Comparative study of experimentally tested tuned liquid column dampers

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In recent decades, studies on tuned liquid column damper (TLCD) performance are limited to numerical simulations, while comparative experimental studies in this direction are scarce. In this paper, a comparative experimental study on optimized TLCDs is presented. Specifically, using nonlinear constrained optimization, geometric layouts of TLCDs are designed for a four-story shear-frame structure, geometry being an influential element on TLCD dynamic behavior. The structural behavior is monitored using a wireless structural health monitoring system designed to measure and process acceleration responses. Results indicate that the TLCDs are tuned effectively since additional damping can be supplemented to the structure. In addition, it is observed that theoretically optimized TLCDs do not necessarily perform as anticipated, as a result from the interference of other physical governing factors.

Keywords: Tuned liquid column damper, structural control, structural health monitoring

1 Introduction

Developments in civil engineering technologies have resulted in significant performance enhancement of structures. Nowadays, an increasing number of structures are assumed to be intelligent, i.e. able to monitor the structural condition through structural health monitoring (SHM) systems as well as to minimize the effect of extreme loadings, by means of control devices (Ko & Ni 2003). SHM is a promising strategy for assessing the condition of structural systems and for estimating structural properties in an attempt to avert hazards posed to public safety as a result of structural degradation. These structural properties usually encompass structural dynamic parameters, such as natural frequencies, mode shapes, and damping ratios (Whelan et al. 2009). A typical SHM system comprises a sensor network, a data transfer unit and a data interpretation system, which measure structural response data, establish connections for transferring the data and analyze the data, respectively. An SHM system can be implemented with wireless or cable-based sensor networks. Wireless sensor networks (WSNs) are characterized by limitations with respect to power supply and to transmission reliability. However, due to the significant cost reduction in applying WSNs, a number of research attempts have been done to address the drawbacks of WSNs (Dragos & Smarsly 2015). SHM systems are frequently complemented with subsystems designed to modify the structural behavior, termed "structural control systems".

Structural control, which has been first introduced in the work of Yao (1972), has emerged as a modern and more effective alternative to conventional methods for minimizing the effect of dynamic loads. Generally speaking, structural control can be classified into three fields: passive (SOONG & DARGUSH 1997), semi-active (HROVAT et al. 1983), and active (SOONG 1990). Both semi-active and active systems require control algorithms, which may be sophisticated in real applications. In contrast, passive control systems are fail-safe systems that, despite their simplicity, could result in effective structural control. A special class of structural control systems, the "tuned liquid column dampers" (TLCDs) have attracted increasing attention. TLCDs, which have been introduced by FRAHM (1910), have emerged for the first time in civil engineering applications by SAKAI et al. (1991). ALTAY et al. (2014) have studied the towers of wind turbines under non-uniform steady-state turbulent wind flow using a U-shaped tank filled with a Newtonian liquid, which has added damping through oscillation of the liquid mass with respect to the structure. As a result, the TLCD has proven to be effective in reducing resonant vibrations of the tower and in improving fatigue life. Similar conclusions have also been reported by COLWELL & BASU (2009).

This paper presents a comparative study between different optimized TLCDs. Specifically, a series of TLCDs with different geometries are designed using an optimization approach and developed in the laboratory. Then, the TLCDs are mounted on a four-story shear-frame structure, and laboratory tests are conducted. During the tests, structural response data is recorded by a wireless SHM system, which is then used for comparing uncontrolled and controlled responses of the structure for each TLCD. In the second section of this paper, the design of the TLCDs is presented. Next, the experimental setup and the laboratory tests are described, followed by a discussion on the test results. The paper ends with a summary and conclusions as well as with an outlook on future research.

2 Design of tuned liquid column dampers

This section presents the design of the three tuned liquid column dampers used in this study. First, the mathematical background on TLCD operation is illuminated and, next, the TLCD optimal design process is described.

