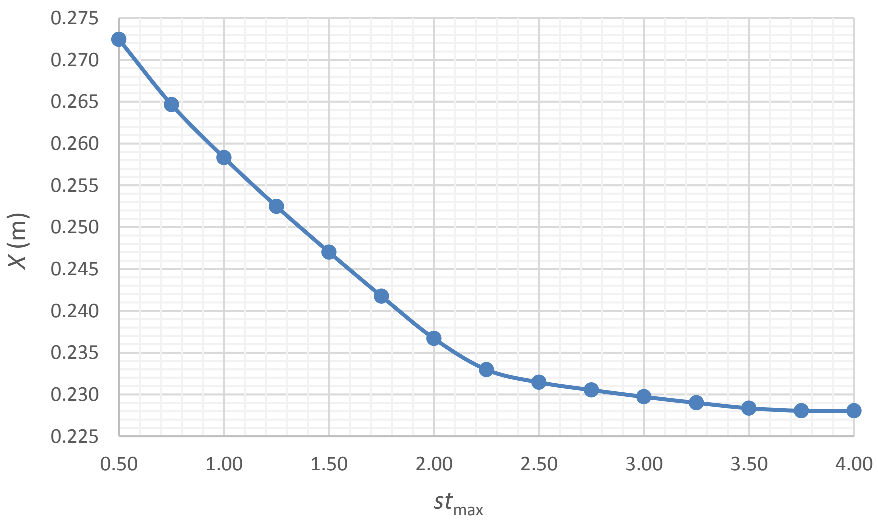

Fig. 5. Relationship of displacement according to st_{max}.

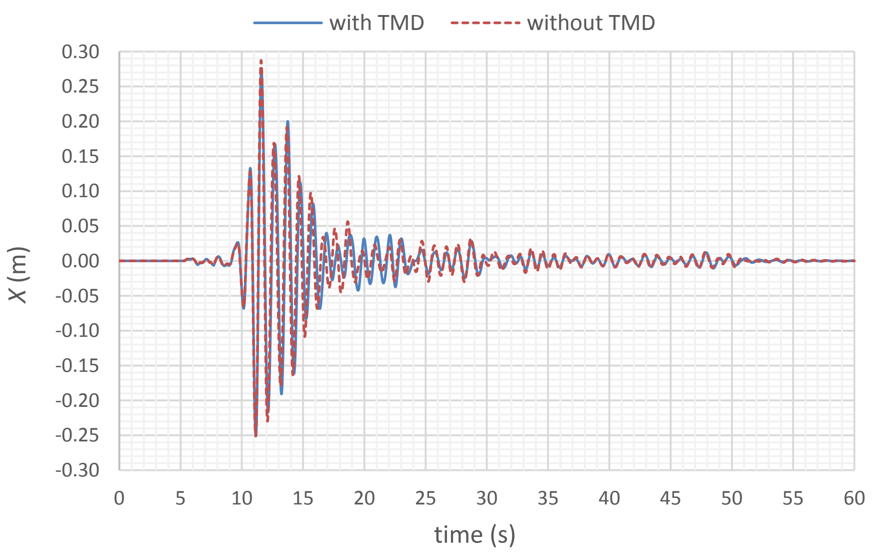

Fig. 6. Time History plots with TMD (st_{max}=0.5) and without TMD cases.

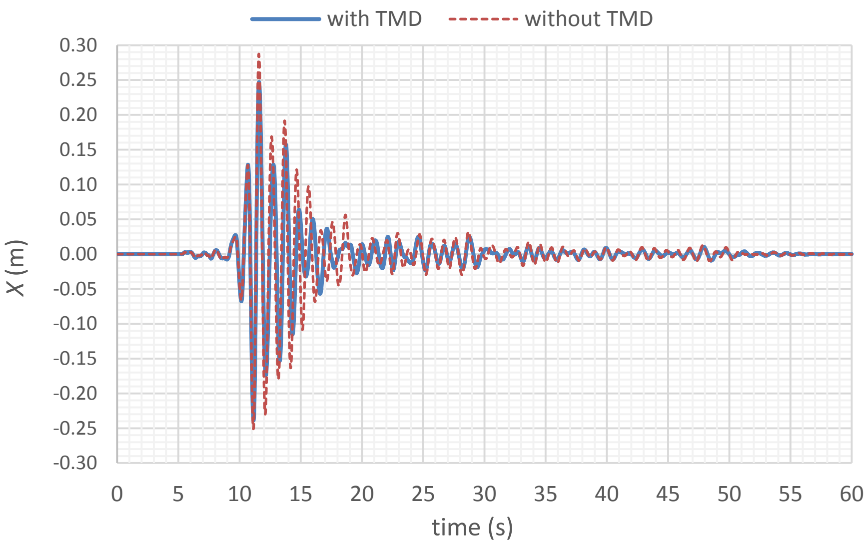

Fig. 7. Time History plots with TMD (st_{max}=1.5) and without TMD cases.

