International Journal of
Advanced Structures and Geotechnical Engineering
ISSN 2319-5347, Vol. 05, No. 01, January 2016

The effect of damping ratio of the dampers on the effectiveness of MTMD in suppressing the response of multi - storey space frame structure

KIRAN K. SHETTY, GOPINATHA NAYAK, DHANALAKSHMI
Department of Civil Engineering, Manipal Institute of Technology, Manipal, India
Email: kiranshettymit@gmail.com, palligopi@rediff.com, dhanushetty85@gmail.com

Abstract: The Dynamic response of a multi-storey asymmetrical space frame structure having six degrees of freedom (three translations along x, y, z – axes and three rotations about these axes) at each node, with multiple tuned mass dampers (MTMD) on its top is studied. MTMD with uniformly distributed frequencies are considered for this purpose. The effect of damping ratio of the dampers on the effectiveness of MTMD is also studied. It is found that the MTMD are more effective than a single TMD in reducing the translation and rotational response of multi-storey asymmetrical space frame structure. It is also observed that there exists an optimum value of damping ratio of the damper at which the response of the structure becomes minimum for both single TMD and MTMD.

Keywords: *Tuned Mass Damper (TMD), Multiple Tuned Mass Damper (MTMD), Multi-storey Asymmetrical Space Frame Structure, Damping Ratio*

Introduction:

In recent years, mitigating the responses of civil engineering structures to environmental loads such as earthquakes and wind loads has drawn the interest of many researchers. Many control devices, passive, semi-active, as well as active, have been developed. Among the available devices, the tuned mass damper (TMD) is one of the simplest and the most reliable control device. A TMD is a passive vibration control device consisting of a mass, damping, and a spring; it is attached to a main structure for suppressing undesirable vibrations induced by earthquake loads. The natural frequency of the TMD is tuned in resonance with the fundamental mode of the structure, so that the huge amount of the structural vibrating energy is transferred to the TMD and dissipated by the damping as the structure is subjected to earthquake loads. The effectiveness of TMD is reduced significantly by the mis-tuning or the off-optimum damping in TMD. As a result, the use of more than one tuned mass damper with different dynamic characteristics has been proposed in order to improve the effectiveness. Multiple tuned mass dampers with distributed natural frequencies were proposed by Xu and Igusa [1],[2] and also studied by Yamaguchi and Harnpornchai [3], Jangid and Datta [4], Abe and Fujino [5], Abe and Igusa [6], Chunxiang [7] and Sadek et.al [8]. Almost all of these studies considered the controlled structure as a single degree of freedom (SDOF) system with its fundamental modal properties to design the TMD and MTMD.

However, a real building usually possesses a large number of degrees of freedom and is actually asymmetric to some degree even with a nominally symmetric plan. It will undergo lateral as well as torsional vibrations simultaneously under purely translational excitations. Thus, the simplified SDOF system, which ignores the structural lateral-torsional coupling and TMD effect on different modes, could overestimate the control effectiveness of TMD Jangid and Datta [9]. Consequently, the controllers have to be designed through taking into account the effect of transverse-torsional coupled vibration modes in such cases. Examination of the TMD and MTMD for structures, which possess transverse-torsional coupled vibration modes has already been recently performed by Jangid and dutta [9], Chunxiang and Weilan [10], Lin et al [11] , singh et al [12]and Pansare and Jangid [13].

The quality of the structural idealization can be improved by more realistic idealizations of buildings that consider beam flexure, all translations along x, y, z-axes and all rotations about these axes. In the present study a multi-storey asymmetrical space frame structure having six degrees of freedom (three translations along x, y, z – axes and three rotations about these axes) at each node, with MTMD on its top is considered. Each TMD is modelled using a two-noded element having two translational degrees of freedom at each node. The effectiveness of MTMD in suppressing the translation and rotational response of the asymmetric structure is determined by comparing the response of corresponding structure without MTMD. The effect of damping ratio of the dampers on the effectiveness of MTMD is also studied.

