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Concept Design of a Parallel-type Tuned Mass Damper - Tuned Sloshing Damper System for Building Motion Control in Wind

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Abstract

Supplementary damping systems, such as tuned mass dampers (TMDs) and tuned sloshing dampers (TSDs) - also known as tuned liquid dampers (TLDs) - have been successfully employed to reduce building motion during wind events. A design of a damping system consisting of a TMD and two TSDs performing in unison has been developed for a tall building in Taiwan to reduce wind-induced motion. The architecturally exposed TMD will also be featured as a tourist attraction. The dual-purpose TSD tanks will perform as fire suppression water storage tanks. Linearized equivalent mechanical TSD and TMD models are coupled to the structure to simulate the multi-degree of freedom system response. Frequency response curves for the structure with and without the damping system are created to evaluate the performance of the damping system. The performance of the combined TMD-TSD system is evaluated against a conventional TMD system by computing the effective damping produced by each system. The proposed system is found to have superior performance in acceleration reduction. The combined TMD-TSD system is an effective and affordable means to reduce the wind-induced resonant response of tall buildings.

Keywords: Tuned mass damper, Tuned sloshing damper, Vibration control, Structural dynamics

1. Introduction

Damping devices have been applied to buildings for seismic vibration control (Tsushi et al. 2019, Yamashita et al. 2018, Kato et al. 2019, Kim 2019). Tuned mass types of damper, such as the tuned mass damper (TMD) and the tuned sloshing damper (TSD) have been implemented in high-rise buildings to reduce wind-induced building motions by providing additional effective damping to the structure (Morava et al. 2012). The TMD reduces the building response by moving out-of-phase with the building motion. As the TMD moves, energy is extracted from the TMD system through its damping mechanism. Similarly, a TSD consists of a tank, partially filled with liquid (typically water) and drag-producing mechanisms (such as screens or paddles). As the structure experiences a resonant response, the liquid in the TSD tank will begin to slosh. Vibrational energy is thereby transferred from the structure to the TSD, where it can be dissipated by the damping mechanisms within the tank. Schematics for a TMD system and a TSD system are shown in Figure 1. While TMDs are usually more compact than TSDs, they also cost more. When the TSD water is also used as the fire suppression water for the building, the incremental costs associated with providing this dual functionality are comparatively low.

Multiple-TMD and multiple-TSD theory has been introduced to improve the efficiency of the damping system using spread-tuning, whereby each TMD or TSD tank is tuned to a slightly different frequency that is close to the target structural frequency (Love and Haskett 2014). Multiple-TSDs have been employed for tall buildings to reduce the building motion induced by winds and the performance of the damping system has been verified and reported (Love et al. 2020).

This study presents a damping system proposed for a building in Taiwan, which consists of a 200 tonne TMD and two 23 tonne TSDs that have been connected in parallel to the structure. The TSDs also serve as a part of the fire suppression water system of the tower. The TMD is architecturally exposed and visible to the public as a tourist attraction. The effectiveness of the proposed system is investigated through frequency domain analysis. Comparisons are then made to a conventional TMD system to evaluate the efficacy of the proposed system.

2. Analytical Modeling

2.1. Mathematical model of structure- TMD system

A single-degree-of-freedom (SDOF) system is used to represent the dynamic response of a structure vibration mode, as defined mathematically by Equation (1). M_s and K_s represent the generalized mass and stiffness of the structural vibration mode, respectively. C_s is the modal damping and $F(t)$ is the generalized force acting on the structure. Stationary wind loads are considered in this study.

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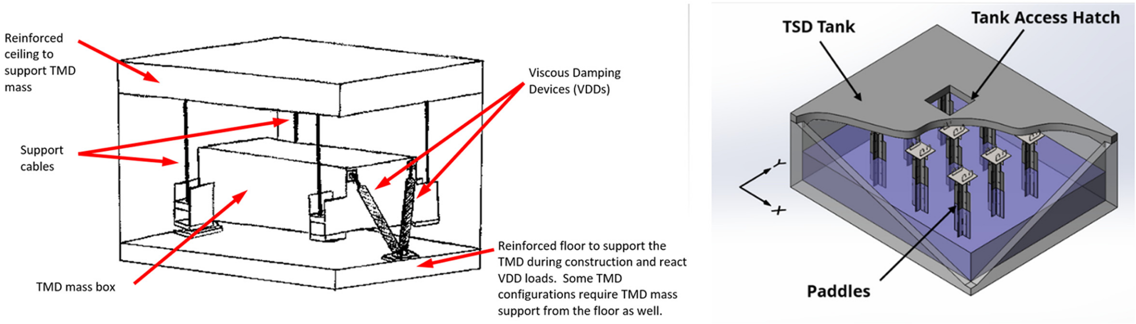

