Title: **Recent Applications of Damping Systems for Wind Response**

Authors: Peter Irwin, RWDI
Brian Breukelman, RWDI

Subject: Wind Engineering

Keywords: Damping
Wind Loads

Publication Date: 2001

Original Publication: CTBUH 2001 6th World Congress, Melbourne

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 Unpublished conference paper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 Unpublished

DESIGN CRITERIA AND LOADS

Recent Applications of Damping Systems for Wind Response

Peter A. Irwin and Brian Breukelman

1 INTRODUCTION

A traditional solution to the problem of excessive motion of tall buildings under wind action is to add more structure so as to stiffen the building and increase the mass. However, another approach is to supplement the damping of the structure. Some of the first buildings where this approach was taken were in North America. An early example is the World Trade Center towers, New York, which were designed in the 1960's with viscoelastic dampers distributed at many locations in the structural system. In the 1970's the Citicorp building in New York, which has a single Tuned Mass Damper, weighing 400 tons, at the top was constructed. The Columbia Seafirst Center in Seattle, with distributed viscoelastic dampers, followed in 1984. There have been a few other applications (e.g. John Hancock tower, Boston, as a retro-fit, 28 State Street, Boston also as a retro-fit) but not many. Bearing in mind the large number of tall buildings constructed since 1960, there have thus been relatively few in North America, compared with Japan say, where the concept of adding damping has been applied for reducing wind response. However, as we view the scene in the year 2000, there does appear to be a renewed surge in activity. At the time of writing there are now at least six tall buildings under construction with dampers incorporated as part of the design to resist wind excitation. These buildings are in Chicago, New York, San Francisco, Boston and Vancouver. The author's firm RWDI became involved with these projects initially through wind tunnel testing models of each building and, in several cases, was assigned the task of designing the damping systems.

2 DESIGN ISSUES

Two approaches have been used to add damping to buildings to reduce wind excitation. The first is to add many sources of damping throughout the structure. Both hydraulic dampers and visco-elastic type dampers have been used in this type of application, and so have multiple small Tuned Sloshing Liquid Dampers. The second approach is to concentrate the damping mechanism at one or two locations, usually near the top of the building. The Tuned Mass Damper (TMD), the Tuned Liquid Column Damper (TLCD) and the large scale Tuned Sloshing Liquid Damper (TSLD) fall into this category.

Distributed Systems. The analysis of structures with various distributed types of dampers is covered in a number of references, e.g. Soong and Dargush (1997) and this paper is not the place to re-iterate the theories involved. However, a full analysis can be complex and it is helpful to have a simple approximate method of estimating required damper properties for preliminary design purposes. For a highly distributed system with small local damping forces, the increment, ζ, in overall damping ratio due to the added dampers is given by

$$\zeta = \left(\sum_{j=1}^{N} C_j \phi_{sj}^2 \right) / \left(2\omega M_G \right) \tag{1}$$

where N = total number of added dampers, C_j = viscous damping constant of the added dampers at the j^{th} level in the tower in terms of the differential velocity between the floors, φ_{sj} is the difference in modal deflection shape between the floors spanned by the dampers at the j^{th} level, ω = circular natural frequency for the particular mode of vibration being considered and M_G = generalised mass of the building for the mode of vibration.

If large dampers are added at only a few locations then the tower's modes of vibration become appreciably altered and Equation 1 will overestimate the amount of damping that will be added because the structure starts to deform around the dampers and they become less effective. As an illustration, if a viscous damping system is installed half way up a building with pure shear flexibility only, and the damping system, with damping constant C_0, spans one floor only, then the damping ratio increase ζ due to the damper can be shown, using methods similar to those employed by Carne (1980), to be approximately given by

$$\zeta = \pi C \lambda^2 / \left(1 + \pi^2 C^2 \lambda^2 \right) \tag{2}$$

where $C = C_0/\sqrt{Gm}$, G = shear constant, m = mass per unit height, and λ = ratio of floor-to-floor height to twice the building height. Note: C_0 = (floor damping force) / (relative velocity of floors). As the damping constant C_0 is increased from zero, ζ initially increases, but it reaches a maximum value of $\zeta = \lambda/2$ at $C = 1/\pi\lambda$.

