Structural Engineering and Mechanics, Vol. 30, No. 1 (2008) 1-20
DOI: http://dx.doi.org/10.12989/sem.2008.30.1.001

Passive, semi-active, and active tuned-liquid-column dampers

Yung-Hsiang Chen†

Department of Civil Engineering, National Taiwan University, Taipei, Taiwan, R.O.C.

Ying-Jan Ding‡

Construction and Planning Agency, Ministry of the Interior, Taipei, Taiwan, R.O.C.

(Received April 6, 2007, Accepted June 3, 2008)

Abstract. The dynamic characteristics of the passive, semi-active, and active tuned-liquidcolumn dampers (or TLCDs) are studied in this paper. The design of the latter two are based on the first one. A water-head difference (or simply named as water head in this paper) of a passive TLCD is pre-set to form the so-called semi-active one in this paper. The pre-set of water head is released at a proper time instant during an earthquake excitation in order to enhance the vibration reduction of a structure. Two propellers are installed along a shaft inside and at the center of a passive TLCD to form an active one. These two propellers are driven by a servo-motor controlled by a computer to provide the control force. The seismic responses of a five-story shear building with a passive, semiactive, and active TLCDs are computed for demonstration and discussion. The responses of this building with a tuned mass damper (or TMD) are also included for comparison. The small-scale shaking-table experiments of a pendulum-like system with a passive or active TLCD to harmonic and seismic excitations are conducted for verification.

Keywords: TLCDs; modelling; controls; experiments.

1. Introduction

The tuned-liquid-column damper (or TLCD) or named as the anti-rolling tank was first used and installed in a ship in order to decrease the rolling motion or to increase the rolling stability of a ship going in ocean waves (Lewis 1989). A kind of active antirolling tank was designed by use of an air-compressor equipment connected to the openings of TLCD to enhance its control performance (Lewis 1989). It has been proved that TLCD has excellent ability to control the ship-rolling motion, particularly in beam seas. The TLCD mitigates the structural vibration by use of the water flow and oscillation inside a long tube, it has also successfully been applied to the other kind of structures like building and tower (Sakai *et al.* 1989, Sun 1994, Balendra *et al.* 1995, Xue *et al.* 2000). In the past two decades. Some interesting research have also been conducted on the performance or application of TLCD (Won *et al.* 1996, Hitchcock *et al.* 1997, Gao *et al.* 1999, Yalla and Kareem

† Professor, Corresponding author, E-mail: ychen@tl.ntu.edu.tw
‡ Assistant Engineer

2000, Chen and Chao 2000). Recently a new kind of an active TLCD controlled by a pair of propellers installed inside and at the center of the horizontal tube is presented (Chen and Ko 2003). The performance of the so-called "propeller-controlled active TLCD" has been studied and proved excellent, and is expected to be employed for practical applications in the near future.

A simple idea of a kind of semi-active TLCD is also presented in this paper by means of a pre-set of the water head of TLCD before earthquake and releasing it at a proper time instant during the seismic excitation. It has been found in this paper that it can improve a passive TLCD to control the seismic response of a building very efficiently and economically. However the control technique of this type of TLCD needs more research effort in future.

The dynamic behavior of a TLCD can be characterized as a single-degree-of-freedom system, the structural model of a TLCD attached to a structural system is also presented. It is essentially a mass-coupling mechanism and can be very easily employed for the structural analysis of a structural system with one or several TLCDs 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 TLCDs might have high potential in various applications.

2. Open and closed TLCDs

The open and closed TLCDs are shown in Figs. 1 and 2. They are a U-shaped vessel consisting of two vertical columns and a horizontal section partially filled with fluid or water. In practice these two vertical columns are usually identical and the cross-sectional area of the uniform horizontal section is equal to or greater than that of the vertical columns, the larger horizontal section seems to have higher efficiency in vibrational control (Chen and Chao 2000). The water can move freely inside the vessel and could be assumed an incompressible flow. The dimension R of the vertical column as defined in Fig. 1 is much smaller than the wetted length of a TLCD; therefore the water surface would be assumed to be flat during vertical motions. The equation of motion of the water surface $y(t)$ of an open TLCD subjected to a horizontal excitation $x(t)$ derived by Hamilton principle (or Lagrange's equation) (Chen and Chao 2000) can be easily modified by taking the air pressure in the air chamber above the water level into account for a closed TLCD given as

