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PRELIMINARY DESIGN OF A TMD WITH A LIQUID-BASED DAMPING SYSTEM FOR BUILDING MOTION CONTROL IN WIND

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Abstract: Supplementary Damping Systems (SDS), such as tuned mass dampers (TMDs), tuned sloshing dampers (TSDs) - also known as tuned liquid dampers (TLDs) - and tuned liquid column dampers (TLCDs) have been successfully employed to reduce building motion during wind events by dissipating the vibrational energy of the building. A TMD generally consists of a mass, a stiffness system and a damping system (traditionally linear or nonlinear dashpots) that dissipates energy. Optimal design of the mass, stiffness, and damping system is critical for a TMD to have best performance. Some practical design challenges for a TMD damping system include heat management, space allocation, and frictional forces. While heat and friction are not concerns for a TSD, a TSD usually requires more space than a TMD. A novel type of TMD is investigated, which consists of a TMD with a liquid-based damping system; a TMD using a TSD as its damping system, to integrate the advantages of a TMD and a TSD into one system. A model is developed to investigate the proposed system. Simple expressions for the optimal TSD mass, tuning ratio, and liquid damping ratios are employed to optimize the novel TMD coupled to a single degree of freedom structure. A design example of the TMD with a liquid-based damping system is presented and compared to a conventional TMD design. The proposed TMD with a liquid-based damping system is shown to be an efficient and affordable device for controlling building motion.

1 INTRODUCTION

Controlling building motion in wind has become one of the more challenging tasks for designing tall and slender buildings. The building acceleration in wind can affect the comfort of occupants. The dynamic response of a structure depends on its mass, frequency, and damping, as well as the characteristics of the external excitation. The building accelerations can be reduced by optimizing the building shape, height and structural dynamic properties (i.e. mass and frequency). However, there are often strong aesthetic and financial reasons to avoid modifying the building shape and height. The adjustability of structural dynamic properties is usually limited once the structural system is determined. Since the structural response can be amplified significantly due to resonance, increasing damping is an effective means to reduce building acceleration, with the resonant response being approximately inversely proportional to the square root of damping ratio improvement. Because the structural inherent damping is usually small in winds for serviceability considerations (in the range of 0.5% to 1.5% of critical for 10-year or lower return period wind events), it is practical to increase the damping by a factor of 2 or more.

Supplementary damping systems (SDS), such as tuned mass dampers (TMD) or tuned sloshing dampers (TSD) are regularly being employed to reduce the building responses to wind by providing additional damping to the structure (Morava et al. 2012). The TMD reduces the building responses by moving out-of-phase with the building motion. As the TMD moves, energy is extracted from the TMD system through its damping mechanism. Viscous damping devices (VDDs) have been successfully used as the damping elements in common practice. The TMD system installed in Taipei 101 is one of the examples using VDDs to dissipate energy (Haskett et al. 2003). However, some details must be carefully considered to ensure the TMD performs optimally, such as limiting VDD friction and managing the generated heat. There are alternative means to remove energy from TMD system. For example, an eddy current damping system is used as the damping system for the TMD installed in Shanghai Centre Tower.

A typical TSD consists of a tank, partially filled with fluid (typically water) and dissipation mechanisms (such as screens or paddles) in the tank. As the structure experiences a resonant response, the fluid 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 dissipation mechanisms in the tank. TMDs are usually more compact than TSDs. However, TMDs are generally more expensive than TSDs. The damping element traditionally associated with TMDs is often one of the most expensive components. A novel type of TMD with a liquid-based damping system, a TSD is considered in this study, is proposed in this paper to be an alternative SDS. The configuration of the TMD with a liquid-based damping system is a series TMD-TSD system. The series configuration of TMDs has been found to be more efficient than a single TMD or two parallel TMDs (Zuo 2009). The effectiveness of the proposed system is investigated through numerical simulation. Comparisons are then made with a conventional TMD system to evaluate the efficacy of the proposed system.

