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Experimental study on a new damping device for mitigation of structural vibrations under harmonic excitation

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Abstract. This manuscript introduces a new damping device which is composed of a water tank and a pendulum. The new damping device can be tuned to multiple frequencies. In addition, it has a higher energy dissipation capacity when compared with the conventional Tuned Liquid Dampers (TLDs). In order to evaluate the efficiency of this new damping device a series of free vibration and forced vibration tests were conducted on a scaled down single-story one-bay steel frame. Two different configurations were studied for the mass of the pendulum that included a completely and a partially submerged mass. It was observed that the completely submerged configuration led to 44% higher damping ratio when compared with the conventional TLD. In addition, the completely submerged configuration reduced the peak displacement response of the structure 1.6 times more than the conventional TLD. The peak acceleration response of the structure equipped with the new damping device was reduced twice more than the conventional TLD. It was also found that, when the excitation frequency is lower than the resonance frequency, the conventional TLD performs better than the partially submerged configuration of the new damping device.

Keywords: tuned liquid damper; free vibration; forced vibration; structural control; dynamic responses

1. Introduction

Increase in the construction of tall and slender buildings together with long span bridges have made the usage of supplemental damping devices inevitable. By providing additional damping, these devices can reduce structural vibrations to a safe and imperceptible level. Tuned liquid column dampers (TLCD), Tuned Mass Dampers (TMD) and Tuned Liquid Dampers (TLD) are among the most common type and widely employed dampers in the construction industry. Among these devices, tuned mass dampers have shown to be more effective in controlling vibrations especially when they have been used as an active vibration controller (Zhang *et al*. 2016, Yang *et al*. 2016). However, construction and maintenance costs of this type of dampers are significantly higher than TLCDs and TLDs. Therefore, in order to achieve to a cost-effective supplemental damping device, many researchers have tried to enhance the performance of conventional TLCDs (Behbahani *et al*. 2017a, Behbahani *et al*. 2017b) and TLDs (Ruiz *et al*. 2016a, Soliman *et al*. 2016).

Owing to low initial and maintenance costs, ease of installation, ease of frequency tuning and no limit of vibration amplitude, TLDs have been a popular damping device for research and practical application. They dissipate energy through intrinsic friction of the liquid, liquid boundary layer friction, floating particles, wave breakage etc. (Ashasi-Sorkhabi *et al*. 2017, Tamura *et al*. 1995). Depending on the wave ratio (water depth (H)/wave length (L)), TLDs are classified into two groups; shallow water and deep water. In shallow water condition, the wave ratio is in the range of 0.5>H/L>0.04 to 0.05 (Sun and Fujino 1994). Shallow water TLDs are well known for the wave breakage phenomena even under low amplitude excitation, which makes their dynamic response nonlinear. However, the shallow water TLDs often provide larger damping under small excitation amplitude when compared to the deep water TLDs (Fediw 1992). The main characteristics of deep water TLDs are relatively linear behaviour for large amplitude excitations and comparatively lower damping (Kim *et al*. 2006). Moreover, in deep water configuration, not all the water inside the tank contributes to energy dissipation (Shad *et al*. 2016).

In recent years, TLDs have gone through many modifications in order to enhance their effectiveness in reducing structural vibrations. Many researchers have tried to augment the relatively lower damping capacity of conventional TLDs. Installation of metal screens inside the water tank of TLDS was one of the early modifications in this regard. It was shown that metal screens were effective for increasing the damping of conventional TLDs and were able to attenuate the nonlinearity of liquid motion (Zhao and Fujino 1993). Cassolato *et al*. (2011) showed that change in the angle of inclined screens can alter the

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damping ratio of TLDs. They also reported that inclined slat screen could result in a constant damping ratio over a range of excitation amplitude. In addition to screens, baffles have been also employed in TLDs in order to enhance their damping capacity. The effectiveness of bottom-mounted baffles with different blockage ratios for increasing the damping capacity of conventional TLDs was examined by Shad *et al*. (2016). It was reported that the TLD with 30% blocking ratio reduced the peak acceleration response of a single-degree-of -freedom structure up to 75% while the conventional TLD reduced it around 58%. In another study, Xue *et al*. (2017) investigated the effect of different configurations for bottom-mounted vertical baffles on suppressing sloshing pressure of TLDs. They showed that perforated vertical baffles suppressed sloshing pressure more than surface-piercing bottom-mounted vertical baffle, especially in high forcing frequency region. As a cost-effective method to reduce the wind-induced vibration of wind turbines, Chen and Georgakis (2015) suggested a tuned liquid damper which was consisted of two-layer hemispherical containers, partially filled with water. Results of experimental tests on a 1/20 scaled model showed that the spherical TLD could effectively improve the anti-fatigue performance of the wind turbine tower. In order to increase the energy dissipation and reduce the forces acting on structures, a horizontal perforated plate was installed inside the tank of a conventional TLD by Jin *et al*. (2014). They reported that the horizontal perforated plate had a negligible influence on the sloshing frequency, however, it significantly reduced the wave amplitude inside the tank. A new type of TLD which was consisted of a traditional TLD with the addition of a floating roof was proposed by Ruiz *et al*. (2016b). A numerical model was developed for the damper and validated experimentally by a series of dynamic excitations. The proposed damper offered a significant level of vibration suppression. Soliman *et al*. (2017) employed screens in order to achieve optimal control performance over a wide range of loading conditions. In their semi-active TLD, the inclination angle of the damping screens was controlled by a gain scheduling scheme. In another study, rotatable baffles were installed inside a conventional TLD by Zahrai *et al*. (2012). The obtained results from a series of shake table tests showed that the dynamic magnification factor of the test structure under harmonic excitation was reduced 2.7%. Saha and Debbarma (2017) examined the application of multiple TLDs for vibration mitigation of a single-degree-of-freedom structure. Results of experimental tests indicated that multiple TLDs were not significantly more effective than a single TLD when the liquid sloshing in the single TLD was large.

