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FULL-SCALE MONITORING OF A TALL BUILDING EQUIPPED WITH AN EFFICIENT TUNED SLOSHING DAMPER SYSTEM

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Abstract: Modern high rise construction materials and techniques have led to the proliferation of tall buildings that are lightweight, flexible, and possess low inherent damping. These structures are often susceptible to excessive wind-induced motions, which may cause discomfort for occupants on the upper storeys. The tuned sloshing damper (TSD) can be employed as an affordable, efficient, and simple means to mitigate building motion. A TSD consists of a tank located near the top of the structure, which is partially filled with water. As the building sways under wind action, the water within the tank will slosh. When properly designed, the force imparted to the structure by the sloshing water will counteract the wind loading, significantly reducing the building's motion. In traditional multi-tank TSD installations, all tanks are tuned to the natural frequency of the structural vibration mode being targeted. More recent research has shown that improved performance can be achieved if the tanks are set to slightly different frequencies near the structural mode being controlled, instead of having all tanks identically designed. This study first overviews a simple model to describe the response and performance of multiple tuned sloshing dampers (MTSDs) with frequencies distributed near the structural frequency of the targeted mode. Using this model, the advantages of considering the MTSD system are illustrated. The performance of the MTSD system is then demonstrated using full-scale measurements of a high rise building located in Toronto, Canada. To the authors' knowledge, this is the first building in the world equipped with this type of efficient MTSD system.

1 INTRODUCTION

Modern tall buildings are lightweight, slender, and lightly damped, which enables them to be particularly susceptible to wind-induced dynamic motion. While these structures can generally be efficiently designed to resist the loads produced during an ultimate wind event, it is often costly to satisfy the serviceability requirements for more common wind events. In particular, it can be challenging to achieve the relevant 1-year and 10-year acceleration criteria. Moreover, non-structural components such as partition walls or façade elements may be damaged if the serviceability drift criteria are exceeded.

To reduce wind-induced dynamic motion, architects and engineers have several options. Firstly, the shape of the building may be modified, which can reduce the wind loading applied to the building, however, this is generally undesirable architecturally. Secondly, the stiffness or mass of the structure can be increased, which generally requires the addition of more building materials, which is costly and is an inefficient use of resources. Lastly, the damping of the structure can be increased through the implementation of a supplementary damping system. Adding damping to the structure is often the preferred approach since it often does not necessitate extensive changes to the structure, and is typically relatively affordable.

Tuned sloshing dampers (TSDs) are increasingly being used in modern high rise buildings to increase the effective damping of the structure. A TSD consists of one or more tanks that are installed near the top of the building and are partially filled with a liquid (typically water). As the building moves, the liquid within the tank will begin the slosh. If the dimensions of the tank and the liquid depth are properly selected, the natural sloshing frequency of the TSD will be closely matched to the natural frequency of the structural vibration mode being controlled. These closely-matched natural frequencies produce a coupled structure-TSD system which modifies the mechanical admittance function of the structure and dramatically reduces its resonant response. Essentially, vibrational energy from the structure is transferred to the sloshing fluid, where it can be dissipated through damping mechanisms within the tank. As the amount of liquid mass participating in the sloshing increases, the structural motion reduction increases.

Traditionally, TSDs have consisted of a single tank being tuned to the natural frequency of the structure according to well-known theory originally developed for tuned mass dampers (Warburton, 1982). When multiple tanks are employed, they are often designed to have an identical natural sloshing frequency and damping. These identical tanks enable the TSD system to be modelled as a single large tank. However, it has been shown that improved performance and robustness of the TSD system can be achieved if the tanks are dissimilarly tuned (Fujino and Sun, 1993). For a multiple-tank TSD system, this dissimilar tuning is easily accomplished by having slightly different tank lengths or maintaining slightly different water depths in each tank. Herein, such a structure-TSD system with dissimilarly-tuned tanks will be called a structure-MTSD (multiple tuned sloshing damper) system. While structure-MTSDs have been reported theoretically in the literature, they have not, to the authors' knowledge, been reported installed and monitored in a full-scale structure.

