

ELASTIC STRUCTURES WITH TUNED LIQUID COLUMN DAMPERS

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Abstract: The influence of Tuned Liquid Column Dampers (TLCDs) on the dynamic response of structures is investigated experimentally. The experimental models consist of a small-scale plane one-storey shear frame, made of aluminum, with a TLCD attached to its rigid beam. TLCDs are rigidly constructed of plastic tubes and filled with liquid (water). Performing free vibration experiments the geometry of the TLCD container and length of the liquid in the TLCD are varied. In the second series of experiments investigations with time-harmonic loading (frequency sweeps) are performed, where an electromagnetic shaker excites the structure's base. The natural frequencies of the frame and the TLCD are tuned by modifying the length of the liquid. The optimal tuning ratio and the optimal geometry of the container are determined.

Keywords: Tuned Liquid Column Damper, free vibration, frequency sweep.

1 INTRODUCTION

Structural vibration control is one of the main goals of civil engineers involved in the structural safety and reliability of buildings. In recent years, several passive, active and hybrid control schemes have been proposed to provide positive control of structural deformation induced by wind and strong ground motion due to earthquakes. Details of these control mechanisms and their applications have been reported in a large number of publications, e.g. [1]. The passive control mechanisms include metallic dampers, friction dampers, viscoelastic dampers, viscous fluid dampers, tuned mass dampers, liquid dampers, smart materials and others. For a survey of passive dampers see [2]. Relatively new types of application of passive liquid dampers are Tuned Liquid Column Dampers (TLCDs). A TLCD is a U-shaped tube of uniform cross-section, containing liquid, and its natural frequency is tuned in general to the first natural frequency of the structure. Vibrational energy is transferred from the structure to the TLCD through the motion of the rigid TLCD container exciting the TLCD liquid. The vibrations of the structure are reduced by the TLCD through the gravitational restoring force acting on the displaced TLCD liquid and the energy is dissipated by the viscous interaction of the TLCD liquid and the rigid TLCD container. The TLCDs have some unique advantages such as low cost, easy installation and adjustment of liquid frequency, and little maintenance needed, etc. Recently, both analytical and experimental analyses have been performed in some publications, see e.g. [3], [4], [5], [6], [7], [8], [9].

The objective of this paper is to investigate experimentally the influence of TLCDs on the structural response, to illustrate their effectiveness in reducing the response to dynamic loading, and to verify results given in the literature. A proper experimental set-up is developed. The experimental models consist of a small-scale single-degree-of-freedom shear frame, with a TLCD attached and they are considered for the case of a switched-on sinusoidal support excitation. The experimental set-up, determination of the system parameters and evaluation of the experimental results are described in detail.

2 EXPERIMENTAL SET-UP AND DATA ACQUISITION

The specimen model studied is depicted in Figure 1, see also [10], [11]. It consists of a plane small-scale one-storey shear frame with a TLCD mounted to its rigid beam. The columns of the shear frame, represented by leaf springs with rectangular cross-sections (15 / 2 mm) and of length $h = 381$ mm, are made of hard aluminum alloy and they are clamped to the horizontal beam. The beam is also composed of aluminum alloy, with a span of 509 mm. The stiffness coefficient and equivalent point mass of the frame are $k = 187$ N/m and $m = 2.52$ kg, respectively. Thereby, the influence of the P - Δ effect on the experimentally determined stiffness coefficient is included.

Rigidly constructed plastic TLCDs of circular cross-section (inside diameter 28 mm) are mounted to the beam of the structure through a vertical rigid plate made of hard aluminum. Fresh water is used as the TLCD liquid in all experiments. The horizontal tube of the TLCD containers can be replaced easily to examine the effect of different geometry of TLCD containers on the structural

Figure 1. Elastic one-storey shear frame with installed TLCD. All dimensions are given in mm.

response. In order to keep the mass of the structural model constant for all considered configurations an additional mass is attached to the beam, which depends on the actual weight of the TLCD container.

The structural model is carried on an elastic shear frame with columns made of aluminum (15 / 2 mm). Its horizontal rigid beam is linked to the armature of an electromagnetic shaker, Brüel & Kjær 4808, through a rigid steel bar. The shaker excites the base by a sinusoidal signal provided by the software LabVIEW 3.1.1.

The excitation acceleration is determined using a piezoelectric accelerometer, Brüel & Kjær 4367. The response acceleration of the structure's beam is also measured by means of a piezoelectric accelerometer of the same type. Each accelerometer is connected to a charge amplifier and integrator, Brüel and Kjær 2635. All signals are recorded by means of the software BEAM through the board of the Digital Amplifier System DMCplus (Hottinger Baldwin Meßtechnik, HBM).