2.1 Mathematical background of tuned liquid column dampers

A TLCD consists of a U-shaped tank filled with a Newtonian liquid that oscillates out-of-phase with the structure on which the TLCD is mounted, as shown in Figure 1. As a result, the energy transferred from the structure to the TLCD is dissipated via the hydrodynamic head losses (LINSHENG et al. 2013). According to the nonlinear Bernoulli equation (ALTAY et al. 2014), the dynamics of the liquid in a TLCD are described as follows:

$$\ddot{u} + \delta\left|\dot{u}\right|\dot{u} + \omega_D^2 u = -\gamma_1\left(\ddot{x} + \ddot{x}_g\right)$$
$$\omega_D = \sqrt{\frac{2g}{L_1}\sin\alpha} \qquad \gamma_1 = \frac{H + 2V\cos\alpha}{L_1} \qquad L_1 = 2V + \frac{A_V}{A_H}H \tag{1}$$

In Equation (1), u is the stream of the liquid column, $\ddot{x}+\ddot{x}_g$ is the absolute acceleration of the structure under both dynamic forces and base excitation, and δ denotes pressure loss as a result of turbulence and friction effects. Parameter ω_D represents the natural frequency of the TLCD depending on the gravitational acceleration g, the inclination angle α, and the effective length L_1, which amplifies the liquid length by the ratio of the cross-sectional areas of the vertical segments A_v and of the horizontal segment A_H, respectively. Finally, γ_1 is a geometric factor determined by the geometry of the TLCD that scales the interaction force between the TLCD and the structure. The equation of motion of a single-degree-of-freedom (SDOF) structure equipped with a TLCD is as follows:

$$\ddot{x} + D_H \omega_H \dot{x} + \omega_H^2 x = -\ddot{x}_g + f(t) - \mu(\ddot{x} + \ddot{x}_g + \gamma_2 \ddot{x})$$
$$\gamma_2 = \frac{H + 2V\cos\alpha}{L_2} \qquad L_2 = 2V + \frac{A_H}{A_V} H \tag{2}$$

In Equation (2), $\mu(\ddot{x}+\ddot{x}_g+\gamma_2\ddot{x})$ is the damping force created by the motion of the liquid mass. Parameters D_H and ω_H are the total damping ratio (inherent to the structure plus the added damping from the TLCD) and the fundamental angular frequency of the structure, respectively, μ is the mass ratio of the liquid mass over the modal mass of the structure at the fundamental vibration mode, $\ddot{x}_g$ is the ground motion, $f(t)$ is the excitation force, and γ_2 is the second geometric factor of TLCD.

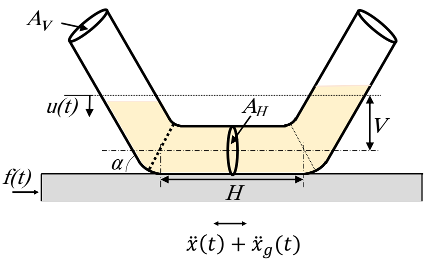

Fig. 1:
Schematic of a typical TLCD excited horizontally

2.2 Optimized design of tuned liquid column dampers

To design a TLCD, it is necessary to know the effect of the variables in Equations (1) and (2) on the dynamic behavior of the TLCD. For example, an increase in μ enhances the efficiency of the TLCD, and higher γ_1 and γ_2 parameters result in larger damping. However, increasing γ_1 also results in an increase of the interaction force between the TLCD and the structure, potentially causing sloping over the liquid. Thus, it is recommended to enhance damping effects by increasing γ_2. Other governing parameters are the optimal frequency $f_{D,opt}$, the optimal damping $D_{D,opt}$, and the active mass ratio μ^*, which are defined as follows:

$$f_{D,opt} = f_H \frac{\sqrt{1-\mu^*/2}}{1+\mu^*} \quad D_{D,opt} = \sqrt{\frac{\mu^*\left(1-\mu^*/4\right)}{4\left(1+\mu^*\right)\left(1-\mu^*/2\right)}} \quad \mu^* = \frac{\mu\gamma_1\gamma_2}{1+\mu\left(1-\gamma_1\gamma_2\right)} \tag{3}$$

Parameters $f_{D,opt}$, $D_{D,opt}$ and μ^* are obtained based on tuning criteria proposed by DEN HARTOG (1947) for tuned mass dampers, by substituting u with $u^* = u/\gamma_1$ in Equation (1) according to the specification proposed by WARBURTON & AYORINDE (1980) for stochastic excitations, such as earthquakes. The next step is to determine the target natural frequency and modal mass of the four-story shear frame structure to which the TLCDs are tuned. As shown in Figure 2, the structure is simulated as a lumped-mass model, which is used for performing modal analysis using finite element software (CLOUGH & PENZIEN 1993).

