ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

Vibration control of Benchmark building with stacked TMDs

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***Abstract:*— Tuned mass dampers (TMDs) placed in sky scrapers show huge deflections and accelerations as they absorb a lot of the energy from the main structure. The responses of these TMDs need to be controlled with some additional dampers to keep their motion in check. The current paper deals with the numerical study of a similar system in which a TMD (secondary TMD) is used to control another TMD (primary TMD). Primary TMD is also analogous to an important equipment such as a server placed in a building which needs to be controlled. In the present study, the response of a 76-storey Benchmark building is investigated under across-wind loads. Dynamic Time History Analysis of the building is performed in MATLAB 2010a using the wind time history data by state space method. In addition to deflections, drift and acceleration responses have also been taken into consideration. Results show that for an optimum mass of primary TMD (0.33%), the overall response (i.e. peak, Root Mean Square (RMS) and average displacement, acceleration and drift) of the structure is reduced up to 56%. Moreover when secondary TMD is placed, for an optimum mass ratio (2%), the overall response reduction of the structure remains same (i.e. 56 %); whereas the overall response of the primary TMD reduces by 36%. With further increase in the mass of secondary TMD, a trend is observed where overall response of primary TMD goes on decreasing whereas that of the structure increases. Thus, a secondary TMD can be used effectively only up to a mass ratio of 2% of primary TMD. If mass ratio of secondary TMD is kept equal to or below 0.4%, more response reduction for primary structure can be achieved.**

***Index Terms* :--Tuned mass damper, benchmark building, frequency ratio, mass ratio**

I. INTRODUCTION

Buildings are built higher, lighter and slender as modern world requirement, with the use of advanced technology, knowledge of new materials, analysis software, which have assured safe constructions and comfort to human life. The main objective of installing control systems on the tall building is to reduce the responses like accelerations and displacements to alleviate the occupant's discomfort and to keep storey drift within specified limit. Tuned mass damper (TMD) is one such control device. A mass-stiffness-damping system, tuned with the primary mode of the structure, used to reduce the structures response is termed as a Tuned Mass damper (TMD). The word tuned mass damper dates back to year 1909, when Frahm invented a vibration control device called dynamic vibration absorber [7]. Ormondroyd and Den Hartog (1928) [7] showed that by introducing damping in Frahm's absorber, its performance can be significantly improved. G. Chen, J. Wu (2001) [1] showed that Multiple TMD can effectively reduce the acceleration of the uncontrolled structure by 10–25% more than a single TMD in case of impulsive forces. J. Almazan, J. De la Llera, J. Inaudi, D. Lopez-Garcıa, L. Izquierdo [2] studied effect of Bi-Directional TMD modelled by using pendulum and linear viscous dampers on response of structure to obtain reduction factors up to 60%. S. Elias, V. Matsagar (2013) [4] showed that distributed MTMDs are more effective than MTMDs concentrated on single floor to control wind induced vibration of the building. V. Thakur and P. Pachpor (2012) [3] found that a soft storey at the top of building reduces deflection of top storey of the building by about 10 to 50%. Thus, new techniques are developing in the use of TMD and further developing new techniques from economic and performance point of view is also essential.

II. PROBLEM DEFINITION AND GOVERNING EQUATION

For the present study, the building considered is a 76-storey benchmark building which is a 306 m high office tower in the city of Melbourne, Australia as shown in Fig.1. It has plan dimensions of 42m × 42m and is a symmetrical structure. Detailed description of benchmark building has been given by B. Samali, K. Kwok, G. Wood and J. Yang (2004) [5]. This is a reinforced concrete building consisting of a concrete core and concrete frame. The core was designed to resist the

