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Comparison of the Dynamic Characteristics of Tuned Liquid Column Dampers with Different Elbow Forms

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ABSTRACT

This study aims to examine experimentally the damping performance of Tuned Liquid Column Dampers (TLCD) by considering different elbow forms. Experiments carried out within the scope of the study point out the dynamic characteristics of TLCD, which has 45 (open) and 90 (closed) degree-elbow forms with theoretical angular frequencies that are the same. Experiments consist of ±5 and ±10 mm harmonic excitation amplitude to observe the relationship between the damping ratio and head loss coefficient with the mass ratio of the TLCD. These experiments with an incremental mass ratio of 0.05% from 0.80% to 1.00% and with an incremental mass ratio of 0.10% from 1.00% to 1.20% had been carried out in detail. Mass and stiffness Modification Factors (MF) are suggested to minimize the difference between numerical and experimental results. Determined MFs are used to examine the earthquake performance of TLCD on a Single-Degree-of-Freedom (SDOF) system. It is shown that the open elbow has an advantage of approximately 25% over the close elbow under earthquake performance on the SDOF system.

Keywords: Tuned liquid column dampers, passive control, shaking table experiments, earthquake simulation.

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1. INTRODUCTION

Passive dampers are used to reduce the effects of a certain level of vibration caused by strong wind or strong ground motions. Passive dampers can reduce the effects of these vibrations in the short term by increasing the energy absorption capacity of the structure to which they are applied, thereby increasing the occupant comfort for the building. One of the passive dampers, the TLCD with the same cross-sectional area in the horizontal and vertical columns, was introduced in the literature by Sakai [1], and its nonlinear mathematical model was described. Researchers [2-7] have carried out experimental and theoretical studies on U-shaped TLCD systems in the following years when numerical and parametric studies have been carried out on the optimum tuning ratio and head loss coefficient values for TLCD systems [8-13]. At the same time, these studies have shown that the TLCD effective length requirement can be easily achieved by choosing different cross-section ratios in the vertical and horizontal columns. Although it is generally accepted in the literature that the mass ratio varies between 0.05% and 5%, it has been shown that there is a correlation between this ratio and the performance of the TLCD, and that the optimum mass ratio is an important consideration in obtaining the optimum damping ratio [12]. It was concluded that the mass ratio should generally be less than 2% for TLCD to be effective and that TLCD efficiency increases as the mass ratio value increases [8]. However, this conclusion is not entirely correct for U-shaped TLCDs with a constant cross-sectional area. As the mass ratio value increases, the control performance of the TLCD decreases as it moves away from the optimum tuning ratio and length ratio values [12, 14]. The studies in the literature focus mainly on single-degree-of-freedom (SDOF) system models. To compare the control performance of passive dampers in Multi Degree of Freedom (MDF) systems, Bigdeli and Kim [15] compared the effects of different dampers on the damping of the structure on a three-story model. Some studies have investigated the relationship between the optimum head loss coefficient and the aperture ratio when controlling the vibrations occurring in the structure under the effect of stochastic loads and concluded that TLCD is more effective in reducing the acceleration and displacement values of the structure when the length ratio and mass ratio are high [16].

In another study on the seismic applications of single TLCD systems and multiple TLCD systems, a single-degree-of-freedom bridge model and a 10-story building model were used. According to the study, design parameters for single and multiple TLCD systems were determined using 72 different earthquake records. These parameters for STLCD were the tuning ratio, the damping ratio, and the ratio of the effective fluid length to the TLCD column width. These parameters for MTLCD are the central tuning ratio, the tuning bandwidth, and the number of TLCD groups. The results showed that the acceleration and displacement responses of the models were reduced by 47% [17]. In another study on multiple TLCD, the dynamic characteristics of the multiple TLCD system are numerically investigated. In addition, the advantages of this system are presented by comparing it with a single TLCD system. The study revealed that the multiple TLCD system has a specific frequency range and damping ratio value to reduce the peak responses under harmonic excitation. In addition, the study also states that more than 5 TLCDs do not show a significant change in improving system performance [18]. These studies have shown that Multiple TLCD performs better and is more effective than single TLCD during seismic events. Multiple TLCDs were found to have a certain optimum center distance ratio. However, placing more than a certain number of multiple TLCDs in the structure did not increase the effectiveness of the system.

In another study on the control performance of the structural system and TLCD [19], it was shown that the performance is related to the acceleration and displacement responses of the structure, depending on the structural system. Considering the acceleration responses of a shear wall system and a frame system with similar stiffness, it was stated that TLCD achieved more effective control performance in the shear wall system. Other theoretical and experimental studies carried out in recent years have developed different forms of TLCDs. The control performance of some new types of TLCDs has been compared with conventional types [20-23]. A pre-design formula was developed by Matteo et al. [24] using statistical methods to calculate the linear equivalent damping ratio of a TLCD, and later, this formula was experimentally investigated on a TSD system [25].

Other studies have examined the control performance of Liquid Column Vibration Absorbers (LCVA) on structures, which is a type of TLCD [26-28]. The dynamic characteristics and control performance of the LCVAs were investigated experimentally and theoretically.

One of the passive type damper derived from the configuration of TLCD is called the Pendulum type liquid damper, which has been experimentally and numerically studied in the literature [32-33].

Tuned liquid dampers (TLDs) are designed to passively control vibrations in structural systems. They consist of a container partially filled with liquid and utilize the liquid's sloshing dynamics to mitigate structural vibrations. The liquid's oscillatory movement generates a force that is directly correlated with its horizontal acceleration. The TLD's control performance and sloshing characteristics have been investigated in various studies under harmonic loads [34-36].

In this study, the effects of harmonic excitation amplitude, elbow form, and mass ratio on TLCD performance are investigated. For this purpose, the dynamic characteristics of two different TLCD designs with the same theoretical angular frequencies consisting of 45 (open elbow) and 90 (close elbow) degree elbow forms are presented. Experimentally obtained dynamic characteristics and damping ratios are compared with theoretical results. Additionally, time history analyses are carried out numerically on the SDOF system using experimentally obtained parameters. The control performance of TLCD is investigated by considering the elbow forms, and adjusted numerical analyses are performed.

2. TLCD SYSTEM DESIGN and EXPERIMENTAL SETUP

TLCDs with open elbow (OE) and close elbow (CE) forms of equal cross-sectional area in horizontal and vertical columns, using PVC material with an external diameter of 75 mm and an internal radius of 35.5 mm were used. For the vertical columns, transparent acrylic material of the same dimensions was preferred. Figure 1 shows the view of the OE and CE TLCDs, and Figure 2 shows the experimental models placed on the shaking table [29]. Frequency-mass relations, head loss coefficient-mass ratio relations, mass ratio-damping ratio relations, and resonance amplitudes for TLCDs with OE and CE were investigated by frequency scanning tests. A uniaxial shaking table controlled by a stepper motor with a stroke of ± 75 mm was used for this purpose. The dimensions and masses of OE and CE TLCD systems are shown in Table 1.

