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Structural Performance of Vertically Distributed Multiple Tuned Mass Dampers in Tall Buildings

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***Abstract*— As today's tall buildings become ever taller and more slender, wind-induced vibration is a serious design issue. Installing tuned mass dampers (TMDs) is a reliable solution to mitigate wind-induced vibration of tall buildings. This paper investigates structural performance of vertically distributed multiple TMDs along the height of the building. Compared with the conventional TMD system, composed of very large TMD masses installed near the top of the building, much smaller TMD masses are used in the vertically distributed TMD system. Though the performance of the vertically distributed TMD masses is somewhat reduced, the system can still be very effective depending on the range of the distribution. In addition, the valuable spaces near the top of tall buildings can be saved for more desirable architectural functions.**

Keywords—tall Buildings, structural motion control, tuned mass dampers

I. Introduction

Tall buildings, which began as about 40m tall office buildings, have grown to more than 10 dozens of supertall buildings taller than 300m throughout the globe. Among them, about 2 dozens are taller than 400m with the tallest one reaching 828m. It is also expected that the height of 1km will be reached soon by a skyscraper under construction. In addition to the dramatic increases in height, many super-slender tall buildings have been emerging in recent years. The slenderness, usually defined as the height to width aspect ratio, of some of the recent tall buildings reached 15:1. It is also expected that the ratio of 20:1 will be exceeded soon.

As tall buildings become ever taller and more slender, wind-induced vibration is a serious design issue. Vortex-shedding induced lock-in phenomena generate severe across wind vibrations and this is generally one of the most serious structural design issues for tall and slender buildings. Among various approaches to resolve this critical structural design issue for tall buildings, installing tuned mass dampers (TMDs) is a very reliable solution.

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TMDs are generally located near the top of the building to generate counteracting inertia forces against wind-induced vibrations of the building more effectively. Therefore, very valuable large spaces near the top of tall buildings are often sacrificed to contain TMDs. This paper investigates the potential of distributing multiple small TMDs vertically over the multiple floors of tall buildings. The effectiveness of vertically distributed TMDs along the building height is predicted using design studies, in comparison with the conventional TMDs installed near the top of tall buildings.

II. Vertically Distributed Tuned Mass Dampers

In order to design a TMD, a tall building's primary structure is usually approximated as a single-degree-of-freedom (SDOF) system, and an additional small mass representing a TMD is attached to the SDOF mass creating a 2DOF system. Then, with the dynamic loads applied to the primary structure, the 2DOF system is optimized through a tuning process until the maximum response of the primary structure is minimized. Figure 1 shows SDOF+TMD model.

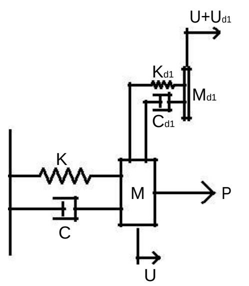

Figure 1. SDOF+TMD System Model.

$$H = \frac{\sqrt{(\rho^2 - f_1^2)^2 + 4 f_1^2 \xi_{d1}^2 \rho^2}}{\sqrt{(f_1^2 m_1 \rho^2 - \rho^4 + \rho^2 + f_1^2 \rho^2 - f_1^2 + 4\xi \rho^2 \xi_{d1} f_1)^2 + (2\rho^3 \xi_{d1} + 2\xi\rho^3 - 2\xi\rho f_1^2 - 2 f_1 \xi_{d1} \rho + 2 m_1 \rho^3 \xi_{d1} f_1)^2}} \quad (1)$$

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$$H_{d1} = \frac{\rho^2}{\sqrt{(f_1^2\bar{m}_1\rho^2 - \rho^2 + \rho^4 + f_1^2\rho^2 - f_1^2 + 4\xi\rho^2\xi_{d1}f_1)^2 + (2\rho\xi_{d1}f_1 + 2\xi\rho^3 - 2\xi\rho f_1^2 - 2f\xi_{d1}\rho^3 + 2\bar{m}_1\rho^3\xi_{d1}f_1)^2}} \quad (2)$$

ξ = primary structure damping
ratio ξ_{d1} = TMD damping ratio
ω = natural frequency of the primary structure
ω_{d1} = natural frequency of the TMD mass
Ω = forcing frequency

$\bar{m}_1 = m_{d1} / m$

$f_1 = \omega_{d1} / \omega$

$\rho = \Omega / \omega$

In Equations 1 and 2, H and H_{d1} express the dynamic amplification factors of the primary structure and the TMD mass, respectively. As the mass ratio is increased, the maximum H and H_{d1} values of the optimally tuned TMD system are decreased.

