The Vibration Performance Experiment of Tuned Liquid Damper and Tuned Liquid Column Damper

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Tuned Liquid damper and Tuned Liquid Column are kind of passive mechanical damper which relies on the sloshing of liquid in a rigid tank for suppressing structural vibrations. TLD and TLCD are attributable to several potential advantages - low costs ; easy to install in existing structures ; effective even for small-amplitude vibrations. In this paper, the shaking table experiments were conducted to investigate the characteristics of water sloshing motion in TLD (rectangular, circular) and TLCD. The parameter obtained from the experiments were wave height, base shear force and energy dissipation. The shaking table experiments show that the liquid sloshing relies on amplitude of shaking table and frequency of tank. The TLCD was more effective control vibration than TLD.

Key Words : Tuned Liquid Damper, Tuned Liquid Column, Shaking Table, Wave, Base Shear Force, Energy Dissipation

1. Introduction

A TLD (Tuned Liquid Damper) and TLCD (Tuned Liquid Column Damper) have been used widely as a passive energy dissipation for preventing vibration. A passive energy dissipation, which tunes the natural frequency of a building using the height of water in a water tank, has presents the following merits. 1) It is easy to install in the existing building because it doesn't depend on the installation place and location. 2) The initial installation cost can be reduced by 50%~70% compared to that of a TMD, and the maintenance and repair (It is required to check the level of water every year. It is necessary to adjust the level of water when the water lever is altered after measuring the natural frequency every five years.) is economically beneficial due to the easy processes. 3) It can be applied to control a different vibration type of multi-degree of freedom system, which has a different frequency for each other. A TLD is generally used as circular and rectangular types and is installed at the highest floor according to the building type or objective for controlling vibration. A TLD can be classified as a shallow water type or a deep water type according to the height of the water. If the ratio of the height of the water h against the length of the water tank L is lower than 0.15, it can be classified as a shallow water type, or as a deep water type when the ratio is more than 0.15. The shallow water type has a large damping effect for a small scale of externally excited vibration, but it is difficult to analyze the system for a large scale of externally excited vibration due to the fact that the sloshing of water in a water tank exhibits nonlinear behavior. In

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the case of the deep water type, the sloshing of water presents linear behavior for a large scale of externally excited force. However, some studies have been conducted to improve a certain problem, which has a low damping effect, in this deep water type.

In the study on the TLD, Modi and Welt (1987), Fujino (1988, 1992, 1993), Sun (1989), Kareem (1990), and Wakahara (1993) preformed experimental and theoretical studies on the sloshing of water in a rectangular TLD water tank. Fujono verified that a MTLD presents a more effective result in lower damping ratios than that of a STLD. Wakahara performed studies on the characteristics of a cylindrical TLD using a TMD analogy and its modeling. In particular, this study proposed an equation for designing a TLD using force spectrums, which were produced from a wind tunnel test. In particular, this study focused on the fluid characteristics in a tank that were used to tune a TMD in order to reduce vibrations in structures.

A TLCD was formed into a U shape tube, and a valve/orifice was installed in the tube. This is a modified type of a TLD used to control damping in a structure. Sakai et al. (1989) applied a TLCD to cable-stayed bridge towers. Studies on a high-rise building, which were affected by wind load, were performed by Xu (1992), Balendra (1995), and other researchers. In particular, the U shape used in a TLCD has been used in a ship. In recent years, Kareem and Yalla (2001) have conducted a study on the TLCD which excited a semi-active idea. The One Wall Center, which is a 48 story building in Vancouver, Canada, was used to investigate the application of a TLCD. A number of performance tests were conducted to improve the damping ratio using a vibration table for a TLD. However, tests for a TLCD have been conducted largely as a numerical analyzing method (Change 1999) or a simple pendulum test using a simplified TLCD structure. In addition, there are few TLCD performance tests using a shaking table, and TLD and TLCD performance tests according to the same natural frequency were also limited. In this paper attempts to investigate the characteristics of the base shear force, wave height, and energy dispersion according to the change in natural frequencies of TLDs (rectangular and circular types) and TLCD water tanks.

2. Characteristics of TLD and TLCD Water Tanks

2.1 Natural frequency

The natural frequency of TLD and TLCD water tanks can be obtained using Eq. (1) ~ (3). The natural frequency of a water tank for a TLD (rectangular and circular types) can be determined using the height of water (h) and length (L or R) of a water tank. In the case of a TLCD, the natural frequency can be determined using the length of water in a vertical and horizontal tube.