The scope of this paper is two-fold. First, it presents a practical equivalent mechanical model to represent the behaviour of a structure-MTSD system subjected to random wind excitation. Using this model, the advantages of an MTSD system are discussed. Secondly, a three-tank structure-MTSD system which has recently been installed in a slender high-rise building in Toronto, Canada, is presented. To the authors' knowledge, this is the first structure-MTSD system ever installed in a building. The structure and the MTSD tanks have been equipped with sensors to simultaneously monitor the building motion as well as the motion of the water within the tanks. With this full-scale monitoring information, the efficacy of the system is reported.

2 STRUCTURE-MTSD MODEL

The i^{th} TSD tank has a length, L_i, width, b_i, and quiescent water depth, h_i, as shown in Figure 1. To increase the inherent damping of the sloshing water, rows of obstructions such as screens or paddles are placed in the tank at distances x_j from the tank wall to provide fluid drag. Each row of obstructions has a loss coefficient, C_l, which can be determined empirically. The temporal response of the first sloshing mode is defined by $q_i(t)$ at the tank end wall.

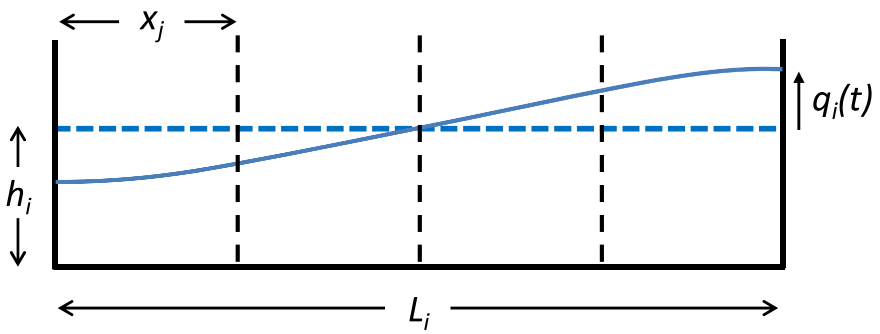

Figure 1: Tank schematic

The TSD response is determined by modelling the TSD as an equivalent mechanical system. With the assumptions that the water is incompressible, irrotational, and inviscid, potential flow theory can be used to represent the sloshing water as an equivalent mechanical system, whose equivalent mass, natural angular frequency, and amplitude-dependent damping ratio for the i^{th} tank are given by (Tait, 2008):

[1] $$m_i = \frac{8\rho b_i L_i^2}{\pi^3}\tanh\left(\frac{\pi h_i}{L_i}\right)$$

[2] $$\omega_i = \sqrt{\frac{\pi g}{L_i}\tanh\left(\frac{\pi h_i}{L_i}\right)}$$

[3] $$\zeta_i(\sigma_i) = C_l^i\sqrt{\frac{32}{\pi^3}}\tanh^2\left(\frac{\pi h_i}{L_i}\right)\Delta_i \Xi_i \frac{\sigma_i}{L_i}$$

where Δ_i and Ξ_i are defined as:

[4] $$\Delta_i = \left(\frac{1}{3} + \frac{1}{\sinh^2\left(\frac{\pi h_i}{L_i}\right)}\right)$$

[5] $$\Xi_i = \sum_{j=1}^{ns}\left|\cos^3\left(\frac{\pi x_j}{L_i}\right)\right|$$

and σ_i, ρ, and g are the RMS response of the equivalent mechanical system, the liquid density, and gravitational acceleration, respectively. The relation between the equivalent mechanical coordinate, $x_i(t)$ and the wave height, $q_i(t)$ can be expressed as (Tait, 2008):

[6] $$q_i(t) = \frac{4}{\pi}\tanh\left(\frac{\pi h_i}{L_i}\right)x_i(t)$$

Each equivalent mechanical system is coupled to the structure, which has a generalized mass, *M*, an inherent damping ratio, ζ_s, a natural angular frequency, ω_s, and is subjected to a generalized force, *F(t)*. The equations of motion for the equivalent mechanical structure-MTSD system are (Love and Tait, 2015):