Connor (2003) presented a solution for a multi-degree-of-freedom (MDOF) system having a single TMD at its last node by reducing the problem to an equivalent SDOF system having a TMD. This approach is employed here for the solution of a MDOF system with vertically distributed multiple TMDs installed at each node. Figure 2 shows NDOF+NTMD system model.

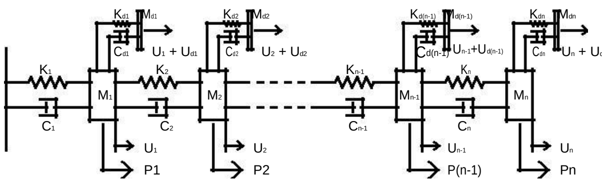


Figure 2. NDOF+NTMD System Model.

The vertically distributed multiple TMD system equations can be set up by reducing the MDOF system, which has ‘n’ nodes, to a SDOF system. Then, the governing equations for the NDOF+NTMD system shown in Figure 2 are

$$mu + cu + ku = p + \frac{\varphi_{11}}{\varphi_{1n}}(k_{d1}u_{d1} + c_{d1}u_{d1}) + \ldots + \frac{\varphi_{1(n-1)}}{\varphi_{1n}}(k_{d(n-1)}u_{d(n-1)} + c_{d(n-1)}u_{d(n-1)}) + (k_{dn}u_{dn} + c_{dn}u_{dn}) \quad (3)$$

$$m_{d1}u_{d1} + c_{d1}u_{d1} + k_{d1}u_{d1} = -\frac{\varphi_{11}}{\varphi_{1n}} m_{d1}u \quad (4)$$

……

$$m_{d(n-1)}u_{d(n-1)} + c_{d(n-1)}u_{d(n-1)} + k_{d(n-1)}u_{d(n-1)} = -\frac{\varphi_{1(n-1)}}{\varphi_{1n}} m_{d(n-1)}u \quad (5)$$

$$m_{dn}u_{dn} + c_{dn}u_{dn} + k_{dn}u_{dn} = -m_{dn}u$$

By solving the equations, H and H_d can be obtained.

III. Design Studies of Vertically Distributed Tuned Mass Dampers

The effectiveness of TMDs is gradually reduced as their locations near the ground. Considering this, TMDs may be installed from the top floor to mid-height of the building as an example. Accordingly, the model shown in Figure 2 can be modified and the equations can also be adjusted.

6DOF+4TMD system, which represents a tall building with vertically distributed multiple TMDs from the top to about the mid-height of the building, is analyzed in order to assess the effectiveness of the system, compared with the conventional case of 6DOF with one TMD at the top. Figure 3 shows the 6DOF+4TMD system model.

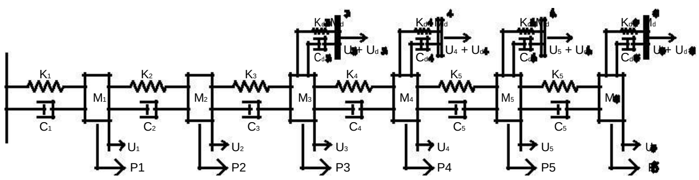
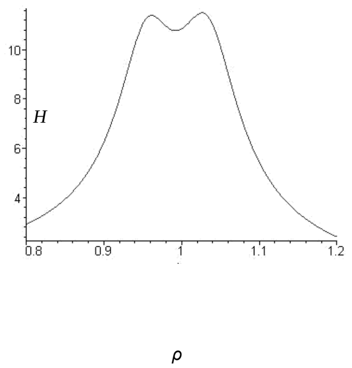


Figure 3. 6DOF+4TMD System Model

A one percent inherent structural damping ratio without TMD system is assumed in this study. In this case, for the periodic excitation, the maximum dynamic amplification factor (H) of the structure is about 50. When a conventional system with a single TMD at node 6, with mass ratio of 1%, is considered, the maximum H value is reduced from about 50 to 11.5. With a 77% reduction of the maximum dynamic response, the original structural damping ratio of 1% is increased to an equivalent damping ratio of about 4.3%. Finally, when the 6DOF+4TMD is optimally tuned with TMD mass ratio of 0.25 % for each at node 6, 5, 4 and 3, the maximum H value is reduced from about 50 to 14 in this case. With a 72% reduction of the maximum dynamic response, the original structural damping ratio of 1% is increased to an equivalent damping ratio of about 3.6%. Figure 4 shows H plots of 6DOF+TMD and 6DOF+4TMD systems.

