Title: **Sloshing Dampers for Slender Concrete Towers**

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Subjects: Structural Engineering
Wind Engineering

Keywords: Damping
Human Comfort
Tuned Liquid Damper
Wind Loads

Publication Date: 2012

Original Publication: CTBUH 2012 9th World Congress, Shanghai

Paper Type:

1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Sloshing Dampers for Slender Concrete Towers

细柔混凝土塔楼的液体晃动阻尼器

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Abstract

Tall towers with very slender aspect ratios of height to width of the structural system are becoming very common as today's architectural idiom. Mitigation of wind-induced motions is of paramount importance in the planning of these slender structures and early inclusion of mitigation systems is necessary for the execution of a successful design. Among a variety of auxiliary damping devices for wind applications, tuned sloshing dampers have proved to be the most economical and effective to provide appropriate response reductions. This paper presents the application of specially designed tuned sloshing dampers such as bi-directional and double decker dampers to two very slender concrete towers currently under construction using unique numerical and experimental techniques for innovative design and performance evaluation of tuned sloshing dampers.

Keywords: Tuned Sloshing Damper, Wind Loads, Dynamic Response, Human Comfort

摘要

在现今的建筑领域，结构体系高宽比很大的高层建筑变得越来越普遍。防范过度的风致振动是规划这些高细结构时的重中之重，对于一个成功的设计，有必要在早期就考虑采用减振系统。在众多应用于风振控制的附加阻尼设备中，实践证明可调谐液体晃荡阻尼器是最经济有效的减弱风振反应的措施。本文阐述了特殊设计的双向和双层可调谐液体晃荡阻尼器在两栋施工中的高细混凝土塔楼上的应用。可调谐液体晃荡阻尼器的应用中采用独特的数值模拟与试验技术，包括针对创新设计和TSD性能评估的液态晃动技术和硬件回路模拟。

关键词：高层建筑、调谐液体阻尼器、风荷载、动力响应、人体舒适度

Introduction

Rapid urbanization has led to the increase in the demand for tall buildings for residential, office or combined use. These buildings may experience excessive motion under wind loads, which may impact their structural integrity and in some cases the comfort of occupants may become a critical design issue. This has posed new challenges for engineers and architects in designing structural systems with adequate stiffness and damping to ensure acceptable performance in survivability, serviceability and habitability.

For wind applications, among all inertial devices, tuned sloshing dampers (TSD) have demonstrated both effectiveness in controlling building/structural motions and their simple configuration requiring minimal maintenance (Kareem et al., 1999). The advantages of TSD systems include low cost, easy tuning to the fundamental frequency of a structure, and easy installation/maintenance because no activation mechanism is required unlike a TMD or a semi-active inertial damping system. In addition, TSD systems are easily mobilized at all levels of structural motions, e.g., motion levels in tall buildings, and such containers can be utilized for building water supply, unlike a tuned mass damper (TMD)

引言

城市化的快速发展增长了对住宅、办公或综合功能的高层建筑的需求量。这些建筑在风荷载下可能产生过度的振动并影响其结构完整性，在某些情况下居住者的舒适性将成为关键的设计参数。因此设计的结构系统应具有足够的刚度和阻尼以保证建筑的安全性、功能性和舒适性，这也给工程师和建筑师带来新的挑战。

对风工程应用来说，实践证明在所有惯性减振系统中，可调谐液体晃荡阻尼器（TSD）不仅能有效控制建筑结构振动，而且构造简单、维护需求较少（Kareem等，1999）。由于没有类似调谐质量阻尼器TMD或半主动式质量阻尼器的机械装置，TSD系统的优点包括造价低、易于调谐至结构基本频率和易于安装维护等。此外，TSD系统在高层建筑的所有振动水平下都可以轻易地启动，而且这些水容器还可以作为建筑供水系统，这与无其它功能的TMD质量块不同。但是在近源地震所产生的地面振动情况下，其有效性还有待于根据具体情况进行评估，这是因为被动系统无法对瞬间的初始地震脉冲作出快速反应。

本文阐述了特殊设计的双向和双层可调谐液体晃荡阻尼器在两栋施工中的高细混凝土塔楼上的应用，包括通过理论分析、数值计算和试验研究对阻尼器进行的设计、

Figure 1. Two residential towers: (Left) 72-story located in Manila, Philippines; (Right) 42-story located in Dallas, TX, USA (Source: (Left) Century Properties Inc.; (Right) http://www.museumtowerdallas.com/)
图1. 两栋住宅塔楼：（左）位于菲律宾马尼拉的72层住宅塔楼；（右）位于美国德克萨斯州达拉斯的42层住宅塔楼（出自：（左）Century Properties公司；（右）http://www.museumtowerdallas.com ）

where the dead weight of the mass has no other functional use. However, their effectiveness in the case of ground motion resulting from near source earthquakes may need to be evaluated on case by cases due to the inability of any passive system to respond quickly to sudden initial pulse of an earthquake.