The natural frequency of a TLD rectangular water tank is

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

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

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

Where

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

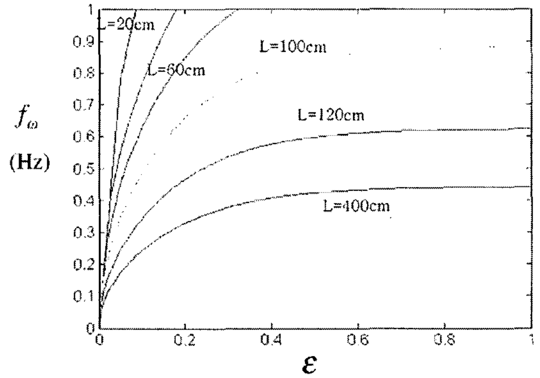
The natural frequency of a TLCD water tank is

$$f_w=\sqrt{\frac{2g}{l}} \tag{3}$$

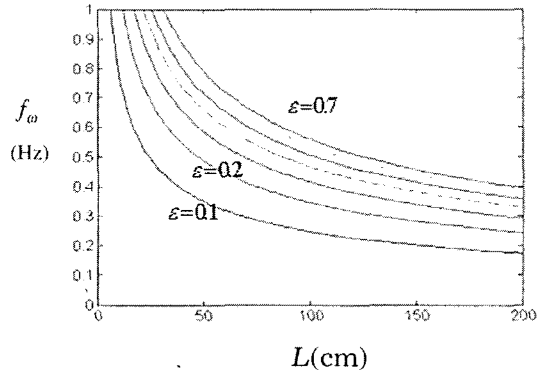
Where

l : Total length of liquid in TLCD tank
g : Acceleration of gravity

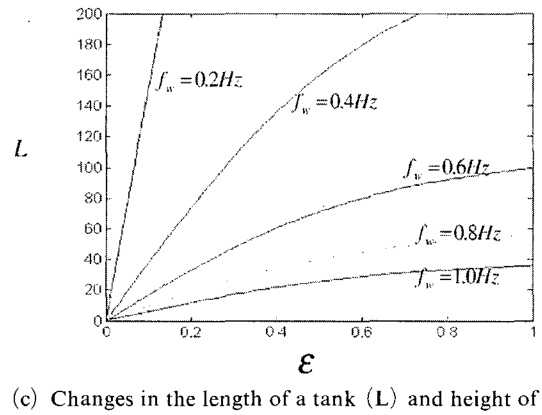
Figure 1(a) presents changes in the length of a rectangular tank (L) according to the changes in the height of water ($\varepsilon=h/(L/2)$) and natural frequency of a water tank (f_ω). The natural frequency generally decreased according to the increase in the height of water, in which the natural frequency changed significantly at the range of $L<50$ cm. However, the changes occurring in the range of $L>100$ cm were small. Fig. 1(b) presents changes in the height (h) of water according to changes in the length of a TLD water tank (L) and natural frequency (f_{ω}). The natural frequency presented a high level according to the increase in the height of water for a constant size of water tanks. Fig. 1(c) presents changes in the natural frequency (f_{ω}) according to changes in the height of water ($\varepsilon=h/(L/2)$) and length of a water tank (L). The low natural frequency is beneficial for the long water tank and shallow water conditions because the length of a water tank (L) is large, and the height of water is low. However, the high natural frequency is beneficial at a short water tank and deep water condition because the length of a water tank (L) is small, and the height of water is high.



(a) Changes in the natural frequency according to the change in the size of water tanks



(b) Changes in the natural frequency according to the change in the height of water



(c) Changes in the length of a tank (L) and height of water (ε) according to changes in the natural frequency

Fig. 1 Parameters for the natural frequency of a rectangular tank

2.2 Characteristics of a dynamic magnification factor

2.2.1 TLD

It is possible to apply the analogy of a TMD to investigate its characteristics or modeling based on the fact that the basic principle of vibration control in a TMD is the same as the principle of a TMD. An advantage to substituting a TLD as an equivalent TMD is that an optimum tuning parameter of a TMD for the characteristics of objective external forces is given in a theoretical manner. This is due to the fact that the relationship between the design parameter of a TLD for the objective response level and the optimum tuning parameter of a TMD can be determined easily. Eq. (4) presents an equation of motion in a TMD-structure system.

$$\begin{bmatrix} M_s & 0 \\ m_t & m_t \end{bmatrix}\begin{bmatrix} \ddot{x}_s \\ \ddot{x}_t \end{bmatrix}+\begin{bmatrix} C_s & -C_s \\ 0 & C_t \end{bmatrix}\begin{bmatrix} \dot{x}_s \\ \dot{x}_t \end{bmatrix}+\begin{bmatrix} K_s & -K_s \\ 0 & K_t \end{bmatrix}\begin{bmatrix} x_s \\ x_t \end{bmatrix}=\begin{bmatrix} F_w \\ 0 \end{bmatrix} \tag{4}$$

where

M_s, C_s, K_s : Mass, Damping, Stiffness of Structure

m_t, c_t, k_t : Mass, Damping, Stiffness of TLD

An equation of a dynamic magnification factor

(DMF) for Eq. (4) can be determined as Eq. (5).

