Supplemental Damping and Using Tuned Sloshing Dampers

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Dynamic Loading and Structural Performance

We tend to think of the structures that we build as solid immovable objects. Much of the standard design approach is based on the application of equivalent static load distributions, which reinforces this notion. However, buildings, bridges, spires, roofs, and other slender or flexible structures move when subjected to environmental forces like wind and earthquakes, or moving loads like cars and pedestrians in the case of bridges.

Under certain conditions, these motions can cause undesirable increases in structural loads due to the inertia of the large masses involved, and occupant motion sensitivity, motion sickness, or fatigue of the structural materials used.

A significant effort is typically expended by the project design team to select and optimize a structural and architectural scheme that is functional, and cost-efficient. For dynamically sensitive structures, the results of this effort (in terms of structural dynamic performance) can be highly dependant upon the initial assumption about the inherent (natural) damping in the structure. This energy absorption and dissipation characteristic is key to reducing dynamic effects as it increases the structure's ability to absorb the energy imparted to it from external excitations. Damping of real structures is generally expressed as a ratio to "critical damping", the energy absorption value which would cause the structure to simply return to center without oscillating if pulled to one side and released.

A "dynamically-sensitive" structure is defined by the National Building Code of Canada (NBCC) 2005, to be higher than 120 meters, or having a height/width ratio of 4 or greater, or being "susceptible to vibrations". ASCE 7 code is not as specific as NBCC 2005 to define these parameters. ASCE 7 does however recognize that dynamic effects for irregular-shaped buildings or those prone to complex wind loads must be accounted for by using analytical procedures and/or wind tunnel testing. Many engineers refer to the procedures outlined in NBCC 2005, as this code is regarded as a leading reference for wind-induced loading.

In common structural design practice, the inherent damping value is chosen based on average values recommended in technical literature, codes, and standards, for steel, concrete or composite structural systems. These values typically are assumed to be in the range of 1% to 2% of critical for buildings, and less for simpler structures. However, since each structure is unique, the actual inherent damping exhibited by the finished structure is also unique due to specific architectural and structural system layout, structural detailing and cladding. Changes of only 0.5% of critical or less in the assumed level of damping can have a significant impact on wind-induced loads and motions of a structure.

One proven way to achieve a specific overall damping level is to incorporate a Supplemental Damping System (SDS) into the structure.

Over the past few years, there has been a noticeable increase in the implementation of supplementary damping in various types of structures such as buildings, bridges, spires, floors, roofs, and grandstands.

An SDS is essentially a supplemental energy dissipation system that is optimally designed to absorb vibration energy from a structure, thereby reducing energy dissipation demand on the structure. There are many ways to add energy absorption to a structural system. Technologies in common use today can be broadly classed as distributed, impact, active mass, semi-active mass, mechanical passive tuned mass, and liquid-based passive tuned mass. The trend has been to use passive damping systems, as these systems need no control electronics or powered drive mechanisms and can be counted on to absorb energy when needed most, even during storms when power outages are most likely to occur.

The remainder of this article will focus on the application of one passive SDS technology to high-rise buildings. Liquid tuned mass dampers typically have one of two forms, Tuned Liquid Column Dampers (TLCD) or Tuned Sloshing Dampers (TSD). The focus will be on Tuned Sloshing Dampers due to their attractive qualities of simplicity, low cost and dependability with little or no maintenance.

Tuned Sloshing Dampers

A Tuned Sloshing Damper (TSD) is an example of an SDS that utilizes liquid waves to absorb energy from vibrating structures through wave travel and viscous action in a partially filled tank of liquid. The tank is designed so that the liquid surface wave has a frequency "tuned" to be near the fundamental frequency of the building. The frequency of the liquid is determined by the density, length, width and depth of the liquid.