This paper presents the application of specially designed tuned sloshing dampers such as bi-directional and double decker dampers to two residential towers including damper designs, response predictions and the performance evaluation of the towers throughout analytical/numerical and experimental studies: one is 72-story located in Manila, Philippines, and the other is 42-story located in Dallas, TX, USA (see Figure 1). Based on preliminary design using web-based data-enabled design module and later wind tunnel experiments, it was expected that the acceleration levels of both towers were around or over the human comfort threshold. In both towers, TSDs were chosen to be most optimal solutions to reduce motions with minimum added complications and to keep life-cycle-cost to the minimum. In addition, unique numerical and experimental techniques such as Aqua Sloshing Technologies (AST) and hardware-in-the-loop (HIL) simulation for innovative design and performance evaluation of TSD are introduced.

Design Approach Of Tuned Sloshing Damper

The two towers were investigated for wind motion sensitivity during preliminary design stage utilizing aerodynamic database-enabled design module (DEDM) at http://vortex-winds.org and http://aerodata.ce.nd.edu developed by the NatHaz Modeling Laboratory (NatHaz), University of Notre Dame (Kwon et al., 2008). These preliminary studies based on the building geometry, preliminary dynamic properties and wind climate indicated potential wind sensitivity issues for both towers. The towers were later tested in boundary layer wind tunnels, one in the Australia and the other in the US, to investigate the response predictions more accurately. These wind tunnel studies

反应预测和性能评估。这两栋塔楼分别是位于菲律宾马尼拉的72层塔楼和位于美国得克萨斯州达拉斯的42层塔楼（见图1）。根据使用基于网络的数据设计模块和之后的风洞试验结果的初步设计，两栋塔楼的预计加速度水平均达到或超过居住舒适度上限。由于TSD系统易于安装并且寿命成本最低，两栋塔楼均选择了TSD作为最优减振方案。另外，还介绍了独特的数值和试验技术，诸如针对创新设计和TSD性能评估的液态晃动技术（AST）和硬件回路模拟（HIL）。

可调谐液体晃荡阻尼器的设计方法

在初步设计阶段，使用NatHaz建模试验室（NatHaz）和圣母大学（Kwon等，2008）开发的空气动力数据库设计模块（DEDM，网址http://vortex-winds.org and http://aerodata.ce.nd.edu）对两栋塔楼的风振敏感度做了调查。这些基于建筑几何形状、初步动力特性和风气候的初步研究显示两栋塔楼都有潜在的风振敏感度问题。之后这两栋塔楼在边界层风洞（风洞分别位于澳大利亚和美国）进行了测试，以更精确地预计风振响应。这些风洞试验研究确认了预计的风振响应超出了居住舒适度可接受水平。因此，需要一个风振控制系统将风振响应减少至目前可接受的正常使用水平。在与项目业主和设计方讨论的基础上，经过仔细评估优缺点、现有的空间、在塔楼目前构造中安装是否方便、需要的风振控制程度以及人员操作等问题，最后决定采用可调谐液体晃荡阻尼器（TSD）。

使用NatHaz开发的液态晃动技术（AST）（见图2）以确定最优的水箱尺寸和在波浪中消耗能量必须的屏板。先进的晃动建模软件包不仅为液体阻尼器在频域和时域提供了设计参数，并且提供了在给定风荷载（如风洞研究结果）情况下有阻尼系统和没有阻尼系统时影响建筑物性能的风响应统计数据。使用AST进行了大量模拟以完成对水箱的初步设计和调谐，以达到附加阻尼的期望值。当完成对TSD的最终设计时，再采用AST对TSD进行了额外的模拟研究以最终确定初步设计的构造，并确认TSD的性能将使结构响应降至可接受的水平。

confirmed the predicted responses as being well above accepted levels of human comforts. Consequently, a wind motion mitigation system was required to reduce the response to a currently acceptable serviceability level. Based on the discussion with the towers' owners/designers, it was concluded that a tuned sloshing damper (TSD) would be used for these projects after careful evaluation of advantages, availability of space, convenience of adaptation in the current tower configuration, required percentage control in response, and the attendant operational issues.

The Aqua Sloshing Technologies (AST) (see Figure 2) developed at NatHaz were utilized to configure the optimal tank size and the attendant screens of a TSD necessary to dissipate energy in the waves. It is an advanced sloshing modeling software package that not only provides the design parameters, in frequency and time domain, for the sloshing damper, but also supplies response statistics regarding the performance of building with or without the damper system under prescribed wind load conditions, e.g., results from the wind tunnel study. Extensive simulations using AST have been conducted to arrive at the preliminary design of the tank and its tuning to achieve a target of additional damping. Once arrived at the final decision of TSD designs, additional simulation studies of the TSD using AST were also proceeded to finalize the preliminary design configuration and confirm the TSD performance to aid in bringing building response within acceptable levels.

