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INTEGRATED MULTIPLE TUNED MASS DAMPERS FOR TALL BUILDINGS

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As tall buildings become taller and more slender, wind-induced vibration is a serious design issue. Installing auxiliary damping devices, such as tuned mass dampers (TMD), is a very reliable solution. TMDs are usually large and located near the top of tall buildings for their effective performance. As a result, very valuable occupiable space near the top of tall buildings is sacrificed to contain large TMDs, and installing TMD systems results in adding additional masses to tall buildings. In order to address these issues, more integrated TMD systems for tall buildings are studied. First, distributing multiple small TMDs to multiple upper floors of tall buildings is investigated. The study results suggest this can be done without substantial loss of the effectiveness of the system. Second, designing existing masses in tall buildings to provide damping mechanism is studied. An emphasis is placed on studying the potential of double skin façades (DSF) as an integrated damping system. For this, the connectors between the inner and outer skins of the DSF system are designed to have very low axial stiffness, and the outer skin masses of the DSF system is utilized as damping mass. Wind-induced vibration of tall building structure can be substantially reduced through this design. Finally, TMD/DSF interaction system is studied to synergistically enhance the performance of the TMD and DSF damping systems.

Keywords: Vertical distribution, Integrated damping system, Double skin facades.

1 INTRODUCTION

Tuned mass dampers (TMDs), which effectively reduce wind-induced dynamic motions of tall buildings, have been installed in many tall buildings throughout the world. TMDs are usually located near the top of tall buildings for effective performance (Soong and Dargush 1997), such as the sliding-type TMDs in the Citicorp Building in New York and the John Hancock Building in Boston, and the pendulum type TMD installed in Taipei 101. When only one or two large TMDs are installed, they occupy a very large space near the top of tall buildings. This paper investigates the option of distributing multiple small TMDs over the building height. By distributing multiple small TMDs to multiple floors, valuable space near the top can be saved for other functions which can maximize the advantage of great views. Further, by distributing multiple small TMDs, greater reliability can be obtained in case some of them do not function properly or have some tuning errors. TMDs are sometimes installed retroactively while buildings are already in use. Distributed multiple small TMDs can be more easily installed with minimum disturbance to building use.

While the horizontal distribution of multiple TMDs has been studied by many researchers (*cf.* Kareem and Klein 1995, Yamaguchi and Harnpornchai 1993), the vertical distribution of TMDs has rarely been investigated. Bergman et al. (1989) presented the effectiveness of vertically-distributed multiple TMDs, using a cantilever-beam building model having a maximum of three TMDs, distributed from the top of the building to three-fifths of the building height. Several cases were presented without specifying optimal tuning for each case.

This paper studies how vertically-distributed multiple TMDs depend on the vertical location of the TMD, and how their optimal tuning frequency ratio and the damping ratio should be adjusted accordingly for optimal performance. Further, this paper investigates the potential of utilizing existing masses in tall buildings for damping purposes. An emphasis is placed on studying the integrative design of double-skin facades (DSF) to produce damping mechanisms.

DSF systems are composed of two layers of facades with substantial gaps between them. While many studies have been performed regarding the environmental performance of the DSF system, research on its structural potential is very rare. In order to investigate the potential of the DSF system as a structural motion control device, the connectors between the inner and outer skins of the DSF system is designed to have very low axial stiffness with a damping mechanism, and the outer skin masses are utilized as damping masses. With this design concept, the wind-induced vibration of tall building structures can be substantially reduced. In order to synergistically enhance the performance of the distributed TMDs and DSF damping systems, TMD/DSF interaction system is also studied.

2 VERTICALLY-DISTRIBUTED MULTIPLE-TUNED MASS DAMPERS

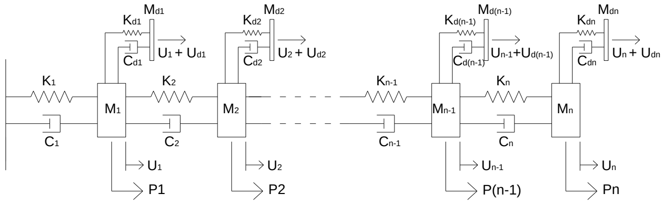


Figure 1. NDOF/NTMD system model.

