CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

ADAPTIVE DAMPING STRATEGY USNG COMPACT SLIDING-TYPE TUNED MASS DAMPERS FOR TALL BUILDINGS

Jeong, U. Y.[1,4], Kurabayashi, H.[2], Ha, D.H.[3,5], Dupelle, L.[1,6], Tarrant, K.[1,7], Ferraro, V.[1,8], Sliasas, A.[1,9]
[1] Gradient Wind Engineering Inc., Canada
[2] Vibro-system, Japan
[3] Konkuk University, South Korea
[4] unyong.jeong@gradientwind.com
[5] hadongho@konkuk.ac.kr
[6] liam.dupelle@gradientwind.com
[7] kevin.tarrant@gradientwind.com
[8] vincent.ferraro@gradientwind.com
[9] andrew.sliasas@gradientwind.com

Abstract: An Adaptive Tuned Mass Damper (TMD) design procedure is proposed to mitigate wind-induced vibration of tall buildings where accelerations moderately exceed the recommended guidelines. The Adaptive TMD design allows for postponing the adoption of a TMD until the necessity is verified through building monitoring, which leads to economical and optimal building dampening design. This adaptive TMD design, which utilizes early, short-term monitoring and a Sliding-type TMD (S-TMD) system, can drastically reduce the size of the TMD or even remove the need for the TMD altogether. A comprehensive study was performed for a tall building with accelerations moderately exceeding the guideline, and the adaptive TMD design process for the building is described in detail. Devices and theoretical formulae, such as a building oscillator and the equation of motion for a building-TMD coupled system required for adaptive TMD design are also described in detail.

1 INTRODUCTION

Among supplemental damping options for the excessive sway dynamic motion of tall buildings, Tuned Mass Dampers (TMDs) are used for of the benefit of their low maintenance cost and compact size as compared to other damper options, such as Tuned Liquid Sloshing Dampers (TLSDs) or Tuned Liquid Column Dampers (TLCDs). Compared to distributed-type dampers such as dashpot dampers or viscoelastic dampers, which are usually embedded in the building structure and have to be designed with other building structural members, the TMD is much simpler in design and easier to accurately quantify the supplemental damping effects for.

Despite these benefits, TMDs are considered to be one of the more expensive options. Also, some types of TMDs such as Pendulum-type TMDs (P-TMDs) occupy a large space taking up to 3 to 6 storeys of typical floors. Early designs of TMDs from the 1970s were low-profile sliding-type TMDs (S-TMDs). Examples of such devices were installed on the Citycorp Building in New York City and the John Hancock Tower in Boston (Conor 2003). Since these early designs required relatively complicated systems such as hydraulic pumps, air springs and control consoles, their use in later buildings became less frequent. These early S-TMDs utilized pressure-balanced oil bearings to obtain a small friction coefficient less than 0.3%.

In order to replace the relatively complicated mechanical systems of early S-TMDs while achieving a low friction coefficient, P-TMDs have been used in several buildings including Taipei 101 in Taiwan and 432 Park Avenue, New York City (Lago et al. 2019). However, P-TMD damper frequencies are solely governed by the pendulum length, and for tall buildings with long building periods close to 8 seconds, the pendulum length has to be more than 15 meters (m) long (which will occupy at least 5 residential storeys). Although the nested pendulum system or a combination of inverted pendulum and nested pendulum systems (Bloomberg Tower, New York City) can reduce the TMD height (Lago et al. 2019), P-TMDs still present the drawback of requiring high headroom.

On the other hand, S-TMDs have been developed in Japan mainly for the earthquake design of buildings. Contrary to P-TMDs, S-TMDs are compact and low to the ground since the frequency of a S-TMD's mass can be achieved by the stiffness (usually provided by springs), and the mass is simply laid on linear guides. Over the years, the fabrication process of the sliding mechanism for S-TMDs has also been improved to the point where the friction coefficient can be as low as 0.3%~ 0.5% without the need for pressurized oil, as was the case for early S-TMDs (Connor 2003). As a low-friction sliding mechanism for S-TMDs, linear guides, rubber bearing supports or combination of both can be used. Stacked rubber bearings can also provide a flexible yet stable support system enabling low TMD frequencies for heavy masses of more than 500 tons, which is referred to as R-TMD (Jeong et al. 2016).