Table 1 - TLCD specifications

TLCD type	Mass (kg)	Outer width (L_1)	Clear width (B)
OE TLCD	1.554	286	211
CE TLCD	1.500	283	208

The equation of motion of the liquid in the TLCD shown in Figure 1 is given in Equation (1).

$$m_d \ddot{y}(t) + \frac{1}{2}\rho A\xi \left|\dot{y}(t)\right| \dot{y}(t) + 2\rho A g y(t) = -m_h \ddot{x}_g(t) \tag{1}$$

A is the cross-sectional area of the TLCD, m_d is the fluid mass (ρAL) in the TLCD, m_h is the mass of the fluid in the horizontal column of the TLCD, g is the acceleration of gravity, $\ddot{x}_g$ is the ground acceleration, y, $\dot{y}$, *and* $\ddot{y}$ are the displacement, velocity, and acceleration of the fluid in the TLCD, respectively. ρ and ξ represent the density of the fluid and the head loss coefficient, respectively.

The numerical solution of the differential equation is challenging due to the nonlinear terms in the dynamic equation associated with TLCD. Therefore, these terms are typically linearized using an equivalent linearization technique [37]. The error between the nonlinear and equivalent linear systems is expressed in Equation (2) as follows.

$$\varepsilon = \frac{1}{2}\rho A\xi \left|\dot{y}\right| \dot{y} - c_{eq}\dot{y} \tag{2}$$

The equivalent damping coefficient is determined through the minimization of the mean square error, leading to the derivation of the expression for the equivalent damping coefficient, assuming the Gaussian distribution of water surface velocity in the water column [9, 13].

$$c_{eq} = \sqrt{\frac{2}{\pi}}\rho A\xi\sigma_{\dot{y}} \tag{3}$$

$\sigma_{\dot{y}}$ denotes the standard deviation of the water surface velocity of the water column. In Equation (4), ζ_{eq} denotes the equivalent damping ratio of the TLCD in Eq. (1). The linearized dynamic equation is as follows.

$$m_d \ddot{y}(t) + 2m_d\omega_d\zeta_{eq}\dot{y}(t) + m_d\omega_d^2 y(t) = -m_h\ddot{x}_g(t) \tag{4}$$

The tuning ratio χ, a critical parameter in TLCD control performance, is calculated using Equation (5).

$$\chi = \frac{\omega_d}{\omega_s} \tag{5}$$

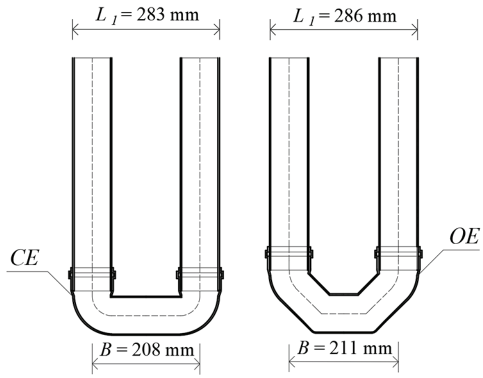


Figure 1 - Design of CE (left), and OE (right) TLCD.

Figure 2 - Views from shake table tests of CE TLCD (left), and OE TLCD (right).

ω_s denote the angular frequency of the structure model, and the angular frequency of the TLCD ω_d is obtained using Equation (6). Tuning ratio of approximately 1 is preferred for the control performance of the TLCD.

$$\omega_d = \sqrt{\frac{2g}{L}} \tag{6}$$

In Equation (6), g represents gravitational acceleration, and L represents the total liquid length in the vertical and horizontal columns. The mass ratio, which is the parameter that affects the control performance of the TLCD and the liquid length L in the system, is calculated using Equation (7).

$$\mu = \frac{m_d}{m_s} \times 100 \tag{7}$$

The mass ratio, mass of the liquid in the TLCD, and mass of the structure are denoted by μ, m_d, and m_s, respectively. In this study, m_s was assumed to be 170 kg.

The half-power bandwidth (3 dB) method is utilized to calculate the damping ratios of experimentally obtained frequency-amplitude curves using Equation (8).

$$\zeta = \frac{f_b - f_a}{2 f_n} \tag{8}$$

Here, f_n is the natural frequency of the TLCD, and f_a and f_b are the projections of the points on the frequency axes of the frequency-amplitude curve that intersect below the maximum by 3 dB.

In order to compare the damping performance of the elbow effect, the non-dimensional Dynamic Response Amplifier (DRA) of the TLCD systems is calculated by Equation (9). The equation is defined by the relationship between the damping ratio and frequency ratio.

$$\text{DRA} = 1 \Big/ \sqrt{\left[1-(\omega/\omega_d)^2\right]^2 + \left[2\zeta(\omega/\omega_d)\right]^2} \tag{9}$$

ω represents the excitation frequency in Equation (9) [30]. Head loss is caused by fluid flow passing through the horizontal column due to the form of the elbows. The friction between the fluid and the inner walls of the TLCD is calculated by Equation (10), where ζ represents the damping ratio, and x_r is the amplitude of the resonance frequency.

$$\xi = 2L\sqrt{\pi}\left(\frac{\zeta}{x_r}\right) \tag{10}$$

3. DETERMINING DYNAMIC CHARACTERISTICS OF TLCDs

Harmonic tests for different amplitude-frequency relationships were performed to determine the dynamic response of TLCD systems considering OE and CE forms. These experiments were carried out for each elbow configuration as frequency scanning tests around the theoretical resonance frequency calculated for the relevant mass ratio. As the TLCD vibrated at the excitation frequency, the fluid oscillation in the transparent columns was measured using an attached ruler. Each harmonic test was settled to 50 cycles for the given excitation frequency to observe the steady-state oscillation in the TLCD column. The experiments were performed with amplitudes of ±5 mm and ±10 mm within a frequency range of 0.85 to 1.40. The objective is to examine the relationship between the damping ratio and amplitude. As a result of these experiments, the frequency response curves obtained for each mass ratio with TLCDs formed with OE and CE are shown in Figures 3-6. Figures 3 and 4 show the OE and CE frequency-response curves under ±5 mm harmonic excitation. In addition, Figure 5 and

Figure 6 show the frequency-response curve of the OE and CE under an amplitude of ±10 mm. The dynamic response of both the OE and CE TLCDs was obtained for mass ratios ranging from 0.80% to 1.20% through frequency scanning.

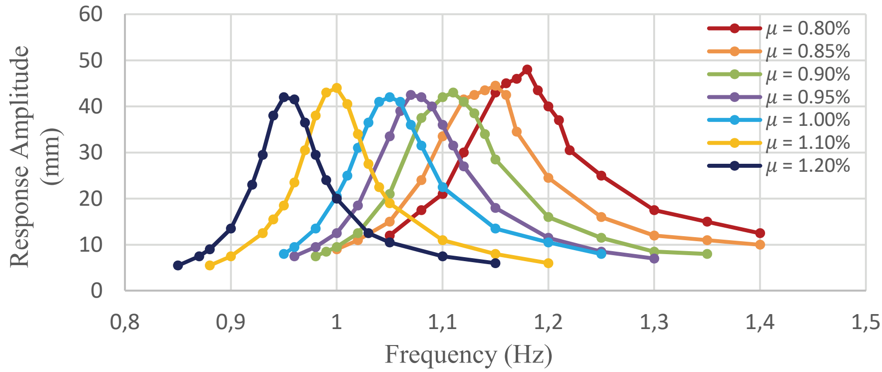


Figure 3 - OE TLCD frequency-response curves under ±5 mm harmonic excitation.

