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Vibration control of a structure by a tuned liquid column damper with embossments

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ABSTRACT

Several studies have examined damping mechanisms to improve damping effects in a tuned liquid column damper (TLCD). The additional damping mechanisms include orifices, valves, and the use of highly viscous liquids. In the present study, in contrast to previous studies, a damping mechanism using embossments on the wall of the TLCD was proposed, and TLCD with embossment (termed as ETLCD) was proposed as a new type of passive damper. The study focuses on an experimental evaluation of the dynamic characteristics of ETLCD and vibration control performance for tall buildings with ETLCD by using a shaking table. Thus, a characteristic experiment was performed with the presence of embossments, total length of the liquid column, and an excitation amplitude ratio as variables. Additionally, a scaled model test of the SDOF building composed of a free vibration test and sine sweep forced vibration test was conducted to verify the vibration control performance of the structure with ETLCD. Consequently, the equivalent damping ratios of conventional TLCD and ETLCD were experimentally compared, and the theoretical natural frequency of TLCD was re-evaluated in the characteristic experiment. Furthermore, the results of the scaled model test indicated that the vibration control performance of the ETLCD was superior to that of the conventional TLCD in terms of response reduction, efficiency, and stability.

1. Introduction

The development of high-strength materials and construction technology have led to longer-spanning and taller buildings. Therefore, the control of vibration induced by lateral loads, such as wind and earthquakes, is an important consideration in the design of high-rise buildings. Typical methods to improve structural safety and serviceability of these high-rise buildings include increasing the stiffness of the buildings to design a strong structure against the lateral load or increasing the damping force of a building by installing an additional vibration suppression device in the existing building. Since the 1980 s, the United States and Japan adopted a variety of vibration control methods by using additional vibration suppression devices for economic considerations as opposed to simply increasing the stiffness of the building itself to reduce vibrations [1]. In Korea, the use of vibration suppression devices for vibration control is increasing since the installation of a secondary mass damper at Incheon International Airport Control Tower for the first time in 1999 [2].

Secondary mass dampers to control the vibration of a building include tuned mass damper (TMD) that consists of a mass similar to steel or concrete, tuned liquid damper (TLD), and tuned liquid column damper (TLCD) that uses the control force by the sloshing of a liquid. The dampers generally dissipate energy by adding an additional mass (approximately 0.5–5% of the total mass of a building) at the top of the building [3,4]. With respect to the dampers, the liquid dampers possess advantages over other damping devices including lower installation cost and few maintenance requirements. Additionally, when water is used as the liquid of the damper, it can be utilized for water supply and firefighting [5]. The TLCD was first proposed by Sakai et al. and is an U-shape liquid damper as shown in Fig. 1 to maximize the kinetic energy of the liquid inside of the conventional TLD [6]. In contrast to TMD that requires additional spring and dashpot elements, TLCD uses gravity as the restoring force and both the viscous interaction and head loss between the liquid and the solid boundary of rigid container as the damping force [7]. Specifically, given that the actual natural frequency of a completed structure may differ from the design natural frequency, the damper is economical and flexible since it can be easily tuned to the primary structure by changing the length of the liquid column [8].

In a manner similar to other dampers, the research on TLCD covers a broad range of topics ranging from fundamental characteristic studies

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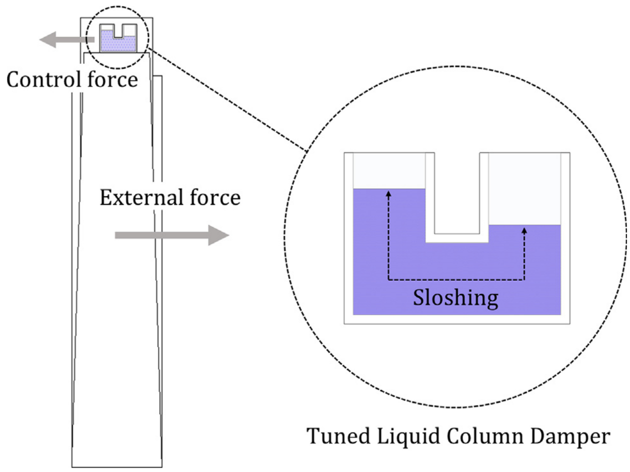

Fig. 1. Tuned liquid column damper (TLCD).

to studies on control performance, optimization techniques, and control strategies with the aim of maximizing the performance and efficiency of vibration control. Sakai et al. presented the governing equation of motion of TLCD and validated it with a series of experiments [6]. Xu, Samali, and Kwok [9], and Balendra, Wang, and Cheong [10] investigated the control performance of TLCD subjected to wind loads, and the control performance for seismic loads was investigated by Won, Pires, and Haroun [11], and Sadek, Mohraz, and Lew [12]. Various studies were also conducted to determine the optimal parameters of TLCD to effectively control the response of buildings [3,5,13]. Recently, control strategies that are not dependent on damper types were actively studied, and novel control strategies that are applied directly to TLCD, such as the optimal design of passive energy dissipation systems by using a decentralized velocity-feedback H_∞ approach, yielded significant results [14–16].

