Effect of MTMD on Seismic Demand of Base-Isolated Buildings

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Abstract

The effectiveness of multiple tuned mass dampers (MTMD) for vibration control of structure over a single tuned mass damper (STMD) is investigated in the paper. A base isolated structure supported with MTMD is considered and the governing differential equations of motion are derived. The response of the structure under four selected earthquake ground motions is obtained by solving the equations of motion numerically using the state space method. A parametric study is also conducted to investigate the effects of important parameters such as number of dampers in MTMD, damper frequency spacing, mass ratio, tuning ratio. It is found that for a given structural system and level of excitation an optimum value of the parameters (i.e. frequency spacing, tuning ratio) exists at which the peak displacement of structure attains its minimum value. The response time history of the structure with STMD and MTMD with respect to their optimum parameters is compared. It is found that the MTMD is more effective in controlling the response of the structure in comparison with the STMD having the same mass.

Keyword- Ground motions, Mass ratio, MTMD, TMD, Tuning frequency

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I. Introduction

Tuned Mass Damper (TMD) has been accepted as an effective passive control device to suppress the structural vibration. The TMD consists of a mass, a spring and a viscous damper attached to a vibrating main system. The natural frequency of the damper is tuned to a frequency near to the natural frequency of the main system. The vibration of the main system causes the TMD to vibrate in resonance; as a result the vibration energy is dissipated through the damping of the TMD. The determination of optimum parameters (i.e., the tuning frequency and the damping) and the effectiveness of a TMD to control structural oscillations caused by different types of excitations is now well established. The main disadvantage of a STMD is its sensitivity of error in the computation of the natural frequency of the structure. The effectiveness of a TMD is decreased significantly by the miss-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. It was shown by Iwanami and Seto that two tuned mass dampers are more effective than a single-tuned mass damper. However, the effectiveness was not significantly improved. Recently, Multiple-Tuned-Mass Dampers (MTMDs) with distributed natural frequencies were proposed by Xu and Igusa, Jangid and Abe and Igusa. It was shown that the MTMDs have advantages over the usual single TMD. Also, there exists an optimum frequency bandwidth for the MTMDs for which effectiveness of MTMDs is maximum. The objectives of the present study are (i) to study effect of MTMD, as compared to that of STMD, on base isolated building to control seismic response, (ii) to investigate the influence of parameters such as mass ratio, tuning ratio and frequency spacing on the performance of MTMD and (iii) to investigate the dynamic response of base-isolated building using MTMD under Far-fault and near fault ground motions

II. System model

Consider the combined system consisting of the base-isolated structure and the MTMD, as shown in Fig. 1(a). We assume the base-isolated structure alone behaves approximately as a SDOF oscillator having an effective mass m_P, a natural frequency ω_P, and a damping ratio ξ_P, where the subscript p refers to ‘‘primary’’. We also assume the TMD by itself behaves approximately as a SDOF oscillator with an effective mass m_s, a natural frequency ω_s, and a damping ratio ξ_s, where the subscript s refers to ‘‘secondary’’. The combined system consisting of the base-isolated structure (the primary subsystem) and the TMD (the secondary subsystem) is a 2- DOF system, as shown in an idealized form in Fig. 1(b) It is known that such a composite primary–secondary system is generally non-classically damped, even when the individual sub-systems are classically damped. Hence, to properly model the system, account must be made of the non-classical damping nature of the combined system.

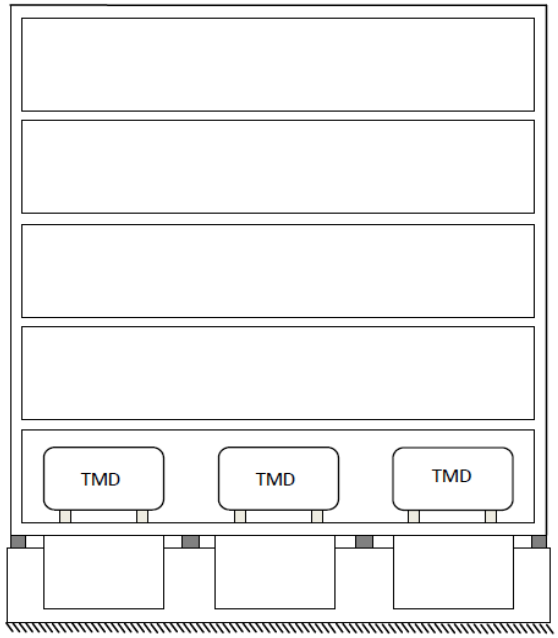


Fig. 1: (a) Base-isolated structures with TMD.

