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Integrated and Sustainable Damping Systems for Tall Buildings

高层建筑中的综合可持续性阻尼系统



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Abstract

Integrated damping systems for tall buildings are studied to mitigate wind-induced vibration of tall buildings. First, vertically distributed multiple tuned mass damper (TMD) systems are investigated in comparison with the conventional TMD systems. TMDs can be distributed along the building height without substantial loss of the system effectiveness. Second, utilizing existing systems in tall buildings, such as double skin Façades (DSF), to provide damping mechanism is studied. The connectors between the inner and outer skins of the DSF system are designed to have very low axial stiffness and damping mechanism. Through this DSF damping (DSFD) system design, wind-induced vibration of the primary building structure can be substantially reduced. However, excessive movements of the DSF outer skin masses are a critical design limitation. Finally, TMD/DSFD interaction system is studied to mitigate the design limitation of the DSFD system, and to address TMD related other design issues. Compared with the conventional TMD system, the TMD/DSFD interaction system requires a significantly reduced TMD mass ratio. Compared with the DSFD system, movements of the DSF outer skin masses can be substantially reduced in the TMD/DSFD interaction system. Further research is required for practical application of these theoretical studies.

Keywords: Tall Buildings, Structural Systems, Tuned Mass Dampers, Double Skin Façades

摘要

高层建筑中的综合性阻尼系统研究是为了减轻高层建筑的结构性风震。首先，竖向分布的多重调谐质量阻尼系统的研究是为了与传统的调谐质量阻尼 (TMD) 系统作比较。调谐质量阻尼器会在不造成重大系统有效性损失的前提下分布在建筑物的不同高度。其次，利用高层建筑的现有系统，例如双层幕墙 (DSF)，来提供阻尼机械装置的方法也在研究中。双层幕墙的内墙和外墙的连接器被设计成有很低的轴向刚度和阻尼的机械装置。通过双层幕墙阻尼 (DSFD) 系统的设计，高层建筑的结构性风震可被显著减轻。然而，双层幕墙外墙的过度移动是一个关键性的设计限制。最后，调谐质量阻尼 / 双层幕墙阻尼交互 (TMD / DSFD) 系统的研究是为了降低双层幕墙阻尼系统的限制和处理其它有关调谐质量阻尼器的设计问题。与传统的调谐质量阻尼系统比较，调谐质量阻尼 / 双层幕墙阻尼交互系统需要一个显著减小的调谐质量阻尼器质量比重。与双层幕墙阻尼系统比较，双层幕墙外墙的过度移动的问题可在调谐质量阻尼和双层幕墙阻尼交互系统中显著减少。更进一步的研究需要对此类理论研究的实际运用。

关键词: 高层建筑、结构系统、调谐质量阻尼器、双层幕墙

Introduction

As tall buildings become ever taller and more slender, wind-induced vibration is a serious design issue. Installing auxiliary damping devices, such as tuned mass dampers (TMD), is a reliable solution. However, TMDs are usually very large and occupy valuable space near the top of tall buildings for their effective performance. In addition, installing TMD systems results in adding additional masses to tall buildings. In order to address these issues, more integrated damping systems for tall buildings are studied.

First, distributing multiple small TMDs to multiple upper floors of tall buildings is investigated. While horizontal distribution of multiple TMDs has been studied by many

序言

随着高层建筑变得越来越细长，结构性风震成为一个严重的设计问题。安装辅助的阻尼系统，例如调谐质量阻尼器 (TMD) 就是一个可靠的解决方案。然而，调谐质量阻尼器重量常常非常大，并且为了它们有效地发挥性能需要占据高层建筑物顶部附近的宝贵空间。另外，安装调谐质量阻尼器还会导致高层建筑增加附加重量。为了处理这些问题，更多高层建筑中的综合性阻尼系统正在研究中。

首先研究将多个小的调谐质量阻尼器安装在高层建筑的多个上部楼层的方法。虽然，横向分布的多重调谐质量阻尼系统已被很多研究人员研究，比如Kareem and Klein (1995)、Yamaguchi和Harnpornchai (1993)，而竖向分布的多重调谐质量阻尼

researchers, such as Kareem and Klein (1995) and Yamaguchi and Harnpornchai (1993), vertical distribution of TMDs has rarely been investigated. Bergman et al. (1989) presented effectiveness of vertically distributed multiple TMDs using a cantilever beam building model having a maximum of three TMDs distributed from the top to the three fifth building height. Several cases were presented without specifying optimal tuning for each case. This paper studies optimally tuned vertically distributed multiple TMDs.

Second, providing damping mechanism with existing systems in tall buildings is studied. An emphasis is placed on studying the potential of double-skin façades (DSF) as an integrated damping system for tall buildings. While a significant amount of studies has been conducted regarding the environmental performance of the DSF system, the structural potential of the DSF has rarely been investigated. Moon (2009) studied the structural capability of the DSF system to mitigate wind-induced vibration of tall buildings. The connectors between the inner and outer skins of the DSF system are designed to have very low axial stiffness to reduce the transmissibility of dynamic wind loads. Through this DSF damping (DSFD) system design, the vibration of the primary building structure can be substantially reduced. However, excessive movements of the DSF outer skin masses are a critical design limitation. This paper reviews Moon's study and further investigations are made regarding the optimal condition of the DSFD system.

