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Analysis of tuned liquid column damper nonlinearities

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ABSTRACT

Broadband environmental excitations from wind, ocean wave and earthquakes are especially dangerous for flexible tall structures such as wind turbines, towers or cable-stayed bridges. Liquid Dampers have been studied for almost thirty years in terms of their capability for suppression of vibration in such structures. The work presented in this paper focuses on the Tuned Liquid Column Damper, both open and sealed, and the identification of its time-varying properties of nonlinear damping, frequency and air pressure identification. Experimental tests are conducted on a full scale model of the damper which is subjected to both white noise and harmonic excitation by means of a hydraulic shaker. Exponential decay of the displacement of the liquid column was measured and analysed. The identification procedure was conducted step-wise, first, mode separation with the use of Continuous Wavelet Transform was carried out and then identification of the instantaneous damping ratio for the first mode of vibration was performed. Results indicate that the damping ratio is nonlinear, time-varying and depends on the level of vibration. The air pressure data in the sealed TLCD was also recorded and analysed to reveal the nonlinear nature of the pressure change and the presence of higher odd harmonics.

1. Introduction

Liquid dampers have been successfully utilized in practise to supress amplitudes of structural vibration under wind, wave and earthquake excitation. The concept of using fluid to stabilize the rolling of ships was developed in the 1860s [1]. This damping technology is known by the name of anti-roll-tanks and widely used in naval architecture [2]. As compared to sloshing [3] or rectangular dampers [4], Tuned Liquid Column Dampers (TLCDs), which dissipate energy by the movement of an oscillatory column of liquid through orifice(s) provided in the cross section of a U-shaped container, have attracted special attention due to their high volumetric efficiency with respect to given amount of liquid, consistent behaviour across a wide range of excitation levels and a damping mechanism that can be quantified in a definite manner. The theoretical concept of the TLCD was developed in [5] and experimentally verified in [6]. Also its nonlinear mathematical description was provided and the relationship between head-loss coefficient and liquid damping validated. Since then, considerable research work has been carried out on the characterization and performance of TLCDs [7–14] including investigations on applicability to control of short period structures, wind turbines and on the impact of soil-structure interaction.

Since a TLCD is described by a relatively simple mathematical model, it is amenable for semi-active and active control. Some studies on TLCD, acting as an active vibration damper, were carried out in [15,16]. Experimental study for calculating the effectiveness of semi-active LCD for wind-induced vibration was carried out in [17]. Effectiveness of the semi-active LCD system and the hybrid viscous damper LCD control system for the suppression of wind-induced motion of high-rise buildings was examined in [18]. Attempts to achieve enhanced TLCD performance by using Electro-Rheological fluid (ER fluid) or Magneto-Rheological fluid (MR fluid) were presented in [19–21]. Experimental and theoretical investigations on the equivalent viscous damping of structures with TLCD having MR-fluids was carried out in [14,22]. Some researchers considered the vertical limbs of the TLCD to be sealed and utilized the air-spring effects in the sealed U-tube to extend the applicability of the control device to the high frequency range [23]. Sealed TLCDs were also studied for the control of wind induced multi-modal lateral and torsional vibration of long span cable stayed bridges by [24] and for the seismic vibration control of steel jacket platforms by [25].

Previous research studies in the field are related mainly to the design and control aspects of TLCDs. Identification of vibration/modal parameters has attracted much less attention. This is particularly

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relevant to the identification and characterisation of the time-varying behaviour of these parameters. The present paper aims to model and experimentally identify nonlinear, time-varying damping in conventional TLCDs and nonlinear behaviour of air pressure in sealed TLCDs. The structure of the paper is as follows. Two simple mathematical models associated with the analysed nonlinear behaviour of the TLCD are presented in Section 2. The identification procedure, based on wavelet analysis, is briefly described in Section 3. Experimental work and results are presented in Section 4. Finally, the paper is concluded in Section 5.

2. Modelling of TLCD

This section briefly describes two nonlinear models associated with the TLCD performance. Firstly, the displacement of the liquid column in the base-excited TLCD is analysed to obtain the relevant equation of motion and to demonstrate the nonlinear, time-variant nature of damping in this equation. Then the air pressure in the limbs above the liquid column in a sealed TLCD is modelled to exhibit its nonlinear behaviour.

2.1. Displacement of liquid column in TLCD

Following the work in [26] this section presents a simple mathematical model that describes the behaviour of the first vibration mode of the analysed TLCD shown in Fig. 1.