Additional studies are performed with 6DOF+3TMD and 6DOF+2TMD systems shown in Figure 5 and Figure 6 respectively. In the former, a 0.33% mass ratio is used for each TMD at node 6, 5, and 4, and in the latter, a 0.5% mass ratio for each TMD at node 6 and 5, to keep the total mass ratio of 1% for every case. The results of these studies as well as the previous ones are summarized in Table 1. As was anticipated, broader vertical distribution of TMDs results in less effectiveness. However, the loss of the effectiveness is not that substantial and, thus, could be acceptable depending on design situations. If the gain through the advantageous aspects of vertical distribution of multiple small TMDs is greater than the loss of effectiveness, the studied system can be a potential design solution over the conventional design.



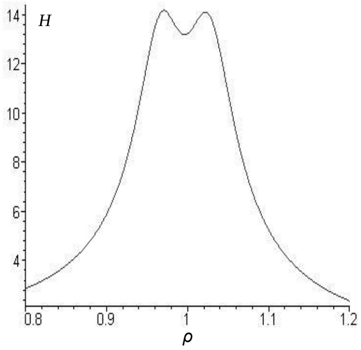


Figure 4. H values of 6DOF+TMD (top) and 6DOF+4TMD (bottom).

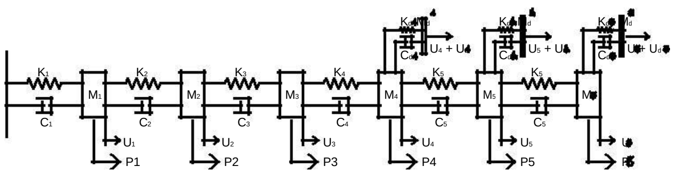


Figure 5. 6DOF+3TMD System Model

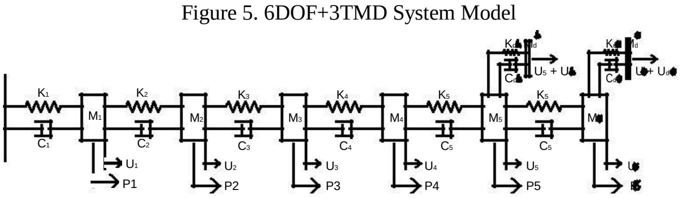


Figure 5. 6DOF+2TMD System Model

Vertically distributed small TMD masses expressed as a single mass at each level in the system models can further be distributed horizontally to make the TMD units even much smaller. By distributing TMDs not only vertically but also horizontally with very small multiple TMDs at each level, the whole system reliability can be enhanced. Furthermore, by distributing TMDs vertically, not only the first mode but also higher modes can be effectively controlled if necessary.

TABLE I. EFFECTIVENESS OF VERTICALLY DISTRIBUTED MTMDS

System Configuration	Maximum H	(Equivalent) Damping Ratio
6DOF without TMD	50.0	1.0%
6DOF+1TMD at Node 6	11.5	4.3%
6DOF+2TMD at Node 6 and 5	12.1	4.1%
6DOF+3TMD at Node 6, 5, and 4	13.0	3.8%
6DOF+4TMD at Node 6, 5, 4, and 3	14.0	3.6%

IV. Conclusions

TMDs can be distributed vertically along the building height without substantial loss of their effectiveness for tall building motion control. By vertically distributing TMDs, valuable space near the top of a tall building can be saved for more desirable architectural functions. Vertically distributed TMDs can be effective not only for the first mode but also for higher modes and the distributed TMD zones for each mode can be determined based on each mode shape.

By distributing multiple small TMDs, their installations become easy due to their reduced masses. Package type TMDs might be a good option for even easier installation, especially for retrospective installation. Though the effectiveness of the TMD system is somewhat reduced by vertically distributing TMD masses, the system still possesses a high potential of practical applications due to their advantages over the conventional system.

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