Analysis:

The super structure is divided into number of elements consisting of beams and columns. The beams and columns are modelled using two noded frame elements with six degrees of freedom at each node i.e., three translations along x, y and z-axes and three rotations about these axes. For each element, the stiffness matrix, consistent mass matrix, and transformation matrix are obtained. The mass matrix and the stiffness matrix of each element from local direction are transformed to global direction as proposed by Paz [14]. The mass matrix and the stiffness matrix of each element are assembled by direct stiffness method to get the overall mass matrix, M, and overall stiffness matrix, K, for the superstructure. Knowing the overall mass matrix, M, and overall stiffness matrix, K, the frequencies for the structure is obtained using simultaneous iteration method. The damping matrix for structure is obtained using Rayleigh's equation, C = α M + β K, where α and β are the constants. These constants are determined easily if the damping ratio for each mode is known. The overall dynamic equation of equilibrium for the entire structure can be expressed in matrix notations as

$$M\ddot{u} + C\dot{u} + Ku = f(t) \qquad (3.7)$$

Where M, C and K are the overall mass, damping, and stiffness matrices of size $6N_1$ x $6N_1$, where N_1 is the number of nodes $\ddot{u}$, $\dot{u}$, u are the relative acceleration, velocity and displacement vectors with respect to ground and f(t) is the nodal load vector. $u = u_1, v_1, w_1, \theta x_1, \theta y_1, \theta z_1, u_2, v_2, w_2, \theta x_2, \theta y_2, \theta z_2, \ldots u_n, v_n, w_n, \theta x_n, \theta y_n, \theta z_n$.

The nodal load vector due to earthquake is obtained using the equation

$$f(t) = -M\,I\,\ddot{u}g(t)$$

Where M is the overall mass matrix, I is the influence vector of size $6N_1$ x 1, üg(t) is the ground acceleration. The resulted equation of dynamic equilibrium is solved using Newmark's method to obtain the displacements and rotation at the nodes as explained in Chopra [15]. Owing to its unconditional Owing to its unconditional stability, the constant average acceleration scheme (with β= 1/4 and γ = 1/2) is adopted.

Modelling of multiple tuned mass dampers:

Each tuned mass damper (TMD) is modeled using a two-noded element having two translational degrees of freedom (x- and z direction) at each node. The natural frequencies of the MTMD are uniformly distributed around their average natural frequency. The natural frequency ωj (i.e. $\omega j = \sqrt{k_j / m_j}$) of the jth TMD is expressed as

$$\omega_j = \omega_T \left[1 + \left(j - \frac{n+1}{2} \right) \frac{\beta}{n-1} \right]$$

and

$$\omega_T = \sum_{j=1}^{n} \omega_j \, / \, n$$

$$\beta = \frac{\omega_n - \omega_1}{\omega_T}$$

Where n is the total number of MTMD, ω_T is the average frequency of all the MTMD and β is the frequency range parameter of the MTMD. As suggested by Xu and Igusa [1], the manufacturing of MTMD with uniform stiffness is simpler than those with varying stiffness. In this study, the distribution of natural frequencies of the MTMD is achieved by keeping the stiffness constant (i.e., with $k1 = k_2 = k_n = k_T$), but allowing the mass of each TMD to vary.

The mass and the damping constant of the j^{th} TMD are expressed as

$$m_j = \frac{k_T}{\omega_j^2}$$

$$c_j = 2 m_j \xi_T \omega_j$$

Where ξ_T is the damping ratio which is kept constant for all the MTMD.

The ratio of total mass of MTMD to the total mass of the structure is defined as the mass ratio i.e.

$$\mu = \frac{\sum_{j=1}^{n} m_j}{m_s} = \frac{m_T}{m_s}$$

The constant stiffness required for each TMD can be evaluated as

$$k_T = \frac{\mu \, m_s}{\sum_{j=1}^{n} 1/\omega_j^2}$$

The average frequency of MTMD corresponds only to the lateral mode of vibration. In case of an asymmetrical building the translations in x and z directions have different dominant modes. Keeping these in view, two different tuning frequency ratios are considered in the study namely;

$$f_1 = \frac{\omega_T}{\omega_{s1}} \quad \text{And} \quad f_2 = \frac{\omega_T}{\omega_{s2}}$$

Where ω_{s1} and ω_{s2} are the natural frequency of lateral vibration of the structure corresponding to the dominant mode in x and z direction respectively.