In the final design stage of the TSD, experimental studies using a shaking table and scaled model were carried out to investigate TSD performance under the level of building displacements/accelerations with design conditions and the nature of sloshing and the adequacy of screen designs determined by numerical analysis (e.g., using AST). Two case studies of TSD applications for 72-story and 42-story residential towers are described in the following sections.

72-Story Residential Tower In Manila, Philippines

This residential tower is aerodynamically sensitive due to its shape and height, which is further influenced by the adjustments in the structural system for optimization. The results of the wind tunnel experiment indicated that the accelerations of the tower would exceed comfort criteria at the expected level of structural damping of 1.0% of critical. However, damping value of 1.5% of critical indicated that all of the relevant occupant comfort criteria would be satisfied. Hence it was recommended that provision be made to incorporate a TSD system capable of providing an additional damping somewhere around 0.5 % to 1% to the tower structure. Typically, the intuitive approach is to add large mass of water in the sloshing tank to garner maximum benefits. However, the increase in mass does not linearly result in added damping effects rather they increase slower than the increase in mass. Thus, one needs to seek the most optimal range of mass to gain maximum damping contribution. The final configuring of the damper was designed using AST with a series of parametric studies for the tank dimensions and sensitivity to changes in building natural frequency. A comparison of root-mean-square (RMS) responses with target added damping of 1% using AST for the level of excitation corresponding to 10-year winds is given in Table 1.

Like a TMD, the tank water sloshing component needs to be damped for optimal performance. There are various means of incorporating this component of damping that can dampen sloshing in the tank that range from using of foam floating beads to use of slats/screens. In this application, like most other liquid dampers in place in buildings,

Figure 2. Aqua Sloshing Technologies: design portal for a tuned sloshing damper (Source: Deepak Kumar)
图2. 液体晃动技术：可调谐液体晃荡阻尼器设计软件（出自：Deepak Kumar）

在TSD的最终设计阶段，使用振动台和缩尺模型进行了试验研究以考察在设计条件的位移/加速度水平下TSD的性能，并确定根据AST数值分析设计的屏板是否足够。在以下几节中将给出对一栋72层和一栋42层住宅塔楼应用TSD的案例研究。

位于菲律宾马尼拉的72层住宅塔楼

该住宅塔楼由于其外形和高度使其对空气动力较为敏感，这种敏感度又进一步受结构系统优化调整的影响。风洞试验结果显示该塔楼在结构阻尼比1.0%的情况下，加速度将超过舒适度标准。然而在阻尼比1.5%时，所有相关的居住者舒适度准则都得到满足。因此建议在塔楼结构中增加能够提供0.5%到1%阻尼比的TSD系统。一般凭借直觉是在晃动水箱中增加大量的水以获得最大的效益。然而，增加质量并不能使阻尼线性增长，阻尼的增长比质量增加慢。因此需要找到最优的质量范围以得到最大的阻尼贡献。最后阻尼器的构造是使用AST设计的，包括一系列对水箱尺寸和结构自振频率变化敏感度的参数研究。表1给出了无阻尼器情况和使用AST对10年一遇激励水平下增加1%目标阻尼的均方根（RMS）响应值的比较。

如同TMD，水箱内水的晃动部分需要被耗能减弱以达到最优性能。有许多方法可以消耗晃动水箱中波浪晃动的能量，如使用泡沫浮球和栅板/屏板。在该项目中，如同大多数已建的液体阻尼器，栅格屏板被置于水箱中间。由于水箱平面几乎为正方形且建筑物在沿长边的切线方向也会产生振动，因此在另一个方向也设计了栅板，即双向屏板（见图3）以更好地处理晃动并排除水箱内复杂的波浪。根据AST对一组栅板/屏板做了相关设计，考虑了波浪的动能和由栅格构造引起的阻力。

Radial direction 径向			Tangential direction 切向		
Building RMS displacement (m) 建筑均方根位移(m)			Building RMS displacement (m) 建筑均方根位移(m)		
without damper 无阻尼器	with damper 有阻尼器	reduction 减少	without damper 无阻尼器	with damper 有阻尼器	reduction 减少
0.038	0.029	24.60%	0.046	0.034	25.10%
Building RMS acceleration (milli-G) 建筑均方根加速度(milli-G)			Building RMS acceleration (milli-G) 建筑均方根加速度(milli-G)		
without damper 无阻尼器	with damper 有阻尼器	reduction 减少	without damper 无阻尼器	with damper 有阻尼器	reduction 减少
7.22	5.61	22.30%	6.88	5.4	21.50%

Table 1. Comparison of RMS response for target added damping of 1% using AST (Source: Deepak Kumar)
表1. 使用AST增加目标阻尼1%的均方根值相应对比（出自：Deepak Kumar）