2 NUMERICAL MODELING

2.1 Mathematical model of structure-TMD system

The dynamic response of a structure for a considered vibration mode can be described by using a single-degree-of-freedom (SDOF) system defined mathematically by Equation [1], and as shown in Figure 1. M_s and K_s represent the generalized mass and stiffness of the vibration mode, respectively. C_s is the modal damping which can be assumed per the loading scenario and structural system (e.g. concrete or steel). *F(t)* is the generalized force acting on the structure. Wind loads are considered in this study.

[1] $$M_s\ddot{X}_s + C_s\dot{X}_s + K_s X_s = F(t)$$

A TMD is a damped secondary inertial system which consists of a mass attached to the building through a spring and damping mechanism. Structure-TMD interaction can be analyzed by using a 2DOF system as shown in the right side of Figure 1. The equations of motion are:

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

where m_{TMD}, c_{TMD}, k_{TMD} are the mass, damping and stiffness of the TMD. X_s is displacement of the structure and y_{TMD} is relative displacement between the TMD and the structure. The effectiveness of a TMD is determined by several design parameters. The three key parameters are mass ratio (the ratio of TMD mass to the generalized mass of the structure), TMD damping ratio and TMD frequency. To incorporate the key parameters into the numerical model, Equation [2] can be re-written as Equation [3].

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

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

The TMD optimal design parameters can be obtained by minimizing the response of the structure (Den Hartog 1956). For a small structural inherent damping ratio and small mass ratio, the classical optimal TMD frequency ratio (the ratio of TMD frequency to the structure frequency) and optimal TMD damping ratio can be obtained from Equations [4] (Warburton 1982):

[4] $$f_{opt} = 1/(1+\mu); \zeta_{TMD(opt)} = \sqrt{\frac{3\mu}{8(1+\mu)}}$$

The effectiveness of the TMD can thus be evaluated by using the 2DOF system for preliminary design. A TMD conceptual design example will be discussed in section 3.