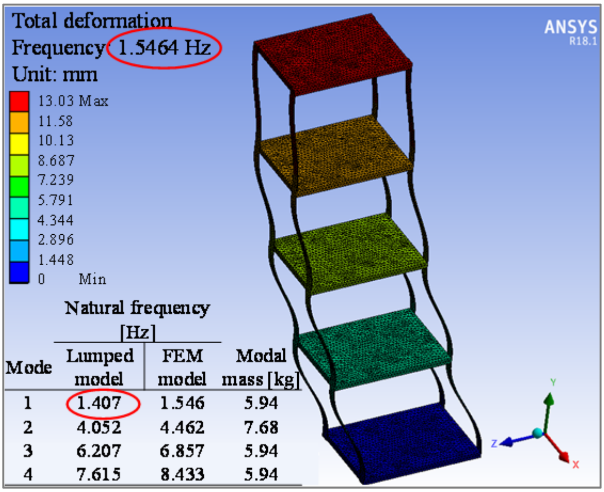

Fig. 2: Modal analysis of the four-story shear frame structure

For optimizing the TLCD layout, a nonlinear constrained optimization problem is formulated by using the generalized reduced gradient (GRG) method and by cross-validating the results via the Trust-Region-Method proposed by XUE & CHEN (2008). In the optimization, the geometric variables V, H, A_V, A_H and α, introduced in Figure 1 are considered. To constrain these variables, physical dimensions of the structure and commercial availability of components are taken into account. According to the aforementioned argument on TLCD efficiency, the objective function adopted for the optimization is $J = \gamma_1\gamma_2$.To consider the influence of the variation of angle α, three angles of 45°, 60°, and 90° are chosen, each corresponding to one of the three TLCDs designed in this study. Furthermore, for purposes of convenience in the manufacturing process, cross section dimensions A_V and A_H are selected close to each other. For TLCD mass calculation, the liquid considered is water. To ensure the TLCD efficiency, maximum tolerable discrepancies between the theoretical values for optimal frequencies and active mass ratios calculated from Equation (3) for each TLCD and the corresponding actual values (Δf_{max} and $\Delta\mu^*_{max}$) are limited to 1% and 0.1%, respectively. The theoretical active mass ratio is set for all cases equal to $\mu^* = 0.073$. The optimal parameters of the three TLCDs are presented in Table 1.

Table 1: Results of the optimization on three TLCDs

TLCD type	V [cm]	H [cm]	A_v [cm^2]	A_H [cm^2]	α [°]	m_D [kg]	f_D [Hz]	$D_{D,opt}$	Δf_{max}	$\Delta\mu^*_{max}$	J
TLCD-45	3.6	15.16	25.05	25.90	45	0.575	1.268	0.135	0.010	0.059	0.820
TLCD-60	3.7	18.93	25.50	25.50	60	0.671	1.279	0.138	0.002	0.100	0.739
TLCD-90	4.0	22.83	27.36	27.63	90	0.851	1.274	0.132	0.010	0.001	0.548

3 Experimental tests

In this section, the experimental tests conducted for performing the comparative study between the three TLCDs are presented. First, the experimental setup is described, next, the tests are shown, and, finally, the test results are discussed.

3.1 Experimental setup

The four-story shear-frame structure consists of aluminum plates of dimensions 300 mm × 200 mm × 15 mm (length × width × thickness) resting on four 20 mm × 2 mm aluminum columns. The plate-to-column connections are fully fixed, and the four columns are clamped to a base plate, which is fixed to a solid block ensuring full fixity at the column base. The story height is 300 mm. According to the optimization results, tubes of 63 mm outside diameter are employed. The tube thickness is selected equal to 1.8 mm for the $TLCD_{90^\circ}$ and 3 mm for the rest of the TLCDs. To control the flow of water, valves with 63 mm internal diameter are installed at the middle of the horizontal parts of the tubes. The layouts of the three TLCDs are illustrated in Figure 3.