Conversely, the study of liquid dampers is a topic that distinguishes them from other dampers in addition to the aforementioned studies. This involves the study of methods to increase the damping force by adding extra energy dissipation mechanism inside the container of the liquid damper. This is due to the inherent characteristics of the liquid damper that uses the aforementioned viscous interaction and head loss between the liquid and the solid boundary of rigid container as the damping force. Water is generally selected as a liquid in a liquid damper. The damping force of water itself is not sufficient, and thus several studies focused on resolving the same [5,17]. In order to improve the damping force of the TLD, methods of changing the shape of the water tank or using a damping net composed of wire meshes, partitions, high viscosity liquids, and floating particles inside the damper were examined [18–22]. Similarly, in order to improve the damping force of the TLCD, Sakai, Takaeda, and Tamaki proposed a damper with an orifice involving an opening ratio [6]. Yalla and Kareem conducted a study on passive and semi-active TLCDs with a controllable valve [3,23]. Additionally, Wang et al. developed a semi-active MR-TLCD by using magnetorheological fluids that can directly change from a viscous fluid to semisolid when exposed to a magnetic field [24]. Al-Saif, Aldakkan, and Foda proposed a passive TLCBD based on the principle that a coated steel ball is placed on the horizontal part of the TLCD to perturb the flow of the fluid [25].

Most extant studies that focus on improvements in the damping force of TLCDs involve the use of pressure losses by orifice or valve-type devices or high-viscosity liquids that do not exploit the various advantages of TLCD while using pure water as the liquid in the damper. In this context, Ju's TLD study is significant because it reflects the characteristics of high-rise buildings in Korea and investigates damping force enhancement through changes in roughness. This is not examined in the area of TLCD. Unlike other countries, water tanks installed on the roofs of most high-rise buildings in Korea are characterized by embossments on water tank side walls. Therefore, given the above facts, Ju conducted a study by directly using the rooftop water tank as a TLD, and the proposed TLD exhibited satisfying control performance in addition to the damping force enhancement effect [20–22]. Given the results of the study and the damping mechanism of TLCD, it is expected that the methodology of changing the roughness by adding embossments inside the TLD will also be sufficiently effective to enhance the damping capacity of TLCD.

Motivated by the aforementioned research outcomes and potentials, the present study focuses on experimental evaluation with respect to the dynamic characteristics of tuned liquid column damper with embossments (ETLCD) and vibration control performance for tall buildings with ETLCD by using embossment as a damping force enhancement mechanism. Balendra, Wang, and Cheong indicated that the opening ratio of an orifice should be generally varied between 0.5 and 1.0 with higher opening ratios for taller towers to investigate the effectiveness of TLCD for vibration control [10]. This fact is also obtained in the real application example while using TLCD with an opening ratio of 1.0 to suppress the wind vibration of a 64 storey high-rise building in Korea [8]. Thus, in the study, TLCD with an opening ratio of 1.0 is especially selected as a control group for the experiments, and this is expected to clarify the effect of the embossments. The rest of the study is organized as follows. Section 2 introduces a simple TLCD analytical model to aid in understanding the experiments that are performed. In section 3, the dynamic characteristics of the ETLCD were evaluated through a characteristics test by using the shaking table. Section 4 verifies the control performance of the structure with ETLCD through a scaled model test of a SDOF building based on the results in Section 3. Finally, in Section 5, conclusions are drawn, and a few directions for future research are presented.

2. Analytical model of TLCD

2.1. TLCD dynamic equation

This section presents a simple analytical model of a typical TLCD to aid in understanding the experiments that are performed. If u equals the displacement of the water surface inside the TLCD, and x equals the lateral displacement of the structure as shown in Fig. 2, then the dynamic equation of TLCD is expressed as Eq. (1) as follows [6]:

$$\rho AL\ddot{u} + \frac{\rho A}{2}\delta|\dot{u}|\dot{u} + 2\rho Agu = -\rho AB\ddot{x} \tag{1}$$

In the equation, ρ, A, L, B, and g denote the density of water, cross-area, total length, horizontal length of the water column, and acceleration of gravity, respectively. The δ generally denotes the dimensionless head loss coefficient that changes based on the opening

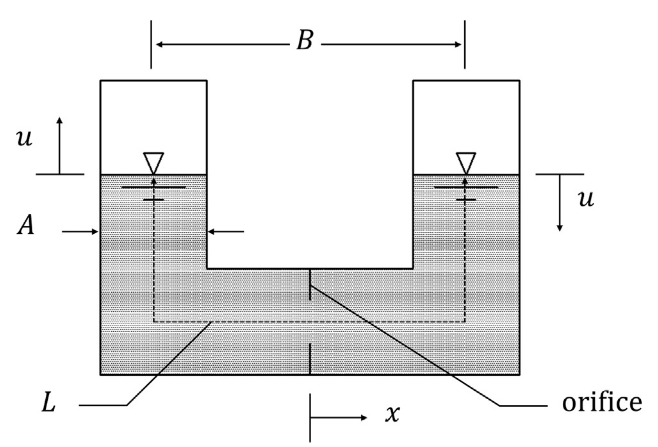

Fig. 2. Modeling of a TLCD.