Due to the compact design of S-TMDs, a flexible and adaptable TMD design is possible. For tall buildings with 40-70 floors, the resultant acceleration often ends up slightly exceeding the guidelines. Since the as-built building properties are usually stiffer than the theoretical ones (based on our experience with tall buildings), it would be prudent to determine the size of the TMD or even the necessity for the TMD based on the measured as-built building frequencies. Although this adaptive strategy is a very efficient tool for economical TMD design, the determination has to be made at early construction stage to enable i) reallocating the space to other purpose when TMD is not required, or ii) fabricating TMD on schedule when TMD is required. Due to the heavy TMD mass, the installation must be finished before the tower crane is removed.

In order to resolve the difficulties of this adaptive damping strategy, an S-TMD, combined with early building monitoring using a building oscillator, is proposed in this paper. By using a compact S-TMD, the reserved space are small and can easily be relocated for other purpose. Also, building oscillator makes building monitoring possible at early construction stage which allows more time for TMD fabrication and installation until taking down tower crane. The details of this adaptive damping strategy are described below taking a 52-storey building as an example.

2 EARLY STAGE BUILDING MONITORING

Early building monitoring allows for enough time to incorporate TMD fabrication in adaptive TMD design. If typical TMD fabrication/installation takes around 6-10 months, the TMD fabrication should start at least 8-12 months before the tower crane is taken down. By this time, tall buildings usually reach the stage of mid to ¾ of the full height. The questions would then be i) whether the building's need for a TMD can be determined based on measurements taken during this early construction stage – an accuracy issue of extrapolating mid-height building properties to the full-height properties, and ii) proper measurement of building frequencies under the construction noise and unfinished cladding, under which wind-excited building motion is weak.

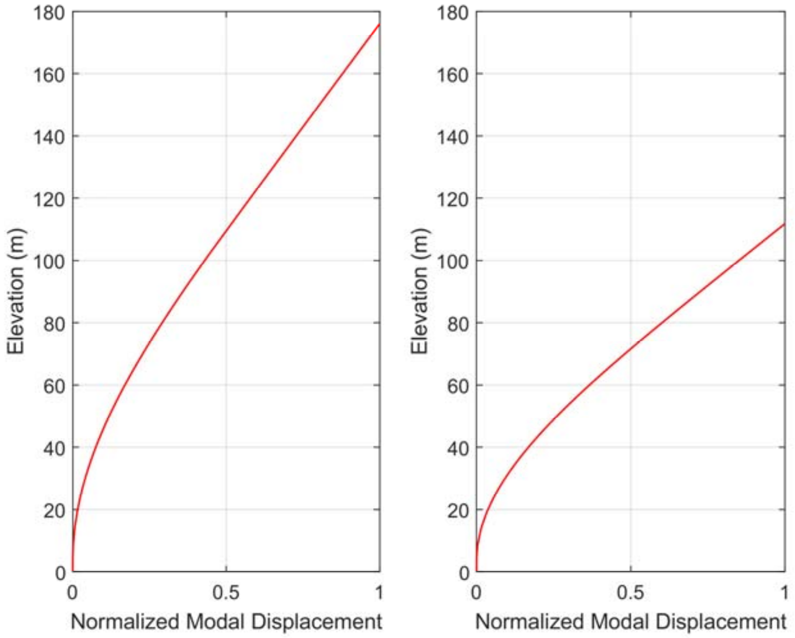

Figure 1: Mode shapes of a 52-storey building at two different construction stages

Specifically, the question of extrapolation relies on the accuracy of extrapolating the building's flexural stiffness from the mid-height structure to the full-height structure. Figure 1 illustrates mode shapes of a 52-storey building at two different construction stages (full height and mid-height, respectively) based on free vibration analysis. As shown in the figure, most flexural deformation occurs near the bottom of the tower because floor heights of the bottom floors are taller than the upper floors. Above the mid-floors, the deformation (the curvature) is moderate. Based on this, it is estimated that the overall building frequency is mainly governed by stiffness of low floors, which means the dynamic properties of the mid-height building can be well extrapolated to the full height.