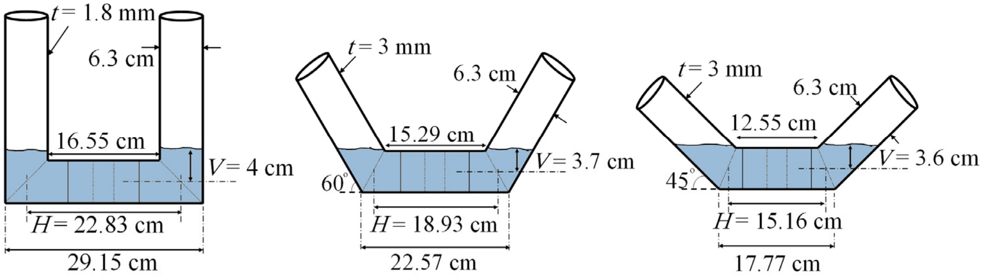

Fig. 3: Specifications of the designed TLCDs

For collecting SHM response data, Oracle SunSPOT wireless sensor nodes are used (ORACLE 2010). The sensor nodes include a Java programmable 400 MHz ARM microprocessor, 1 MB RAM for data storage and 4 MB flash memory. Sensor nodes are equipped with digital accelerometers measuring at sampling rates up to 250 Hz and at measurement ranges of ±2g, ±6g, or ±8g. The analog-to-digital conversion rate is 8 bit. As shown in Figure 4, one sensor node is placed at the center of each story.

To excite the structure, an initial deflection of 5 cm is applied at the top story, after which the structure vibrates freely. The TLCDs are tuned to the fundamental frequency of the structure, and the sampling rate for collecting acceleration response data is set equal to 125 Hz.

3.2 Results and discussion

To demonstrate the effect of the TLCDs on the structural behavior, the acceleration responses at the 4th story are shown for both uncontrolled and controlled states (i.e. without TLCDs and with TLCDs). The uncontrolled state is achieved by keeping the valve closed, while the controlled state corresponds to an open valve. The TLCDs are installed on the 4th story for all tests.

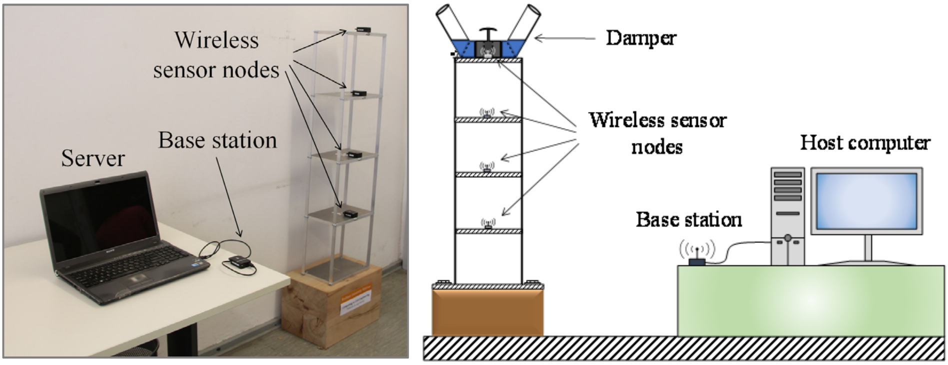

Fig. 4: Experimental setup

In the uncontrolled state, acceleration responses exhibit no notable reduction for the first 16 seconds of oscillation, as shown in Figure 5, thus indicating low damping. By contrast, a significant effect of damping can be seen in the responses of the controlled state shortly after initiating the excitation. The uncontrolled and controlled acceleration responses of the 4th story and the corresponding spectral amplitudes are presented for all TLCDs in Figure 5. According to the expected efficiency of each TLCD shown in Table 1, the $TLCD_{45^\circ}$ should show the highest damping effect and the $TLCD_{90^\circ}$ the lowest. However, the results of the tests displayed in Figure 5 show that the $TLCD_{90^\circ}$ actually performs best and the $TLCD_{45^\circ}$ demonstrates the worst performance. The disagreement between theoretical analysis and experimental results with respect to the TLCD performance can be attributed to two parameters: the mass of the liquid and the intrinsic damping in each device. In the optimization, the criterion kept constant for all three TLCDs is the active mass ratio of the liquid μ^*, which does not necessarily result in the same liquid mass m_D for each damper (see Table 1). In addition, each device produces different intrinsic damping based on its specifications. Inherently, in the 90° TLCD, friction effects at the corners are stronger than in other TLCDs; for improving the damping effects further tests are required, which fall beyond the scope of this paper.