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

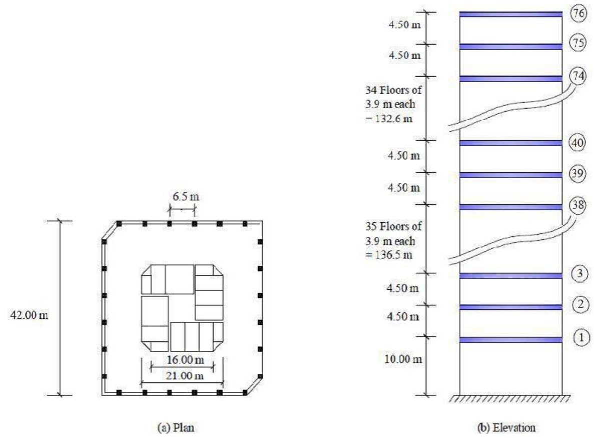
majority of wind loads whereas the frame was designed to primarily carry the gravitational loads and part of the wind loads. The building has a square cross section with chamfer at two corners as shown in Fig. 1. The total mass of the building, including heavy machinery in the plant rooms, is 153,000 metric tons. The total volume of the building is 510,000 m3, resulting in a mass density of 300 kg per cubic meter, which is typical of concrete structures. The building is slender with a height-to-width ratio (aspect ratio) of 306.1/42=7.3; therefore, it is wind sensitive.

The perimeter dimension for the center reinforced concrete core is 21 m × 21 m. The reinforced concrete perimeter frame consists of columns spaced 6.5 m apart, which are connected to a 900 mm deep and 400 mm wide spandrel beam on each floor. There are 24 perimeter columns on each level with six columns on each side of the building. The lightweight floor construction uses steel beams with a metal deck and a 120 mm slab. The compressive strength of concrete is 60 MPa

and the modulus of elasticity is 40 GPa. Column sizes, core wall thickness, and floor mass vary along the height, and the building has six plant rooms.

The 76-storey tall building is modeled as a vertical cantilever beam (Bernoulli–Euler beam). A finite element model is constructed by considering the portion of the building between two adjacent floors as a classical beam element of uniform thickness, leading to 76 translational and 76 rotational degrees of freedom. Then, all the 76 rotational degrees of freedom have been removed by the static condensation. This results in a 76 degrees of freedom DOF, representing the displacement of each floor in the lateral direction. The first five natural frequencies are 0.16, 0.765,
1.992, 3.790, and 6.395 Hz. The (76×76) damping matrix for the building with 76 lateral DOF is calculated by assuming
1% damping ratio for the first five modes using Rayleigh's approach.

The time history data from wind tunnel tests obtained by B. Samali, K. Kwok, G. Wood and J. Yang (2004) [6] are used for analysis purpose.



(a) Plan (b) Elevation
Fig 1. Benchmark Building

CONTROL SYSTEMS:

Fig. 2 shows two control systems considered in this study. The system with single TMD over structure (Fig 2 (a)) will be referred to as system 1 and that with a smaller TMD controlling the larger TMD (Fig. 2(b)) will be referred to as System 2 or stacked TMD system. The larger TMD controlling the main structure will be referred to as primary TMD and the smaller TMD controlling the primary TMD will be referred to secondary TMD henceforth in this paper.

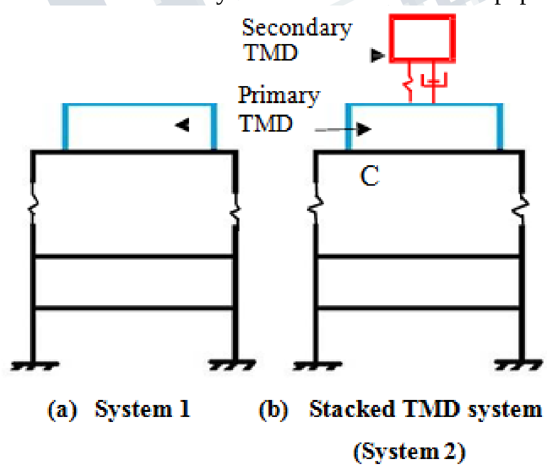


Fig 2. Control Systems

For the wind excited benchmark building along with stacked TMDs, the governing equations of motion are obtained by considering the equilibrium of forces at the location of each Degree Of Freedom (DOF) during wind excitations. Therefore, the governing equations of motion for the controlled building structure model subjected to wind excitations can be written as

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\} = \{F\}$$

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
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where [M], [C] and [K] are the mass, damping and stiffness matrices of the building of order [78×78], respectively. $\{x\}$,$\{\dot{x}\}$ and $\{\ddot{x}\}$ are the unknown floor displacement, velocity and acceleration vectors respectively and [F] is the wind load vector; all of order[78×1]. 77th and 78th DOF is for primary and secondary TMD respectively. Hence system 1 would contain only 77 DOFs.