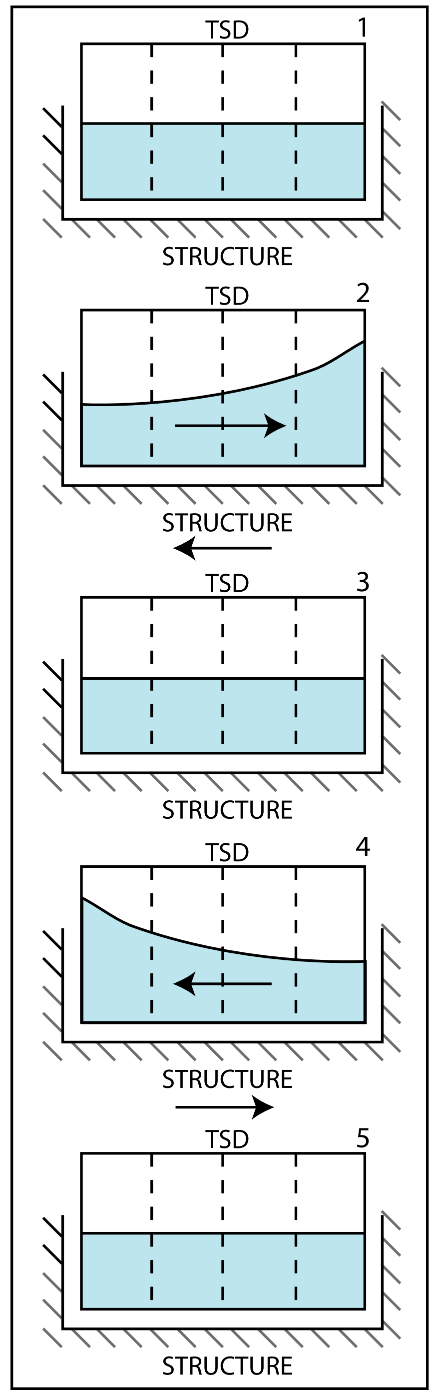

Figure 1: How it works.

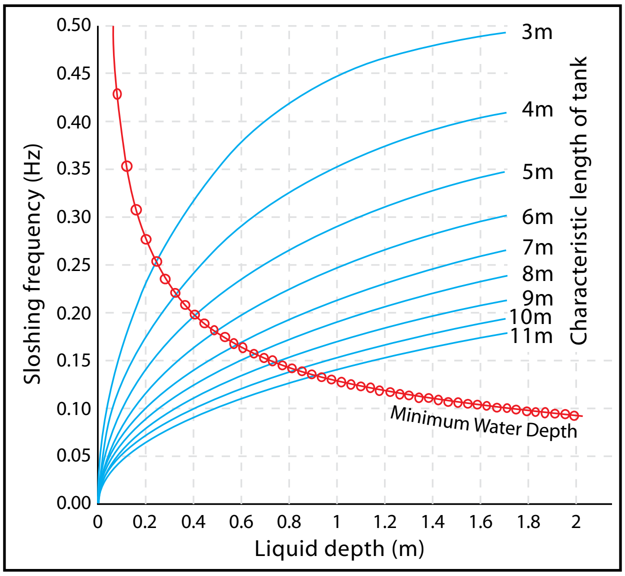

Figure 2: A TSD design chart indicating the minimal water depth (for a range of tank depths and sloshing frequencies) below which the liquid behavior will become highly non-linear.

Figure 1 depicts the basic principle of the fluid motion in the TSD:

Frame 1: Wind event not started. Structure not moving. TSD Fluid at rest position.

Frames 2 to 4: Wind event starts. Structure begins to oscillate due to wind. Wave in TSD fluid moves in opposite direction of structure due to fluid inertia from gravity. Fluid motion is damped due to turbulence caused by flow restrictions (screens, posts, or louvers). Oscillation of structure is reduced. This cycle repeats for the duration of the wind event.

Frame 5: Wind event completed.