The natural frequency, stiffness, damping and mass parameters of the dampers in x-direction are denoted by ω_{jx}, k_{Tx}, c_{jx} and m_{jx}. Similar parameters for the dampers along the z-direction are denoted by ω_{jz}, k_{Tz}, c_{jz} and m_{jz}. It is to be noted that the stiffness and damping parameters of the j^{th} TMD in x and z directions are different whereas mass parameter of the j^{th} TMD in x and z direction are same ($m_{jx} = m_{jz} = m_j$).

The stiffness, damping and mass matrices of each TMD is expressed as

$$k_{TMD} = \begin{pmatrix} k_{Tx} & 0 & -k_{Tx} & 0 \\ 0 & k_{Tz} & 0 & -k_{Tz} \\ -k_{Tx} & 0 & k_{Tx} & 0 \\ 0 & -k_{Tz} & 0 & k_{Tz} \end{pmatrix}$$

$$c_{TMD} = \begin{pmatrix} c_{jx} & 0 & -c_{jx} & 0 \\ 0 & c_{jz} & 0 & -c_{jz} \\ -c_{jx} & 0 & c_{jx} & 0 \\ 0 & -c_{jz} & 0 & c_{jz} \end{pmatrix}$$

$$m_{TMD} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & m_j & 0 \\ 0 & 0 & 0 & m_j \end{pmatrix}$$

The stiffness, damping and mass matrices of each TMD are added to the overall mass matrix, overall stiffness matrix and overall damping matrix of structure at corresponding global degrees of freedom.

Result and discussion:

Figure - 1 shows a four-storey asymmetrical space frame structure with MTMD on its top. The material and geometric properties of the structure considered for the study are given in Table 1. The natural frequency of lateral vibration of the structure corresponding to the dominant mode in x and z direction are ωs_1 = 8.376 rad/sec and ωs_2 = 8.737 rad/sec respectively. The structural damping (ξ_S) is 2% of critical, tuning frequency ratio (ρ) is taken as unity, frequency range parameter β=0.2 and mass ratio (μ) is 1%. The structure is subjected to bi-directional (x and z directions) harmonic ground excitation equal to a_0 sin (ωt) (where a_0 is equal to 20% of acceleration due to gravity and ω is the excitation frequency). In the present study the variation of resultant maximum horizontal top floor displacement and rotation (θ_Y) of the structure against frequency ratio are studied.

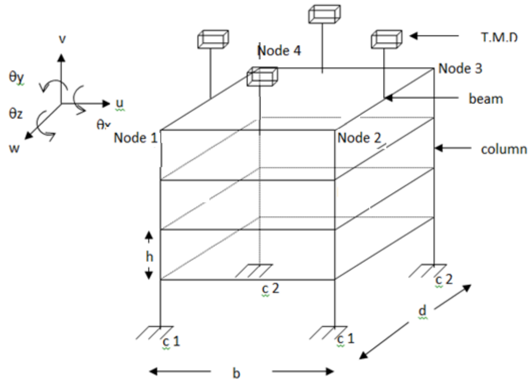

Figure 1 *– Four Storey asymmetric space frame structure with MTMD on its top*

Table 1*: The Properties of asymmetric space frame structure*

T_s(sec)	0.75
Mass on each beam kN-sec^2/m^2	2.9
b (m)	6
d (m)	6
h (m)	3.3
Size of beam(m)	0.3 X 0.3
Size of column(m) C1	0.4 X 0.4
C2	0.6 X 0.6

