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Use of TLD and MTLD for Control of Wind-Induced Vibration of Tall Buildings

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Excessive acceleration experienced at the top floors in a building during wind storms affect the serviceability of the building with respect to occupant comfort and discomfort. Tuned liquid damper (TLD) and multiple tuned liquid damper (MTLD), which are passive control devices consisting of a rigid tank filled with liquid, are used to suppress vibration of structures. These TLD and MTLD offer several potential advantages - low costs, easy installation in existing structures and effectiveness even for small-amplitude vibrations. This study carries out a theoretical estimation of the most effective damping ratios that can be achieved by TLD and MTLD. Damping by TLD an MTLD reduced the frequency response of high-rise buildings by approximately 40% in urban and suburban areas.

Key Words : Serviceability, Tuned Liquid Damper, Multiple Tuned Liquid Damper, Passive Control Device

1. Introduction

Because tall buildings are vulnerable to certain vibrations, researchers have studied various methods of vibration response reduction of tall buildings. Certain methods that modify the shape and change the dynamic characteristics of tall buildings reduce the vibration responses of tall buildings. One method changes the air flow patterns around buildings by producing a pathway, which induce air flows around tall buildings. These pathways minimize wakes that are produced at the back side of a building and thus, reduce vibration responses of the building. Another method controls the dynamic characteristics of tall buildings, such as mass (m), stiffness (k), and damping (c) to configure a desirable vibration response level. However, these methods require extremely high costs and present many limitations shapes. The control technology of building vibrations without any changes in building shape and its dynamic characteristics has been extensively studied. This control technology reduces vibration responses of buildings by installing additional masses. In relation, TLD (tuned liquid damper) and TMD (tuned mass damper), which are types of manual vibration control devices, have been widely studied as well. A TLD is not limited by an installation space and has several advantages over a TMD in terms of costs, easy control ability of the natural frequency

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of a building, and operation performance for certain low additional vibrations. In a TLD related study, Modi and Welt proposed the application of a tuned liquid damper (TLD), which has been used to eliminate vibrations in artificial satellites and ships, in 1987. In 1990, Kareem determined that a TLD could reduce vibrations by about 30~40% for tall buildings subjected to wind load. Noji et al. (1988). verified the applicability of a TLD, which has the deep depth of water, through various, actual field tests. The data obtained from these field tests were used to increase the damping ratios of TLD, in 1991. Fujino and Sun performed a fluid mechanical study of TLD, which suppresses the horizontal motion of a building, in 1992 and verified vibration reduction effects of a MTLD by analyzing the vibration levels of STLD and MTLD in 1993. The majority of studies suggested optimized damping ratios and frequency ratios for control devices. A few studies applied the wind tunnel test results to buildings. Because these studies revealed limited options for terrain categories, the present study verified the effect of damping on the frequency response of high-rising buildings constructed in urban and suburban areas.

2. Characteristics of a Tuned Liquid Damper

This section investigates the effect of a TLD according to the mass ratio between structures and TLD, frequency ratios, and damping ratios by using the frequency responses functions.

2.1 Frequency responses of an equivalent TMD-structure

When vibration is dependent on wind conditions, the main response type of tall buildings is a 1st mode. A matrix function for the vibration equation of an equivalent TMD-structure system (Kareem, 1990 ; Chen, 1995 ; Wakahara, 1998) can be expressed as Eq. (1)

$$\begin{bmatrix} M_s & 0 \\ m_t & m_t \end{bmatrix}\begin{bmatrix} \ddot{y}_s \\ \ddot{y}_t \end{bmatrix}+\begin{bmatrix} C_s & -c_t \\ 0 & c_t \end{bmatrix}\begin{bmatrix} \dot{y}_s \\ \dot{y}_t \end{bmatrix}+\begin{bmatrix} K_s & -k_t \\ 0 & k_t \end{bmatrix}\begin{bmatrix} y_s \\ y_t \end{bmatrix}=\begin{bmatrix} F_w \\ 0 \end{bmatrix} \quad (1)$$

where

M_s, C_f, K_s : Mass, Damping, Stiffness of Structure
m_t, c_t, k_t : Mass, Damping, Stiffness of TLD
F_w : Exciting force

In Eq. (1) if $F_w=e^{iwt}$, Eqs. (2) and (3).

