行政院國家科學委員會專題研究計畫　成果報告

主動開口及閉口式諧調液柱阻尼器之動力特性與試驗

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主動開口及閉口式諧調液柱阻尼器之動力特性與試驗

Dynamic Characteristics and Experiments of Active Open and Closed TLCD's

計畫編號：NSC 92-2211-E-002-074
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主持人：陳永祥　　國立台灣大學土木工程研究所

ABSTRACT

The dynamic parameters (the tuned frequency and the optimal damping ratio) and the small-scale model tests of an active propeller-controlled open or closed tuned liquid-column damper (or TLCD) attached to a structural system are presented and discussed. It can be found that the closed TLCD is more flexible in practice than the open one; therefore it might have high potential in various applications. The design charts of the open and closed TLCD's are also presented and can be used as the design guide in practice. A simple pendulum-like model test is carried out to study the dynamic behavior and the effectiveness of the vibration control of a TLCD.

INTRODUCTION

The achievement of using of the water sloshing and oscillation inside a container (or vessel) have also been developed for suppressing vibration of building and bridge structure over the past several years. Both the tuned liquid damper (or TLD) and the tuned liquid-column damper (or TLCD) have been studied and have some remarkable advantages such as low cost, easy to install, easy to adjust frequency of liquid motion, and excellent in vibrational control. TLD can reduce the structural vibration by liquid sloshing inside a tank [1-4] and has been installed in several structures recently such as "Shin Yokohama Prince Hotel" in Japan [5] and Tokyo International Airport Tower for examples [6]. TLCD mitigates the structural vibration by the water flow and oscillation inside a long tube [7-9]. Some recent interesting researches have been conducted on the performance or application of TLCD, such as the multiple TLCD 's (or MTLCD's) [10], the non-uniform TLCD's [11] and the optimal damping of TLCD's [12] for examples. Recently a kind of an active TLCD controlled by a pair of propellers installed inside and at the center of the horizontal tube is presented [13]. The performance of the so-called "propeller-controlled active TLCD" has preliminarily been proved excellent, and it is expectantly to be employed for practical applications in the near future.

The dynamic behavior of a TLCD can be characterized as a single-degree-of–freedom system; therefore the structural analysis of a structural system with one or several TLCD's can be very easily carried out by use of the finite-element method. Additionally the TLCD might have the following advantages: (1) it is easy to build and maintain, (2) it is space saving, (3) there is no need to change the structural system of a structure under vibrational control, (4) high performance in vibrational control, and (5) it is economical. Therefore TLCD might have high potential in various applications.

The equation of motion, the dynamic characteristics, and the important parameters such as the tuned frequency and the optimal damping ratio of an open or closed TLCD are formulated and intensively discussed. The comparison of the experimental and numerical results are also included.

EQUATION OF MOTION OF A SYSTEM WITH TLCD

A passive or active TLCD is added to a single-degree-of-freedom system as shown in Figure 1, where m_1, K, and C represent the mass, the stiffness, and the damping coefficients of the system. If this system with TLCD is subjected to a ground acceleration $\ddot{x}_g(t)$, the equation of motion can be written as [13]

$$\begin{bmatrix} M & m'\alpha \\ m'\alpha & m' \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix}+\begin{bmatrix} C & 0 \\ 0 & c' \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix}+\begin{bmatrix} K & 0 \\ 0 & k' \end{bmatrix}\begin{Bmatrix} x \\ y \end{Bmatrix}=-\begin{Bmatrix} M \\ -m'\alpha \end{Bmatrix}\ddot{x}_g+\begin{Bmatrix} 0 \\ 1 \end{Bmatrix}Fc(t) \qquad (1)$$

where $M = m_1 + m'$; m', c', and k' represent the water mass, the damping coefficient, and the stiffness of TLCD ; x and y represent the motions of the main system and the water surface of TLCD ; α represents the length ratio of TLCD which is the ratio of the length of the horizontal tube to the wetted length (l) of TLCD ; $Fc(t)$ represents the control force generated by the propellers.