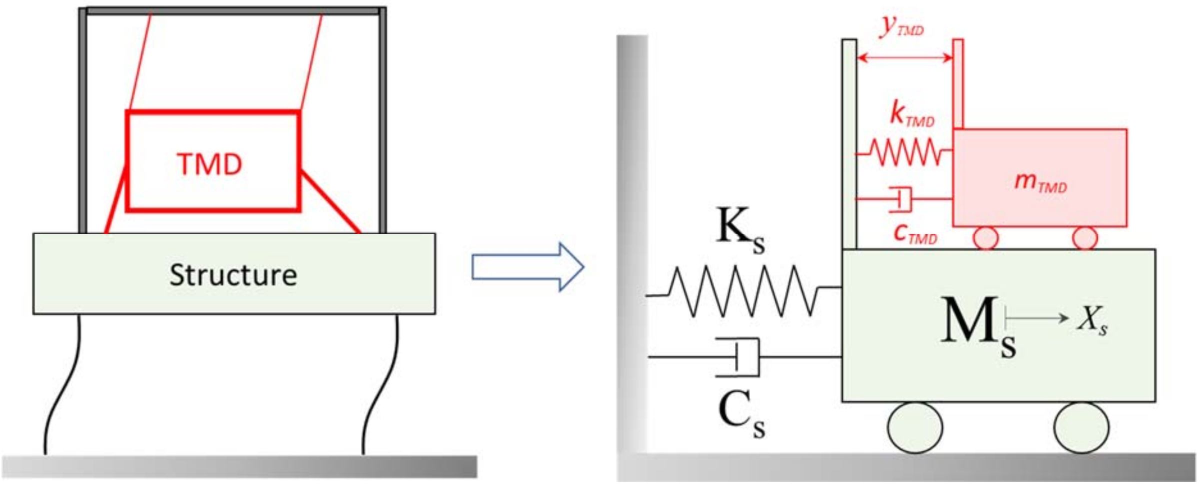


Figure 1. The 2DOF model of structure-TMD system

2.2 Numerical model of structure- series TMD-TSD system

A TMD with a liquid-based damping system is investigated in this paper. A TSD is selected as the liquid-based damping system for the study, although other liquid-based dampers are also expected to be practical. The configuration of the system is a series TMD-TSD system. Since a TSD is a dynamic system, one more degree-of-freedom needs to be added into the 2DOF system discussed in 2.1 to analyze the interaction between structure, TMD and TSD. The response of the TSD degree of freedom is nonlinear due to the velocity-squared liquid damping, and the nonlinear coupling among the sloshing modes (Love and Tait 2010). To simply the analysis for preliminary 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:

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

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

where *L*, *b*, and *h* are the tank length, width (into page), and water depth of the TSD. ρ is the fluid 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 a series TMD-TSD system can then be analysed as a linear 3DOF system as shown in Figure 2. The equations of motion for a structure with the series TMD-TSD system can be expressed as:

$$
[7]\quad \begin{bmatrix} 1+\mu_{TMD}+\mu_{TSD} & \mu_{TMD}+\mu_{TSD} & \mu_{TSD} \\ \mu_{TMD}+\mu_{TSD} & \mu_{TMD}+\mu_{TSD} & \mu_{TSD} \\ \mu_{TSD} & \mu_{TSD} & \mu_{TSD} \end{bmatrix} \begin{pmatrix} \ddot{X}_s \\ \ddot{y}_{TMD} \\ \ddot{y}_{TSD} \end{pmatrix} + \begin{bmatrix} 2\zeta_s\omega_s & 0 & 0 \\ 0 & 2\mu_{TMD}\zeta_{TMD}\omega_{TMD} & 0 \\ 0 & 0 & 2\mu_{TSD}\zeta_{TSD}\omega_{TSD} \end{bmatrix} \begin{pmatrix} \dot{X}_s \\ \dot{y}_{TMD} \\ \dot{y}_{TSD} \end{pmatrix}
$$

$$
+ \begin{bmatrix} \omega_s^2 & 0 & 0 \\ 0 & \mu_{TMD}\omega_{TMD}^2 & 0 \\ 0 & 0 & \mu_{TSD}\omega_{TSD}^2 \end{bmatrix} \begin{pmatrix} X_s \\ y_{TMD} \\ y_{TSD} \end{pmatrix} = \begin{pmatrix} F(t)/M_s \\ 0 \\ 0 \end{pmatrix}
$$

Where the subscript "$_{TSD}$" denotes a property associated with the TSD. In this manner, the TSD has a mass, damping constant, stiffness, and relative displacement with respect to the TMD. For each degree of freedom, the natural angular frequency and damping ratio are defined as:

$$
\omega_s = \sqrt{\frac{K_s}{M_s}};\ \omega_{TMD} = \sqrt{\frac{k_{TMD}}{m_{TMD}}};\ \omega_{TSD} = \sqrt{\frac{k_{TSD}}{m_{TSD}}}
$$

$$
\zeta_s = \frac{C_s}{2\omega_s M_s};\ \zeta_{TMD} = \frac{c_{TMD}}{2\omega_{TMD} m_{TMD}};\ \zeta_{TSD} = \frac{c_{TSD}}{2\omega_{TSD} m_{TSD}}
$$

Two mass ratios have been defined for the TMD and TSD, respectively:

$$
\mu_{TMD} = \frac{m_{TMD}}{M_s} \qquad \mu_{TSD} = \frac{m_{TSD}}{M_s}
$$

Note that a portion of the liquid mass, ρbhL - m_{TSD}, does not participate in the sloshing motion, and is therefore considered to be part of the TMD mass.