$$DMF=\sqrt{\frac{(r^2-\beta^2)^2+(2\xi_a r\beta)^2}{[(r^2-\beta^2)(1-\beta^2)-r^2\beta^2\mu]^2+(2\xi_a r\beta)^2(1-\beta^2-\beta^2\mu)^2}} \quad (5)$$

where

$\mu=\frac{m_t}{M_s}$: Mass ratio

$\gamma=\frac{f_t}{f_s}$: Tuning ratio

$\beta=\frac{f}{f_s}$: Structure-excited frequency ratio

ξ_a : Damping ratio of TMD

Figure 2 presents a dynamic magnification factor having a 1% of mass ratio (μ) of an equivalent TMD for the mass of a structure, and damping ratios (ζ_a) of an equivalent TMD are given as 3%, 5%, 10%, and 15%. Two peaks were presented when the damping ratio was given as 3% and 5%, respectively. However, a peak was presented for the damping ratio of 10% and 15%, respectively.

2.2.1 TLCD

An equation of motion for a TLCD-structure system can be expressed as Eq. (6).

$$\begin{bmatrix} M_s+m_t & am_t \\ am_t & m_t \end{bmatrix}\begin{bmatrix} \ddot{x}_s \\ \ddot{x}_t \end{bmatrix}+\begin{bmatrix} C_s & 0 \\ 0 & C_t \end{bmatrix}\begin{bmatrix} \dot{x}_s \\ \dot{x}_t \end{bmatrix}+\begin{bmatrix} K_s & 0 \\ 0 & K_t \end{bmatrix}\begin{bmatrix} x_s \\ x_t \end{bmatrix}=\begin{bmatrix} F_w \\ 0 \end{bmatrix} \quad (6)$$

where

M_s, C_s, K_s : Mass, Damping, Stiffness of Structure

m_t, c_t, k_t : Mass, Damping, Stiffness of TLCD

An equation of a dynamic magnification factor (DMF) for Eq. (6) can be determined as Eq. (7).

$$H(f)=\sqrt{\frac{b\left(\frac{a}{b}+\xi^2\right)}{d\left(\frac{c}{d}+\xi^2\right)}} \quad (7)$$

where $a=(1-\gamma^2+a^2\mu^2\gamma^2)^2$, $b=(2\gamma)^2$, $c=[(1-\beta^2)(1-\gamma^2)-(a\mu\beta\gamma)^2]^2$, $d=[2\gamma(1-\beta^2)]^2$

$\beta=\frac{f}{f_s}$: Structure-excited frequency ratio

$\gamma=\frac{f}{f_s}$: TLCD-excited frequency ratio,

ξ : Damping ratio of TLCD

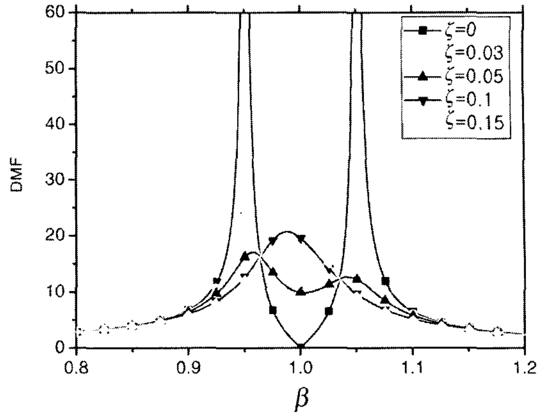


Fig. 2 Dynamic magnification factors for an equivalent TMD

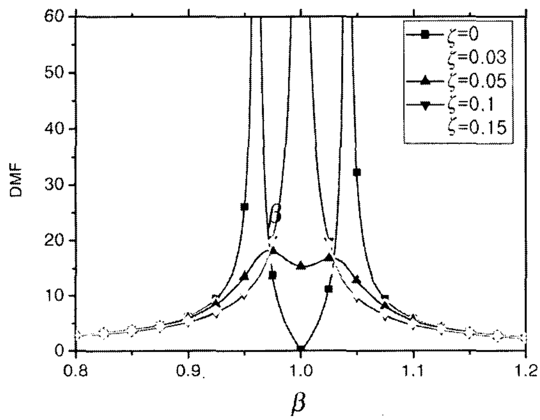


Fig. 3 Dynamic magnification factor of a TLCD

Figure 3 presents a dynamic magnification factor that has a 10% of mass ratio (μ) for a TLCD with the mass of a structure, and damping ratios (ξ_a) of a TLCD are given as 3%, 5%, 10%, and 15%. Two peaks were presented when the damping ratio of a TLCD was given as 3% and 5%, respectively. However, a peak was presented for the damping ratio of 10% and 15%, respectively. The most ideal damping ratio in a TLCD was 5%, which was the same as an equivalent TMD. It is evident that a damping ratio exceeding 10% was disadvantageous to the system.

