Engineering Structures 75 (2014) 528–538

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental validation of a direct pre-design formula for TLCD

A. Di Matteo [a], F. Lo Iacono [b], G. Navarra [b], A. Pirrotta [a,*]

[a] Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali (DICAM), Università degli Studi di Palermo, viale delle Scienze, I-90128 Palermo, Italy
[b] Facoltà di Ingegneria ed Architettura, Università degli Studi di Enna "Kore", Cittadella Universitaria, Enna Bassa, I-94100 Enna, Italy

ARTICLE INFO

Article history:
Received 27 July 2013
Revised 4 April 2014
Accepted 27 May 2014
Available online 5 July 2014

Keywords:
Experimental investigation
Tuned liquid column damper
Statistical linearization technique

ABSTRACT

The passive control of vibrations has received in recent years a great deal of attention from researchers. Several types of devices have been proposed in order to reduce the dynamic responses of different kinds of structural systems. Among them, the Tuned Liquid Column Damper (TLCD) has proved to be very effective in reducing vibration of structures. However, since the equations governing the TLCD controlled systems response is nonlinear, the calibration of TLCD parameters is time consuming and not convenient to perform in a pre-design phase. In this context, it has recently been introduced by the authors a formula that allows to choose the optimal parameters of TLCD in a direct and fast way. This ready-to-use and straightforward proposed formulation has been verified by comparison with the numerical Monte Carlo simulation based on the nonlinear complete system. In this paper numerical results obtained with the proposed formulation are validated through an experimental campaign on a small scale SDOF shear-type model, built in the Experimental Dynamic Laboratory of University of Palermo, and equipped with a TLCD excited at the base with random noises through a shaking table.

1. Introduction

The increasing height and span of structures is resulting in their increased vulnerability to environmental forces such as winds, earthquakes and sea waves. In addition to structural failure possibilities, issues such as functional performance and human discomfort are of major concerns. To improve the design and performance of these structures, several design modifications are available. Among them, passive systems, where a device is attached to a main system to be controlled, thus reducing the responses without external power supply, are simpler than active systems where external forces are needed together with an expensive feedback or feedforward control. Tuned Liquid Column Damper (TLCD) systems can be considered as a particular type of passive mass dampers and represent an effective alternative to Tuned Mass Damper (TMD) systems [1,2] to control the vibration level of structures. Readers may refer to Ziegler [3] for a detailed analysis on the usefulness and worthiness of TLCD among different types of passive vibration control systems.

TLCDs dissipate vibration energy by a combined action of the movement of the liquid in a U-shaped container, the restoring force on the liquid is due to the gravity and the damping effect is generated by the hydrodynamic head losses that arise during the motion of the liquid inside the TLCD.

The TLCD is generally modeled as a single degree of freedom (SDOF) oscillator which is rigidly attached to a vibrating structure [4] and, like TMDs, the effectiveness of a TLCD depends on proper tuning and damping value. However, unlike traditional TMDs, the TLCD response is nonlinear and the optimal damping parameters cannot be established *a priori* unless the loading magnitude is known and numerical optimization methods are used [5–11].

Several investigations on TLCDs controlled structures under stochastic loads have been recently conducted. Balendra et al. [12,13] studied the effect of TLCD for suppressing large displacements and accelerations on towers and tall buildings under wind excitations by using the statistical linearization technique for several values of the main structure and TLCD parameters.

Won et al. [14,15] investigated the seismic performance of TLCDs for the passive control of flexible structures using time-domain non-stationary random vibration analysis. In their works a non-stationary stochastic process with frequency and amplitude modulation is used to represent the earthquake strong motion, and a simple equivalent linearization technique is used to account for the nonlinear damping force in the TLCD. Furthermore a parametric study is conducted to investigate the effects of the mass ratio, coefficient of head loss for the damper, and loading intensity on the TLCD performance.

* Corresponding author. Tel.: +39 3204395957.
E-mail address: antonina.pirrotta@unipa.it (A. Pirrotta).

http://dx.doi.org/10.1016/j.engstruct.2014.05.045
0141-0296/

In Chang and Hsu [16] and Chang [17] two sets of common formulas for the optimal properties as well as some useful design formulas for both TLCD and TMD have been derived in closed forms, under a broad-band white noise excitation of either wind or earthquake type of loading. Similar formulas have been presented by Yalla and Kareem [11] in the cases of single degree of freedom (SDOF) and multi degree of freedom (MDOF) primary structures subjected to white noise and filtered white noise excitations. The same authors found that explicit expressions for optimal parameters are only feasible for a simple undamped primary system subjected to white noise because, as the systems and forcing functions become more complex, numerical solutions are needed to evaluate the optimal parameters.

Similar conclusions arise from Wu et al. [18] where the authors derive a design procedure for TLCDs attached to damped SDOF structures under a white noise type of wind excitation through numerical optimization. The procedure has been then calibrated on experimental results and modified formula to predict head loss coefficients for TLCDs with sharp-edged elbows is proposed [18,19].

Finally optimization procedure for MDOF structures with single TLCD or several TLCDs is described in [7], while design of special TLCD configuration is detailed in [20].

