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Vibration Control of Building Frames with Multiple Tuned Mass Dampers

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***Abstract*—Tuned Mass Dampers (TMDs) have been found to be effective in controlling the responses of flexible tall structures subjected to earthquake ground excitations. In the present paper, the performance of single TMD and multiple TMD (MTMD) in reducing the seismic vibrations induced in structures are studied. The structure considered is a ten-storey RC building frame available in literature. Structures with and without TMDs subjected to different recorded earthquake ground motions are considered. Controlled responses of structures with TMDs and MTMDs are compared with the uncontrolled responses. It is observed that both the TMDs and MTMDs are able to reduce the vibrations in structures caused by earthquakes; however, the MTDMs are found to be more effective in reducing the responses of structures. From the present study it is concluded that, the performance of the tuned mass dampers depend on the characteristics of the ground motion to a great extent and a parametric study to investigate this effect is carried out.**

***Keywords*—Tuned mass damper (TMD), MTMD, earthquake.**

I. Introduction

The control of structures subjected to seismic excitation represents a challenging task for the civil engineering profession. Recently, in the past years, considerable attention has been given to the new concepts of passive structural control systems. A passive control system consists of one or more devices, which is attached or embedded to a structure that is designed to modify the stiffness or the structural damping in a manner that it does not require any external power source for their operation and developing the control forces opposite to that of the motion of the structure

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Examples of such common passive control systems have been classified as: base isolation devices such as bearings, dissipating devices such as friction dampers, hysteretic damper, tuned mass damper (TMD), tuned liquid damper (TLD), tuned liquid columns damper (TLCD) etc.

A. *Tuned Mass Damper*

In 1940's, the first concept of Tuned mass damper was proposed by Den Hartog[1]. It consists of additional mass with properly tuned spring and damping elements placed at the top of the structure to counteract ground motion which provides a frequency-dependent hysteresis that increases damping in the primary structure. Tuned mass damper systems are practically well accepted in the area of structural control for flexible structures especially for tall structures

The principle of suppressing structural vibrations by attaching a TMD to the structures is to transfer the vibration energy of the structure to the TMD and to dissipate the energy in the TMD i.e. the frequency of the damper is tuned to the particular natural structural frequency so that when that particular frequency is excited, the TMD will resonate out of phase with the structural motion.

From numerical and experimental results, it is seen that the effectiveness of the TMD in reducing the response of the same structure under different earthquakes or of different structures during the same earthquake is significantly different. This means that there is a dependency of the attained reduction in response on the characteristics of the ground motion that excites the structure. This response reduction is large for resonant ground motion and it decreases as the dominant frequency of the ground motion gets further away from the structure's natural frequency to which the TMD is tuned. It is clear that the TMD's effectiveness is limited under pulse-like loading. These advantages of the device made it popular for use but the limitation on the other hand opened the door for further research in this relatively new engineering development.

In 1988, the concept of multiple tuned mass dampers (MTMDs) together with an optimization procedure was proposed by Clark [2]. Since, then, a number of studies have been conducted on the behaviour of MTMDs a doubly tuned mass damper (DTMD), which consists of two masses connected in series to the structure which was proposed by Setareh [3] in 1994.

John R. Sladek and Richard E. Klingner [4] studied the effect of Tuned mass damper on seismic response. The purpose of their study was to investigate the performance of TMD and study the response reduction of structures with TMD subjected to earthquake ground motions.

In this paper, we will also discuss the characteristics of ground motion as it plays a very important role in the performance of TMD. The parameters thus considered also differ from one earthquake to other earthquakes. Here, 15 different earthquake acceleration records are considered for the analysis. Acceleration records of earthquake ground motion considered are:ElCentro(1940),Kobe(1995),Northridge(1994),Bhuj(2001),Chichi(1999),Chalfant(1986),Sanfransisco(1906),Imperial(1979),Kocaeli(1999),Parkfield(1966),Tabas(1978),Lomaprieta(1989),SanFernando(1971),Landers(1992),Coalinga(1983) which are obtained from PEER Earthquake Database.