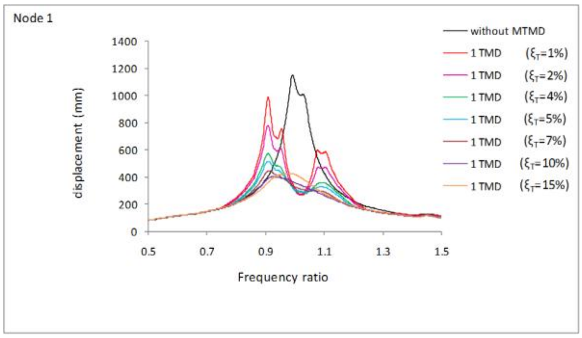

Figure - 2(a) *Variation of resultant maximum horizontal top floor displacement against frequency ratio for Single* TMD

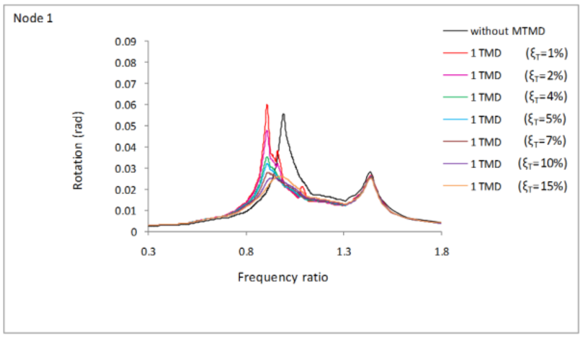

Figure - 2(b) *Variation of rotation against frequency ratio for Single TMD*

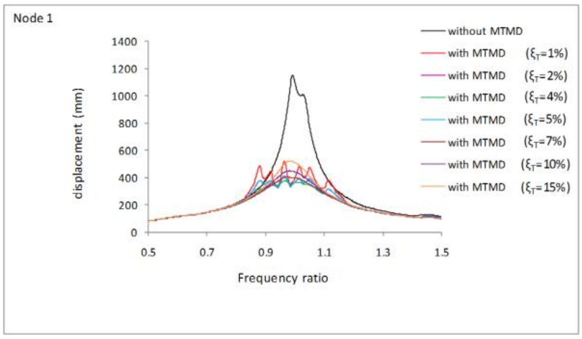

Figure -3(a) *Variation of resultant maximum horizontal top floor displacement against frequency ratio for MTMD*

Figure 2(a) ,2(b) and 3(a) , 3(b) shows the variation of resultant maximum horizontal top floor displacement and rotation (θ_Y) of the structure against the frequency ratio at node 1 for damping ratio ξ_T=0.01, 0.02, 0.04, 0.05, 0.07 & 0.1 for single and 12 TMD respectively.

The Figure 2(a) and 2(b) shows that at higher damping ratio controlled structural response is transformed from two peak characteristics to a one-peak characteristic. Figure 3(a) and 3(b) shows that there exist significant secondary peaks, which are caused by the resonances of the TMD's, in case of small damping ratios, and that one of the secondary peaks gives the maximum response of the structure. On the contrary, the secondary peaks may vanish if the damping ratio is larger enough and the maximum response of the structure occurs at the primary peak at the resonance frequency of the structure. The maximum response of the primary peak, however, becomes larger if the damping ratio is too large. This is because the response of each TMD is not significant in the case of a very large damping ratio and the TMD cannot dissipate the vibration energy of structure.

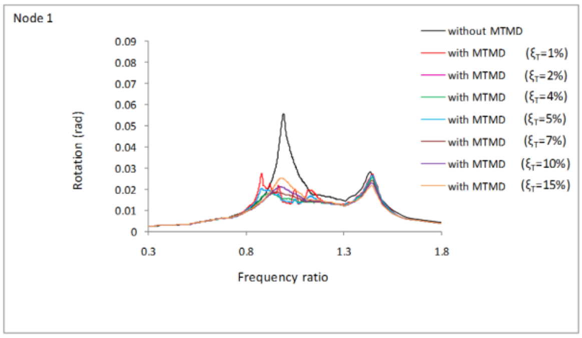

Figure - 3(b) Variation of rotation against frequency ratio for MTMD

As the TMD damping increases, the peak response of the controlled structure first decreases, there by attaining a minimum value, and then increases with the increase of TMD damping, indicating that there exists a value of TMD damping for which the response of the structure attains a minimum value. This is the optimum damping of the TMD. Further, the optimum damping ratio of the MTMD system is found to be sufficiently lower as compared with the single TMD system.

