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Moving orifice circular liquid column damper for controlling torsionally coupled vibration

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HIGHLIGHTS

- A Circular Liquid Column Damper with Moving Orifice has been proposed.
- The proposed damper is shown to be more efficient in controlling torsionally coupled vibration.
- The damper significantly reduce the liquid displacement in the column as well.
- The optimal damper parameters are presented through stochastic optimization under random loading.
- Performance of the Damper is experimentally validated using the Shake Table Test on scaled model.

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ABSTRACT

The effectiveness of the Tuned Liquid Column Damper (TLCD) has been established in controlling the vibration of structures from wind or earthquakes. The present study demonstrates the effectiveness of the Circular Liquid Column Ball Damper (CLCBD), in conjunction with the Tuned Liquid Column Ball Damper (TLCBD) in controlling torsionally coupled vibration of building subjected to wind excitations. Unlike TLCDs, these devices are equipped with moving orifice, implemented via steel balls, placed at the middle of the liquid tube. The set of equations of motion of the combined structure–damper system are derived using the Lagrange's approach. The optimal performance is ensured through selection of optimal parameters by minimization the stochastic responses, obtained from random vibration analysis. This is in order to adequately take care of the stochastic excitations. The optimal performances are further verified in respect to the time history responses under simulated wind excitations. Parametric studies are conducted to assess the performance robustness. The proposed TLCBD–CLCBD system offers enhanced control efficiency and significant reduction of the displacement of liquid column than the TLCD. Experimental investigation using Shake table test facility also corroborate with the findings from the analysis.

1. Introduction

Acute space scarcity compels the modern urban development to switch over to vertical expansion, which have resulted in construction of tall structures. These structures are light and flexible due to the recent developments in lighter construction materials with increasing strength and stiffness. Because of their flexible nature, these structures are particularly vulnerable to wind induced, long period dynamic loading. Although, current design practices ensure adequate safety margin against the

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pertinent limits state of failures, quite often, the vibration in these structures cause serviceability problems. This is associated with the floor acceleration and the resulting responses of floor mounted secondary systems. This was a matter of intensive research in the past (Kareem, 1985; Liang et al., 1997) and is also being actively researched at present (Venanzi et al., 2007; Correa and Bentz, 2011). Violation of serviceability due to exceedingly large lateral and/or torsional floor acceleration can be mitigated by employing appropriate vibration control methodology. A number of alternative vibration control technologies have been employed for this purpose. The most commonly adopted control devices are the tuned mass damper, tuned liquid damper and the Tuned Liquid Column Damper (TLCD). The period of sloshing of the liquid column is in close proximity to the dominant periods in the wind excitations and therefore effective in controlling the wind induced vibrations.

The TLCD was introduced by Sakai et al. (1989), which was widely accepted by the researchers due to its simplicity in manufacturing and applicability to wide range of excitation frequencies. A TLCD consist of U-shaped container with an orifice at the middle of the horizontal portion. The tube is filled with liquid, preferably water. In the course of motion, the TLCD impart damping to the structures from the forces of the liquid motion, acting with a phase lag to the motion of the structure. The flow through orifice also causes dissipation of the input energy to the structure from the excitations. The optimum parameters for the TLCD are also obtained in close form (Shum, 2009; Wu et al., 2005). These studies consider harmonic and white noise excitations. The optimal TLCD parameters were reiterated considering limitation on the excessive displacement of the liquid in the column (Chakraborty et al., 2012). The original TLCD has been modified with varying cross section of tube, referred as liquid column vibration absorber (LCVA) (Hitchcock et al., 1997a, b). The control efficiency and its robustness has been improved by employing multiple TLCDs (Gao et al., 1999). The tuning of TLCD to short period structures were also facilitated (Ghosh and Basu, 2004) by introducing a linear spring between the damper and the structure subjected to seismic excitations. This spring was later replaced by one made of shape memory alloy (Gur et al., 2014a, b). Another important yet simple modification of the TLCD was proposed by replacing the orifice with a steel ball (Saif et al., 2011). The ball acts like a moving orifice and is referred as the Tuned Liquid Column Ball Damper (TLCBD). It was revealed that the control performance of TLCBD largely depend on tuning ratio and the ball-to-tube diameter ratio (Gur et al., 2015). Among the most recent studies regarding TLCDs or its variant, Cavalagli et al. (2017) studied the hysteretic energy dissipation mechanism by the sloshing fluid using computational fluid dynamic simulation along with experimental observations. Altunisik et al. (2018) investigated the performance of the TLCD by considering various angle of incidence of the ground excitations to show that the sloshing induced damping is more effective at certain angle of incidence. The nature of nonlinearity encountered in TLCD with sealed container has been recently presented by Dziedziech et al. (2018) using a wavelet based identification algorithm. Xu et al. (2018) proposed a system by combining immersed mass and sloshing liquid and establishes its superiority over the conventional system. Lei et al. (2018) places tuned oscillator into tuned liquid damper in view of enhancing the energy dissipation. However, it may be noted that all these studies are focused on controlling the lateral vibration of structure.

