Full-Scale Performance Evaluation of Structure-Dynamic Vibration Absorber Systems

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1 Abstract

Modern tall buildings are often susceptible to excessive wind-induced motion, which can cause occupant discomfort and decrease component longevity. Increasing the effective damping of these buildings using a dynamic vibration absorber (DVA) is often the preferred option to decrease motion, especially for serviceability-level performance. A tuned mass damper (TMD) is one form of DVA that consists of a steel or concrete mass that is supported near the top of the building. A tuned sloshing damper (TSD) is another type of DVA that consists of a tank that is partially filled with water and located near the top of the tower. In both cases, when the building moves during a wind event, the motion of the TMD mass or sloshing TSD water lags behind the motion of the structure. A properly designed DVA thereby produces forces that continually oppose the tower's motion, substantially reducing its response. Although numerous DVAs have been installed worldwide, very little reporting has been published on the full-scale performance of the damping systems. This paper will present the results of measurements conducted on several tall buildings equipped with DVAs. The measured results are compared to theoretical predictions to evaluate performance.

Keywords: high-rise buildings; wind loading; structural motion; tuned mass dampers, tuned sloshing dampers; full-scale monitoring

2 Introduction

Modern tall buildings are often susceptible to excessive wind-induced motion during common wind events. This motion can result in occupant discomfort, and reduce the longevity of nonstructural components such as partitions and facade elements due to large inter-storey drifts. In the past, if wind tunnel testing indicated that a building was expected to exceed the serviceability motion criteria, it was common to increase the building's mass or stiffness to reduce building motions. However, it is often more efficient and cost effective to increase the structural damping.

Although there is considerable scatter in the data set, the inherent damping of many tall buildings is 0.5% - 2% of critical [1]. Increasing the level of damping can dramatically reduce the structural motion. For a building subjected to broadband wind excitation, the peak building accelerations, $\hat{\hat{X}}_0$ and $\hat{\hat{X}}_1$, corresponding to two levels of damping, ζ_0 and ζ_1, respectively, are related by

$$\frac{\hat{\hat{X}}_1}{\hat{\hat{X}}_0} = \sqrt{\frac{\zeta_0}{\zeta_1}} \tag{1}$$

Therefore, increasing the total damping from 1% to 4% would reduce building accelerations by a factor of two.

Over the last two decades, dynamic vibration absorbers (DVAs), in the forms of tuned mass dampers (TMDs) or tuned sloshing dampers (TSDs), have been increasingly employed to increase the effective damping of tall buildings. A TMD consists of a solid mass that is free to oscillate laterally, and is connected to the structure through elements that add stiffness (restoring forces), and dissipate energy (damping forces). When the structure moves, the mass of a properly designed TMD will oscillate out-of-phase with the motion of the structure, thereby applying a force that opposes the structure's motion. A TSD consists of a tank with a specific length, width, and liquid depth, as well as properly-selected damping elements in the form of screens, poles, or baffles [2]. When the structure moves, the liquid (typically water) of a properly-designed TSD will slosh out-of-phase with the motion of the structure, thereby applying a sloshing force that opposes the structure's motion. Both types of DVAs are located near the top of a building, where the building motion is greatest, to provide the best performance. Moreover, the natural frequencies and damping ratios of the DVAs must be carefully selected to provide optimal performance [3].

While DVAs have received considerable research attention both theoretically and experimentally (at reduced-scale model), only a few studies have focused on their real-world full-scale performance in tall buildings [4, 5, 6]. This study will present results from full-scale monitoring that has recently been conducted on tall buildings equipped with DVAs. The performance of the DVAs during common wind events will be compared to the theoretically-predicted performance.

3 DVA Modeling

A simplified model is employed to describe the structure-DVA system. M_s, ω_s, and ζ_s are the generalized mass, natural angular frequency, and damping ratio of the structural vibration mode being controlled, and m_a, ω_a, and ζ_a are the effective mass, natural angular frequency, and damping ratio of the DVA. The structural response is $X(t)$, and the relative motion between the DVA and structure is $x_r(t)$.

During common wind events, when the excitation amplitudes are small, TSDs are often represented as an equivalent mechanical model [2]. The equivalent mass, damping, and natural frequency of the tank are calculated as functions of the tank dimensions (length, width, and liquid depth) using simple formulae. One notable difference is that statistical linearization is employed to represent nonlinear liquid damping as amplitude-dependent viscous damping [2]. This nonlinear damping ensures that, while optimal performance can be achieved at a target response amplitude, performance during *very* light winds typically decreases.