3. Test for a Shake Table

Figure 4 presents a schematic diagram for the vibration test of a water tank. A TLD and TLCD

Table 1 Instruments used in the vibration table test

Instruments	Specifications	Objectives
3-component force balance	Max. range : 2 kg	Measuring the force of the sloshing of water
Capacity type Wave gauge	Max. range : ±100 cm	Measuring the height of waves in the tank
Accelerometer	PCB-393A03	Measuring the acceleration for the vibration
Displacement meter	±20 mm	Measuring the displacement of shaking table

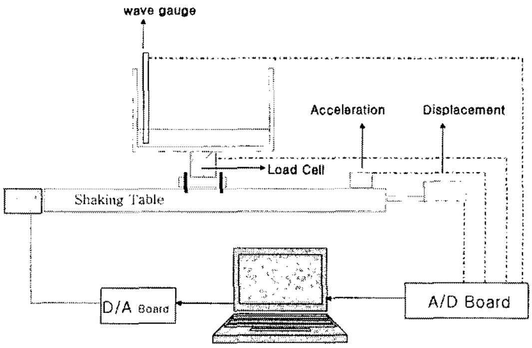


Fig. 4 Schematic diagram of the shaking table of a water tank

water tank were installed on a shake table where the harmonic vibration of a sine wave was applied, and the sloshing of water was tested. The water tanks used in the test were TLD's (rectangular and circular types) and TLCD. The specification of the instruments used in the test was noted in Table 1. The measuring frequency was 200 Hz, and the measuring time was 60 seconds. A 100 Hz of low-pass filter was used to remove noises in the instrument and equipment. Two methods were used to measure the force of water in the TLD and TLCD as follows. The first method used two 3-component force balances on the shake table. This method applied a simple subtraction method, F1-F2, using a water tank on the first 3-component force balance (F1) and a dummy, which was the same weight as the water tank, on the second 3-component force balance (F2). The second method used a 3-component force balance and accelerometer. This method subtracted the force F2 that multiplied an acceleration signal ($\ddot{a}$), which was measured from the shake table, by the mass (m) of an empty water tank from the force F1. In order to guarantee the reliability of this method, a comparison between the force F1, which was produced by loading an empty tank on the 3-component force balance, and the force F2, which was measured using an acceleration signal, was performed.

This paper used the second method. A non-dimensional equation in the base shear force for the sloshing of water used in a water tank can be denoted as Eq. (8). This is the value that is measured from a 3-component force balance divided by the mass of water in a water tank, frequency, and amplitude. The objective of measuring the base shear force was to investigate the force of water for the sloshing of water according to the frequency of the excited vibration, which was excited on the shake table. A wave gauge was used in the TLD test in order to verify the characteristics of waves in a water tank according to the amplitude of the excited vibration. The reference height of waves according to the excited vibration was defined as the height of water at a calm state, and the wave gauge was set at the closest position of the water tank wall Eq. (9) is an equation used to produce the height of waves and presents non-dimensional values. This is the value that was measured from the wave gauge divided by the height of water in the excited vibration. Fig. 5 presents the dimension of the TLD and TLCD used in this test. Table 2 notes the specification of the TLD and TLCD model. In addition, Img. 1 shows the vibration table where a TLCD water tank was installed.

$$F'_w = \frac{F_w}{m_w w^2 A} \tag{8}$$

where

m_w : mass of water in the tank
w : Excited frequency of shaking table
A : Amplitude of shaking table

$$\eta'_{\max} = \frac{\eta_{\max}}{h} \tag{9}$$

where

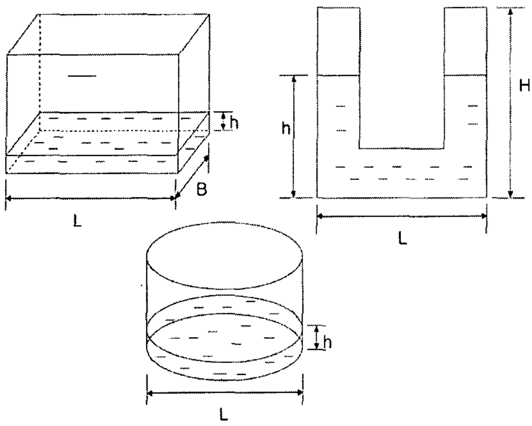
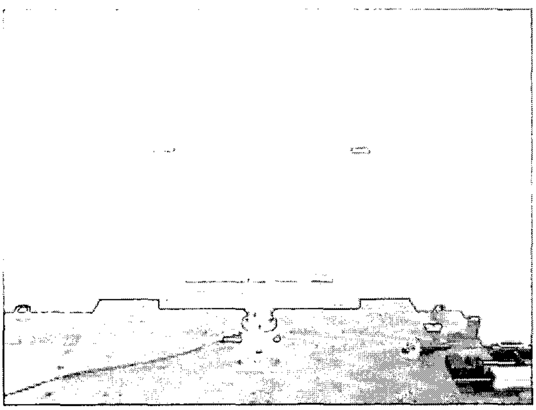


