

EFFECTIVENESS OF PENDULUM TUNED MASS DAMPER SYSTEM FOR STEEL FRAME STRUCTURE SUBJECTED TO SEISMIC ACTION

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Abstract

The paper presents the analysis of using tuned mass damper system modelled as pendulum tuned mass damper (TMD) for reducing the response of structure subjected to lateral force, such as earthquake action. The assumed steel eight-storey steel frame building is examined. The tuned mass damper system is modeled as 2 joint link in SAP2000, attached to top storey of the building. The effect of TMD system on structural responses for building under seismic excitation was evaluated by the results of maximum displacement and acceleration of the building. A sensitivity study of mass ratio showed that most effective case is TMD with mass ratio of 5%.

Keywords: *Pendulum tuned mass damper; steel frame; seismic action.*

1. Introduction

As we all know, to ensure the need for high density in large urban area all over the world, tall buildings have been introduced. In the past few decades, taller and slenderer structures have been built thanks to the improvement of construction technology, new light construction materials [2]. The tall, supertall and mega tall buildings appear everywhere all over the world [4]. They are designed with additional flexibility, which lead to an increase of vibrations in their response to external load, which can cause damage, discomfort for the occupants and in some cases event structural failure. The problem of response mitigation of building has become important and practical in structural engineering.

High-rise buildings have to undergo various external forces that are different from low-rise. Therefore, different structural solutions must be used. The design philosophy of those is modification of stiffness, increase of damping, e.g. energy dissipation, while minimizing structure weight. To achieve an adequate displacement of building, selection of structural system (tubes, diagrids, transfer beam, outrigger system...) that affects the stiffness is one of the choices. However, there might be problem with acceleration response. The alternate approach is increase of building energy dissipation potential by

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installing damping devices. This method has been judged more effective than the old one, thanks to broad researches in recent years and the performance of devices.

According to Kareem et al. [10] damping systems are classified into three categories: passive; active semiactive and hybrid, and seismic isolation. Passive and seismic isolation systems work based on their fixed properties and do not need any external power source. Passive system relies on the movement of the main structure. On the contrary, active systems depend on the load and need external energy source. The passive systems are more common than active systems, thanks to their economy and reliability. They can be subdivided into material-based systems and mass-based systems [3], as in Figure 1. The first category of passive damper is a part of main structural systems and will be located within bracing systems. The latter is usually positioned at the top of the structure, where is occupied. The mass-based damping systems generate large movements of dampers to convert motion into other energy form. Among them, tuned mass dampers are widely used in many structures, such as Taipei 101, John Hancock Tower..., because of its reliability, simplicity and effectiveness.

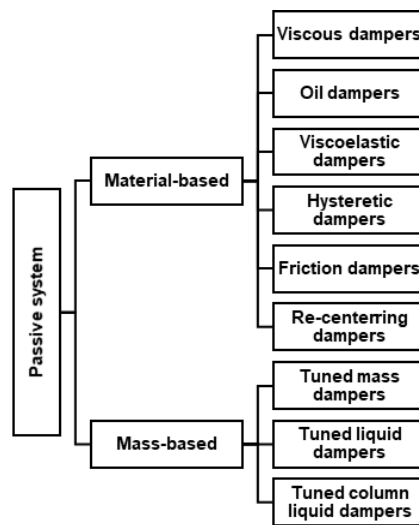


Figure 1. Possible passive damping systems for tall buildings

TMD in the simple form consists of a mass, spring and damper [5] properly tuned, is attached to a structure to reduce dynamic response. In Figure 2, the TMD system is connected to main structure in the form of single degree of freedom system (SDOF) [5]. The TMD was first proposed by Frahm [8], and then has been properly studied by Den Hartog [6], who found optimum frequency and damping of system under harmonic load. The frequency of the damper is tuned to a structural frequency so that the damper will resonate out of phase with the motion of structure. The vibration of building then will be transferred to the TMD and dissipated by damper.