Figure 3. Tuned sloshing damper model (scale 1:10) (Source: Ahsan Kareem and Deepak Kumar)
图3. 可调谐液体晃荡阻尼器模型（比例1：10）（出自：Ahsan Kareem和Deepak Kumar）

slatted screens were used in the middle of the tank. Since the tank is almost a square in plan and the building does experience motion in the tangential direction along the long axis, slats were designed for the other direction as well, i.e., bi-directional screens (see Figure 3), to better manage sloshing and preclude any complex wave motions in the tank. Accordingly a set of slats/screens were designed based on the AST, which takes into account the wave kinematics and the drag introduced by the slat profile.

In order to observe actual performance of sloshing at the level of building accelerations, model scale experiments were conducted to see the nature of sloshing and the adequacy of screen design. In view of the capacity of the shaking table used in this experiment, the TSD model was determined as the 1:10 scale for this study. This scale provided sufficient water depth and the range of frequencies needed to make necessary observations regarding the performance of the tank under prescribed levels of motions. A picture of the tank is given in Figure 3 for the overview of the TSD model that includes stainless steel slats for managing/dissipating sloshing. The tank was mounted on a shaking table and range of tank base motions was introduced to mimic the building motion at the location of the TSD. The liquid motion in these experiments was carefully monitored with and without the screens to observe the wave action and the contributions of the slats in the tank. A series of movies recorded of the sloshing action in the tank were captured while the shaking table amplitude in model scale corresponded to the level of motion building that would be expected to experience for 10-year winds at site. The frequency of excitation of the shaking table was close to the natural frequency of the building to replicate building motion at design level winds for human comfort consideration. In the presence of the screens, the performance of the liquid sloshing damper was noted to be within the linear range which validates the premise of the damper design methodologies (see Figure 4a). The sloshing action tended to be more nonlinear without the screens and water mass slammed on the tank walls periodically which generated a wave surface topology leading to nonlinear performance of the tank (see Figure 4b). Should nonlinear behavior of the wave surface profile be observed, additional slat spacing would have been necessary to dissipate more energy and dampen higher modes in sloshing actions to tailor more effective performance of the damper.

为了观察液体晃动在建筑加速度水平下的真实性能，做了模型试验以确定液体晃动规律和设计的屏板是否合适。根据试验用的振动台容量，TSD模型试验采用1:10比例。该尺度提供了足够的水深和频率范围以对规定振动水平下的水箱性能做必要的观察。图3给出了TSD模型水箱的图片，包括用于控制/消耗晃动能量的不锈钢栅格。将水箱安装于振动台上并模拟大楼振动时TSD位置的水箱底部的振动情况。试验过程中，仔细监控了在有屏板与没有屏板情况下的液体运动，以观察水箱内波浪运动和栅格的作用。在振动台振动幅度与建筑物10年一遇强风情况下的振动水平一致时录制了一系列晃荡运动的视频。将振动台的振动频率调整到与建筑物自振频率接近以再现考虑居住舒适度的设计风速下的建筑物振动。在有屏板的情况下，注意到液体晃荡阻尼器的性能处于线性范围内，这证实了阻尼器设计方法的前提条件（见图4a）。在没有屏板的情况下晃动趋向于非线性且波浪周期性地撞击水箱壁，产生波浪表面拓朴结构并造成水箱的非线性特性（见图4b）。如果发现波浪表面轮廓的非线性特性，则有必要增加栅格间距以消耗更多的能量，并减弱液体晃动的高振型以将阻尼器性能调至更佳。

位于美国德克萨斯州达拉斯的42层住宅塔楼

基于1%阻尼比假定的分析和风洞试验，预计该塔楼在某一方向上的响应将超出居住舒适度的上限，因此建议使用附加阻尼设备如TSD来增强阻尼。鉴于可用空间和需要的响应控制比例，在初步设计阶段设计了一个创新的双层布置的多水箱晃荡阻尼器，将多个水箱分置于上下两层。这有助于晃动液体获得更高的质量比，从而能对结构响应进行更好的控制。基于使用AST软件进行的大量模拟，确定了水箱和其调谐的初步设计以达到用四个分置于上下两层的相同尺寸水箱来增加1.5%左右阻尼的目标。更多的水箱会多少减少对增加阻尼的最后贡献，但不会很多。使用AST软件对最终的阻尼器构造做了校核，并确定使用三个包含数个栅格的屏板来消耗晃动能量。屏板及其栅格也是基于AST设计的，并考虑了波浪动能和栅格引起的阻力。表2给出了使用 AST设计的10

(a)

(b)