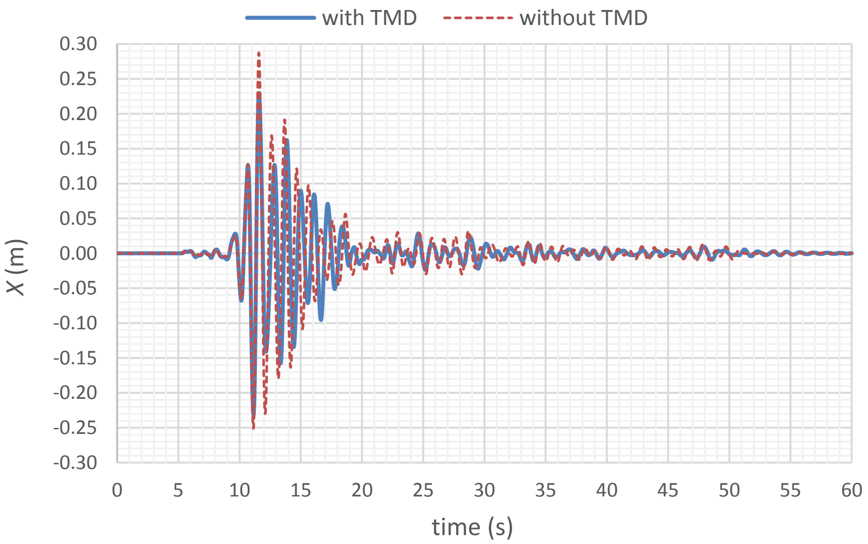

Fig. 8. Time History plots with TMD (st_{max}=2.5) and without TMD cases.

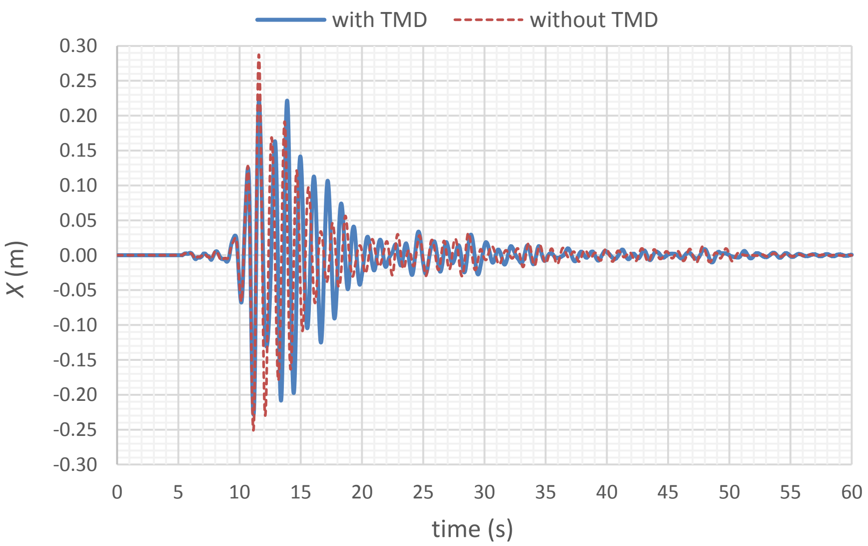

Fig. 9. Time History plots with TMD (st_{max}=3.5) and without TMD cases.

4. Conclusions

According to the results, the stroke limitation is highly effective in the change of optimum TMD parameters. In order to find an economical solution, the stroke of TMD must be limited. Also, a small stroke is useful in positioning TMD. As with classical knowledge, the optimum TMD period is close to the main structure period. The optimization process generally validates this and increases the optimum TMD damping to reduce the stroke in highly limited cases. In the case of maximum damping ratio limit is not effective to reduce the stroke, the ratio of periods of TMD and structure decreases. In that case, the practical application may always be suitable to design with classical methods.

The $st_{\max}$ value (Eq. (8)) is a value that indirectly indicates the TMD's ability to move (maximum movement limit). This mobility is therefore also related to optimum TMD parameters and performance. However, the extent to which this situation will be effective depends on the external influence and the characteristics of the structural system.

As the performance of TMD in the study, a stroke limit bigger than 2.5 is not more effective than the case of $st_{\max}$=2.5. In that case, these huge stroke values are not useful, and they are very expensive to apply. The maximum displacement for critical excitation is 0.2873m and it reduces between 5.18% and 20.62% for stroke-limit cases. Also, the design that maximum reduces the displacement have a stroke value smaller than 2.75. In the cases with stroke capacity bigger than 2.75, the optimum design of TMD is the same.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

References

Araz O, Cakir T, Ozturk KF, Kaya D (2023). Effect of foundation embedment ratio in suppressing seismic-induced vibrations using optimum tuned mass damper. *Soil Dynamics and Earthquake Engineering*, 171, 107981.

