Chapter 11
Preliminary Design of Liquid-Based Damping Systems for Building Motion Control in Wind

Lee, Chien-Shen, McNamara, Kevin, Mills, Matthew J., and Robinson, Jamieson K.

Abstract Supplementary Damping Systems (SDS), such as tuned mass dampers (TMDs), tuned sloshing dampers (TSDs) and tuned liquid column dampers (TLCDs) have been successfully employed to reduce building motions during wind events by dissipating the vibrational energy of the building. A liquid-based damping system known as "Hummingbird damping system" has been developed, which consists of water cylinders and air springs. The water is contained within the cylinder between two flexible membranes that are connected to an air spring. All systems are designed to operate at a natural frequency that is close to the natural frequency of the structural vibration mode to be controlled, and each system is designed to exhibit a specified amount of damping (energy dissipation). As the building moves under dynamic wind loads, the mass of the damping system will begin to move out-of-phase with the motion of the tower and energy is extracted by the integrated energy dissipation devices. A concept design of implementing liquid-based damping systems, including a Hummingbird damping system and TSDs, was developed for a building in Taiwan to reduce wind-induced motion. Unlike traditional damping systems, this TSD system is modular, simplifying both design and installation. The proposed system is found to be an effective and affordable means to reduce the wind-induced resonant response of buildings.

Keywords Tuned mass damper · Tuned sloshing damper · Vibration control · Structural dynamics · Wind engineering

Problem description

Building motions due to wind may affect structural integrity. Furthermore, it could cause discomfort to the building occupants. It becomes a challenge for structural engineers and architects to keep the wind-induced building motion within acceptable limits. Depending on the building surroundings, the building motions can be induced by across-wind excitation by vortex shedding, or through general wind buffeting due to the roughness of the surroundings (Irwin, P. A. 2008).

A 25-story steel structural building is selected as an example for this study. The building is located in a dense urban area adjacent to other towers and is affected by both vortex shedding and buffeting resulting in wind-induced building motions. The signature dynamic effects of the building response due to vortex shedding can be identified through the wind tunnel test results. Figure 1(a) shows an example of the predicted base bending moment of the building for all wind directions based on the wind tunnel test results. At around 110 degrees heading of wind direction, the mean response is near zero, but the peak responses of the positive and negatives reach the maximum, which implies that dynamic effects dominate the response from this wind direction. Figure 1(b) shows the predicted accelerations of the building as a function of the wind direction, and the maximum acceleration also occurs at 110 degrees, as expected, due to the dynamic responses induced by wake buffeting. The predicted peak accelerations exceed the comfort criteria.

Established engineering strategies were employed to mitigate building accelerations, including enhancements to both mass and structural stiffness. Figure 2(a) shows the sensitivity analysis of the building accelerations to its mass and stiffness. It can be observed that increasing mass and/or increasing stiffness (i.e. reducing the building period) can generally reduce the building accelerations for this building.

Lee, Chien-Shen · McNamara, Kevin · Mills, Matthew J. · Robinson Jamieson K.
Motioneering Inc., 600 Southgate Dr, Guelph, ON N1G 4P6 Canada
e-mail: Tom.Lee@motioneering.ca; Kevin.McNamara@motioneering.ca; Matthew.Mills@motioneering.ca; Jamieson.Robinson@motioneering.ca

Kristin B. Zimmerman, PhD (eds.), *Dynamics of Civil Structures, 2026, Vol. 2*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/97887-438-1441-2_11

