BUTTERWORTH HEINEMANN

Engineering Structures, Vol. 17, No. 9, pp. 609–621, 1995
Elsevier Science Ltd
Printed in Great Britain
0141–0296/95 $10.00 + 0.00

0141–0296(95)00031-3

Effectiveness of tuned liquid dampers under wind excitation

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Full-scale measurements of the wind-induced responses of four buildings (two airport towers, an observatory tower and a high-rise hotel) were conducted to prove the efficiency of tuned liquid dampers (TLDs). The damping ratios of the buildings with and without TLD were evaluated by both the run-down test technique and the random decrement technique. The wind-induced responses of the buildings were measured before and after installation of TLDs. The exceedance frequency of the response over the human perception thresholds was also examined. The results obtained in this study demonstrate that the TLDs could significantly improve the serviceability of the buildings.

Keywords: tuned liquid dampers, sloshing motion, vibration control, damping ratio, wind-induced responses, full-scale measurements, tall buildings, serviceability

1. Introduction

Due to the shortage of land space in urban Japan, the number and height of tall office, hotel and residential buildings are inevitably increasing. It is most important for the sick or aged occupants living in residential buildings not to experience discomfort caused by strong winds or typhoons, which often last several hours. The occupants can hardly abandon the building even during severe typhoons.

Higher airport towers are being constructed even at local airports, because the runways tend to be expanded to accommodate huge jet planes and the increase in the number of flights. Air-traffic controllers working on the top floor of the airport tower are under highly stressed mental conditions.

Observation towers are also increasing as one of the measures for economic promotion by local governments. Business or service may be inhibited in some of these towers from the restriction for the usage of the elevator or human discomfort due to severe vibrations.

Tall buildings in Japan are mostly steel structures to resist seismic loads, which are generally the predominant design loads. The higher strength materials, the use of welding for fastening and more efficient and economic design have also been encouraging the trend toward higher, lighter and low damping structures. Such a lightweight and flexible structure is vulnerable to vibration caused by wind.

Therefore, not only from the viewpoint of wind-resistant design but also from the viewpoint of workability and the comfort of occupants, the problem of wind-induced vibration has become an important issue for discussion.

One of the solutions to the problem is the use of the tuned liquid damper (TLD). In the field of spacecraft, the damper utilizing liquid has been used for satellite spin stabilization[1,2]. The first proposal to apply the liquid damper to ground structures was made to suppress wind-induced instabilities[3], where it was named 'a nutation damper'. The TLD absorbs vibration energy by the sloshing motion of the liquid contained in a vessel, and dissipates it through intrinsic friction of the liquid, friction at the surface of walls or floating particles, collision of the particles etc. There are some advantages in the TLD such as: low initial cost, free maintenance, ease of frequency tuning, no limit of vibration amplitude and applicability for existing buildings by dispersed installation of vessels. Furthermore, the TLD is efficient for very low amplitude vibrations around human perception thresholds. Additionally, the water inside the vessels could be available for various uses after severe disasters.

The purpose of this paper is to prove the efficiency of the TLD under wind excitations by full-scale measurements. Four buildings are discussed: two airport towers, and observatory tower and a hotel building.

Notation

D_D	diameter of vessels (m)
f_S	fundamental natural frequency of buildings (Hz)
f_D	fundamental natural frequency of sloshing motion of contained water (Hz)
H_D	height of vessels (m)
H_S	height of buildings (m)
h_W	water depth in each layer of vessel (m)
M_D	total mass of TLD including floating particles $= N \times (m_W + m_F)$ (kg)
m_F	mass of floating particles contained in a vessel (kg)
M_S	total mass of buildings above ground (kg)
M_{S1}	fundamental generalized mass of buildings, where tip displacement is set at unity (kg)
m_W	mass of water contained in a vessel (kg)
N	number of vessels installed
n	number of layers each vessel contains
V	mean windspeed at height of anemometer (m/s)
V_1	1-year-recurrence mean windspeed at height of anemometer (m/s)
x	axis along shorter side of plan of buildings
y	axis along longer side of plan of buildings
ζ_S	structural damping of fundamental mode defined as ratio to critical value (%)
ζ_D	damping ratio of damper or sloshing motion (%)
μ	mass ratio $= M_D/M_S$ (%)
μ_1	mass ratio $= M_D/M_{S1}$ (%)
ϕ	frequency ratio $= f_D/f_S$

2. Full-scale measurements at Nagasaki Airport Tower[4]

2.1. *Nagasaki Airport Tower (NAT)*

The Nagasaki Airport was constructed in 1974 on a very flat island, which was levelled by man, surrounded by the Omura Bay in Nagasaki Prefecture. The air-traffic control tower is a steel-framed tower placed on a low-rise reinforced concrete building with a height of 4 m as its base. The entire height of the tower is 42 m above ground level. The tower has a 5.15 m square cross-section. An air-traffic control room with a square plan is mounted at the top as shown in *Figure 1*. The height of the control room floor is 38.5 m above the ground. The total mass of the tower $M_S = 0.17 \times 10^6$ kg. Significant information about the buildings discussed in this paper is tabulated in *Table 1*.

2.2. *TLD installed on NAT*

The TLD was temporarily installed on the floor of the air-traffic control room and stair landings for approximately two weeks in March 1987. This may be the first TLD installation on an actual ground structure. The TLD was an assembly of 25 cylindrical multilayered vessels containing only water, without any floating particles. The vessel was a vinyl chloride cylinder, with a height of about 0.50 m and a diameter of 0.38 m as shown in *Figure 2*. It was divided into seven layers each being 0.07 m in height. The depth of water contained in each layer was 0.048 m. The fundamental natural frequency of the sloshing motion of water was almost in tune with the fundamental natural frequency of the tower. The total water mass in one vessel was about 38 kg. As indicated in *Figure 1*, 12 vessels were placed on the air-traffic control room floor, in a dispersed manner, and several on each of the stair landings making a total of 25 vessels. Thus, the total water mass was 950 kg, which is 0.56% of the total mass of the tower. This is 1.5% of the fundamental generalized mass of the tower.

Important information on the TLDs is tabulated in *Table 2*.

2.3. *Measurement systems for NAT*

Measurements were made before and after installation of the TLD for approximately one month. The windspeed and wind direction were measured by a three-cup anemometer and vane at the north-east corner, 1.5 m above the roof as shown in *Figure 1*. Three displacement transducers and two accelerometers were placed on the floor of the air-traffic control room. Here, the gauge-type accelerometers were

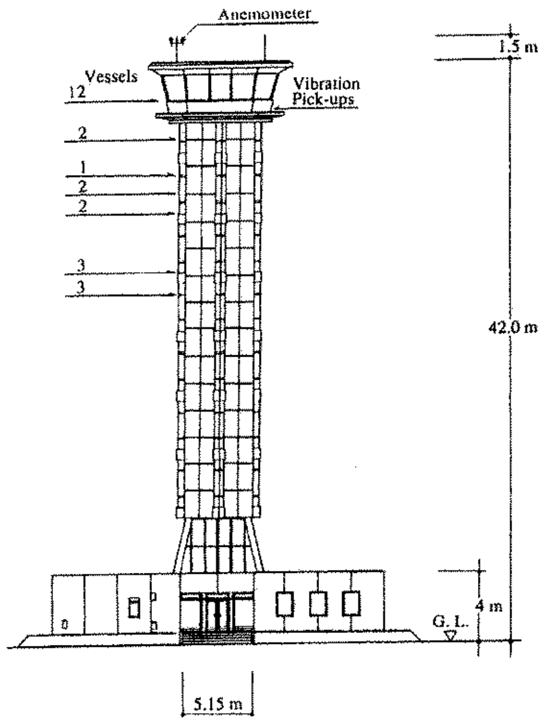


Figure 1 Nagasaki Airport Tower (NAT)

Table 1 Dynamic characteristics of buildings without TLD

Buildings	H_S (m)	M_S (kg)	f_S (Hz)			ζ_S (%)		TLD installation
			x-direction	*y*-direction	torsion	*x*-direction	*y*-direction	
NAT	42.0	0.17×10^6	1.07	1.07	2.07	0.9	0.9	1987
YMT	101.3	0.54×10^6	0.55		1.40	0.6		1987
SYPH	149.4	26.40×10^6	0.31	0.32	0.56	1.0	1.0	1992
TIAT	77.6	3.24×10^6	0.77	0.98	1.40	0.84	1.24	1993