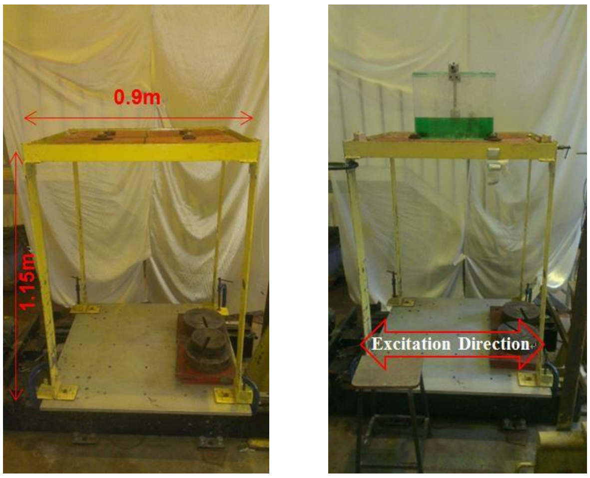
A review of the literature shows that there are ongoing efforts for augmenting the damping capacity of conventional TLDs. In this study, for enhancing the damping capacity of conventional TLDs, a submerged tuned pendulum is introduced. The tuned pendulum enhances the energy dissipation of conventional TLDs through increase in the water sloshing and wave breakage. In addition, in deep water TLDs, the pendulum can mobilize that part of the liquid which remains steady at the bottom of the tank during excitations (Tait *et al*. 2008). Therefore, it increases the anti-phase inertia force which is imparted to the structure by the liquid. Furthermore, while the sloshing frequency of the liquid can be tuned to the first resonance frequency of a structure, the natural frequency of the pendulum can be tuned to other resonance frequencies for the condition in which a multiple-mode damper is needed (Koh *et al*. 1995). It should be also mentioned that, since the natural frequency of a pendulum is related to its arm length, multiple pendulums with different lengths can be used in order to tune a conventional TLD to multiple frequencies without changing its depth ratio (i.e., the ratio of water depth to the tank length). In other words, pendulums are tuned to the natural frequencies of important mode shapes of the structure and then installed inside the water tank of the TLD. In this case, the total mass of the TLD can be distributed between the water and pendulums based on the effective modal masses that are obtained for each mode shape.

This paper employs a scaled down Single-Degree-of-Freedom (SDOF) structure in order to conduct extensive experimental tests on the modified TLD system. In the next sections, at first, specifications of the test structure together with the new damping device which will be referred to as PTLD are illustrated. Then, the performed experimental tests are presented and discussed.

2. Specification of the test structure and designed TLD and PTLDs

As mentioned in the previous section, in order to make the obtained results from PTLDs easily comparable with the conventional TLDs, a SDOF structure was designed and constructed for this study. Two important characteristics were considered in the design and scaling of the test structure. The first characteristic was related to the natural frequency of the test structure. The stuffiness and the mass of the test structure were adjusted in such a way that the resulted fundamental natural period became relatively large. The main reason for such design relies on the fact that TLDs are often installed on tall buildings that have a large natural period. The second characteristic of the test structure which was taken into account was its damping ratio. Supplemental damping devices like TLDs are often installed on structures that have a low damping ratio. Therefore, the damping ratio of the test structure was kept around 1%. It should be mentioned that a similar scaling scheme has been employed by other researchers (e.g., Jin *et al*. 2007) in order to make the obtained results from experimental tests conducted on TLD-structure systems comparable with those in real-life.

The test structure, as shown in Fig. 1(a), is a one-bay single story steel frame with the total height of 1.15 m. It has an identical span length of 0.9 m in both principal directions. All columns are constructed by mild steel plates having 6 mm thickness and 100 mm width. All beams are constructed by steel angles with the sizes of 60x60 mm and thickness of 6 mm. All beam-to-column connections are fixed. In addition, a fixed connection was designed and constructed for the base of columns. The frame rests on a shaking table capable of generating harmonic displacements



(a) (b)

Fig. 1 (a) Steel frame used for experimental tests. (b) PTLD-frame system and direction of excitation

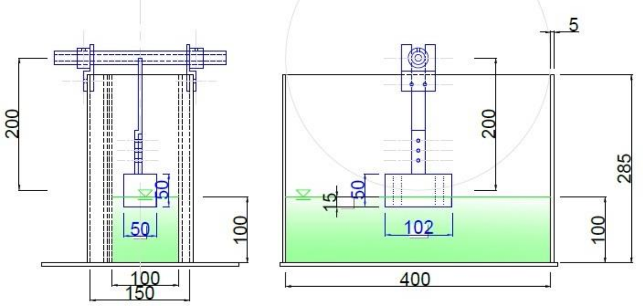


Fig. 2 Details of the proposed PTLD

having different frequencies. As shown in Fig. 1(b), in the experimental tests, the frame is excited perpendicular to the weak axis of columns. The total mass of the frame including the added mass to the roof is 228 kg.