Regarding the second issue of building excitation during monitoring/ without cladding, it is difficult to excite building motion under moderate winds. Furthermore, when long- or mid-term monitoring is required, the measurements inevitably include the construction noise, and the monitoring system can be physically or electronically damaged. To resolve these issues, a building oscillator as shown in Figure 2 can be utilized. The building oscillator can quickly sweep through frequencies where building frequency will lie, which enables quick and clean building frequency monitoring (typically performed in the evening, after the construction work has subsided). When the building oscillator is used, the steady state solution of resonant response (acceleration), $\hat{a}$, of the building can be obtained as follows:

[1] $\hat{a} = \frac{m_a}{\tilde{m}} \frac{1}{2\xi} \hat{a}_0$

where m_a= actuator mass; $\tilde{m}$ building's modal mass based on the mode shape being 1 at the floor of interest; ξ = inherent structural damping ratio; $\hat{a}_0$= the acceleration amplitude of the oscillator. Based on this equation, an oscillator, which consists of a typical mass of 1-ton oscillating with an amplitude of +/- 1 m at a typical building frequency, can generate building accelerations of around 0.5 milli-g or higher, which is high enough to extract the building frequency.

Once the as-built building frequency is measured for the mid-floor height, the full height as-built building frequency can be extrapolated with good accuracy by applying the ratio between full-height to mid-height building frequencies from a structural analysis model of the building. The necessity of a TMD for the building can be determined based on wind-induced response analysis of the building using the as-built building frequencies measured from the building monitoring.

Figure 2: Building Oscillator with 1-ton mass developed by Gradient Wind Engineering Inc.

3 EVALUATION OF BUILDING RESPONSE WITH TMD

3.1 Equation of Motion in Generalized Coordinate

The equation of motion of the TMD-building coupled system is derived in generalized coordinate for wind analysis of buildings. For simplicity, a building is modeled as following a single-degree of freedom model:

[2] $\ddot{\tilde{x}}_1 + 2\xi_1\omega_1\dot{\tilde{x}}_1 + \omega_1^2\tilde{x}_1 = \tilde{m}_1{}^{-1}\tilde{f}_1 + \tilde{m}_1{}^{-1}\tilde{f}_{1m}$

where ξ_1, ω_1 and $\tilde{m}_1$= damping ratio, angular frequency and modal mass respectively of the mode of interest; $\tilde{x}_1$, $\dot{\tilde{x}}_1$, and $\ddot{\tilde{x}}_1$= the zero (displacement), first (velocity) and second order (acceleration) time derivatives of the generalized coordinate; $\tilde{f}_1$ and $\tilde{f}_{1m}$= generalized force measured from wind tunnel testing and generalized force from the TMD respectively;

[3] $\tilde{f}_{1m} = \phi_{1mx}m(2\xi_m\omega_m\dot{x} + \omega_m^2 x)$

where ϕ_{1mx}= mode shape at the location of TMD; ξ_m, ω_m = damping ratio and angular velocity of TMD mass; x and $\dot{x}$= the zero and first order time derivatives of the relative displacement between the TMD and the building at the TMD location.

The other governing equation is derived from the dynamic equilibrium state of the free-body of the TMD mass, which can be expressed in the following form:

[4] $(\ddot{x} + \ddot{x}_s) + 2\xi_m\omega_m\dot{x} + \omega_m^2 x = 0;$

where m= TMD mass; $\ddot{x}$ = the second order time derivative of the relative displacement between TMD and the building motion at the TMD location (x_s); $\ddot{x}_s$ = building acceleration at the TMD location and $\ddot{x}_s = \phi_{1mx}\ddot{\tilde{x}}_1$. When it is rewritten, the second order time derivative of TMD relative motion can be expressed as follows for the State-Space formula:

[5] $\ddot{x} = \phi_{1mx}\omega_1^2\tilde{x}_1 + \phi_{1mx}2\xi_1\omega_1\dot{\tilde{x}}_1 - (\phi_{1mx}^2 r\omega_m^2 + \omega_m^2)x - (\phi_{1mx}^2 2r\xi_m\omega_m + 2\xi_m\omega_m)\dot{x} - \phi_{1mx}\tilde{m}_1^{-1}\tilde{f}_1.$

where mass ratio, $\mathrm{r} = \mathrm{m}/\tilde{\mathrm{m}}_1$.