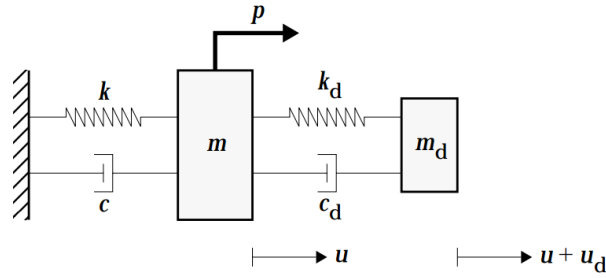


Figure 2. Single degree of freedom - TMD system [5]

There are several design procedures in literature for TMD systems, but no specified design recommendations in any standard codes. These proposed methods used simplified consideration to find the optimal properties of damper: mass, stiffness and damping. The main structures are subjected to harmonic forces, harmonic ground motion and white-noise ground acceleration of wind/seismic load. The important researches in TMD topic can be listed as Soong and Dargush (1997), Mc Namara et al. (1999), Connor (2003), Christopoulos and Filiatrault (2006), Min et al. (2014), Tuan and Shang (2014) and Chang (2015).

This paper presents the analysis of dynamic structural response changing when using TMD. The objects are:

- Define the effectiveness of TMD to the fundamental period of the building;
- Define the peak acceleration and displacement of the top node of the building under seismic action;
- Define effectiveness of mass of TMD on the structural response.

2. Basic principle of TMD

The system with TMD [5] can be considered as two degree of freedom system with two mass and stiffness, damping properties of base structure and absorber, respectively.

In Figure 2: m is the main structure mass, m_d is the damper mass, k is the main structure spring stiffness, k_d is the spring stiffness of absorber, c is the structure damping, c_d is the absorber damping, $P(t)$ is the force acting on the main mass.

The equation of motion of the main mass is given here [5]:

$$(m + m_d)\ddot{u} + c\dot{u} + ku = P(t) - m_d\ddot{u}_d \quad (1)$$

For the absorber:

$$m_d(\ddot{u} + \ddot{u}_d) + c_d\dot{u}_d + k_d u_d = 0 \quad (2)$$

Introducing the following notation:

$$\omega^2 = \frac{k}{m}; c = 2\xi\omega m \quad (3)$$

$$\omega_d^2 = \frac{k_d}{m_d}; c_d = 2\xi_d\omega_d m_d \quad (4)$$

and defining $\bar{m}$ as the mass ratio of damper, equations (1) and (2) can be written as:

$$(1 + \bar{m})\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = \frac{P}{m} - \bar{m}\ddot{u}_d \quad (5)$$

$$\ddot{u}_d + 2\xi_d\omega_d\dot{u}_d + \omega_d^2 u_d = -\ddot{u} \quad (6)$$

As mentioned above, the TMD will be tuned so that its frequency is equal to main structure's frequency. Here we have:

$$\omega_d = \omega \quad (7)$$

and the stiffness of TMD with equation (3), (4) taken into account, will be:

$$k_d = \bar{m}k \quad (8)$$

If the external load is periodic excitation $P = \tilde{P}\sin\Omega t$, the solution for equations (1) and (2) has following form:

$$u = \tilde{u}\sin(\Omega t + \delta_1) \quad (9)$$

$$u_d = \tilde{u}_d\sin(\Omega t + \delta_1 + \delta_2) \quad (10)$$

where $\tilde{P}, \tilde{u}, \tilde{u}_d, \delta$ denote the amplitude of external load, displacement of main structure, phase shift, respectively.

In the resonant scenario, when $\Omega = \omega$, the amplitude has the following solution:

$$\tilde{u} = \frac{\tilde{P}}{k\bar{m}} \sqrt{\frac{1}{1 + \left(\frac{2\xi}{\bar{m}} + \frac{1}{2\xi_d}\right)^2}} \quad (11)$$

$$\tilde{u}_d = \frac{1}{2\xi_d} \tilde{u} \quad (12)$$

3. TMD modelling as pendulum tuned mass damper

In order to simulate the TMD in tall building, a linear link was introduced in SAP2000 [9]. The TMD is considered as the pendulum absorber. The link has the stiffness, damping, and mass assigned to it and is connected to a rigid joint [3].

The parameter of TMD: natural frequency and the equivalent stiffness and effective damping are determined as following [9].

The natural period of the pendulum mass is calculated using formula below:

$$T_d = 2\pi\sqrt{\frac{m}{k}} = 2\pi\sqrt{\frac{m}{mg/L}} = 2\pi\sqrt{\frac{L}{g}} \quad (13)$$

where T_d is natural period of pendulum (TMD) in seconds; L is length of pendulum in meters; g is acceleration of gravity in m/s^2 .