Conclusion:

The effectiveness of TMD and MTMD in controlling the dynamic response of a multi-storey asymmetrical space frame structures having six degrees of freedom at each node are investigated. The responses of the structure with MTMD are compared with those of the same structure without MTMD. The effect of damping ratio of the dampers on the effectiveness of MTMD is also studied. The results of the study lead to the following conclusions:

- TMD and MTMD are effective in reducing translation and rotation response of the structure.
- The MTMD system is found to be more effective than the single TMD system to suppress the translation and rotation responses of the asymmetrical structure.
- The optimum damping ratio exists in a MTMD in the same manner as for a single TMD. Further, the optimum damping ratio of the MTMD system is found to be sufficiently lower as compared with the single TMD system.

References:

[1] Xu., K. Igusa, T., (1992) “Dynamic characteristics of multiple substructures with closely spaced frequencies”, Earthq. Eng. and Struct.Dyna., 21, 1059-1070.

[2] Igusa, T. and Xu, K.,(1994), “Vibration control using Multiple Tuned Mass Dampers”, J. of Sound and Vibration, 175, 491-503.

[3] Yamaguchi, H., Harnpornchai. N., (1993) “Fundamental characteristics of multiple tuned mass dampers for suppressing harmonically forced oscillations”, Earthq. Eng. and Struct.Dyna., 22, 51-62.

[4] Jangid, R.S., Datta, T.K., (1994) “Dynamic characteristics of structure with multiple tuned mass dampers”, Proceedings of 10th symposium on Earthq. Eng., University of Roorkee, India, 259-267.

[5] Abe, M., Fujino, Y., (1994) “Dynamic characterization of multiple tuned mass dampers and some design formulas”, Earth. Eng. and Struct.Dyna., 23, 813-835.

[6] Abe, M., Igusa, T., (1995) “Tuned mass dampers for structures with closed spaced natural frequencies”, Earthq. Eng. and Struct.Dyna., 24, 247-261.

[7] Chunxiang., Li., (2000) “Performance of multiple tuned mass dampers for attenuating undesirable oscillations of structures under the ground acceleration”, Earthquake Engineering and structural Dynamics, 29(9) , 1405 – 1421.

[8] Sadek, F. Mohraz, B. Taylor, A. and Chung, R., (1997) “A method of estimating the parameters of Tuned mass dampers for seismic applications”, Earthq.Eng. and Struct.Dyna., 26, 617-635.

[9] Jangid, R.S and Datta, T.K. (1997) “Performance Of Multiple Tuned Mass Dampers For Torsionally Coupled System ”, Earthquake Engineering and structural dynamics,Vol 26, Issue3, pages 307–317.

[10] Chunxiang Li and Weilian Qu ., (2006) “Optimum properties of multiple tuned mass dampers for reduction of translational and torsional response of structures subjected to ground acceleration” , Engineering Structures, Vol. 28, pp. 472-494.

[11] Lin, C. C., Ueng, J. M., Huang., T. C., (1999) “Seismic Response reduction of irregular building using Tuned Mass Dampers”, Engineering Structures, Vol 21, 513–524.

[12] Singh,M.P., Singh,S., Moreschi., L.M., (2002) “Tuned mass Dampers for response control of tortional building”, Earthquake Engineering And Structural Dynamics, Vol 31,749-769.

[13] A.P. Pansare., R.S. Jangid.,(2003) “Tuned mass dampers for torsionally coupled systems”, Wind and Structures, Vol. 6, pp. 23-40

[14] Paz M., (2001), Structural dynamics, 2nd ed., CBS publishers, Delhi.

[15] Chopra Anil K., (2003) Dynamics of Structures, 2nd ed., Prentice_Hall of India Private Limited, New Delhi.