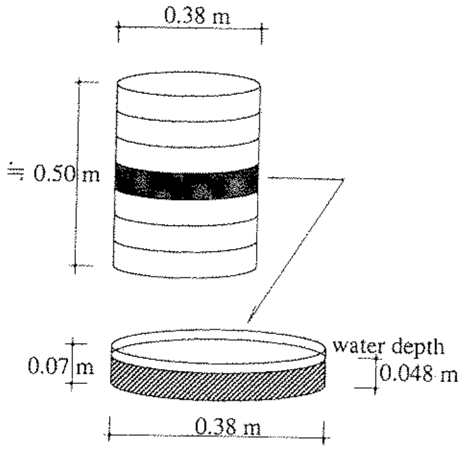


Figure 2 TLD vessel installed on NAT

Figure 3a shows the run-down test record without TLD. The amplitude first increased by the excitation due to the movement of the mass of a man, where the movement was in tune with the fundamental natural frequency of the tower. Then, damped-free oscillations appeared after a sudden stopping of the excitation. The lowest natural frequency was obtained at 1.07 Hz, and the damping ratio was about 0.9%. There was no significant difference between the *x*- and *y*-directions.

Additionally, the equivalent damping ratio during strong wind was evaluated by the random decrement technique (RDT)[5–7]. This technique is used to extract the damped-free oscillation component of a single-degree-of-freedom system under random excitations. If the dominant peaks of the power spectrum of the response of a multi-degree-of-freedom system are sufficiently separated, the technique can be applied to evaluate the damping ratio of a particular mode.

Table 2 Dimensions of a vessel and characteristics of TLDs

Buildings	$D_D \times H_D$ (m × m)	n (layers)	N (vessels)	h_w (m)	f_D (Hz)	m_W (kg)	m_F (kg)	M_D (kg)	ϕ	μ (%)	μ_1 (%)
NAT	0.38×0.50	7	25	0.048	1.02	38.1	0	0.95×10^3	0.95	0.56	1.5
YMT	0.49×0.50	10	39	0.021	0.54	39.6	0	1.54×10^3	0.98	0.29	0.98
SYPH	2.00×2.01	9	30	0.120	0.31	3390.0	0	101.7×10^3	0.97	0.39	0.97
TIAT	0.60×0.125	1	1404	0.053	0.74	14.9	1.2	22.7×10^3	0.96	0.70	3.5*

**x*-direction

used, but they exhibited drift. Displacement transducers were also used in measurements. The displacement transducers frequency response was constant down to a frequency of 0.2 Hz, and the components of displacements with a frequency lower than 0.2 Hz could not be evaluated. The windspeed, displacement and acceleration data were sampled every 0.025 s with an average time of about 100 s, except for the evaluation of damping ratios. The displacement records were analysed and decomposed into the *x*-direction displacement, *y*-direction displacement and torsional angle at the centre of the air-traffic control room floor. The anemometer may not be high enough, because the Civil Aviation Bureau enforced height restrictions. Therefore, the available data were limited to northerly and easterly winds. In this paper, only the records for the north winds, which are perpendicular to one side of the tower, were analysed. The north winds mean, of course, the sector with an angle of 22.5° centred north.

2.4. *Dynamic characteristics of NAT without TLD*

The run-down tests were conducted on calm days to obtain the dynamic characteristics of the tower, i.e. the natural frequency and damping ratio.

Figures 4a and *b* show along-wind and across-wind damping ratios obtained by the RDT, together with the value from the run-down test. These plots were evaluated from different 30-min samples. The standard error of the RDT evaluation is estimated to be less than 20%[7]. The abscissa indicates the RMS acceleration amplitude of the respective sample. As can be seen in *Figure 4a*, the along-wind damping ratio presents a clear tendency to increase with the amplitude, and the run-down result is lying in the normal range of dispersion of these strong wind data. On the other hand, the across-wind damping ratio does not show significant dependence on amplitudes (*Figure 4b*).

Figures 5a and *b* show an example of the trajectory of the displacement of the geometric centre of the air-traffic control room and the variations of the RMS displacements with windspeeds. It is clear that the across-wind component predominates over the along-wind component.

2.5. *Efficiency of TLD on NAT*

Figures 3b–e show the records of run-down tests with TLD. *Figure 3b* is the case where 7 vessels were placed on the air-traffic control room floor, and the water mass ratio to the total mass of the tower was $\mu = 0.17\%$. *Figure*

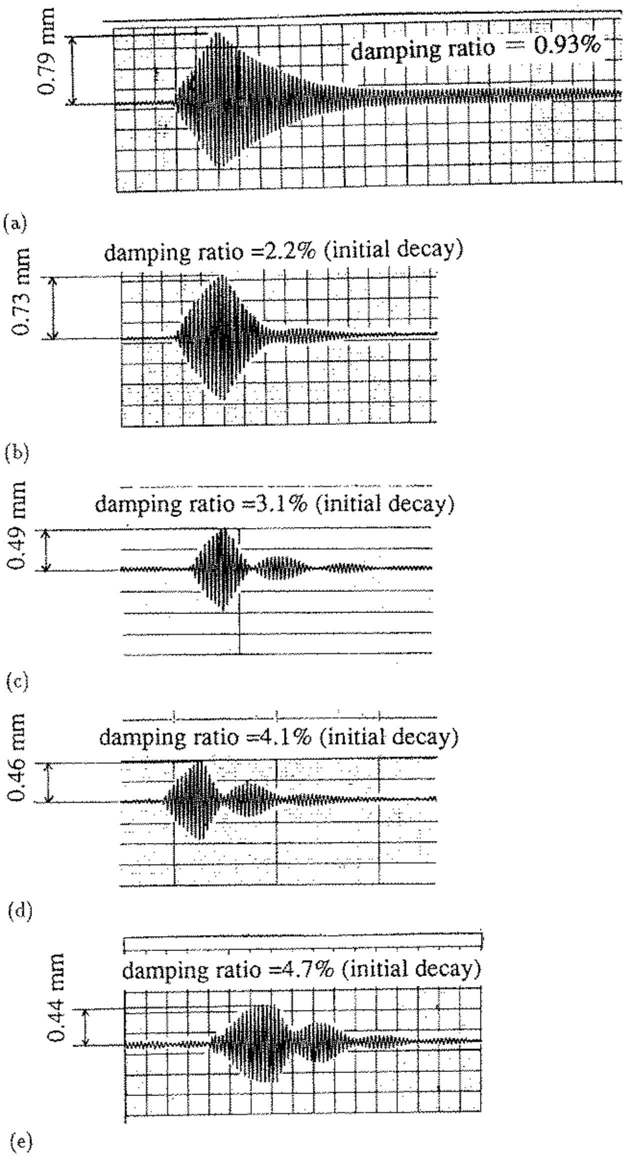


Figure 3 Examples of damped-free oscillations of NAT obtained by run-down tests. (a) without TLD; (b) with TLD (7 vessels); (c) with TLD (14 vessels); (d) with TLD (19 vessels); (e) with TLD (25 vessels)

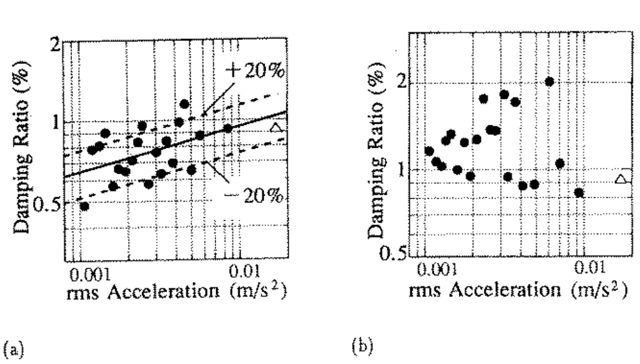


Figure 4 Damping ratios of NAT obtained by RDT (•) and run-down test (△) (without TLD). (a) along-wind; (b) across-wind

