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Experimental study on control performance of tuned liquid column dampers considering different excitation directions

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A B S T R A C T

This paper gives experimental tests' results for the control performance of Tuned Liquid Column Dampers (TLCDs) installed on a prototype structure exposed to ground motions with different directions. The prototype structure designed in the laboratory consists of top and bottom plates with four columns. Finite element analyses and ambient vibration tests are first performed to extract the natural frequencies and mode shapes of the structure. Then, the damping ratio of the structure as well as the resonant frequency, head-loss coefficient, damping ratio, and water height-frequency diagram of the designed TLCD are obtained experimentally by the shaking table tests. To investigate the effect of TLCDs on the structural response, the prototype structure-TLCD coupled system is considered later, and its natural frequencies and related mode shapes are obtained numerically. The acceleration and displacement time-histories are obtained by the shaking table tests to evaluate its damping ratio. To consider different excitation directions, the measurements are repeated for the directions between 0° and 90° with 15° increment. It can be concluded from the study that TLCD causes to decrease the resonant frequency of the structure with increasing of the total mass. Damping ratio considerably increases with installing TLCD on the structure. This is more pronounced for the angles of 0°, 15°, 30° and 45°.

1. Introduction

In structural analyses of high-rise buildings, effect of lateral forces such as wind and earthquake should be evaluated in detail. These buildings may be exposed to the resonant condition under the lateral forces due to the low-frequency content. To avoid harmful effects of the resonant vibrations, the first solution to be considered is to increase the damping capacity of the structure. Seismic isolation, active, passive, semi-active control systems, and other supplemental damping systems are among the various alternatives to reduce the structural vibrations. In active control systems, external power is required to produce the forces to resist the dynamic forces acting on. In passive control systems, dynamic energy is absorbed in the system without any external power supply. Damping and stiffness of semi-active control systems can be controlled during the movement. Semi-active control systems need less energy than active ones.

Among the passive control systems, Tuned Liquid Dampers (TLDs) is water confined in a container that uses the sloshing energy of water to reduce the dynamic response of the structure during excitation. TLDs are very effective for absorbing the low-frequency vibrations [1]. As a special case of TLD, Tuned Liquid Column Dampers (TLCDs) having U-shaped tube containing liquid that is usually water has been developed. TLCD can reduce the structural vibrations through the motion of liquid

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residing in the container which counteracts the action of the external excitations [2]. The damping effect of TLCD is produced by the head loss of hydraulic pressure of the liquid due to the orifice installed inside of the container, and the viscous action in the boundary layers. Applications of TLCD on civil engineering structures were first proposed by Sakai and Takeda [3]. Balendra et al. [4] studied on the effectiveness of TLCD for vibration control of towers. Chang and Hsu [5] investigated the control performance of liquid column vibration absorbers for buildings. Gao et al. [6] used a numerical method to account for nonlinearity of the governing equation to determine the effectiveness of TLCD in controlling structural vibrations. Yalla and Kareem [7] performed an experimental study to examine the performance of a prototype semi-active TLCD. Wu et al. [8] proposed the guidelines for industrial practice related to the design of TLCD for damped single-degree-of-freedom structures under wind excitations. Wu et al. [9] summarized the optimal design parameters of TLCD using non-uniform cross-sections in horizontal motion. Chaiviriyawong et al. [10] simulated TLCD using an elliptical flow path estimation method. A modified version of TLCD is proposed by Al-Saif et al. [11] as a passive vibration control device at low-frequencies. Mousavi et al. [12] carried out a detailed investigation on the optimum geometry of tuned liquid column-gas damper for vibrations of an offshore jacket platform under seismic excitations. Sarkar et al. [13] proposed a passive hybrid type damper derived from a pendulum type tuned mass damper and a TLCD. Mensah and Dueñas-Osorio [14] developed a dynamic model of wind turbine to accommodate single/multiple TLCD to control the excessive vibrations. Bigdeli and Kim [15] compared three passive vibration control devices such as Tuned Mass Damper (TMD), TLD and TLCD experimentally. Behbarani et al. [16] showed the effect of TLCD with maneuverable flaps on the vibration control of structures.

Ground motions due to earthquakes have three components with different intensities in lateral (longitudinal and transverse) and vertical directions. Almost all design codes suggested the simultaneous implementation of two lateral components such as in x- and y-directions of structures. However, the simultaneous effect of ground motion to whole structure in x- and y-directions is almost impossible. It can be more realistic approach to consider dynamic loads with different directions acting on the structure.

This paper presents the experimental tests' results for the control performance of Tuned Liquid Column Dampers (TLCDs) installed on a prototype structure exposed to ground motions with different directions. For this aim, a prototype structure and a TLCD are designed in the laboratory. They are exposed to the shaking table and ambient vibration tests for obtaining their dynamic characteristics. Finite element analyses are also performed for verification. Different excitation directions are considered by repeating the measurements within 0–90° excitation directions of 15° increment.

2. Analytical background

Fig. 1 schematically shows a TLCD model. Equation of motion of liquid surface in TLCD was obtained by Gao et al. [6] with the aid of energy principles associated with the Lagrange's equations as follows:

$$\ddot{y}(t) + \frac{1}{2}\frac{\zeta}{L_e}\upsilon|\dot{y}(t)|\dot{y}(t) + \omega_0^2 y(t) = -\frac{b}{L_e}\ddot{x}_g(t) \tag{1}$$

where $\ddot{x}_g(t)$ is the acceleration practiced to TLCD; $\ddot{y}(t)$, $\dot{y}(t)$, $y(t)$ are the acceleration, velocity and displacement of the liquid inside TLCD, respectively; A_v, A_h are the vertical and horizontal cross-sections of TLCD, respectively; υ is the cross-section ratio (A_v/A_h); ζ is the damping ratio; ω_0 is the natural frequency of damper; L_e is the total length of liquid in TLCD which can be calculated by

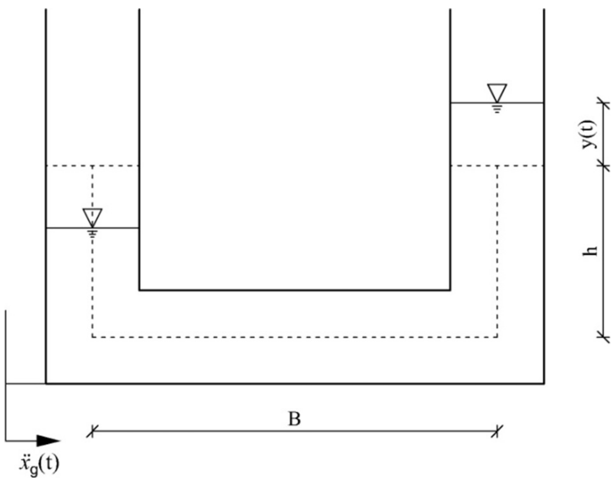

Fig. 1. Configuration of a TLCD system.