In state-space form, the coupled TMD-building motion can be expressed as follows in generalized coordinate using a state vector $\mathrm{X} = \left\{\tilde{\mathrm{x}}_1, \dot{\tilde{x}}_1, x, \dot{x}\right\}^T$:

[6] $\dot{\mathrm{X}} = \mathrm{AX} + \mathrm{B}\tilde{f}_1$;

[7] $$\mathrm{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\omega_1^2 & -2\xi_1\omega_1 & r\phi_{1\mathrm{mx}}\omega_m^2 & 2r\phi_{1\mathrm{mx}}\xi_m\omega_m \\ 0 & 0 & 0 & 1 \\ \phi_{1\mathrm{mx}}\omega_1^2 & \phi_{1\mathrm{mx}}2\xi_1\omega_1 & -(r\phi_{1\mathrm{mx}}^2\omega_m^2 + \omega_m^2) & -(2r\phi_{1\mathrm{mx}}^2\xi_m\omega_m + 2\xi_m\omega_m) \end{bmatrix};$$

[8] $$\mathrm{B} = \begin{bmatrix} 0 \\ \tilde{\mathrm{m}}_1^{-1} \\ 0 \\ -\phi_{1\mathrm{mx}}\tilde{\mathrm{m}}_1^{-1} \end{bmatrix}.$$

3.2 Wind Loading from Wind Tunnel Testing

Wind loading on tall buildings can be accurately assessed by High-Frequency Force Balance (HFFB) wind tunnel testing. Once wind loads are measured in the wind tunnel, modal wind force, $\tilde{\mathrm{f}}_1$, in equation [5] can be derived as follows based on HFFB theory and mode shape correction (Tscanz 1982, Tschanz and Davenport 1983, Jeong 2015, Ho et al. 2014):

[9] $\tilde{\mathrm{f}}_1 = k_m M$

[10] where mode shape correction factor, $\mathrm{k_m} = \frac{\int_0^H \phi p(z)dz}{\int_0^H zp(z)dz}$;

Z= height above the grade; H= building height; M= base bending motion; $\mathrm{p(z)}$= wind load distribution along the height.

The characteristic of wind loading is different from sinusoidal or white-noise type loading because it represents realistic wind loading on the building that includes vortex-shedding and wind turbulence from the neighbouring buildings, as well as boundary layer turbulence measured in the wind tunnel.

Once wind load time history is determined, as per equation [9] above, the dynamic motion of the building-TMD coupled system can be analyzed based on equation [6] in State-Space. In the analysis, the as-built building properties from the building monitoring, as mentioned in Section 2, can be used to assess the building motion more accurately. From this analysis, key TMD design parameters such as relative displacement of TMD mass and TMD damping effects can be determined and verified.

4 EXAMPLE – ADAPTIVE TMD DESIGN FOR 52-STOREY BUILDING

Figure 3 shows a photograph of an HFFB model of a 52-storey building in the wind tunnel. Based on the testing, the building's 10-year return period peak acceleration was estimated to be 24.0 milli-g and was governed by one-directional motion of 21 milli-g under an inherent structural damping of 1.75%. In order to mitigate the resultant building acceleration down to the accepted level of 18 milli-g for residential buildings, the building required 1.7% supplemental damping. A 50-ton S-TMD was required to achieve this level of supplemental damping.

An adaptive TMD design will be applied to this building due to the following two main reasons: i) although the acceleration is not acceptable, the excess is moderate; ii) the acceleration based on the as-built building frequencies would very likely reduce to the level where a TMD may not be required or where TMD size could be substantially reduced. Based on the adaptive TMD design strategy, the building monitoring will be performed using the building oscillator when the building construction reaches around the 36th floor (where the building properties of full building height can be well extrapolated). This will allow enough time to fabricate and install a TMD before the tower crane is taken down, if supplemental damping is found to be required based on the building monitoring. Until the monitoring occurs, a relatively small space is reserved on top of the roof, and the floor/roof is structurally designed to accommodate TMD weight.

A 50-ton one-directional S-TMD was designed for the top of the building to provide the noted supplemental damping of 1.7%. Figure 4 illustrates a 3-D image of the TMD. As shown in the figure, the S-TMD is compact and can comfortably fit in a space of 4m x 5m x 2m (height).

Figure 3: High-Frequency Force Balance (HFFB) wind tunnel testing of study building - Gradient Wind Engineering Inc.