The steel frame was equipped with an accelerometer located on its roof to measure acceleration responses and a LVDT at the same place to measure displacement responses. The type of accelerometer used in this study was DYTRAN, model 3110A with a sensitivity of 95.2 mV/g. The accelerometers were connected to the 8-channel SIRIUSi8 data acquisition system produced by DEWESoft. The SIRIUSi8 data acquisition system uses a combination of analogue filtering, oversampling and digital filtering in order to get the best possible anti-aliasing results. The analogue filter in the SIRIUSi8 is a 2nd order low-pass Butterworth filter which will switch its filter-frequency automatically, depending on the sampling rate. The LVDT was connected to an 8 channel SDA-810C data acquisition system produced by TML. It should be mentioned that accelerations were recorded every 0.005 sec. while displacements were measured every 0.05 sec A series of free vibration tests (which are presented in the next section) showed that the natural frequency of the frame is 1.12 Hz. This value is close to the fundamental natural frequency of a 9-story full- scale building (ASCE 2013).

Considering the dynamic characteristics of the steel frame, a conventional TLD with 0.4 m length, 0.15 m width, and 0.28 m height was constructed. This TLD represented a conventional TLD and was used as a reference for comparison with the results of PTLDs. In order to calculate the sloshing frequency of this TLD (f_w) the proposed equation by Housner (1963) (see Eq. (1)) was used. Based on this equation, the sloshing frequency depends on the TLD's length (L) and its water depth (H). By using Eq. (1), for a water depth of 0.1m, the sloshing frequency of the TLD is tuned to that of the steel frame. The 0.1 m water depth results in 6 kg mass for the TLD. Therefore, the mass ratio of the conventional TLD (defined as the mass of TLD to the mass of the steel frame) equaled 2.63%. It is noteworthy that the mass ratio employed in previous studies have been in the range of 1~4% (Ashasi-Sorkhabi *et al*. 2017). Herein, in order to make the influence of TLD installation on the dynamic responses more tangible, a slightly higher mass ratio compared to the average of previous studies is used (i.e., 2.63%).

$$f_w = \frac{1}{2\pi}\sqrt{\frac{3.16g}{L}tanh\left(\frac{3.16H}{L}\right)} \tag{1}$$

In order to investigate the effectiveness of the new damping device in suppressing structural responses, four different PTLDs were constructed. Fig. 2 displays the schematic view of the constructed PTLDs together with their pendulums. As can be seen from this figure and Table 1, PTLDs are similar to the conventional TLD in terms of their water depth and the length of their water tank, therefore, PTLDs and the TLD have similar sloshing frequency. However, all PTLDs have a pendulum at the middle length of their water tank. In order to make the obtained results from the conventional TLD and PTLDs comparable, their mass ratios were kept constant. Therefore, for all PTLDs, the mass of pendulum together with the water inside their tank was also 6 kg. As shown in Fig. 2, in order to adjust the mass ratio in PTLDs, a partition was placed inside their water tank. It should be mentioned that presence of the partition inside the tank alters the boundary condition and affects the energy dissipation that occurs through friction between tank walls and the water. However, it should be noted that at the resonance frequency, the excitation amplitude is large, therefore, breaking waves occur and energy is mostly dissipated due to wave breaking rather than the friction (Sun *et al*. 1995). Therefore, in this study, the effect of the partition on the damping capacity of PTLDs was considered to be insignificant.

Since the sloshing frequency is independent of the width of TLD's water tank, the volume of the water inside the tank of PTLDs can be adjusted based on the considered mass for the pendulum. Table 1 displays the sizes of tanks and the pendulum masses for the four studied PTLDs. It can be seen that the pendulum mass ratio (defined as the mass of pendulum to the mass of water in the conventional TLD (i.e. 6kg)) varies from 16.6% to 33.3%. All masses were cubical in shape and had similar dimensions of 50x50 mm perpendicular to the direction of excitation (see Fig. 2). However, their lengths were different and were calculated based on the total mass considered for each of them.

In this study, two different cases were investigated for

Table 1 Specification of studied PTLDs

Name of PTLD	Size of tank (cm)	Mass size (cm)	Pendulum mass ratio	Submerge Condition
PTLD 1	40x10x10	5x5x10.2	33.3%	Partially
PTLD 2	40x112x10	5x5x7.6	25%	Partially
PTLD 3	40x125x10	5x5x5.1	16.6%	Partially
PTLD 4	40x112x10	5x5x7.6	25%	Fully

PTLDs that included partially submerged pendulums and a fully submerged pendulum. As presented in Table 1 and displayed in Fig. 2, for the first three cases, all masses were partially submerged into the water such that only 15 mm of the front side of masses was inside the water. In the second case, which was only applied to the PTLD2 and referred to as PTLD4, the mass was totally submerged.

The length of the arm for pendulums was calculated such that their natural frequency was equal to that of the steel frame. This way, when a pendulum sways, its mass counteracts the excitation force and helps to reduce structural responses. Since the steel frame used in this study was intentionally designed to be a SDOF structure, only its first mode of vibration was significant for the dynamic responses and therefore, the natural frequencies of all pendulums were tuned to 1.12 Hz. It should be mentioned that for multi-degree-of-freedom structures, the natural frequency of the pendulum can be tuned to any mode shape's natural frequency that has a significant contribution to the dynamic responses. It should be also noted that, although in this study only one pendulum was employed in the damping device, installation of more pendulums is available if required.

