1 개의 TLD 를 이용한 건물의 양방향 진동제어
Bi-directional response control of a building using one TLD

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ABSTRACT

This paper proposes a tuned liquid column sloshing damper(TLCSD) and presents experimental results to evaluate its control performance. The proposed damper acts as a tuned liquid column damper(TLCD) and a tuned liquid damper(TLD), respectively, in both principal axes of building structures. Shaking table test was performed to grasp its dynamic characteristics. Testing results showed that under inclined incident excitations, a TLCSD used in this study have dynamic characteristics coupled by both TLCD and TLD.

***Keywords** : tuned liquid column damper(TLCD), tuned liquid damper(TLD), tuned liquid column sloshing damper(TLCSD), liquid column vibration absorber with sloshing(LCVAS), shaking table test*

1. INTRODUCTION

Tuned liquid column dampers(TLCDs) have been proven to be effective for reducing responses of building structures subjected to dynamic loads by many researchers. Hitchcock *et al.* have developed a special type of TLCD, called as a liquid column vibration absorbers(LCVAs), of which sectional areas of the horizontal and vertical columns are different with each other [1]. They have also developed a LCVA which can be applied to reduce bidirectional responses of building structures. In terms of simplicity in manufacturing and installation, a TLCD has dominant advantages over other passive types of energy-dissipating dampers. For example, its natural period is easily tuned to that of a structure by adjusting a liquid column length. Also, its inherent damping is simply determined by regulating the head loss coefficient that depends on the size of an orifice to resist to the flow of liquid in the horizontal column. Recent researches on TLCDs have been focused on their optimal designs [2], design guidelines [3] and practical application to real building structures [4, 5].

Being exceeded to certain serviceability standards on both principal axes of building structures, bidirectional responses of building structures are needed to be suppressed. Generally, two mass-type dampers can be applied to control bidirectional responses of building structures. In such a case, however, the live load is increased due to auxiliary masses of dampers, and the retrofitting of a building is additionally required for the story where the dampers are installed. In this study, a tuned liquid column sloshing damper(TLCSD) is proposed, in which such a sloshing of liquid is used for inducing the behavior of a tuned sloshing damper(TSD) in the direction

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perpendicular to a LCVA and without requiring the additional installing vertical partition walls. Accordingly, the proposed TLCSD has a role as a LCVA in the direction of one principal axis, and also acts as a tuned sloshing damper(TSD) that effectively uses the liquid sloshing occurring in the direction perpendicular to a LCVA.

2. Tuned Liquid Column and Sloshing Damper

The configuration of the TLCSD proposed in this study is shown in Fig. 1. Its configuration is same as that of a LCVA. The liquid sloshing of the vertical column in the transverse direction of the LCVA, however, induces the TLCSD to the behavior of two TSDs.

The equation of motion of the TLCSD is derived based on several assumptions: (i) the liquid sloshing in LCVA direction is negligible; (ii) the liquid flow is incompressible (i.e. flow rate is constant); (iii) the width of vertical column of a LCVA is much smaller than the horizontal length of a LCVA; (iv) the first modal configuration of liquid surface due to the liquid sloshing in a TSD direction is expressed as a cosine function, and the higher modal configurations of liquid surface are negligible; (v) A slamming phenomenon of liquid surface is negligible. The equation of liquid surface motion subjected to base acceleration, $\ddot{X}$, as shown in Fig. 1, in the LCVA direction is represented by [6]

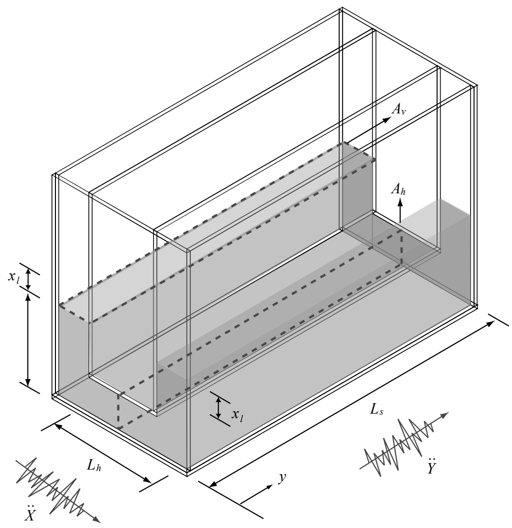


Figure 1. TLCSD subjected to bidirectional base input motion

$$\rho A_h \nu L_e \ddot{x}_l + (1/2)\rho A_h \nu^2 \eta |\dot{x}_l| \dot{x}_l + 2\rho A_h g \nu x_l = -\rho A_h \nu L_h \ddot{X} \tag{1}$$