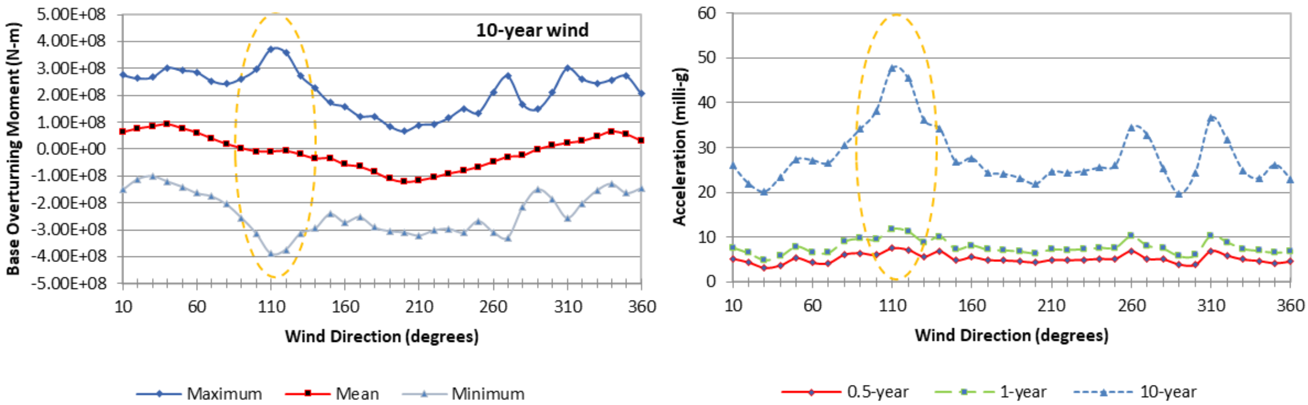

Fig. 1 Example of Wind Responses of the Building (a) base overturning moment (b) acceleration

However, achieving the required 35% reduction in acceleration cannot be effectively accomplished through increases in mass and stiffness alone. Even a 20% increase in mass combined with a 24% reduction in structural period falls short of meeting the performance criteria. Additionally, the structural costs associated with pursuing this approach would be substantial.

While increasing mass and stiffness can help reduce wind-induced accelerations, it also leads to significantly higher seismic design loads. This introduces further complexity and challenges for the structural design, potentially offsetting the benefits gained.

Similarly, Figure 2(b) shows the sensitivity analysis results of the building accelerations to its damping. Increasing the damping from 1% to 2% can reduce the acceleration by approximately 30%.

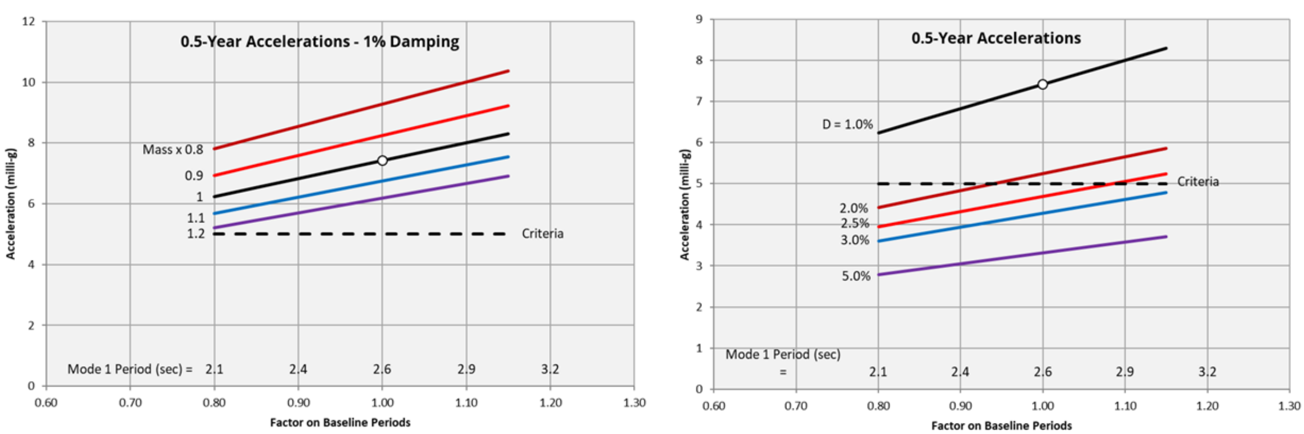

Fig. 2 Example Sensitivity Analysis of Wind Responses of the Building (a) accelerations to mass and period (b) accelerations to damping and period

If the damping can be increased to 2.5%, the resulting reduction in acceleration brings the building's performance within acceptable limits. Enhancing damping through a supplemental damping system offers a practical advantage—it does not require major modifications to the structural system, thereby avoiding the significant costs associated with structural measures aimed at reducing building accelerations.