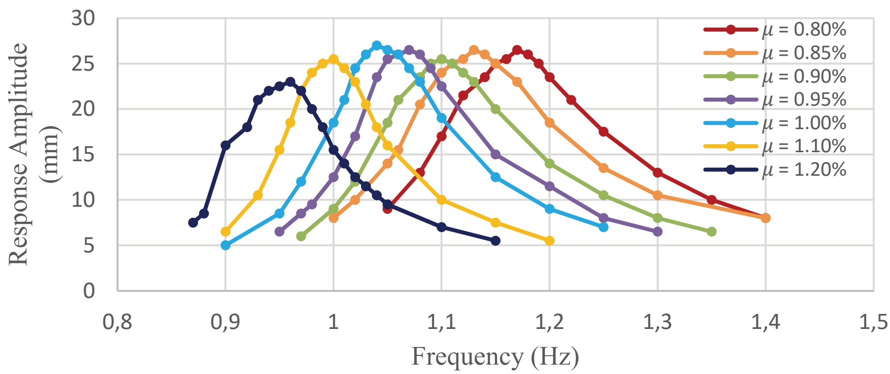


Figure 4 - CE TLCD frequency-response curves under ±5 mm harmonic excitation.

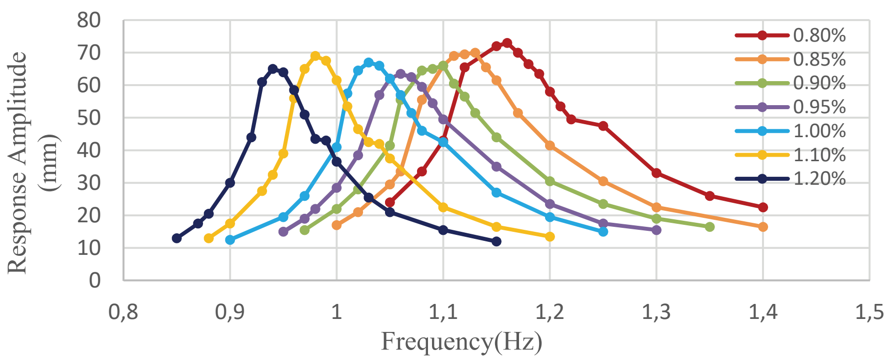


Figure 5 - OE TLCD frequency-response curves under ±10 mm harmonic excitation.

Figure 7 for the OE and Figure 8 for the CE give the frequency-mass ratio relationships under ±5 mm and ±10 mm amplitudes to determine the consistency between the experimental and theoretical results.

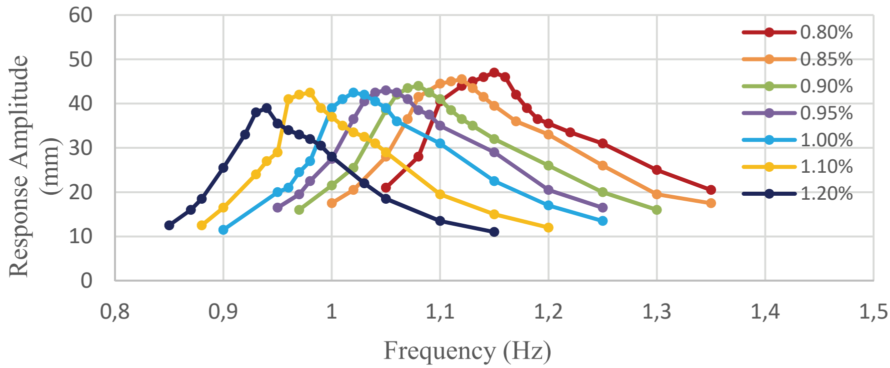


Figure 6 - CE TLCD frequency-response curves under ±10 mm harmonic excitation.

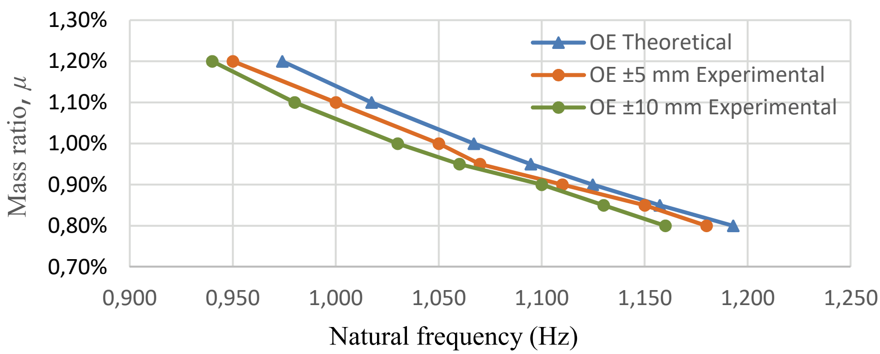


Figure 7 - OE TLCD frequency-mass ratio relation.

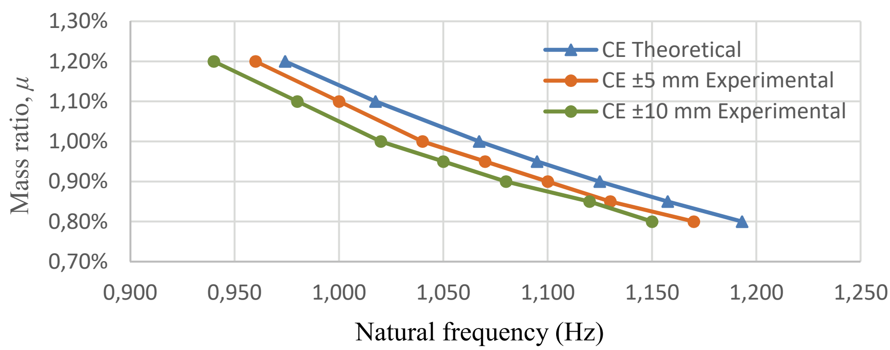


Figure 8 - CE TLCD frequency-mass ratio relation.

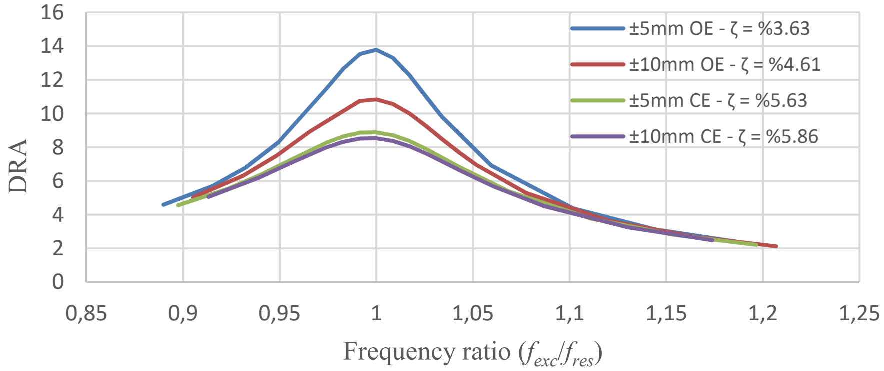


Figure 9 - DRA-frequency ratio relationship for mass ratio 0.80%.