[7] $$\begin{gathered}\left(1 + \sum_{i=1}^{n}\mu_i\right)\ddot{X} + 2\zeta_s\omega_s\dot{X} + \omega_s^2 X + \sum_{i=1}^{n}\mu_i\ddot{x}_i = \frac{F(t)}{M} \\ \ddot{x}_i + 2\zeta_i(\sigma_i)\omega_i\dot{x}_i + \omega_i^2 x_i = -\ddot{X}\end{gathered}$$

where *X* is the structural response, and $\mu_i = m_i/M$, is the ratio relating the equivalent mechanical mass of the individual TSD tanks to the generalized mass of the structure. Figure 2 shows a schematic of this model where the system has been normalized by the generalized mass of the structure. It is tedious but straightforward to solve the system of equations in the frequency domain using Cramer's Rule. The system of equations can also readily be solved in the time domain using the Runge-Kutta-Gill method.

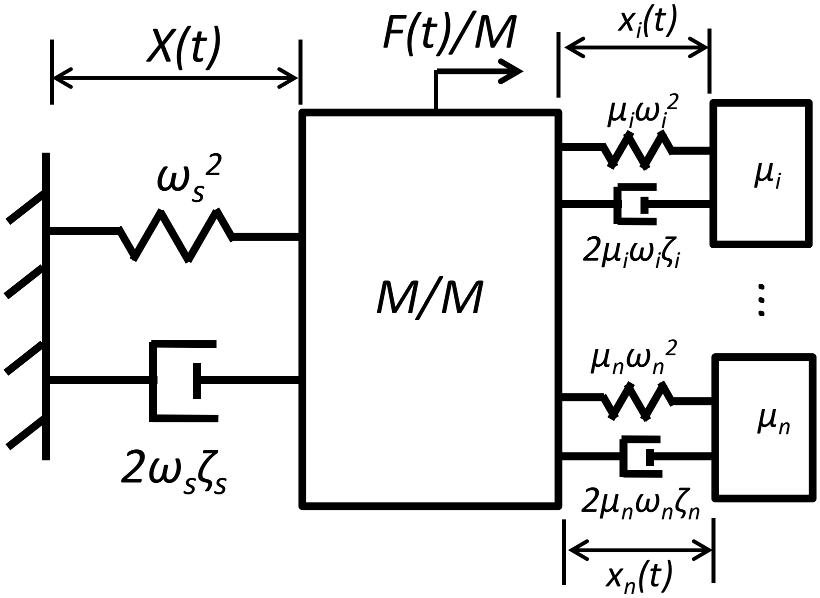

Figure 2: Structure-MTSD equivalent mechanical model representation

3 FULL-SCALE STRUCTURE

A recently completed 56 storey (185m) building located in Toronto, Canada has been equipped with a three tank MTSD system to decrease the wind-induced resonant response of its first sway mode. The building has typical floor plate dimensions of 35m x 18m and its lateral force resisting system consists of a reinforced concrete core braced with shear walls running along the principal structural axes. The analytically-predicted natural frequencies of the first three modes are 0.176 Hz (x-sway), 0.279 Hz (y-sway), and 0.362 Hz (torsion). The associated generalized masses for the first three modes are $1.12\text{x}10^7$kg, $1.33\text{x}10^7$kg, and $1.60\text{x}10^7$kg when the mode shape is normalized to unity at the MTSD level, elevation +182m above ground. An inherent structural damping ratio of 1.5% was assumed for the wind response analysis which was based on the wind tunnel test data.

Results of the wind tunnel study indicated that the predicted 1-year and 10-year mean peak hourly accelerations were 13 milli-g and 22 milli-g, respectively, which exceed the applicable motion comfort criteria of 9 milli-g and 18 milli-g, respectively. Since the wind-induced structural response was dominated by motion in the x-direction (mode 1), a unidirectional TSD system was proposed.

Structural monitoring occurred for a period of approximately two months in January-March 2017, when the building was nearly fully fit-out, but water had not yet been added to the MTSD tanks. This monitoring, discussed later, revealed that the as-built frequencies were 0.17 Hz, 0.27 Hz, and 0.36 Hz, with damping ratios of approximately 0.8%, 1.3%, and 1.8%, respectively.

The MTSD system consists of three tanks with lengths of 11.50m. The tank widths, final water depths (determined based on the measured as-built X-direction frequency), and loss coefficient for each tank are summarized in Table 1. Table 1 also summarizes the natural sloshing frequency and equivalent mass of each MTSD tank.