Figure 1 shows the NDOF/NTMD system model. Vertically-distributed TMD system equations can be set up approximately by reducing the NDOF system primary structure to a SDOF system, considering the importance of the first-mode response (Hartog 1956, Connor 2003). By solving the equations below, the dynamic amplification factor of the primary structure can be obtained.

$$m\ddot{u}+c\dot{u}+ku=p+\frac{\phi_{11}}{\phi_{1n}}(k_{d1}u_{d1}+c_{d1}\dot{u}_{d1})+......+\frac{\phi_{1(n-1)}}{\phi_{1n}}(k_{d(n-1)}u_{d(n-1)}+c_{d(n-1)}\dot{u}_{d(n-1)})+(k_{dn}u_{dn}+c_{dn}\dot{u}_{dn}) \quad (1)$$

$$m_{d1}\ddot{u}_{d1}+c_{d1}\dot{u}_{d1}+k_{d1}u_{d1}=-\frac{\phi_{11}}{\phi_{1n}}m_{d1}\ddot{u} \quad (2)$$

$$m_{d2}\ddot{u}_{d2}+c_{d2}\dot{u}_{d2}+k_{d2}u_{d2}=-\frac{\phi_{12}}{\phi_{1n}}m_{d2}\ddot{u} \quad (3)$$

$$m_{d(n-1)}\ddot{u}_{d(n-1)} + c_{d(n-1)}\dot{u}_{d(n-1)} + k_{d(n-1)}u_{d(n-1)} = -\frac{\phi_{1(n-1)}}{\phi_{1n}} m_{d(n-1)}\ddot{u} \tag{4}$$

$$m_{dn}\ddot{u}_{dn} + c_{dn}\dot{u}_{dn} + k_{dn}u_{dn} = -m_{dn}\ddot{u} \tag{5}$$

TMDs located on the floors close to the ground are not as effective as ones located on the higher floors with regard to the first mode. The model shown in Figure 1 can be modified, and the equations shown above adjusted accordingly. Figure 2 shows 6DOF/4TMD system as an example.

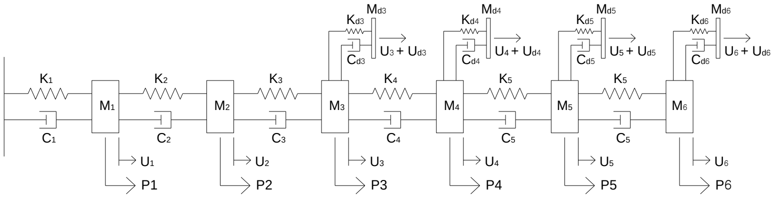
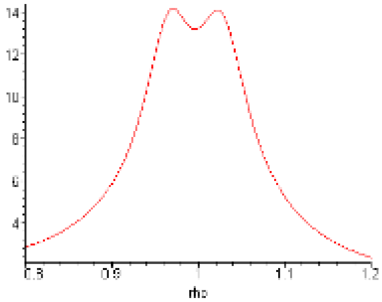


Figure 2. 6DOF/4TMD system model.

Once the 6DOF primary structure is reduced to a SDOF system, the solution due to periodic excitation can be expressed as:

$$\bar{u} = \frac{\hat{p}}{k} He^{i\delta} \tag{6}$$

Here, $\bar{u}$ is the displacement at node 6 of the 6DOF system, and H is the dynamic amplification factor. Figure 3 shows the H plot when four TMDs, with mass ratio of 0.25% for each, are installed at nodes 3, 4, 5 and 6, and tuned for the optimal performance by iteration. The inherent structural damping ratio of 1% without a TMD system is assumed in this study. With the vertically distributed TMDs shown in Figure 2, the equivalent damping ratio is increased to 3.6%.



f3 = 0.995, f4 = 0.994, f5 = 0.993, f6 = 0.991 (f: frequency ratio)
$\xi d3$ = 0.035, $\xi d4$ = 0.045, $\xi d5$ = 0.055, $\xi d6$ = 0.065 (ξd: TMD damping ratio)

Figure 3. H value of the 6DOF/4TMD system model.