Optimal formulae for a series-type double-mass TMD have been derived for an undamped structure (Asami 2017). For the structure-TMD-TSD system considered, the optimal parameters that will minimize the variance of the structural response are given by (Asami 2017):

$$
[8]\quad \zeta_{TMD}^{opt} = 0;\ \omega_{TMD}^{opt}/\omega_s = \sqrt{1+2\mu};\ \ \mu = \mu_{TMD} + \mu_{TSD}
$$

$$
[9]\quad \mu_{TSD}^{opt}/\mu_{TMD} = 2\mu;\ \omega_{TSD}^{opt}/\omega_s = (1+2\mu)^{-1};\ \zeta_{TSD}^{opt} = \frac{1}{2}\sqrt{\frac{3\mu}{1+2\mu}}
$$

After selecting an initial TMD mass using conventional design formulae that estimate TMD performance based on the mass ratio, the optimal equivalent mass, natural frequency, and damping for the TSD are determined using Equations [8] and [9]. The tank dimensions and liquid damping arrangement that produces these optimal TSD parameters are then selected based on Equations [5] and [6]. The effectiveness of the series TMD-TSD system can be evaluated by using the 3DOF system for preliminary design. A conceptual design example for the proposed TMD-TSD system will be discussed in section 3.

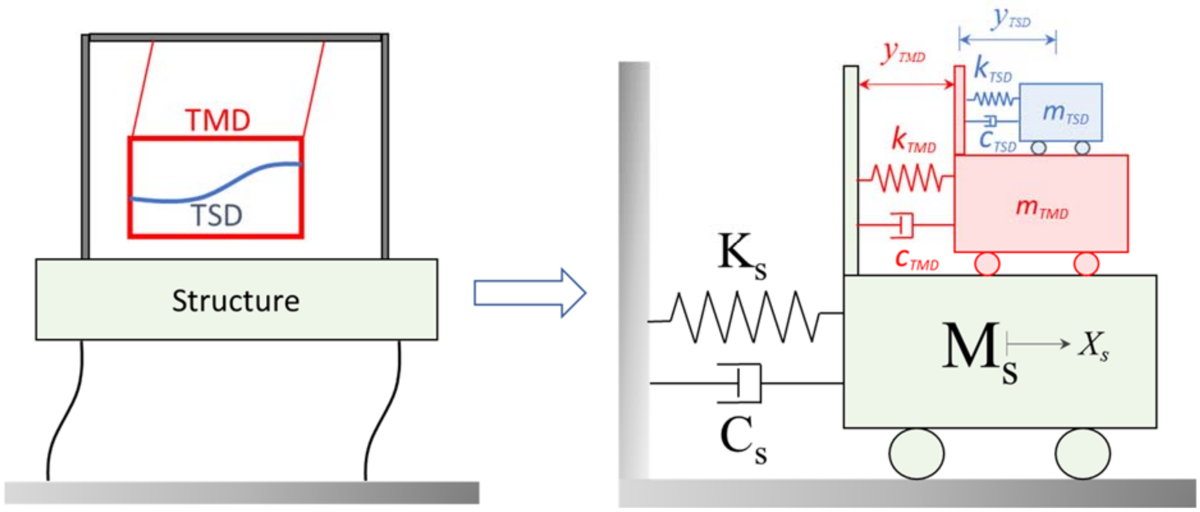


Figure 2. The 3DOF model of structure-TMD-TSD system

3 A DESIGN EXAMPLE

A sixty-four story, 265 m tall steel building is selected for the damping system preliminary design example. The building considered has a generalized mass of 28,000 tonne, an inherent damping ratio of 1%, and a natural vibration period of 4.76 sec (frequency of 0.21 Hz). The uncontrolled building acceleration is near 12 milli-g (mean peak hourly) at 1-year return period wind. Two 10 m (length) x 8 m (width) x 9 m (height) spaces are reserved as the damper rooms at the top story of the building. The target performance for the SDS is to reduce the acceleration by 50% for 10-year and lower return period winds. The equivalent total damping ratio is expected to be increased from 1.0% to 4.0% of critical damping for the considered return period winds. The design practice for a TMD with a liquid-based damping system is investigated in this section.