Fig. 5 Dimension of TLD and TLCD



Img. 1 TLCD installed on the vibration table

h : height of water in the tank

4. Results and Analysis

4.1 Time history

Figures 6 and 7 present the time history of the base shear force for the frequency ratio (β) of 0.95～1.05 at the natural frequency of 0.64 Hz of a rectangular TLD and TLCD water tank. In the case of the rectangular TLD as shown in Fig. 6, the base shear force was measured as a constant type up to the frequency ratio (β) of 1, but there were two peaks in a single phase from the frequency ratio (β) of 1.05. These results were considered as the high frequency that was produced due to the wave-breaking. In the case of the TLCD presented in Fig. 7, there were no secondary peaks exhibiting the certain high frequency

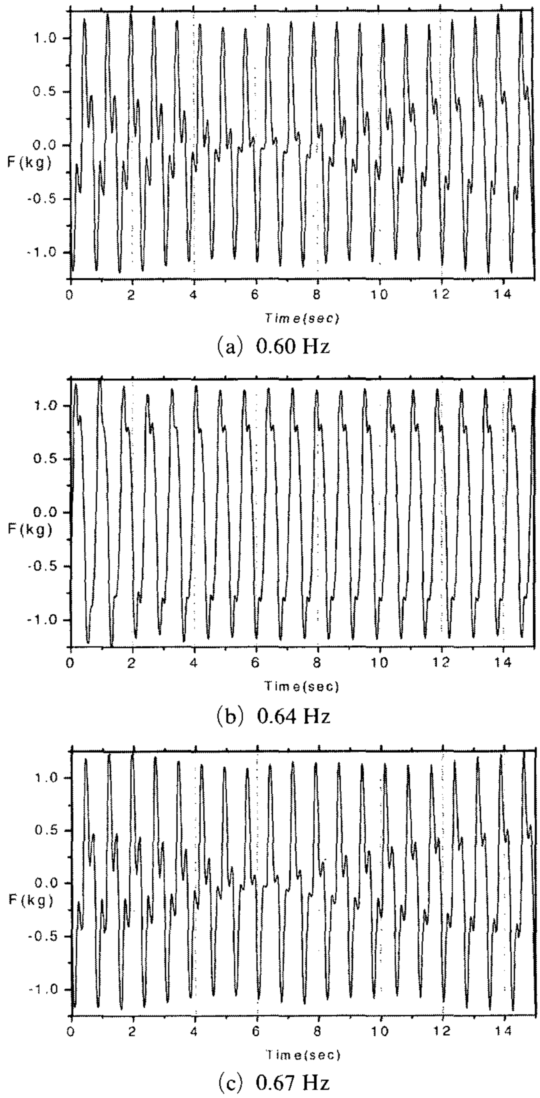
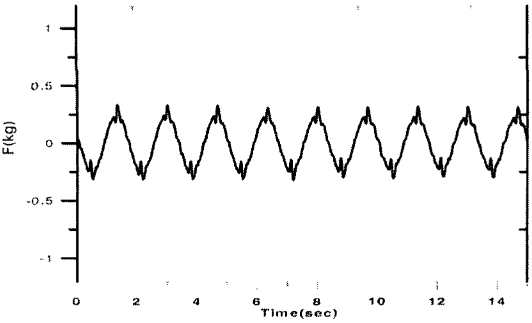
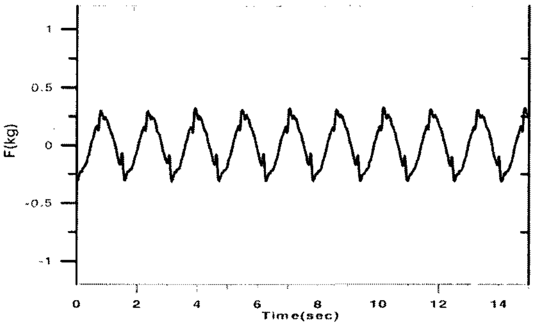


Fig. 6 Time history of the base shear force (TLD rectangular water tank) (Excited amplitude (A): 10 mm, Natural frequency : 0.64 Hz)