$$M_s\ddot{y}_s+C_s\dot{y}_s-c_t\dot{y}_t+K_sy_s-k_ty_t=e^{iwt} \quad (2)$$

$$m_t\ddot{y}_t+c_t\dot{y}_t+k_ty_t=-m_t\ddot{y}_s \quad (3)$$

In Eq. (2), if $y_s=H(w)e^{iwt}$, Eqs. (2) and (3) can be denoted as Eqs. (4) and (5).

$$\begin{aligned} &M_s(-w^2)H(w)e^{iwt}+C_s(iw)H(w)e^{iwt} \\ &+K_sH(w)e^{iwt}-c_t\dot{y}_t-k_ty_t=e^{iwt} \end{aligned} \quad (4)$$

$$m_t\ddot{y}_t+c_t\dot{y}_t+k_ty_t=m_tw^2H(w)e^{iwt} \quad (5)$$

In Eq. (5), if $m_tw^2H(w)=A$, it can be expressed as Eq. (6).

$$m_t\ddot{y}_t+c_t\dot{y}_t+k_ty_t=Ae^{iwt} \quad (6)$$

Eq. (7) can be obtained by calculating Eq. (6) for $y_t=\bar{H}(w)Ae^{iwt}$

$$\begin{aligned} &m_t(-w^2)\bar{H}(w)Ae^{iwt}+c_t(iw)\bar{H}(w)Ae^{iwt} \\ &+k_t\bar{H}(w)Ae^{iwt}=Ae^{iwt} \end{aligned} \quad (7)$$

On both sides of Eq. (7), Eq. (8) can be obtained by deleting Ae^{iwt}.

$$m_t(-w^2)\bar{H}(w)+c_t(iw)\bar{H}(w)+k_t\bar{H}(w)=1 \quad (8)$$

$\bar{H}(w)$ can be obtained as Eq. (9) by using Eq. (8).

$$\bar{H}(w)=\frac{1}{k_t\left(1+2\zeta_i i\frac{w}{w_t}-\frac{w^2}{w_t^2}\right)} \quad (9)$$

where

ζ_t : Damping of TLD

Eq. (10) can be obtained by substituting Eq. (9) to $y_t=\bar{H}(w)Ae^{iwt}$

$$y_t=\bar{H}(w)Ae^{iwt}=\frac{1}{k_t\left(1+2\zeta_i i\frac{w}{w_i}-\frac{w^2}{w_t^2}\right)}Ae^{iwt} \quad (10)$$

Eq. (11) can be obtained by substituting Eq. (10) to Eq. (2).

$$\bar{H}(w)=\frac{1}{M_s w_s^2\left(\left[1-\left(\frac{w}{w_s}\right)^2+2\zeta_s i\left(\frac{w}{w_i}\right)\right]-\frac{w^2}{w_s^2}\frac{m_t}{M_s}\left[\frac{1+2\zeta_i i\left(\frac{w}{w_i}\right)}{1-\left(\frac{w}{w_t}\right)^2+2\zeta_i i\left(\frac{w}{w_t}\right)}\right]\right)} \tag{11}$$

When MTLD is used, the equation can be expressed as Eq. (12).

$$\bar{H}(w)=\frac{1}{M_s w_s^2\left(\left[1-\left(\frac{w}{w_s}\right)^2+2\zeta_s i\left(\frac{w}{w_i}\right)\right]-\frac{w^2}{w_s^2}\sum\frac{m_t}{M_s}\left[\frac{1+2\zeta_i i\left(\frac{w}{w_i}\right)}{1-\left(\frac{w}{w_t}\right)^2+2\zeta_i i\left(\frac{w}{w_t}\right)}\right]\right)} \tag{12}$$

Tuning ratio is the ratio for the natural frequency of a TLD between the mass ratio, which can be determined by the structure's mass and TLD's mass, and the natural frequency of a structure. This tuning ratio can be expressed (Wakahara, 1998) as Eq. (13).

$$\text{Mass ratio}: \frac{m_t}{M_s}=\mu \tag{13a}$$

$$\text{Tuning ratio}: \frac{w_t}{w_s}=\gamma \tag{13b}$$

In the natural frequency of water $w_t=(2\pi f_t)$, the natural frequency that corresponds to the 1st mode can be expressed as Eq. (14) according to the type of water tank, such as a rectangular or cylindrical tank.