3.1 Preliminary design of a conventional TMD system

A conventional TMD system is considered first for the comparison. Based on the requirements, a conceptual design of two identical 250 tonne TMDs (total 500 tonne) is developed to achieve the target performance. The mass ratio of the 500 tonne TMD is approximately 1.8%. The TMD parameters are calculated based on the TMD optimal parameter formulae in 2.1 and are listed in Table 1. The configuration of the TMD system is shown in Figure 3(a). VDDs are used as the energy dissipation element in this design. The system performance will be assessed by determining the effective damping of the system, ζ_{eff} which is calculated based on:

$$[10]\quad \zeta_{eff} = \zeta_s \frac{\sigma_{s-0}^2}{\sigma_s^2}$$

where σ_s^2 and $\sigma_{s\text{-}0}^2$ are the response variances of the structure with and without the damping system, respectively.

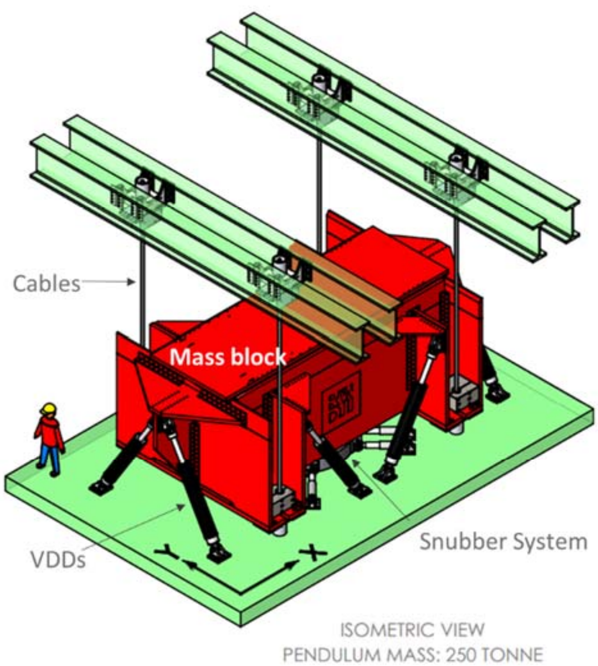
The TMD performance is predicted by using the 2DOF system through frequency domain and time domain analysis. The predicted results indicate that the TMD system can achieve a total equivalent damping of 4.0% of critical corresponding to 50% of acceleration reduction. The frequency domain response and a segment of time domain response of the building with and without the TMD are shown in Figures 4(a) and 5(a), respectively. The structure and TMD responses for the selected time segment are shown in Figure 6(a).

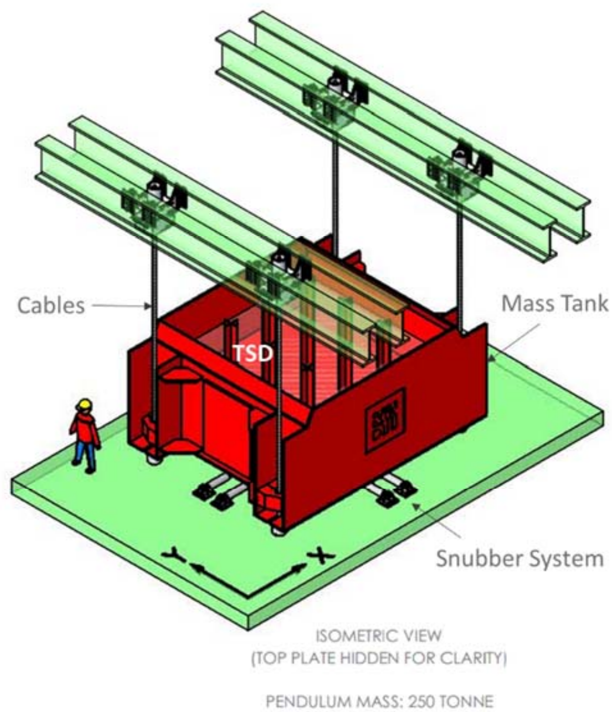
3.2 Preliminary design of a series TMD-TSD system