Figure 1. Schematics for a TMD system (left) and a TSD system (right).

$$M_s\ddot{X}_s+C_s\ddot{X}_s+K_s\ddot{X}_s=F(t) \tag{1}$$

A TMD can be modeled as an additional mass-spring-damper system attached to the primary structure. Structure-TMD interaction can be analyzed using a 2DOF system, where the coupled equations of motion are:

$$\begin{bmatrix} M_s & m_{TMD} \\ m_{TMD} & m_{TMD} \end{bmatrix}\begin{pmatrix} \ddot{X}_s \\ \ddot{y}_{TMD} \end{pmatrix}+\begin{bmatrix} C_s & 0 \\ 0 & c_{TMD} \end{bmatrix}\begin{pmatrix} \dot{X}_s \\ \dot{y}_{TMD} \end{pmatrix}+ \begin{bmatrix} K_s & 0 \\ 0 & k_{TMD} \end{bmatrix}\begin{pmatrix} X_s \\ y_{TMD} \end{pmatrix}=\begin{pmatrix} F(t) \\ 0 \end{pmatrix} \tag{2}$$

where m_{TMD}, k_{TMD} and c_{TMD}, are the mass, stiffness and damping of the TMD. X_s is displacement of the structure and y_{TMD} is relative displacement between the structure and the TMD. By introducing the mass ratio as the ratio of TMD mass to the generalized mass of the structure, Equation (2) can be re-written as

$$\begin{bmatrix} 1+\mu_{TMD} & \mu_{TMD} \\ \mu_{TMD} & \mu_{TMD} \end{bmatrix}\begin{pmatrix} \ddot{X}_s \\ \ddot{y}_{TMD} \end{pmatrix}+\begin{bmatrix} 2\omega_s\zeta_s & 0 \\ 0 & 2\mu_{TMD}\omega_{TMD}\xi_{TMD} \end{bmatrix} \begin{pmatrix} \dot{X}_s \\ \dot{y}_{TMD} \end{pmatrix}+\begin{bmatrix} \omega_s^2 & 0 \\ 0\ \omega_{TMD} & \mu_{TMD}^2 \end{bmatrix}\begin{pmatrix} X_s \\ y_{TMD} \end{pmatrix}=\begin{pmatrix} F(t)/M_s \\ 0 \end{pmatrix} \tag{3}$$

where $\omega_s=\sqrt{\frac{K_s}{M_s}}$; $\omega_{TMD}=\sqrt{\frac{k_{TMD}}{m_{TMD}}}$; $\zeta_s=\frac{C_s}{2\omega_s M_s}$;

$$\zeta_{TMD}=\frac{c_{TMD}}{2\omega_{TMD}m_{TMD}};\ \mu_{TMD}=\frac{m_{TMD}}{M_s}$$

The TMD optimal design parameters can be obtained as the quantities that minimize the response of the structure (Den Hartog 1956). For a small inherent structural damping ratio and small mass ratio, the optimal TMD frequency ratio (the ratio of TMD frequency to the structure frequency) and optimal TMD damping ratio based on white noise random excitation can be obtained as (Warburton 1982):

$$f_{opt}=\frac{\sqrt{(1+\mu_{TMD}/2)}}{(1+\mu_{TMD})};$$

$$\zeta_{TMD(opt)}=\sqrt{\frac{\mu_{TMD}(1+3\mu_{TMD}/4)}{4(1+\mu_{TMD})(1+\mu_{TMD}/2)}} \tag{4}$$

Using these design formulae, the TMD design parameters can be established, and the motion reduction performance estimated as part of the concept design.