Similar studies were performed with 6DOF/3TMD and 6DOF/2TMD systems, with individual TMD mass ratios of 0.33% and 0.5% respectively. Equivalent damping ratios of 3.8% and 4.1% were obtained for the former and later respectively. Broader vertical distribution of TMDs results in less effectiveness. However, the reduction of the effectiveness is not significant and could be acceptable depending on design situations.

3 TALL BUILDING MOTION CONTROL USING DOUBLE SKIN FACADES

Wind loads are initially applied to the building facades and then transmitted to the primary structures. Considering this fact, the connectors between the DSF outer skins and the building's primary structure are designed to have very low axial stiffness, so the transmissibility of the dynamic wind loads can be reduced through them.

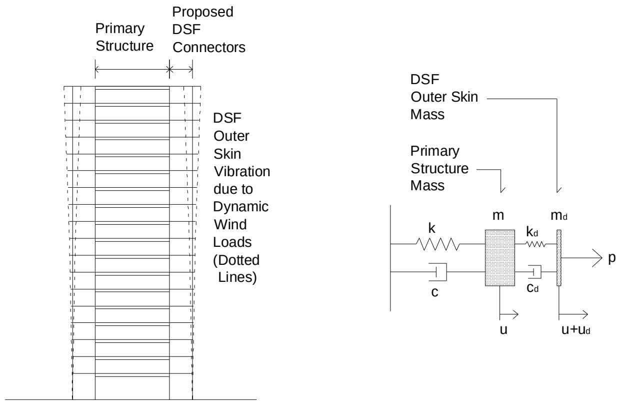


Figure 4. DSF Damping system concept and simplified model.

Figure 4 shows a concept diagram and simplified model of the system. The system is composed of the primary mass (m), which corresponds to the primary building structure including the inner skins of the DSF system, and the secondary mass (md), which corresponds to the outer skins of the DSF system. The two masses are connected by low-axial-stiffness spring (Kd) and damper components (Cd). Sinusoidal load (p) is applied to the secondary mass to anticipate the system performance in vortex-shedding-induced vibration conditions. The dynamic amplification factors for the primary structure (H) and the DSF outer skin (Hd) can be expressed as:

$$H = \frac{\sqrt{f^4 + 4f^2 {\xi_d}^2 \rho^2}}{\sqrt{(f^2 \overline{m} \rho^2 - \rho^4 + \rho^2 + f^2 \rho^2 - f^2 + 4\xi \rho^2 \xi_d f)^2 + (2\rho^3 \xi_d f + 2\xi \rho^3 - 2\xi \rho f^2 - 2f \xi_d \rho + 2\overline{m} \rho^3 \xi_d f)^2}} \tag{7}$$

$$H_d = \frac{\sqrt{(\rho^2 - 1)^2 + 4\xi^2 \rho^2}}{m\sqrt{(f^2 \overline{m} \rho^2 - \rho^4 + \rho^2 + f^2 \rho^2 - f^2 + 4\xi \rho^2 \xi_d f)^2 + (2\rho^3 \xi_d f + 2\xi \rho^3 - 2\xi \rho f^2 - 2f \xi_d \rho + 2\overline{m} \rho^3 \xi_d f)^2}} \tag{8}$$

ξ = primary structure damping ratio; ξ_d = façade connector damping ratio; ω = natural frequency of the primary structure; ω_d = natural frequency of the DSF outer skin; $\overline{m} = {}^{m_d}\!/_{m}$; $f = {}^{\omega_d}\!/_{\omega}$; $\rho = {}^{\Omega}\!/_{\omega}$, Ω: Forcing Frequency.

The DSF outer skin mass is assumed to be 1% of the primary structure mass in this study. Figure 5 shows the study results of the case when the natural frequency of the DSF connector is half that of the primary structure (f = 0.5). With this low axial stiffness of the DSF connectors, the proposed system substantially reduces the transmissibility of the applied dynamic wind loads from the DSF outer skins to the primary structure. The maximum H value is about 16 with optimal tuning, with the DSF connector damping ratio of about 4%. However, the Hd value for the DSF outer skin is very high in this case.