The equations of motion and the frequency response functions for the system are well-known [7]. The theoretically-determined frequency response functions are calculated based on the structural and DVA properties, and are used to determine response spectra for the structure and DVA. The measured response spectra are then compared to the predicted spectra to confirm the system is responding and performing as intended.

Through full-scale monitoring, the measured added effective damping, ζ_{add} provided by the DVA is given by [8]:

$$\zeta_{add} = \frac{\mu\omega_s E\left[\ddot{X}\dot{x}_r\right]}{2E\left[\ddot{X}^2\right]} \tag{2}$$

where $E[]$ denotes the expected value, and $\mu = m_a/M_s$ is the DVA mass ratio. The total effective damping for the structure is given by $\zeta_{eff} = \zeta_s + \zeta_{add}$. The building motion reduction is determined by substituting ζ_{eff} and ζ_s into Eq. (1).

4 Full-Scale Monitoring

Full-scale monitoring data is presented for three anonymous buildings equipped with DVAs. For presentation, the frequency axes of the spectral plots are normalized by the natural frequency of the structure, and the spectral amplitudes are normalized by taking the square root and then dividing by the standard deviation of the measured response.

4.1 Building #1

Building #1 is a 47-storey tower located in the United States. The measured natural angular frequency of the tower is 1.61 rad/s (0.26 Hz). It is equipped with four identical unidirectional TSD tanks, each with a length, width, and water depth of 7.47 m, 3.58 m, and 2.01 m, respectively. Obstructions in the form of paddles are positioned in the tank to increase the liquid damping. The DVA mass ratio of all tanks combined is 1.58%.

During the commissioning of the TSD system in the summer of 2018, the motion of the tower was monitored using accelerometers, while the TSD motion was monitored using ultrasonic wave probes in two of the four identical tanks. During the 48-hour monitoring period, the winds were quite light, resulting in a peak tower acceleration of 0.7 milli-g at the top of the building, and a peak wave height of 0.02 m.

Figure 1(a) and (b) shows the normalized response spectra corresponding to the two hours during which the response was greatest. The amplitude-dependent TSD damping is very low due to the small excitation amplitudes, which results in two pronounced peaks in the response spectrum. As the excitation amplitude increases, the TSD damping will also increase towards its optimal value, and TSD performance will improve. At these low excitation levels, the added effective damping is 0.5%; however, at larger amplitudes, the added effective damping will approach 3%. The inherent structural damping at these low levels is expected to be ~0.5%, which suggests that the TSD has reduced dynamic motions by 30%. At the stronger wind levels targeted by the design, the TSD is expected to reduce dynamic motions by 50%, assuming 1% inherent structural damping.

4.2 Building #2

Building #2 is a 60-storey tower located in the United States. The fundamental sway frequency is 1.29 rad/s (0.21 Hz). It is equipped with a single unidirectional TSD whose length, width and water depth are 10.36 m, 13.41 m, and 2.13 m, respectively. Obstructions in the form of paddles are positioned within the tank to increase liquid damping. The DVA mass ratio is 0.74%, with an intention to provide 1.5% added effective damping.

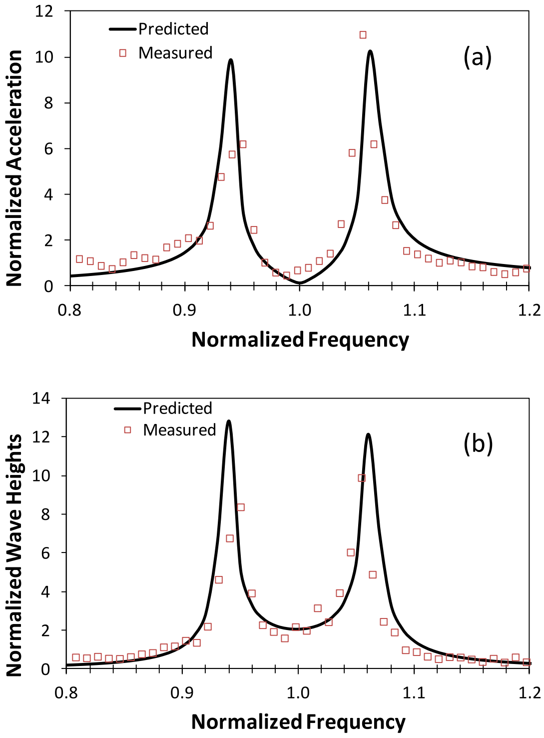

Figure 1: Building #1: a) building acceleration spectra, b) TSD wave height spectra

The building was initially monitored for two days in June 2018 when the building was nearly complete, but prior to the tank being (partially) filled. During this monitoring period, a thunderstorm occurred in which accelerations peaked at 1.2 milli-g. Since the tank was not filled, the random decrement technique was employed to determine that the inherent structural damping was 0.9% at this excitation amplitude, as shown in Figure 2 (a).