In the frequency domain, it is observed in Figure 5 (bottom left) that all dampers are well-tuned to the fundamental natural frequency of the structure (around 1.59 Hz), since the spectral amplitudes are diminished at this frequency. At higher frequencies the peak suppression effect is smaller. Figure 5 (bottom right) also illustrates the better performance of $TLCD_{90^\circ}$ compared to the rest of the TLCDs, characterized by the splitting of the peak at the fundamental frequency of the bare frame into two adjacent frequencies following the fundamental principles of optimal tuned mass damper operation (CONNOR 2002). While for the other two dampers, the peak suppression effect is visible, calibrations regarding the optimum damping are necessary to achieve the peak splitting.

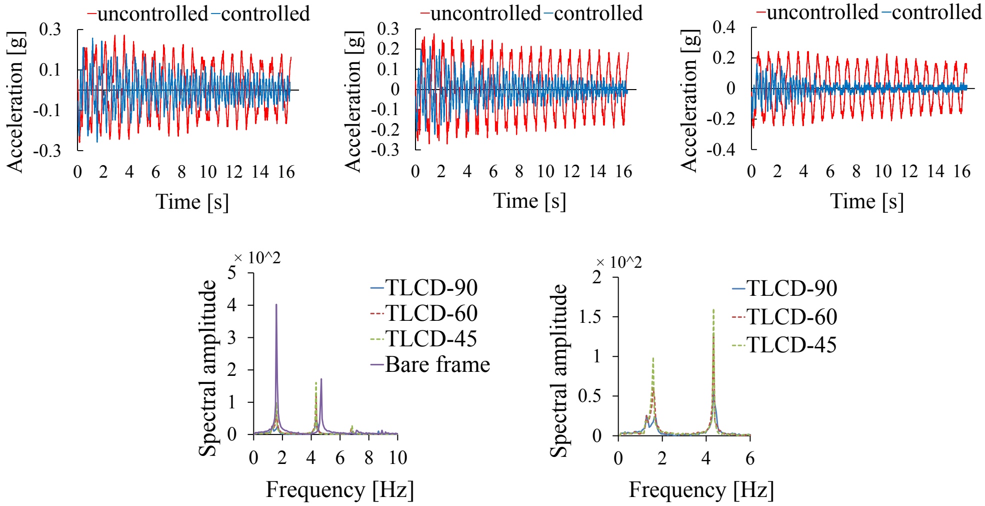

Fig. 5: Uncontrolled and controlled acceleration responses of the 4th story when TLCD45º (top left), TLCD60º (top middle) and TLCD90º (top right) are mounted, and the respective spectral amplitudes (bottom left). Comparison between spectral amplitudes of the three TLCDs (bottom right).

4 Summary and conclusions

This paper has presented a comparative study to investigate the performance of different TLCDs on a four-story shear-fame structure. Three TLCDs with column inclinations of 45º, 60º, and 90º, respectively, have been designed using the GRG optimization approach. The TLCDs have been tested in the laboratory and structural response data has been recorded by wireless sensor nodes. The results have shown that all TLCDs have been well-tuned to the fundamental frequency of the structure, since the TLCDs have been able to significantly dampen the excitation energy. Moreover, comparisons between the expected results from the numerical analysis of the TLCDs and the experimental results have indicated that theoretically optimized TLCD performance might not be in accordance with experimental TLCD performance. Specifically, although the $TLCD_{90°}$ has been expected to possess the lowest efficiency, this TLCD has shown the best performance, the disagreements being potentially attributed to differences in the intrinsic damping of the TLCDs or to the mass of the liquid employed. These disagreements reveal that a mere optimization cannot ensure efficient TLCD performance, rendering further investigation necessary for achieving experimentally optimized TLCDs.

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