3e is the case of 25 vessels installed as shown in *Figure 1*, and the mass ratio $\mu = 0.56\%$. With a 7 vessel TLD, the amplitude of the damped-free oscillation was rapidly reduced initially as seen in *Figure 3b*, and the damping ratio is evaluated at 2.2%. With a 25 vessel TLD, the initial amplitude decay became steeper as shown in *Figure 3e*, the damping ratio evaluated from the initial amplitude decay is 4.7%. The presence of the beat phenomenon is of interest. It is significant, especially, in *Figures 3c–e*. This can be explained from the viewpoint of energy transfer. It is attributed to the back and forth transfer of energy between the tower and the sloshing water. Since the energy dissipating ability of water alone was insufficient, once the energy was absorbed from the tower it could not be dissipated thoroughly. The remaining energy was then returned once again to the tower. One of the solutions for reducing the beat phenomenon was by using floating particles. The floating particles have been added to the vessels of the TLD in the last example, Tokyo International Airport Tower[8,9]. It should be noted that neither the initial decay of the curves in *Figures 3b–e* represent the damping of the building with TLD when beat phenomena occur. In such a case, the building with TLD behaves as a two-degree-of-freedom system with natural frequencies close to each other. Neither does the fundamental modal damping of the two-degree-of-freedom system represent the damping of the building with TLD. Therefore, the damping index, defined as a normalized RMS value for a specified period of the damped-free oscillation, was used to evaluate the energy dissipating ability of the TLD[8]. From this point of view, *Figure 3* implies that the larger mass ratio provides a larger initial decay of the building amplitude but does not necessarily mean a more efficient damping performance, if the damping ratio of the sloshing motion remains at a low value.

Figure 6 compares the across-wind responses of the tower with and without TLD. Here, there were 25 vessels. As the number of the data with TLD is less than that without TLD, the reliability of the regression line of the response with TLD is relatively low. However, according to the regression lines, the response might be reduced to 35% of the RMS displacement response of the tower without TLD with windspeeds around 20 m/s, and the efficiency of the TLD seems to become more significant as the windspeed increases.

Additionally, the maximum accelerations of several return periods were calculated by using the past meteorological wind data and the regression lines such as *Figure 6*. They were compared with the serviceability criteria of the NBCC[10], AS1170-2[11] and ISO[12]. The tower without TLD had a vibration level which satisfied the NBCC and AS1170-2 criteria for office buildings, but did not meet the acceptable levels for residential buildings in the NBCC and ISO. However, the response of the tower with TLD was estimated to satisfy all of these criteria. The air traffic-controllers were also requested to answer questionnaires on their perception of vibrations, and the correspondence of the answers with the measured responses was studied[4].

3. Full-scale measurements at Yokohama Marine Tower[4]

3.1. Yokohama Marine Tower (YMT)

The YMT is a steel trussed structure with a height of 101.3 m, and has been the symbol of Yokohama Port since 1961. The cross-section of the tower is decagonal. On the top of the tower, there is the highest lighthouse in the world. *Figure 7* shows the elevation of YMT. There is an observatory room under the lighthouse. The fundamental generalized mass M_{S1} is estimated at 0.157×10^6 kg. Additional information on the tower is tabulated in *Table 1*.

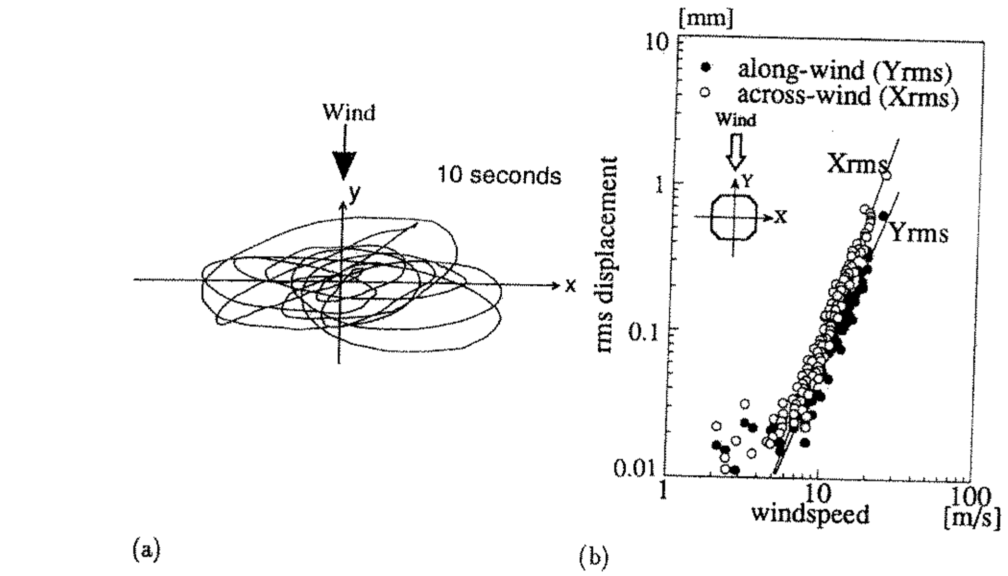


Figure 5 Wind-induced displacements of NAT without TLD. (a) trajectory of geometric centre; (b) variation with windspeeds

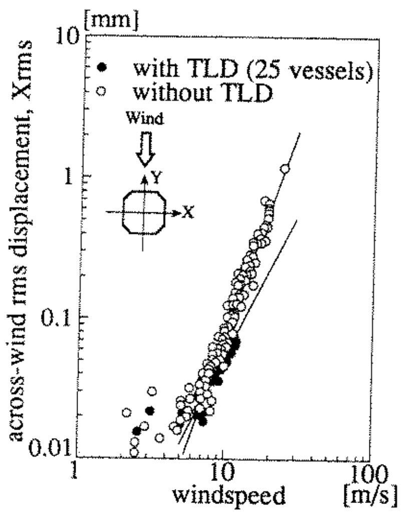


Figure 6 Comparisons of across-wind responses of NAT with/without TLD

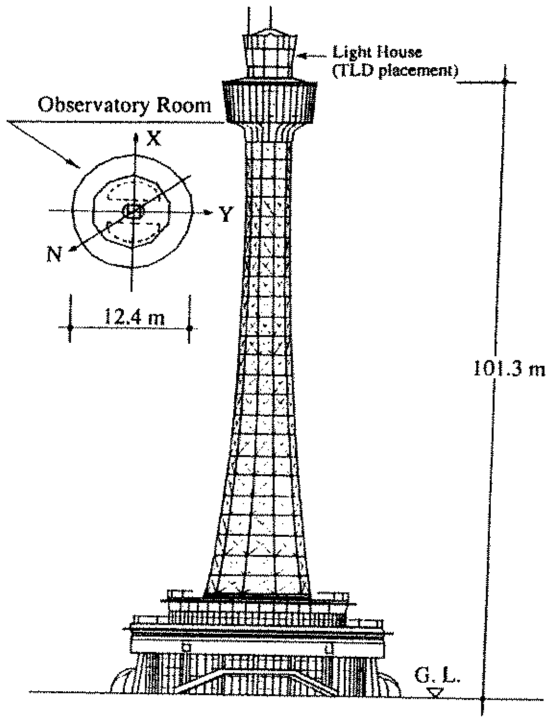


Figure 7 Yokohama Marine Tower (YMT)

3.2. TLD installed on YMT

The TLD, which is quite similar to that of the NAT, was installed in June 1987. As shown in *Figure 8*, the TLD is an assembly of 39 cylindrical multilayered vessels of acryl, with a height of 0.50 m, and a diameter of 0.49 m. The vessel is divided into 10 layers at every 0.05 m. The layers contained only water with a depth of 0.021 m. The sloshing frequency was almost tuned to the lowest natural frequency of the tower. The total mass of the TLD (1.54×10^3 kg, see *Table 2*) is approximately 1% of the generalized mass of the tower.

3.3. Measurement systems for YMT

The windspeed and wind direction were measured at 4 m above the tower's roof by a three-cup anemometer and vane. Since the effects of the tower on the observed windspeeds were not inevitable, the observed wind data were only used for reference. Three servo-type accelerometers were placed on the lighthouse floor at 99 m to measure the x- and y-translational components as well as the torsional component.