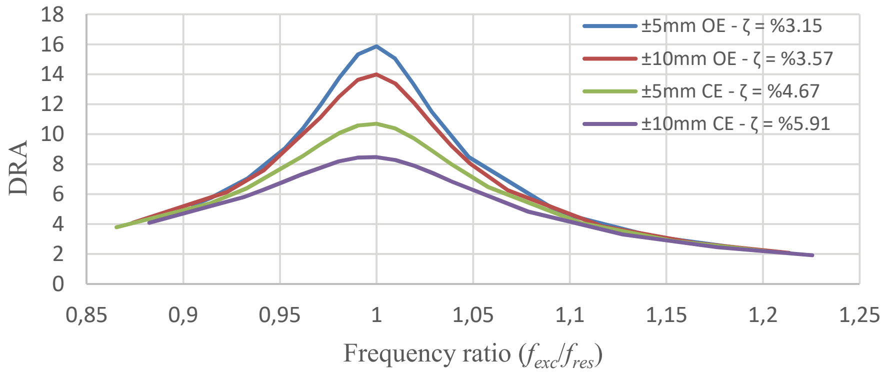


Figure 10 - DRA-frequency ratio relationship for mass ratio 1.00%.

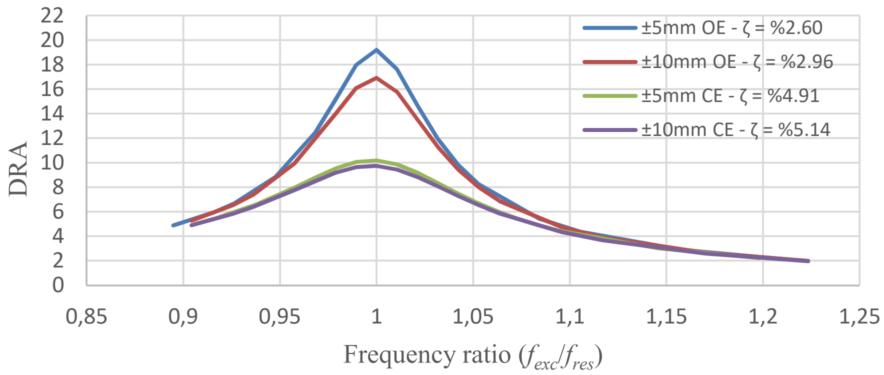


Figure 11 - DRA-frequency ratio relationship for mass ratio 1.20%.

The DRA-frequency ratio curves corresponding to the displacement responses of the system were calculated using Equation (9). DRA-frequency ratio curves were obtained for 0.80%, 1.00%, and 1.20% mass ratios to investigate the effect of OE and CE forms on the damping ratio under harmonic excitation amplitude. Figures 9 - 11 show the DRA-frequency ratio curves for mass ratios of 0.80%, 1.00%, and 1.20%, respectively.

TLCD systems were subjected to frequency scanning tests using a shake table at around resonance frequencies. As a result, Figure 12 shows the peak amplitude values at steady-state oscillation corresponding to the resonant frequencies for two different harmonic excitation amplitudes of TLCDs with OE and CE for different mass ratios.

Figure 13 represents the frequency response curve obtained for an OE form and a mass ratio of 1.20%, which was determined by the frequency scanning test under ±5mm harmonic excitation and between 0.85 Hz and 1.15 Hz. The response amplitude obtained for the system's resonance frequency was observed at 0.96 Hz, which is 41.5 mm. The 3 dB projection points on the frequency axis are calculated as f_a = 0.93 Hz and f_b = 0.98 Hz. As a result, the damping ratio obtained using Equation (8) is 2.6%.

The damping ratio-mass ratio relationships were calculated by applying the 3dB method to the frequency-amplitude curves obtained by the frequency scanning method for OE and CE TLCD systems, as shown in Figure 14. This figure presents the effect of the mass ratio, harmonic excitation amplitude, and elbow form on the damping ratio of the TLCD. The effect of elbow form on response amplitude compared to damping ratio response can be observed from Figures 12 and 14. Although in Figure 12, OE ±5 mm and CE ±10 mm tests give similar results, significant differences can be seen in Figure 14.

The head loss coefficient ξ is determined by the orifice opening ratio, where ξ= 0 represents full orifice opening, and $\xi = \infty$ indicates full orifice closure, and it is widely acknowledged in the literature that the head loss coefficient depends not only on the mass ratio but also on the response amplitude of the TLCD [17]. In addition, the head loss is known to be caused by the fluid flow passing through the orifice in the horizontal column of the TLCD, but it can also be due to the form of elbows and the friction between the fluid and the inner walls of the TLCD [31]. In this respect, the head loss coefficients corresponding to the mass ratios were obtained in this study to observe the effect of the elbow form. Figure 15 shows the head loss coefficient corresponding to each mass ratio obtained using Equation (10).

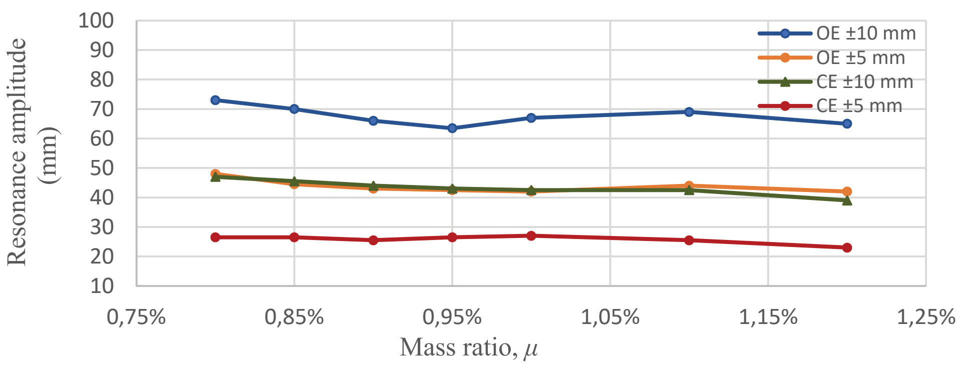


Figure 12 - Resonance amplitudes corresponding to the mass ratio of OE and CE TLCD.

