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Analytical and experimental investigations on performance of tuned liquid column dampers with various orifices to wind-excited structural vibration

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ABSTRACT

A detailed study on the dynamic characteristics of passive damping devices of TLCDs with different blocking ratios in orifices is analytically and experimentally conducted for investigation of the optimal control performance of the TLCDs for a wide range of wind loading. In the analytical phase of this study, the control performance is thoroughly investigated for a single degree-of-freedom primary structure equipped with a TLCD for varying intensities of wind loading and blocking ratios. It is verified that the passive-type TLCD with an optimally designed small blocking ratio still shows good performance for strong wind excitation. Next, a series of experiments are carried out to investigate the control performance of a prototype of the TLCD using harmonic and white noise wind excitation and blocking ratios in the orifice by use of a shake table. The damping ratio of the TLCD with various blocking ratios is predicted by the head loss coefficient obtained from the measured data and used for estimating the control efficiency. It is confirmed that the optimal control performance is maintained under conditions of strong wind excitation and an optimally designed small blocking ratio.

1. Introduction

Recently, serviceability of buildings has been emphasized due to an increase in the construction of high-rise buildings and resident requirements. Liquid-type dampers such as tuned liquid dampers (TLDs) and tuned liquid column dampers (TLCDs) have been frequently adopted to reduce acceleration response to wind and to maximize serviceability of buildings. They have definite advantages over other damping devices including low cost, easy installation, and economic maintenance. TLCDs have significant advantages over TLDs: (1) the natural frequency of TLCDs is only determined by the length of the liquid column; (2) damping of TLCDs can be overall accounted for by the head loss coefficient that depends on the orifice size, because the damping is generated by flow passing through the orifice (Wu et al., 2005). Since the TLCD was introduced by Sakai et al. (1989), researchers have investigated characteristics of the TLCD subjected to various dynamic excitations: for example, Shum (2009) and Lee et al., (2012) experimentally studied harmonic responses of the TLCD for wind excitations; Xu et al. (1992), Yalla and Kareem (2000), Battista et al. (2008), and Min et al., (2005,2014b) investigated stochastic behaviors of the TLCD under Gaussian random excitations deriving analytical formulae for design purposes.

The main design parameters of the TLCD are its natural frequency, damping characteristics and effective mass. Among these parameters, the liquid damping of a TLCD is hard to quantify because of its nonlinearity depending on external loading. In general, an equivalent linearization technique is employed in order to simplify the problem. The experimental data of the liquid column tube further indicated that nonlinearity of the orifice damping was not significant and, in terms of application to practical structures, the method of equivalent linearization has potential especially for narrow-band response (Caughey, 1963; Wen, 1980). Thus, it is reasonable to adopt the method of equivalent linearization to deal with the nonlinear damping. The optimal frequency and the optimal damping ratio for a TLCD can be derived by taking the derivative of the building response variance with respect to the natural frequency and damping ratio of a TLCD. The optimal frequency is much closer to the first natural frequency of the building not related to wind loading. However, the optimal damping coefficient depends on the standard deviation of the liquid surface velocity, which varies with wind loading. The presence of this loading dependent nonlinear damping term implies that, for a passive-type TLCD, optimal control performance can only be achieved for the given loading intensity. If the loading intensity deviates too much from the design value then the TLCD may become ineffective.

Chang studied the control performance of three types of mass dampers assuming that the head loss coefficient can be actively adjusted so that the damping ratio of a TLCD can be treated as a constant value (Chang, 1999). The damping coefficient for a TLCD is