The TSD system was commissioned in the fall of 2018, and it was monitored for a one-day period after the tank was filled to the proper depth. A significant wind event occurred during this monitoring period. The peak acceleration measured during this event was 1.3 milli-g, and the peak wave height was 0.1 m. With the TSD operational, stronger winds were required to achieve an acceleration amplitude that was similar to that recorded with the TSD empty.

Figure 2(b) and (c) show the measured and predicted normalized response spectra of the structural acceleration and TSD wave height, respectively. The predicted and measured results are in good agreement, indicating the system is functioning as intended. At this level of excitation, the added effective damping is 0.6%, for a total effective damping of 1.5%, resulting in a dynamic motion reduction of 23%. At the acceleration amplitudes of interest (1-year and 10-year mean recurrence intervals), the TSD is predicted to provide 1.5% added effective damping, which will result in a 39% reduction of dynamic motion.

The TSD was tuned to a frequency 2-3% lower than optimal at the current structural frequencies. This tuning was chosen to accommodate the small amount of live load that was yet to be added to the building, as well as a small amount of building softening due to cracking. Therefore, the TSD performance is expected to improve further as the building ages, and the frequency ratio shifts closer to optimal.

4.3 Building #3

Building #3 is a super-tall (>300 m) tower located in southeast Asia. The measured fundamental sway frequency is 0.67 rad/s (0.11 Hz). The tower has a linear TMD with a mass ratio of 1.0%, to add 1.7% effective damping to the structure. The TMD was commissioned in the winter of 2016.

During the summer of 2018, the TMD was locked-out for approximately 30 minutes during a wind event to assess the inherent structural damping. The peak acceleration recorded during this period was 1 milli-g. The random decrement technique was employed to estimate the inherent structural damping to be 0.9% as shown in Figure 3(a).

The TMD was released and the motions of the TMD and structure were recorded during another significant wind event. During this event, the peak tower acceleration was 1.7 milli-g, while the peak TMD displacement was 0.25 m. The measured and predicted normalized spectral responses of the structural acceleration and TMD displacement are shown in Figure 3(b) and (c) to be in reasonable agreement. The TMD provides 2.0% added effective damping, independent of excitation intensity, which reduces dynamic motion by 44%.

5 Conclusions

This study has evaluated the performance of tall buildings equipped with DVAs. The full-scale response and performance matched predictions. The following conclusions are made:

- Building #1 was equipped with four identical TSD tanks, which provided 0.5% added effective damping during very light winds. Added effective damping of 3% will be provided during the 1-year and 10-year wind events.
- Building #2 possessed 0.9% inherent damping and was equipped with a TSD, which provided 0.6% added effective damping, and reduced motions by 23%. During larger wind events, the TSD will provide 1.5% added effective damping, which will reduce motions by 39%.
- Building #3 possessed 0.9 % inherent damping and was equipped with a linear TMD. The TMD provided 2.0% added effective damping, which reduced dynamic motion by 44%.