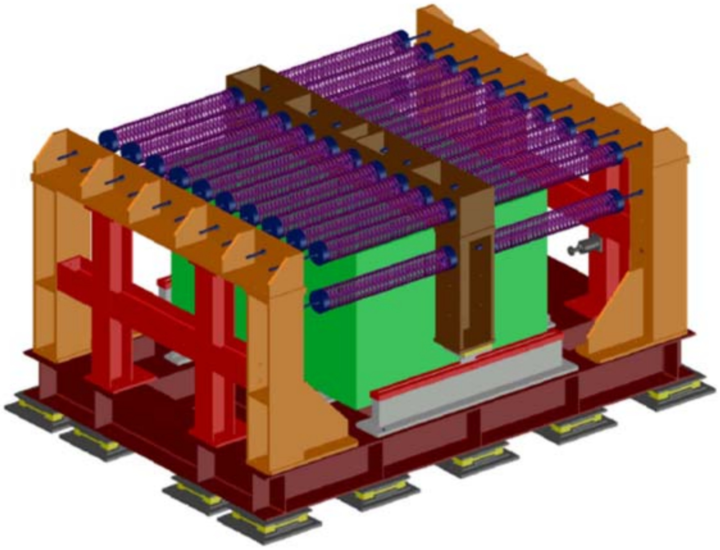

Figure 4: 50-ton Sliding-Type Tuned Mass Damper to be installed on top of the roof (Gradient Wind Engineering Inc.)

Table 1: Example building and TMD properties

	Building Property	TMD-1	TMD-2
Natural Frequency [Hz]	0.165	0.164	0.164
Damping Ratio	0.0175	0.034	0.060
Peak Building Acceleration [milli-g] under 10-year Wind Load	21.0	15.3	15.7
Mass [kg]	9.86×10^6 *	50,000	50,000
Maximum Relative Displacement of TMD mass [m] under 10-Year Wind Load	-	1.94	1.46

* Building Modal Mass

An optimal S-TMD is adapted for the building and a time domain analysis of building-TMD coupled system was performed based on equation [6] by using 10-year return period wind loads measured in the wind tunnel. Figure 5 illustrates a time series of building response around its peak with and without TMD. As shown in the figure, the peak building response is reduced from 21.0 milli-g to 15.3 milli-g due to the supplemental damping effect of the TMD. This supplemental damping effect is also clearly shown in the building's response spectra, which drastically reduces around the peak as illustrated in Figure 6.

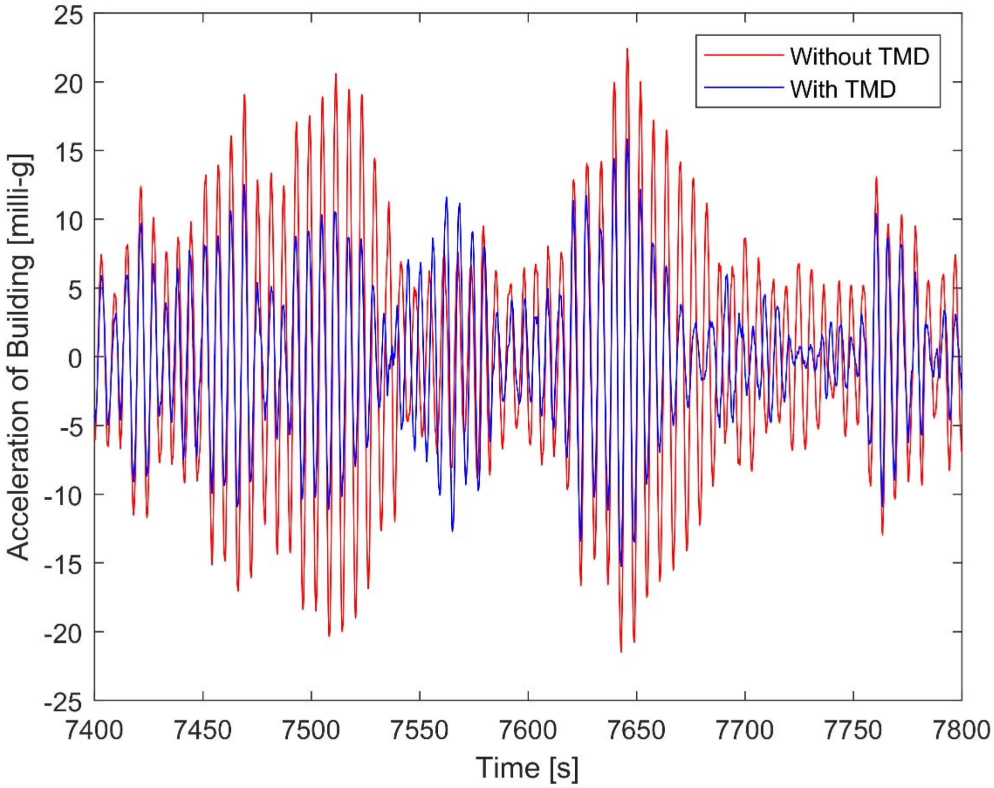

Figure 5: Peak acceleration at top occupied level corresponding 10-year return period wind load, TMD damping ratio = 0.034 (optimal damping).