The equivalent stiffness of damper is calculated using formula below:

$$k_{eq} = \frac{W_d}{L} \quad (14)$$

where k_{eq} is equivalent stiffness of damper in N/m ; W_d is weight of damper in Newtons; L is length of pendulum in metres.

The effective damping is calculated using formula below:

$$C_{eff} = 2\xi\sqrt{k_{eq}m_d} = 2\xi\sqrt{m_d^2g/L} = 2\xi m_d\sqrt{\frac{g}{L}} \quad (15)$$

where C_{eff} is effective damping; ξ is coefficient of modal damping; m_d is mass of damper.

4. Numerical examples and discussion

The dynamic behavior of eight-storey steel frame building without TMD (Figure 3) is examined under seismic action by time history analysis. The model with TMD (Figure 4) is investigated to compare structural responses with those calculated from model without TMD.

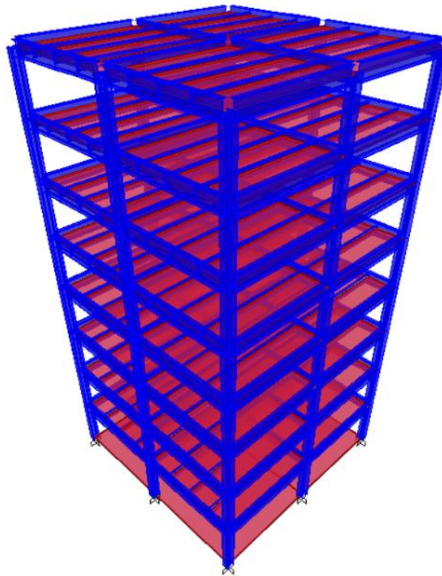


Figure 3. Eight-storey steel frame building without TMD

The data of structure is: frame column with section W14x193, beam section W27x102; module $E = 2.0 \times 10^8$ MPa; the modal damping $\xi = 0.05$. The frame is subjected to seismic action at the Imperial Valley in southeastern Southern California on May 18, 1940. The data of this earthquake is taken from time history functions of SAP2000. The fundamental period of building is 0.688 seconds.

4.1. Effect of TMD on fundamental period of the building

TMD is attached in to the top story of the building with a mass of $30 \text{ kN.s}^2/\text{m}$, 5% of the structure mass. It has a length of 0.12 meters, which is calculated by formula (13), considering the period of TMD equals the fundamental period of building. The effective stiffness k_{eq} is approximately 2500 kN/m according to formula (14).

The analysis results show that, with the TMD, the fundamental period of the building was increased from 0.688 seconds to 0.818 seconds, which is about 18.86 percentage. The periods of modes in both cases are presented in Table 1.

Table 1. Periods of building modes in both cases

Mode	Period		Difference ratio
	Without TMD	With TMD	
1	0.688181	0.818	18.86
2	0.580031	0.759	30.86
3	0.512514	0.585	14.14
4	0.22899	0.530	131.45
5	0.190051	0.513	169.93
6	0.170529	0.227	33.12
7	0.134511	0.189	40.51
8	0.108635	0.171	57.41
9	0.099756	0.134	34.33
10	0.094394	0.109	15.47
11	0.074183	0.100	34.80
12	0.073283	0.094	28.27

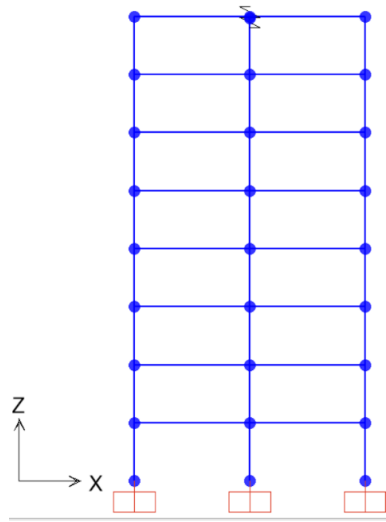


Figure 4. Building model with TMD

4.2. Structural response under earthquake

Using the TMD brings the structure better behavior under seismic action. The acceleration and displacement at the top-storey node 200 of models without and with TMD is shown in Figure 5 and Figure 6, respectively. Comparing with responses of model without TMD, the maximum acceleration was decreased by 18% from 0.639 m/s^2 to 0.524 m/s^2 . The peak displacement was decreased by 5.97% from $7.976\text{e-}03 \text{ m}$ to $7.590\text{e-}03 \text{ m}$.