where, x_l is the displacement of liquid surface in the LCVA direction. ρ denotes the liquid density. η is the head loss coefficient of a LCVA. L_h and L_v are the horizontal and vertical liquid lengths, respectively, and A_h and A_v are the horizontal and vertical cross-sectional areas of a LCVA, respectively. $\nu = A_v / A_h$ is the cross-sectional area ratio of vertical column to horizontal column. $L_e = \nu L_h + 2L_v$ is the effective liquid length of the LCVA. $\omega_l = \sqrt{2g / L_e}$ is the natural frequency of liquid in the LCVA direction.

As a liquid sloshing occurs in the transverse direction of the LCVA, the vertical liquid length, L_v , varies with the width coordinate, y , of a TSD.

$$L_v(y,t) = H_0 - H(t)\cos\left(\frac{\pi}{L_s} y\right) \tag{2}$$

where, H_0 is the vertical liquid length without liquid sloshing. L_s is the width length of the TLCSD in the TSD direction.

The liquid sloshing of a TSD with the rectangular cross-sectional area, which is subjected to base acceleration, $\ddot{Y}$, in the transverse direction of the LCVA, is expressed by using a lumped mass, springs and dashpots, on the basis of the equivalent mechanical analogy [7]. A lumped mass, stiffness and damping are obtained based on the linear wave theory [8]. The linear wave of liquid is composed of several modes, and usually the first mode with the most participation of control force is considered in an analysis. The n-th modal effective mass and natural frequency of a TSD are expressed by

$$m_n = M_l \left(\frac{8 \tanh\{(2n-1)\pi r\}}{\pi^3 r (2n-1)^3} \right); \quad n = 1, 2, \cdots \tag{3}$$

$$\omega_n^2 = \frac{g(2n-1)\pi \tanh\{(2n-1)\pi r\}}{L_s}; \quad n = 1, 2, \cdots \tag{4}$$

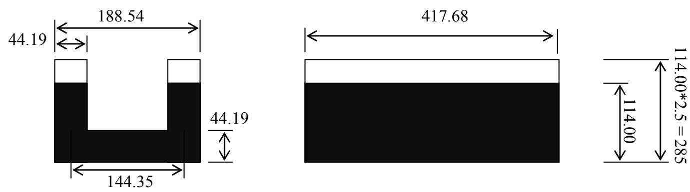
where, M_l is the total mass of liquid within a TSD. $r = L_v / L_s$ denotes the ratio of the liquid height to the width of a TSD.

Accordingly, the inactive mass in the TSD direction is given by

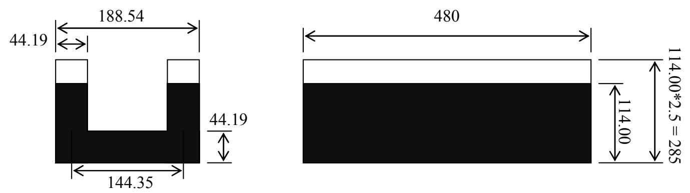
$$m_0 = M_l - \sum_{n=1}^{\infty} m_n \tag{5}$$

3. Test Model of TLCSD and Shaking Table Test

To experimentally evaluate the performance of the proposed TLCSD by using the shaking table, it is ideally recommended that the real-scale test of the device. Fig. 2 shows the test specimen used in this study. Test model denoted by 'S-1' was tuned by the same frequencies in both LCVA and TSD directions, as shown in Fig. 2 (a). Test model represented by 'S-2' shown in Fig. 2 (b) was designed to investigate the independent behavior of the TLCSD in both directions and the coupled effect by a LCVA and a TSD. The natural frequencies in both the LCVA and the TSD directions are tuned by modulating the effective liquid length, L_e, which depends on the liquid elevation and by modulating the liquid width, L_s, through installing U-shaped partitions, respectively.