The natural frequency of a TLD rectangular water tank is

$$f_t=\frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\left(\frac{\pi h}{L}\right)} \tag{14a}$$

Where

L : Length of tank
h : Height of water in the rectangular tank
g : Acceleration of gravity

The natural frequency of a TLD circular water tank is

$$f_t=\frac{1}{2\pi}\sqrt{\frac{1.841g}{R}\tanh\left(\frac{1.841h}{R}\right)} \tag{14b}$$

Where

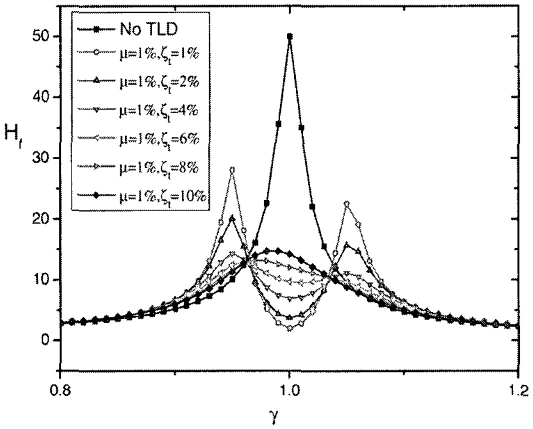
R : Radius of a circular tank
H : Height of the water in the circular tank
g : Acceleration of gravity

2.2 Frequency response functions of a STLD

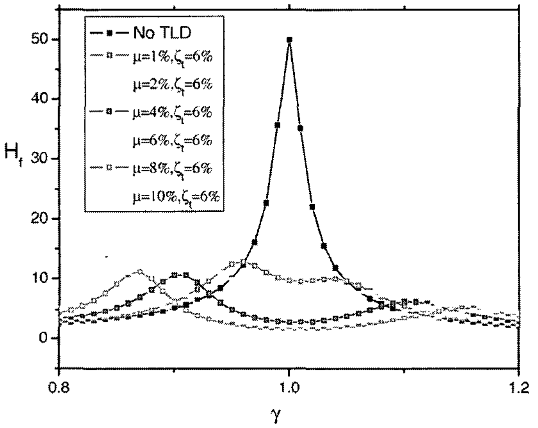
Figure 1 presents the changes in the damping ratio and mass ratio of a TLD obtained by using Eq. (11). Fig. 1(a) presents the frequency response graph according to the change in the damping ratio of a TLD for 1% fixed mass ratio. The values of the frequency response function decreased with the increase in the damping ratio of the TLD. There were two peaks at the frequency ratios of 0.95 and 1.05 up to the low damping ratio, such as 4%. A single peak was presented up to the TLD's damping ratio of 6%~10%. The values of the frequency response function increased at the TLD's damping ratios of 8% and 10% more than that at the damping ratio of 6%. Fig. 1(b) presents the analysis of frequency response according to mass ratio for the fixed damping ratio of 6%. In the case of the low mass ratio, the peak was presented around the frequency ratio of 1, but the peak occurred at a low frequency ratio according to the increase in the mass ratio.

2.3 Frequency response functions of MTLD

MTLD is preferred over STLD because it is more effective for controlling frequency: it responds to changes in natural frequency of structures more easily. But STLD has particularly difficult to match with the natural frequency of a structure because of water sloshing. However, the use of MTLD does not mean that a single natural frequency is available for every TLD. If MTLD consists of 3 TLDs, three different frequencies (0.95 Hz 1 Hz, 1.05 Hz, etc. for instance) are used to have variations. And only the central frequency (f_0) that represents these three frequencies needs to be interpreted. When MTLD is applied, the frequency response function can be produced by using Eq. (9). Fig. 2 shows a type of MTLD that applies several TLDs on a structure. These TLDs have their own natural frequencies. The central frequency (f_c), frequency width (ΔR), and frequency interval (β_j) of an MTLD can be defined (Fujino and Abe, 1993) by Eq. (15) as follows.



(a) Changes in the damping ratio of a TLD



(b) Changes in the mass ratio of a TLD

Fig. 1 Frequency response functions for the change in the damping ratio and mass ratio of a STLD ($\zeta_s=1\%$)

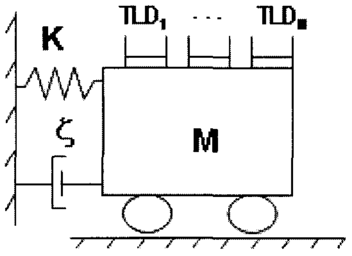


Fig. 2 MTLD

$$f_0=\frac{f_N+f_1}{2}\text{: central frequency} \qquad (15a)$$

$$\Delta R=\frac{f_N-f_1}{f_0}\text{: frequency band width} \qquad (15b)$$

$$\beta=(f_{i+1}-f_i)/(N-1)\text{: frequency spacing} \qquad (15c)$$

where

f_1 and f_N : lowest and highest of frequency

The characteristics of the frequency response according to the number of TLD, frequency width (ΔR), and tuning ratio ($\Delta\gamma$) can be expressed as follows. In the analysis, the reduction ratio of a structure and damping ratio of a TLD were assumed to be 1% and 2%, respectively. In addition, the mass ratio of a TLD was assumed to be 1%.