Recently, the authors of this paper presented a modified mathematical formulation of the TLCD equation of motion which has been proved to be very effective in the prediction of the experimental system vibrations when the input is deterministic and periodic [21,22].

Then in [23], considering the TLCDs driven by random excitation, the statistical linearization technique has been used in order to develop a pre-design simplified formula for choosing the TLCD parameters on lightly damped single-degree-of-freedom structures. Some approximations have been introduced in order to achieve a new reliable and simplified design formulation that directly relates geometrical system parameters of TLCD and the linear equivalent damping ratio. This ready-to-use and straightforward proposed formulation has been verified by comparison with numerical Monte Carlo simulation based on the nonlinear complete system [23] and, here, numerical results obtained with the proposed formulation are proved to be in very good agreement with the results obtained by an experimental campaign.

In particular, a small scale SDOF shear-type model has been built in the Laboratory of Experimental Dynamic at University of Palermo and equipped with three different TLCD devices. Shaking tables has been used for exciting main systems, controlled systems and TLCD devices with random noises at the base.

2. Problem formulation

It is assumed that the main uncontrolled structure (Fig. 1(a)), a light-damped shear-type single-degree-of-freedom (SDOF) system, is subjected to base excitation and is mitigated by using a tuned liquid column damper (Fig. 1(b and c)).

The equation of motion of the main system (Fig. 1(a)) may be expressed as:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -M\ddot{x}_g(t) \tag{1}$$

while the governing equation for the motion of the fluid inside the tube (Fig. 1(b)) is in the form

$$m_{TLCD}\ddot{y}(t) + \frac{1}{2}\rho A\xi|\dot{y}(t)|\dot{y}(t) + 2\rho Agy(t) = -m_h\ddot{x}_g \tag{2}$$

finally classical formulation of the equations of motion, widely used in literature [3,4], for the TLCD controlled system (Fig. 1(c)) can be represented as

$$\begin{cases} (M + m_{TLCD})\ddot{x}(t) + m_h\ddot{y}(t) + C\dot{x}(t) + Kx(t) = -(M + m_{TLCD})\ddot{x}_g \\ m_h\ddot{x}(t) + m_{TLCD}\ddot{y}(t) + \frac{1}{2}\rho A\xi|\dot{y}(t)|\dot{y}(t) + 2\rho Agy(t) = -m_h\ddot{x}_g \end{cases} \tag{3-a, b}$$

In the previous equations M, C and K are the mass, damping and stiffness parameters of the SDOF system, respectively, $\ddot{x}_g$ represents the ground acceleration, x and y are the relative displacement of the SDOF, and the displacement of the liquid in vertical columns, respectively, $m_{TLCD} = \rho AL$ is the total liquid mass of the TLCD, $m_h = \rho Ab$ represents the liquid mass of the horizontal portion only, being ρ the liquid mass density, A the cross sectional area ($A = \pi d^2/4$), b the horizontal liquid length and L the total liquid length inside the tube ($L = b + 2h$). The head loss coefficient and the gravitational constant are denoted by ξ and g, respectively. The upper dots mean time derivatives.

It is worth stressing that, in order to obtain Eq. (2), the non-conservative force $Q_y = -1/2\rho A\xi|\dot{y}(t)|\dot{y}(t)$ has been used, which should take into account the head loss caused by the presence of an orifice inside the TLCD and the head losses caused by sharp-edged turn-elbow, the transition of the cross section in the vicinity of the elbow [18] and viscous interaction between the liquid and the rigid container wall [24]. This leads to the classical nonlinear equation of motion for the displacement of the liquid inside the tube (2), as well as the corresponding Eq. (3-b) for the response of the TLCD controlled system.

Let us consider that the TLCD-controlled system depicted in Fig. 1(c) is excited by random forces like earthquake ground accelerations, modeled as zero mean Gaussian processes. It follows that main system and liquid displacements and their derivatives are

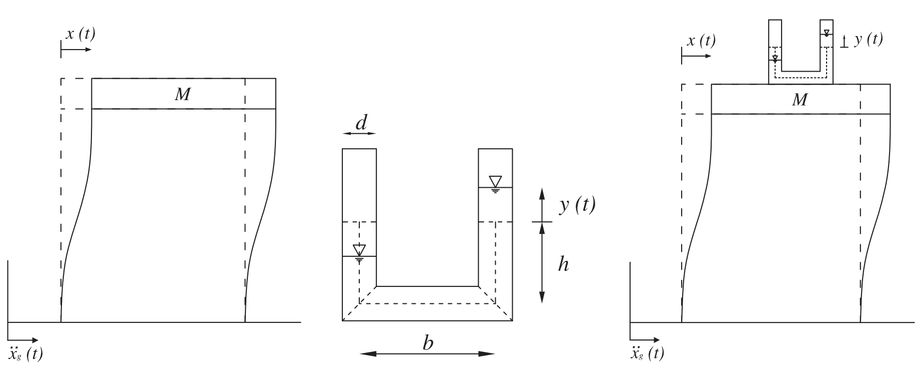

Fig. 1. (a) Main system; (b) TLCD device and (c) TLCD controlled system.