Table 1: MTSD Tank Properties

Tank ID, i	b_i (m)	h_i (m)	C_l	f_i (Hz)	m_i (kg)
1	2.92	1.50	3.0	0.162	3.9×10^4
2	2.80	1.90	3.2	0.170	4.1×10^4
3	2.80	1.67	3.2	0.180	4.6×10^4

3.1 Robustness

Using the properties of the tower and tanks in Table 1, the equivalent mechanical model presented previously is employed to investigate the robustness of the MTSD design over the traditional (singly-tuned) TSD system having the same tank plan dimensions.

Figure 3 shows the predicted acceleration reductions produced by a MTSD or traditional TSD at different levels of the uncontrolled building response amplitude. The uncontrolled building response is the peak acceleration the building would experience if there was no MTSD or TSD system employed to control accelerations. As shown in Figure 3, the performance of both systems is maximized between 5-10 milli-g, during which the acceleration reduction slightly exceeds 50%. Due to the nonlinear damping in the system, the performance of both systems decreases away from this amplitude, as the liquid damping deviates from its optimal value. The acceleration reduction produced by the MTSD is greater than that of the traditional TSD over the entire range shown, indicating superior performance compared to the traditional, single frequency tuned TSD.

Figure 4 shows the predicted acceleration reduction of the MTSD and TSD for various structural frequency shifts. These results assume that the systems are optimally tuned to the measured structural frequency (0.17 Hz), but the frequency of the structure changes over time without a corresponding re-tuning of the tanks. This structural frequency shift could occur as a result of concrete cracking, or the live load changing in the building. The results show that the MTSD system produces the greatest acceleration reduction over the range of structural frequencies considered.

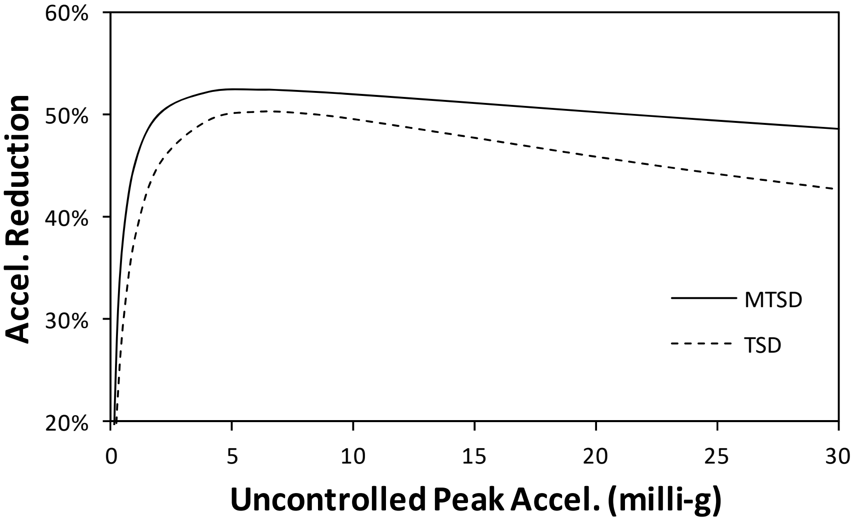

Figure 3: Acceleration reduction for various uncontrolled structural accelerations