Based on the same requirements, a conceptual design of two identical 250 tonne of series TMD-TSD systems is developed to achieve the target performance. The design parameters of the TMD-TSD system are calculated based on the optimal design formulas in section 2.2 and are listed in Table 1. The configuration of the TMD-TSD system is shown in Figure 3(b). The system is comprised of three general component categories; cables, a steel tank with an internal TSD system and snubbing system. Wire rope cables are used to provide both the low-friction suspension and restoring force necessary to correctly tune the system to the as-built building frequency. The steel tank provides desired mass and serves as the TSD container as well. The internal TSD is designed to be the energy dissipation mechanism for the system. The snubbing system prevents local damage due to large displacements during extreme wind or seismic events.

The dimensions of the TMD-TSD pendulum mass is 6.5 m (length) x 5 m (width) x 5 m (height). The TMD-TSD system can be fitted into the reserved space with allowance for 1.5 m maximum pendulum mass amplitude. The TSD liquid dimensions are 4.9 m x 4.9 m with a water depth of 0.44 m. The amount of water provides the desired equivalent mechanical mass and frequency. The total water mass is 11 tonne for each TMD-TSD system. 79% of the water mass (8.7 tonne) is effective mass and the rest (2.3 tonne) will not participate in the sloshing motion. However, the latter part of water can be considered as useful TMD mass. High utilization of water is one of the advantages of the proposed system.

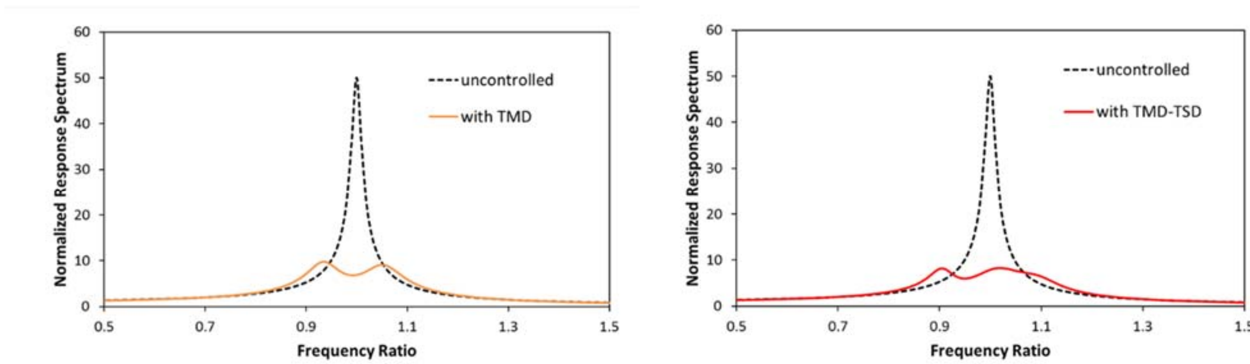
The frequency domain and time domain analysis results show that the TMD-TSD system can achieve a total equivalent damping of 4.3%. The corresponding acceleration reduction is 52%. The analysis results indicate that the TMD-TSD system performance is superior to the target performance. The frequency domain response and a segment of time domain response of the building with and without the TMD-TSD are shown in Figures 4(b) and 5(b), respectively. The structure, TMD and TSD responses for the selected time segment are shown in Figure 6.