A long-term automatic measurement was intended at the YMT as well as the SYPH and TIAT as is discussed in the paper. Long cables were necessary to connect transducers on the floors with amplifiers and recording instruments in the measurement room. The signals should be high quality in S/N ratio and the zero level drift should be minimized. In order to resolve these problems, servo-type accelerometers were used in the measurements at the YMT and SYPH. They can cover the frequency range from DC to 500 Hz, and the amplitude range from $-10\ \mathrm{m/s^2}$ to $+10\ \mathrm{m/s^2}$ with a $10^{-5}\ \mathrm{m/s^2}$ resolution. The data were sampled every 0.04 s, and the length of a run was set at 180 s.

Figure 8 TLD vessels installed on YMT

3.4. Dynamic characteristics of YMT without TLD

As expected from the shape, there is not a significant directional difference in dynamic properties. The lowest three natural frequencies were measured to be: 0.55 Hz of the first translational mode, 1.4 Hz of the torsional mode, and 2.5 Hz of the second translational mode. The damping ratio was found to be 0.6% for the lowest mode. Open circles in *Figures 9a* and *b* indicate the along-wind and across-wind components of the tower without TLD, respectively. The across-wind component was slightly larger than the along-wind one, and the torsional component at the periphery of the room was found to be less than 10% of the translational components during strong winds.

The RMS acceleration of the tower reached 0.02–0.03 m/s^2 under a strong wind equal to 15–20 m/s as shown in *Figure 9b*. According to the experimental data on perception threshold[13], sinusoidal vibration with an acceleration amplitude 0.02–0.03 m/s^2 and a frequency 0.55 Hz can be perceived by 50–70% of people. The windspeed equal to 15–20 m/s at the top of the tower is equivalent to 10–15 m/s at 10 m above the ground. Therefore, most visitors might often perceive vibrations[4].

3.5. Efficiency of TLD on YMT

In the run-down tests, the damping ratio was found to be 4.5% with the TLD, which was about seven times the value without the TLD.

Solid circles in *Figures 9a* and *b* show the response with TLD. The effects of the TLD provided a very significant reduction of the response for both the across-wind and along-wind components. The TLD reduced the RMS acceleration amplitude to 1/3 with windspeed equal to almost 20 m/s.

According to a 160 min sample with 10 min average windspeeds 15–18 m/s, the acceleration of the tower without TLD exceeded the ISO minimum perception range at 0.55 Hz[12] for 36% of the sample length. The acceleration with TLD exceeded only 1%. *Figure 10* compares the time series of across-wind responses of the tower with and without TLD. Broken lines indicate the ISO minimum perception level[12]. If one wants to see how often the time series of the wind-induced vibration of the building exceeds the perception threshold, it is better to compare the results in terms of the amplitude. However, the ISO perception levels are defined in terms of RMS values. As is well-known, almost all data on human perception thresholds were obtained experimentally for sinusoidal steady-state vibrations, so was the data source for the ISO. Therefore, the ISO minimum perception level was converted to the amplitude by multiplying by √2. This value corresponds to the acceleration level where 5% of people can perceive the vibration[13]. *Figure 10* clearly proves the improvement in habitability for the tower by the TLD.

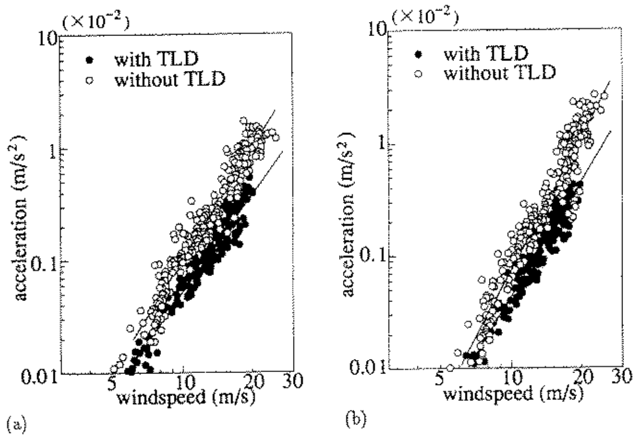


Figure 9 Comparisons of RMS acceleration responses of YMT with/without TLD. (a) along-wind; (b) across-wind

4. Full-scale measurement at Shin-Yokohama Prince Hotel[14]

4.1. Shin-Yokohama Prince Hotel (SYPH)

The SYPH was constructed in 1992 at a site very close to the Shin-Yokohama Station of the New Tokaido Line (Shinkansen). *Figure 11* shows the vertical section of SYPH. The building is a cylindrical structure with a height of 149 m and a diameter of 38.2 m. The information on SYPH is tabulated in *Table 1*. The fundamental generalized mass M_{S1} is estimated to be 10.5×10^6 kg.

4.2. TLD installed on SYPH

The TLD was installed on the roof floor of SYPH in March 1992. The TLD is an assembly of 30 cylindrical multilayered vessels with a 2 m diameter and about 2 m height. The vessel is divided into nine layers at every 0.22 m. Each

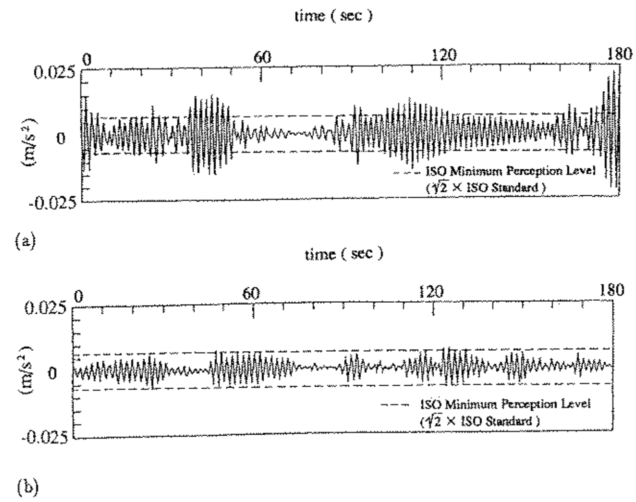


Figure 10 Comparison of time series of across-wind acceleration responses of YMT with/without TLD. (a) without TLD; (b) with TLD

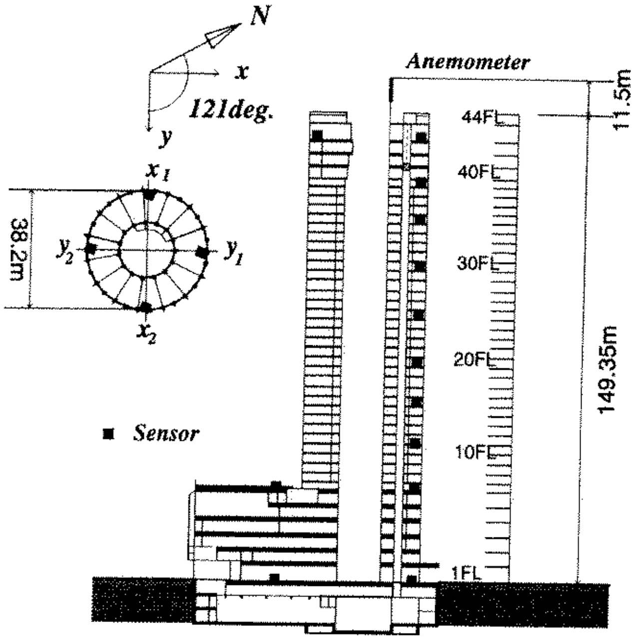


Figure 11 Shin Yokohama Prince Hotel (SYPH)

layer contains only water, but has 12 protrusions to preclude the swirling motion and to obtain additional energy dissipation in the vessel. The outlines of the vessel are shown in *Figure 12*. Based on a series of experimental and theoretical studies, the number of vessels, the sloshing frequency etc. were decided. The water depth of 0.124 m in each layer is required to be tuned to the lowest natural frequency of the tower. The total water mass (101.7×10^3 kg, see *Table 2*) is 1% of the fundamental generalized mass of the tower. The damping ratio of the damper itself ζ_D, calculated by modelling the TLD as a tuned mass damper (TMD), was expected by experimental studies to be optimal in the range of acceleration 0.02–0.03 m/s^2.

Figures 13a and *b* show the arrangement of the vessels at the top of the building.