When the structure begins to move under wind forces, the liquid resonates out of phase with the structure and energy is dissipated from the liquid by flow-damping devices such as screens, louvers, or posts in the tank that resist the wave action. Different shapes of tanks, such as rectangular or circular, can be used in TSD implementations to achieve certain goals. A rectangular tank can be tuned to two different frequencies in two orthogonal directions.

Implementing Tuned Sloshing Dampers – Design and Performance Testing

The process for implementing an SDS into a building design is one where the Structural Motion Consultant, who has the expertise and experience to ensure optimum SDS performance, works closely with the design team to help balance energy absorption goals with structural performance and architectural design goals. Examples of this process are presented for two residential building projects (each between 55 and 65 stories tall) currently under construction in New York City. For these projects, additional damping was deemed more effective and beneficial than traditional methods of increasing mass and/or stiffness to reduce building motions to acceptable levels for serviceability.

At the early design stage of the building, a technology feasibility study identified that water tank TSDs were most suitable for the projects since adequate floor space could be made available at the top of the building. Initially, the space requirement was based on simplified analysis to allow the engineer and architect to reserve adequate space. A number of possible TSD configurations were investigated, including both deep tank and shallow tank types. The decision regarding the optimal type and size of TSD was made based upon weighting the relative importance of space availability for the TSD on the mechanical floor, TSD performance targets (in terms of reduction of building motions), TSD construction costs, and the immediate and longer term cost benefits of minimizing structure while maintaining building motion serviceability targets.

As the projects progressed into Detailed Design and Construction Documents, more comprehensive time-domain simulations of building and TSD motions and scale models of the tanks were developed and tested to fine-tune the damper and to ensure optimal performance at the specified return period.

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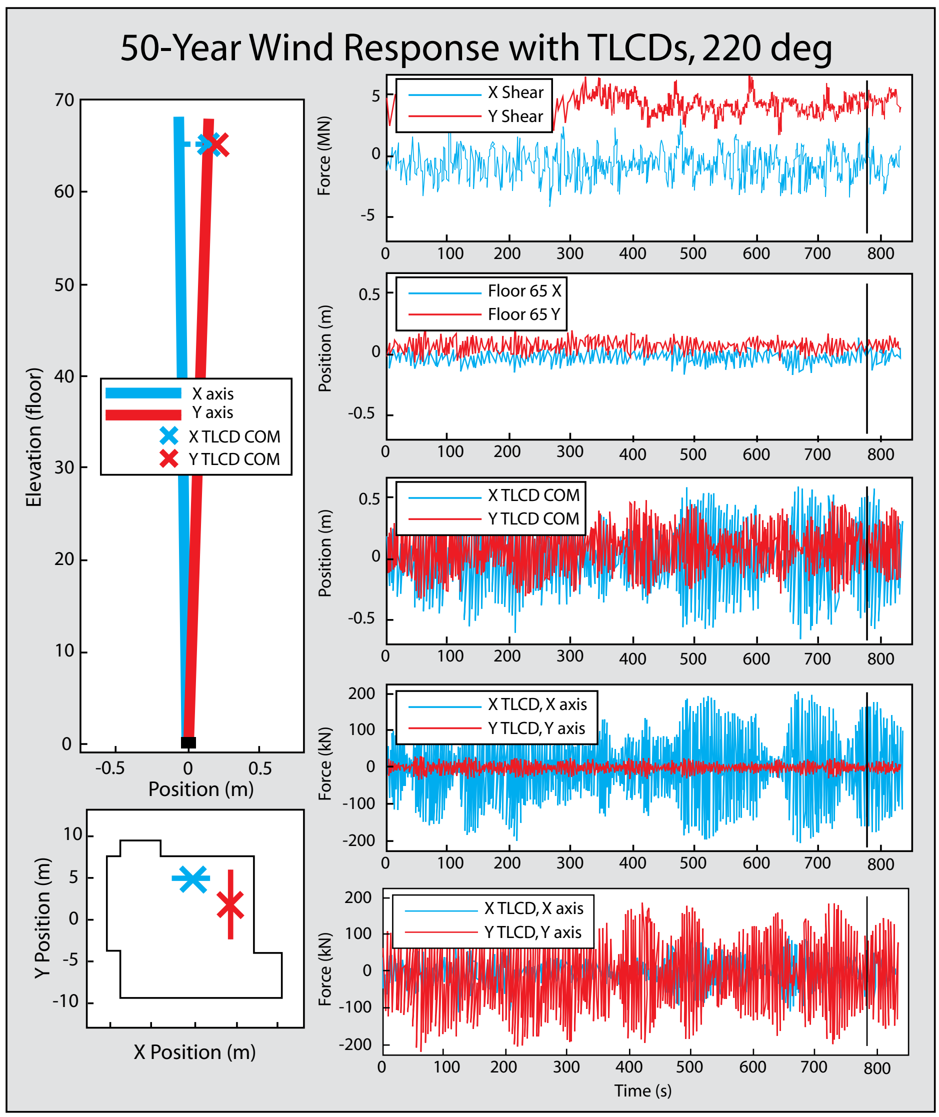