2.3.1 Number of TLD (N)

Figure 3 presents the frequency response functions for MTLDs. The frequency width and damping ratio were configured as and 1%, respectively, to analyze MTLD. A STLD presented 2 peaks at the frequency ratios of 0.95 and 1.05. The MTLD presented a single peak. The MTLD presented more effective results than the STLD. A small number of peaks were produced according to the

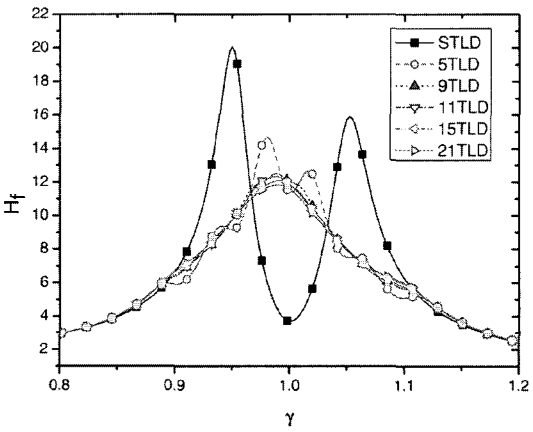


Fig. 3 Effect of MTLD

number of TLD. When 5 TLDs were used, 6 small peak frequency ratios were present in the region of 0.8～1.2. However, only one peak was produced around the frequency ratio of 1 for 9, 11, 15, and 21 TLDs. The effect of MTLD was not sensitive to the number of TLDs, when the number of TLD exceeded a specific number of TLDs.

2.3.2 Frequency bandwidth (ΔR)

The effect of MTLD according to vibration can vary because of the frequency width difference between the lowest and the highest vibration of the water tank, which was used in a TLD. Fig. 4 presents the characteristics of the frequency transfer function when the frequency widths of TLD are configured as $\Delta R=0.05(0.975\int_0^2 f_i/f_o<1.025)$, $\Delta R=0.1(0.95<f_i/f_o<1.05)$, $\Delta R=0.2(0.90<f_i/f_o<1.1)$, $\Delta R=0.4(0.8<f_i/f_o<1.2)$ and $\Delta R=0.5(0.75<f_if_o<1.25)$ for 21 TLDs. For $\Delta R=0.2$, and f_0 can be defined as $f_N=1.1\ f_0$, where f_0 is the vibration of the structure. For $\Delta R=0.1$, the peak was around the frequency ratios of 0.95 and 1.05, which were similar to those of the STLD. A single peak was present around the frequency ratio of 1.0 for $\Delta R=0.2$. For $\Delta R=0.5$, the peak location of the transfer function presented the largest value around the frequency ratio of 1.0, which was a larger value than that of the STLD. The values of $\Delta R=0.1$ and $\Delta R=0.2$ yielded better results than the value of $\Delta R=0.5$. The frequency width greatly affects the optimum effect of the MTLD rather more than the number of TLD does.

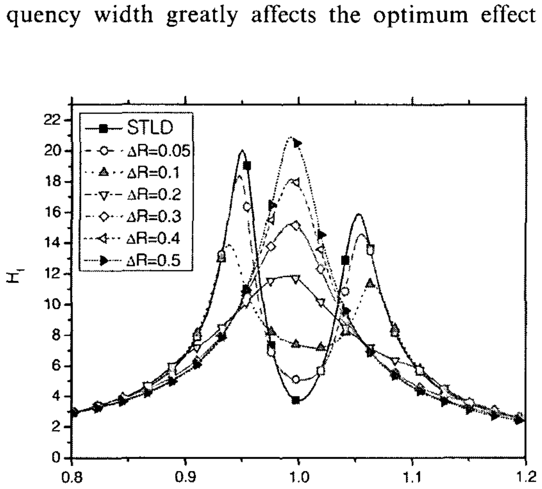
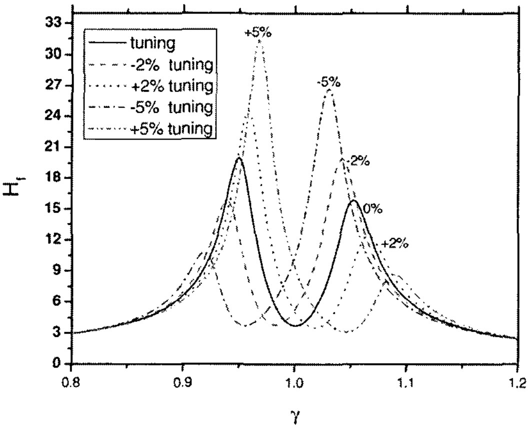