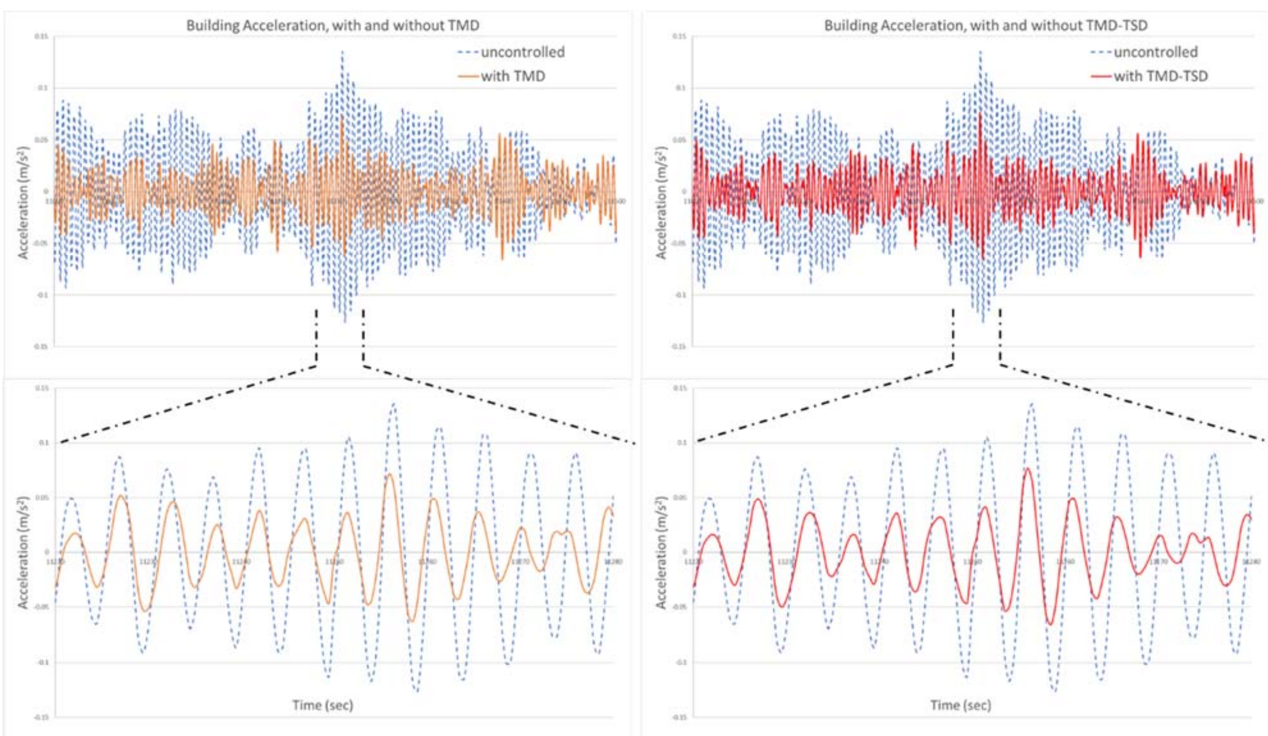
(a) Conventional TMD System (b) Proposed Series TMD-TSD system

