Engineering Structures 177 (2018) 785–794

Contents lists available at ScienceDirect

Engineering Structures

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

# Simulation of control characteristics of liquid column vibration absorber using a quasi-elliptic flow path estimation method

P. Chaiviriyawong[a,*], P. Panedpojaman[a], S. Limkatanyu[a], T. Pinkeaw[b]

[a] Department of Civil Engineering, Prince of Songkla University, Songkhla, Thailand
[b] Department of Civil Engineering, Chulalongkorn University, Bangkok, Thailand

ARTICLE INFO

*Keywords:*
TLCD
LCVA
Panel method
Quasi-elliptic flow path estimation method
Natural frequency

ABSTRACT

Tuned liquid column dampers (TLCDs) and liquid column vibration absorbers (LCVAs) are good substitutes for mechanical dampers to counter seismic activity exerted to tall buildings. The existing simplified effective length method could predict good results corresponding to test outcomes on TLCDs and LCVAs with small transition zones, but is found to yield larger discrepancy as larger transition zones are needed, often due to limited space constraints. The numerical panel method could be effectively employed to give more accurate results, but is not simple to formulate and needs to be re-modified for each new configuration. This paper proposes a new quasi-elliptic flow path estimation method to simulate control characteristics of TLCDs and LCVAs with relatively large transition boundary between the vertical columns and the horizontal cross-over duct, since liquid velocity's variation inside the large transition boundary cannot be assumed to occur at a single point. The simulation results are compared with experimental investigations conducted on a shake table, yielding satisfactorily better outcomes for large transition zones, as well as for small transition zones. This new formulation has been verified with a few other studies and has been found to be an excellent viable option with a respectable better, or at least comparable, accuracy level.

## 1. Introduction

Under dynamic loading, several means can be used to improve building performance in accordance with either serviceability or safety criteria, or both. Generally, strengthening of a building or installing of a base-isolation system are costly or difficult to perform. Installing a passive mass damper into the building is less expensive and much simpler to perform and many researches on passive dampers have been conducted in recent years. Among passive damper types, Tuned Liquid Column Damper (TLCD) has been found to be most attractive due to these features: (*a*) lower cost; (*b*) easy handling; *c)* low maintenance requirement; and (*d*) the liquid (water) in the TLCD (tank) could be used for firefighting and hence no additional weight in the structural design.

TLCD proposed by Sakai [1] is a passive liquid vibration absorber used to control tall flexible buildings. The liquid in TLCD, in a U-shaped tank with an orifice, achieves similar control characteristics as tuned mass dampers (TMD) that consist of mass and spring systems. It is crucial that the natural frequency of the motion of fluid inside be tuned to the fundamental frequency of the building, and the damping ratio of fluid motion is set to a case-specific optimum to be effective [2–4]. Unfortunately, damping induced by liquid motion is response-dependent, thus the optimum damping ratio and tuning ratio cannot be determined a priori unless the excitation amplitude is obtained or can be estimated beforehand. However, many researches have demonstrated the effectiveness of the liquid vibration absorber under typical ground motions [5–11].

Watkins [12] proposes a variation of TLCD in which the cross-section of vertical column and horizontal cross-over duct is non-uniform, and called it LCVAs (Liquid Column Vibration Absorbers). The fundamental frequency of the liquid is obtained from the tank's "effective length" relating to tank geometry, and particularly the area ratio of the vertical column to that of the horizontal cross-over duct [13].

Most researches previously conducted focus on LCVA with a small ratio of transition boundary on the corner-to-corner width (between the vertical/horizontal edges on either side) to the horizontal length (in the range of 0.04–0.20) [1, 2, 3, 9 and 13]. Many studies have proposed different definitions for the effective length of LCVA based on different idealization of the moving liquid, resulting in different values of the derived fundamental frequencies [3, 9 and 13].

For structures with limited and narrow space, it needs to configure a liquid damper with a relatively larger ratio of the corner-to-corner

---

[*] Corresponding author.
*E-mail address:* cpassagorn@eng.psu.ac.th (P. Chaiviriyawong).

https://doi.org/10.1016/j.engstruct.2018.09.088
Received 14 March 2018; Received in revised form 28 September 2018; Accepted 28 September 2018
0141-0296/

width to the horizontal length [14]. Then, there would be a significantly larger transition boundary in which the liquid's flow is greatly not uniform, this liquid damper's configuration would not yield a good approximation of the average liquid velocity within each portion of the moving of liquid inside transition zone. Because a more precise estimation of the vibration characteristics of a liquid damper is crucial in vibration control problems, a more refined procedure is deemed necessary.

As mentioned earlier, the optimum damping ratio and tuning condition of TLCD (of uniform cross-section), and thus also LCVA (of non-uniform cross-section), cannot be established a priori unless the excitation is known and liquid damper parameters are calibrated. Traditional *design* method of TLCD is time-consuming and inconvenient. Di Matteo et al. [15] had presented a *new pre-design* through a statistical linearization technique applied through a small computational procedure with very close responses to experiments. Di Matteo et al. [16–17] had also presented a *new formulation* for TLCD liquid displacement using fractional differential equation of motion, whereby the sloshing effect of fluid inside the vertical columns is considered under various transition zones. Their obtained results were found to be very satisfactorily accurate.