III. PERFORMANCE CRITERIA

The responses of the controlled and uncontrolled structure are normalized as the ratio of controlled to uncontrolled response which is also called as performance criterion. To facilitate the direct comparison and to evaluate the capabilities of the two systems, a set of 8 performance criteria are proposed by B. Samali, K. Kwok, G. Wood and J. Yang (2004) [5]. However, in this paper the authors have considered responses of all the storeys to calculate the average response to get more accurate results. Also, 4 more parameters are proposed by the authors in which drift parameters are included for better understanding. Table I shows the meaning of each performance criterion. Performance criteria J1 to J4 represent the displacement responses, J5 to J8 represent the acceleration responses and J9 to J12 represent the drift responses. Average Peak and average RMS responses considering all the 76 storeys are used to get displacement and drift parameters. For acceleration, data only up to 75th storey are considered for getting average values.

Table I: Performance criteria definitions

J_1	Peak Floor displacement(76th floor)
J_2	RMS Floor displacement(76th floor)
J_3	Average Peak Floor displacement
J_4	Average RMS Floor displacement
J_5	Peak Floor acceleration(75th floor)
J_6	RMS Floor acceleration (75th floor)
J_7	Average Peak Floor acceleration
J_8	Average RMS Floor acceleration
J_9	Peak inter storey drift (75th to 76th floor)
J_{10}	RMS inter storey drift(75th to 76th floor)
J_{11}	Average Peak inter storey drift
J_{12}	Average RMS inter storey drift

IV. OPTIMIZATION

Optimum parameters like mass ratio, frequency ratio and damping ratio for primary TMD are obtained. Performance criteria J1 to J12 are used for optimization of system 1. Mass ratio for primary TMD is the ratio of mass of primary TMD to mass of structure. Whereas, mass ratio for secondary TMD is the ratio of mass of secondary TMD to mass of primary TMD. Similarly, frequency ratio for primary TMD is defined as the ratio of natural frequency of primary TMD to natural frequency of the structure. And for secondary TMD it is the ratio of natural frequency of secondary TMD to the natural frequency of primary TMD. It is seen from the definition of performance criterion in section III that lesser the performance criteria more is the response reduction. It was found in the 'TMD mass vs performance criterion' graphs that performance criteria values reduce with increase in primary TMD mass. Optimized mass ratio is taken as the point beyond which further increase in primary TMD mass does not cause significant decrease in the performance criteria. While those frequency and damping ratios which minimize most of the performance criteria are taken as optimum. Optimum Parameters for System 1 are mass ratio =0.33%, frequency ratio=0.98, damping ratio =0.04.
Optimization of secondary TMD is carried out by considering the optimized parameters for system 1. Performance criteria J1, J2, J5, J6, J8, and J9 are used for this purpose. This is explained further in results and discussions section

V. RESULTS AND DISCUSSIONS

Fig 3 to 8 show the graphs for mass of secondary TMD v/s various performance criteria for System 2. Figures show the graphs for performance criteria of both the structure and the primary TMD. The responses shown in the graphs are obtained for optimum frequency and optimum damping ratio for the corresponding masses of secondary TMD. In the graphs, 0 tons secondary TMD mass represents System 1.

In all the graphs performance criteria of primary structure show a minimum value for 2 ton secondary TMD mass. Thus, system 2 shows a reduction of 4.6% for Peak drift, 5.5% for peak displacement, and 8.7 % for peak acceleration, compared to that of System 1. Whereas, RMS responses remain almost same (about 0.4% response reduction). But in addition to this, primary TMD shows significant response reduction up to 16.9%.

For 10 ton secondary TMD mass, performance criteria values for structure in System 2 are almost similar to System 1 except J5 (peak acceleration) which shows a response reduction of 5.6%. But in addition, primary TMD

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ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

show response reduction up to 36.6% which is quite significant.