Finally, TMD/DSFD interaction system is studied to resolve the limitation of the DSFD system and to address TMD related other design issues. Compared with the conventional TMD system, the TMD/DSFD interaction system requires a significantly reduced TMD mass ratio to obtain the identical target damping ratio. Compared with the DSFD system, the movements of the DSF outer skin masses can be substantially reduced in the TMD/DSFD interaction system.

It is expected that the number of tall buildings in major cities throughout the world will be continuously increased, and the importance of their design for safety, comfort and sustainability cannot be overemphasized. This research investigates integrated damping systems for tall buildings, focusing on the potential of the DSF system – one of the most advanced and sustainable façade systems for tall buildings (Oesterle et al., 2001) – as a damping mechanism through synergistic systems integration.

Distributed Multiple TMDs

When only one or two large TMDs are installed, they occupy very large space near the top of tall buildings. By distributing multiple small TMDs to multiple floors, however, 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 as retrospective actions while buildings are already in use. Distributed multiple small TMDs can be more easily installed with minimum disturbance to building use.

Depending on the vertical location of the TMD, its tuning frequency ratio as well as damping ratio should be adjusted accordingly for optimal performance (Moon, 2010). Figure 1 shows 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 (Connor, 2003; Hartog, 1956). Equations 1 through 5

系统却很少被研究。Bergman等人(1989)通过使用一个悬臂梁建筑模型,演示了竖向分布的多重调谐质量阻尼系统的有效性,这个模型拥有三个调谐质量阻尼器分布在高层建筑顶部到建筑五分之三高度的范围内。还有几个案例在没有具体指出每个案例的优化调谐情况下被演示。本文将研究优化调谐的竖向分布的多重调谐质量阻尼系统。

其次,研究利用高层建筑现有系统来提供阻尼机械装置的方法。这项研究的重点被放在研究双层幕墙(DSF)作为高层建筑的一种综合性阻尼系统的可能性。虽然已经有很大一批关于双层幕墙系统的环境性能的研究,但是关于双层幕墙的结构可能性还很少被研究。Moon(2009)研究了双层幕墙系统对于减轻高层建筑的结构性风震所展现的结构性能。双层幕墙的内墙和外墙的连接器被设计成有很低的轴向刚度以减低动力风荷载的传递。通过双层幕墙阻尼(DSFD)系统的设计,建筑物的原有结构的震动可被显著减小。然而,双层幕墙外墙的过度移动是一个关键性的设计限制。本文回顾了Moon的研究成果并且提供了关于优化双层幕墙阻尼系统的进一步研究。

最后,调谐质量阻尼/双层幕墙阻尼交互系统的研究是为了解决双层幕墙阻尼系统的限制和处理其它有关调谐质量阻尼器的设计问题。与传统的调谐质量阻尼系统比较,调谐质量阻尼/双层幕墙阻尼交互、系统需要一个显著减少的调谐质量阻尼器质量比重以得到同样的目标阻尼比重。与双层幕墙阻尼系统比较,双层幕墙外墙过度移动的问题可在调谐质量阻尼/双层幕墙阻尼交互系统中显著减少。

可以预见的是,全世界主要城市的高层建筑数目仍会持续增长,而对于有关它们安全性,舒适度和可持续性设计的重要性不能被强调。这项研究涉及到高层建筑中的综合性阻尼系统,专注于双层幕墙阻尼系统——高层建筑中最先进和可持续的幕墙系统之一(Oesterle等人,2001),即通过综合协同系统作为阻尼机械装置的可能性。

分布式的多重调谐质量阻尼系统

当只有一个或两个大型的调谐质量阻尼器被安装时,它们占据了高层建筑物顶部附近的宝贵空间。然而,通过把多个小型调谐质量阻尼器分布在多个楼层,高层建筑物顶部附近的宝贵空间可被节省出来用作其它功能,而这也可以使景观优势最大化。另外,通过把多个小型调谐质量阻尼器分布在多个楼层可以提高可靠性,避免其中有些调谐质量阻尼器不能正常运作或者发生调谐错误。调谐质量阻尼器有时在建筑使用过程中被追加安装。分布式的多个小型调谐质量阻尼器可在最小程度影响建筑物使用功能的情况下被更容易地安装。

取决于调谐质量阻尼器的竖向位置,它的调谐频率和阻尼比重也需要相应作出调整以达到优化的性能(Moon, 2010)。

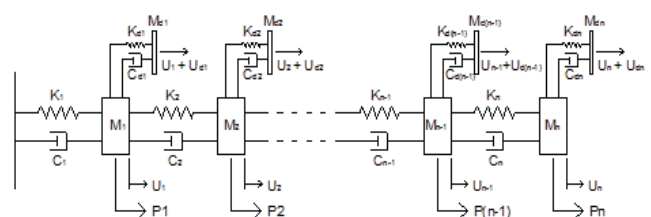


Figure 1. NDOF/NTMD system.