Given these benefits, the design team has opted to implement a supplemental damping system to effectively control wind-induced building motions.

Solution: Damping system

Supplemental Damping Systems

Tuned types of dampers, such as a tuned mass damper (TMD) and a 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 damper reduces the building response by moving out of phase with the building motions. As a 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 energy dissipation mechanisms. 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.

Hummingbird damper was developed by Thornton Tomasetti in collaboration with the National Aeronautics and Space Agency (NASA) (Ghisbain et al. 2017). The system consists of water cylinders and air springs. It is intended to reduce building movement using the same physics that TMDs and TSDs employ. All systems are designed to operate at a natural frequency close to the natural frequency of the structural vibration mode to be controlled. Each system is designed to exhibit a specified amount of damping (energy dissipation).

Damping System Preliminary Design

The considered design example of a 25-story building has a generalized mass of 4,000 tonnes, an inherent damping ratio of 1% of critical for the acceleration analysis, and a natural vibration period of 2.63 sec (frequency of 0.38 Hz) for the mode of vibration to be controlled. The uncontrolled building acceleration is near 7.5 milli-g (mean peak hourly) at 6-month return period winds. Some space on the roof was allocated for implementing this damping system. The target performance for the damping system is to reduce the acceleration by approximately 35% for 6-month and higher return period winds. The equivalent total damping ratio is expected to be increased from 1.0% to 2.3% of critical damping for the considered return period winds after installing the damping systems.

A damping system combined with TSD and Hummingbird was selected by the design team as the preferred option by considering the building vibration frequency, the available space for the damping system, the ability for installation sometime after the building construction is complete, and the required additional damping. The damping system is comprised of five (5) Tuned Sloshing Dampers (TSDs) and a Hummingbird Damper, as shown in Figure 3. Two (2) bi-directional TSDs are oriented longwise in the X-Direction. Three (3) uni-directional TSDs and the Hummingbird Damper are oriented in the Y-Direction.

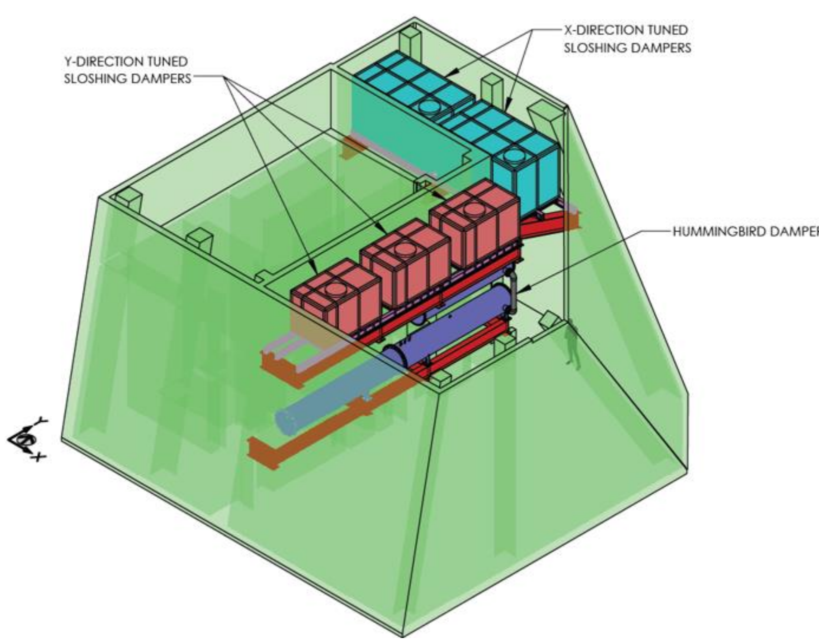

Fig. 3 Overview of Proposed Damping System for the Building

Analytical Modelling of the Damping System with the Building

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.