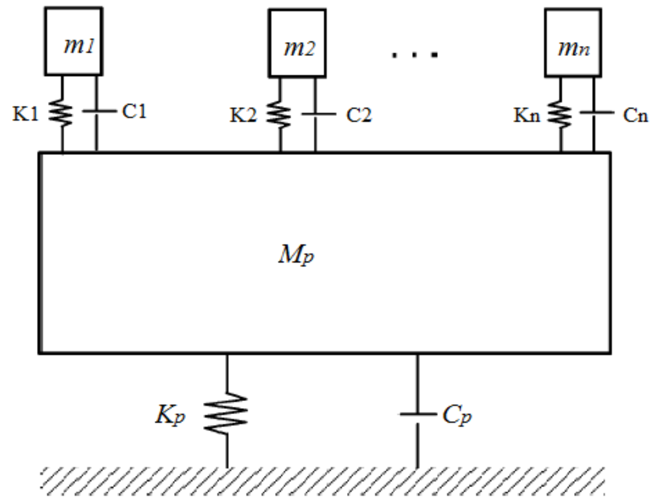


Fig. 1: (b) Schematic diagram of base-isolated structure with TMD.

For the subsequent analysis, it is useful to introduce some basic parameters

- Let ω_T be the average frequency of the MTMDs (i.e $\omega_T = (1/n)\ \Sigma_j\ (\omega J)^2$) and n be the total numbers of MTMDs then the natural frequency of the Jth TMD is expressed as

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

- Where the parameter β is the non-dimensional frequency bandwidth of MTMDs defined as

$$\beta = \frac{\omega_n\text{-}\omega_1}{\omega_T} \qquad (2)$$

- Mass and Damping constant for jth TMD is taken as

$$m_j = \frac{k_T}{(\omega_J)_2} \qquad (3)$$

$$c_j = 2\xi_T m_j \omega_j \qquad (4)$$

- Where ξ_T = damping constant and k_T = constant stiffness of each TMD
- The ratio of the total mass, m_s, of the MTMDs to the mass of the main system, m_S, is defines as the term mass ratio

$$\gamma = \frac{\Sigma j\ mj}{mS} = \frac{mT}{mS} \qquad (5)$$

- Stiffness constant for each TMD

$$k_T = \frac{\gamma\ m_s}{\Sigma_j\left(\frac{1}{(\omega_J)^2}\right)} \qquad (6)$$

- Frequency ratio can be taken as

$$f_1 = \frac{\omega_T}{\omega_b} \qquad (7)$$

- The mass ratio describes the size of the TMD; we consider values in the range 0.01 to 0.1. The tuning parameter describes the proximity of the natural frequencies of the two sub-systems. The TMD is more effective when γ is large and β is small.

III. GOVERNING EQUATIONS OF MOTION

The governing equations of motion of the combined system is described by

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{1\}f(t) \qquad (8)$$

Where $\{X\}=\{X_s,X_1,X_2\ldots\ldots..,X_n\}^T$ is the displacement vector of the system model, X_s is the displacement of the main system, X_j (j = 1,2,….,n) is the displacement of the th tuned mass damper, f(t) is the lateral excitation force acting at the CM of the main system, $\{1\} = \{1,0,0,\ldots.,0\}^T$, [M], [C] and [K] are the mass, damping and stiffness matrices

$$[M] = \mathrm{diag}\ [m_s, m_1, m_2, \ldots..,m_n] \qquad (9)$$

$$[C]=\begin{bmatrix} c_p+\sum_{j=1}^{n}c_i & -c_1 & -c_2 & \dots & -c_n \\ -c_1 & c_1 & 0 & \dots & 0 \\ -c_2 & 0 & c_2 & \dots & 0 \\ . & . & . & . & . \\ -c_n & 0 & 0 & \dots & c_n \end{bmatrix} \quad (10) \qquad [K]=\begin{bmatrix} k_p+\sum_{j=1}^{n}k_i & -k_1 & -k_2 & \dots & -k_n \\ -k_1 & k_1 & 0 & \dots & 0 \\ -k_2 & 0 & k_2 & \dots & 0 \\ . & . & . & . & . \\ -k_n & 0 & 0 & \dots & k_n \end{bmatrix} \quad (11)$$

The mass, damping constant and stiffness of primary system are calculated as

a) $M_b = \gamma m_s$ (12)

b) $C_b = 2\ \xi_b\ m_b\ \omega_b$ (13)

c) $K_b = m_b\,(\omega_b)^2$ (14)

– Thus mass matrix, damping coefficient matrix and stiffness matrix are generated.
– Here the solution of the governing equations of motion is solved using above parameters with the state space method.