Figure 4. Sloshing of liquid in model tank with or without screen (captured from video): (a) with screen; (b) without screen (Source: Ahsan Kareem and Deepak Kumar)
图4b. 有屏板和无屏板模型水槽中液体的晃动（截取自视频）：(a)有屏板；(b)无屏板（出自：Ahsan Kareem和Deepak Kumar）

42-Story Residential Tower In Dallas, TX, USA

Based on the analysis of this tower for 1% damping and wind tunnel experiments, it was expected that response in one direction exceeded the threshold levels of human comforts, thus it was recommended to enhance the damping by using an auxiliary damping device like a TSD. In view of available space and required percentage control in response, the sloshing damper with multiple tanks in an innovative double decker configuration were designed such that sloshing tanks were installed in two levels (Lower and upper level) in the preliminary design stage. This helps in having higher mass ratio of sloshing liquid, which helps in achieving better control of structure responses. Based on extensive simulations using AST software, the preliminary design of the tank and its tuning was determined to achieve a target added damping of somewhere around 1.5% with four tanks: two at lower level and two at upper level with the same dimension at each level. Having more tanks reduced the final contribution of added damping but not by a significant amount. The final configuration of the damper was also checked using AST software and decided that three screens, where each consists of several slates, were used to dampen the water sloshing component. The screen and its slates were also designed based on AST, which takes into account the wave kinematics and drag introduced by slates. A comparison of peak and RMS responses of building with and without TSD using AST designed for the level of excitation corresponding to 10 year winds is given in Table 2.

Upon completion of the computational design procedure that was based on structural dynamics of the building and the dynamic sloshing action, model scale experiments involving three stages in this project were performed to validate the TSD performance. The first stage of the experimental study followed a similar test methodology to the case of 72-story tower earlier, using 1:10 scale model mounted on top of a shaking table to carefully observe the effectiveness of the screens and their blockage ratios as well as spacing and number of rows (see Figure 5). It was observed that the behaviors of the sloshing were satisfactory and the trends with or without screens were similar to the shaking table results in 72-story tower earlier, e.g., Figure 4.

In order to assess the forces induced on the screens by the sloshing action of water, extensive computational studies with some simplifications were conducted because the nonlinear wave action was mathematically not easily tractable. Therefore, the second stage of the experimental study was conducted to measure wave forces in the screens mounting two small load cells in each end of a screen that are connected to data acquisition system (see Figure 5). The measured wave forces on the screens showed a good match with numerical results, thus validating our design. Then, this information was used to find loads on each slat based on an intermediate post to support the screen and assuming wave load to be uniformly distributed on a beam fixed at its ends.

The third stage of the experimental study was to validate TSD performance involving the combined building-damper system response and to assess the effectiveness of the damper in reducing the tower motion in an advanced way. The current practice in this regard has been to carry out simplified experiments, e.g., to simply represent structural motions by a swing or a hanging slab frame system with exciter/pre-tensioned drive springs to model external sinusoidal loads (Fujino et al., 1992; Tait et al., 2004). While these tests may be useful to investigate the performance of a TSD in a convenient way, they are limited to specific loading pattern, i.e., sinusoidal forces or vibrations with constant amplitude as well as excited frequency, whereas wind loadings acting on full-scale structures are indeed random in nature. In addition, TSD has amplitude dependent characteristics,

Building RMS displacement (m) 建筑均方根位移(m)			Building RMS displacement (m) 建筑均方根位移(m)		
without damper 无阻尼器	with damper 有阻尼器	reduction 减少	without damper 无阻尼器	with damper 有阻尼器	reduction 减少
0.18	0.11	38.8 %	0.052	0.032	37.5 %
Building Peak acceleration (milli-G) 建筑峰值加速度(milli-G)			**Building RMS acceleration (milli-G) 建筑均方根加速度(milli-G)**		
without damper 无阻尼器	with damper 有阻尼器	reduction 减少	without damper 无阻尼器	with damper 有阻尼器	reduction 减少
22.63	16.1	28.9 %	6.47	4.59	28.8 %

Table 2. Comparison of peak and RMS responses of building with and without TSD using AST (Source: Deepak Kumar)
表2.使用AST的有TSD和无TSD下建筑峰值和均方根值相应对比（出自：Deepak Kumar）

为了确定由水体晃动导致的屏板上的力，做了大量简化的数值计算，这是由于波浪力的非线性不易进行数学处理。并因此做了第二阶段的试验研究，通过在屏板末端安装两个连接至数据采集系统的小型测力传感器（见图5）以测量屏板上的波浪力。屏板上测得的波浪力显示了与数值结果的一致性，也验证了我们的设计。之后，使用这些信息并根据中间立柱支撑屏板以及假定波浪荷载在其末端的均匀分布来确定每个栅格上的荷载。