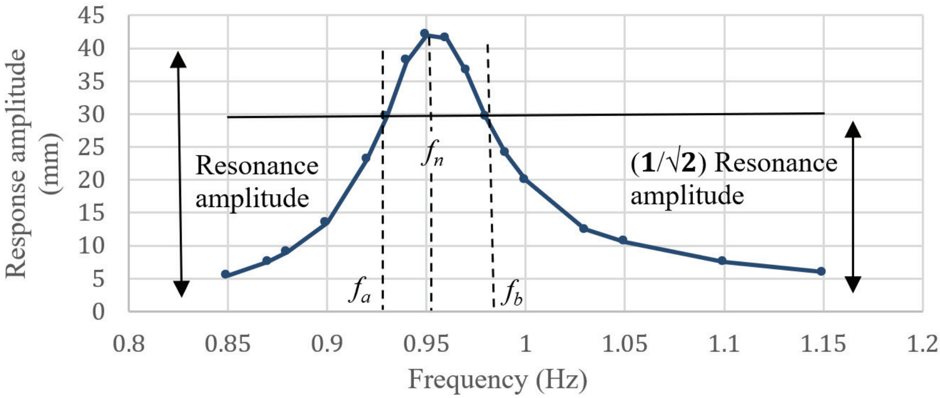


Figure 13 **-** *3dB method example of frequency response curve for a mass ratio of 1.20%.*

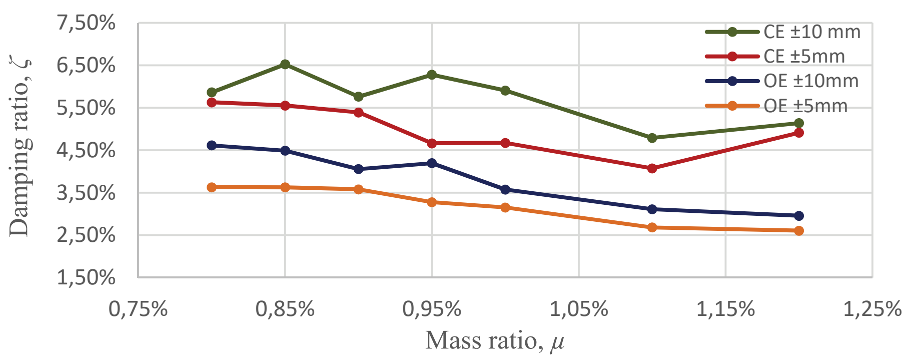


Figure 14 - Damping-mass ratio relation for OE and CE TLCD.

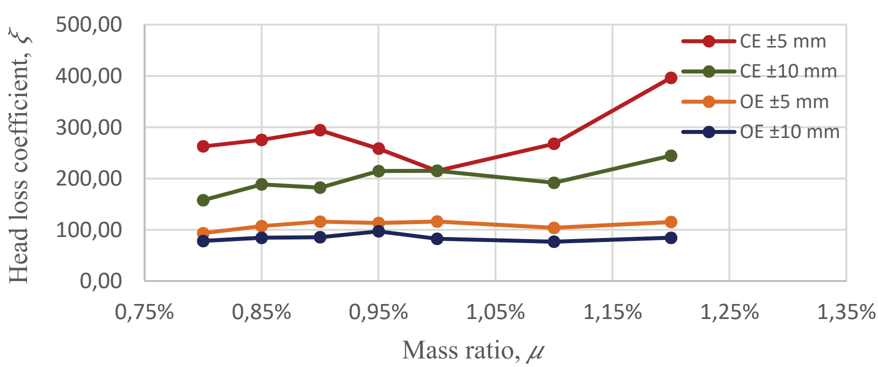


Figure 15 - Head loss coefficient-mass ratio relation for OE and CE TLCD.

4. ADJUSTING THE NUMERICAL ANALYSIS USING EXPERIMENTAL RESULTS

The vibration of a structure is damped by a TLCD through the gravitational restoring force exerted on the displaced fluid within the TLCD. At the same time, energy is dissipated through the viscous interaction between the TLCD fluid and its rigid walls. In addition, energy is lost through the orifices installed inside the TLCD container and elbows area [20, 26]. In this study, numerical analyses revealed that in representing the actual behavior by the equation of motion, an adjustment must be made in accordance with the experimentally determined harmonic behavior of the TLCD. A proposed set of coefficients, called Modification Factors (MF), is suggested to correlate the numerical results with the frequency-amplitude curves obtained from experimental results.

Figures 16 and 17 show numerical and experimental frequency-response curves for the mass ratio of 0.80% for the OE and CE, respectively. The equation proposed by Park et al. [20] with an equivalent damping ratio does not match the experimental results obtained in this study. Replacing the equivalent damping ratio with the experimental damping ratio, although the numerical response amplitude becomes closer to the experimental, resonance frequency shows a significant difference. The reason for this is that some of the liquid in the TLCD cannot participate in the motion due to friction and turbulence occurring in the elbows area. In this respect, mass (α) and stiffness (β) modification factors were obtained by considering experimental results. Equation (11) is used for α and β modification factors to minimize the difference between experimental and numerical results. As an example, using the calculated MF for OE and CE, it is found that the adjusted numerical results are now in good agreement with the experimental results, as shown in Figures 16 and 17. α and β coefficients are determined for the mass ratio of μ= 0.80% as 0.845 and 0.96 for the OE, and 0.975 and 0.95 for the CE, respectively.

$$\alpha m_d \ddot{y}(t) + 2m_d \omega_d \zeta_{eq} \dot{y}(t) + \beta\left(m_d \omega_d^2\right) y(t) = -m_h \ddot{x}_g(t) \tag{11}$$

The comparison of experimental and adjusted numerical results obtained for all mass ratios for CE and OE are shown in Figures 18 and 19, respectively. The mass and stiffness MFs related to this study might be applicable for the length ratio (B/L) resembling the specimens used in the experiments (0.34–0.6). The determined MFs for mass ratios are given in Table 2.

Table 2 - MFs according to mass ratios.

	OE		CE	
Mass ratio, μ (%)	α	β	α	β
0.80	0.845	0.960	0.974	0.950
0.85	0.850	0.965	0.930	0.950
0.90	0.848	0.968	0.941	0.950
0.95	0.8768	0.960	0.991	0.950
1.00	0.880	0.965	0.922	0.950
1.10	0.892	0.959	1.020	0.960
1.20	0.875	0.957	0.859	0.960

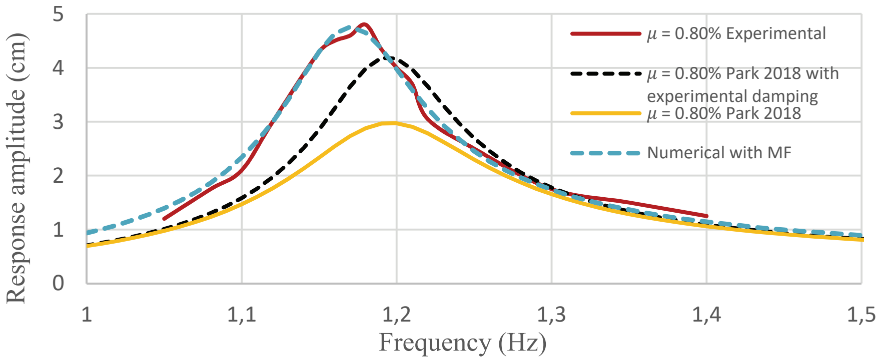


Figure 16 - Frequency-response curve for OE TLCD with a mass ratio of 0.80%.