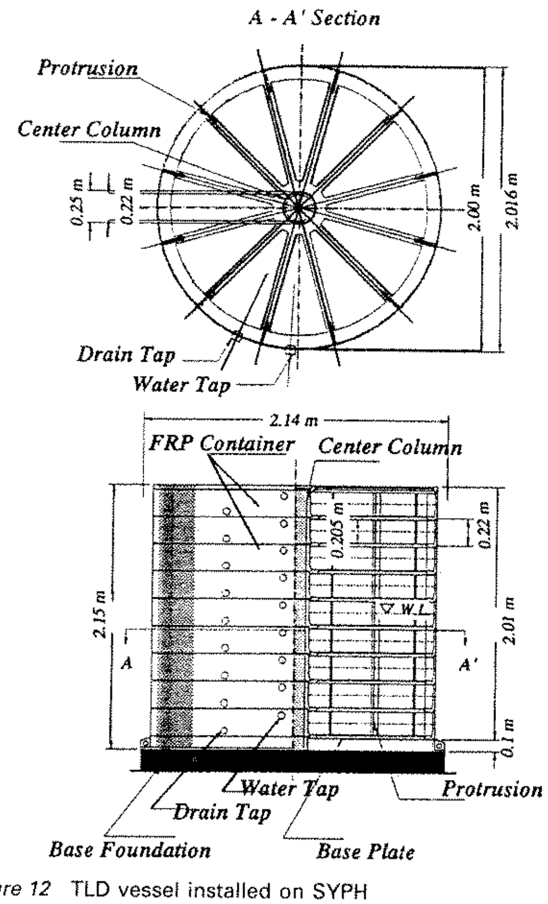


Figure 12 TLD vessel installed on SYPH

4.3. *Measurement systems for SYPH*

An anemometer was mounted on the building at 160 m above ground level, and four servo-type accelerometers were installed on the top floor as shown in *Figure 11*. In order to detect the dynamic characteristics of the building, microtremors were measured by additional accelerometers placed on nine other floors. The type of the accelerometers is the same as for the YMT. The data were sampled every 0.05 s and averaged in 600 s.

4.4. *Dynamic characteristics of SYPH without TLD*

The fundamental natural frequencies obtained from microtremors and the damping ratio obtained by run-down tests were presented in *Table 1*. The natural frequency of the 2nd translational mode bending (x-direction) was found to be 1.00 Hz. Significant directional differences were not found.

4.5 *Efficiency of TLD on SYPH*

Figures 14a and *b* show the comparisons of the acceleration trajectories of the building with and without TLD in almost the same wind conditions, i.e., both mean wind directions were SSW and the 10 min average mean windspeeds were 25.8 m/s and 25.9 m/s. *Figure 14a* without TLD shows the large across-wind responses, but *Figure 14b* represents the significant reduction of amplitudes in both along- and across-wind.

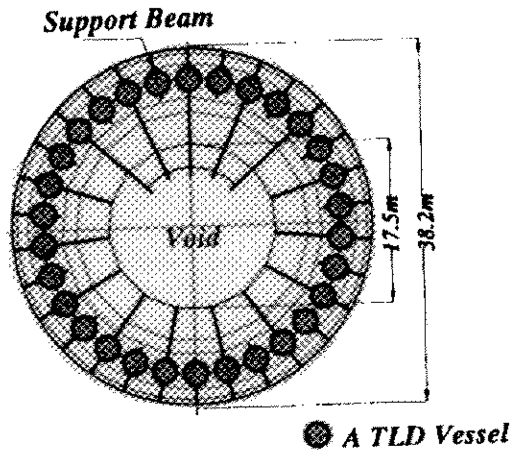
Figures 15a and *b* also show the comparisons of the RMS accelerations for along-wind and across-wind components, respectively. Open circles indicate the response without TLD, and solid with TLD. The efficiency of the TLD is clearly confirmed from the regression lines. With the windspeed range higher than 25 m/s, a reduction of almost 50% of the acceleration response was achieved. The tendency to become more effective in higher windspeeds is one of the common features of the TLD with water. This is explained as follows: the energy dissipating ability of water in a low amplitude regime is not sufficient, but it increases with the amplitude, thus becoming close to the optimum value.

The one-year-recurrence windspeed V_1 is estimated to be 26 m/s, and its RMS acceleration without the TLD is over 0.01 m/s^2. That with the TLD is reduced to less than 0.006 m/s^2, which is the ISO minimum perception level[12] at 0.31 Hz.

5. Full-scale measurements at the Tokyo International Airport Tower[9]

5.1. *Tokyo International Airport Tower (TIAT)*

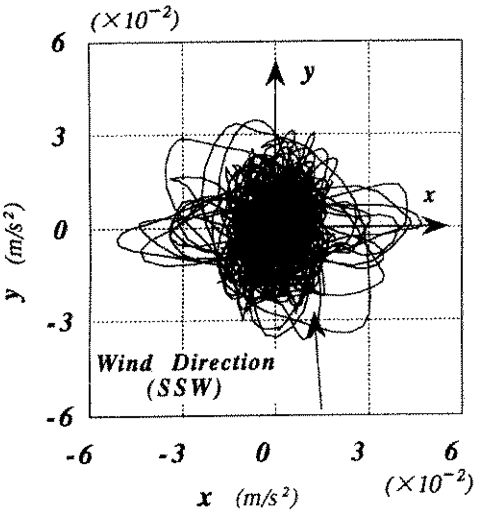
The Tokyo International Airport was constructed in 1993 and a new air-traffic control tower was built in 1992. It is located in the Tokyo Bay area. The air-traffic control tower is 77.6 m high with a mass of 3.24×10^6 kg (see *Table 1*). The air-traffic control room near the top of the tower is



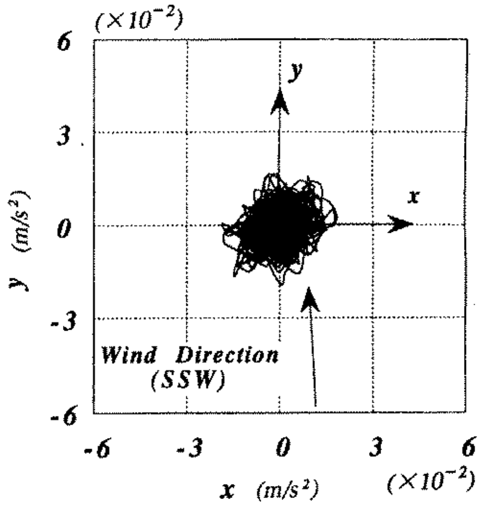
(a)

(b)

Figure 13 Arrangements of TLD on SYPH. (a) plan of roof floor; (b) photo of vessels installed



(a)



(b)

Figure 14 Comparison of acceleration trajectories of SYPH with/without TLD. (a) without TLD (SSW, $V = 25.8$ m/s); (b) with TLD (SSW, $V = 25.9$ m/s)

supported by two huge vertical shafts as shown in *Figure 16*. The vibration of the tower is dominant in the x-direction, i.e., perpendicular to the spanwise direction of the shafts, and our main focus for vibration control was centred on this direction.

5.2. *TLD installed on TIAT*

The TLD was installed in a room of the tower in January 1993. The TLD is an assembly of about 1400 vessels containing water, floating particles and a small amount of preservatives. The vessel is a shallow circular cylinder with a 0.60 m diameter and a 0.125 m height as shown in *Figure 17*. An injection tap and handles are put as projections, and four conical dents on both the upside and the base. Those projections and dents, together with the surface irregularities, provide additional stiffness for standing up to long-term installation in stacks, and give easy access to changing the water, vessel setting and inspection for maintenance. The vessels were made of polyethylene and manufactured in a large quantities at a very low cost by blowing the materials into a mold.

The three-layered shelves made of steel frames were placed from the floor to the ceiling in a space with a height of 4.35 m and a 6.3 m × 12.73 m plan, with aisles remaining for maintenance. The vessels were closely packed being piled up in six layers on each shelf as shown in *Figure 18*. The floor of the TLD room has not been waterproofed and eight water leak sensors have been installed in it.