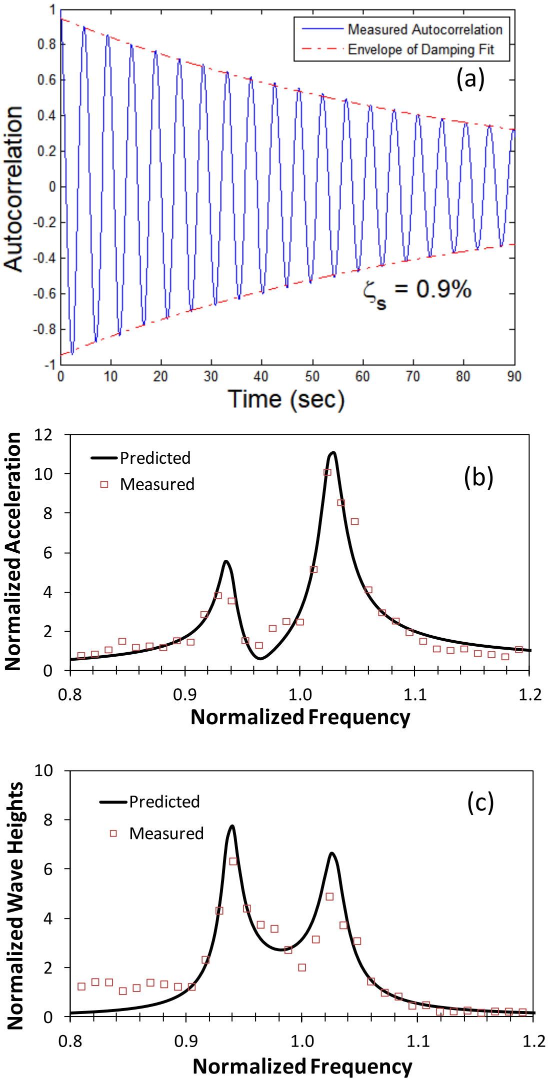

Figure 2: Building #2: a) random decrement signature without TSD, b) building acceleration spectra, c) TSD wave height spectra

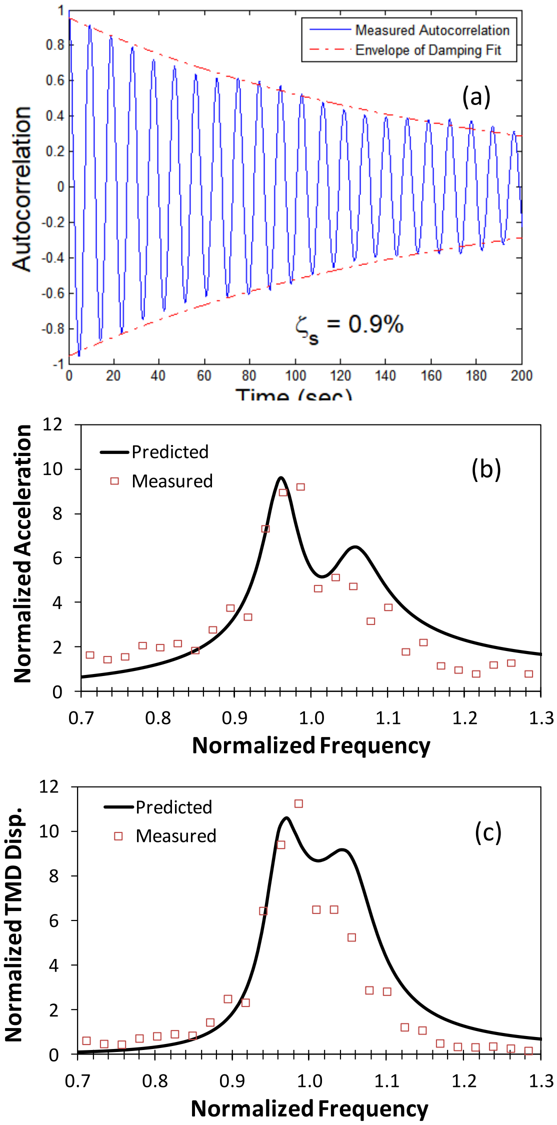

Figure 3: Building #3: a) random decrement signature without TMD, b) building acceleration spectra, c) TMD displacement spectra

6 References

[1] R. Smith, R. Merello and M. Willford, "Intrinsic and supplementary damping in tall buildings," *Structures and Buildings,* vol. 163, no. SB2, pp. 111-118, 2010.

[2] M. Tait, "Modelling and preliminary design of a structure-TLD system," *Engineering Structures,* vol. 30, pp. 2644-2655, 2008.

[3] G. Warburton, "Optimum absorber parameters for various combinations of response and excitation parameters," *Earthquake Engineering and Structural Dynamics,* vol. 10, pp. 381-401, 1982.

[4] Y. Tamura, K. Fujii, T. Ohtsuki, T. Wakahara and R. Kohsaka, "Effectiveness of tuned liquid dampers under wind excitation," *Engineering Structures,* vol. 17, no. 9, pp. 609-621, 1995.

[5] J. Love, T. Haskett and B. Morava, "Effectiveness of dynamic vibration absorbers implemented in tall buildings," *Engineering Structures,* vol. 176, pp. 776-784, 2018.

[6] J. Love and B. Morava, "Full Scale Monitoring of a Tall Building Equipped with and Efficient Tuned Sloshing Damper System," in *6th International Structural Specialty Conference*, Fredericton, NB, 2018.

[7] R. McNamara, "Tuned mass dampers for buildings," *Journal of the Structural Division,* vol. ST9, pp. 1785-1798, 1977.

[8] J. Love and M. Tait, "Estimating the added effective damping of SDOF systems incorporating multiple dynamic vibration absorbers with nonlinear damping," *Engineering Structures,* vol. 130, pp. 154-161, 2017.