The important parameters identified are: Peak ground acceleration, Seismic Moment, Moment Magnitude, Duration of ground motion, Energy content, Frequency content.

The objective of this study is to investigate the performance of single TMDs as well as MTMDs in reducing the seismic vibrations in tall flexible structures. Four different schemes are adopted for tuning the MTMDs and are then evaluated based on their effectiveness. The performance of the MTMDs is compared with that of the single TMD. The effect of ground motion characteristics on the vibration control by the TMDs is also studied.

II. Numerical Study

In the analysis, a 10 storey structure from the literature [5] is considered in order to study the effectiveness of TMD. The TMD is installed at the top storey of the structure. Time history analysis is performed to calculate the response of the structure with and without TMD subjected to 15 different earthquake records

The mass for each floor is 50 kg, and stiffness for 1st to 10th floor are 9.487×10^{4}, 8.3699×10^{4}, 8.8611×10^{4}, 8.8933×10^{4}, 9.2577×10^{4}, $.8183\times10^{4}$, 8.3379×10^{4}, 8.2403×10^{4}, 8.7211×10^{4} and 8.2986×10^{4} N/m respectively.

The equation of motion of the structure is given by:

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=Du(t)+Ef(t) \qquad (1)$$

The solution of the control problem and the development of control algorithm are obtained by writing the control equation of motion in state-space of the form:

$$\dot{z}(t)=Az(t)+Bu(t)+Hf(t) \qquad (2)$$

$A=\begin{bmatrix}0 & I\\ -M^{-1}K & -M^{-1}C\end{bmatrix}$ is the 2n ×2n system matrix, and

$B=\begin{bmatrix}0\\ M^{-1}D\end{bmatrix}$ and $H=\begin{bmatrix}I\\ M^{-1}E\end{bmatrix}$

are 2n × m and 2n × r location matrices specifying respectively, the locations of controllers and external excitations in the state-space. 0 and I denote respectively, the null matrix and the identity matrix of appropriate dimensions.

While single TMD could be effective in reducing the response of structure under external excitations, but they suffer from some drawbacks such as sensitivity problem of detuning the TMD frequency, TMD damping ratio and uncertainty in dynamic properties of main structure which may cause significant reduction in the effectiveness of TMD. Also in practical application of TMD on tall buildings it may require a heavy mass consequently a considerable space for its installation. For high-rise buildings in which the higher modes may play a considerable role on total response, designing a single TMD tuned to the first mode of vibration may have a little effect on controlling the response of higher modes. To overcome these shortcomings, application of multiple tuned mass dampers (MTMDs) has been proposed to be used instead of a single TMD with distributed masses and natural frequencies.

A. MULTIPLE TUNED MASS DAMPER

The series multiple TMDs consists of a multiple masses and absorbers connected in series to the primary structure as shown in figure 3. Here, two lumped masses are attached to the primary system. The primary system of mass m_s is supported on the base with a spring of stiffness k_s and a dashpot damper of coefficient c_s. Additional masses m_1, and m_2 are attached to the primary system with spring of stiffness k_1 , and k_2 and dampers of damping coefficients of c_1 , and c_2 . The primary system is subjected to the external disturbance, such as dynamic wind load and seismic excitation .Then, the dynamics equations of this series TMD with auxiliary masses can be written as:

$$m_S\ddot{x}_s+c_S\dot{x}_S+c_1(\dot{x}_S-\dot{x}_1)+k_Sx_S+k_1(x_S-x_1)=-m_S\ddot{x}_g$$
$$m_1\ddot{x}_1+c_1(\dot{x}_1-\dot{x}_S)+c_2(\dot{x}_1-\dot{x}_2)+k_1(x_1-x_S)+k_2(x_1-x_2)=-m_1\ddot{x}_g$$
$$m_2\ddot{x}_2+c_2(\dot{x}_2-\dot{x}_1)+k_2(x_2-x_1)=-m_2\ddot{x}_g$$

Which can be further expressed in the following form:

