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A design procedure of two-way liquid dampers for attenuation of wind-induced responses of tall buildings

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ABSTRACT

A new design procedure of a two-way liquid damper which reduces wind-induced responses of a tall building is presented as a quick guide for structural engineers. The two-way liquid damper combines the (1) Tuned Liquid Column Damper (TLCD) in which liquid moves through a U-shape tube and the (2) Tuned Sloshing Damper (TSD) in which liquid sloshes within a container, respectively for two orthogonal directions. Dimensions of the damper, such as horizontal liquid column length and the thickness of the TLCD, the width of the TSD, and liquid height are determined given the condition of tuning the natural frequencies of liquid motion in the damper to those of the building. The design procedure is a trial and error process of satisfying geometrical constraints (i.e., maximum space where the damper is installed) and varying controlled response factors (i.e., performance of vibration attenuation). A design example of the damper is illustrated in the paper for its installation at a 64-story reinforced-concrete residential building.

1. Introduction

Tuned mass dampers (TMDs) and tuned liquid dampers (TLDs) are passive energy-absorbing devices that have been suggested to solve wind-induced vibration problems of tall buildings (Kareem and Kijewski, 1999). Recently, TLDs have been installed in several buildings, since they offer several advantages over TMDs: TLDs are simply constructed and easily maintained (Soong and Dargush, 1997). Tuned sloshing dampers (TSDs), a type of TLDs, utilize sloshing motion of liquid in containers of the shape of either cubes or cylinders. A small fraction of the whole liquid in TSDs (i.e., liquid near a free surface) participates in the sloshing motion. To increase the participation of liquid, tuned liquid column dampers (TLCDs) are proposed. TLCDs consist of U-shaped containers partially filled with a volume of liquid. As the building with an attached TLCD is excited, the whole liquid oscillates through U-shaped containers and dissipates energy generating proper viscous damping (Hitchcock et al., 1997a, b; Hochrainer and Ziegler, 2006; Reiterer and Ziegler, 2006; Sakai et al., 1989). A transfer-matrix formulation for nonperiodic structures has been developed for reducing the wind-induced response of buildings using the TLCDs and tuned liquid column/mass dampers (Xu et al., 1992).

Majority of the passive energy-absorbing devices are installed to suppress vibrations of a tall building in a single axis, since its plan is a narrow rectangular shape so that the building vibrates mainly in flexurally weak axis. However, vibrations in two orthogonal directions can simultaneously occur especially for the buildings with a square plan. Moreover, tall buildings often vibrate in the axis perpendicular to wind direction due to buffeting phenomena. Although the buildings do not vibrate simultaneously in both directions, change of wind direction may require vibration absorbers located in two orthogonal directions. In practice, two separate dampers in both orthogonal directions are needed to control the two responses of a tall building but their installation requires considerable cost and space. As a result, there has been a practical/economic necessity for a bidirectional single damper.

The use of a single TSD with a rectangular plan was proposed to control vibration modes along two orthogonal directions: Tait et al. (2008) experimentally verified the independence between two orthogonal liquid sloshing motions in a rectangular TLD under two-directional excitation. Zhang et al. (1993) proposed a liquid damper to suppress bi-directional response using crossed tube-like liquid container. Tamura et al. (1995) investigated the vibration control effect of cylindrical TLDs obtained in both orthogonal directions of the building plan. Heo et al. (2009) presented a TLCD connected to the primary building with spring and dashpot, which acts as a TMD in the transverse direction of the liquid motion. Lee et al. (2011) proposed a TLCSD (Tuned Liquid Column Sloshing Damper) which behaves as both TLCD and TSD in both orthogonal

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directions. A shaking table test for a partial scale building was conducted to identify the dynamic characteristics of a TLCSD. More recently, Min et al. (2014) experimentally verified the control performance of a bidirectional tuned liquid mass damper installed at a full scale five-story building model.

The optimal tuning frequency ratio and optimal damping ratio have been first established for TMD application (Den Hartog, 1956; Warburton and Ayorinde, 1980; Chang, 1999) and then studied for the TLD: Chang and Qu (1998) derived analytically unified formulas for optimal tuning frequencies and equivalent damping ratios for passive dynamic absorbers including TLD. A study by Park and Min (2012) addressed the optimal shape of a liquid column vibration absorber (LCVA) for vibration control of a SDOF building under along wind excitation by using the optimal properties suggested by Chang and Qu (1998). In the study, an optimal design procedure of a LCVA focusing on the proportion of the U-shape liquid is proposed based on the optimal tuning law by Chang and Qu for wind excitation. Wu et al. (2005) proposed useful guidelines for designing TLCD for damped SDOF structures under a white noise type of wind loading.

This study proposes a design procedure of a two-way liquid damper (i.e., a liquid damper of combined TLCD and TSD) for attenuating translational building vibrations induced by wind in two orthogonal directions. The design procedure proposed is a trial and error process to satisfy both geometrical constraints and target controlled response factors. For the purpose of providing building design engineers an intuitive design guide, the relation between building response reductions and damping ratios is directly utilized in the design phases. A practical design example is given for reducing wind response of a 64-story reinforced-concrete residential tower.