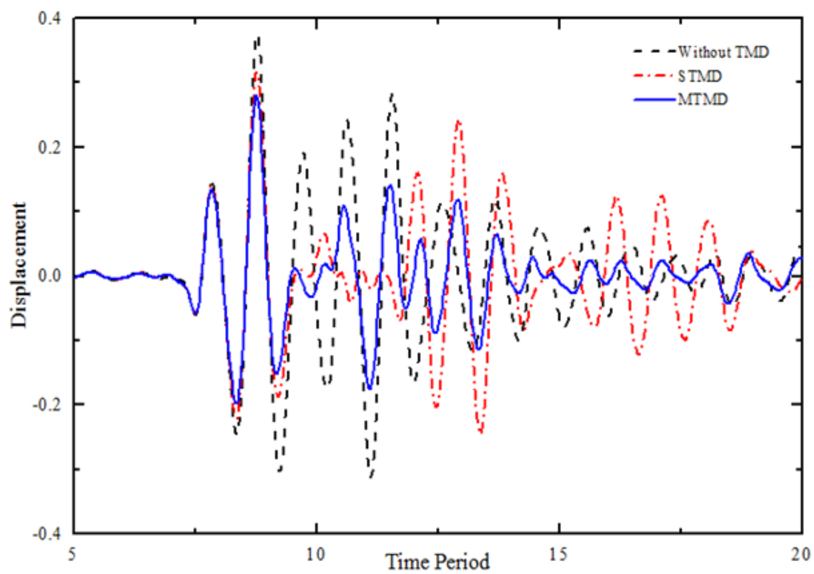
IV. NUMERICAL STUDY

For the numerical study, a base isolated structure with mass m_p, stiffness K_p, and damping C_p where suffix p stands for primary system. The earthquake time histories for far-field ground motions with their peak ground acceleration and components, which are used for this study, are represented in table 1. The displacement response spectra of the above mentioned are shown below in fig.2, 3, 4, and 5 for 2% critical damping, for Imperial Valley, Loma Prieta, and Kobe earthquakes. The spectra of these ground motions indicate that they are recorded on a rocky site or on firm soil. The response quantity of interest is the peak displacement of the structure. For the numerical study, the MTMD is assumed to be attached to the base storey of the structure.

The important parameters on which the efficiency of MTMD depends such as mass ratio, frequency spacing, number of TMD units in MTMD are discussed here, to investigate the effectiveness of the MTMD over STMD, the response of the system is compared with the response of uncontrolled and controlled system with STMD, respectively.

SR. NO	*Earthquakes*	*Recording station*	*Component*	*PGA (g)*
1	*KOBE JAPAN, 1995*	*KJMA*	*KOBE KJM000*	*0.821*
2	*KERN COUNTY, 1952*	*TAFT LINCOLN SCHOOL*	*TAF111*	*0.178*
3	*LOMA PRIETA, 1989*	*UCSC 16 (LGPC)*	*LOMAP LGP000*	*0.563*

Table 1: Details for Far-fault ground motions considered for study

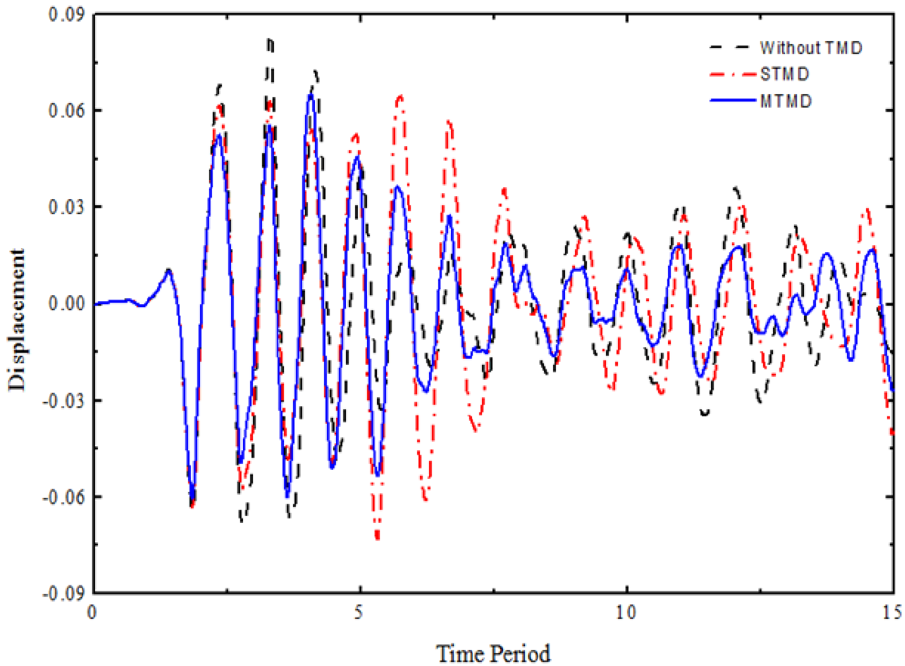


Kobe, 1995

Fig. 2: Displacement of base isolated structure response without TMD with STMD and MTMD