图1. 多自由度 / 多重调谐质量阻尼系统

show the governing equations. By solving these equations, dynamic amplification factor of the primary structure can be obtained.

$$\begin{aligned} \ddot{m}u + \dot{c}u + ku &= p + \frac{\phi_{11}}{\phi_{1n}}(k_{d1}u_{d1} + c_{d1}\dot{u}_{d1}) + \dots + \frac{\phi_{1(n-1)}}{\phi_{1n}}(k_{d(n-1)}u_{d(n-1)} + c_{d(n-1)}\dot{u}_{d(n-1)}) + (k_{dn}u_{dn} + c_{dn}\dot{u}_{dn}) \\ m_{d1}\ddot{u}_{d1} + c_{d1}\dot{u}_{d1} + k_{d1}u_{d1} &= -\frac{\phi_{11}}{\phi_{1n}}m_{d1}\ddot{u} \\ m_{d2}\ddot{u}_{d2} + c_{d2}\dot{u}_{d2} + k_{d2}u_{d2} &= -\frac{\phi_{12}}{\phi_{1n}}m_{d2}\ddot{u} \\ m_{d(n-1)}\ddot{u}_{d(n-1)} + c_{d(n-1)}\dot{u}_{d(n-1)} + k_{d(n-1)}u_{d(n-1)} &= -\frac{\phi_{1(n-1)}}{\phi_{1n}}m_{d(n-1)}\ddot{u} \\ m_{dn}\ddot{u}_{dn} + c_{dn}\dot{u}_{dn} + k_{dn}u_{dn} &= -m_{dn}\ddot{u} \end{aligned}$$

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

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

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

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 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%.

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 could be acceptable depending on project specific design situations.

DSFD Systems

Installing TMDs results in adding additional masses to tall buildings. This section investigates utilizing existing systems in tall buildings to produce damping mechanism. The use of DSF systems for tall buildings has been gaining increased interest due to their superior environmental performance. The structural potential of DSF systems is investigated here. Wind loads are initially applied to the building Façades and then transmitted to the primary structures. Considering this fact, the connectors between the DSF outer skins and the building's primary structure is designed to have very low axial stiffness, so the transmissibility of the dynamic wind loads can be reduced through them.

Figure 4 shows a concept diagram and simplified model of the DSFD 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

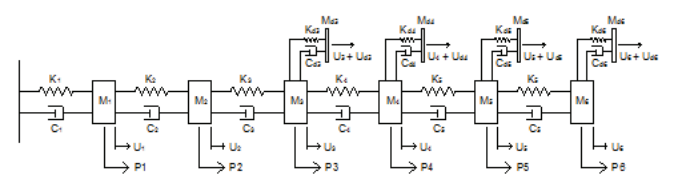


Figure 2. 6DOF/4TMD system.
图2. 6自由度 / 4个调谐质量阻尼系统

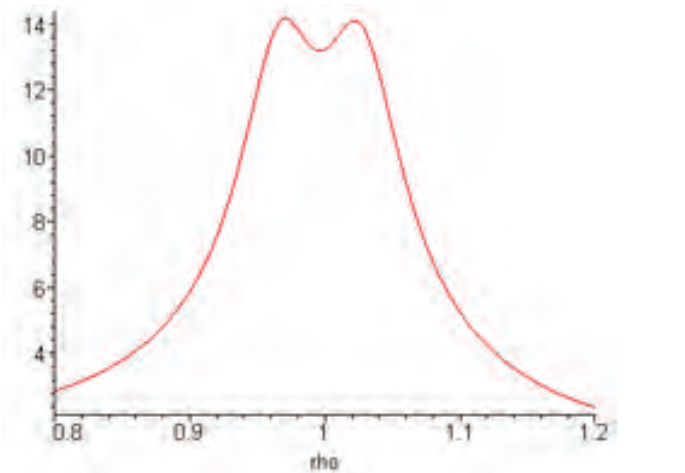


Figure 3. H value of the 6DOF/4TMD system model with frequency ratio f3 = 0.995, f4 = 0.994, f5 = 0.993, f6 = 0.991, TMD damping ratio d3 = 0.035, d4 = 0.045, d5 = 0.055, d6 = 0.065.
图3. 示意了6个自由度 / 4个调谐质量阻尼系统中当频率f3 = 0.995, f4 = 0.994, f5 = 0.993, f6 = 0.991, TMD 阻尼比重 d3 = 0.035, d4 = 0.045, d5 = 0.055, d6 = 0.065 时, H值的变化