(a) Test model (S−1)

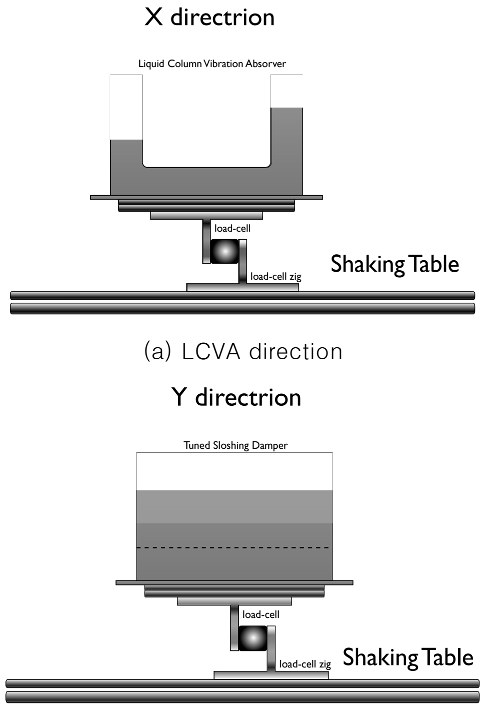


(b) Test model (S−2)

Figure 2. Test specimen of TLCSD

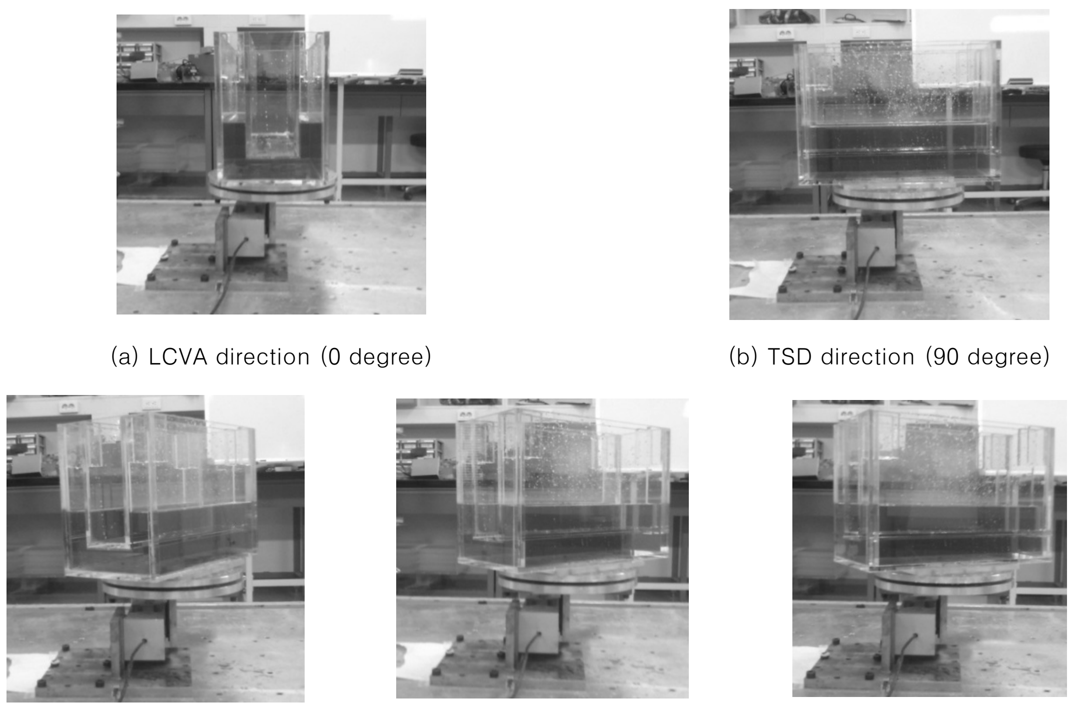
In order to verify the independent behavior of the TLCSD in each x- and y-direction, the TLCSD specimen mounted in a rotational jig is excited by the shaking table with the installation of shear-type load-cell located between the TLCSD and the shaking table, as shown in Fig. 3. Also, an accelerometer was attached on the shaking table to monitor its motion. The shaking table was uniaxially excited by a white-noise input motion, on which the TLCSD was mounted by rotating it with angles of 0, 30, 45, 60 and 90 degrees, as shown in Fig. 4. The data acquisition and implementation of the digital controller were conducted using a real-time digital signal processor (DSP). The primary tasks of the data acquisition board are the analog-to-digital (A/D) conversion of