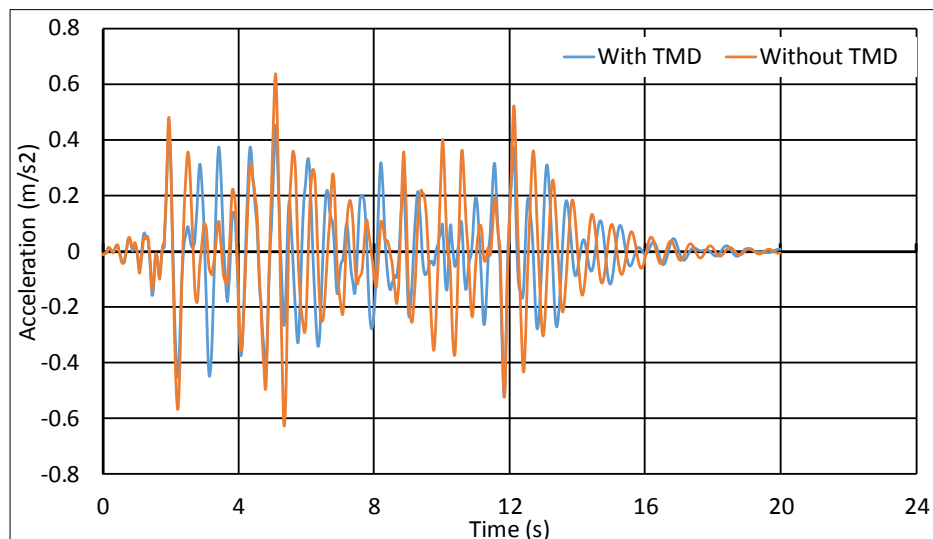


Figure 5. Acceleration of node 200 of models without and with TMD

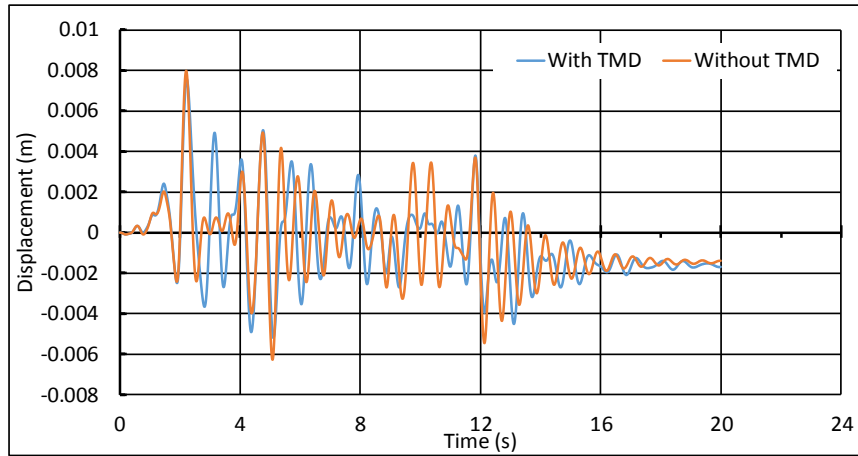


Figure 6. Displacement of node 200 of models without and with TMD

4.3. Effect of mass ratio on structural response

To understand the effectiveness of TMD mass on the structural behavior, a sensitivity analysis was conducted to compare the structural response in cases with different mass ratio: 5%, 10% and 15%. The results, acceleration and displacement of top-storey node 200 are shown in Figure 7 and Figure 8. It can be seen that the structural response is reduced quickly with the increase of mass ratio. However, increasing mass ratio produced negative effect on structure. Peak displacements of node 200 are 7.46×10^{-3} m (with mass ratio 10%) and 8.925×10^{-3} m (with mass ratio 15%), those are more than data calculated in case with mass ratio 5%. Similarly, the maximum accelerations of node 200 are 0.614 m/s^2 (with mass ratio 10%) and 0.661 m/s^2 (with mass ratio 15%), which are also more than results given in case with mass ratio 5%.