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

A damping system can be modelled as an additional mass-spring-damper system attached to the primary structure. The dynamic responses of a structure vibration mode equipped with damping system along Y-direction can be analysed using a 3DOF system as shown in Figure 4, where the coupled equations of motion are:

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

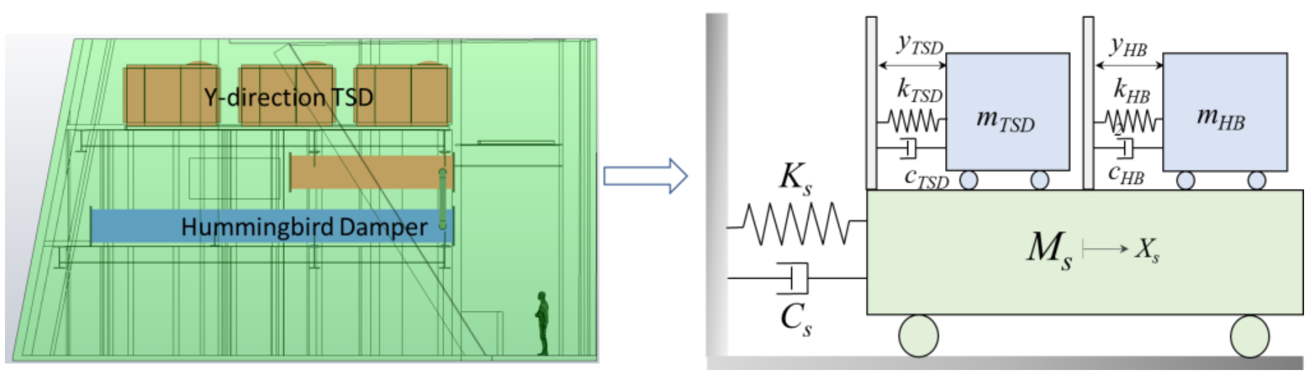

Fig. 4 An illustration of the 3DOF of structure - damping system (Y-direction)

Where X_s is the displacement of the structure and y_{TSD} and y_{HB} are the relative displacement between the centre of mass of the TSD and the Hummingbird damper system and the structure, respectively. In this manner, each damper has a distinct mass, damping constant, stiffness, and relative displacement with respect to the structure. For each damper, the natural angular frequency and damping ratio are defined as:

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

$$\zeta_s = \frac{C_s}{2\omega_s M_s};\ \zeta_{TSD} = \frac{c_{TSD}}{2\omega_{TSD}m_{TSD}};\ \zeta_{HB} = \frac{c_{HB}}{2\omega_{HB2}m_{HB}}$$

Two mass ratios have been defined for the damping systems:

$$\mu_{TSD} = \frac{m_{TSD}}{M_s};\ \mu_{HB} = \frac{m_{HB}}{M_s}$$

The total mass ratio of the damping system is approximately 0.35%. Multiple-TMD or multiple-TSD theory has been introduced to improve the efficiency of the damping system using spread-tuning, whereby each supplemental damper is tuned to a slightly different frequency close to the target structural frequency (Love and Haskett 2014). Multiple-TSDs have been employed for tall buildings to reduce the building motions induced by winds, and the performance of the damping system has been verified and reported (Love et al. 2020 and Lee et al. 2021). The damping system can also utilize spread-tuning, where the different damper units are tuned to different frequencies, since it contains two units along each vibration direction.

The optimal parameters are obtained by minimizing the variance of the structural response. The effectiveness of the damping systems can be evaluated using this 3DOF system during the concept design phase. With the wind tunnel data and the structural model for the tower, frequency domain-based analysis and time domain-based simulations are applied to evaluate the performance for the preliminary design. Several iterations were performed to study the nonlinear damping to control high return period amplitudes while maintaining the desired motion reduction performance during common wind events.

Predicted Performance of the Damping System

The damping system performance is assessed by determining the effective damping of the system, ζ_{eff}, which is calculated based on:

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

where σ_s and σ_{s-0} are the response variances of the structure with and without the damping system, respectively.

The predicted results indicate that the damping system can achieve a total equivalent damping of 2.3% of critical corresponding to 35% of acceleration reduction to meet the 6-month wind comfort criteria. The frequency-domain responses of the building with and without the damping system are shown in Figure 5.