Figure 3: Time-domain simulation animation graphics output. Using the wind tunnel test data for the project provided by the wind tunnel consultant as an input, analytical simulations investigate the performance of the damping system for the 1-year, 5-year, 10-year, and 50-year return wind storms.

Time Domain Analysis Simulations

As wind action fluctuates with time, so does the behavior of the structure. The time domain simulations are an important part of the design process, since wind forces, building responses, and damping system motions are not constant with time. Referring to the chart in *Figure 2 (see page 15)*, the red line indicates a threshold, below which the liquid behavior in a TSD can become highly non-linear. It is important to account for the non-linear behavior of the TSD during the design stage by using advanced time domain analysis techniques.

Figure 4: Single-Axis TSD Scale Model Performance Test: For fine-tuning TSD design parameters; ensuring maximum possible damping is achieved in one direction.

Time domain simulations are performed predicting the actual non-linear interaction between the moving structure under fluctuating wind loads and the moving mass (the sloshing water) in the damping system. Using the wind tunnel test data for the project provided by the wind tunnel consultant as an input, analytical simulations were used to investigate the performance of Tuned Sloshing Damper for the 1-year, 5-year, 10-year, and 50-year return wind storms. This ensured that the peak loads on the tank walls and screens, as well as peak water wave amplitudes and damping levels were accurately predicted for design purposes. This approach can also be used to predict the Ultimate State Design loading for the damper/structure interface where non-linearity at higher excitation levels requires better assessment of appropriate load factors. This makes sense when considering that the TSD has several hundred tons of moving mass positioned at the top of the building.

Visual "animation-style" time domain analysis results can be provided. These graphics are often helpful to the design team to visualize and understand the building time response and damping system action. *Figure 3 (see page 15)* is from a project where such animations were provided.

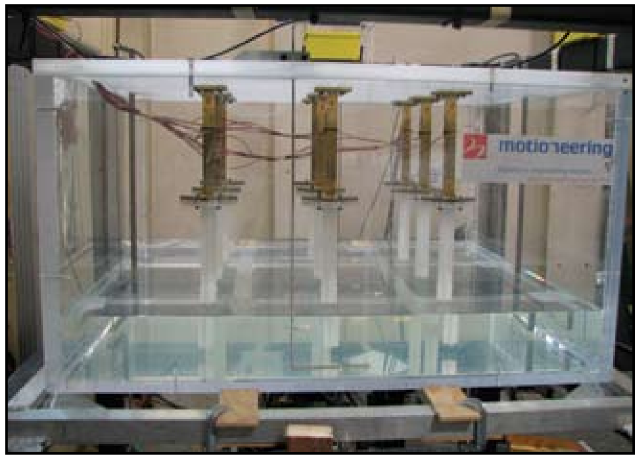

Figure 5: Dual-Axis TSD Scale Model Shake-Table Performance Test: For fine-tuning TSD design parameters; ensuring maximum possible damping is achieved in two directions simultaneously.