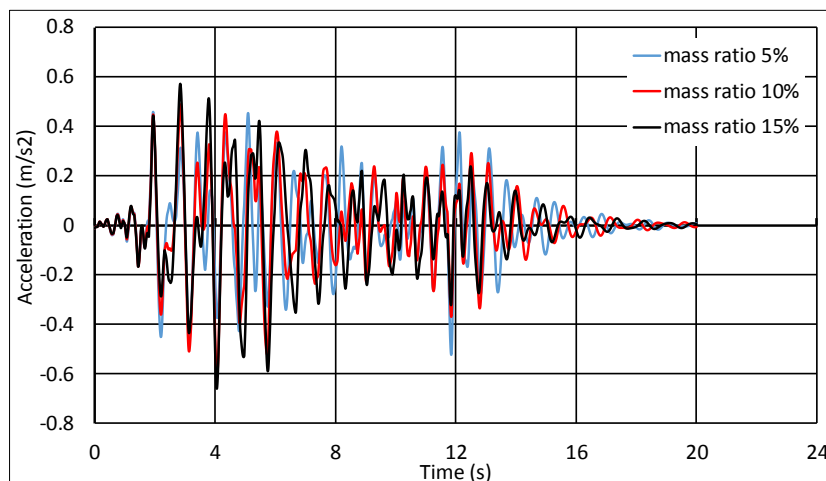


Figure 7. Acceleration of node 200 of models with different TMD mass ratios

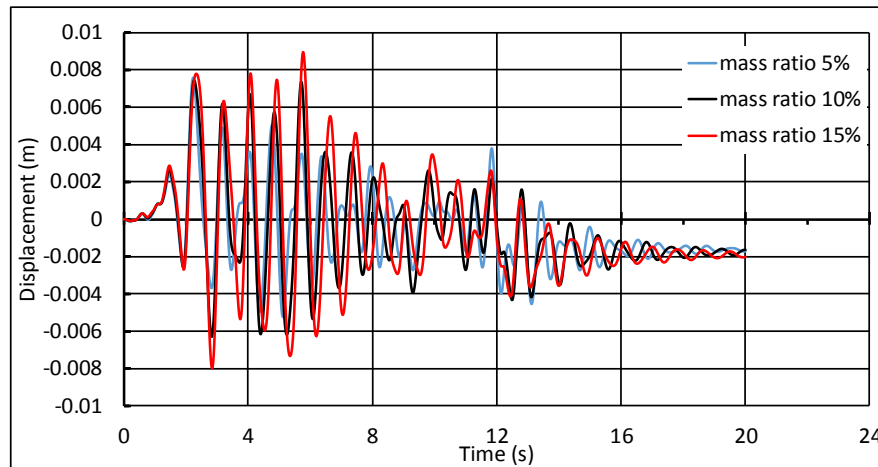


Figure 8. Displacement of node 200 of models with different TMD mass ratios

5. Conclusions

When performing time history analysis of frame building under seismic action, the effect of TMD has been proven. The peak of acceleration and displacement of top-storey node are reduced relatively. The investigation of effectiveness of TMD mass on structural response shows that, in some cases the increasing mass ratio may has negative effect on structure. Therefore, in each specific case, it is necessary to be cautious in choosing TMD mass to achieve beneficial effect of it.

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HIỆU QUẢ CỦA TMD DẠNG QUẢ LẮC ĐỐI VỚI HỆ KẾT CẤU KHUNG THÉP CHỊU TÁC ĐỘNG ĐỘNG ĐẤT

Tóm tắt: Bài báo trình bày phân tích hiệu quả sử dụng hệ thống giảm chấn (TMD), mô hình dưới dạng TMD quả lắc nhằm mục đích giảm phản ứng của hệ kết cấu chịu tải trọng ngang như tác động động đất. Hệ khung thép tám tầng được nghiên cứu. Hệ thống TMD được mô hình dưới dạng liên kết hai điểm trong chương trình SAP2000, được kết nối với tầng trên cùng của tòa nhà. Hiệu quả của TMD đối với công trình dưới tác dụng của tải trọng động đất được đánh giá thông qua chuyển vị và gia tốc lớn nhất. Nghiên cứu độ nhạy của khối lượng TMD cho thấy trường hợp có hiệu quả tốt nhất là TMD với khối lượng tỉ lệ 5%.

Từ khóa: Giảm chấn quả lắc; khung thép; tác động động đất.

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