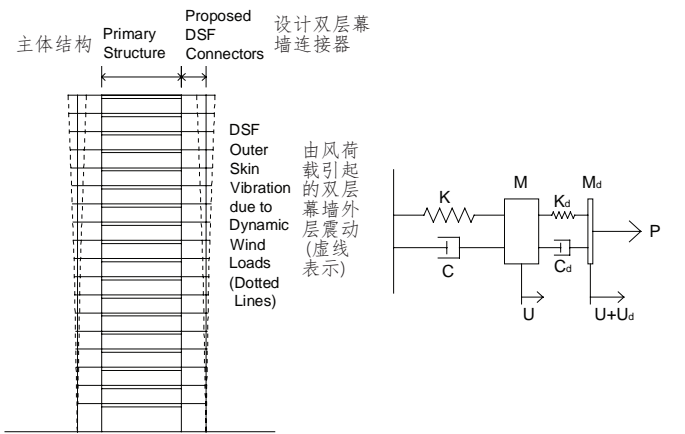


Figure 4. DSFD system concept (left) and simplified model (right).
图4. 双层幕墙概念 (左) 和简化模型 (右)

图1示意了多自由度 / 多重阻尼系统模型。考虑到第一振型反应 (Connor, 2003; Hartog, 1956) 的重要性, 可以通过把原有结构的多自由度系统简化为单自由度系统来近似建立竖向分布的调谐质量阻尼系统公式。公式1到5示意了控制的公式。通过求解这些公式可以得到原有结构的动力放大系数。

$$\begin{aligned} \ddot{m}u + \dot{c}u + ku &= p + \frac{\phi_{11}}{\phi_{1n}}(k_{d1}u_{d1} + c_{d1}\dot{u}_{d1}) + \dots + \frac{\phi_{1(n-1)}}{\phi_{1n}}(k_{d(n-1)}u_{d(n-1)} + c_{d(n-1)}\dot{u}_{d(n-1)}) + (k_{dn}u_{dn} + c_{dn}\dot{u}_{dn}) \\ m_{d1}\ddot{u}_{d1} + c_{d1}\dot{u}_{d1} + k_{d1}u_{d1} &= -\frac{\phi_{11}}{\phi_{1n}}m_{d1}\ddot{u} \\ m_{d2}\ddot{u}_{d2} + c_{d2}\dot{u}_{d2} + k_{d2}u_{d2} &= -\frac{\phi_{12}}{\phi_{1n}}m_{d2}\ddot{u} \\ m_{d(n-1)}\ddot{u}_{d(n-1)} + c_{d(n-1)}\dot{u}_{d(n-1)} + k_{d(n-1)}u_{d(n-1)} &= -\frac{\phi_{1(n-1)}}{\phi_{1n}}m_{d(n-1)}\ddot{u} \\ m_{dn}\ddot{u}_{dn} + c_{dn}\dot{u}_{dn} + k_{dn}u_{dn} &= -m_{dn}\ddot{u} \end{aligned}$$

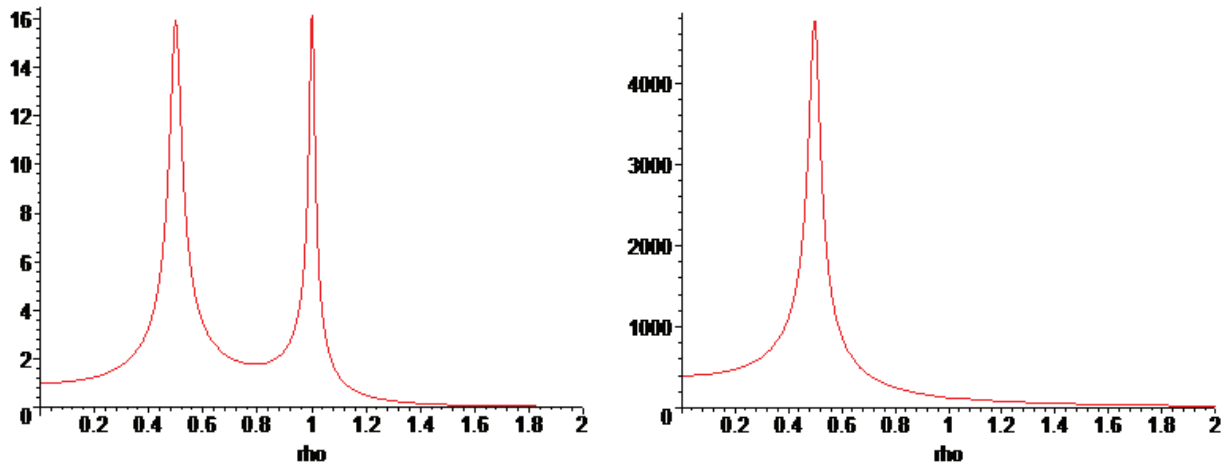


Figure 5. Dynamic amplification factor of the primary structure, H (left) and DSF outer skin, Hd (right) with $f = 0.5$ and $d4\%$.
图5原有结构的动力放大系数，H值(左)和双层幕墙外墙，Hd值(右)， $f=0.5$, $d4\%$