TSD Scale Model Performance Tests

As the New York projects progressed into Detailed Design and Construction Documents, scale models of the tanks were developed and tested to fine-tune the damper and to ensure optimal performance at the specified return period. The tests were performed on a shake-table that simulated the wind-induced motions of the structures in which the TSDs were to be installed.

Figures 4 and *5* show scale models test for two types of TSDs. *Figure 4* is for a single-axis TSD. This type of TSD is designed so that the sloshing action of the liquid is tuned in only one direction, so that effective supplementary damping can enhance building performance for a singular direction of motion. This is useful when building responses acting in one principal direction are the highest contributor to overall building motions.

In this case, the TSD used static screen elements installed within the moving water to generate turbulence, and thus a means for energy dissipation (damping) within the TSD.

Figure 5 is of a dual-axis TSD scale model. In contrast to the one-directional TSD, the dual-axis TSD can enhance the damping performance in two directions simultaneously.

> *In geographic regions where seismic design is also required, the time domain simulations using earthquake ground motions are used to check the performance of damping system and to determine the loading produced between the TSD and the structure. For this purpose, many modes of structural vibration need to be examined.*

The bi-directional TSD on this project used cruciform-shaped, static "posts" suspended into the moving water as the means to generate turbulence, and thus energy dissipation (damping).

Summary of TSD Test Parameters: Full-Scale and Model-Scale

Parameter	Full Scale		Model Scale 1:9	
	Imperial	Metric	Imperial	Metric
Length (L_y)	26.247 ft	8.000 m	2.916 ft	0.889 m
Width (L_x)	23.186 ft	7.067 m	2.576 ft	0.785 m
Nominal Water Depth	3.052 ft	0.930 m	0.339 ft	0.103 m
Tank Depth	14.000 ft	4.267 m	1.556 ft	0.474 m
Nominal fy Frequency	0.185 Hz	0.185 Hz	0.556 Hz	0.556 Hz
Nominal fx Frequency	0.208 Hz	0.208 Hz	0.625 Hz	0.625 Hz
Upper Sweep Frequency	0.344 Hz	0.344 Hz	1.031 Hz	1.031 Hz
Lower Sweep Frequency	0.083 Hz	0.083 Hz	0.250 Hz	0.250 Hz
Minimum TSD Floor/ Table Amplitude	0.075 ft	0.023 m	0.008 ft	0.003 m
Maximum TSD Floor/ Table Amplitude	0.806 ft	0.246 m	0.090 ft	0.027 m
Low Frequency Low Amplitude Peak Force	4851 lbf	21580 N	7 lbf	30 N
Low Frequency Low Amplitude Peak Force	30282 lbf	134700 N	42 lbf	185 N

Table 1: Test parameters comparing characteristics of a full-scale TSD in the building to the model-scale TSD tested in the laboratory.

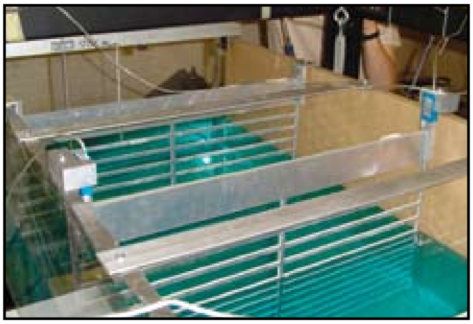

Figure 6: Close-up view of TSD scale model damping screens. Load cells are used to measure shear forces and drag loads on the screens from the moving waves.

The shake-table test was arranged to impose horizontal motions on the TSD scale model. The motions imposed on the TSD were sinusoidal, with control over the amplitude and frequency of the oscillations.