Kobe, 1995 (KJMA)					
	Mass Ratio	β_{opt}	f_{opt}	*Peak displacement*	*Percentage reduction (%)*
n = 0				*0.3760*	*-*
n = 1	*0.1*	*0.1*	*1*	*0.3172*	*15.00*
n = 11				*0.2804*	*25.42*

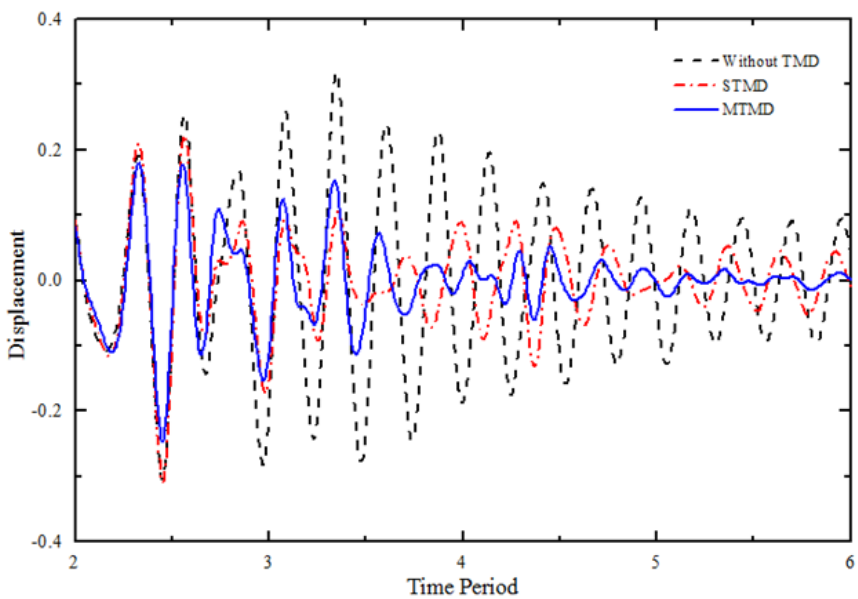
Table 2: Optimum parameters of MTMD for Far-fault ground motions considered for study (Kobe, 1995)



Kern County, 1952
Fig. 3: Displacement of base isolated structure response without TMD with STMD and MTMD

KERN COUNTY, 1952 (Taft Lincoln School)					
	Mass Ratio	β_{opt}	f_{opt}	*Peak displacement*	*Percentage reduction (%)*
n = 0				*0.0849*	*-*
n = 1	*0.1*	*0.9*	*1*	*0.0728*	*14.25*
n = 11				*0.0653*	*23.08*

Table 3: Optimum parameters of MTMD for Far-fault ground motions considered for study (Kern County, 1952)



LOMA PRIETA, 1989
Fig. 4: Displacement of base isolated structure response without TMD with STMD and MTMD

LOMA PRIETA, 1989 (UCSC 16 (LGPC))					
	Mass Ratio	β_{opt}	f_{opt}	*Peak displacement*	*Percentage reduction (%)*
n = 0	*0.1*	*0.9*	*1*	*0.3207*	-
n = 1				*0.3088*	*3.71*
n = 11				*0.2463*	*23.199*

Table 4: Optimum parameters of MTMD for Far-fault ground motions considered for study (Loma Prieta, 1989)

V. CONCLUSION

The response of a Base-isolated system with STMD and MTMD is investigated under four different seismic excitations. The parametric study is conducted to study the effect of important parameters such as number of TMD unit in MTMD, frequency spacing, mass ratio and tuning ratio on the performance of MTMD. The optimum parameters are found out to compare the performance of structure with TMD and MTMD. On the basis of trends of results obtained, the following conclusions are drawn:

1) The MTMD is more effective in controlling the response of the system in comparison to the STMD having the same mass ratio.
2) The higher mass ratio is preferred for significant response reduction of structure using MTMD
3) An optimum value of tuning frequency ratio exists at which the response of the system reduces to minimum value. The response is directly dependent on the number of TMD units in MTMD system and the value of optimum tuning ratio and mass ratio.
4) An optimum value of frequency spacing exists for which the reduction of response by MTMFD is maximum which is again dependent on the number of TMD units in MTMD system and mass ratio.
5) After an increase of number of TMD units in a MTMD, the reduction in response remains almost the same.

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