试验研究的第三阶段是证实建筑—阻尼组合系统响应下的TSD性能，并确定阻尼器减少塔楼振动的有效性。目前实践的方法是简化试验，如简单地用摇摆或悬吊的平板框架系统和激励器或预拉驱动弹簧模拟外部正弦荷载（Fujino等，1992；Tait 等，2004）。这些试验可较便捷地用于考察TSD性能，但其受限于特定的荷载形式（即振幅和频率恒定的正弦力或振动），作用于全尺度结构的风荷载应是随机的。此外，TSD具有依赖于振幅的特性，并且因非线性的液体晃动/撞击和波浪破碎等而复杂化，由于这些试验所考虑的建筑物振动的局限性，一般无法反映TSD依赖于振幅的特性。为克服这些限制，本试验应用先进的试验系统，建立TSD系统有效性的硬件回路（HIL）模拟。该试验方法的理念近来被地震工程领域所采纳，称之为混合试验（NEES 2011）。该方法中，组合系统是基于一个虚拟的结构线性模型（计算模型）和一个代表非线性TSD的水箱模型（物理模型）（见图6）。设置于振动台上的水箱与振动台之间装有底部天平（荷载传感器）以测量TSD中液体净晃动力。两个系统进行实时交流并提供结构—阻尼器组合系统的即时性能评估。

对结构—阻尼器组合系统，动力学方程为：

$$M_s \ddot{x}_s + C_s \dot{x}_s + K_s x_s = F_e + F_{net} \quad (1)$$

Figure 5. Experimental set up for screen force measurement on a shaking table (scale 1:10) (Source: Dae Kun Kwon)
图5. 振动台上的屏板测力仪器安装（比例1：10）（出自：Dae Kun Kwon）

which are complicated by the nonlinear liquid sloshing/slamming and wave breaking actions, which in general cannot be captured by such experimental studies due to limited level of building motions typically considered for these experiments. To overcome some of these limitations, this study instead ushered into high-tech era utilizing an advanced experimental system to establish the effectiveness of a TSD system, hardware-in-the-loop (HIL) simulation (Isermann et al., 1999), and this concept has been recently picked up by the earthquake engineering group and they refer to it as a hybrid testing (NEES 2011). In this approach, the combined system is based on a virtual linear model of the structure (computational model) and a nonlinear TSD is represented by a scale model of the tank (physical model) (see Figure 6). The tank is mounted on a shaking table with sensors such as a base balance (load cell) between the tank and the shaking table to measure net sloshing force of liquid in a TSD. The two systems communicate in real-time and provide on-the-fly the performance evaluation of a combined structure-damper system.

For the combined structure-damper system, the equation of motion can be written as:

$$M_s\ddot{x}_s + C_s\dot{x}_s + K_s x_s = F_e + F_{net} \quad (1)$$

where M_s, C_s and K_s = generalized mass, damping and stiffness matrices of a structure in fundamental mode, respectively; X_s = modal displacement of a structure; F_e = external force acting on a structure which is inputted as a time history in digital format (e.g., data file); F_{net} = net sloshing force (reactive force) of a $TSD(=F_{total} - M_{tank} \cdot \ddot{x}_s)$; F_{total} = total base force of a TSD model measured by a base balance; M_{tank} = mass of the empty tank and screens; $\ddot{x}_s$= acceleration of shaking table motions measured by an accelerometer. The displacement of a structure (x_s) is calculated in a computer by solving Eq. (1) which is converted to a corresponding voltage to drive the shaking table. In this manner, a real-time dynamic coupled structure-TSD analysis is conducted on-the-fly without the use of a large-scale structure or heavy actuators to excite the structure. In the HIL simulation, any type of the excitations including random loadings, i.e., F_e in Eq. (1), can be implemented under the capacity of a shaking table. In view of the adequacy of water depth and the capability of experimental facilities such as a base balance and a shaking table, scale of 1:20 model describing one of four tanks in this HIL simulation (see Figure 7). It is worth noting that the TSD designed in this tower consists of four tanks, while the HIL experiments were performed with only one of four tanks. To account for this discrepancy, the reactive force (F_{net}) in the equation of motion (Eq. 1) was increased by four times to solve Eq. (1).

In order to validate the effectiveness of the tuned sloshing dampers, a suite of wind loading scenarios such as sinusoidal and random were used to assess the efficacy of HIL experiment as well as performance of the TSD, however, a random loading case is shown here for brevity. A random external force to describe modal wind loads was generated from random white noise for 60 sec in duration, which are filtered at 3.0 Hz using 5th order of Butterworth filter numerically as shown in Figure 8 (top plot). Note that amplitude level of the random force was determined to yield as close as the maxima in structural displacement of 0.2 m and acceleration of 22 milli-G in full-scale structure without TSD system, which were based on the results of wind tunnel experiments. It was observed that tuned sloshing damper showed very good performance in mitigating both displacements and accelerations as shown in Figure 8 (blue line = without damper; red line = with damper), and the maximum and root-mean-square (RMS) of responses were summarized in Table 3. The experimental study involving the assessment of building equipped with the current sloshing damper configuration in a "Hardware-in-the-loop" confirms the findings