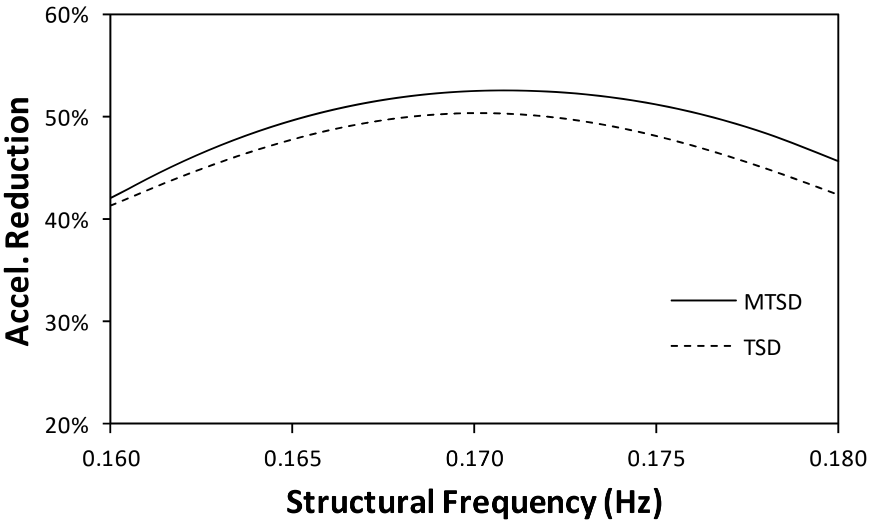

Figure 4: Acceleration reduction for various structural frequency shifts

The modelled results of Figures 3 and 4 indicate that the MTSD system provides greater acceleration reductions over a reasonable range of structural response levels and structural frequency shifts. The acceleration reductions of the MTSD system are expected to exceed 50% when the uncontrolled building accelerations are between 2 and 30 milli-g.

3.2 Full-Scale Monitoring

The monitoring of this structure consists of two phases: phase one occurred for approximately two months prior to the MTSD tanks being commissioned in March 2017, and phase two occurred after the tanks were tuned and commissioned, and this phase is ongoing. The structural accelerations were monitored using two tri-axial accelerometers installed at the MTSD level at opposite ends of the building. When water was added to the tanks during commissioning, ultrasonic wave probes were installed near the tank end walls to measure the wave heights. This study will focus on the x-direction of motion (mode 1), which dominates the response.

3.2.1 Phase 1: Prior to MTSD Commissioning

Structural accelerations were recorded for approximately two months prior to the MTSD being commissioned. This monitoring enabled the natural structural frequencies and inherent structural damping to be determined without the effects of the MTSD. Figure 5 shows building accelerations that were recorded for the x-direction on March 2, 2017, as well as the associated response spectrum and free decay (generated from the autocorrelation of the response). The peak building acceleration was approximately 7 milli-g, which was a substantial wind event. The response spectrum indicates that the natural frequency is 0.17 Hz in the x-direction (mode 1). The free decay presented in Figure 5 is estimated by calculating the autocorrelation of the acceleration response. By fitting the free decay and applying the logarithmic decrement technique, the damping ratio for the first mode of vibration is estimated to be 0.7%. Although not the focus of this paper, the measured natural frequencies of the second and third modes are 0.27 Hz, and 0.36 Hz, and the associated damping ratios are 1.3%, and 1.8%. Therefore, the measured natural frequencies are very close to those predicted by the structural model (within ~4% error). The measured damping of the second and third modes is close to the assumed 1.5%; however, the damping of the first mode is approximately half of what was originally assumed. This result suggests that the typical assumption of 1-2% damping for tall buildings may be unconservative, even when the building response is modest at 7 milli-g level. This lower level of damping would lead to dynamic structural responses that are greater than those originally predicted from the wind tunnel study. However, the installation of an MTSD system eliminates this risk, since a significant known amount of damping (~2.8%) is added to the system.