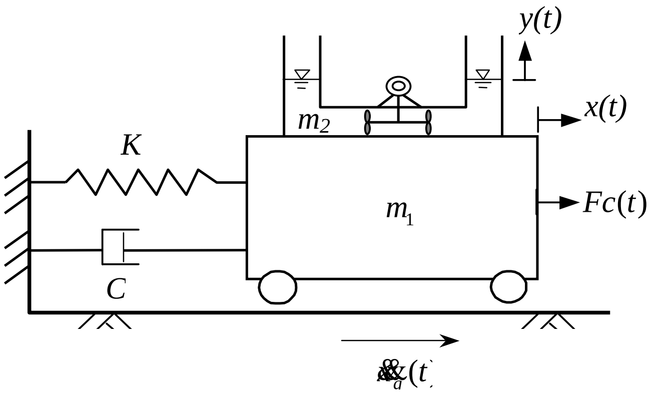

Figure 1. A simple ATLCD system

The previous equation would be rewritten in a nondimensional form as

$$\begin{bmatrix} 1 & \alpha\mu^2 \\ \alpha\mu^2 & \mu^2 \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix}+\begin{bmatrix} 2\eta\omega_p & 0 \\ 0 & 2\xi\omega_u\mu^2 \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix}+\begin{bmatrix} \omega_p^2 & 0 \\ 0 & \mu^2\omega_u^2 \end{bmatrix}\begin{Bmatrix} x \\ y \end{Bmatrix}=-\begin{Bmatrix} 1 \\ -\mu^2\alpha \end{Bmatrix}\ddot{x}_g+\begin{Bmatrix} 0 \\ 1/M \end{Bmatrix}Fc(t) \qquad (2)$$

Where

$$\mu^2=\frac{m'}{M}, \quad \eta=\frac{C}{2M\omega_p}, \quad \xi=\frac{c'}{2m'\omega_u}, \quad \omega_p=\sqrt{\frac{K}{M}}, \quad \omega_u=\sqrt{\frac{2g}{l}} \qquad (3)$$

The basic parameters of a TLCD such as the tuned frequency ω_u and the optimal damping ratio ξ can be determined by Hartog's method [13,14].

A closed TLCD with an airtight cover on the top of each vertical column is shown in Figure 4. Let P_0, V_0, and h_0 be the air pressure, air volume, and column length of air. While the TLCD is under disturbed, the fluid surface in each column moves up and down by a vertical distance dy from the still fluid surface. The force F_g due to the unbalanced liquid weight and the force F_{air} due to the unbalanced air pressure in the these vertical columns are defined as

$$F_g = -2\rho g A_y dy \qquad (4)$$

$$F_{air} = -(P_1 - P_2)A_y \qquad (5)$$

where P_1 and P_2 are the air pressure in the closed column when the water surface reaches the highest and lowest positions, ρ is the density of liquid, and g is the gravitational acceleration. The relationship between the air pressure and the air volume in the closed column above the water is given by Boyle's Law as

$$P_0V_0 = P_1(V_0 - A_y dy) = P_2(V_0 + A_y dy) \qquad (6)$$

Substituting the previous equation into equation (5) yields the following result as

$$\begin{aligned} F_{air} &= -(P_1-P_2)A_y = -\left(\frac{P_0V_0}{V_0-A_ydy}-\frac{P_0V_0}{V_0+A_ydy}\right)A_y \\ &= -P_0A_y\left[\left(1-\frac{A_ydy}{V_0}\right)^{-1}-\left(1+\frac{A_ydy}{V_0}\right)^{-1}\right] \\ &\cong -P_0A_y\left[1+\frac{A_ydy}{V_0}-1+\frac{A_ydy}{V_0}\right] \\ &= \frac{-2P_0A_ydy}{h_0} \end{aligned} \qquad (7)$$

The restoring force F_R is defined as:

$$F_R = -kdy$$
$$= F_g + F_{air} = -2\rho g A_y dy - \frac{2P_0 A_y dy}{h_0} \quad (8)$$
$$= -(2\rho g A_y + \frac{2P_0 A_y}{h_0})dy$$

Therefore

$$k = 2\rho g A_y + \frac{2P_0 A_y}{h_0} \quad (9)$$

The effective fluid mass m' in the TLCD is $\rho A l'$, the natural frequency of this closed TLCD can be derived and given as:

$$T_u = 2\pi\sqrt{\frac{m'}{k}} = 2\pi\sqrt{\frac{\rho A_y l'}{2\rho g A_y + \frac{2P_0 A_y}{h_0}}} = 2\pi\sqrt{\frac{l'}{2g'}} \quad (10)$$

where

$$g' = g(1 + \frac{P_0}{\rho g h_0}) \quad (11)$$

The natural frequency of a closed TLCD can be adjusted by choosing the effective wetted length l', the air pressure P_0 and the height of air chamber h_0 appropriately. Therefore the closed TLCD is much more flexible in practical design than the open one. All the formulations of the equations of motion and the dynamic properties given in Equations (1)~(3) for the open TLCD are also valid for the closed one, except that the gravity acceleration g appeared in Equation (3) should be replaced by g' as given by Equation (11).