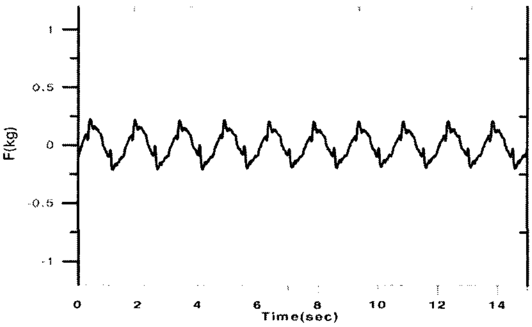
of the TLD, and constant sine waves were measured. The base shear force presented the highest value at the frequency ratio (β) of 1. Because the mass of a TLD is 5 times larger than that of a TLCD, the base shear force of a TLD is larger than that of a TLCD. A TLCD doesn't generate a secondary peak, which includes a certain high frequency, because it doesn't produce a type of wave-breaking as well as a TLD due to the upward and downward vibration of a narrowed vertical tube.



(a) 0.60 Hz



(b) 0.64 Hz

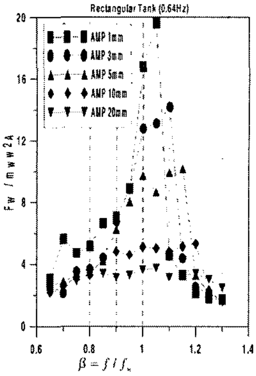


(c) 0.67 Hz

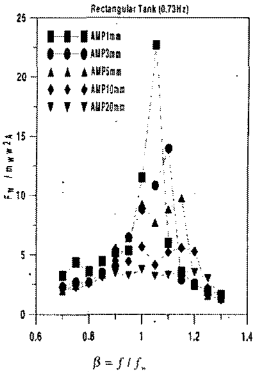
Fig. 7 Time history of the base shear force (TLCD rectangular water tank) (Excited amplitude (A): 10 mm, Natural frequency: 0.64 Hz

4.2 Base shear force

The base shear force of a water tank is a test used to investigate changes in the sloshing of water according to the excited frequency, which is measured from the bottom of a water tank. Figs. 8~10 present the base shear force of a TLD and TLCD according to the change in the natural frequency and amplitude of the excited frequency. The numerator of F_ω of the horizontal axis as presented in Figs. 8~10 presented the base shear force measured in a 3-component force balance,

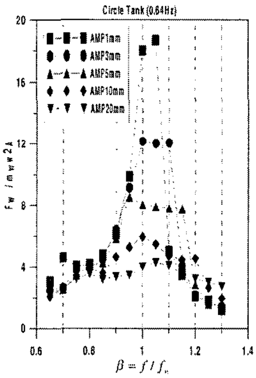


(a) 0.64Hz

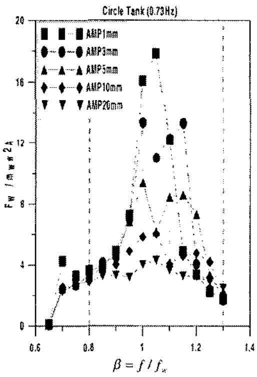


(b) 0.73Hz

Fig. 8 Base shear force in a rectangular TLD water tank for the natural frequency