To simulate the induced liquid velocity distribution inside the liquid vibration absorber, a *numerical potential-flow method*, known as the *numerical panel method*, has been applied by Chaiviriyawong et al [14]. This method yields accurate vibration characteristics of both TLCD and LCVA over a wide range of liquid damper configurations. The main result obtained from the potential-flow method is the induced velocity distribution of fluid inside. Other important characteristics of the damper (such as effective length or effective mass) cannot be obtained directly, and more careful numerical implementation is needed. Moreover, though proven accurate, the governing equation of the fluid inside the damper could not be obtained directly either and thus is cumbersome to formulate the vibration characteristics. Different users would usually get different results, though all are normally close.

Nevertheless, one notable observation from the above-mentioned numerical method on the induced liquid velocity distribution inside the liquid damper is that the fluid at the bottom corners of the transition zone remains quite stationary, especially when the size of the transition zone is relatively large. The flow path of the liquid in this transition zone could be assumed partly elliptic, and the liquid velocity here gradually changes with this flow path. This so-called "quasi-elliptic" flow path estimation method is then adopted in further investigations to simulate the vibration characteristics of LCVA with large transition zone.

As mentioned earlier, researches previously conducted on LCVAs have been on small ratios of transition zone. Formulation of its governing equation has, moreover, been found to be increasingly inaccurate as the size of transition zone increases [14,16]. Development of a more suitable governing equation of liquid motion inside the damper to simulate the vibration characteristics of LCVAs for large transition zone – when the size between the corner-to-corner width is large compared to the horizontal width – is needed. And this is the objective of this research, together with the employment of the concept of a quasi-elliptic flow path.

In this regard, three scaled models with large transition zone to horizontal width ratios are experimentally investigated under various excitations (free-vibration and sinusoidal base excitation). The simulation results are then verified with the experimental results, and also with those obtained from other studies.

## 2. Formulation

In this section, governing equations for motion of fluid subjected to horizontal excitation will be derived, based on energy principles, for traditional LCVAs with small transition zone, as well as the *newly proposed method* employing a quasi-elliptic flow path for LCVAs with relatively larger transition zone. All these are based on assumptions that the fluid is incompressible; that the *motion* of the liquid is unsteady and non-uniform; and that the internal energy of the fluid remains unchanged during motion.

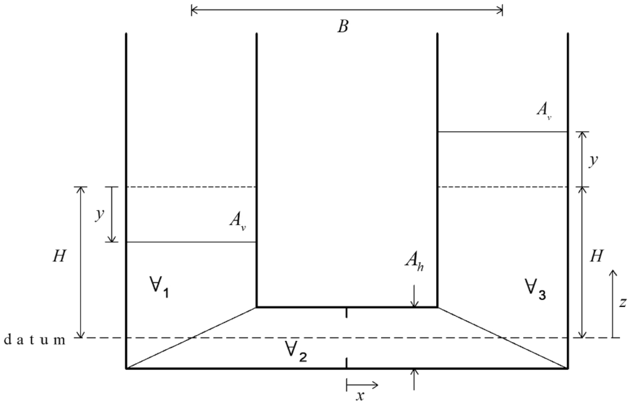

**Fig. 1.** LCVA parts and notations.

### 2.1. Traditional analytical model for LCVA

Fig. 1 shows a LCVA configuration subjected to a base displacement *x(t)*. The vertical column and the horizontal cross-over duct cross-sectional areas are respectively given as $A_v$ and $A_h$. During a motion, the fluid volume inside the U-shape container could be divided into two vertical column portions ($\forall_1$and$\forall_3$), and one horizontal cross-over duct portion ($\forall_2$). In the two vertical column portions, the fluid is assumed to move vertically relative to the tank with an average velocity of$\dot{y}$. From continuity, the horizontal fluid velocity in the horizontal portion is approximately uniform with an average velocity of $r\dot{y}$, where $r = A_v/A_h$ is the cross-sectional area ratio of the vertical column to the horizontal cross-over duct of the damper.

Using energy principles, from the Lagrange equation, the governing equation of the liquid inside LCVA can be derived, as follows:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{y}}\right) - \frac{\partial T}{\partial y} + \frac{\partial V}{\partial y} = Q \tag{1}$$

where $T$ is the total kinetic energy of the system and $V$ is the total potential energy; and $Q$ is the total non-conservative force in the direction of liquid movement ($y$), which is related to the LCVA's head loss.

The equation of motion for the liquid inside the LCVA can be obtained from Eq. (1) [3,9], thus:

$$\rho A_v L_e \ddot{y} + \frac{1}{2}\rho A_v r\delta\,|\dot{y}|\,\dot{y} + 2\rho A_v g y = -\rho A_v B\ddot{x} \tag{2}$$

where $\rho$, $\delta$ and$g$represent liquid density, head loss coefficient, and gravitational acceleration, respectively. The LCVA's effective length, $L_e$, can be determined from the horizontal width $B$ and the vertical column height $H$ of the liquid inside the damper as follows:

$$L_e = rB + 2H \tag{3}$$

The fundamental frequency of oscillation of liquid inside the damper can be determined from $\omega_f = \sqrt{2g/L_e}$.

### 2.2. Proposed model employing quasi-elliptic flow path estimation

From simulation results obtained from the numerical panel method [14], induced velocity distributions of the LCVAs with large transition zone are derived. As observed from the induced velocity distributions of liquid inside the tank (Fig. 2), there is very low induced velocity for liquid at the bottom corner of transition zones between the vertical and horizontal portions, especially in the LCVA with a larger transition zone