Further increases in damping constant will actually be counter productive since ζ will only decrease due to the excessive restraint imposed by the damper. For a 50 storey simple shear building, for example, the increment in damping ratio can be no more than 0.005 according to Equation 2. Since real buildings flex and twist as well as shear, the actual maximum possible damping may be even less than this in reality. So generally it is necessary to add viscous or visco-elastic damping systems to many floors for them to work efficiently. To fully evaluate the effectiveness of a given system of viscous type dampers (linear or non-linear) it is best to undertake a full time history simulation, using wind tunnel derived time histories of the input wind forces and a full structural model incorporating the dampers, such as described by McNamara and Huang (2000).

Since typical floor to floor deflections of interest are only one or two millimetres, it may be necessary to use a mechanical linkage system that will magnify the damper stroke for a given floor to floor deflection, as used on the 111 Huntington St. tower in Boston (MacNamara and Huang, 2000). Also, the exponent in the damping force versus velocity relationship can be important. Available hydraulic dampers obey a force versus velocity relationship of the form force $\propto$ (velocity)$^{\alpha}$. The classic, strictly viscous, damper has $\alpha = 1.0$. However, there are advantages to using exponents less than 1.0 in distributed damping systems for motion reduction purposes. To avoid the dampers putting excessive forces into the structure locally in full design winds or under seismic actions an exponent α less than 1.0 is desirable. Typically a value of about 0.7 is found to work well.

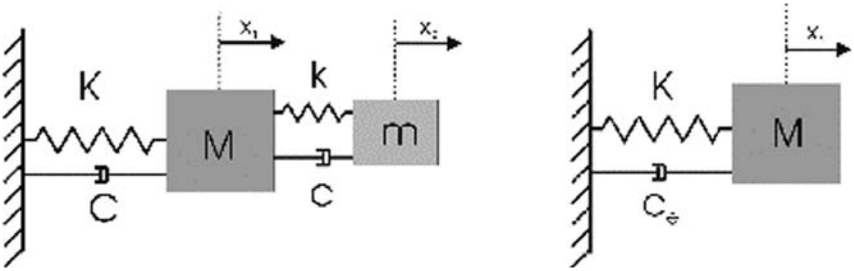

Figure 1 Conceptual Model of a Tuned Mass Damper and System with Same Effective Viscous Damping.

Tuned Mass Dampers. The principle of the Tuned Mass Damper is illustrated in Figure 1. The main mass, M, in Figure 1 represents the generalised mass of the building in its fundamental mode in a particular direction and the spring connecting the main mass to ground represents the stiffness of the building. The viscous damper connecting the main mass to ground represents the inherent damping of the building. The secondary mass, m, is the mass of the TMD, which is connected to the main mass via a suspension system, the stiffness and damping of which is represented in Figure 1 by the spring and viscous damper between the main and secondary masses. In practice the stiffness of the "spring" connecting the secondary mass to the main mass can be the stiffness arising from pendulum action when the TMD mass is hung from cables attached to the building structure.

The equations of motion of the TMD were laid out by Den-Hartog (1956) and have been re-iterated in many references. Therefore they will not be described here. The TMD is most effective in damping motion of the main mass when optimally tuned. The optimum frequency ratio, optimum TMD damping ratio, and resulting maximum dynamic amplification factor for the case where the damping of the main mass is zero are given respectively by

$$f_2 / f_1 = \frac{1}{1+\mu}\ , \quad \varsigma_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}}\ , \quad \frac{\mathrm{x}_{1\max}}{\mathrm{x}_{\mathrm{static}}} = \sqrt{1+\frac{2}{\mu}} \qquad \textbf{(3)}$$

where f_1 and f_2 are the natural frequencies of the main mass and secondary mass respectively, μ is the mass ratio m/M, $\boldsymbol{x}_{1\max}$ is the maximum deflection of the main mass under the sinusoidal loading and $\boldsymbol{x}_{static}$ is the main mass deflection under the action of a static force equal to the amplitude of the sinusoidal force. In reality the wind loading of the structure is not sinusoidal but has a broad band of frequencies. Also, of course, the structural damping is not zero. However, most towers are lightly damped and the above simple relationships can be useful for arriving at preliminary estimates of optimal tuning and TMD damping. Weisner (1979) has published computations done for the Citicorp building TMD for various assumed inherent damping values for the building.