As shown in Eq. (2), the natural frequency of a pendulum depends only on its arm's length (L_p) and gravitational acceleration (g).

For obtaining the natural frequency of 1.12 Hz, the arm length of pendulums should equal to 0.2 m. It is noteworthy that Eq. (2) has been obtained for the condition in which the rotation of the pendulum is small (i.e., less than 15 degree) and when there is no resistance against oscillation of the pendulum (i.e., friction with air). However, as shown in section 3.2, this equation has been able to estimate the natural frequency of the pendulum submerged in the water with a good accuracy.

It should be mentioned that since pendulums' arms were constructed from a lightweight material, their mass was not included in the calculations. Similarly, because of using a lightweight Perspex plates for fabrication of TLDs, the mass of their tanks was not included in this study.

$$f_r = \frac{1}{2\pi}\sqrt{\frac{g}{L_p}} \quad (2)$$

2. Experimental studies

Experimental studies in this research are divided into two groups that include free vibration and forced vibration tests. Free vibration tests were applied on the steel frame to estimate its natural frequency and damping ratio. In addition, free vibration tests were employed to estimate damping ratios of TLD-frame and PTLD-frame systems. All free vibration tests were repeated three times and the average of obtained results was reported in this paper. Forced vibration tests were first conducted on the TLD and PTLDs in order to examine the accuracy of natural frequencies calculated by Eqs. (1) and (2). Then, a series of forced vibration tests were conducted on the TLD-frame and PTLD-frame systems in order to compare their dynamic responses. In the next section, results related to the free vibration tests are presented, followed by an explanation of the forced vibration tests.

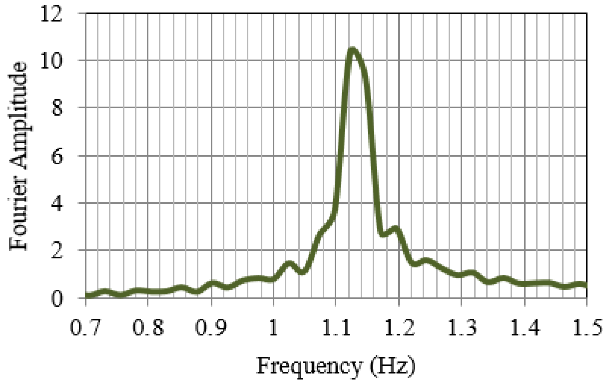


Fig. 3 FFT of steel frame's acceleration time history

3.1 Free vibration tests

The first free vibration test was performed on the steel frame to calculate its natural frequency and damping ratio. The frame was pulled 30 mm at its roof level and then it was released to vibrate freely. Then, displacement and acceleration responses were recorded. This test was repeated three times. By applying the fast Fourier transform (FFT) on the measured acceleration time histories the natural frequency of the steel frame was estimated. As can be seen from Fig. 3, a clear peak in the frequency domain of the decomposed signal indicates that the natural frequency of the frame is 1.12 Hz. Moreover, by applying logarithmic decrement technique on the measured displacement time histories, the damping ratio of the steel frame was estimated 0.9%, which was an indication for a lightly damped structure. Fig. 4 displays the displacement time history of the frame which is obtained from one of the free vibration tests.

In addition to the steel frame, the free vibration tests were applied to the TLD-Frame and PTLD-Frame systems. The main intention behind these free vibration tests was to investigate the increase in the damping ratio of the steel frame because of the presence of the TLD and PTLDs on its roof. Fig. 5 displays the displacement time histories obtained for the PTLD1 and TLD. A periodic increase and decrease in the displacement responses can be observed for both TLD-Frame and PTLD1-Frame systems, which are because of the beat phenomenon. Beats appear in the time histories of dynamic responses when two closely spaced frequencies (i.e., the TLD and the structure) exist in the

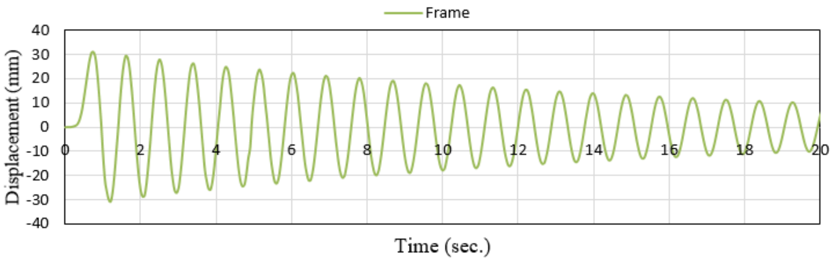


Fig. 4 Displacement time history of steel frame obtained from free vibration test