2.2. Mathematical model of structure- parallel TMD-TSD system

A damping system consisting of a TMD and two TSDs connected in parallel is investigated in this paper. Since a TSD is a dynamic system, two more degrees-of-freedom need to be added to the 2DOF system discussed in Section 2.1 to analyze the interaction between structure, TMD and TSDs. The response of the TSDs is nonlinear due to the velocity-squared liquid damping, and the nonlinear coupling among the sloshing modes (Love and Tait 2010). To simplify the analysis for concept design, linearized equivalent TSD parameters are considered to represent the sloshing liquid as an equivalent spring-mass-dashpot system (Tait 2008). The equivalent mechanical mass and natural frequency for the TSD are given by (Tait 2008) as:

$$m_{TSD}=\frac{8\rho bL^2}{\pi^3}tanh\left(\frac{\pi h}{L}\right) \tag{5}$$

$$\omega_{TSD}=\sqrt{\frac{\pi g}{L}tanh\left(\frac{\pi h}{L}\right)} \tag{6}$$

where L, b, and h are the tank length, width, and water depth, ρ is the liquid density, and g is gravitational acceleration. The damping coefficient can be determined by using empirical relationships (Tait et al. 2005). The dynamic responses of a structure with the parallel TMD-TSD system can then be analyzed as a linearized 4DOF system, and expressed as:

$$\begin{bmatrix} 1+\mu_{TMD}+\mu_{TSD1}+\mu_{TSD2} & \mu_{TMD} & \mu_{TSD1} & \mu_{TSD2} \\ \mu_{TMD} & \mu_{TMD} & 0 & 0 \\ \mu_{TSD1} & 0 & \mu_{TSD1} & 0 \\ \mu_{TSD2} & 0 & 0 & \mu_{TSD2} \end{bmatrix} \begin{pmatrix} \ddot{X}_s \\ \ddot{y}_{TMD} \\ \ddot{y}_{TSD1} \\ \ddot{y}_{TSD2} \end{pmatrix} +$$

$$\begin{bmatrix} 2\zeta_s\omega_s & 0 & 0 & 0 \\ 0 & 2\mu_{TMD}\zeta_{TMD}\omega_{TMD} & 0 & 0 \\ 0 & 0 & 2\mu_{TSD1}\zeta_{TSD1}\omega_{TSD1} & 0 \\ 0 & 0 & 0 & 2\mu_{TSD2}\zeta_{TSD2}\omega_{TSD2} \end{bmatrix}$$

$$\begin{pmatrix} \dot{X}_s \\ \dot{y}_{TMD} \\ \dot{y}_{TSD1} \\ \dot{y}_{TSD2} \end{pmatrix} + \begin{bmatrix} \omega_s^2 & 0 & 0 & 0 \\ 0 & \mu_{TMD}\omega_{TMD}^2 & 0 & 0 \\ 0 & 0 & \mu_{TSD1}\omega_{TSD1}^2 & 0 \\ 0 & 0 & 0 & \mu_{TSD2}\omega_{TSD2}^2 \end{bmatrix} \begin{pmatrix} X_s \\ y_{TMD} \\ y_{TSD1} \\ y_{TSD2} \end{pmatrix}$$

$$= \begin{pmatrix} F(t)/M_s \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{7}$$

where the subscript "TSD" denotes a property associated with the TSD. In this manner, each TSD has a distinct mass, damping constant, stiffness, and relative displacement with respect to the structure. For each TSD, the natural angular frequency and damping ratio are defined as:

$$\omega_{TSD1} = \sqrt{\frac{k_{TSD1}}{m_{TSD1}}}; \quad \omega_{TSD2} = \sqrt{\frac{k_{TSD2}}{m_{TSD2}}}$$

$$\zeta_{TSD1} = \frac{c_{TSD1}}{2\omega_{TSD1}m_{TSD1}}; \quad \zeta_{TSD2} = \frac{c_{TSD2}}{2\omega_{TSD2}m_{TSD2}}$$

Two mass ratios have been defined for the TSDs:

$$\mu_{TSD1} = \frac{m_{TSD1}}{M_s}; \quad \mu_{TSD2} = \frac{m_{TSD2}}{M_s}$$

The optimal parameters are obtained by minimizing the variance of the structural response. The effectiveness of the parallel TMD-TSD system can be evaluated using this 4DOF system during the concept design phase. The layout of the TMD-TSD system along with the schematic of the 4DOF model are shown in Figure 2.

3. The concept Design

In this section, concept designs are presented for a conventional TMD system, and a parallel TMD-TSD system coupled to the building. The building height is approximately 190 m and the natural vibration periods of the first two modes are approximately 5 seconds.

3.1. Conventional TMD system

A single 200 tonne TMD system is considered first for the comparison. The mass ratio is approximately 0.76%. The TMD parameters are calculated based on the TMD optimal parameter formulae in Section 2.1 and are listed in Table 1. The system performance is assessed by determining the effective damping of the system, ζ_{eff} which is calculated as:

$$\zeta_{eff} = \zeta_s \frac{\sigma_{s0}^2}{\sigma_s^2} \tag{8}$$

where σ_s^2 and σ_{s0}^2 are the response variances of the structure with and without the damping system, respectively.