Design curves of the open and closed uniform TLCD's.

The natural period of an open or closed TLCD of uniform cross-section can be given by Equation (10). This equation can be rewritten as $l = \left(g'/2\pi^2\right)T_u^2$. If $g' = g$, it is the case for an open TLCD. Let h_0=100cm, P_0 =1atm=1.013kg/cm^2, then g' defined by Equation (11) for a closed TLCD is equal to 11.13g. Therefore the wetted length of a closed TLCD will be 11.13 times longer than that of an open one. The curve for l v.s T_u is shown in Figure 2. It can be seen from this figure that the length design of a closed TLCD is more flexible than an open one. This is the reason that a great number of the open TLCD's should be usually used in practice, especially for the large structure such as the high-rise building. The design curves for R v.s W for a specific T_u are shown in Figures 3 and 4 for the open and closed TLCD's, respectively. Figures 2~4 can be considered as the design charts, which would be useful in applications.

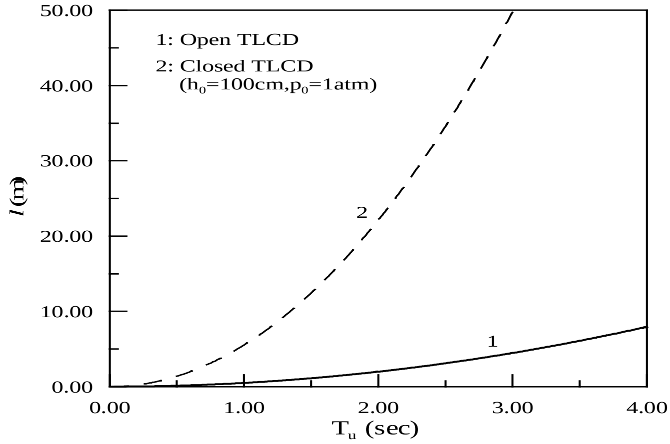

Figure 2. Wetted length vs. tuned period

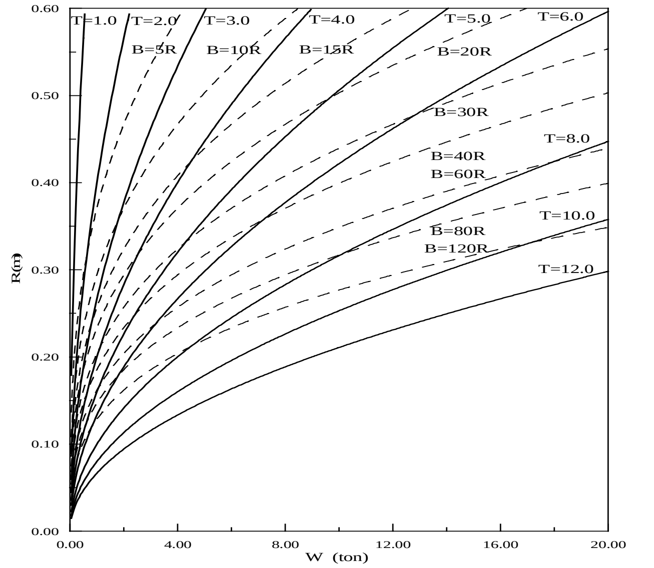

Figure 3. Radius vs. water weight of an open TLCD

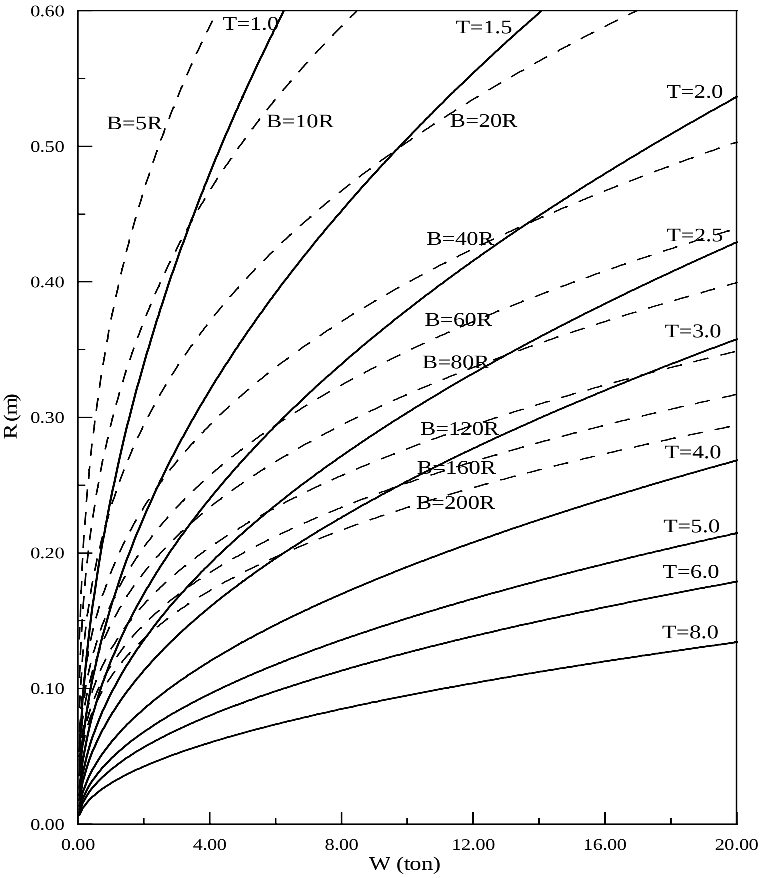

Figure 4. Radius vs. water weight of a closed TLCD (h_0=100cm, p_0=1atm)

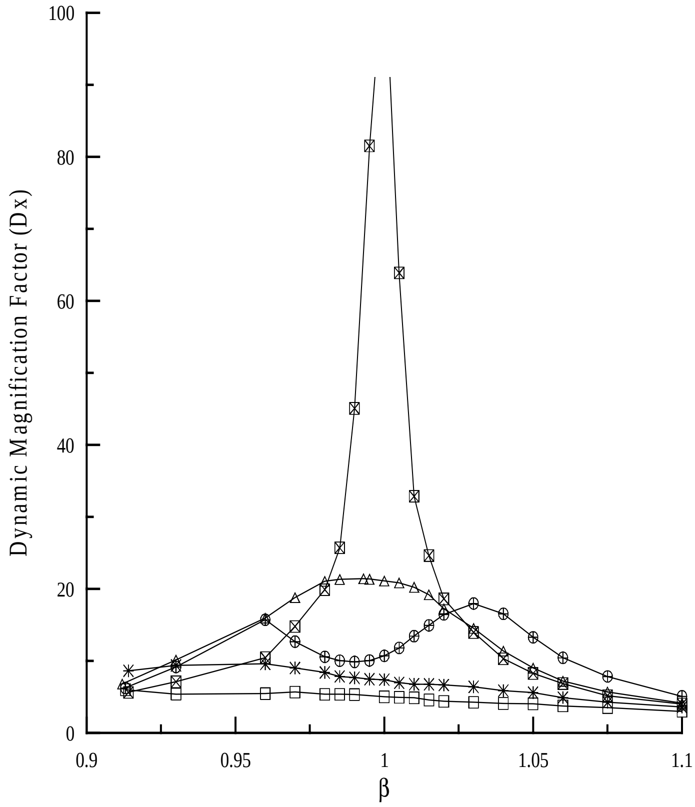

Figure 5**:** The dynamic magnification factor of main structure (□: R=0.1, ✳: R=1, Δ: ATLCD without power, ⊕: passive TLCD, ⊠: W/O control device)

Experiments and numerical results

In order to show the vibrational control performance of an ATLCD, a small-scale model test on shake table is carried out. The wave gage, displacement and velocity sensors are linked to the personal computer for data acquisition.

The horizontal length B is 128cm, the still water height h 16.5cm, the diameter D is 4 cm, and the water mass 2kg of the ATLCD, respectively. The total mass of the main structure including the platform and the ATLCD without water is 210.8 kg. The natural frequency is 3.506 rad/sec and the damping ratio is about 0.002 measured by the free-vibrational test of this system without water. The damping ratios of the testing TLCD with and without propellers are measured as 0.0633 and 0.0528. The tuned frequency and the optimal damping of TLCD are given as 3.4908 rad/sec and 0.0473, respectively. The platform response are shown in Figure 5.

■CONCLUSION

This study presents a new-type vibrational control device, namely the active open or closed tuned liquid column damper with propellers. It is not only simply and excellent but also very economical and efficient. Therefore it would have high potential in many practical applications. In the future study, more research efforts should be encouraged on the design of the practical application, and particularly the additional structural-model tests with earthquake excitation.

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