A useful concept is that of effective viscous damping. The effective viscous damping provided by a TMD depends on the type of loading being applied to the main mass. The definition of effective viscous damping is that it is the viscous damping ratio that would give the same root-mean-square building response as the TMD under the selected type of loading. In Figure 1 this is represented by the damping constant C_e in the right hand diagram. Since wind excitation is typically broad band in nature, one type of loading frequently used in the definition is white noise excitation, i.e. assuming equal excitation at all frequencies.

There are a number of practical considerations in the design of a TMD. One of these is needed to limit the motions of the TMD mass under very high wind loading such as will occur in the design storm or under ultimate load conditions. One way of doing this is to use a nonlinear hydraulic damper in the TMD. By employing a damper with an exponent $\alpha = 2$, say, rather than 1.0 or less, the motions of the TMD mass can be greatly reduced under very high wind loading conditions or under strong seismic excitation. A further safeguard against excessive TMD motion is to install hydraulic buffers around the mass. When the mass comes into contact with the buffers high velocities are quickly reduced.

To properly simulate the response of a TMD with nonlinear dampers and with hydraulic buffers it is best to undertake time history simulations of the tower response in both wind and earthquake loading, (Breukelman, *et al.*, 2001). These simulations can be used not only to evaluate the motions of the TMD and tower but also to determine the maximum forces the TMD will impart locally to the tower structure.

Tuned mass dampers can in principle be readily converted to be an active system by incorporating sensors and feedback systems that can drive the TMD mass to produce more effective damping than is possible in a purely passive mode. As a result a larger effective damping can be obtained from a given mass.

This approach has been used in several commercially available ready-to-install systems. The TMD is thus made more efficient, a benefit to be weighed against the increased cost, complexity and maintenance requirements that are entailed with an active system.

Liquid Column Dampers and Sloshing Dampers. Tuned liquid column dampers are in many ways similar to tuned mass dampers. The difference is that the mass is now water (or some other liquid). The detailed equations of motion for a TLCD have been worked out by several researchers (e.g. Xu *et al*, 1992). The damper is essentially a tank in the shape of a U, i.e. it has two vertical columns connected by a horizontal passage and filled up to a certain level with water. Within the horizontal passage there may be screens or a partially closed sluice gate. The TLCD is mounted near the top of the building and when the building moves the inertia of the water causes the water to oscillate into and out of the columns, travelling in the passage between them. The columns of water have their own natural period of oscillation which is determined purely by the geometry of the tank. If this natural period is close to that of the building's period then the water motions become substantial. Thus the building's kinetic energy is transferred to the water. However, as the water moves past the screens or partially opens the sluice gate in the horizontal portion of the tank the drag of these obstacles to the flow dissipates the energy of the motion and results in damping.

An even simpler liquid type damper is a rectangular tank filled to a certain level with water (Isyumov *et al.,* 1995). In this case the tank's natural period of wave oscillation is approximately matched to the building period by appropriate geometric design of the tank. If screens and baffles are placed in the tank then dissipation of the waves takes place and the result is again that the tank behaves like a TMD. However, analysis indicates that a sloshing water tank does not make as efficient use of the water mass as a TLCD.