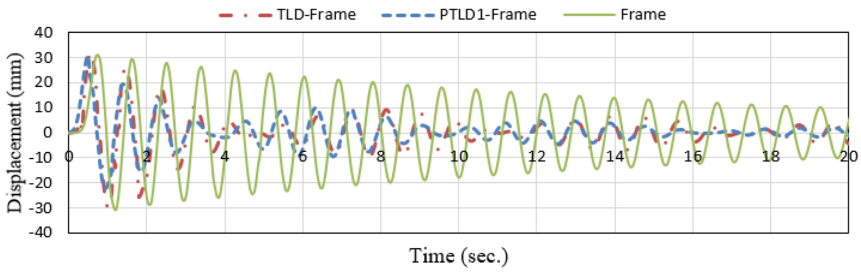


Fig. 5 Displacement time histories of PTLD1 and TLD obtained from free vibration tests

excited system. For example, in the current study, when the TLD is installed on the test structure, its mass is added to the total mass of the bare structure. This slightly alters the natural frequencies of the test structure when compared with the bare structure. Therefore, the tuning ratio will slightly differ from the considered value, which results in the beat phenomena. When the beat phenomenon occurs, a fraction of absorbed energy is transferred back from the liquid to the structure which appears in the measured signal through the periodic increase and decrease in the displacement responses. It should be noted that the beat phenomena has been also observed in the response of TLD-structure systems by other researchers (Yalla and Kareem 2001, Shad *et al.* 2018). It can be seen in Fig. 5 that compared to the TLD-Frame system, for the first four cycles of vibration, PTLD1-Frame exhibits smaller amplitudes for peaks in the displacement responses. However, after the occurrence of the beat phenomenon some out of phase responses can be observed for PTLD1-Frame compared to TLD-Frame system, which makes the comparison of displacement responses difficult. A similar trend to that of PTLD1-Frame system was observed for other PTLD-Frame systems when compared with the TLD-Frame system. Considering the first four cycles of displacement responses, the damping ratio of all structures were calculated using logarithmic decrement technique. Table 2 summarizes the obtained results. It can be seen that the presence of TLD on the roof of the frame has increased its damping ratio from 0.9% to 4.4%. In addition, compared to TLD-Frame system, PTLD-Frame systems have exhibited higher damping ratios. The maximum damping ratio for the cases in which the pendulum mass is partially submerged belongs to PTLD1, which is 56% more than that of the conventional TLD. Moreover, the PTLD4 that has a completely submerged pendulum mass provides 15% higher damping ratio compared to the PTLD2 which has a similar pendulum mass ratio but its mass is partially submerged. In addition, the PTLD4 shows 79% higher damping ratio

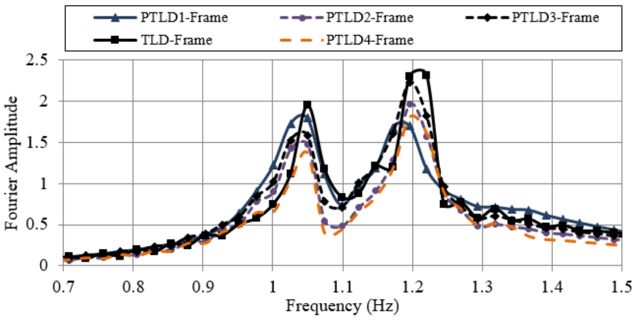


Fig. 6 Fast Fourier Transform of response accelerations obtained from free vibration tests

compared to the conventional TLD. These results indicate the enhancement in the damping ratio of the structure when pendulums are added to the conventional TLD. It is noteworthy that the increase in the pendulum mass has resulted in slightly higher damping ratio for partially submerged PTLDs.

Fig. 6 displays the FFT results of measured response accelerations for TLD-Frame and PTLD-Frame systems. Similar to Fig. 5, the presence of beat phenomenon can be seen in the decomposed signals. The existence of two peaks in the frequency domain is because of the closeness of natural frequencies of the TLD and PTLDs to that of the frame. In other words, coalescing of the modal frequencies of the combined TLD-Frame system has resulted in the beat phenomenon. It is noteworthy that the natural frequencies corresponding to the first and second peaks, respectively, are slightly smaller and larger than the natural frequency of the frame (i.e., 1.12 Hz). One clear observation from these peaks is that, compared to the TLD-Frame system, all PTLD-Frame systems show slightly smaller frequencies for the first and second peaks. However, since the differences are very small, it can be concluded that the presence of the pendulum inside the water tanks has had a negligible impact on the natural frequency when compared with the TLD-

Table 2 Results of damping ratios for different cases

Type of TLD	TLD-frame	PTLD1-frame	PTLD2-frame	PTLD3-frame	PTLD4-frame
Damping ratio	4.4%	6.9%	6.7%	6.5%	7.9%

Table 3 Measured sloshing frequencies and natural frequencies of pendulums

Type of TLD	TLD	PTLD1	PTLD2	PTLD3	PTLD4
Sloshing frequency (Hz)	1.12	1.12	1.10	1.10	1.12
Pendulum frequency(Hz)	-	1.13	1.12	1.12	1.14

Frame system. This observation correlates well with the results of forced vibration tests on PTLDs which are presented in the next section.

3.2 Forced vibration tests

Forced vibration tests were applied on the TLD, PTLDs, TLD-frame system and PTLD-frame systems. The main intention behind forced vibration tests on TLD and PTLDs was to examine the accuracy of natural frequencies calculated from Eqs. (1) and (2). Although the accuracy of these two equations has been demonstrated in the past studies, they have been obtained based on some assumptions that the presence of the pendulum inside the water tank could disturb them. Therefore, it was necessary to make sure that all sloshing frequencies and the natural frequency of pendulums have been calculated accurately when using the equations. In order to measure the sloshing frequencies and natural frequencies of pendulums, the TLD and PTLDs were fixed on a shake table capable of imposing controlled harmonic displacements to their base. Then, they were excited by a series of harmonic displacements with variable frequencies ranging from 0.95 Hz to 1.25 Hz (This range is around ±15% of the calculated frequencies using the equations).