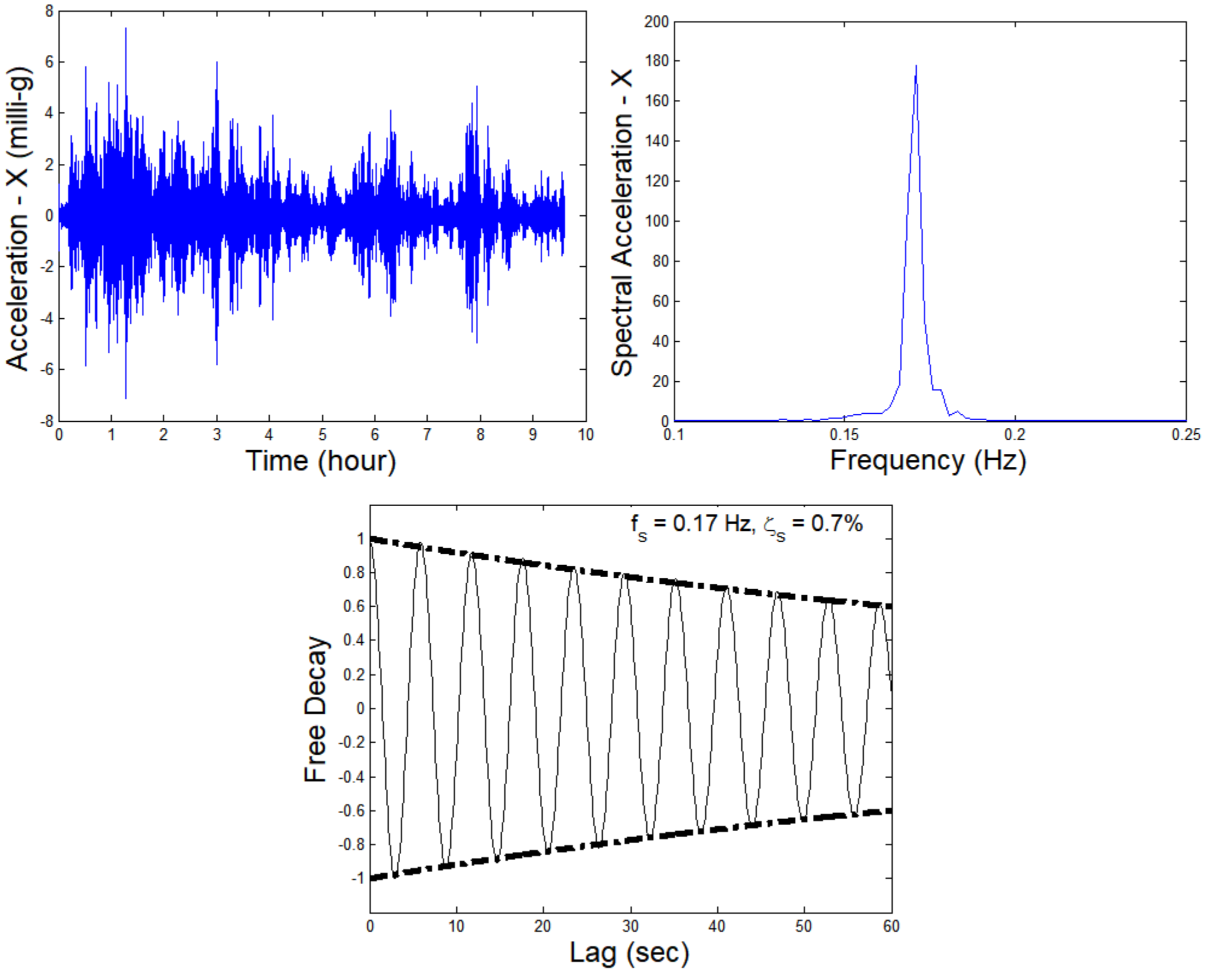

Figure 5: Typical acceleration, spectrum, and free decay trace of uncontrolled structure

3.2.2 Phase 2: After the MTSD Commissioning

The MTSD system was tuned and commissioned in mid-March 2017, and monitoring of the wave heights within each MTSD tank commenced immediately. Figure 6 shows typical acceleration and wave heights records from a wind event which occurred on October 15th, 2017, where the peak building acceleration exceeded 4.5 milli-g. Also shown is an enlarged segment where it is seen that the three tanks have a non-identical response in the time domain, which is indicative of the slightly different tuning of each tank of the MTSD.

Figure 7 shows the spectrum of the building accelerations and MTSD wave heights for each tank. The building acceleration spectrum contains multiple peaks due to the presence of the MTSD. The wave height spectra also contain multiple peaks, and each tank is responding at a different frequency due to the dissimilar tuning. The multiple peaks present in the building and MTSD response spectra are indicative of a coupled system, whereby building vibrational energy is transferred to the MTSD tanks. Compared to the uncontrolled building spectrum shown in Figure 5, this spectrum is much broader and less peaked.