3 RECENT APPLICATIONS

Simple Pendulum Damper Application. Recently RWDI designed a TMD for the 67 storey Park Tower, Chicago, Figure 2, in cooperation with architects Lucien Lagrange and Associates and structural engineers Chris Stefanos and Associates and is currently in the process of commissioning it. The developers are the Hyatt Development Corporation. The wind tunnel tests showed that with the initially planned structural system the accelerations would be above the desired values for a residential building. The 10 year return period acceleration was predicted to be in the range of 26 to 30 milli-g at 2% damping ratio and a target of 15 milli-g had been set. The higher than normal accelerations were primarily due to wind flows off the John Hancock Tower nearby. After extensive investigations into various structural or shape change solutions, the decision was made to add damping. From the developer's point of view the damping system had to be economical, require little maintenance and avoid compromising valuable floor space. The design selected consisted of a simple pendulum damper

Figure 2 Photo of the Park Tower under construction.

mounted under the mansard roof of the tower, an area being used for mechanical equipment. With some minor changes in the geometry of the mansard, there was enough space to accommodate a simple pendulum TMD. Figure 3 illustrates the design. It consists of a 300 T mass block slung from cables with lengths adjustable up to 34.5 ft. This mass represented approximately 1.4% of the building's generalised mass in the first mode of vibration. The simplicity of the design minimises the need for maintenance and also kept the cost low. The only components in need of maintenance will be the hydraulic dampers and present day hydraulic dampers can be manufactured to have very low maintenance.

Features of the TMD are that it has a tuning frame which can be moved up and down and clamped on the cables to allow the natural period of the pendulum to be adjusted. The damper constants can be adjusted. The dampers are nonlinear with a force proportional to velocity squared so as to prevent excessive mass motions during extreme wind events. The mass is connected to an anti-yaw device to prevent rotations about a vertical axis. Below the mass there is a bumper ring connected to hydraulic buffers to prevent travel beyond the hydraulic cylinder length. The main hydraulic dampers of the TMD are sloped from their floor mountings up to the TMD mass. This was found to be advantageous in shortening the stroke required of the dampers which reduced cost. Installation of the TMD is in progress at the time of writing. The building frequencies have been measured using accelerometers mounted in the building and by recording motions caused by ambient winds. The measured sway frequencies were within 10%–20% of computed modes. The results of the measurements will allow the correct pendulum length to be set. The predicted 10-year acceleration for the building with the TMD in operation is 15 milli-g.

Nested Pendulum Damper Application. In some situations the height available in the building is insufficient to allow a simple pendulum TMD to fit. In such a case, at the cost of a little more complexity in design, a nested pendulum design can be used. RWDI has recently completed such a TMD design of mass 600 T for another tall North American residential tower. The nested TMD design is illustrated in Figure 4. The total vertical space occupied by the damper, which has a natural period of about 6 seconds, is less than 25 ft. The cost, including installation, is anticipated to be about $2.5 million US.

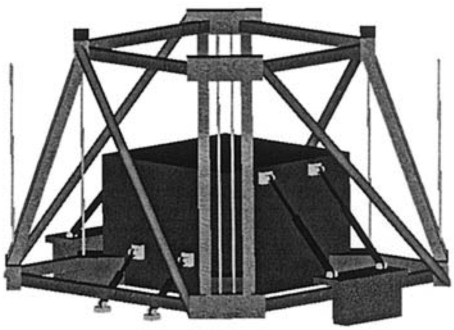

Figure 3 Nested Pendulum Design.

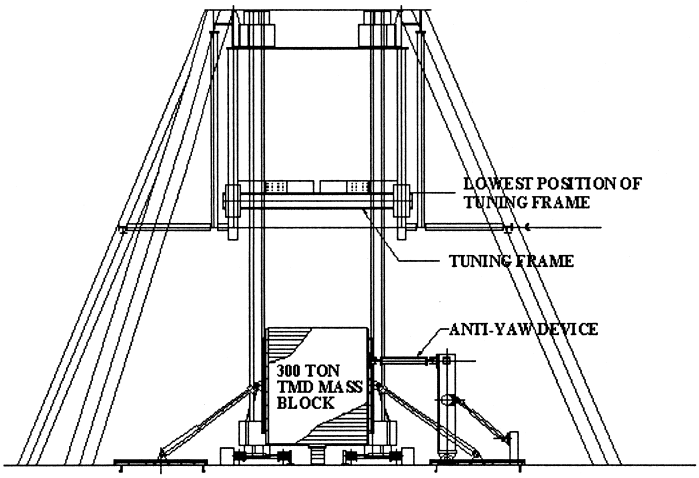

Figure 4 Park Tower Damper Design.