The TMD performance is predicted using the 2DOF system through frequency domain analysis. The predicted results indicate that the TMD system can increase the damping of the structure from an assumed inherent damping ratio of 1% (all damping ratio references herein

Table 1. Design parameters used for the damping system

Damping System	Optimal Parameters
200 tonne TMD	$m_{TMD} = 200$ tonne ($\mu_{TMD} = 0.76\%$), $\omega_{TMD} = 1.185$ rad/s, $\xi_{TMD} = 4.3\%$
Parallel TMD-TSD	$m_{TMD} = 200$ tonne ($\mu_{TMD} = 0.76\%$), $\omega_{TMD} = 1.204$ rad/s, $\xi_{TMD} = 5.1\%$ $m_{TSD1} = m_{TSD2} = 23$ tonne ($\mu_{TSD1} = \mu_{TSD2} = 0.085\%$), $\omega_{TSD1} = \omega_{TSD2} = 1.142$ rad/s, $\xi_{TSD1} = \xi_{TSD2} = 1.81\%$

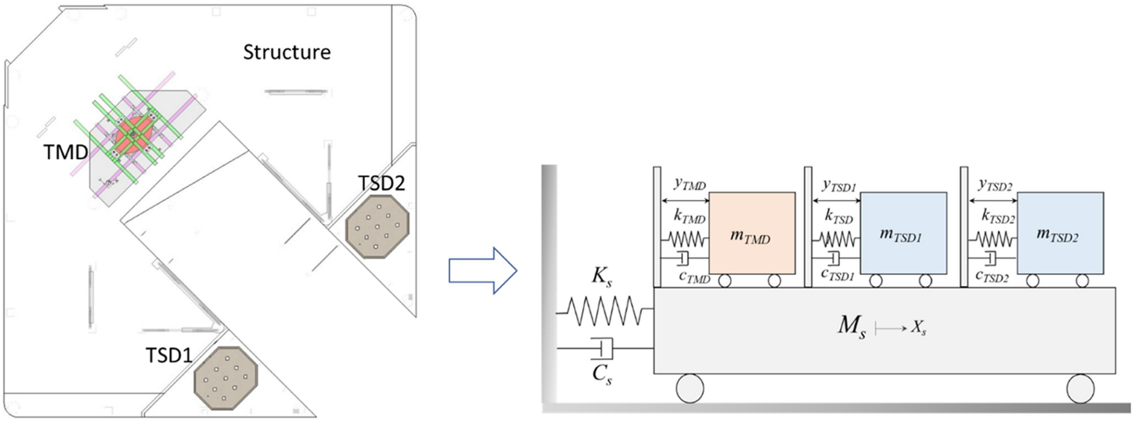

Figure 2. The layout of the TMD-TSD system (left) and the schematic of the 4DOF model of structure-TMD-TSD system (right).

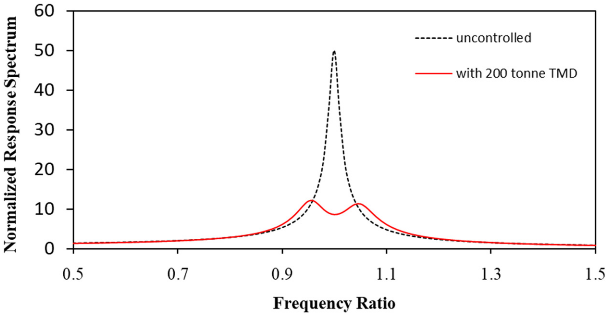

Figure 3. Frequency domain response of structure with/without the TMD system.

are indicated as "percent of critical") to a total equivalent damping of 2.9%, which corresponds to a 40% reduction of accelerations. The frequency domain response of the building with and without the TMD are shown in Figure 3.

3.2. Parallel TMD-TSD system

A conceptual design of a parallel TMD-TSD system is developed. There are two fire suppression water tanks on the floor below the TMD room in the building. The water tanks function in parallel with the TMD to increase the rate of energy dissipation of the structure, reducing the wind-induced building motions.