A fast speed camera recorded the sloshing of the water and movements of the pendulums during excitations. Then, by using the recorded videos, the time for completing one cycle of movement was measured for the water inside tanks and pendulums. Since the height of water inside a TLD reaches its maximum when the frequency of excitation approaches its resonance frequency, the sloshing frequencies were easily determined by measuring and comparing the water heights at each excitation frequency. Similar procedure was employed to measure the natural frequencies of pendulums. Table 3 summarizes the average of three measurements of the natural frequencies. It can be seen that the calculated natural frequencies correlate well with those obtained from the equations. This indicates that the presence of pendulum inside the water tank has had a negligible effect on the sloshing frequency and the natural frequency of the pendulums. It is worth mentioning that, during forced vibration tests, the maximum displacement of the shake table was limited to 10 mm in order to prevent the water from spilling out of the tank. Fig. 7 shows the forced vibration test of PTLD4 when it is excited by a harmonic force with the 1.1 Hz frequency.

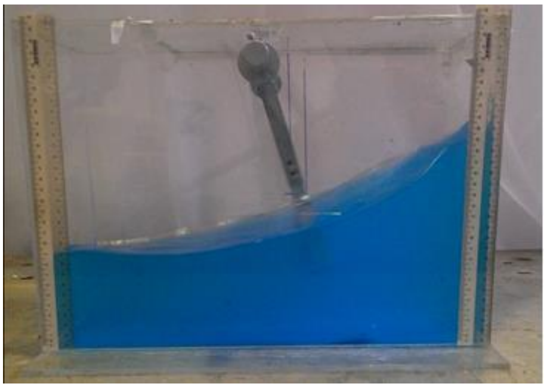


Fig. 7 Harmonic forced vibration test of PTLD4 when excited by 1.1 HZ frequency

Table 4 Reduction in the peak displacement response at the resonance frequency

TYPE	TLD-Frame	PTLD1-Frame	PTLD2-Frame	PTLD3-Frame	PTLD4-Frame
Reduction (%)	18.3	13.8	13.1	6.4	30.5

In the second phase of forced vibration tests, all TLD-Frame and PTLD-Frame systems were fixed on the shake table and were excited by a series of harmonic displacements at their base with variable frequencies ranging from 0.9 Hz to 1.29 Hz. Fig. 8 shows the sample of the time history of displacements with the frequency of 0.9 Hz which was applied to the base of the test structure. Fig. 9 displays the obtained results for maximum displacement responses measured at the roof level of the steel frame.

The first observation from this figure is that the peak responses of TLD-Frame and PTLD-Frame systems have occurred at different resonance frequencies. Similar to Fig. 6, resonance frequencies of PTLD-Frame systems are smaller than the TLD-Frame system. In other words, the addition of PTLDs to the frame has decreased the resonance frequencies of combined systems when compared to the TLD-Frame system and the bare frame. It can also be seen that all PTLD-Frame systems have reached their maximum displacement responses at an identical frequency of 1.1 Hz. This observation indicates that in PTLD-Frame systems, the pendulum mass ratio has no influence on the resonance frequency in which the maximum displacement response occurs.

Fig. 9 also shows that the maximum displacement response of TLD-Frame and PTLD-Frame systems are all smaller than that of the bare frame signifying the positive effect of TLD and PTLDs on the dynamic response of the bare frame at the resonance frequency. Table 4 summarizes the percentage of reductions in the peak displacement responses compared to the bare frame. As can be seen from this table, the least reduction belongs to the PTLD3-Frame system and the maximum reduction occurs for the PTLD4-Frame system. It can be also seen that the PTLD4-Frame system has a completely submerged mass compared to the PTLD2-Frame system that has similar pendulum mass ratio; however, its mass is partially submerged, thereby reducing

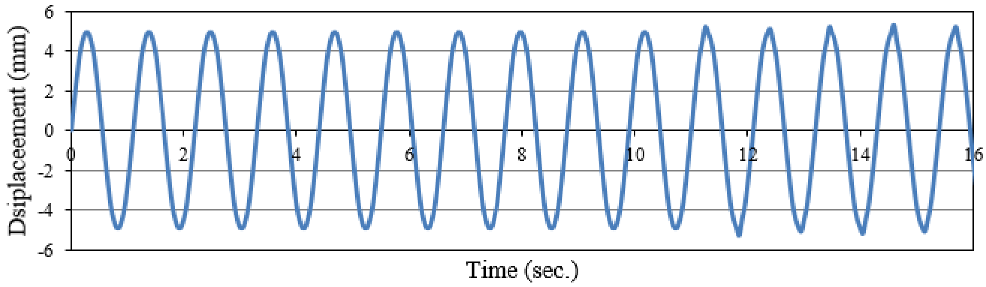


Fig. 8 A sample of the time history of displacement applied to the base of the structure