The vibration control was intended for the x-direction, and the TLD was tuned to the natural frequency of this direction. The tuning of the sloshing frequency was based on the measured natural frequency after completion of the tower. The water contained in a vessel is 14.9 kg, and the height of the water is 0.053 m. The total mass of the TLD,

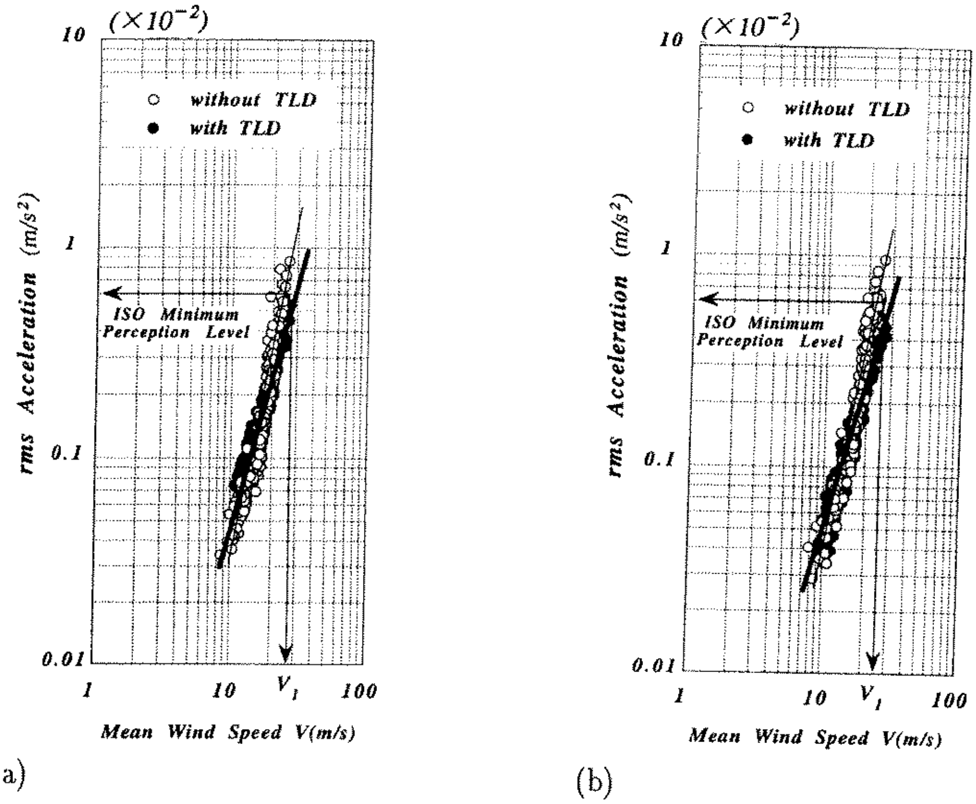


Figure 15 Comparison of RMS acceleration responses of SYPH with/without TLD. (a) along-wind; (b) across-wind

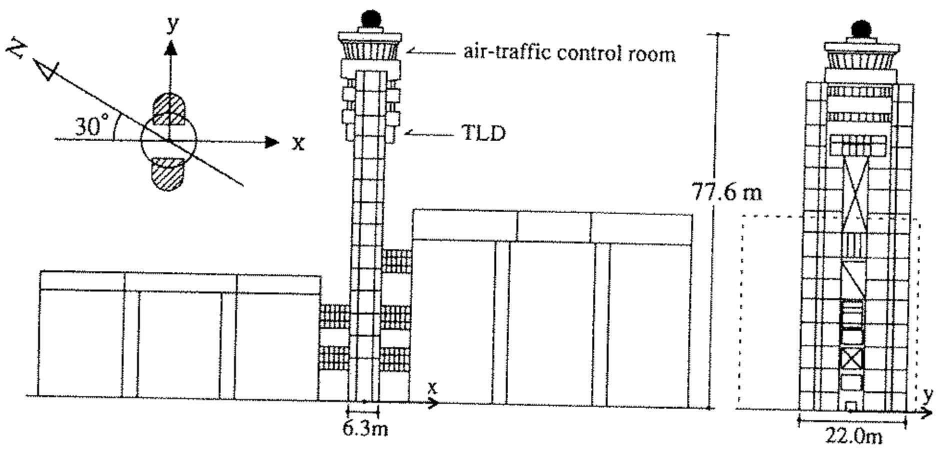


Figure 16 Tokyo International Airport Tower (TIAT)

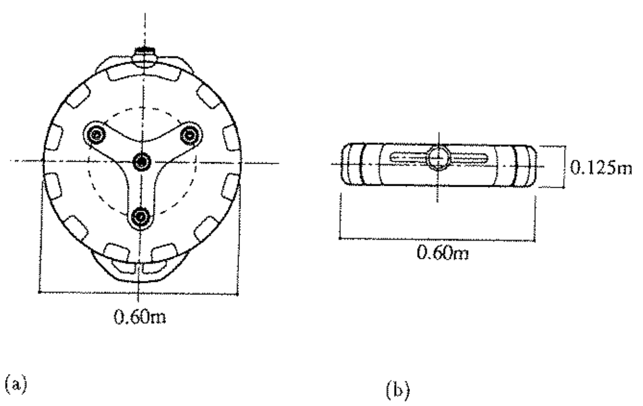


Figure 17 TLD vessel installed on TIAT. (a) plan; (b) elevation

which is the sum of water and floating particles (22.7×10^3 kg, see *Table 2*), is 3.5% of the fundamental generalized mass of the tower for the x-direction. The fundamental natural frequency of the sloshing motion was estimated at 0.74 Hz theoretically. This sloshing frequency of 0.74 Hz is slightly lower than the natural frequency of the tower for the x-direction, i.e. 0.77 Hz (see *Table 1*), and is almost equal to the optimum natural frequency of the damper, evaluated as 0.743 Hz by the well-known TMD theory. It should be noted that the sloshing frequencies of the TLDs in all the other examples were also slightly smaller than the lowest natural frequencies of the buildings.

In order to optimize the energy dissipation inside the vessels, floating hollow cylindrical polyethylene pieces (mass density 0.8, outside diameter 8 mm, wall thickness 0.8 mm and length 10 mm) were added. An increase in surface area together with collisions between particles resulted in higher

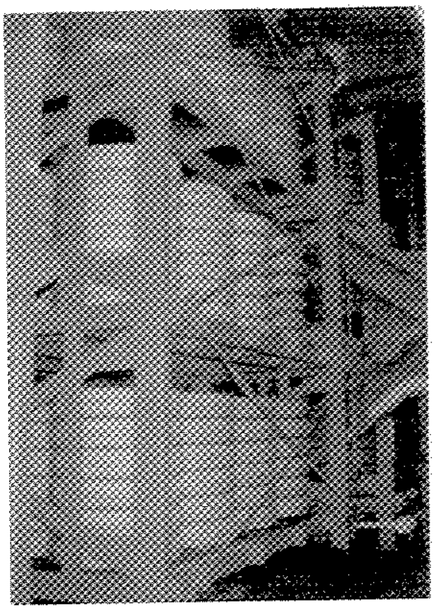


Figure 18 Installation of vessels in TLD room on TIAT

damping. The rate of dissipation can be controlled by the number of floating elements met with the optimum value from the TMD theory[8]. A small amount of minerals (Clinka) were added to the vessels as preservatives. The exposure experiments for more than a year suggested that severe problems due to decomposition or mosses might not occur. The preservatives were adopted as a precaution so that the water was suitable for human use after a severe disaster.

5.3. *Measurement systems for TIAT*

Full-scale measurements of the wind-induced responses of the tower were conducted over 13 months: from August 1992 to January 1993 without TLD, and from February 1993 to August 1993 with TLD.

Three velocity transducers were set on the floor of the air-traffic control room. Two of them were set at the geometrical centre of the circular plan of the control room to detect the translational motions of the x- and y-directions. Another one for torsional motions was set 4 m away from the centre. Servo-type velocity transducers were used. The used transducers showed very good performance (S/N, noise and stability), and were appropriate for the long-term automatic measurement. According to the results of our own tests conducted beforehand, the frequency components higher than 0.1 Hz could be measured sufficiently well. The transducers can also measure accelerations and displacements by the differentiation and integration in the electrical circuits.

The windspeed and wind direction were measured at 10 m above the runway field, located 1.7 km WNW of the tower. All data were sampled every 0.05 s. The strong wind observation started when the mean windspeed or acceleration response exceeded a specified trigger value.

5.4. *Dynamic characteristics of TIAT without TLD*

Figure 19a shows an example of damped-free oscillations of the tower without TLD, which were obtained after the sudden stopping of man-made excitations. The measurements of the damped-free oscillations were made three times, and the evaluated average damping ratios for the x- and y-directions were 0.84% and 1.24%, respectively.