Figure 5 Wall Centre under construction.

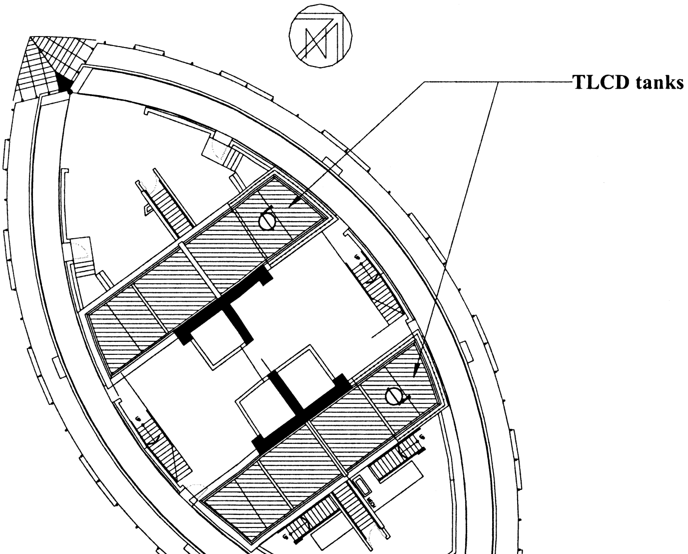

Figure 6 Cross-section of Wall Centre.

Tuned Liquid Column Damper Application. The Wall Centre is a 48 storey residential tower currently under construction in Vancouver, BC, Figure 5. Its cross-section is illustrated in Figure 6. From wind tunnel tests predicted 10 year accelerations were in the range 28 to 40 milli-g, depending on the structural systems being explored by the structural designers Glotman Simpson Engineers. The effects of shape changes were also examined in conjunction with the architects, Busby and Associates, and have been described by Irwin (1999). However, in the end, when all things were considered by the owners, the Wall Financial Corporation, and the design team, it was decided that the approach of increasing the damping was preferable. In discussions with the owner it transpired that a damper using water could serve a dual purpose by also providing a large supply of water high up in the tower for fire suppression. Therefore a TLCD was designed. Initially a sloshing water damper was considered but the TLCD was found preferable due to its greater efficiency in using the available water mass. The TLCD design turned out to be a remarkably economical solution in this case, especially considering the saved cost of having to install a high capacity water pump and emergency generator in the base of the building, as initially required by fire officials. The total mass required was in the order of 600 T which corresponds to a large volume of water. However, sufficient space was available. Also a helpful factor was that the motions of the tower were primarily in one direction only. Therefore only one direction needed to be damped which simplified the design.

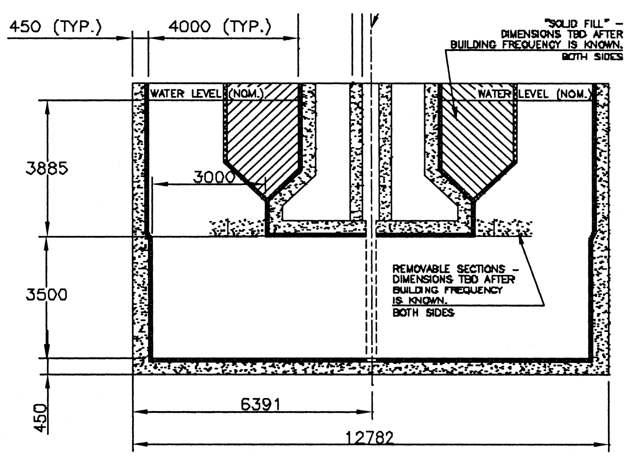

Figure 7 Tuned Liquid Column Damper design for Wall Centre.