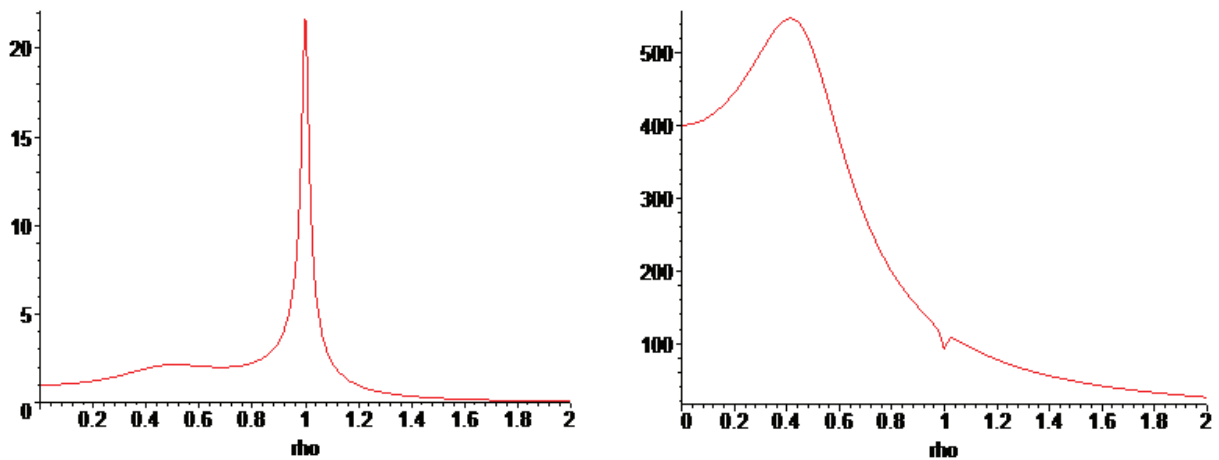


Figure 6. Dynamic amplification factor of the primary structure, H (left) and DSF outer skin, Hd (right) with $f = 0.5$ and $d40\%$.
图6原有结构的动力放大系数，H值(左)和双层幕墙外墙，Hd值(右)， $f=0.5$, $d40\%$

system performance in vortex-shedding-induced vibration conditions. Equations 7 and 8 express the dynamic amplification factors for the primary structure, H, and the DSF outer skin, Hd (Moon, 2009)

$$H = \frac{\sqrt{f^4 + 4f^2\zeta_d^2\rho^2}}{\sqrt{(f^2\bar{m}\rho^2 - \rho^4 + \rho^2 + f^2\rho^2 - f^2 + 4\zeta_d^2\zeta_d f)^2 + (2\rho^3\zeta_d f + 2\zeta_d\rho^3 - 2\zeta_d f^2 - 2\bar{m}\rho^3\zeta_d f)^2}}$$

$$H_d = \frac{\sqrt{(\rho^2 - 1)^2 + 4\zeta_d^2\rho^2}}{m\sqrt{(f^2\bar{m}\rho^2 - \rho^4 + \rho^2 + f^2\rho^2 - f^2 + 4\zeta_d^2\zeta_d f)^2 + (2\rho^3\zeta_d f + 2\zeta_d\rho^3 - 2\zeta_d f^2 - 2\bar{m}\rho^3\zeta_d f)^2}}$$

primary structure damping ratio; d façade connector damping ratio; ω = natural frequency of the primary structure; d = natural frequency of the DSF outer skin; $\bar{m} = m_d/m$ $f = \omega_d/\omega$ $\rho = \Omega/\omega$ Forcing Frequency.

The DSF outer skin mass is assumed to be 1% of the primary structure mass in this study. Figure 5 shows H and Hd plots of the case when the natural frequency of the DSF connector is half that of the primary structure ($f = 0.5$) and the system is optimally tuned for H. With this low axial stiffness of the DSF connectors, the 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, Hd value for the DSF outer skin is very high in this case.

By increasing the DSF connector damping ratio to 40%, Hd value can be significantly reduced as can be seen in Figure 6. However,

位于靠近地面楼层的调谐质量阻尼器没有位于高处楼层的有效。图1所示模型和以上的公式可被相应调节。图2示意了6自由度 / 4个调谐质量阻尼系统的例子。

一旦原有结构的6自由度被简化为单自由度系统，由于周期性激励导致的结果可被表示为

$$\bar{u} = \frac{\hat{p}}{k} H e^{i\delta}$$

在此 \bar{u} 是6自由度中6号位的位移，而H是动力放大系数。图3示意了当有4

个调谐质量阻尼器在每个质量比重为0.25%的条件下，安装在3、4、5、6的点位并多次调试已得到优化表现时H值的变化。在这项研究中，固有结构的阻尼比重被假设为1%没有阻尼系统。在图2示意的调谐质量阻尼竖向分布的情况下，相应的阻尼比重增加到3.6%。