3 TEST PROCEDURE

In advance of the experiments the dynamic properties of the elastic shear frame without TLCD installed are determined from its free vibration response. The beam of the shear frame is given an initial displacement, subsequently released and the decay of oscillation of the beam is monitored using an accelerometer. Transformation of the free vibration response into the frequency domain renders the natural frequency of the shear frame, $f_0^S = 1.37$ Hz. From the decay rate follows a damping coefficient ζ_S of 0.0015. Also the damping coefficients of the TLCDs (not attached to shear frame) are determined from their free vibration response. A ball of polystyrene with a diameter of 25 mm is placed to one end of the liquid. The ball is given an initial displacement, released and the ensuing vibration of the liquid is measured via the displacement of the ball using a laser transducer. Since the decay rate of the liquid depends on the initial displacement, actual amplitude of vibration and dimension of the TLCD only the mean of the damping coefficient for all TLCDs is specified, $\zeta_{TLCD} = 0.061$.

The free vibration response of the elastic shear frame with TLCDs of different configurations is studied. Thereby, the beam of the shear frame is given an initial displacement of 30 mm. During all free vibration tests the beam of the elastic support is fixed immovable to its initial position. In the first series of experiments, the natural frequency f_0^{TLCD} of the TLCD is tuned to the natural frequency f_0^S of the shear frame. According to [5], [7] f_0^{TLCD} depends only on the overall length L of the liquid column and gravitational acceleration g ,

$$f_0^{TLCD} = \frac{1}{2p} \sqrt{\frac{2g}{L}} \quad (1)$$

Since the natural frequency f_0^S of the shear frame is 1.37 Hz an overall length L of 270 mm is selected, i.e. f_0^{TLCD} is 1.36 Hz. This corresponds to a tuning ratio f_0^{TLCD} / f_0^S of 0.99. While L remains constant the horizontal column length B is varied. B is an important interaction parameter for the transfer of energy between the structure and the TLCDC but it does not alter the natural frequency of the TLCDC. The second series of free vibration experiments involves maintaining a constant horizontal column length of $B = 130$ mm while the overall column length L is varied from 210 to 310 mm.

In the second part of this investigation a series of harmonic excitation tests with differently assigned excitation frequencies are performed in order to characterize the influence of the TLCDC on the structural response. A sinusoidal excitation is generated in the computer, amplified and at time instant $t = 0$ switched on to the electromagnetic shaker. The support of the shear frame is excited, sweeping the frequencies between 1.0 and 1.8 Hz. Relating the amplitudes of the steady-state response to the amplitudes of the ground acceleration results in the amplitude frequency response function of acceleration. Again, the horizontal column length B is varied while the overall length L of the liquid column remains constant with $L = 275$ mm. Thereby, the width B of the TLCDCs tested are 130 mm, 160 mm, 190 mm and 230 mm. The overall liquid column length L is subsequently varied ($L = 250$ mm, 270 mm, 275 mm and 280 mm) while B remains constant, $B = 130$ mm.

Table 1. Dimension, mass and natural frequency of different TLCDCs, mass and natural frequency ratio, decay time of the free vibration response of the shear frame.

	TLCDC installed									no TLCDC installed
	270	270	270	210	230	250	275	290	310	
L [mm]	270	270	270	210	230	250	275	290	310	--
B [mm]	130	160	190	130	130	130	--	130	130	--
m_{TLCDC} [g]	166	166	166	129	142	154	169	179	191	--
m_{TLCDC} / m_S	0.066	0.066	0.066	0.051	0.056	0.061	0.067	0.071	0.076	--
f_0^{TLCDC} [Hz]	1.36	1.36	1.36	1.09	1.47	1.41	1.34	1.31	1.27	--
f_0^{TLCDC} / f_0^S	0.99	0.99	0.99	0.80	0.93	1.03	0.98	0.96	0.92	--
t_0 [s]	22	19	16	43	26	14	--	24	32	275

Figure 2. Free vibration response of the shear frame. (a) No TLCDC installed. (b) TLCDC installed: overall length of the liquid column $L = 270$ mm, horizontal length of the liquid column $B = 130$ mm.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Results from free vibration tests

The effect of different TLCD configurations on the free vibration response of the shear frame is studied. In particular the decay time t_0 of the free vibration acceleration of the beam is recorded. Here, t_0 is the period within the initial magnitude of approximately 1.9 m/s^2 is reduced to 0.05 m/s^2 . In Table 1 results are given for indicated TLCD configurations. The corresponding natural frequency and mass of the TLCDs, and the natural frequency and mass ratios to the shear frame are included in the same table.

It is readily observed that the decay time of the main structure will be considerably reduced, if a TLCD is installed. Also a detuned liquid column damper (e.g. $L = 310 \text{ mm}$) reduces the decay time to approximately 12% of a structure without damper since energy is dissipated by the viscous interaction of the TLCD liquid and the TLCD container. For TLCDs, which are perfectly tuned to

Figure 3. Amplitude ratio of total acceleration of the shear beam with respect to the acceleration of the base. Structure without and with TLCD installed.