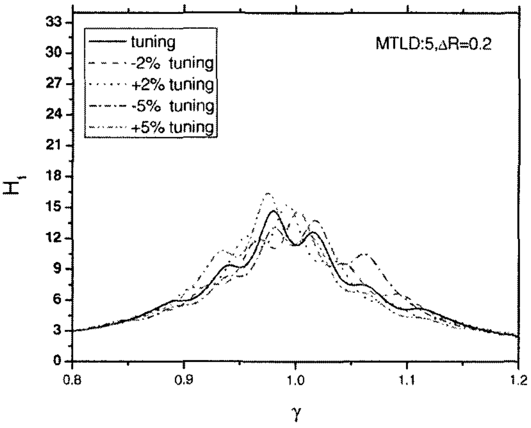
Fig. 4 Frequency bandwidth

2.3.3 off-tuning ratio ($\Delta\gamma$)

The TLD vibration is designed to tune with the natural frequency of a structure. However, off-tunings can occur sometimes due to various factors. This section investigates the MTLD effect at off-tuning. Therefore, a tuned case and an off-tuned case must be considered. Fig. 5(a) presents the response of a STLD structure under certain conditions of tuning and off-tuning. The values of the frequency response function increased according to the increase in the off-tuning ratio from 2% to 5%. In the case of the STLD, the frequency response function of a structure increased the most at the off-tuned condition. Fig. 5(b)



(a) STLD



(b) MTLD

Fig. 5 Off-tuning STLD and MTLD

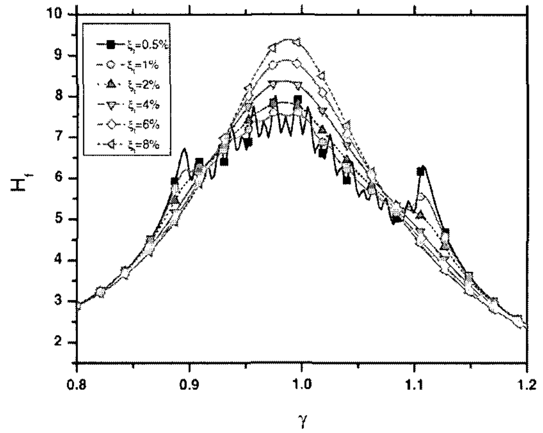


Fig. 6 Frequency response function for the change in the damping ratio of a TLD

presents the response of the MTLD at the frequency bandwidth of (ΔR=0.2).

2.3.4 changes in damping ratio

Figure 6 presents changes in the magnitude of the frequency response function according to the change in the damping ratio of a MTLD installed structure, in which 21 TLD was used in this structure. Several small peaks were shown at the damping ratio (ζ_t) of the TLD that was configured as 0.5%. However, the magnitude value of the peak decreased from the damping ratio of 1%, and only one single peak was shown at the damping ratio of 1%. The magnitude of the peak at the frequency ratio of 1 increased according to the increase in the damping ratio of a TLD.