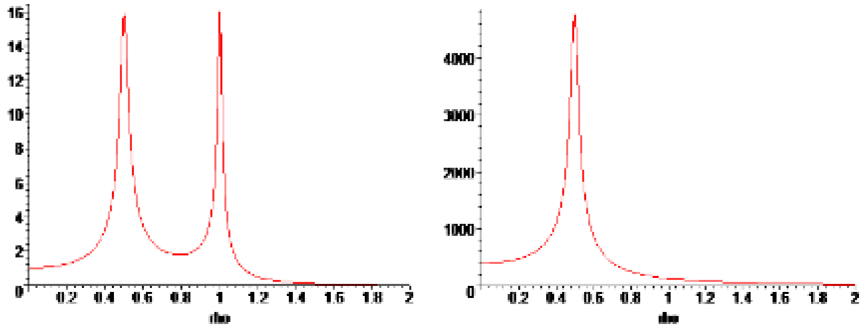


Figure 5. Dynamic amplification factor of the primary structure, H (left) and DSF outer skin, Hd (right) with f = 0.5 and $\xi_d = 4\%$.

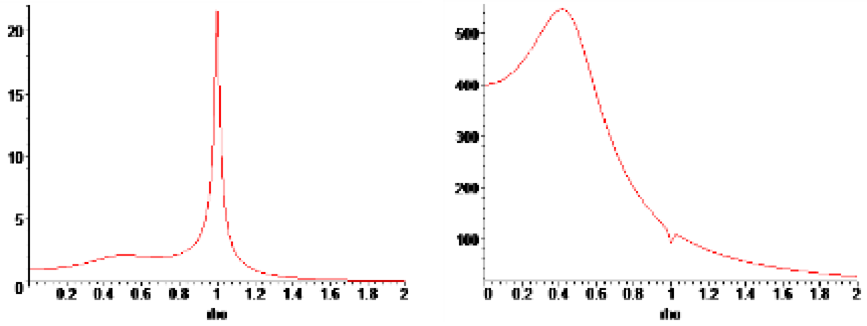


Figure 6. Dynamic amplification factor of the primary structure, H (left) and DSF outer skin, Hd (right) with f = 0.5 and $\xi_d = 40\%$.

By increasing the DSF connector-damping ratio to 40%, the Hd value can be significantly reduced as per Figure 6. However, the maximum H value in this case is increased to 22. In order to resolve this issue, the TMD/DSF interaction system is studied. By incorporating the conventional TMD concept with the studied DSF damping system, the effectiveness of the whole system can be significantly increased. Figure 7 shows a simplified model of the interaction system. In this model, M is the primary structure mass, Md1 is the TMD mass, and Md2 is the DSF outer skin mass. With a TMD mass ratio of only 0.1%, and the studied DSF damping system having a mass ratio of 1%, the maximum H value of the optimally-tuned TMD/DSF damping interaction system is about 8. With the conventional TMD system, this H value can be obtained with a mass ratio of about 2.5.

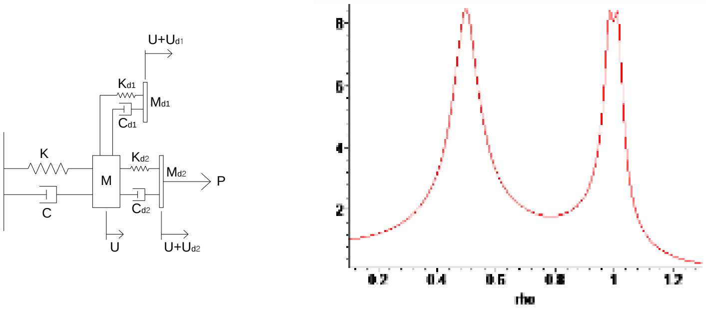


Figure 7. TMD/DSF interaction system model (left) and optimal H value plot (right) with TMD mass ratio = 0.1% and DSF outer skin mass ratio = 1%.

4 CONCLUSION

Through the studies of the vertically distributed TMDs, DSF damping mechanism with low stiffness connectors and the TMD/DSF damping interaction system, new design strategies to mitigate wind-induced vibrations of tall buildings were presented. Further studies are required for practical applications of the presented theoretical studies. With rapid development of new building technologies, studies on more integrative ways of designing building systems are crucial to synergistically enhance their performances. More rigorous investigative work on new building technologies will eventually produce higher quality and more sustainable built environments.

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