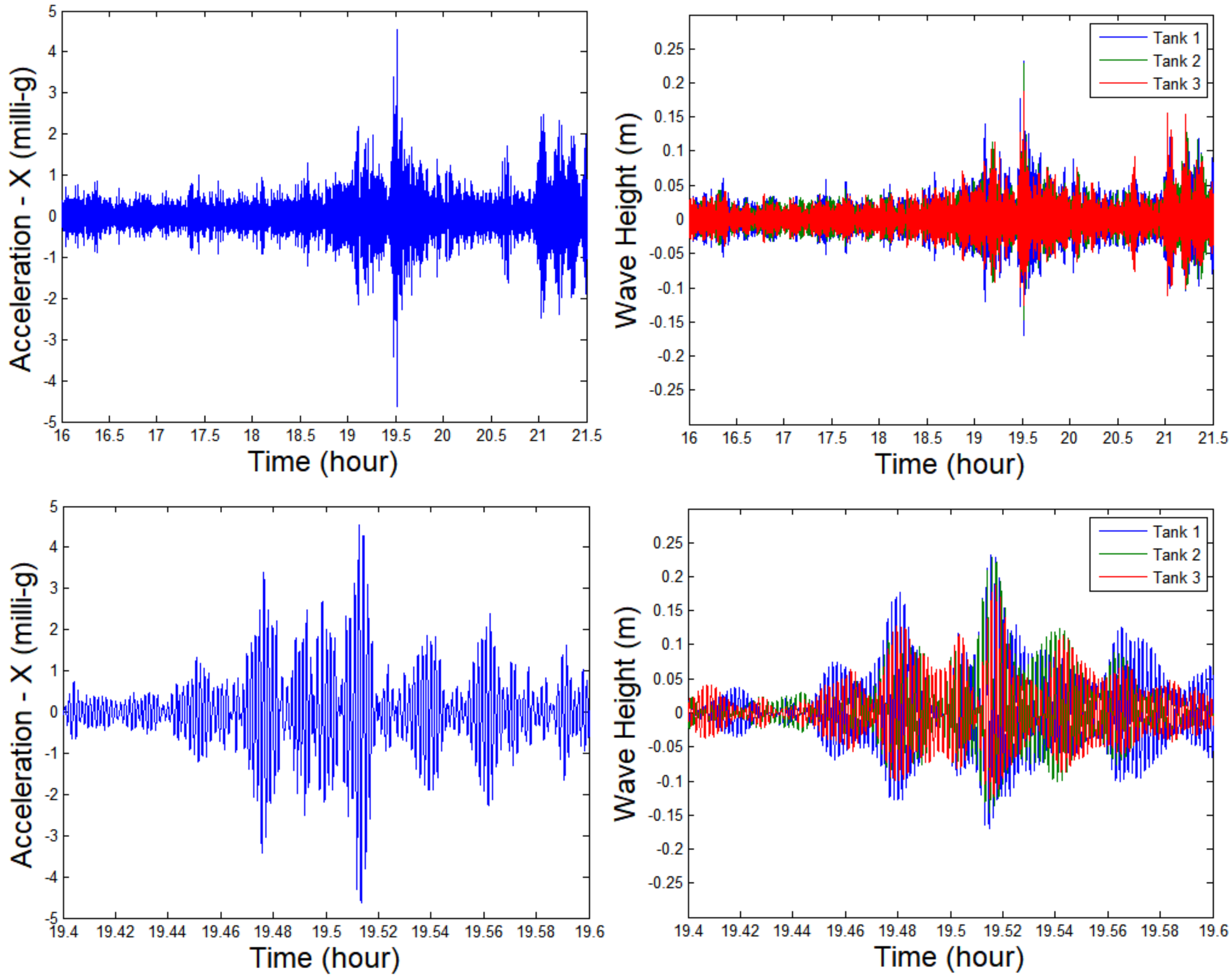

Figure 6: Typical building acceleration and wave heights (with enlarged portion)