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Nomenclature

A	cross-section area of a TLCD (m^2)
c_s	structural damping coefficient (N s/m)
$C_{eq} = 2m_d\xi_d\omega_d$	equivalent damping of a TLCD (N s/m)
$f(t)$	wind loading (N)
g	acceleration of gravity, ($\mathrm{m/s^2}$)
J	control performance index of a TLCD
k_s	structural stiffness (N/m)
L_v	vertical column length of a TLCD (m)
L_h	horizontal column length of a TLCD (m)
$L_e = 2L_v + L_h$	effective column length of a TLCD (m)
$m_d = \rho A L_e$	effective mass of a TLCD (kg)
$m_h = \rho A L_h$	horizontal mass of a TLCD (kg)
m_s	structural mass (kg)
$N_a = \omega_d S_a/(16g^2)$	non-dimensional power spectral density of the shake table acceleration
$N_0 = \omega_s S_0/(16g^2)$	non-dimensional power spectral density of the wind acceleration
S_a	power spectral density of the shake table acceleration ($\mathrm{m^2/s^3}$)
$S_f(\omega)$	power spectral density of the wind acceleration ($\mathrm{m^2/s^3}$)
$S_0 = S_f(\omega_s)$	power spectral density of the wind acceleration ($\mathrm{m^2/s^3}$)
$x(t)$	displacement of a structure with a TLCD (m)
$\dot{x}(t)$	velocity of a structure with a TLCD (m/s)
$\ddot{x}(t)$	acceleration of a structure with a TLCD ($\mathrm{m/s^2}$)
$y(t)$	displacement of the liquid surface (m)
$\dot{y}(t)$	velocity of the liquid surface (m/s)
$\ddot{y}(t)$	acceleration of the liquid surface ($\mathrm{m/s^2}$)
$\alpha = L_h/L_e$	length ratio of a TLCD
$\beta = \omega_d/\omega_s$	frequency ratio between a TLCD and structure
$\gamma = \omega_d/\omega$	frequency ratio between a TLCD and excitation
η	head loss coefficient
$\mu_1 = m_d/m_s$	mass ratio of effective mass of a TLCD versus structure
$\mu_2 = m_h/m_s$	mass ratio of horizontal mass of a TLCD versus structure
ξ_d	equivalent damping ratio of a TLCD
ξ_s	structural damping ratio
ρ	fluid density ($\mathrm{kg/m^3}$)
σ_x	standard deviation of the structural displacement with a TLCD (m)
$\sigma_{\dot{x}}$	standard deviation of the structural velocity with a TLCD (m/s)
$\sigma_{\ddot{x}}$	standard deviation of the structural acceleration with a TLCD ($\mathrm{m/s^2}$)
$\sigma_{x.uncontrolled}$	standard deviation of the uncontrolled structural displacement (m)
$\sigma_{\dot{x}.uncontrolled}$	standard deviation of the uncontrolled structural velocity (m/s)
$\sigma_{\ddot{x}.uncontrolled}$	standard deviation of the uncontrolled structural acceleration ($\mathrm{m/s^2}$)
σ_y	standard deviation of the liquid surface displacement (mm)
$\sigma_{\dot{y}}$	standard deviation of the liquid surface velocity (m/s)
φ_x	displacement amplitude of the shake table (mm)
φ_y	displacement amplitude of the liquid motion (mm)
ψ	blocking ratio of a TLCD
ω	frequency of excitation (rad/s)
$\omega_d = \sqrt{2g/L_e}$	natural frequency of a TLCD (rad/s)
$\omega_s = \sqrt{k_s/m_s}$	natural frequency of a structure (rad/s)

directly related to the wind excitation and the head loss coefficient, which can be set by its orifice size. Theoretically, the orifice size must be adjusted actively in real time depending on wind excitation to maintain constant optimal damping. Some active and semi-active orifice control methodologies have been proposed recently to achieve this. The performance of a structure-TLCD system was investigated experimentally by adopting the semi-active control strategy (Yalla and Kareem, 2003, Haroun et al., 1996). The TLCD is too large for tuning to the very low natural frequency of a real building and for maintaining appropriate mass ratio compared to the building mass. For instance, Wu suggested a building space accommodating a TLCD with the horizontal length of 11 m, vertical length of 2.365 m and a cross-section of 29.4 m^2 (Wu et al., 2005). The actual size of the two-way liquid damper for the real 37 story building is 20.4 m in length, 5.5 m in width and 5 m in height (Min et al., 2014b). Therefore, it is nearly challenging to change the size of the orifice semi-actively or actively, which is installed in the middle of the horizontal column of such a huge TLCD.

In the literature, the control efficiency of a TLCD is discussed in terms of the head loss coefficient by varying blocking ratio and wind excitation (Wu et al., 2005, Yalla and Kareem, 2000). Wu et al. (2005) proposed experimentally an empirical formula to predict the head loss coefficient expressed in terms of area blocking ratio only, which is directly related to orifice size. They investigated the control performance of a TLCD for a building by finding the distribution surface of the mean square of a building response on the head loss coefficient-frequency tuning ratio. It was observed that the control performance of building response is less sensitive to small changes in head loss coefficient varying at the vicinity of the optimal head loss coefficient than optimal tuning frequency. They determined the range of head loss coefficient that corresponds to 5% degradation from the best performance to take into account possible uncertainty existing in a practical situation. Yalla and Kareem (2000) investigated that optimum head loss coefficient is indirectly proportional to the intensity of white noise excitation and at high loading intensities, a very low value of the head loss coefficient is required, i.e., the orifice is nearly open. They found that at higher levels of excitation, a fully open valve is closer to optimum damping, so the semi-active system does not offer any substantial improvement in performance.

Since the damping ratio of a TLCD is dependent on the value of wind excitation, it is expected to be difficult to maintain the optimal damping ratio under a wide range of wind intensities. Therefore, control performance of a TLCD may deteriorate if it has been optimally designed for one specific design wind excitation, and has been addressed as one of the drawbacks of a TLCD. In this paper, detailed studies on the influence of various orifices on damping characteristics and the control performance of the TLCD at a wide range of wind intensities are presented both analytically and experimentally to investigate the robustness of an optimally designed TLCD. Based on the analytical and experimental findings in this study, the control performance of a TLCD with a small blocking ratio subjected to strong wind excitation is proven to be robust against changes in the intensities of wind excitation.

2. SDOF damped structure equipped with a TLCD

2.1. gEquivalent damping coefficient

A schematic view of a single degree-of-freedom (SDOF) primary structure with a TLCD is illustrated in Fig. 1. Coupled equations of