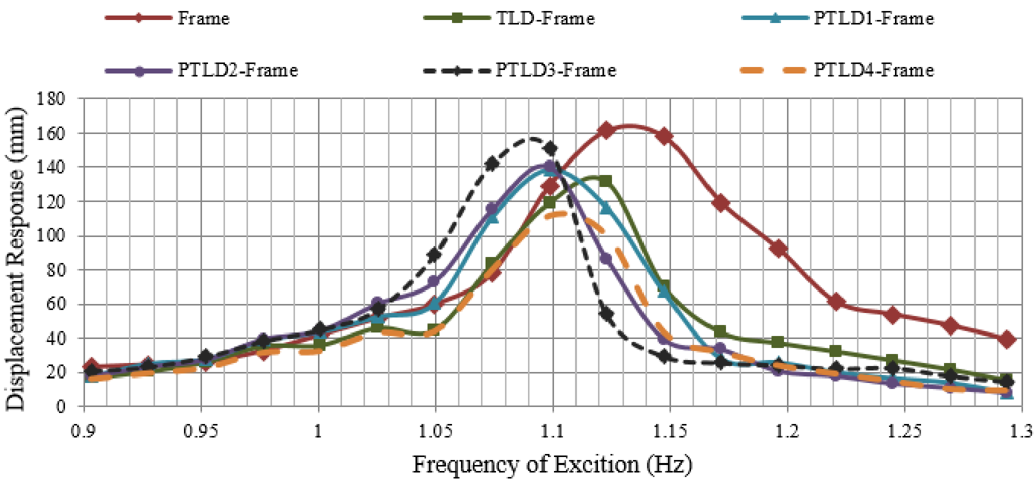


Fig. 9 Displacement responses obtained from forced vibration tests

the peak displacement more than twice. This implies that when the mass is completely submerged it can dissipate more energy compared to the time it is partially submerged. One main reason for this observation is that in deep water TLDs the water adjacent to the lower levels of the tank does not significantly contribute to the energy dissipation of the system and during excitation behaves like steady water (i.e., does not slosh). When the mass of the pendulum has completely submerged, the movements of its mass inside the water activates the steady water and increases its contribution to energy dissipation. The better performance of the completely submerged mass compared to the partially submerged mass can be also seen in the measured damping ratios presented in Table 2.

Another observation from Fig. 9 relates to the reduction in the displacement responses before and after resonance frequencies. Compared to the TLD-Frame system and the frame, PTLD1, PTLD2, and PTLD3-Frame systems show an increase in the displacement responses for excitation frequencies lower than their resonance frequency. However, after the resonance frequencies, their displacement responses are significantly smaller than that of TLD-Frame system and the bare frame. This implies that the partially submerged PTLDs are effective in reduction of displacement responses when the imposed load to the structure is rich in high frequencies (i.e., like earthquakes). On the other hand, for low-frequency excisions like wind load, the partially submerged PTLDs may not be helpful in mitigation of displacement responses. It should be noted that, unlike the partially submerged PTLDs, the PTLD4-Frame system has reduced the displacement responses for the entire range of exciton frequencies when compared with the TLD-Frame system and the bare frame. This again demonstrates the importance of the completely submerged configuration for activating the steady water inside the tank. Table 4 also indicates that increase in the pendulum mass ratio of partially submerged pendulums has led to a better performance for the PTLD-Frame systems at their resonance frequency.

Fig. 10 displays the maximum acceleration responses measured at the roof level of the steel frame under the forced vibration tests. Similar to Fig. 9, the peaks in the acceleration responses of PTLD-systems occur at a resonance frequency which is smaller than that of the TLD-Frame system and the bare frame. However, unlike Fig. 9, the peak of acceleration responses of all PTLD-systems not only are smaller than that of the bare frame but are also lower than that of the TLD-Frame system. This implies that the PTLD-Frame systems have been more effective in mitigation of maximum acceleration responses when compared with the TLD-Frame system. Table 5 displays the percentage reduction in the peak acceleration responses at the resonance frequencies compared to that of the bare frame.

In general, reductions in the peak acceleration responses are smaller than the peak displacement responses. In addition, it can be seen that similar to Table 4 increase in the pendulum mass ratio of the partially submerged PTLDs has slightly improved their efficiency at the resonance frequency. Table 5 also shows that, similar to displacement

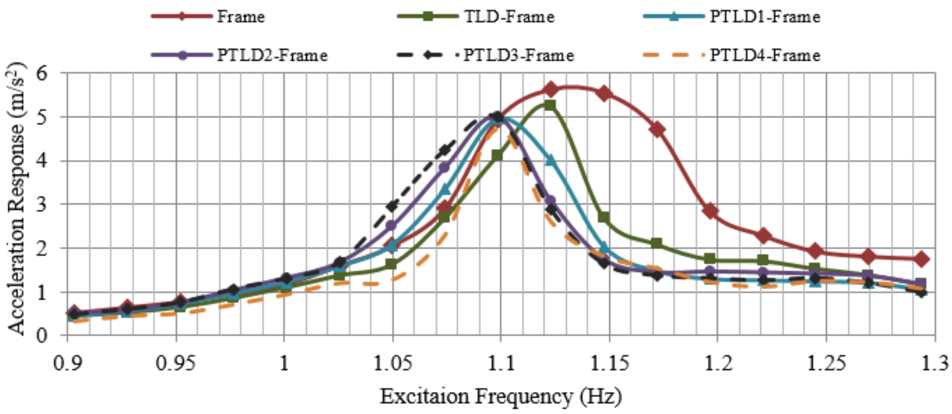


Fig. 10 Acceleration responses obtained from forced vibration tests

Table 5 Reduction in the peak acceleration responses at the resonance frequency

TYPE	TLD-Frame	PTLD1-Frame	PTLD2-Frame	PTLD3-Frame	PTLD4-Frame
Reduction (%)	6.7	11.6	11.1	10.9	15.7

Table 6 Comparison of damping ratios obtained from free vibration tests

	PTLD-structure	TU-structure	TB-structure
Damping ratio (%)	7.9	6.9	7.6

Table 7 Reduction in the peak displacement response of the test structure at its resonance frequency