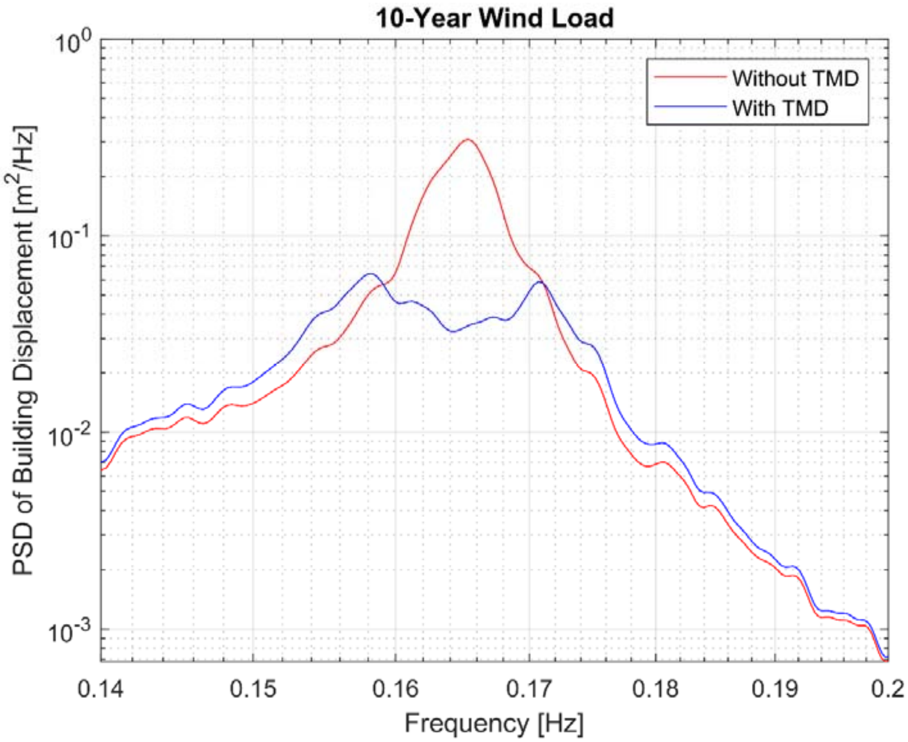

Figure 6: Comparison of building displacement spectra with and without TMD corresponding 10-year wind load, TMD damping ratio= 0.034 (optimal damping)

Because adaptive TMDs are usually small, they have a low mass ratio of around 0.5%, which leads to large TMD mass stroke during the operation. The large stroke introduces two problems: i) the large stroke increases the possibility of oil leakage of the dashpot damper over long term, and ii) TMD requires bigger (longer) space. These problems can be resolved by using different damper types other than dashpot dampers, such as Viscous Wall Dampers (VWDs), and by increasing the damping while slightly sacrificing efficiency of the TMD. For this reason, the TMD utilizes VWD to accommodate the relatively large stroke, as illustrated in Figure 4. Figure 7 illustrates the time history of TMD mass stroke under 10-year wind loading for optimal TMD damping of 3.4%. As shown in the figure, the maximum TMD mass stroke reaches almost 2.0 m and reaches approximately 1.2 m most of the time. Since this stroke is very high, the damping coefficient of the VWD was increased to 6.0% to reduce the stroke.

Figure 8 illustrates the TMD mass stroke for a damping coefficient of 6.0% damping. As shown in the figure, the damper stroke reduced substantially, the peak is 1.46 m, and the stroke remains below 1.0 m most of the time. Figure 9 illustrates the building acceleration with a TMD damping ratio of 6.0%. The building acceleration is slightly increased compared to the TMD with optimal damping; however, the peak acceleration remains at an acceptable level of 15.7 milli-g. In summary, the excess TMD stroke can be reduced by increasing TMD damping without considerably sacrificing TMD efficiency.