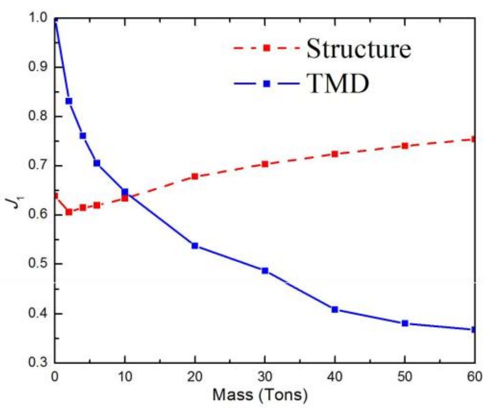

Fig 3: Secondary TMD mass vs J1 (Peak Floor displacement)

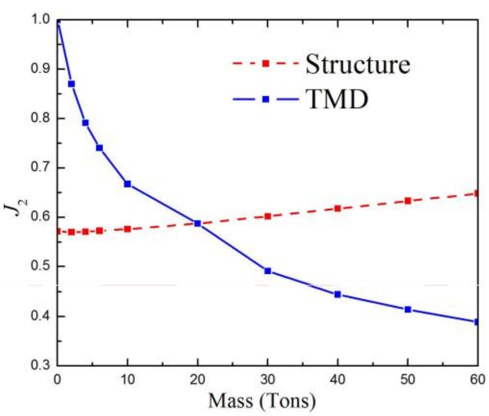

Fig 4: Secondary TMD mass vs J2 (RMS Floor displacement (76th floor))

Here after all the responses for the structure show a significant increase with increase in the secondary TMD mass whereas responses for primary TMD show rapid decrease as is seen in the graphs with the respective increase or decrease of performance criteria curves. Values for all the performance criteria for 0 tons (i.e. no secondary TMD), 2 tons, and 10 ton secondary TMD mass are given in table II. In system 2, secondary TMD moves in opposite phase with primary TMD, which itself is out of phase with the main structure. Thus main structure and secondary TMD are in phase with each other which is the cause of increase in response of main structure. Here lower masses of secondary TMD do not affect response of the structure much.

Optimum parameters for secondary TMD are taken as those at which structure's response remain unaffected compared to system 1 and which minimize most of the performance criteria. Optimum parameters are; mass ratio = 2%, frequency ratio = 0.85, damping ratio = 0.15; or it may also be taken as those at which structure's response is minimum and which minimize most of the performance criteria. Here optimum parameters are; mass ratio = 0.4 %, frequency ratio = 0.98, damping ratio=0.03 and 0.06 (0.03 for peak responses and 0.06 for RMS responses).

Table II: Performance criteria values for structure and primary TMD

Mass of secondary TMD (tons) →	0	2	10	2	10
Performance criteria ↓	Structure			Primary TMD	
J_1	0.639	0.606	0.633	0.832	0.647
J_2	0.571	0.57	0.576	0.87	0.667
J_3	0.663	0.627	0.653	-	-
J_4	0.578	0.576	0.582	-	-
J_5	0.459	0.419	0.433	0.844	0.634
J_6	0.432	0.43	0.439	0.862	0.64
J_7	0.548	0.54	0.542	-	-
J_8	0.491	0.489	0.496	-	-
J_9	0.612	0.584	0.611	0.856	0.644
J_{10}	0.565	0.563	0.57	0.867	0.651
J_{11}	0.648	0.617	0.643	-	-
J_{12}	0.574	0.573	0.579	-	-

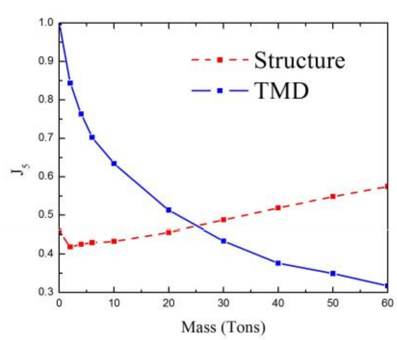

Fig 5: Secondary TMD mass vs J5 (Peak Floor acceleration (76th floor))

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ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 2, Issue 3, March 2017

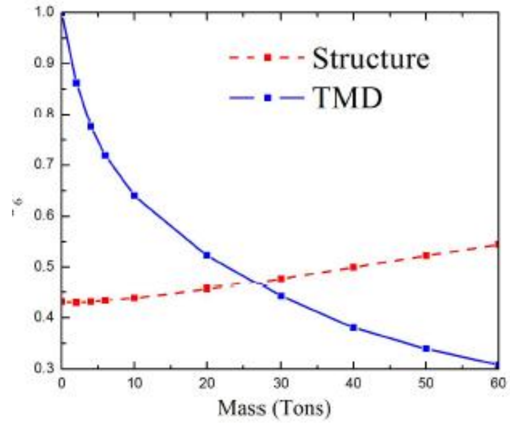

Fig 6: Secondary TMD mass vs J6 (RMS Floor acceleration (76th floor))