3. Wind Tunnel Test

The wind tunnel test applied in this study was performed at a boundary layer wind tunnel at Chonbuk National University. The test section of the wind tunnel was 12 m of length, 1.5 m of width, and 1.2 m of height, and variable wind velocities ranged 0.5~20 m/s. Each country has its own requirements for terrain categorization with respect to the location of the structure. There are four different terrain categories - urban (α= 0.33), city area (α=0.22), suburban (α=0.15) and coastal area (α=0.10) in Korea. α indicates the terrain category of the region on which a structure is to be constructed. The boundary layer applied in this test corresponded to a suburban area where the exponent α was defined as α=0.15 (exposure C) and α=0.33 (exposure A). Fig. 7 presents the results of the vertical distribution of the mean wind speed and turbulence intensity, which were applied in the wind tunnel. The model used in this test was built to a scale of 1 : 400, and the cross-section was 100 cm^2, side ratio (B/D) was 1, and aspect ratio ($H/\sqrt{B \times D}$) was 4. Table 1 presents the dimensions of the model used in this test. The test applied a wind angle of 0° direction. The wind speed for the wind test was determined by the designed wind velocity, which can be defined by a similitude law, and scales of the model, and time. The basic wind speed, which was measured at a 10 m height to determine the designed wind velocity of a building, was measured to 30 m/s (urban area) and 40 m/s (suburban) based on the criteria used in Korea at the

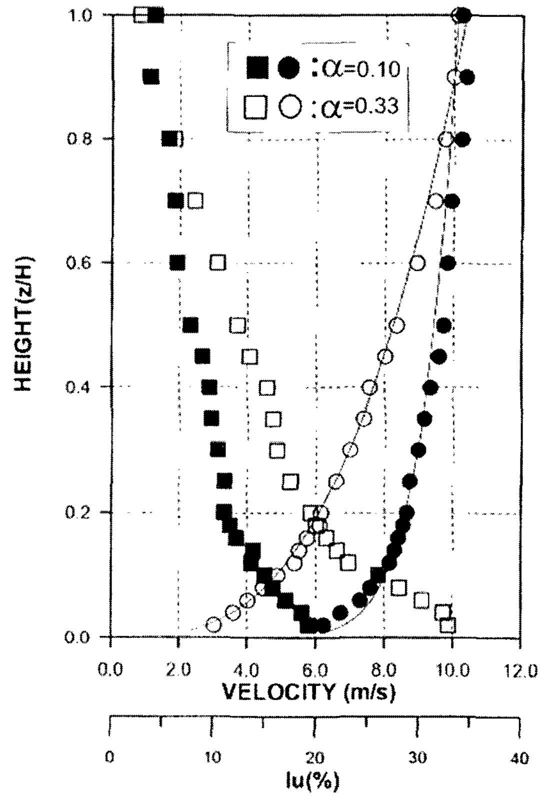


Fig. 7 Vertical distributions of the mean wind speed and turbulence intensities

Table 1 Dimensions of model

D/B (Side ratio)	B (cm)	D (cm)	H (cm)
1	10	10	40

Table 2 Dynamic characteristics for the objective building

Natural Frequency	0.3 Hz
Damping ratio	0.01
Dimension of building (m) $(B \times D \times H)$	40×40×160
Density (kg/m^3)	192

present time. Table 2 presents the dynamic characteristics of the building, which were used to calculated the acceleration responses after TLD installations, using the results of the wind tunnel test.

3.1 Analysis of the response

The mean root response value of generalized displacements can be expressed (Kareem, 1990) as Eq. (16).

$$\sigma^2=\int_0^{\infty}(2\pi f_n)^{2r}\,|H^2(f)|\,S_F(f)\,df \tag{16}$$

Eq. (12) can be obtained by applying a residue theorem to the integral equation presented (Kareem et al., 1999) in Eq. (17).

$$\sigma^2=\frac{\pi f_n S_F(f_n)\,(2\pi f_n)^{2r}}{4(2\pi f_n)^4\zeta_n m_1^2} \tag{17}$$

where

m_1: generalized mass of 1st mode,

f_1 : natural frequency of structure.

r : 1 (velocity), 2 (acceleration),

ζ_n : damping ratio

The rms acceleration response can be expressed as Eq. (18).

$$\sigma=\sqrt{\frac{\pi f_n S(f_n)}{4\zeta m_i^2}} \tag{18}$$

The response of a TLD or MTLD installed building can be evaluated by using Eq. (19).