The two tanks are each the same size, with dimensions 7.7 m by 6.5 m and 2.2 m in height, and four truncated/chamfered corners of 1.75 m. Since the tanks are not precisely rectangular, the equivalent tank length and width are calculated first based on the sloshing frequency analyzed by the procedure developed by Love and Tait (Love and Tait 2011). The equivalent mechanical mass and natural frequency are then calculated by using Equations (5) and (6) with the equivalent tank length and width of 6.9 m and 5.9 m, respectively. The water mass for each tank is approximately 30 tonne. With this geometry, approximately 75% of the water mass (23 tonne) is the effective mass of the damper and the rest (7 tonne) will not participate in the sloshing motion. A 200 tonne TMD is still considered but the design parameters are different from the TMD discussed in Section 3.1. The new design parameters of the TMD-TSD system are optimized based on minimizing the variance of the structural response at the target return period wind and are listed in Table 1. The effective damping of the TMD-TSD system is predicted using the 4DOF system analyzed in the frequency domain. The results show that the TMD-TSD system can achieve a total effective damping of 3.3%. The corresponding acceleration reduction is 45%. The frequency domain response with and without the TMD-TSD system are shown in Figures 4. The results indicate that by adding the two TSDs as a parallel damping system, the total equivalent damping can be increased by approximately 14% (relative), from 2.9% to 3.3%.

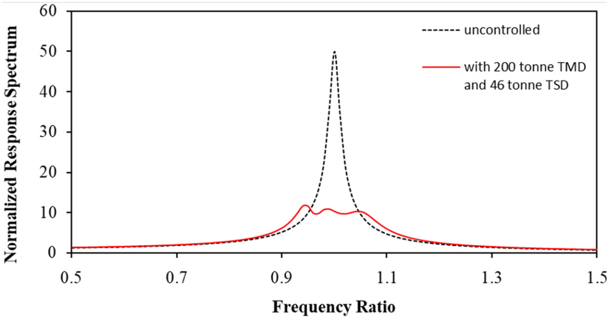

Figure 4. Frequency domain response of structure with/without the TMD-TSD system.

4. System Comparison

The conventional TMD and proposed parallel TMD-TSD systems are compared by considering their motion reduction performance, as well as the components required for each system. The predicted performance results from the frequency domain analysis indicate that the TMD-TSD system can increase the performance of the conventional TMD system by 14%. The performance comparison is summarized in Table 2. The TMD and TSD only interact effectively with the vibration mode to which the dampers are tuned, so the effective damping or the acceleration reduction is only applied to the tuned vibration mode.

The major material and components of the TMD system includes 200 tonnes of steel with associated suspension cables and viscous damping devices. Considering the fire suppression water tanks are essential for the building, the incremental change in cost to facilitate the dual functionality as TSDs for the parallel TMD-TSD system is minimal, attributed only to the dissipation mechanisms (paddles) in the tanks. These paddles are fabricated with steel, at a total of only 3 tonnes additional material for both tanks.

To understand the equivalent conventional TMD mass required to have the same performance achieved by the TMD-TSD system, the analysis described in Section 3.1 is repeated by increasing the TMD mass until a total effective damping of 3.3% is obtained. The results indicate that a 260 tonne TMD would have the same performance

Table 2. Predicted performance for the damping system

Damping System	Effective Damping	Reduction in Acceleration
200 tonne TMD	2.9%	40%
Parallel TMD-TSD	3.3%	45%

Table 3. Main material and components used for the damping system to achieve the same performance of 3.3% effective damping

Damping System	Steel	Cables	VDDs	Steel for Paddles
260 tonne TMD	260tonne	4 sets	8 units	0
Parallel TMD-TSD	200tonne	4 sets	8 units	3 tonne

that the TMD-TSD achieved. Comparing to the material required for a 260 tonne TMD, the TMD-TSD system saved 57 tonnes of steel. A comparison of the main material and components is summarized in Table 3.

5. Conclusions

A damping system consisting of a TMD and two TSDs for wind-induced building motion control is investigated in this study. In the system, the TMD and the TSDs are connected to the building in parallel. A linearized 4DOF system analytical model is developed to determine the dynamic response of the structure-TMD-TSD system. Linearized equivalent TSD parameters are used in the model to simplify the nonlinear behaviour of the sloshing liquid. The effectiveness of the proposed TMD-TSD system is compared to a conventional TMD system through a design example. The comparison suggests that the proposed TMD-TSD system provides better motion reduction performance than the conventional TMD and requires less material. Therefore, the proposed TMD-TSD system could be considered as an affordable solution to control wind-induced building motion.

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