The TLCD considered is composed of a tube-like container of horizontal dimension B and cross-sectional area A. The total effective length of the liquid column in the damper, denoted by L, is the sole parameter that controls the natural frequency of liquid oscillation in the conventional TLCD. This parameter is used for tuning the natural frequency of the TLCD to the structural frequency for the purpose of vibration control. The static height of liquid in the vertical limbs of the U-tube is given by h. It contains liquid of mass density ρ. Orifice(s) are installed in the horizontal portion of the tube. The coefficient of head loss, controlled by the opening ratio of the orifice(s), is denoted by ξ. The dynamic equilibrium of the horizontal forces acting on the liquid in the horizontal portion of the TLCD leads to the equation of motion of the liquid mass oscillating in the U-tube, when excited at the base. Let the TLCD be subjected to a horizontal base acceleration $\ddot{z}(t)$. The change in elevation of the liquid column is denoted by $x(t)$. The inertia force of the liquid in the horizontal portion of the TLCD can be expressed as

$$F_1 = \rho AB(\ddot{x} + \ddot{z}) \tag{1}$$

where the overdots represent differentiation with respect to time. The force due to head-loss caused by the orifice is given by

$$F_2 = \frac{1}{2}\rho A\xi\left|\dot{x}\right|\dot{x} \tag{2}$$

The hydrostatic force from the left limb of the damper on the horizontal portion may be written as

$$F_3 = -\rho A(h - x)(g - \ddot{x}) \tag{3}$$

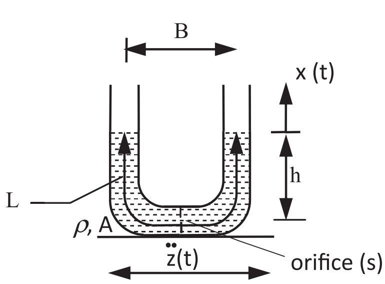

Fig. 1. Schematic diagram of the analysed TLCD system.

where g is the acceleration due to gravity. The hydrostatic force from the right limb of the damper on the horizontal portion can be expressed as

$$F_4 = \rho A(h + x)(g + \ddot{x}) \tag{4}$$

Total effective length L of the liquid column is given as

$$L = B + 2h \tag{5}$$

The algebraic summation of all these forces leads to the equation of motion

$$\rho AL\ddot{x} + \frac{1}{2}\rho A\xi\left|\dot{x}\right|\dot{x} + 2\rho Agx = -\rho AB\ddot{z} \tag{6}$$

A quadratic damping model is clearly visible in this equation. Though in past studies on the TLCD the liquid motion considered is the oscillation of the liquid column in the U-tube container, it is possible that the liquid in the vertical limbs may be subjected to sloshing. This has been earlier studied in [27] in the case of the Liquid Column Vibration Absorber (LCVA) in which the cross-sectional area of the vertical limbs is greater than that of the horizontal portion of the damper. Furthermore, as also noted in [28], higher value of the ratio of the horizontal length B to the total effective length L of the liquid column is desirable for higher damper efficiency. This leads to shallower depth of liquid in the vertical limbs of the damper. As a result, the propensity of the liquid in the limbs to sloshing is greater. For a TLCD with a relatively larger column width, the sloshing of the liquid in the limbs can represent a higher mode of vibration of the liquid motion.

2.2. Air pressure in sealed TLCD

Once both limbs are sealed, the air pressure above the liquid level can be analysed. Let P_0, V_0 be the initial pressure and volume in each sealed limb above the liquid level. As the liquid column oscillates, let $x(t)$ be the change in liquid level, due to which the changes in pressure P, and volume V, are denoted by $\delta P(t)$ and $\delta V(t)$ respectively. Considering the polytropic relation $PV^n = c$, where n and c denote the polytropic index and constant respectively, the following equations for the two sealed limbs are obtained.

$$(P_0 + \delta P(t))(V_0 - \delta V(t))^n = c \tag{7}$$

$$(P_0 - \delta P(t))(V_0 + \delta V(t))^n = c \tag{8}$$

By the generalized binomial theorem, Eq. (7) can be expanded as

$$P_0 + \delta P(t) = c'\left(1 - \frac{\delta V(t)}{V_0}\right)^{-n} = c'\left(1 - \alpha_1\frac{\delta V(t)}{V_0} + \alpha_2\left(\frac{\delta V(t)}{V_0}\right)^2 - \alpha_3\left(\frac{\delta V(t)}{V_0}\right)^3 \ldots\right) \tag{9}$$

where c' and $\alpha_i, i = 1,2,\ldots$ represent constants.

Similarly, Eq. (8) can be expanded as

$$P_0 - \delta P(t) = c'\left(1 + \frac{\delta V(t)}{V_0}\right)^{-n} = c'\left(1 + \alpha_1\frac{\delta V(t)}{V_0} + \alpha_2\left(\frac{\delta V(t)}{V_0}\right)^2 + \alpha_3\left(\frac{\delta V(t)}{V_0}\right)^3 \ldots\right) \tag{10}$$

Eqs. (9) and (10) leads to

$$2\delta P(t) = 2c'\left(-\alpha_1\frac{\delta V(t)}{V_0} - \alpha_3\left(\frac{\delta V(t)}{V_0}\right)^3 - \alpha_5\left(\frac{\delta V(t)}{V_0}\right)^5 \ldots\right) \tag{11}$$

Since $\delta V(t) = Ax(t)$, Eq. (11) can be written as

$$\delta P(t) = \beta_1 x(t) + \beta_2 x^3(t) + \beta_3 x^5(t)\ldots \tag{12}$$

and if $x(t)$ is harmonic, then Eq. (12) becomes