$$\sigma^2=\int_0^{\infty}(2\pi f)^4\,|H^2(f)|\,S_F(f)\,df \tag{19}$$

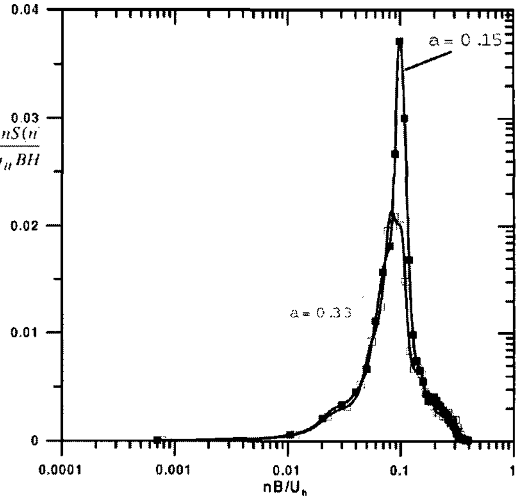


Fig. 8 Wind load spectrums of the transverse direction for the boundary layers

where

$|H^2(f)|$: structure + transfer function of TLD or MTLD

$S_F(f)$: power spectrum of windload

In Eq. (13), the TLD provided an additional damping ratio of a structure by modifying the transfer function of a structure. Because a TLD reduces the vibrations applied in a structure, it is necessary to consider the addition of certain damping ratios of a structure. The Eq. (16) and the results of the numerical analysis can be expressed as Eq. (20).

$$\sigma^2=\frac{\pi f_n S_F(f_n)\,(2\pi f_n)^{2r}}{4(2\pi f_n)^4\zeta_e m_1^2} \tag{20}$$

where $\zeta_e=0.9\frac{\sqrt{\mu}}{4}+0.8\zeta_n$

μ : mass ratio,

ζ_n : damping ratio of structures

3.2 Results of the analysis

Figrue 8 presents wind force spectrums of the acrosswind direction that correspond to a suburban area (α=0.15) and urban area (α=0.33).

Figures 9 and 10 present the acceleration responses for the change in wind velocities and boundary layer with or without TLD at the assumed mass ratio of the TLD of 2%. The acceleration response increases with the increase in

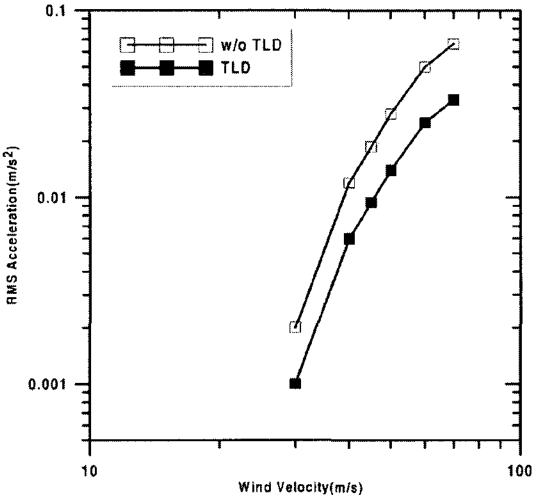


Fig. 9 Acceleration responses of a suburban

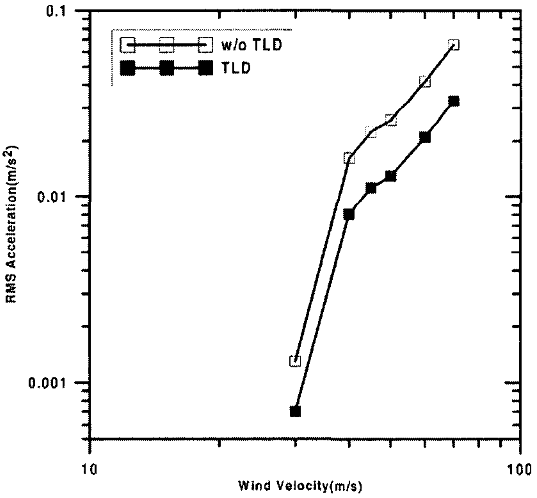


Fig. 10 Acceleration responses of a urban area

the wind velocity. The rms acceleration response with TLD decreases more than that without TLD by about 40%. The results presented constant value without showing significant differences in the boundary layer, because the r.m.s acceleration analysis region of the wind force spectrum was around the dimensionless wind velocity of 0.1~0.4, which presented no significant differences.

4. Conclusions

The following results were found based on the theoretical analysis of the effects of TLD and MTLD on frequency control of a structure and on the wind tunnel test.

TLD and MTLD effectively dampened frequency responses when they used the damping ratio of 6% and frequency ratio of 1%. However, the MTLD gave better frequency ratio, off-tuning ratios and damping ratio than the TLD. In this study, based on wind load spectrum analysis and theoretical analysis, which used the optimum damping ratio of TLD, the r.m.s. acceleration response of the structure was decreased by 40%.

Acknowledgments

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