Figure 3: Conceptual design of the considered damping systems



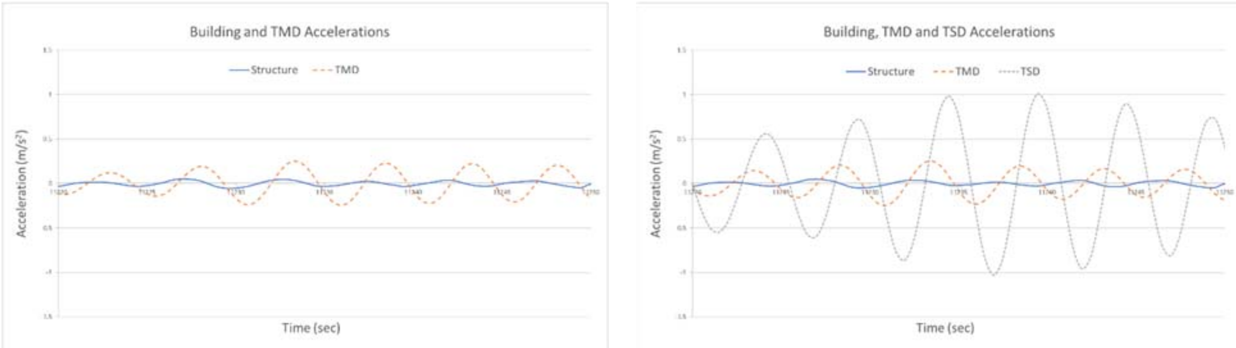
(a) Conventional TMD System (b) Proposed Series TMD-TSD system

Figure 4: Frequency domain responses – with and without the damping systems



(a) Conventional TMD System (b) Proposed Series TMD-TSD system

Figure 5: A segment of time domain analysis results – building accelerations with and without the damping systems



(a) Conventional TMD System (b) Proposed Series TMD-TSD system

Figure 6: A segment of time domain analysis results – building and damping system responses

Table 1: Design parameters used for the damping systems

Damping System	Optimal Parameters
TMD	$\mu_{TM\Delta}$ =500 tonne, ω_{TMD} = 1.301 rad/s, ξ_{TMD} = 6.6%
Series TMD-TSD	m_{TMD} =483 tonne, ω_{TMD} = 1.332 rad/s, ξ_{TMD} = 0.5%
	m_{TSD} =17 tonne, ω_{TSD} = 1.297 rad/s, ξ_{TSD} = 11.1%,
	L = 4.9 m, b = 4.9 m, h = 0.433 m

4 COMPARISON OF TMD AND TMD-TSD SYSTEM EFFECTIVENESS

The TMD and TMD-TSD systems are compared based on performance, material and components, and required space per the preliminary design constraints in the example. The predicted performance results from frequency domain and time domain analysis indicate that for a given total damper mass, the TMD-TSD system has superior performance for the target return period winds. The performance comparison is summarised in Table 2. Additionally, the TMD-TSD system is more easily completed with no friction which ensures its performance at lower return period winds. The system also has no heat generation concern at higher return period winds, since the TSD has a great ability to absorb heat. Note that friction and heat generation are not included in the numerical model. The major material and components of the overall TMD system includes 500 tonne steel, 8 sets of cables, 16 units of VDDs and 2 sets of snubber systems. The TMD-TSD system consists of 478 tonne steel, 22 tonne water, 8 sets of cables and 2 sets of snubber systems. The comparison of main material and components is summarised in Table 3. The two systems have similar required space for this design example.

Table 2: Predicted performance for the damping system

Damping System	Effective Damping	Reduction in Acceleration
TMD	4.0%	50%
Series TMD-TSD	4.3%	52%

Table 3: Main material and components used for the damping system

Damping System	Steel	Cables	VDDs	Snubber	Water
TMD	500 tonne	8 sets	16 units	2 sets	0
Series TMD-TSD	478 tonne	8 sets	0	2 sets	22 tonne

5 CONCLUSION

A novel type of supplementary damping system, a TMD with a liquid-based damping system, for building motion control in wind is investigated in this study. In the system, a TMD and a TSD are connected in series. The connected TSD is the damping mechanism of the system and the energy will be dissipated through the sloshing fluid within the TSD. A linear 3DOF system numerical model is developed to simulate the dynamic response of the structure-TMD-TSD system in wind. Linearized equivalent TSD parameters are used in the model to simplify the nonlinear behaviour of the sloshing fluid.

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 superior performance and has less material costs and components. The two damping systems have similar space demand for the considered example. Therefore, the proposed TMD-TSD system could be considered as an affordable alternative solution to a conventional TMD for building motion control in wind.

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