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=F(t) \qquad (3)$$

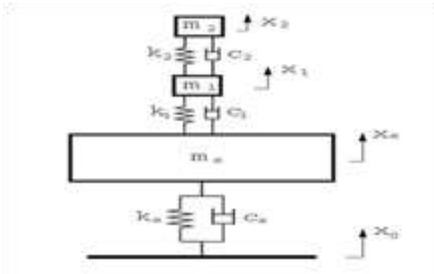

Fig 1. Primary system with series multiple TMDs

For the analysis of series MTMDs, the four possible cases have been considered to see the better performance of MTMDs Also, different parameters of ground motion are considered in this analysis in order to examine which parameters of earthquake ground excitations is the most responsible for the response of the structure. The structure used for the analysis is same as the previous section used in single TMD. The parameter of the structure (ie mass,stiffness and damping) are all same. The only difference is in the connection of TMDs and also in tuning of TMDs.

III. Results and Discussion

A. *Single TMD*

A ten storey RCC building frame is subjected to 15 different earthquake ground excitations for the analysis. The parameters of the TMD are obtained by tuning the TMD frequency to the first natural frequency of the structure. Time history analyses of the structure are performed with and without the TMD.

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Among all the results obtained the effectiveness of TMD in reducing the response of the building for 5 earthquakes only is also shown for demonstration purpose in Table 1. Almost all the displacement and acceleration values are reduced in controlled case. It is seen from the Table that in case of displacement control, El Centro earthquake has the maximum percentage control whereas Coalinga earthquake has the minimum percentage control. The comparison of uncontrolled and controlled values of displacements and acceleration are shown in the Fig 2.

Fig 3 shows the variation of percentage control of the displacement and acceleration responses in terms of energy content.The figure expalins that the percentage control of responses by TMDs and the energy content of the earthquake ground motions are related, though no unique relationship can be established from the results. However, it is evident that for the cases, where the displacement control is low the control in acceleration is high and vice versa. Hence, it can be said that some sort of inverse relationship exists between displacement control and acceleration control.

B. *Multiple TMD in Series*

Four different cases have been considered to see the better performance of series MTMDs under the 15 different earthquake ground excitations. TMD with percentage mass of 5% is used. Also, different parameters of ground motion are considered in order to examine influence of these parameters on the response of the TMD-structure system. The four different cases of series MTMD are briefly described below:

Case I: When the first and second mass of the TMDs are tuned to the first and second natural frequency of the primary structure considered respectively.

Case II: When the first mass of the TMD is tuned to the first natural frequency of the primary structure and then considered as a part of the primary structure (ie first mass of the TMD combined with the primary structure and act as whole structure) and the second mass of the TMDs is tuned to the first natural frequency of this new primary structure.

Case III: When both the first mass and second mass of the TMDs are tuned to the first natural frequency of the primary structure used.

Case IV: When the equivalent mass, stiffness and damping coefficients of the first and second mass of the TMD are found out and then tuned to the first natural frequency of the primary structure respectively.

From the analysis of the above cases, it is observed that II and IV are the most effective ones in terms of reduction of displacements and accelerations respectively for the considered fifteen earthquake ground motion. The calculation of percentage of control for both displacements and accelerations respectively for case II and IV are shown in Table 2 and Table 3. It can be observed that in all the four cases Kobe earthquake has the maximum percentage controlled both in displacements and accelerations which is followed by El Centro earthquake and so on. This may be due to the fact that the PGA of Kobe earthquake is quite high and its frequency content is also high.