For the New York projects performed by Motioneering, the total full-scale mass of the TSDs are about 170,000 kg or 190 tons (with a length of 13.7 meters and width of 5.5 meters) for one project, and about 66,000 kg or 73 tons (with a length of 8.0 meters and a width of 7.1 meters) for the other project. The model scale required for the shake-table tests was 1:9. This translated to a TSD model dimension of 1.5 meters in the long-axis (primary testing) direction for one project and 0.9 meters in the long-axis for the other. The full-scale and model-scale test parameters are summarized in *Table 1*.

The TSD scale model was mounted on a platform suspended by four steel bars from a rigid frame. The purpose of these bars was to carry the vertical load of the tank, while the shear forces were measured with load cells at the joints between the frame and the platform. The vertical displacement of the fluid at the end walls of the TSD tank was recorded, as well as the horizontal displacement of the shake-table to verify the input. The horizontal accelerations of the shake-table were also recorded.

Each test consisted of a frequency sweep, where lower and upper bounds, the amplitude of excitation, and number of cycles and time interval at each frequency were specified. At each frequency, the maximum vertical

Figure 7: Constructing the TSD atop a new 60 floor residential building in New York City. The TSD tank walls were constructed with cast-in-place poured concrete, since the material and labor to install was easily obtainable.

displacement of the fluid surface at the end walls of the TSD tank was recorded. The resulting maximum amplitude versus frequency plot was used to establish the natural frequency of the TSD system (see *Figure 6, page 17*).

The tests were an important part of the TSD design process. Necessary information was obtained for the detailed design of the tank, such as hydrostatic and hydrodynamic forces on the tank walls and ceiling during serviceability and design wind events. The tests also provided valuable information to: (a) optimize the porosity of the screens that are used to create local flow damping and energy dissipation, (b) refine the predictions of wave amplitudes that generate shear forces and screen drag loads, and (c) optimize screen or vane selection. This ensured that the design of the tank and screens was safe and the performance objectives were achieved.

Figure 8: Damping Screen installation inside a TSD Tank. Screen geometry is designed for ease of fabrication and installation.

TSD Construction

The General Contractor team performed construction of the TSDs. The TSD tank walls were constructed with cast-in-place poured concrete, since the material and labor to install was easily obtainable. A waterproofing membrane was used to seal the tank walls. Since the top of the tank is usually dry, the damping louvers or screens were anchored to the tank roof and suspended into the water in the TSD tank. Automatic water level monitoring was provided using a standard float-type sensor and water supply make-up solenoid valve. The need for water level replenishment is generally infrequent, since the only means for water loss is through evaporation (which is minimal in an enclosed tank).

At the time of writing this article, TSD construction for the two residential projects in New York was ongoing. *Figures 7 (page 17), 8* and *9* show some of the construction work.

TSD Commissioning

Once the construction of the TSDs is completed and the site is ready for commissioning, then final building motions (using accelerometers) are measured using our portable data acquisition equipment. The fundamental building frequencies are determined using FFT analysis of the acceleration data. Final adjustment of the TSD water level is performed to "tune" the tank to the optimal frequency, thus matching the building frequencies for best possible damping performance. As with any building system, periodic visual inspections are recommended as part of a routine maintenance plan.

Figure 9: TSD Damping Screens are fastened to the tank roof, avoiding piercing of the waterproofing membrane.

Summary

A range of different types of Supplementary Damping Systems (SDS) can be used to enhance the damping capabilities of a structure. This article has focused upon the design and implementation of one type of passive damping system – the Tuned Sloshing Damper (TSD). These types of damping systems are an effective means to reduce dynamic effects by increasing the structure's ability to absorb the energy imparted to it from external excitations.

A TSD is an efficient SDS option for structures with a moderate need for additional damping. For a typical mid-rise to high-rise structure, total effective damping levels of 3% to 4% of critical can often be achieved.

TSDs are attractive due to their qualities of simplicity, low cost and dependability with little or no maintenance.

Other alternative and very effective damping options also exist, some of which will be discussed in future articles in STRUCTURE® magazine.▪

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