2. Dynamics of a two-way liquid damper

The configuration of the two-way liquid damper is shown in Fig. 1. The damper has a cross section identical to that of conventional TLCDs and lengthened width to accommodate liquid sloshing. The damper utilizes its two vertical liquid columns as tuned sloshing dampers (TSDs) for the control of orthogonal response of a tall building. x and y denote the directions of TLCD and TSD actions, respectively. Four design parameters of the damper are horizontal liquid column length, L_h, liquid height, h, thickness of TLCD, t, and width of TSD, L_w, as illustrated in Fig. 2.

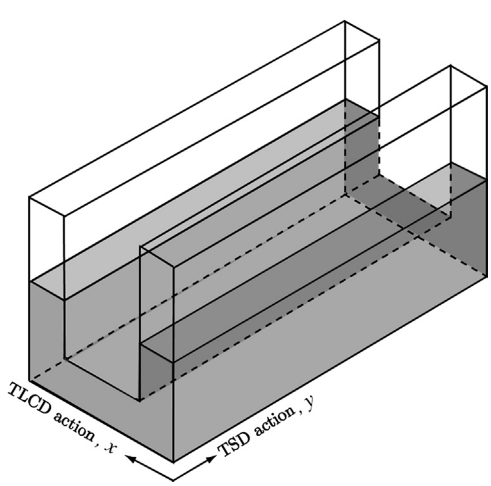

Fig. 1. Two-way liquid damper.

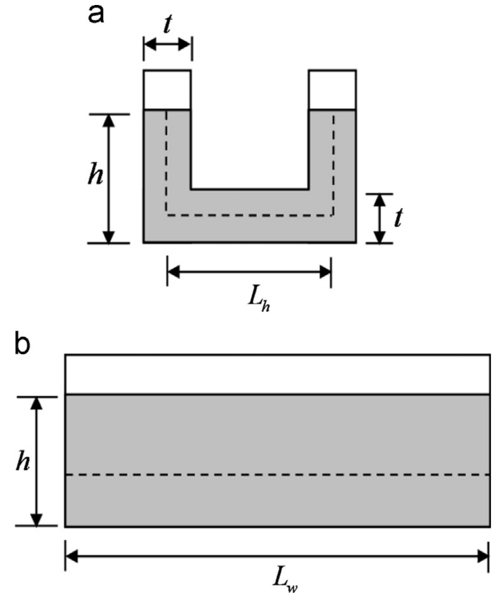

Fig. 2. Geometry of a two-way liquid damper: (a) Front view – TLCD; (b) Side view – TSD.

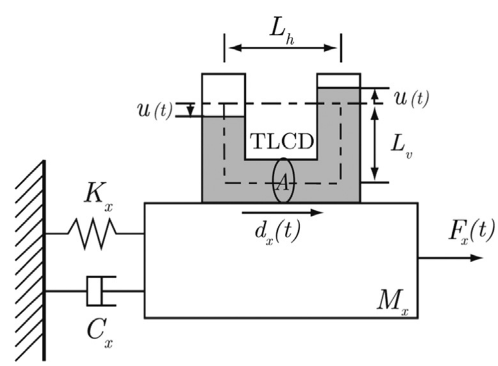

Fig. 3. Two-DOF system of TLCD on building.

2.1. TLCD action

The two-way liquid damper acts as a TLCD for the vibration of the primary building in the x-direction in Fig. 1. The TLCD on the primary building is modeled as a two-DOF system seen in Fig. 3. $d_x(t)$ is the horizontal displacement of the building. $u(t)$ is the vertical displacement of the liquid surface in the TLCD columns M_x, C_x and K_x represents the first modal mass, damping, and stiffness coefficients of the building idealized as a single-DOF system. The equation of motion of the TLCD starts from a non-linear quadratic equation as

$$\rho A L_e \ddot{u}(t) + \frac{1}{2}\rho A \eta \left|\dot{u}(t)\right| \dot{u}(t) + 2\rho A g u(t) = -\rho A L_h \ddot{d}_x(t) \quad (1)$$

where ρ is the density of liquid; A is the cross-sectional area of the liquid column; $L_e = 2h - t + L_h$ is the total liquid column length; η is the head loss coefficient; and g is the acceleration of gravity. The equivalent damping coefficient can be obtained by minimizing the mean square value of the error between the nonlinear and equivalent system linearized, which leads to the expression of the standard deviation of the liquid elevation velocity, $\sigma_{\dot{u}(t)}$, (Yalla and Kareem, 2000) and then the equivalent damping coefficient, C_{eq}, is written as

$$C_{eq} = \sqrt{\frac{2}{\pi}} \rho A \eta \sigma_{\dot{u}(t)} \quad (2)$$