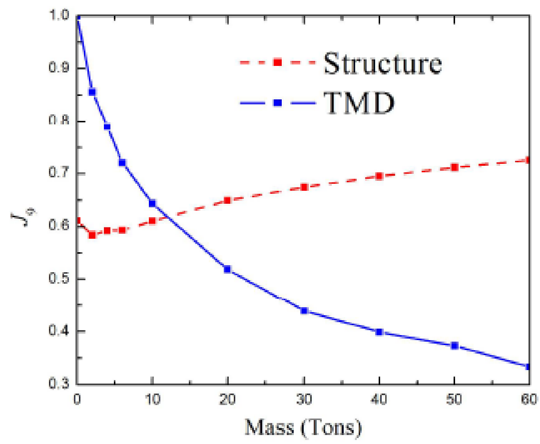

Fig 7: Secondary TMD mass vs J9 (Peak inter storey drift)

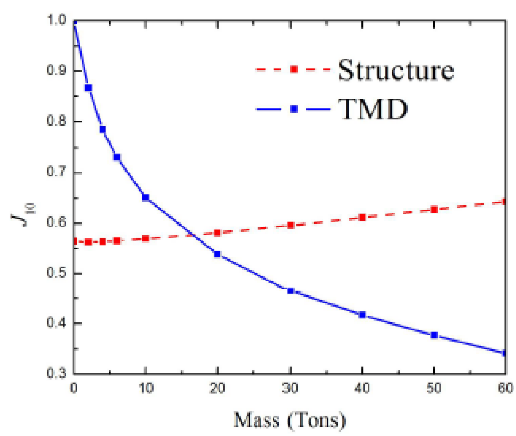

Fig 8: Secondary TMD mass vs J10 (RMS inter storey drift)

VI. CONCLUSIONS

In current study, stacked TMD system is studied by placing it at the top of benchmark building. Following are the concluding points:

1. If mass ratio of secondary TMD is kept equal to or below 0.4%, additional response reduction for primary structure, around 8.7% of that of system 1, can be achieved. In addition to that, 16.9% response reduction of primary TMD is also achieved.

2. Secondary TMD, if tuned with primary TMD, up to a mass ratio of 2% can be used to control it effectively. For this mass ratio, stacked TMD system provides, in addition to the same response reduction of the main structure as with system 1, a complementary response reduction up to 36% for primary TMD.

3. The capacity needs of the additional dampers, usually required to control the response of primary TMD, will be lowered significantly or may also be reduced to nil.

4. Secondary TMD with mass ratios more than 2% of primary TMD should not be used as it tend to increase the responses of the main structure significantly. Though current study has yielded good results, still these results could be further improved by use of Multiple TMDs and Multiple Distributed TMDs. Hence, study of stacked TMD system using Multiple TMDs and Multiple Distributed TMDs should be carried out in future.

REFERENCES

[1] G. Chen, Jingning Wu (2001), "Optimal placement of multiple tune mass dampers for seismic structures", Journal of Structural Engineering, Vol. 127, No. 9.

[2] J. Almazan, J. De la Llera, J. Inaud, D. Lopez-Garcıa, L. Izquierdo (2007), "Bidirectional and homogeneous tuned mass damper: A new device for passive control of vibrations", Engineering Structures29, pp. 1548–1560

[3] V. Thakur, P. Pachpor, (2012) "Seismic Analysis of Multistoried Building with TMD (Tuned Mass Damper)", International Journal of Engineering Research and Applications (IJERA), Vol. 2, Issue 1, pp. 319-326.

[4] S. Elias, V. Matsagar (2013), "Wind response control of 76- storey benchmark building with distributed multiple tuned mass dampers", The Eighth Asia- Pacific Conference on Wind Engineering.

[5] J. Yang, A. Agrawal, B. Samali, and J. Wu (2004) "Benchmark Problem for Response Control of Wind-Excited Tall Buildings", Journal of Engineering Mechanics, Vol. 130, No. 4.

[6] B. Samali, K. Kwok, G. Wood and J. Yang(2004), "Wind tunnel tests for wind-excited benchmark building", Journal of Engineering Mechanics, Vol. 130, No. 4.

[7] R. Rana (1996), "Response control of structures by tuned mass dampers and their generalizations", Eleventh World Conference on Earthquake Engineering, paper no. 498.