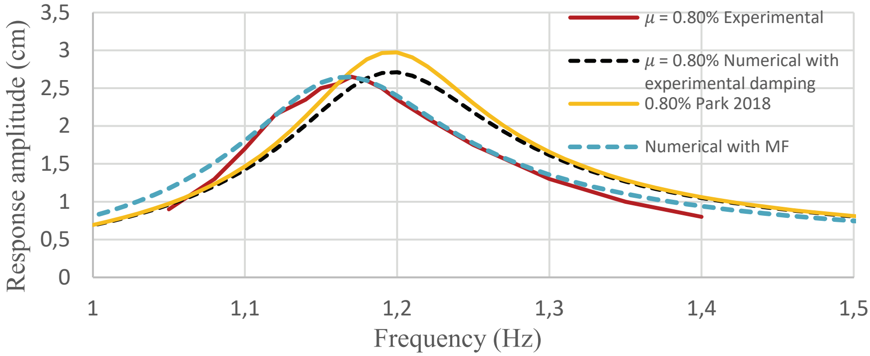


Figure 17 - Frequency-response curve for CE TLCD with a mass ratio of 0.80%.

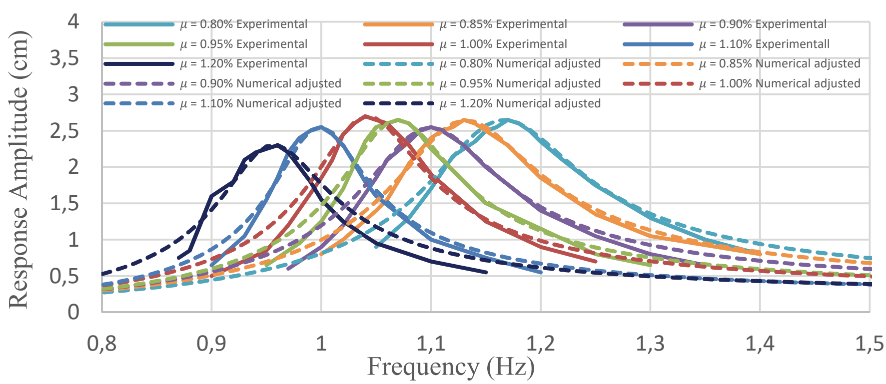


Figure 18 - Adjusted (numerical) and experimental frequency-response curves for CE TLCD.

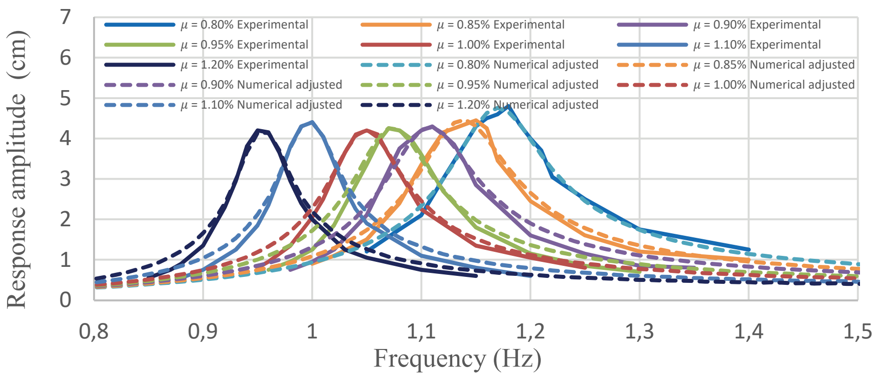
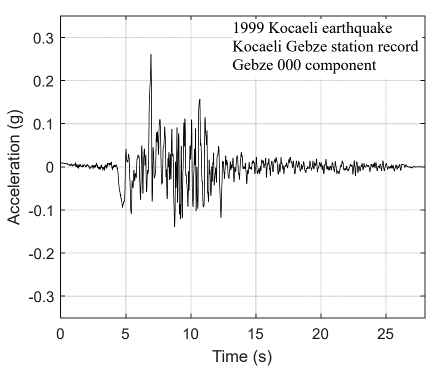


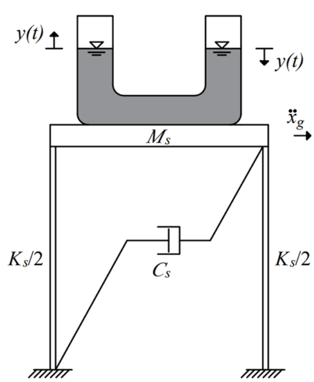
Figure 19 - Adjusted (numerical) and experimental frequency-response curves for OE TLCD.

5. NUMERICAL ANALYSIS OF A SDOF SYSTEM COUPLED WITH TLCD

A SDOF building model is represented to investigate the interaction between the structure and the TLCD. M_s, C_s, and K_s denote the mass, damping, and stiffness of the structure, respectively, as shown in Figure 20b. Horizontal component acceleration records of the 1999 Kocaeli earthquake that is shown in Figure 20a were obtained from the PEER Strong Ground Motion Database [38]. The damping ratio of the SDOF system is assumed to be 5%. M_s and C_s are assumed to be 101.9368 kg (total weight= 1 kN) and 5500 N/cm, respectively. The dynamic equation of the SDOF system coupled with TLCD is expressed in Equation (12). The time history analyses are conducted using the Newmark linear acceleration method [30] using Equation (12).

$$\begin{bmatrix} M_s + m_d & m_h \\ m_h & m_d \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix} + \begin{bmatrix} C_s & 0 \\ 0 & 2m_d \omega_d \zeta_{eq} \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix} + \begin{bmatrix} K_s & 0 \\ 0 & m_d \omega_d^2 \end{bmatrix} \begin{Bmatrix} x \\ y \end{Bmatrix} = -\begin{Bmatrix} M_s + m_d \\ m_h \end{Bmatrix} \ddot{x}_g \qquad (12)$$





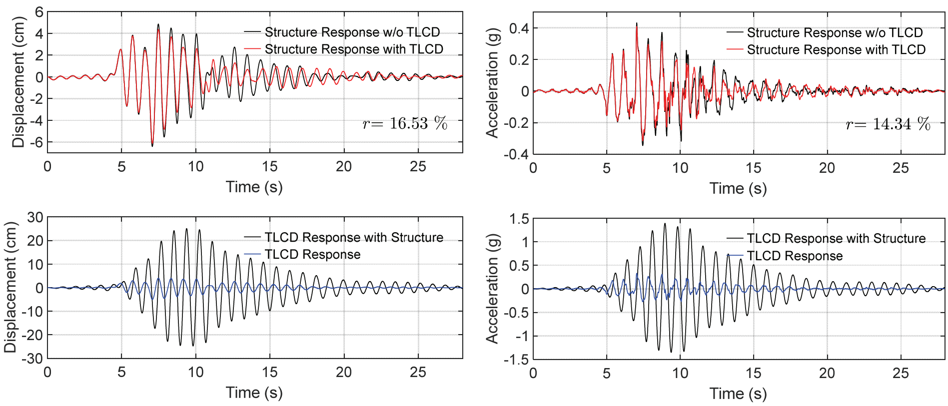
(a) (b)

Figure 20 - (a) Kocaeli Earthquake record, (b) Representation of modeling of TLCD installed on a SDOF system.

The OE and CE TLCDs were found to be successful in reducing the acceleration and displacement responses of the SDOF system. To show the control performance of OE and CE, the root-mean-square (RMS) ratio (r) of the acceleration values was calculated using Equation (13). As a result, the TLCD with an OE reduces the RMS ratio by 14.34%, while the CE reduces it by 11.53%.