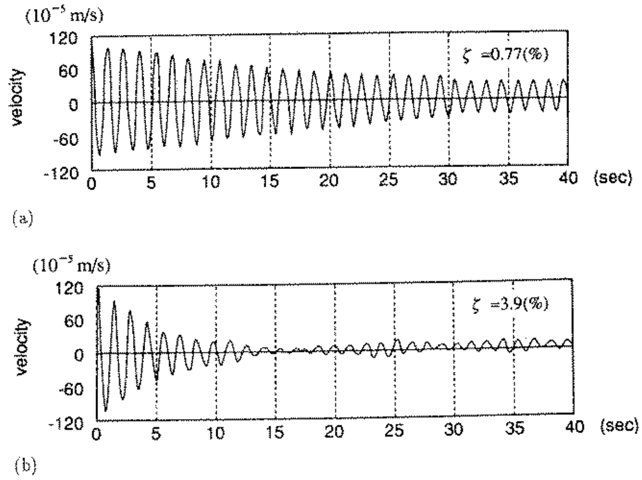


Figure 19 Examples of damped-free oscillations of TIAT by run-down tests (x-direction). (a) without TLD, (b) with TLD

The damping ratios of the tower without TLD during strong winds were also evaluated by the RDT[9]. *Figure 20a* shows an example of damped-free components, which was extracted from a 1 h acceleration record by the RDT. The vibration of the x-direction always predominated in any wind direction as was expected at the design stage.

The six month full-scale measurements of wind-induced responses of the tower without TLD provided valuable information on the dynamic characteristics of the tower under wind excitation. As demonstrated in Reference 9, the natural frequencies decrease with vibration amplitude, while the damping ratios increase considerably with amplitude. This nonlinearity of the dynamic characteristics cannot necessarily be ignored in the design of damping devices.

5.5. *Efficiency of TLD on TIAT*

A result of the run-down tests with TLD is shown in *Figure 19b*. The evaluated damping ratio was 3.9%. The damping ratio increased up to around 4.5 times due to the TLD installation, thus the effect of the TLD is both significant

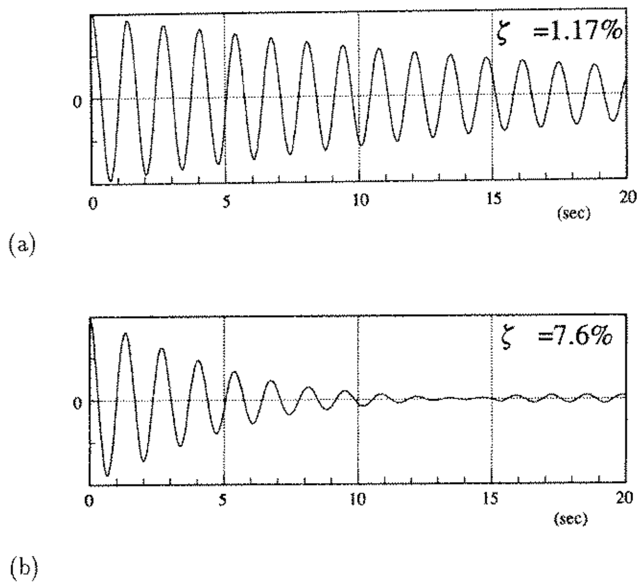


Figure 20 Examples of damped-free oscillation components of TIAT under wind excitations abstracted by RDT (x-direction). (a) without TLD; (b) with TLD

and satisfactory. The beat phenomena was observed after the initial vibration ceased, but is very small. This suggests that both the tuning of the sloshing frequency and the adjustment of the energy dissipating ability by the floating particles were quite appropriate.

Next, the damping ratio of the tower with TLD evaluated during strong winds will be discussed. Wind-induced responses of the tower with TLD observed during 24 h, i.e. from 0:00 to 24:00 on 29 March 1993, are presented here. A storm passed near the site, and the maximum instantaneous windspeed was recorded at 25 m/s. The strong wind began at about 8:00 a.m. and increased to its maximum between 2:00 p.m. to 3:00 p.m., then ceased in the late evening.

The equivalent viscous damping ratio of the tower with TLD was also evaluated by the RDT. This technique is appropriate only to a system with well-separated natural frequencies as mentioned previously. In the case of the TIAT, the damping ratio of the sloshing motion ζ_D was increased up to almost 6% due to the floating particles, and the beat phenomena did not appear on the damped-free oscillations in *Figure 19b*. Two-mode interactions of a two-degree-of-freedom system, consisting of the tower and TLD, were presumed to be very small and the RDT was applied. The time averaging type superimposition was made for each 1 h record. An example of a damped-free oscillation component extracted by the RDT is shown in *Figure 20b*.

The temporal variations of the evaluated damping ratios by the RDT are shown in *Figure 21*, together with the RMS acceleration of the tower for each 1 h period. The damping ratios before 8:00 a.m. were almost 1% for both the x- and y-directions, but they began to increase when the RMS acceleration exceeded 0.0005 m/s^2. The increase of the damping ratio is significant for the x-direction, for which the TLD was tuned. The damping ratio of the x-direction reached the maximum value of 7.6% before the RMS acceleration recorded the maximum. Then it reduced with the decrease of the RMS acceleration to the initial value of 1% for the low amplitude regime. For the range of data obtained, the damping ratio of the x-direction tends to increase with the amplitude as shown in *Figure 22*, and the efficiency of the damper is very significant. However, that of the y-direction does not seem to be affected much by the TLD.

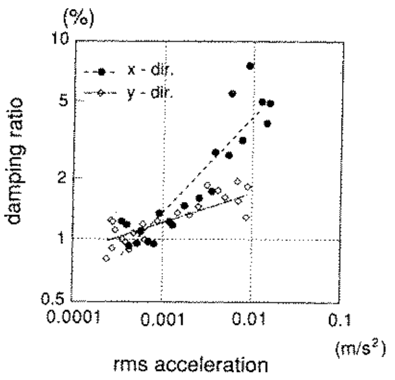


Figure 22 Variations of damping ratio of TIAT with amplitude under wind excitations (with TLD)

Figure 23 shows the comparisons of the x-direction RMS accelerations of the TIAT with and without TLD. The TLD reduced the response to around 60% of the RMS acceleration response of the tower without TLD.

6. Discussion

The measurements of the responses of the four buildings were made with the tip mean windspeed lower than 30 m/s. Since the main purpose of the TLD for all the cases was to improve the buildings' habitability for daily winds, it can be said that the object of the full-scale measurements has been accomplished. However, the efficiency of the TLD at higher amplitudes is also of interest.

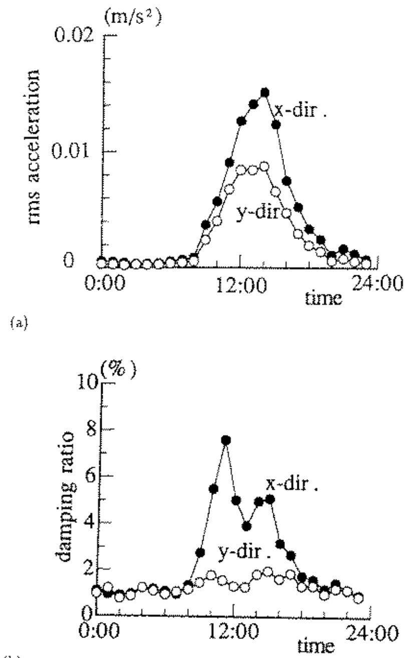


Figure 21 Temporal variation of RMS acceleration and damping ratio of TIAT in a day (with TLD, 29 March 1994). (a) RMS acceleration; (b) damping ratio

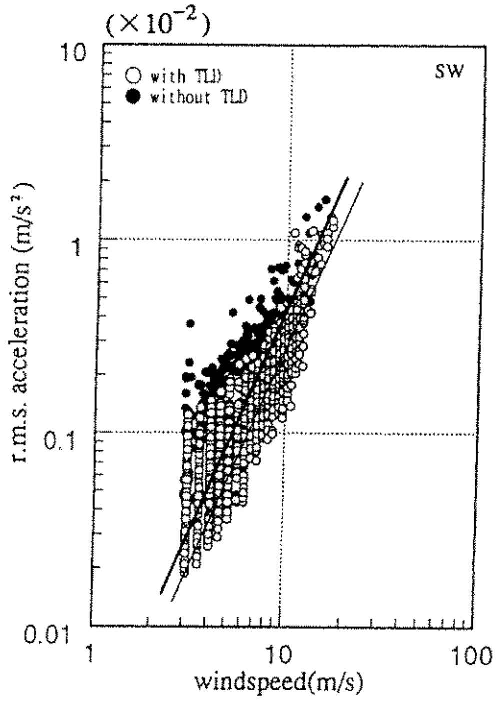


Figure 23 Comparisons of RMS acceleration responses of TIAT with/without TLD (x-direction, ≈ across-wind)