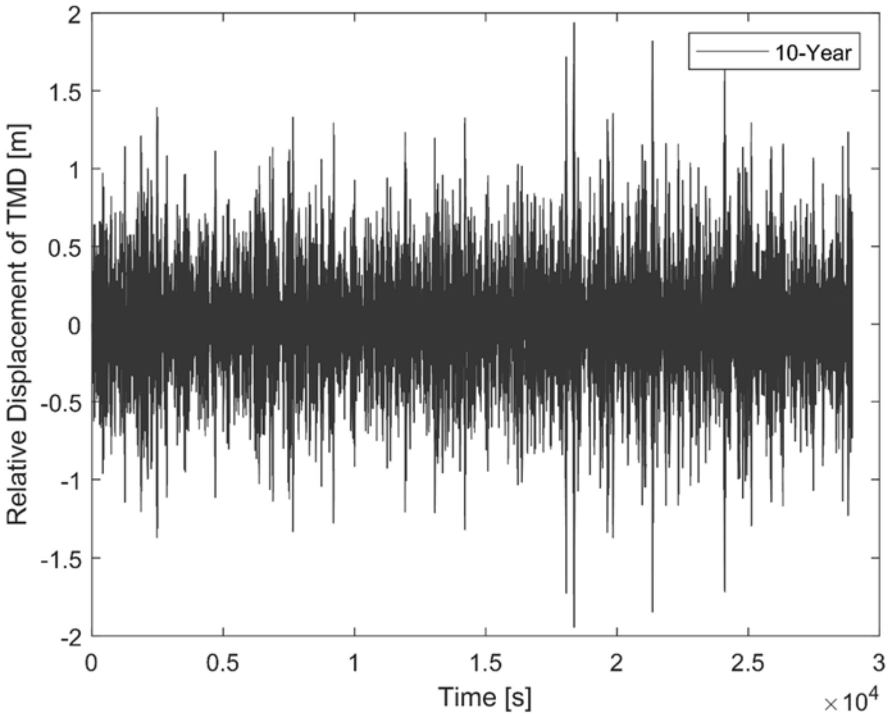

Figure 7: Relative displacement of TMD mass corresponding 10-year wind load, TMD damping ratio= 0.034 (optimal damping)

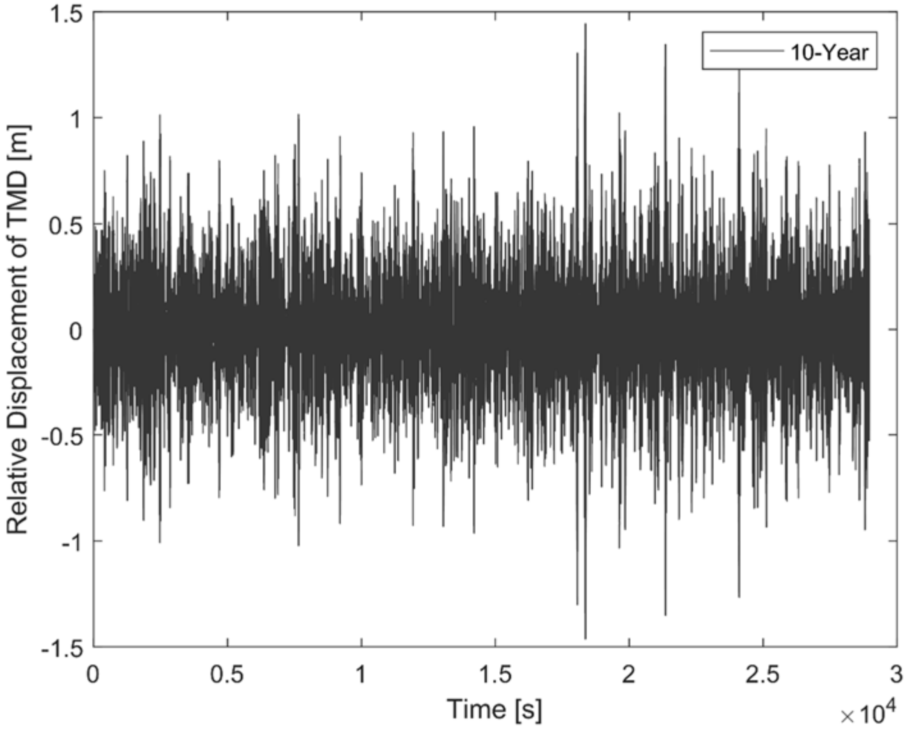

Figure 8: Relative displacement of TMD mass corresponding 10-year wind load, TMD damping ratio= 0.060