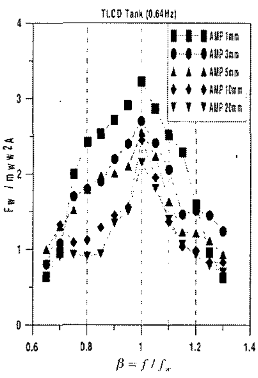


(a) 0.64Hz

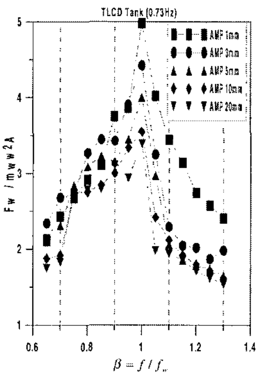


(b) 0.73Hz

Fig. 9 Base shear force in a circular TLD water tank for the natural frequency



(a) 0.64Hz

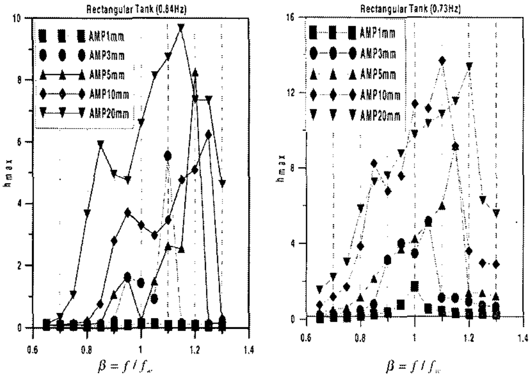


(b) 0.73Hz

Fig. 10 Base shear force of a TLCD water tank for the natural frequency and the denominator presented the mass in a water tank and amplitude of the excited vibration (A) in the natural frequency of a water tank. These were non-dimensional values. In addition, the mass of a rectangular TLD was 15% larger than that of a circular TLD. In the case of the TLCD, the difference was about 50%. This test was performed at the frequency ratio of the excited vibration from 0.6 to 1.3 Hz for the natural frequency of the rectangular and circular TLD water tank. In the response curve according to the natural frequency of the rectangular water tank as presented in Fig. 8, the largest base shear force was produced at a small amplitude (1 mm) of the excited vibration. The base shear force decreased according to the increase in the amplitude of the excited vibration. Constant frequency response curves were presented from the amplitude of the excited vibration more than 10 mm. The large shear force produced in the small amplitude of the excited vibration presented large values according to the increase in the natural frequency of a water tank. This is due to the fact that the sloshing of water can't be generated at a low level of the excited vibration, and consequently the base shear force for the externally excited vibration. However, the base shear force was generated at a high level due to the wave-breaking at the wall of water tank after increasing the sloshing of water at a high level of the excited vibration. The position of the maximum response peak for the base shear force was verified at the frequency ratio of the excited vibration ($\beta > 1$) that was higher than the natural frequency. It is evident that the high frequency can be generated according to the increase in the frequency ratio of the excited vibration. The circular water tank illustrated in Fig. 9 also presented the same results as the rectangular water tank. The position where the maximum base shear force occurred in a circular water tank was around $\beta = 1.05$, and the circular water tank also presented a high frequency region due to the wave-breaking as well as a rectangular water tank. The difference between a circular and a rectangular water tank is that the circular water tank presented a low shear force compared to the rectangular water tank. Fig. 10 presents the scale of the base shear force of a TLCD water tank according to the natural frequency. The lower amplitude of the excited vibration produced the larger base shear force. However, a small base shear force occurred when the increase in the amplitude of the excited vibration was the same as the TLD. In the case of the TLCD, it is evident that the tuning was greatly performed with the natural frequency of a water tank due to the fact that a large base shear force was generated at the frequency ratio (β) of 1 in all amplitudes of the excited vibration differing from the TLD. In addition, there were no large differences in the base shear force according to the change in the amplitude of the excited vibration from the TLD. In the case of the TLD, the difference between the maximum base shear force, and the base shear force with 20 mm of the amplitude of the excited vibration, was about 80% for 1 mm of the amplitude of the excited vibration. However, the TLCD presented about 30%. It is evident that the TLCD presented more effective control of the externally excited vibration than that of the TLD.

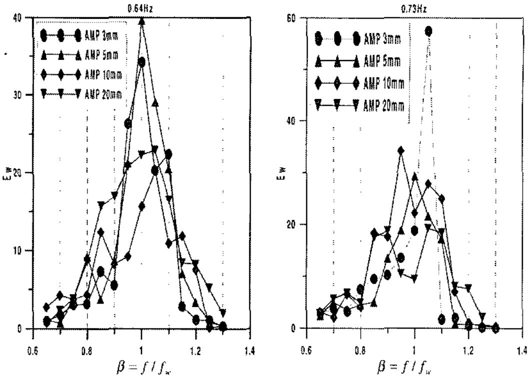
4.3 Wave height

Figures 11 and 12 present the test results of the wave gauge installed in a rectangular and circular TLD in order to measure changes in the sloshing of water from the externally excited vibration in a water tank. The horizontal axis presented in Figs. 11 and 12 was $\eta'_{max} = \frac{\eta_{max}}{h}$ where h is the height of water before excited the vibration in a water tank, and η_{max} is the maximum height of water when waves were generated after applying the vibration in a water tank in which these parameters were non-dimensional values. In the case of the TLCD, a wave gauge was not installed due to the narrowed vertical tube of the TLCD. The highest wave height in the rectangular TLD water tank as shown in Fig. 11 increased according to the increase in the natural frequency. The wave height according to the change in the amplitude of the excited vibration (A = 1 mm, 3 mm, 5 mm, 10 mm, and 20 mm) presented the highest wave height at the largest amplitude of 20 mm. The position of peaks in the large amplitude of the excited vibration appeared at an area that has a larger value



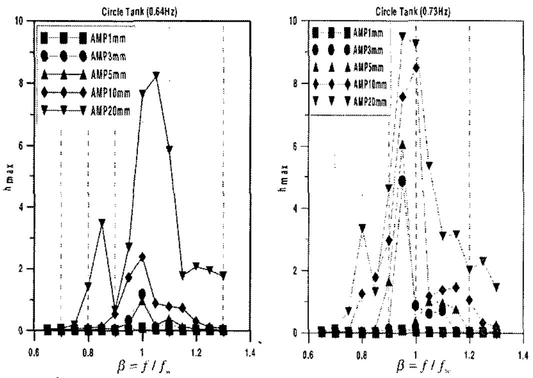
(a) 0.64Hz (b) 0.73Hz

Fig. 11 Wave height of a rectangular TLD water tank for the natural frequency



(a) 0.64Hz (b) 0.73Hz

Fig. 13 Energy dispersion of a rectangular TLD water tank for the natural frequency