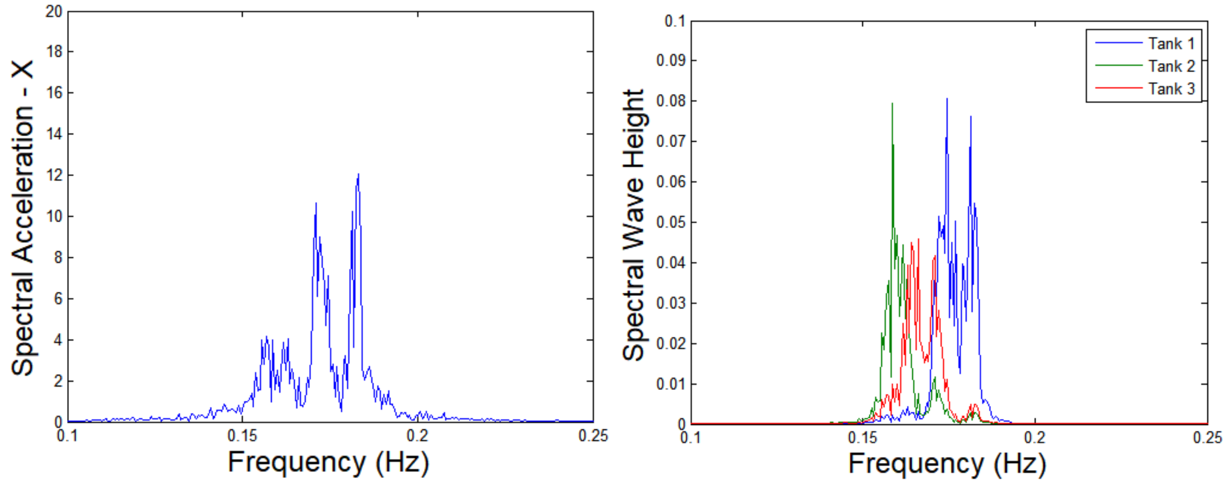

Figure 7: Spectrum of building acceleration and wave heights

To demonstrate the performance of the MTSD system, the acceleration responses of the building before and after the tanks were commissioned are compared. Wind events from 270-290 degrees are isolated both before and after the MTSD was commissioned. The hourly RMS building accelerations from these wind events are then plotted versus the recorded wind speed in Figure 8. Trend lines are included for the two data sets, which show that for wind speeds above approximately 5 m/s, the MTSD system decreases the accelerations significantly. At low wind speeds, the RMS building accelerations for the system with and without the MTSD are indiscernible, which is believed to be a result of noise in the recorded accelerations. At higher wind speeds, the RMS building accelerations are markedly decreased when the MTSD is present. The 50% acceleration reduction predicted theoretically appears consistent with the observed RMS accelerations at wind speeds above 5-10 m/s. This long term structural monitoring data therefore suggests that the MTSD system is effective in reducing motion and maintaining the serviceability performance of the building in line with the design criteria.

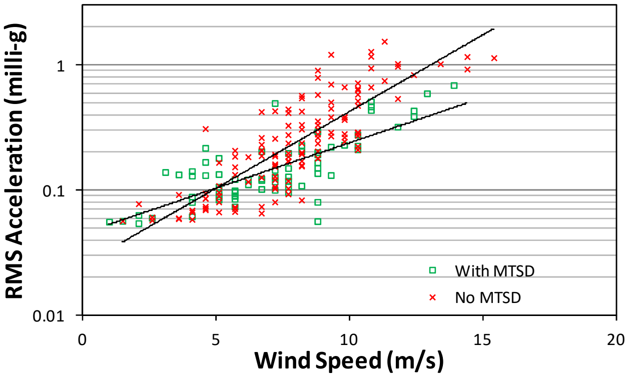

Figure 8: RMS acceleration versus mean-hourly wind speed at 10m height in open terrain

4 CONCLUSIONS

An efficient type of tuned sloshing damper system in which the tanks are dissimilarly tuned is investigated using full-scale structural monitoring. The system is termed a multiple tuned sloshing damper (MTSD) system. It is shown that the MTSD provides superior performance compared to a traditional, singly tuned TSD. The MTSD provides greater acceleration reductions over a range of excitation amplitudes and changes to the structure's natural frequency. Next, the results of structural monitoring conducted on a high rise building located in Toronto, Canada and equipped with an MTSD system are reported. Monitoring conducted prior to the MTSD tuning and commissioning indicated that the inherent structural damping of the first sway mode was 0.7%, which is below the 1-2% damping that is often assumed in tall buildings. Adding the MTSD significantly decreases the risk associated with the uncertainty in the inherent structural damping. The performance of the MTSD system is demonstrated by plotting the building accelerations against wind speed before and after the MTSD was commissioned. The novel system is shown to reduce structural motion by approximately 50% at wind speeds greater than approximately 5 m/s.

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