类似的研究在6自由度 / 3个调谐质量阻尼以及6自由度 / 2个调谐质量阻尼的情况下执行，单个调谐质量阻尼器的质量比重相应为0.33%和0.5%。前后两者得到的相应阻尼比重分别为3.8%和4.1%。调谐质量阻尼器广泛地竖向分布会导致其有效性降低。然而，有效性的降低可以视项目的具体设计情况而被接受。

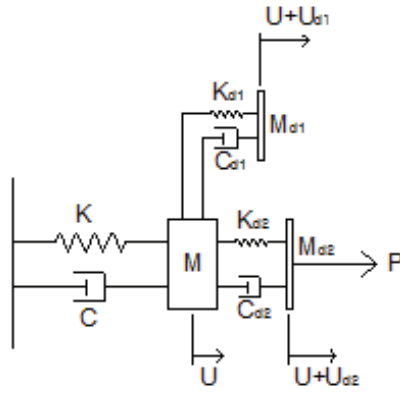


Figure 7. Simplified TMD/DSFD system model.
图7. 简化的调谐质量阻尼 / 双层幕墙阻尼系统模型

the maximum H value in this case is increased to 22. Therefore, the effectiveness of the system in terms of controlling the vibration of the primary structure is substantially reduced. Hd values can also be decreased by increasing the DSF outer skin mass ratio. A mass ratio of 1% was used for the DSF outer skin in this study. By increasing the mass ratio to 2%, for example, the maximum Hd value can be reduced by 50%. However, considering that one of the most important purposes of the DSFD system study is to utilize existing systems in tall buildings as damping mechanism, increasing the DSF outer skin mass results in adding additional masses, and, consequently, does not satisfy the important purpose of the study. Another strategy to decrease Hd values is to increase the axial stiffness of DSF connectors. However, as the stiffness ratio, f, is increased, the effectiveness of the DSFD system is reduced significantly. In fact, as the stiffness ratio becomes about 1, the DSFD system no longer performs as damping mechanism. The system performs as a force amplifier instead. In order to resolve the issue of excessive movements of DSF outer skins in the DSFD system, TMD/DSFD interaction system is studied in the following section.

TMD/DSFD Interaction Systems

By incorporating the DSFD with the conventional TMD system, the effectiveness of the combined 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.

Below are the governing equations of the system shown in Figure 7.

$$\ddot{m}u + \dot{c}u + ku = c_{d1}\dot{u}_{d1} + k_{d1}u_{d1} + c_{d2}\dot{u}_{d2} + k_{d2}u_{d2}$$

$$m_{d1}(\ddot{u}_{d1} + \ddot{u}) + c_{d1}\dot{u}_{d1} + k_{d1}u_{d1} = 0$$

$$m_{d2}(\ddot{u}_{d2} + \ddot{u}) + c_{d2}\dot{u}_{d2} + k_{d2}u_{d2} = p$$

The solutions due to a harmonic excitation can be expressed as

$$\bar{u} = \frac{\hat{p}}{k} H e^{i\delta_1}$$

$$\bar{u}_{d1} = \frac{\hat{p}}{k} H_{d1} e^{i\delta_2}$$

$$\bar{u}_{d2} = \frac{\hat{p}}{k} H_{d2} e^{i\delta_3}$$

双层幕墙系统

安装调谐质量阻尼器会导致高层建筑增加附加重量。这个章节将探讨利用高层中的现有系统来作为阻尼机械装置的方法。在这节中，将研究双层幕墙的结构可能性。风荷载首先影响到建筑物表皮，然后传递到主要结构。考虑到这个事实，双层幕墙的内外墙连接器被设计成有很低的轴向刚度，以减小动力风荷载的传递。

图4展示了双层幕墙系统的概念图和简化模型。这个系统是由包括双层幕墙中内墙的原有的建筑结构重量 (m) 以及外墙重量 (md) 等参数描述的。这两个重量则是由低轴向刚度弹簧 (Kd) 和阻尼成分 (Cd) 联系起来的。

在此研究中，双层幕墙的外墙重量被假设为原有结构的1%。图5显示当双层幕墙连接器的固有频率是原有结构的一半时，系统根据H值经过优化后 (f=0.5) 对于H和Hd的计算。带有较低轴向刚度连接器的双层幕墙阻尼系统则可以大幅度减小由外墙到原有结构的风荷载传递。H的最大值大约为16，双层幕墙连接器的阻尼比被优化为4%。但是在这样的情况下双层幕墙外墙的Hd值仍然非常高。

当双层幕墙阻尼连接器比重上升为40%的时候，Hd值被有效地减小到如图6所示。但是，在这样的情况下H的最大值上升为22。因此，系统对于控制原有结构震动的功效被大大削减了。Hd值可以因双层幕墙外墙比重的增大而减小。在此研究中双层幕墙外墙的比重为1%。当该比重上升为2%时，Hd的最大值可以减少50%。但是，考虑到研究双层幕墙阻尼系统的一个重要因素是运用现有高层建筑的系统作为阻尼机构，以增加外墙重量的方式来增加总体重量并不是主要的研究目的。而降低Hd值的另外一种方式是增加双层幕墙阻尼连接器的轴向刚度。但是，当刚度比f增加时，双层幕墙阻尼系统的功效将会大大降低。实际上，当刚度比大约为1时，双层幕墙阻尼系统将不再是阻尼机构。这个系统将成为增力机构。以下章节将讨论调谐质量阻尼 / 双层幕墙阻尼交互系统，来解决双层幕墙阻尼系统中外墙过度震动的问题。