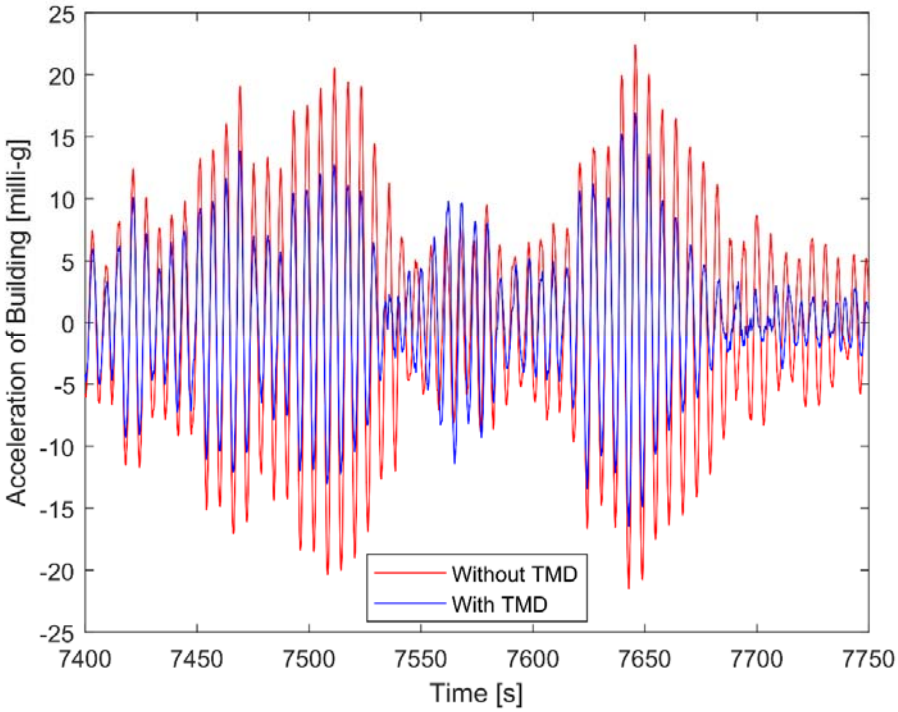

Figure 9: Time History of peak acceleration at top occupied level corresponding 10-year wind load, TMD damping ratio= 0.060

5 CONCLUSIONS

This paper presents a compact S-TMD system that can be utilized as a cost-efficient supplemental damping measure for buildings where wind-induced accelerations moderately exceed the guidelines. The adaptive TMD design procedure proposed in this paper can be utilized to postpone the adoption of a TMD until the necessity is verified through building monitoring. This adaptive design strategy, which utilizes early short-term monitoring and an S-TMD system, enables flexible damper design that can drastically reduce the size of the TMD or even remove the TMD based on as-built building properties.

6 REFERENCES

Connor, J. J. 2003. *Introduction to Structural Motion Control*, Prentice-Hall, Englewood Cliffs, NJ.

Ho. E, Jeong, U.Y and Case P. 2014. Components of Wind Tunnel Analysis using Force Balance Test Data. *Wind and Structures – An International Journal*, **19**: 347-373.

Jeong, U.Y. 2015. Advances in Tall Building Design under Strong Winds. *ASCE/SEI Conference*, ASCE, Portland, Oregon, USA.

Jeong, U. Y., Tarrant, K., Sliasas, A. and Ferraro, V. 2016. *Preliminary Structural Wind loads and Building Motion – Yonge and Gerrard – 100-storey option*, Gradient Wind Engineering Inc., Ottawa, ON, Canada.

Lago, A., Trabucco D. and Wood A. 2019. *Damping Technologies for Tall Buildings*, Elsevier, Kidlington, Oxford, United Kingdom.

Tschanz T. and Davenport A.G. 1983. The Base Balance Technique for the Determination of Dynamic Wind Loads. *Journal of Wind Engineering and Industrial Aerodynamics*, **13**: 429-439.