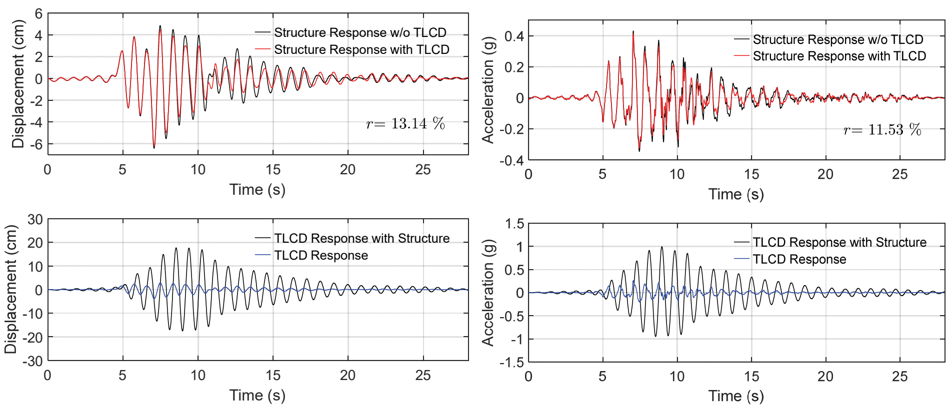
$$r = \left(\frac{\mathrm{RMS}_{WOT} - \mathrm{RMS}_{WT}}{\mathrm{RMS}_{WOT}} \right) \times 100 \tag{13}$$

The Kocaeli Earthquake was applied to the SDOF system to examine the seismic performance of OE and CE TLCD systems. The acceleration and displacement responses of the SDOF system are shown in Figures 21 and 22, respectively.



(a) (b)

Figure 21 - Time history curves for OE: (a) displacement response of SDOF system and TLCD, (b) acceleration response of SDOF system and TLCD



(a) (b)

Figure 22 - Time history curves for CE: (a) displacement response of SDOF system and TLCD, (b) acceleration response of SDOF system and TLCD

6. CONCLUSIONS

The dynamic characteristics and damping ratio of TLCDs with two different elbow forms with the same theoretical frequencies are investigated experimentally. The following findings are obtained by comparing the empirical and theoretical results for each mass ratio.

- Passive dampers are widely recognized for their ease of installation and ability to counteract vibrations caused by wind and strong ground motions without relying on active control. Therefore, additional damping may be required to avoid the dynamic effects of these external excitations. This study shows that additional damping can be provided to the structure by modifying the elbow shape of the TLCD without changing its dimensions, which does not require additional space.
- Empirical results indicated a decreasing trend in resonance amplitude as the mass ratio increased, while the response curves showed nonlinear behavior.
- As a result of the harmonic excitations, the maximum difference between the theoretical and experimental natural frequencies was obtained for each mass ratio when the harmonic excitation amplitude was ±10 mm. This value reached 4.624% for CE and 3.810% for OE TLCD designs.
- In the experiments performed for the harmonic excitation amplitude of ±5 mm, the maximum difference between the experimental and theoretical frequencies reached 2.612% and 2.530% for the CE and OE, respectively.
- It is inferred that the difference between the theoretical and experimental frequencies is due to the surface friction of the fluid in the TLCD. However, considering that the differences from the experimental results are within 5%, it can be interpreted that the results are in an acceptable range.
- Experimental natural frequencies obtained for OE and CE TLCD configurations with equal theoretical frequencies show that the largest difference between OE and CE TLCDs was 5.26% under ±5 mm harmonic excitation at a mass ratio of 1.20%. For ±10 mm harmonic excitation, the difference was 1.85% for a mass ratio of 0.90%.
- This study has experimentally demonstrated that the head loss coefficient depends not only on the opening ratio of the orifice but also on the form of the elbow, considering two types of TLCD designs with OE and CE forms.
- It was found that the elbow form significantly affects the damping ratio of the TLCD system when the same mass ratios are considered. It can be concluded that the damping performance of the TLCD with CE form is superior to that of the OE. This result is also related to the harmonic excitation amplitude. In the design of the TLCD, the excitation amplitude should also be considered an important parameter.
- Considering the earthquake performance of TLCD through the numerical analysis results, OE shows superiority over the CE. The comparison of the damping performance on acceleration and displacement time histories using RMS ratios shows that OE has an advantage of approximately 25% over CE.
- The equivalent damping proposed by Park et al. [20] has been compared with experimental results, revealing discrepancies. Adjustments to the motion equations have

been made using modification factors based on experimentally obtained damping ratios, aiming to minimize the difference between experimental and numerical results. Obtained MFs are valid for the length ratios of between 0.34 and 0.6.

- In this study, the control performance of TLCD is investigated by considering the elbow form, and adjusted numerical analyses are performed. Future studies are suggested to investigate the optimal elbow forms.

Symbols

A	: Cross-sectional area of the TLCD
B	: Effective horizontal length of the TLCD system
c_{eq}	: The equivalent damping coefficient
C_s	: Damping coefficient of SDOF system
g	: Acceleration of gravity
L	: Total length of liquid in the TLCD
L_1	: Out-to-outer length of the TLCD system
K_s	: Stiffness of SDOF system
m_d	: Liquid mass in the TLCD system
m_h	: Mass of liquid in the horizontal column of the TLCD
m_s	: Mass of structural model
M_s	: Mass of SDOF system
RMS_{WOT}	: RMS value of SDOF system without TLCD
RMS_{WT}	: RMS value of SDOF system with TLCD
r	: RMS ratio
t	: Time
x	: Displacement response of SDOF system
$\dot{x}$	: Velocity response of SDOF system
$\ddot{x}$	: Acceleration response of SDOF system
$\ddot{x}_g$	: Ground acceleration
x_r	: Amplitude of the resonance frequency
y	: Displacement response of the fluid in the TLCD
$\dot{y}$	: Velocity response of the liquid in the TLCD
$\ddot{y}$	: Acceleration response of the fluid in the TLCD

α	: Mass modification factor for liquid in the TLCD
β	: Stiffness modification factor for the TLCD
ε	: Error between the nonlinear system and equivalent linear system
ζ	: Damping ratio
μ	: Mass ratio
ξ	: Head loss coefficient
ρ	: Density of the liquid
$\sigma_{\dot{y}}$	: Standard deviation of the water surface velocity of water column $\dot{y}$
χ	: Tuning ratio
ω	: Excitation frequency
ω_d	: Angular frequency of TLCD
ω_s	: Angular frequency of structure model

References

[1] Sakai, F., Takaeda, S., Tamaki, T., Tuned liquid column damper new type device for suppression of building vibration, Proc. Int. Con. on High-rise Buildings, Nanjing, China, 1989, 926-931, 1989.

[2] Kwok, K.C.S., Samali, B., Xu, Y.L., Control of wind induced vibration of tall structures by optimised tuned liquid column dampers, Proc. Asia-Pacific Conf. On Computational Mechanics, Hong Kong, 569-574, 1991.

[3] Samali, B., Kwok, K.C.S., Young, G., Xu, Y. L., Effectiveness of optimised tuned liquid column dampers in controlling vibration of tall buildings subject to strong ground motions, Proc. 2nd Int. Conf on Highrise Buildings, Nanjing, China, 402 -407, 1992.