调谐质量阻尼 / 双层幕墙阻尼交互系统

通过结合双层幕墙阻尼和传统的调谐质量阻尼而形成的新交互系统可以大幅提高系统的功效。图7展示了简化的调谐质量阻尼 / 双层幕墙阻尼系统模型。在这个模型中，M是原有的结构质量，Md1是调谐质量阻尼的质量，Md2是双层幕墙外墙的质量。

以下是图7中系统的主要公式

$$\ddot{m}u + \dot{c}u + ku = c_{d1}\dot{u}_{d1} + k_{d1}u_{d1} + c_{d2}\dot{u}_{d2} + k_{d2}u_{d2}$$

$$m_{d1}(\ddot{u}_{d1} + \ddot{u}) + c_{d1}\dot{u}_{d1} + k_{d1}u_{d1} = 0$$

$$m_{d2}(\ddot{u}_{d2} + \ddot{u}) + c_{d2}\dot{u}_{d2} + k_{d2}u_{d2} = p$$

在谐波激励下的解决方案可以被表达为:

$$\bar{u} = \frac{\hat{p}}{k} H e^{i\delta_1}$$

$$\bar{u}_{d1} = \frac{\hat{p}}{k} H_{d1} e^{i\delta_2}$$

$$\bar{u}_{d2} = \frac{\hat{p}}{k} H_{d2} e^{i\delta_3}$$

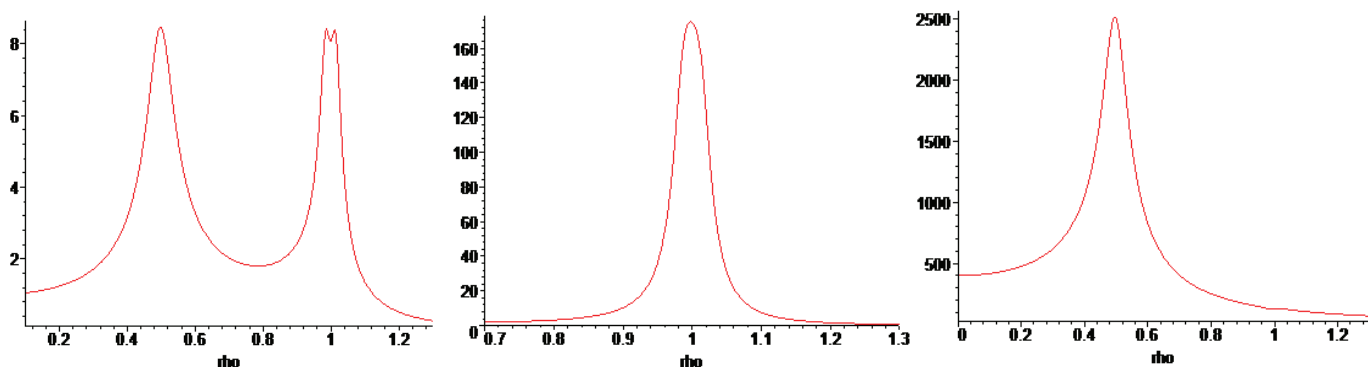


Figure 8. TMD/DSFD system's H (left), Hd1 (middle) and Hd2 (right) with $m_1=0.001$, $m_2=0.01$, $f_1=0.998$, $f_2=0.5$, d_1d_2
图8. 的调谐质量阻尼 / 双层幕墙阻尼系统的H值(左), Hd1值(中)和Hd2值(右), $m_1=0.001$, $m_2=0.01$, $f_1=0.998$, $f_2=0.5$, $x=0.01$, $xd_1=0.023$, $xd_2=0.08$