In the cases of the NAT, YMT and SYPH, the vessels contain only water and the damping of the sloshing motion is smaller than the optimum value implied by the TMD theory. According to our laboratory experiments, the damping of the sloshing motion increases significantly with the amplitude of vibration. When the optimal value of the amplitude is reached, the most efficient performance of the TLD is achieved. The regression lines in *Figures 6, 9* and *15* imply that the reduction of the responses becomes larger at higher windspeeds and the optimum performance may be realized at a higher windspeed, beyond the range of the measurements. As mentioned earlier, experimental studies have predicted that the optimum damping of the TLD for the SYPH will be realized at a building acceleration amplitude of 0.02–0.03 m/s^2.

In the case of TIAT, the damping ratio of the sloshing motion was set at about 6% by adjusting the amount of floating particles. This damping value was estimated to be optimal for the mass ratio, μ_1, equal to 1%. However, more space became available and more TLD vessels were installed. The mass ratio increased to 3.5% of the fundamental generalized mass (see *Table 2*), and the optimum damping ratio was estimated to be 11%. To achieve this value, more particles need to be added to each vessel. Nevertheless, the amount of floating particles was not increased. At high amplitude of motion the damping of the sloshing becomes closer to the optimum value, and the equivalent total structural damping ratio of the TIAT increased with amplitude as shown in *Figures 21* and *22*. As is inferred in *Figure 22*, the optimum damping is achieved at an acceleration of around 0.01 m/s^2. The reduction rate of the response of the TIAT due to the TLD is almost constant, independent of windspeed as shown in *Figure 23*. This feature is different from the other three cases.

The vessels for the YMT, SYPH and TIAT have a capacity of almost twice the contained water volume, but the vessels used temporarily at the NAT had a relatively smaller capacity. The clearances between water surface and the vessel ceiling were 0.022 m, 0.029 m, 0.103 m and 0.072 m for the NAT, YMT, SYPH and TIAT, respectively. If neither broken waves nor water collisions with the vessel ceiling occur, the response of the building and the efficiency of the TLD can easily be predicted. In the experimental study of the TLD for the SYPH, for example, the water collision with the ceiling was observed when the steady-state vibration amplitude reached 0.08 m/s^2. The TLD is expected to become inefficient at vibration amplitudes higher than 0.08 m/s^2. However, the vibration level of 0.08 m/s^2 is very high for the wind-induced vibration of the SYPH, as indicated in *Figure 15*.

The efficiency of the TLD mainly depends on both the mass ratio of the water to the building and the damping ratio of the sloshing motion. In general, the ratio of the mass of TLD or TMD to the fundamental generalized mass is set at around 1%. A larger mass ratio provides more damping in the building if the damping of the sloshing motion is kept optimal. The vessel configuration affects the damping of the sloshing motion. The damping of the sloshing is also easily controlled by the floating particles, baffles, nets and other means, and need not be controlled by the configuration. The vessel configuration and the number of vessels might be decided according to the installation conditions and cost. In the four cases presented in this paper, there is no relation between the configuration and mass ratio.

The reduction of the wind-induced responses of the TIAT, which is equipped with the TLD of the largest mass ratio (see *Table 2*), is around 40% as can be seen from the regression lines in *Figure 23*. According to the damping ratio indicated in *Figure 22*, more than 50% reduction of the response is expected. However, the use of the largest mass ratio did not result in a higher reduction rate. This is assumed to be due to the TLD room elevation. The TLD for the TIAT was installed on a floor located almost three-quarters towards the top of the tower, while the TLDs for the other three cases were installed at the roof or on floors near the top.

Conclusions

The results of full-scale measurements of the four buildings with and without TLD, conducted by the authors, have been reviewed. The TLD have also been installed on other buildings, e.g. the 87.3 m high airport tower at the New Tokyo International Airport (Narita) by some of the authors. All the results of the full-scale measurements prove that the TLD is not only efficient, but performs excellently. Generally, the TLD could reduce the acceleration responses during strong winds down to 1/2–1/3 of the response without the TLD, when the water mass ratio to the total mass of buildings was around 1/350–1/150. Then, vibration perceived by occupants was significantly reduced, and the habitability and serviceability of buildings were considerably improved.

There have not been any reports of problems such as leakage of water or discomfort experienced by the occupants.

The full-scale data also represented the considerable nonlinearity of the dynamic characteristics of buildings. This can be a quite important problem for the design of passive/active damping devices.

Acknowledgments

The authors would like to thank the owners of the buildings studied herein, for giving us the opportunity to measure the wind-induced responses. They would also like to thank Prof. V. J. Modi of the University of British Columbia for his useful suggestions and comments on the design of the TLD for the TIAT.

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0141-0296/95 $10.00 + 0.00

0141–0296(95)00032-1

Chain dampers for control of wind-induced vibration of tower and mast structures

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This paper outlines the operation of hanging chain impact dampers and their use in reducing vibration amplitudes of tower and mast structures due to wind excitation. Hanging chain dampers are employed inside towers to increase their structural damping, thus reducing the amplitude of forced vibration and reducing the possibility of structural damage. Four case histories are examined which detail the design of individual chain dampers.

Keywords: hanging chain impact dampers, vibration, wind excitation

1. Introduction

When wind acts on a mast at the critical velocity, which occurs when the vortex shedding frequency and the natural frequency of the mast coincide, the tower will be forced into large amplitude vibration if the inherent damping is low. The amplitude of the resulting cross-wind vibration will depend on the amount of damping existing in the structure. Large amplitudes of vibration can generate cracking of joints and welds in the short term and fatigue in the long term. For such cases, where the oscillation is essentially in one plane, the addition of a simple hanging chain impact damper will increase the structural damping, reduce the vibration amplitude and prevent structural damage.

The theory and experimental verification of the use of hanging chain dampers (HCD) to reduce vibration of tall flexible structures has been given by Reed[1]. A hanging chain damper consists of a chain hung from the top of a vibrating structure and as the structure moves the amplitude of motion of the free end of the chain increases (see *Figure 1*). If the amplitude becomes sufficiently large an impact occurs between the chain and the structure and if the chain is enclosed in a cylinder, of specific diameter, more than one impact per cycle of vibration can occur. The impact occurs not only at the free end but also along most of the length of the chain as the vibration becomes more severe. The effective damping provided by a hanging chain damper is thus dependent on many variables which can be grouped as dimensionless pi products as explained below. If the tower is circular and narrow enough in diameter then the chain can be hung directly in the tower, otherwise a cylinder has to be inserted in the tower in which the chain is hung.

Two energy dissipation mechanisms exist in the operation of an HCD, firstly, the energy loss due to the inelastic impact of the chain against the wall of the cylinder; and secondly, the internal friction of the chain links rubbing against each other. The impact mechanism, when optimum, provides an equivalent viscous damping coefficient between five to ten times greater than that given by the friction due to the rubbing of the chain links. Different

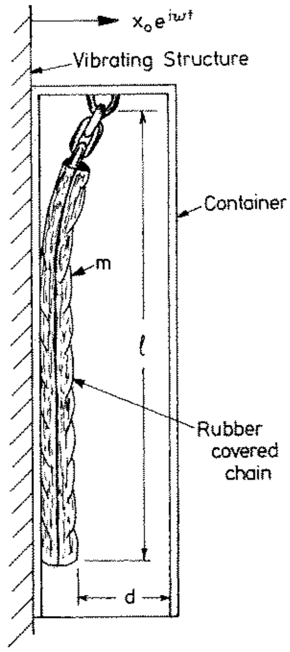

Figure 1 Hanging chain damper configuration. Container is referred to as a cylinder in text of this paper (taken from Figure 1 in Reference 1)