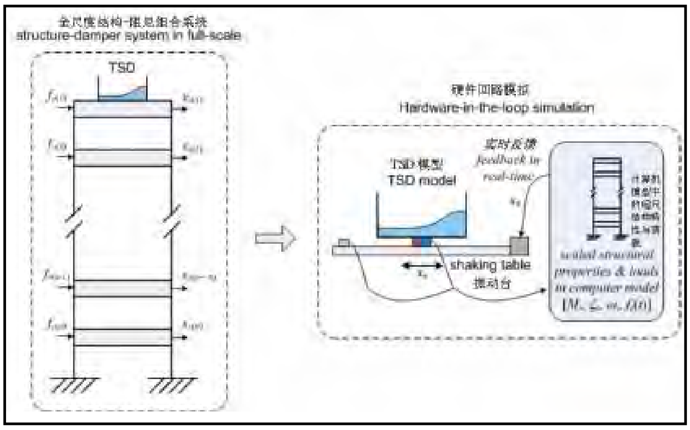

Figure 6. A schematic of a hardware-in-the-loop experiment for a TSD system (Source: Dae Kun Kwon)
图6. TSD系统硬件回路试验原理（出自：Dae Kun Kwon）

其中M_s, C_s和 K_s分别为基本振型下结构的 广义质量、阻尼、和刚度矩阵；X_s为结构振型位移；F_e是作用于结构的外部力，以数据化时程函数方式输入（如数据文件）；F_{net} 为TSD净晃动力（反力）$(=F_{total} - M_{tank} \cdot x_s)$；$F_{total}$ 为底部天平测得的TSD模型总基底反力；M_{tank} 为空水箱和屏板的质量；x_s为加速度计测得的振动台振动加速度。结构位移（x_s）是由计算机求解式(1)得到的，并转换为驱动振动台的相应电压。该方法中，不使用大尺度结构或重型激振器来进行实时结构—TSD动力耦合分析。在HIL模拟中，包括随机荷载在内的任何形式的激振力，即式(1)的F_e，可以在振动台的适用范围内使用。根据水深是否足够和底部天平与振动台等试验设备是否适用，以1:20的模型模拟了HIL模拟中四个水箱中的一个（见图7）。值得注意的是塔楼中设计的TSD包括四个水箱，而HIL试验中只有一个水箱。为考虑该不一致，对动力方程式(1)中反力（F_{net}）增加了四倍来解方程。

为验证可调谐液体阻尼器的有效性，使用了一组包括正弦或随机的风荷载工况以确定HIL试验的效果和TSD的性能，为简要起见这里仅给出了一个随机荷载的工况。从60秒时长的随机白噪声生成了一个随机外力以表示模型风荷载，并使用5阶Butterworth数字滤波器在3.0Hz进行滤波，如图8所示（上图）。注意该方法中基于风洞试验结果，确定了与没有TSD系统时最大结构位移0.2m和最大加速度22 milli-G相接近的随机力振幅。如图8所示，可调谐液体晃荡阻尼器具有非常好的减小位移和加速度的性能（蓝线为无阻尼器情况；红线为有阻尼器情况），响应的最大值和均方根值（RMS）归纳于表3中。硬件回路试验方法中对安装有液体阻尼器的建筑物评估结果确认了基于设计软件AST的计算模型。阻

Figure 7. Experimental setup for a combined structure-TSD system in the HIL simulation (Source: Dae Kun Kwon)
图7. HIL模拟中结构—TSD组合系统的试验设置（出自：Dae Kun Kwon）

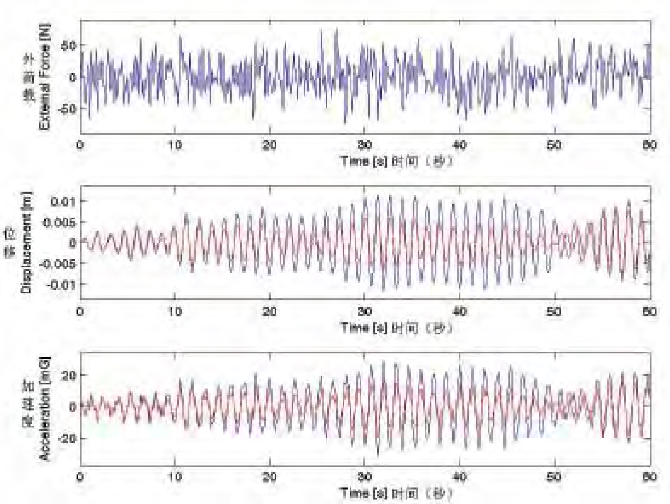

Figure 8. Results of HIL simulation (top: external force; middle: displacements; bottom: acceleration; blue line = without damper, red line = with damper; model-scale values are depicted) (Source: Dae Kun Kwon)
图8. HIL模拟结果（上：外力；中：位移；下：加速度；蓝线=无阻尼器，红线=有阻尼器；描述了模型尺度数值）（出自：Dae Kun Kwon）