Figure 4. Amplitude ratio of total acceleration of the shear beam with respect to the acceleration of the base. Different TLCD configurations: overall length L of the liquid column is varied, horizontal length B of the liquid column remains constant.

the main structure, the horizontal column length B is varied while the overall length L remains constant. As it is expected the interaction effect between the shear frame and the TLCD increases for increasing B since the dynamic effective mass of the damper is the portion of liquid, which remains in the horizontal tube of the TLCD.

For comparison Figure 2 shows recorded time histories of the free vibration acceleration for two structures. The free vibration response of the structure without TLCD installed is displayed in Figure 2a, whereas Figure 2b represents the response acceleration of the structure with an attached TLCD of the dimensions $L = 270$ mm and $B = 130$ mm. These Figures demonstrate effectively that the arrangement of a TLCD leads to a considerably reduction of the decay time of the free vibration.

4.2 Results from forced vibration tests

TLCD effectiveness is most easily demonstrated by comparing the frequency sweep response of the primary structure with and without TLCD installed, as shown in Figure 3. In this graph the amplitude ratio is the ratio of the dynamic amplitude of total acceleration of the shear frame to the amplitude of acceleration of the base. The response of the shear frame without a TLCD installed displays the typical characteristics of a single-degree-of-freedom system, with a single peak amplitude ratio occurring at the natural frequency of the shear frame. While the magnitude of the peak amplitude ratio would theoretically be $1/2 \zeta_s = 333$ a peak amplitude ratio of approximately 145 is reached.

The frequency sweep response of the shear frame installed with a TLCD characteristically experiences two peak amplitude ratios, one occurring at an excitation frequency less than the natural frequency of the primary structure, the other occurring at an excitation frequency greater than the natural frequency of the primary structure. Furthermore, the TLCD operates most efficiently when the applied load is close to its natural frequency. It can be seen in Figure 3 that the installation of a TLCD can significantly reduce the peak amplitude ratios experienced by the shear frame. An acceleration reduction to 14.5% is achieved with a damper mass equivalent to 6.7% of the building mass.

It is only the natural frequency, which can be changed easily once a TLCD has been installed. Frequency sweep studies are performed to determine the natural frequency ratio, which would provide optimum vibration mitigation for a given TLCD configuration. TLCD and primary structure configurations are tested to provide natural frequency ratios of 0.97 ($L = 280$ mm), 0.98 ($L = 275$ mm), 0.99 ($L = 270$ mm) and 1.03 ($L = 250$ mm). The results of these experiments are presented in Figure 4. It can be seen that a natural frequency ratio of 0.98 provides the most favorable vibration mitigation. This optimum ratio has been also found by Hitchcock et al. [6]. Figure 4 also shows that the second peak amplitude ratio is greater than the first for natural frequency ratios greater than 0.98.

Next, the effect of the horizontal liquid column length B on the frequency sweep response is

Figure 5. Amplitude ratio of total acceleration of the shear beam with respect to the acceleration of the base. Different TLCD configurations: overall length L of the liquid column remains constant, horizontal length B of the liquid column is varied.

examined. B is varied through values of 130 mm, 160 mm, 190 mm and 230 mm while for all TLCD configurations the optimal overall liquid column length of 275 mm is selected. Figure 5 contains graphs of the amplitude ratios for all tested structures. It can be observed that an increase of the horizontal length B up to 190 mm leads to an improvement of the damper efficiency. In all till now described experiments the amplitude of the liquid oscillation is within the order of magnitude so that B is always filled with liquid. However, for a ratio B/L approaching 1 this cannot be achieved for strong excitation and splashing of the liquid in the TLCD does occur. Due to this effect the efficiency of the TLCD in a certain frequency range is considerably reduced. From Figure 5 it can be clearly seen that splashing occurs for a TLCD with a B of 230 mm.

5 CONCLUSIONS

A small-scale experimental set-up has been developed to study the effect of Tuned Liquid Column Dampers (TLCDs) on the dynamic response of structures. Experimental investigations on small-scale models are cheap when compared to full-scale tests, and hence, mechanical models for numerical analyses can be verified easily. In the particular studies of this paper, the response of a small-scale shear frame with different TLCD configurations installed is investigated in free vibration and frequency sweep experiments. Factors are determined which effect the characteristics of TLCDs on the structural response. For TLCDs with mass ratios of approximately 7%, the most favorable vibration mitigation of the shear frame is approached for a particular TLCD configuration when the TLCD natural frequency is approximately 98% of the primary structure natural frequency. Further investigations are planned to use the proposed experimental set-up for systematic investigations of TLCDs attached to buildings thereby varying the material parameters, tuning frequencies and excitation records.

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