the measured force and acceleration data, and the digital-to-analog (D/A) conversion of the reference signal computed by the control program *Matlab Simulink* [9]. An 8-channel data acquisition system was adopted using a NI PCI-6052E board and a NI BNC-2110 cable connector. Fig. 4 shows experimental setup of TLCSD upon the shaking table and shear-type load-cell at each rotated angle



(b) TSD direction

Figure 3. Concept of shaking table test



(a) LCVA direction (0 degree) (b) TSD direction (90 degree)

(c) 30 degree (d) 45 degree (e) 60 degree

Figure 4. Rotated TLCD

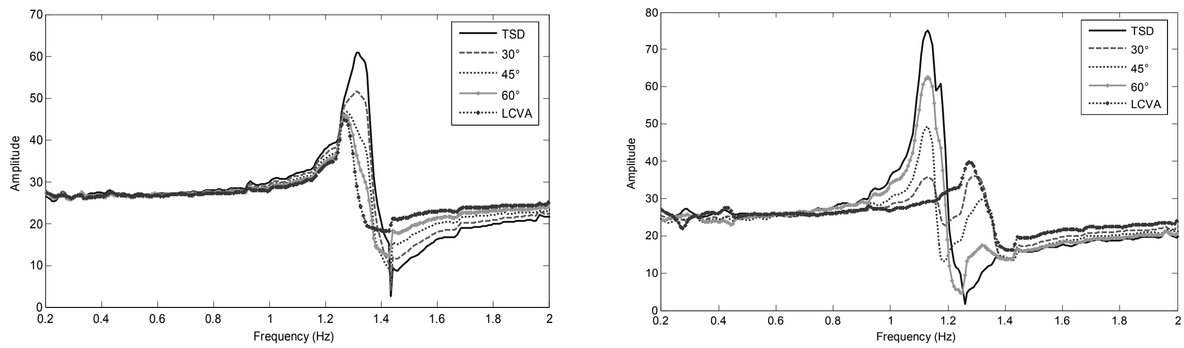
4. Test Result

4.1 Test Model ‘S−1’

Fig. 5 (a) shows the transfer function of test model ‘S-1’ from the shaking table acceleration to the load cell force, which is experimentally observed by rotating the load cell jig. It is observed that the natural frequency in the LCVA direction of the test model ‘S-1’, which is designed to be tuned to same frequencies in both directions, is same as the designed frequency of 1.27 Hz. However, the natural frequency gradually reaches to 1.33 Hz by rotating the TLCSD from 30 degree to 60 degree in the TSD direction. It is considered that since two TSDs of the proposed TLCSD are connected by the horizontal column of a LCVA with each other, the liquid flow in the corresponding part is different from that in the traditional TSDs.

4.2 Test Model ‘S−2’

Fig. 5 (b) shows the transfer function from the experiment of test model ‘S-2’ with different natural frequencies in both the LCVA and the TSD directions. It is noted that two peaks are observed in 1.15 Hz and 1.27 Hz that correspond to the natural frequencies of the TSD and the LCVA, respectively. It is observed that those peaks are intersected with each other according to the increase of rotational angle. The frequency shift within the limit of 3 %, however, is appeared in the LCVA direction with the increase of a rotational angle. This means that the proposed TLCSD is advantageous in terms of the control robustness, while it does not behave independently in both directions.



(a) ‘S−1’ model (b) ‘S−2’ model

Figure 5. Transfer function of test model ‘S−1’ according to rotational angles

5. Conclusions

In this paper, a tuned liquid column sloshing damper(TLCSD) was developed and was tested for its control force characteristics. The proposed damper acts as a tuned liquid column damper(TLCD) and a tuned liquid damper(TLD), respectively, in both principal axes of building structures. Shaking table test was performed to grasp its dynamic characteristics. Testing results showed that under inclined incident excitations, a TLCSD used in this study produces coupled control forces by both TLCD and.

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