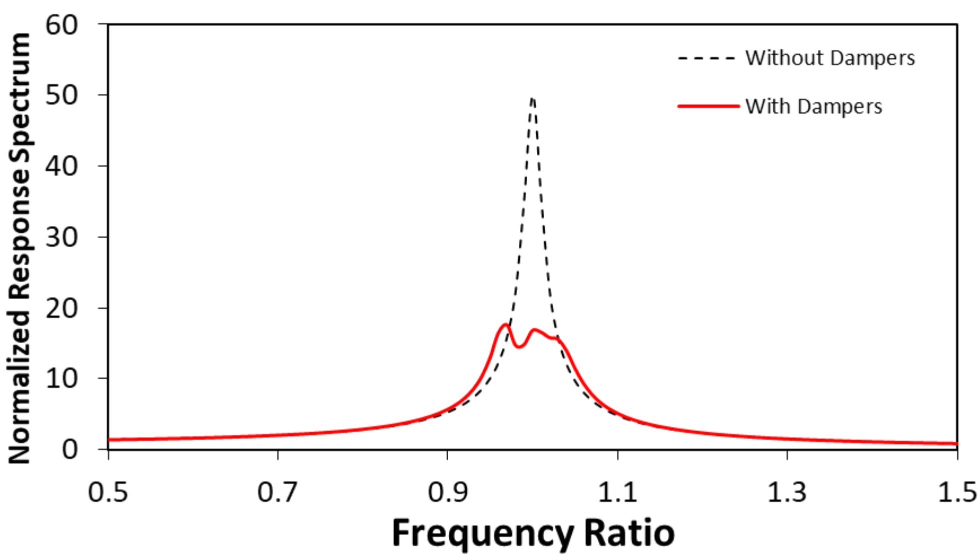

Fig. 5 Frequency domain responses – with and without the damping systems

Conclusion

This study demonstrates the effectiveness of a liquid-based damping system in controlling wind-induced building motion. After a comprehensive evaluation of the building's dynamic characteristics, spatial constraints, and post-construction feasibility, the design team selected a combination of tuned sloshing dampers and a Hummingbird damping system as the optimal solution. A 3DOF numerical model was developed to simulate the interaction between the structure and the damping system, using optimized parameters to assess performance. The results indicate that the proposed system can increase effective structural damping from 1% to 2.3%, successfully reducing building accelerations to meet the 6-month wind comfort criteria. Given its performance, cost-effectiveness, and minimal impact on the structural design, the liquid-based damping system presents a practical and innovative solution for mitigating wind-induced motion in tall buildings.

References

1. Irwin, P. A., 2008. Bluff body aerodynamics in wind engineering. Journal of Wind Engineering and Industrial Aerodynamics 96: 701–712.
2. Morava, B., Haskett T., and Smith, A., 2012. Enhancing the serviceability performance of tall buildings using supplemental damping systems. Ingegneria Sismica, XXIX(1): 60-69.
3. Ghisbain P, Mendes S, Pinto M, Malsch E and Scarangello T., 2017. Design and Commissioning of a New Liquid Damper System for Wind - Induced Vibrations of Buildings. 39th IABSE Symposium – Engineering the Future, Vancouver, Canada.
4. Zuo, L. 2009. Effective and robust vibration control using series multiple tuned-mass dampers. Journal of Vibration and Acoustics, 131.
5. Love, J. S., and Haskett, T. C., 2014. Using Multiple Tuned Sloshing Dampers (MTSDs) with Distributed Tuning for Improved Motion Control of Buildings. 6th World Conference on Structural Control and Monitoring.
6. Lee, C. S., Love, J. S., Haskett, T. C., and Robinson, J. K., 2021. Concept Design of a Parallel-type Tuned Mass Damper- Tuned Sloshing Damper System for Building Motion Control in Wind. International Journal of High-Rise Buildings, Vol 10, No 2, 93-97. https://doi.org/10.21022/IJHRB.2021.10.2.93.