Figure 7 illustrates the TLCD design which consisted of two identical U-shaped concrete tanks. Since the building was concrete it was relatively easy to incorporate the tanks into the design and to construct them as a simple addition to the main structure. The locations of the two TLCDs in the tower cross-section can be seen in Figure 6. The dimensions of the TLCDs were initially worked out using analytical methods. However, since a number of assumptions are inherent in these methods a scale model was also constructed at RWDI's Guelph, Ontario, laboratories. The model behaviour gave good confirmation of the theoretical results.

The tower is currently under construction and its natural frequencies have been checked by vibration tests. Commissioning will consist of adjustments to the sluice gate to obtain the correct TLCD damping and adjustments to the water level in the columns to obtain the desired natural frequency. The design incorporates a system for sealing off the top of a vertical column, pressurizing it and then releasing the seal so as to set the TLCD into oscillation. From the decay of oscillations the TLCD's internal damping can be measured. The predicted 10 year accelerations with the TLCDs operational are 16 milli-g, within 1 milli-g of the target.

Tuned Mass Damper as a Building Feature. The view of many owners is that the presence of a special damping device in the building is not something that they necessarily want widely broadcast. In most cases it is tucked away out of view. However, the architects, C. Y. Lee and Associates, and owners of the 101 storey Taipei Financial Centre, have taken the route of making the RWDI designed TMD a feature of the building. A special space has been allocated for it near the top of the building and people will be able to walk around it and view it from a variety of angles. It will be brightly coloured and special lighting effects are planned. The design, which consists of an 800 T steel ball slung on cables is illustrated in Figure 8. Time history simulations of both the wind response and seismic response of the building/TMD system have been undertaken to verify its performance, Breukelman *et al.* (2001).

Figure 8 Taipei Financial Center TMD rendering.

REFERENCES

Breukelman, B., Haskett, T. C., Gamble, S. L. and Irwin, P. A., 2001
ANALYSIS AND MODEL TECHNIQUES FOR DETERMINING DYNAMIC BEHAVIOUR OF CIVIL STRUCTURES WITH VARIOUS DAMPING SYSTEMS. Proceedings, Council on Tall Buildings and Urban Habitat, 6th World Congress, Melbourne, Australia, Feb. 26–Mar. 2.

Carne, T. G., 1980
GUY CABLE DESIGN AND DAMPING FOR VERTICAL AXIS WIND TURBINES, Sandia National Laboratories Report No. SAND80-2669 Albequerque, New Mexico.

Den Hartog, J. P., 1956
MECHANICAL VIBRATIONS, 4th edition, McGraw-Hill, New York.

Irwin, P. A., Breukelman, B., Williams, C. J. and Hunter, M. A., 1998
SHAPING AND ORIENTING TALL BUILDINGS FOR WIND, Proceedings, Structural Engineers World Congress, San Francisco, July 19–23, CD ROM, Elsevier.

Isyumov, N., Breukelman, B., Fediw, A. A. and Montpellier, P., 1995
INFLUENCE OF A TUNED SLOSHING WATER DAMPER ON THE WIND-INDUCED RESPONSE OF A TALL OFFICE TOWER, Proceedings, ASCE Structures Congress, Boston.

McNamara, R. and Huang, C.D., 2000
VISCOUS DAMPER WITH MOTION AMPLIFICATION DEVICE FOR HIGH-RISE BUILDING APPLICATION, Proceedings, ASCE Structures Congress, Philadelphia, May 8–10.

Soong, T. T. and Dargush, D. F., 1997
PASSIVE ENERGY DISSIPATION SYSTEMS IN STRUCTURAL ENGINEERING, John Wiley & Sons.

Wiesner, K. B., 1979
TUNED MASS DAMPERS TO REDUCE BUILDING MOTION, ASCE ANNUAL CONVENTION AND EXPOSITION, Boston, Preprint 3510 April 2–6.

Xu, Y. L., Samali, B. and Kwok, K. C. S., 1992
CONTROL OF ALONG WIND RESPONSE OF STRUCTURES BY MASS AND LIQUID DAMPERS, *J. of Engrg Mech.*, ASCE, 118(1), pp. 20–39.