Bekdaş G, Nigdeli SM (2017). Metaheuristic based optimization of tuned mass dampers under earthquake excitation by considering soil-structure interaction. *Soil Dynamics and Earthquake Engineering*, 92, 443–461.

Bishop RED, Welbourn DB (1952). The problem of dynamic vibration absorbers. Engineering, London 174–769.

Caicedo D, Lara-Valencia L, Blandon J, Graciano C (2021). Seismic response of high-rise buildings through metaheuristic-based optimization using tuned mass dampers and tuned mass dampers inerter. *Journal of Building Engineering*, 34, 101927.

De Domenico D, Ricciardi G (2018). Optimal design and seismic performance of tuned mass damper inerter (TMDI) for structures with nonlinear base isolation systems. *Earthquake Engineering & Structural Dynamics*, 47(12), 2539–2560.

Den Hartog JP (1949). Mechanical Vibrations. İ.T.Ü. Printing House, İstanbul.

Den Hartog JP (1956). Mechanical Vibrations. 4thed. Mc Graw-Hill, New York.

Domizio M, Garrido H, Ambrosini D (2022). Single and multiple TMD optimization to control seismic response of nonlinear structures. *Engineering Structures*, 252, 113667.

Falcon KC, Stone BJ, Simcock WD, Andrew C (1967). Optimization of vibration absorbers: a graphical method for use on idealized systems with restricted damping. *Journal of Mechanical Engineering Science*, 9(5), 374–381.

FEMA P-695 (2009). Quantification of Building Seismic Performance Factors. Federal Emergency Management Agency, Washington DC.

Frahm H (1909). Device for Damping Vibration of Bodies. US Patent 989958.

Frans R, Arfiadi Y (2015). Designing optimum locations and properties of MTMD systems. *Procedia Engineering*, 125, 892–898.

Ioi T, Ikeda K (1978). On the dynamic vibration damped absorber of the vibration system. *Bulletin of the Japanese Society of Mechanical Engineers*, 21(151), 64–71.

Khatibinia M, Akbari S, Yazdani H, Gharehbaghi S (2023). Damage-based optimal control of steel moment-resisting frames equipped with tuned mass dampers. *Journal of Vibration and Control*, 10775463221149462.

Li Y, Li S, Chen Z (2020). Optimization and performance evaluation of variable inertial tuned mass damper. *Chinese Journal of Vibration Engineering*, 33(5), 877–884.

Leung AYT, Zhang H (2009). Particle swarm optimization of tuned mass dampers. *Engineering Structures*, 31(3), 715–728.

Marian L, Giaralis A (2014). Optimal design of a novel tuned mass-damper–inerter (TMDI) passive vibration control configuration for stochastically support-excited structural systems. *Probabilistic Engineering Mechanics*, 38, 156–164.

Matlab with Simulink (2018). The MathWorks. Natick, MA.

Ormondroyd J, Den Hartog JP (1928). The Theory of Dynamic Vibration Absorber. *Transactions of ASME*, 50(7), 9–22.

Petrini F, Giaralis A, Wang Z (2020). Optimal tuned mass-damper-inerter (TMDI) design in wind-excited tall buildings for occupants' comfort serviceability performance and energy harvesting. *Engineering Structures*, 204, 109904.

Rao, R. (2016). Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems. *International Journal of Industrial Engineering Computations*, 7(1), 19–34.

Soheili S, Zoka H, Abachizadeh M (2021). Tuned mass dampers for the drift reduction of structures with soil effects using ant colony optimization. *Advances in Structural Engineering*, 24(4), 771–783.

Tsai HC, Lin GC (1993. Optimum tuned - mass dampers for minimizing steady - state response of support - excited and damped systems. *Earthquake Engineering and Structural Dynamics*, 22(11), 957–973.

Villaverde R, Koyama LA (1993). Damped resonant appendages to increase inherent damping in Buildings. *Earthquake Engineering and Structural Dynamics*, 22(6), 491–507.

Warburton GB, Ayorinde EO (1980). Optimum absorber parameters for simple systems. *Earthquake Engineering and Structural Dynamics*, 8(3), 197–217.

Xu K, Igusa T (1992). Dynamic Characteristics of multiple substructure with closely spaced frequencies. *Earthquake Engineering and Structural Dynamics*, 21(12), 1059–1070.

Yücel M, Bekdaş G, Nigdeli SM (2022). Metaheuristics-based optimization of TMD parameters in time history domain. In *Optimization of Tuned Mass Dampers: Using Active and Passive Control* (pp. 55–66). Cham: Springer International Publishing.

Zucca M, Longarini N, Simoncelli M, Aly AM (2021). Tuned mass damper design for slender masonry structures: a framework for linear and nonlinear analysis. *Applied Sciences*, 11, 3425.