(a) 0.64Hz (b) 0.73Hz

Fig. 12 Wave height of a circular TLD water tank for the natural frequency

than a resonance area ($\beta=1$). In addition, the larger amplitude of the excited vibration generated the more rapidly decreased wave height after the resonance. In the case of the circular TLD water tank presented in Fig. 12, the wave height presented large values according to the increase in the amplitude of the excited vibration. The reason for the wave-breaking in a circular water tank was that the swirling along the circumference occurred according to the increase in the amplitude of the excited vibration.

4.4 Energy dispersion

Energy dispersion, which is an important factor in controlling vibration, was measured. A displacement meter (LVDT) was used to measure the shear force (f_ω), which is generated by the sloshing of water in a water tank, and displacement of the shake table. Energy dispersion can be defined using the measured water displacement for 1 cycle and the base shear force of water. Eq. (10) presents this energy dispersion. The scale of energy dispersion can be expressed as an area for the force-displacement cycle.

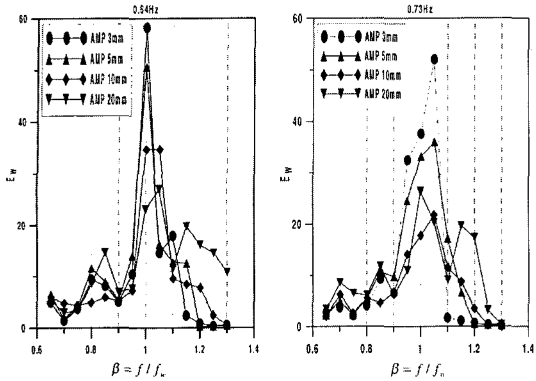
$$\Delta E=\int^{t+T} F(t)\,dx_s(t) \tag{10}$$

Eq. (11) presents a non-dimensional equation for the energy dispersion per cycle.

$$\Delta E'=\frac{\Delta E}{\left(\frac{1}{2}m_w(wA)^2\right)} \tag{11}$$

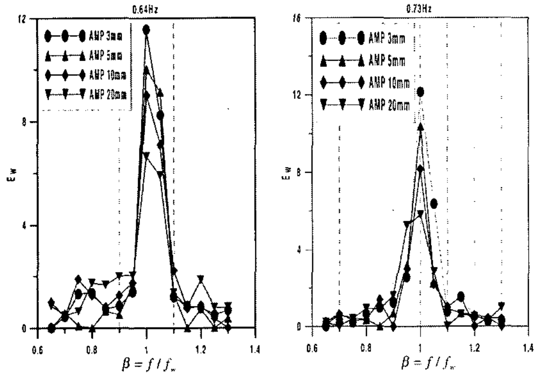
Figures 13 and 14 present the energy dispersion for the frequency of the excited vibration according to the natural frequency in a rectangular and circular water tank. The energy dispersion presented a large level according to the increase in the natural frequency of a water tank. The increase in the natural frequency and amplitude of the externally excited vibration caused an increase of sloshing in a water tank. It also presented a lower level in the frequency response of energy dispersion due to an increase in the decreasing ratio.

Figure 15 presents the energy dispersion according to the change in the natural frequency in a TLCD water tank. The largest energy dispersion occurred at the tuning ratio of 1 regardless of



(a) 0.64Hz (b) 0.73Hz

Fig. 14 Energy dispersion of a circular TLD water tank for the natural frequency



(a) 0.64Hz (b) 0.73Hz

Fig. 15 Energy dispersion in a TLCD water tank for the natural frequency

the amplitude of the excited vibration, and the difference in the energy dispersion according to the amplitude of the excited vibration presented small values compared to the TLD.

5. Conclusions

This study obtained some conclusions from the test for a shaking table using rectangular and circular TLD and TLCD water tanks.

It is evident that the TLD and TLCD presented effective results in vibration control from the results of the vibration performance test for TLD and TLCD water tanks that have the same natural frequency. From the results of the analysis of the base shear force and wave height, it was difficult to synchronize the tuning ratio due to the wave-breaking in the case of the TLD, but the synchronization of the tuning ratio in the TLCD was greatly improved regardless of the amplitude of the excited vibration. In the comparison between the rectangular TLD and the circular TLD, the circular TLD presented more effective results in the synchronization of the tuning ratio and damping effect for the base shear force, wave height, and energy dispersion. In the case of the base shear force and energy dispersion according to the amplitude of the excited vibration, the TLCD was not significantly affected by the amplitude of the excited vibration compared to the TLD.

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