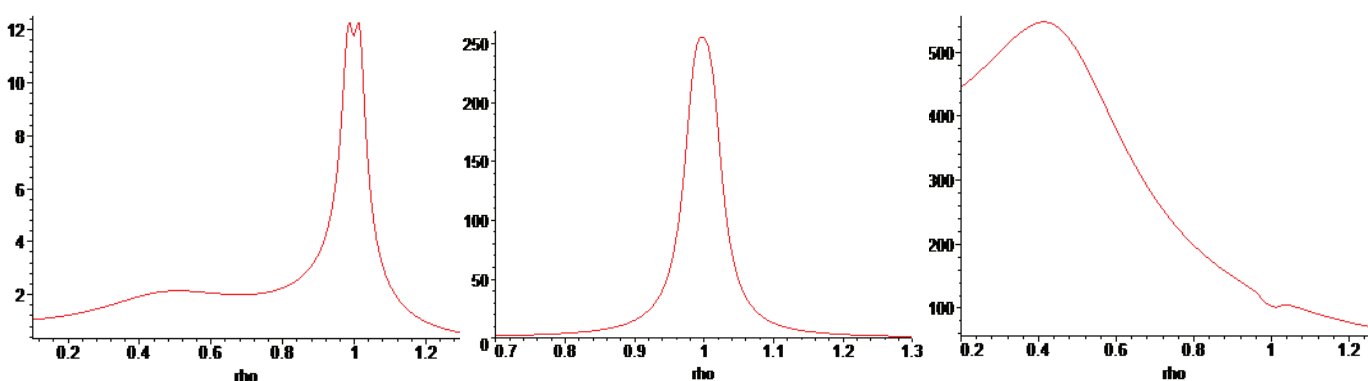


Figure 9. TMD/DSFD system's H (left), Hd1 (middle) and Hd2 (right) with $m_1=0.001$, $m_2=0.01$, $f_1=0.997$, $f_2=0.5$, d_1d_2
图9. 比重的调谐质量阻尼 / 双层幕墙阻尼系统的H值(左), Hd1值(中)和Hd2值(右), $m_1=0.001$, $m_2=0.01$, $f_1=0.997$, $f_2=0.5$, $x=0.01$, $xd_1=0.023$, $xd_2=0.4$

H, Hd1 and Hd2 are the dynamic amplification factors of the primary structure, TMD and DSF outer skin, respectively. With mass ratios of only 0.1% for the TMD and 1% for the DSFD, the maximum H value of the optimally tuned TMD/DSFD interaction system is about 8.5 as can be seen in Figure 8. With the conventional TMD system, this H value can be obtained with a mass ratio of about 2.5. However, Hd2 value in this case is still very large. The DSF connector damping ratio can be increased to reduce the excessive vibration of the DSF outer skin masses.

Figure 9 shows H, Hd1 and Hd2 plots of the TMD/DSFD interaction system with a larger TMD connector damping ratio of 40% than the optimal value of about 8%. With this DSF connector damping ratio, the maximum Hd2 value is significantly reduced to only 20% of the previous case with the optimal connector damping ratio. The maximum H value is increased from the optimal value of about 8.5 to 12.

Conclusions

New design strategies to mitigate wind-induced vibrations of tall buildings were presented through the studies of the distributed TMDs, DSFD with low stiffness connectors and the TMD/DSFD interaction system. TMDs can be distributed over the multiple upper floors of tall buildings without losing much of their effectiveness. The reduction of the effectiveness could be acceptable depending on project specific design situations. DSF systems, which provide

H, Hd1和Hd2分别是原有结构, 调谐质量阻尼和双层幕墙外墙的动力放大系数。当调谐质量阻尼的质量比重为0.1%, 且双层幕墙阻尼的质量比重为1%时, 优化的调谐质量阻尼 / 双层幕墙阻尼交互系统中H的最大值约为8.5, 如图8所示。在传统的调谐质量阻尼系统中, H值约为2.5。但在这种情况下Hd2的值仍然非常大。应当增加双层幕墙连接器阻尼的比重, 来减少外墙体的过多震动。

图9展示了当调谐质量阻尼 / 双层幕墙阻尼交互系统中双层幕墙阻尼连接器的比重高达40% (远高于优化的8%) 时H, Hd1和Hd2值的计算。在这种条件下, Hd2的最大值被减少到之前优化比重的20%。H的最大值从优化的8.5上升到12。

结论

新的针对减小高层风震的设计方案是通过研究分布的调谐质量阻尼、带有低刚度连接器的双层幕墙阻尼以及这两个系统的互动而形成的。调谐质量阻尼可以被分布在一些高楼层中, 以避免过于影响这些楼层的功效。这些被影响的部分在一些特定的设计方案中是可以接受的。调谐质量阻尼系统具有更良好的环境控制, 可以被用于结构性阻尼机构的设计中。带有低刚度连接器的双层幕墙阻尼系统则可以大幅度减小高层建筑的结构性风震。但是, 双层幕墙外墙的过度震动是一个严重的设计限制。由调谐质量阻尼和双层幕墙阻尼组成的交互系统则可以有效地弥补双层幕墙阻尼

superior environmental control, can be designed to produce structural damping mechanism. DSFD system with low axial stiffness connectors can mitigate wind-induced structural vibrations of tall buildings substantially. However, excessive movements of the DSF outer skins are a serious design limitation. TMD/DSFD interaction system can substantially resolve the design limitation of the DSFD system and conventional TMD related other design issues. 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 and eventually produce higher quality and more sustainable built environments.

和传统的调谐质量阻尼的设计不足。以上理论需要通过实际应用来更深入地研究。日新月异的建造技术使建筑系统的设计变得更为综合性，这对协同地提高系统功效和创造更高质量和更可持续的建造环境格外重要。

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