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# Fast vision-based wave height measurement for dynamic characterization of tuned liquid column dampers

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ABSTRACT

In this study, a novel and rapid vision-based sensing strategy is developed exclusively for dynamic wave height measurement of tuned liquid column dampers (TLCDs). The image processing algorithm of the vision-based sensing method simply counts white pixels in a binary image and thus expedites the vision-based wave height measurement. In addition to the experimental achievement, a practical methodology of dynamic characterization for the TLCDs is proposed combining linearized equations for the TLCDs and experimental data measured. An experimental characterization of dynamic behaviors and damping properties of the TLCDs is undertaken utilizing the vision-based sensing developed.



## 1. Introduction

Structural developments in design and construction of buildings and towers have rendered structures tall, slender, and flexible. The tall and slender structures are vulnerable to dynamic loading such as wind and earthquakes. While the structures operate within safety limits, they may suffer from lack of serviceability due to undesirable vibrations induced by the dynamic loading. Structural control is needed to reduce the dynamic responses of the structures and to maintain their functional performances. A constant flow of developing novel and effective devices incorporated in structures for attenuation of structural vibration has been seen over the past decades [1].

One of the pervasive strategies widely applied to attenuate structural vibration is the installation of a secondary mass damper on the top floor of a building, i.e., a device generating a reaction force induced from the oscillating motion of a secondary mass. The secondary mass is a small fraction of the entire mass of the primary structure and interfaced to inherent damping devices for increasing the energy dissipation capability. Depending on the oscillatory media, the secondary mass dampers are categorized into two groups: tuned mass damper (TMD) and tuned liquid damper (TLD). The TMDs are mechanical devices of a solid mass with springs and dashpots attached to the primary building [2] and the TLDs are liquid containers [3]. As the counterpart of the TMDs, the TLDs have proven their advantages: for example, simplicity, low cost, easy installation and maintenance, just to name a few [4–7].

Two different configurations of the TLDs have been investigated and adopted in construction sites [8]. Tuned Liquid Mass Damper (TLMD) and Tuned Liquid Column Damper (TLCD) utilize energy dissipating liquid motions of oscillation in narrow tubes and wave braking/sloshing in free liquid surface, respectively. Referring to numerous design parameters relating the configuration of the TLCDs and resultant tuning feasibility to determine their dynamic characteristics, practical advantages of the TLCDs over the TLMDs have frequently been emphasized in the literature [4,9,10].

Prior to installation of a TLCD at a site, a factory test for verification and tuning of dynamic characteristics must be conducted with the pre-fabricated TLCD. Among the dynamic characteristics of the TLCD, optimal tuning frequency and damping ratio are considered primal, since they are directly related to control performance, i.e., vibration suppression of the primary structure. Wave height of the oscillating liquid column of the TLCD is measured during the factory test and the dynamic characteristics are then estimated from wave height data measured.

To date, capacitive wavemeters immersed into liquid have been dominantly used for measurement of varying wave heights. However, a number of intrinsic disadvantages associated with the contact sensors have been constantly addressed: high price, laborious installation, and a loss of accuracy due to interference from a liquid medium, e.g., parasitic capacitance. While great advances have been made in analytical studies of dynamic behaviors of the TLCDs

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[6,10,11] and practical design formulas/guidelines [9,12,13], comparatively less research has been conducted toward novel measurement strategy and further characterization of the TLCDs based on experimentally measured data.

Recently, there has been growing interest in noncontact sensing in the areas of structural monitoring and assessment [14]. The precedent works of noncontact sensing, especially vision-based remote sensing, are found in the literature [15–19]. In this study, a rapid, high precision, and cost-effective vision-based sensing system is developed exclusively for dynamic wave height measurement of the TLCDs. A practical methodology of experimental estimation of dynamic characteristics of the TLCDs is also proposed based on both dynamic equations derived and experimental data measured. Finally, a series of experimental investigations are conducted for the verification of the vision-based sensing system and for showcasing the methodology of dynamic characterization of the TLCDs.

## 2. Formulation of dynamic behavior of tlcds

The equations of dynamic behavior of the TLCDs are derived for estimation of their dynamic characteristics based on the experimental data measured. While natural frequencies of the TLCDs can be directly determined by measurements, damping estimation requires physics-based relationships between damping and measurable quantities. Thus, a practical equation for estimating the damping ratio of the TLCDs is derived in this section.

### 2.1. Derivation of linearized equation of motion

A simplified model of the TLCD built on the primary structure is illustrated in Fig. 1. The TLCD considered here has two vertically upright tubes connected together at the bottom orifice forming sharp-edged elbows. Identical cross sectional areas, denoted as $A$ in Fig. 1, of the vertical and horizontal tubes are considered. The displacements of horizontal structural motion of the exciting primary structure and vertical surface motion of oscillating liquid of the TLCD are denoted as $x$ and $y$, respectively. As for the dimensions of the TLCD, the horizontal and vertical column lengths are defined as $L_h$ and $L_v$, respectively.