of the computational model based on our design portal, AST. The damper provides approximately 1.5% ~ 1.6% of additional damping. This would bring the total system damping in the building to 2.5 ~ 3.1 % assuming the basic structural damping is 1 ~ 1.5%. Although the maximum reduction of acceleration in the experiment was 17.37 milli-G, the maximum acceleration without the damper was 28.72 milli-G which was larger than the tower acceleration at the top floor of 22 milli-G under 10-year recurrence interval winds. In view of reduction percentage in the maximum acceleration, about 40 % shown in Table 3, though such control effects depend on amplitude of responses, the sloshing damper designed for the DMT will help in reducing the top floor acceleration level to 16 milli-G, a widely accepted level of acceleration in the tall building design/development communities.

Concluding Remarks

Two very slender concrete towers currently under construction were investigated for the sensitivity of wind-induced motions sensitivity and tuned sloshing dampers were considered to mitigate the responses to currently acceptable human comfort level. Based on careful evaluation of advantages, availability of space, convenience of adaptation in the current tower configurations, required percentage control in response, and the attendant operational issues etc., specially designed tuned sloshing dampers such as bi-directional and double decker dampers including screens to two towers were designed using an advanced TSD design tool, Aqua Sloshing Technologies. The performance of the TSDs were further evaluated based on a series of experiments using scaled models with a shaking table, including an innovative experimental technique, Hardware-In-the-Loop simulation, for better establishing the effectiveness of TSD systems. It was observed that the sloshing dampers designed for the towers would help in reducing the top floor acceleration level to a widely accepted level of acceleration in the tall building design/development communities.

Building RMS displacement (m) 建筑均方根位移(m)			Building RMS displacement (m) 建筑均方根位移(m)		
Without Damper 无阻尼器	With Damper 有阻尼器	Reduction 减少	Without Damper 无阻尼器	With Damper 有阻尼器	Reduction 减少
0.23	0.16	30.4 %	0.11	0.06	45.5 %
Building Peak Acceleration (Milli-G) 建筑峰值加速度(Milli-G)			**Building Rms Acceleration (Milli-G) 建筑均方根加速度(Milli-G)**		
Without Damper 无阻尼器	With Damper 有阻尼器	Reduction 减少	Without Damper 无阻尼器	With Damper 有阻尼器	Reduction 减少
28.72	17.37	39.5 %	12.34	6.89	44.1 %

Table 3. Summary of HIL simulation for peak and RMS responses (converted to full-scale values) (Source: Dae Kun Kwon)
表3. 峰值和均方根值响应的HIL模拟概要（转换为全尺度数值）（出自：Dae Kun Kwon）

尼器提供了大约1.5% ~ 1.6%的额外阻尼。假定基本结构阻尼是1 ~ 1.5%，阻尼器使建筑物总体系统阻尼达到2.5 ~ 3.1 %。虽然试验中最大加速度减为17.37 milli-G，但没有阻尼器的最大加速度为28.72 milli-G，大于塔楼顶层在10年重现期风速下的22 milli-G。鉴于最大加速度的降低比例（约40%，表3所示），虽然控制效果取决于响应幅度，但是为DMT设计的液体晃荡阻尼器将减少顶层加速度至16 milli-G，16 milli-G是能被高层建筑设计开发领域广泛接受的加速度水平。

结语

本文考察了两栋在建的高细混凝土塔楼风致振动敏感性，并考虑了可调谐液体晃荡阻尼器以降低结构响应至目前可接受的舒适度水平。基于对优点、可用空间、目前塔楼构造中的安装方便性、需要的相应控制程度和人员操作问题等方面仔细的考虑，采用了先进的TSD设计工具——液体晃动技术，对两栋塔楼特别设计了包括屏板的可调谐液体晃荡阻尼器（双向和双层液体晃荡阻尼器）。并使用缩尺模型和振动台试验验证了TSD的性能，其中包括有创意的硬件回路模拟以更好地建立有效的TSD系统。试验发现设计的液体晃荡阻尼器将有助于将顶层加速度减至高层建筑设计开发领域能广泛接受的水平。

值得注意的是在阻尼器应用中，必须有待于大楼建成后才能通过现场实测确定塔楼的实际动力特性。如果需要，之后设计的阻尼器必须进行调谐使之与实际动力特性一致。简单的足尺监控系统将能更好地估计塔楼的这些动力特性，以确定现场调节阻尼器的必要性，并获得阻尼器运行前后建筑—阻尼器组合系统有效性的更精确估计。

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