Vibration at the lateral degrees of freedoms (dofs) are of primary interests as the structures are subjected to wind/earthquakes. However, the torsional vibrations are also commonly encountered in structures with asymmetry in plan (Hejal and Chopra, 1989). Although there are ample literature on controlling the lateral vibration using TLCD; studies on controlling torsionally coupled vibration using TLCD are limited. A special configuration of TLCDs have been used in suppressing the pitching motion of bridges (Wu et al., 2008; Xue et al., 2000). The effectiveness of multiple TLCDs, eccentrically placed on the roof of the building in order to reduce torsional vibration were investigated (Shum and Xu, 2002; Xu and Shum, 2003). Xue et al. (1999) have conducted free and forced vibration test to judge the performance of TLCD in suppressing the pitching motion of structure. The use of TLCD, circular in plan was proposed by Huo et al. (2004) in view of controlling its torsional vibration. The results from numerical simulation revealed that the Circular Liquid Column Damper (CLCD) is effective in controlling the torsional vibration mode.

In this study, the CLCD is modified by replacing the fixed orifice with a movable orifice implemented by a steel ball at the middle of the horizontal portion. This is in line of the previous studies (Al-Saif et al., 2011; Gur et al., 2015). The efficiency of the proposed modification is checked in controlling the wind induced coupled lateral–torsional vibration of flexible building. This device is being referred as Circular Liquid Column Ball Damper (CLCBD). The equations of motion of the coupled structure–damper system are derived by following the Lagrange's approach. The optimal parameters for the CLCBD are obtained through systematic design optimization under stochastic wind loading, following a frequency domain random vibration analysis. Thereafter, deterministic time history responses of the optimal damper–structure system are obtained under simulated wind excitations (Kaimal et al., 1972; Kareem, 2008). The effectiveness of the proposed device is verified by comparing its performance with the conventional TLCD. An experimental program has been taken up to verify the performance of the CLCBD system using a Shake table test facility, simulating narrow band lateral excitation, typical to wind. A relative assessment of its performance robustness is also presented.

1.1. Formulation of the equations of motion

The structural model considered herein is a single storied two degrees of freedom (dofs) (one translational and the other is rotational) torsionally coupled building, the plan of which is shown in Fig. 1a. The lateral dimensions of the rigid floor along the x and y directions are denoted by d and b, respectively. The rigid floor is supported by four flexible columns, offering the flexural–torsional stiffness. The stiffness of the columns are adjusted to attain the desired eccentricity (e_x) along the x-direction, only. The mass of the structure is denoted as m_s and the stiffness of the column in the y-direction is denoted as k_y. The building is subjected to wind excitations along the y- direction to induce coupled lateral–torsional vibration. A