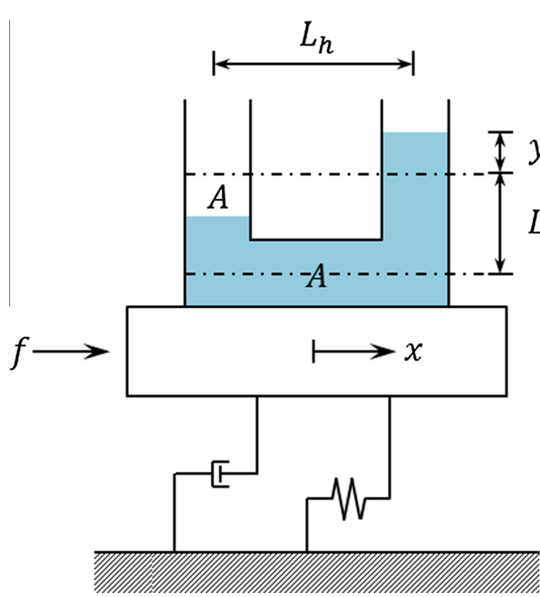


**Fig. 1.** A TLCD subjected to a vibrating structure.

The Lagrange's equations of motion on the basis of the Hamilton's principle for conservative systems [20] are adopted to formulate equations of motion of the TLCD [6,21,22]. Summation of the kinetic energy of the oscillating liquid along the two vertical and one horizontal columns leads to

$$T = \rho A L_v(\dot{y}^2 + \dot{x}^2) + \frac{1}{2}\rho A L_h(\dot{y}^2 + 2\dot{x}\dot{y} + \dot{x}^2) \tag{1}$$

where $\rho$ is the density of the liquid filled in the TLCD. Considering wave height changes in the two vertical liquid columns, the potential energy is expressed as

$$V = -\rho A(-y)g\frac{y}{2} + \rho A y g\frac{y}{2} = \rho A g y^2 \tag{2}$$

The energy dissipated by the liquid flow passing through the orifice is often referred to as head loss in fluid dynamics. Combining the energy balance equation, i.e., the Lagrange's equation, and the non-conservative force of the head loss leads to

$$\frac{d}{dt}\left(\frac{\partial(T-V)}{\partial\dot{y}}\right) - \left(\frac{\partial(T-V)}{\partial y}\right) = -\frac{1}{2}\rho A\eta|\dot{y}|\dot{y} \tag{3}$$

where $\eta$ is the head loss coefficient. The equation of motion of the TLCD is derived by inserting Eqs. (1) and (2) into Eq. (3):

$$m_1\ddot{y} + c_1\dot{y} + k_1 y = -m_2\ddot{x} \tag{4}$$

where the total mass of the liquid column is $m_1 = \rho A(L_h + 2L_v)$; the mass of the horizontal liquid column is $m_2 = \rho A L_h$; the nonlinear friction damping coefficient is $c_1 = (1/2)\rho A\eta|\dot{y}|$; the term related to stiffness is $k_1 = 2\rho A g$.

The nonlinear friction damping can be treated as linear viscous damping by the concept of equivalent damping. Considering a harmonic excitation of the primary structure with the frequency, $\omega$ and corresponding sinusoidal displacement response of the vertical liquid motion with the amplitude, $\varphi_y$, i.e., $y = \varphi_y \sin\omega t$, the non-conservative force of nonlinear friction damping is calculated as

$$f_{nc1} = c_1\dot{y} = \frac{1}{2}\rho A\eta\varphi_y^2\omega^2|\cos\omega t|\cos\omega t \tag{5}$$

The energy dissipated in a full cycle is calculated by integrating the non-conservative damping force in the first quarter cycle and quadrupling the result:

$$\begin{aligned} E_{D1} &= 4\int f_{nc1}dy = \int_0^{\varphi_y} 2\rho A\eta\varphi_y^2\omega^2\left\{1 - \left(\frac{\varphi_y \sin\omega t}{\varphi_y}\right)^2\right\}dy \\ &= \frac{4}{3}\rho A\eta\varphi_y^3\omega^2 \end{aligned} \tag{6}$$

On the contrary, the non-conservative force is composed with the linear viscous damping as

$$f_{nc2} = c_{eq}\dot{y} = c_{eq}\varphi_y\omega\cos\omega t \tag{7}$$

The energy dissipated by the linear viscous damping is calculated as

$$\begin{aligned} E_{D2} &= \int f_{nc2}dy = \int_0^{\frac{2\pi}{\omega}} f_{nc2}\dot{y}dt = \int_0^{\frac{2\pi}{\omega}} c_{eq}\varphi_y^2\omega^2\cos^2\omega t dt \\ &= c_{eq}\pi\varphi_y^2\omega \end{aligned} \tag{8}$$

By equating the dissipated energy of the nonlinear friction damping to that of linear viscous damping, the equivalent viscous damping is derived as

$$c_{eq} = \frac{4}{3\pi}\rho A\eta\varphi_y\omega \tag{9}$$