Considering the single TMD and series MTMDs it is observed that series MTMDs are effective in controlling the accelerations of the structure whereas single TMDs can effectively control the displacements of the structure

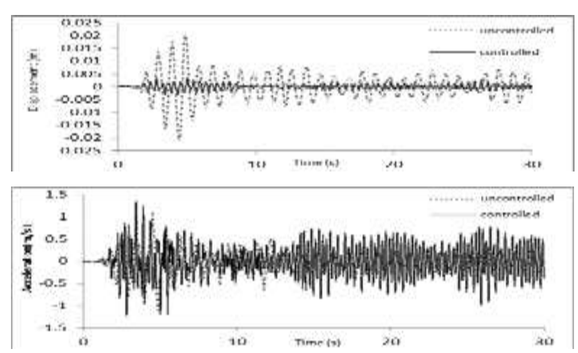

Fig: 2 Time history of uncontrolled and controlled displacements and accelerations of tenth storey building frame subjected to the El Centro earthquake ground motion

TABLE 1: PERCENTAGE CONTROL FOR THE SINGLE TMD

Earthquake Data	Displacement (mm)			Accelerations (m/s^2)		
	UC	*C*	*%C*	*UC*	*C*	*%C*
El Centro	22.1	3.7	83	1.17	1.39	-19
Kobe	60.4	47.4	22	4.1	2.59	37
Chalfant	7.7	4.3	44	0.55	0.41	26
San Fernando	54.3	38	31	3.52	1.55	56
Coalinga	2.1	2.1	0	0.39	0.2	47

UC-uncontrolled-controlled

TABLE 2: PERCENTAGE CONTROL FOR CASE II OF SERIES CONNECTION

Earthquake Data	Displacement (mm)			Accelerations (m/s^2)		
	UC	*C*	*%C*	*UC*	*C*	*%C*
El Centro	22.1	10.2	54	1.17	0.44	63
Kobe	60.4	56.8	6	4.1	1.63	60
Chalfant	7.7	5.4	30	0.56	0.32	43
San Fernando	54.3	55.6	-2	3.53	1.52	57
Coalinga	2.1	2.2	-5	0.39	0.11	71

UC-uncontrolled-controlled

TABLE 3: PERCENTAGE CONTROL FOR CASE IV OF SERIES CONNECTION

Earthquake Data	Displacement (mm)			Accelerations (m/s^2)		
	UC	*C*	*%C*	*UC*	*C*	*%C*
El Centro	22.1	13.2	40	1.17	0.31	73
Kobe	60.4	18.1	70	4.11	0.82	80
Chalfant	7.7	5.5	29	0.56	0.21	63
San Fernando	54.3	36.2	33	3.53	1.22	65
Coalinga	2.1	1.9	10	0.39	0.09	76

UC-uncontrolled-controlled

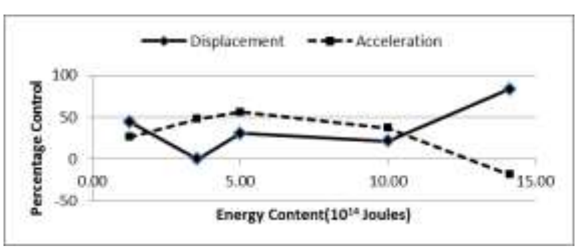

Fig 3.Percentage control of displacement in terms of energy content for single TMD

IV. Conclusion

Present study is focused on investigating the performance of tuned mass dampers and multiple tuned mass dampers in series in tall flexible structures under different earthquake ground motions. A ten storey building, available in literature, is considered and it is subjected to 15 different earthquakes. Four different schemes are adopted for tuning the MTMDs and are then evaluated based on their effectiveness. From the study the following conclusions are made:

. TMDs are very effective in controlling the acceleration and displacement responses respectively of a structure.

Series MTMDs are effective in controlling the accelerations of the structure whereas single TMDs can effectively control the displacements of the structure.

The percentage control of responses by TMDs and the energy content of the earthquake ground motions are related, though no unique relationship can be established from the results. However, it is evident that for the cases, where the displacement control is low the control in acceleration is high and vice versa. Hence, it can be said that some sort of inverse relationship exists between displacement control and acceleration control.

There seem to exist mutually exclusive bands or ranges of earthquakes (with related characteristic properties like energy content, magnitude, frequency content etc.) for which, the TMDs are effective in controlling displacement and acceleration respectively.

In case of series MTMDs, it can be stated that Case II and Case IV are the more effective ones in terms of reduction of displacements and accelerations respectively for the considered fifteen earthquake ground motion.

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