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

J. Shayne LOVE  
Project Engineer  
RWDI Inc.  
Guelph, ON, Canada  
Shayne.Love@rwdi.com  
Since joining RWDI in 2012, Shayne has been involved with dozens of projects involving structural vibration and structural control.

Trevor C. HASKETT  
Senior Technical Director  
RWDI Inc.  
Guelph, ON, Canada  
Trevor.Haskett@rwdi.com  
Trevor has been working with RWDI since 1999, finding applications for his mechanical engineering training in vibration control to tame the motions of buildings and bridges.

Contact: Shayne.Love@rwdi.com

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, $\ddot{x}_0$ and $\ddot{x}_1$, corresponding to two levels of damping, $\zeta_0$ and $\zeta_1$, respectively, are related by

$$\frac{\ddot{x}_1}{\ddot{x}_0} = \frac{\zeta_0}{\sqrt{\zeta_1}}$$  \hspace{1cm} (1)
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, \(\zeta_{add}\) provided by the DVA is given by [8]:

\[
\zeta_{add} = \frac{\mu\omega_2 E[\hat{X}\hat{X}_r]}{2E[\hat{X}^2]} \quad (2)
\]

where \(E[\cdot]\) denotes the expected value, and \(\mu=m_o/M_s\) is the DVA mass ratio. The total effective damping for the structure is given by \(\zeta_{eff} = \zeta + \zeta_{add}\).

The building motion reduction is determined by substituting \(\zeta_{eff}\) and \(\zeta\) 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
September 4-6, 2019, New York City
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

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
6 References