[4] Samali, B, Kwok, K.C.S., Parsanejad, S., Xu, Y.L., Vibration control of buildings by tuned liquid column dampers, Proc. 2nd hzt. Conf on Highrise Buildings, Nanjing, China, 425-430, 1992.

[5] Xu, Y.L., Samali, B., Kwok, K.C.S., Control of along-wind response of structures by mass and liquid dampers, Journal of Engineering Mechanics- ASCE, 118 (1), 20-39, 1992.

[6] Xu, Y.L., Kwok, K.C.S., Samali, B., The effect of tuned mass dampers and liquid dampers on cross-wind response of tall/slender structures, Journal of Wind Engineering and Industrial Aerodynamics, 10, 33-54, 1992.

[7] Aydın, E., Öztürk, Kebeli, Bati, M., Kavaz, Y., Kilic, B., Effects of Tuned Liquid Column Damper Properties on The Dynamic Response of Structures, ASCE-EMI 2019 International Conference, 2019.

[8] Gao, H., Kwok, K.C.S., Samali, B., Optimization of tuned liquid column dampers. Engineering Structures, 19(6), 476–86, 1997.

[9] Yalla, S.K., Kareem, A., Optimum absorber parameters for tuned liquid column dampers, Journal of Structural Engineering, 126(8), 906–15, 2000.

[10] Wu, J.C., Chang C.H., Lin, Y.Y., Optimal design of non-uniform tuned liquid column dampers in horizontal motion, Journal of Sound and Vibration, 326, 104–22, 2009.

[11] Shum, K.M., Closed form optimal solution of a tuned liquid column damper for suppressing harmonic vibration of structures, Engineering Structures, 31, 84–92, 2009.

[12] Hochrainer, M.J., Ziegler, F., Control of tall building vibrations by sealed tuned liquid column dampers, Structural Control Health Monitoring, 13, 980–1002, 2006.

[13] Balendra, T., Wang, C.M., Cheong H.G., Effectiveness of tuned liquid column dampers for vibration control of towers, Engineering Structures, 17(9), 668-678, 1995.

[14] Min, K.W., Kim H.S, Lee S.H, Kim H., Ahn S.K., Performance evaluation of tuned liquid column dampers for response control of a 76-story benchmark building, Engineering Structures, 27, 1101-1112, 2005.

[15] Bigdeli, Y., Kim, D., Damping Effects of the Passive Control Devices on Structural Vibration Control: TMD, TLC and TLCD for Varying Total Masses, KSCE journal of Engineering, 20, 301-308, 2016.

[16] Balendra, T., Wang, C.M., Rakesh, G., Vibration control of various types of buildings using TLCD, Journal of Wind Engineering and Industrial Aerodynamics, 83, 197–208, 1999.

[17] Sadek, F., Mohraz B., Lew, H.S., Single- and multiple-tuned liquid column dampers for seismic applications, Earthquake Engineering and Structural Dynamics, 27, 439– 63, 1998.

[18] Gao, H., Kwok, K.S.C., Samali, B., Characteristics of multiple tuned liquid column dampers in suppressing structural vibration, Engineering Structures, 21, 316–331, 1999.

[19] Hitchcock, P.A., Glanville, M.J., Kwok, K.C.S., Watkins, R.D., Samali, B., Damping properties and wind-induced response of a steel frame tower fitted with liquid column vibration absorbers, Journal of Wind Engineering and Industrial Aerodynamics, 83,183-196, 1999.

[20] Park, B.J., Lee, Y.J., Park, M.J., Ju, Y.K., Vibration control of a structure by a tuned liquid column damper with embossments, Engineering Structures, 168 290–299, 2018.

[21] Gur, S., Roy K., Mishra, S.K., Tuned liquid column ball damper for seismic vibration control, Structural Control and Health Monitoring, 22, 1325–1342, 2015.

[22] Lee, S.K., Min, K.W., Lee, H.R., Parameter identification of new bidirectional tuned liquid column and sloshing dampers, Journal of Sound and Vibration, 330 (7), 1312-1327, 2011.

[23] Lee, H.R., Min, K.W., Reducing Acceleration Response of a SDOF Structure with a Bi-Directional Liquid Damper, Procedia Engineering, 14, 1237-1244, 2011.

[24] Matteo, A.D., Iacono, F.L., Navarra, G., Pirrotta, A., Direct evaluation of the equivalent linear damping for TLCD systems in random vibration for pre-design purposes, International Journal of Non-linear Mechanics, 63, 19-30, 2014.

[25] Matteo, A.D., Iacono, F.L., Navarra, G., Pirrotta, A., Experimental validation of a direct pre-design formula for TLCD, Engineering Structures, 75, 528-538, 2014.

[26] Hitchcock, P.A., Kwok, K.C.S., Watkins, R.D., Samali, B., Characteristics of liquid column vibration absorbers (LCVA)-I, Engineering Structures, 19 (2), 126-134, 1997.

[27] Balendra, T., Wang, C.M., Rakesh, G., Effectiveness of TLCD on various structural systems, Engineering Structures, 21, 91–305, 1999.

[28] Chang, C.C., Hsu C.T., Control performance of liquid column vibration absorbers, Engineering Structure*s*, 20 (7), 580-586, 1998.

[29] Damcı, E., Şekerci, Ç., Development of a Low-Cost Single-Axis Shake Table Based on Arduino, Experimental Techniques, 43, 179-198, 2019.

[30] Chopra. A. K., Dynamics of structures: theory and applications to earthquake engineering, 4th Edition, Pearson Education, USA, ISBN: 978-0-13-285803-8, 2011.

[31] Wu, J.C., Shih, M.H., Lin, Y.Y., Shen, YC., Design Guidelines for tuned liquid column damper for structure responding to wind, Engineering Structures, 27, 1893-1905, 2005.

[32] Aydın, E., Öztürk, Kebeli, Y.E., Gültepe, G., An Experimental Study on the Effects of Different Pendulum Damper Designs on Structural Behavior, 17th World Conference on Seismic Isolation, 2022.

[33] Sarkar, A., Gudmestad, O.T., Pendulum type column damper (PLCD) for controlling vibrations of a structure – Theoretical and experimental study, Engineering Structures, 49, 221-233, 2013.

[34] Aydın, E., Öztürk, B., Dutkiewicz, M., Çetin, H., Okkay, O., Ohancan, U., Şirin, Y.E., Experiments of tuned liquid damper (TLD) on the reduced shear frame model under harmonic loads, EPJ Web of Conference, 143, 02001, 2017.

[35] Zhang, Z., Numerical and experimental investigations of the sloshing modal properties of sloped-bottom tuned liquid dampers for structural vibration control, Engineering Structures, 204, 2020.

[36] Ashasi-Sorkhabi, A., Malekghasemi, H., Ghaemmaghami, A., Mercan, O., Experimental investigations of tuned liquid damper-structure interactions in resonance considering multiple parameters, Journal of Sound and Vibration, 388, 141-153, 2017.

[37] Wen, Y.K., Design Equivalent Linearization for Hysteretic Systems Under Random Excitation, Journal of Applied Mechanics, 47(1), 150-4, 1980.

[38] PEER Ground Motion Database - PEER Center. http://ngawest2.berkeley.edu/ (Accessed, 9th May 2024).