	PTLD-structure	TU-structure	TB-structure
Reduction (%)	66	75	77

Table 8 Reduction in the peak acceleration response of the test structure at its resonance frequency

	PTLD-structure	TU-structure	TB-structure
Reduction (%)	67	76	75

responses, the maximum reduction in the acceleration responses belongs to the PTLD4-Frame system. From Fig. 10 it can be seen that acceleration responses for excitation frequencies lower than their resonance frequency are larger than that of TLD-frame system. However, for excitation frequencies larger than the resonance frequency, the measured acceleration responses are smaller than that of TLD-frame system. This observation is similar to the presented results for displacement responses. It can be also seen that the PTLD4-system before and after the resonance frequency results in smaller acceleration responses when compared with TLD-frame system and the bare frame.

In short, this can be concluded that, for the partially submerged configuration, the PTLD-Frame system can reduce displacement and acceleration responses more than TLD-frame system when the excitation frequency is larger than the resonance frequency. However, for the completely submerged configuration, the PTLD-Frame system can reduce displacement and acceleration responses more than TLD-Frame system regardless of excitation frequency.

4. Comparative study

A comparative study was performed between the results of this study and two other studies that used conventional TLDs modified by upper-mounted (TU) and bottom-mounted (TB) baffles (Shad *et al*. 2016, Shad *et al*. 2018). It should be mentioned that the test structure and the mass ratio of TLDs in all three studied cases have been similar. However, the amplitude of the applied displacement to the base of the test structure in the current study (i.e., 5 mm) has been twice larger the other two studies (2.5 mm). Table 6 compares the obtained maximum damping ratios of PTLD-systems with those obtained from the TU and TB-structure systems. It is evident from Table 6 that the installation of PTLDs on the test structure has resulted in a slightly larger damping ratio when compared with the TLDs modified by upper and bottom-mounted baffles. Table 7 compares the maximum reductions in the displacement response of the test structure when it is excited at its resonance frequency (i.e., 1.12 Hz). As the table shows, the TLD with the upper-mounted baffle has been able to reduce the peak displacement of the test structure 77% while PTLDs have reduced it 66%. It can also be seen from Table 8 that while PTLDs have been able to reduce the peak acceleration response of the test structure 67%, the TLD with upper-mounted baffle has reduced it 76%. These results indicate that the TLDs modified by the bottom and upper-mounted baffles have reduced the peak displacement and acceleration of the test structure, respectively, 14% and 11% more than PTLDs. It should be mentioned that although the TLDs modified by baffles show a better efficiency in reducing structural responses of the test structure at its resonance frequency, unlike PTLD4, they were unable to decrease the structural responses for the entire range of the excitation frequencies (Shad *et al*. 2016, Shad *et al*. 2018).

5. Conclusions

This study investigated the effectiveness of a modified TLD for suppressing structural responses under free and forced vibration tests. The modified TLD consisted of a conventional TLD and a tuned pendulum which was submerged inside its water tank. Four modified TLDs that were referred to as PTLDs were constructed and tested. The natural frequencies of water and pendulums were similar in all PTLDs, however, the value of their pendulum mass was different. For the sake of comparison, a conventional TLD with a similar mass ratio to that of PTLDs (i.e., 2.63%) was also constructed. The conventional TLD and PTLDs were installed separately on a single-story scaled steel structure and subjected to the free and forced vibration tests. Then, the displacement and acceleration responses were measured and compared. The obtained results from free and forced vibration tests can be summarized as follows:

I. The PTLD-structure systems exhibited a higher damping ratio when compared with the conventional TLD-structure system. The damping ratios of PTLD-structure systems were 47% to 79% larger than TLD-structure. The PTLD with the completely submerged pendulum had the largest damping ratio (i.e., 7.9%).

II. PTLD-structure systems decreased the peak displacement response of the test structure up to 30.5% while the conventional TLD-structure system decreased it 18.3%.

III. PTLD-structure systems decreased the peak acceleration response of the test structure up to 15.7% while the conventional TLD-structure system decreased it 6.7%.

IV. Unlike the conventional TLD, the PTLD with the completely submerged pendulum was able to decrease the peak displacement and acceleration responses of the test structure for the entire range of excitation frequencies.

V. It was also found that increase in the pendulum mass of partially submerged pendulums slightly enhanced their efficiency in suppressing structural responses.

VI. A comparative study showed that the completely submerged PTLD had, respectively, 14% and 4% larger damping ratio when compared with TLDs modified by upper and bottom-mounted baffles. However, TLDs modified by bottom and upper-mounted baffles were able to decrease the peak displacement and acceleration responses, respectively, 14% and 11% more than the completely submerged PTLD.

In general, the experimental results indicated that the proposed system can significantly enhance the damping capacity of conventional TLDs. However, the proposed system is more efficient for the use in deep water TLDs in which not all the water inside the tank contributes to the energy dissipation. It should be noted that more research needs to be conducted in order to develop a numerical model that can quantify the damping capacity of the proposed system based on the characteristics of the employed TLD and pendulums. It should be also mentioned that, for real application in full scale structures, since the size of the pendulum mass becomes large it is difficult to submerge it inside the water of the TLD. One solution to this problem is to use multiple pendulums. In other words, instead of having one large pendulum which is tuned to the required natural frequency of the structure, many smaller size pendulums but with the same natural frequency are used.

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