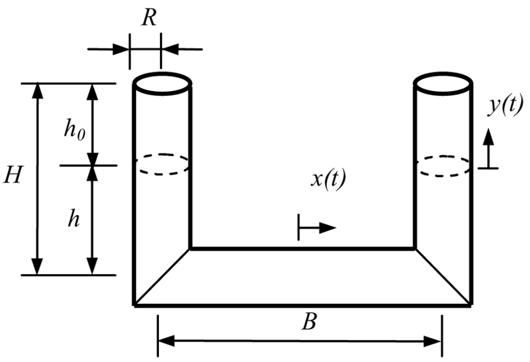

Fig. 1 An open TLCD

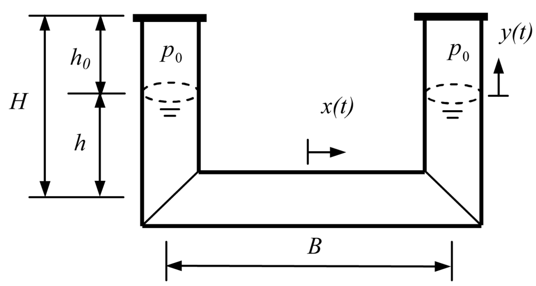

Fig. 2 A closed TLCD

$$m'\ddot{y} + c'\dot{y} + k'y = -m'\alpha\ddot{x} \tag{1}$$

where m', c', k' and α represent the effective water mass, the coefficient of the equivalent linear viscous damping, the stiffness, and the length ratio, respectively. m', α, k' and the natural frequency ω_u of a TLCD are defined as follows

$$m' = \rho A_y l', \quad \alpha = \frac{B}{l'}, \quad k' = 2\rho g' A_y, \quad \omega_u = \sqrt{\frac{2g'}{l'}}$$

where $$l' = \int_0^l \frac{A_y}{A(s)} ds, \quad g' = g\left(1 + \frac{p_0}{\rho g h_0}\right) \tag{2}$$

in which ρ represents the water density, A_y and $A(s)$ the cross-sectional areas of the vertical column and the vessel at any position, g the gravitational acceleration, l' the effective water length, α the ratio of the effective horizontal length to the effective water length, h_0 and p_0 the height and the air pressure of the air chamber above the water level as shown in Fig. 2, respectively. p_0 can be set as zero ($p_0 = 0$) for an open TLCD. If a TLCD is uniform along its length, the effective water length is equal to the water length and the effective water mass is equal to the water mass, i.e., $l' = l = 2h + B$ and $m' = m = \rho Al$, where A is the area of the uniform cross section; if a symmetrical TLCD consisting of two identical uniform columns of the cross-sectional area A_y and an uniform horizontal section of cross-sectional area A_x, the effective length becomes $l' = 2h + B/r$, where $r = A_x/A_y$.

The nonlinear damping force resulting from the water-head loss due to the friction between the water and vessel surface of a TLCD for the steady-state harmonic excitation is given by

$$\begin{aligned} F_d &= \frac{\rho A_y}{2} c_d |\dot{y}|\dot{y} \\ &= \frac{m'}{2l'} c_d \omega^2 y_0^2 |\cos\omega t|\cos\omega t \end{aligned} \tag{3}$$

where c_d represents the nonlinear damping coefficient, ω and y_0 represent the frequency and the amplitude of $y(t)$, respectively.

Omitting the high-order terms of the Fourier expansion of the nonlinear damping force F_d, the equivalent linear viscous damping force F_e can be obtained and approximated

$$\begin{aligned} F_e &= c'\dot{y} \\ &= 2m'\xi\omega_u\dot{y} \end{aligned} \tag{4}$$

where the equivalent linear viscous damping ratio ξ is given by

$$\xi = \frac{2\omega y_0}{3\pi\omega_u l'} c_d \tag{5}$$

The previous result of ξ can also be obtained from the fact that the energy per cycle done by the nonlinear damping force F_d and by the linear viscous damping force F_e are the same. Let us consider a TLCD under a steady-state harmonic excitation with the following example properties: $m' = 10/\pi$, $\xi = 5\%$, $\omega = \omega_u = \pi$, and $y_0 = 1.0$. The force-displacement diagrams having the same area corresponding to the same energy per cycle done by $f_d(t)$ and $f_e(t)$ are shown in Fig. 3. Therefore, the equivalent linear viscous damping can give good approximation.

A propeller-controlled active TLCD (or ATLCD) is added to a single-degree-of-freedom system as shown in Fig. 4, where m_1, K, and C represent the mass, stiffness, and damping of the system. If

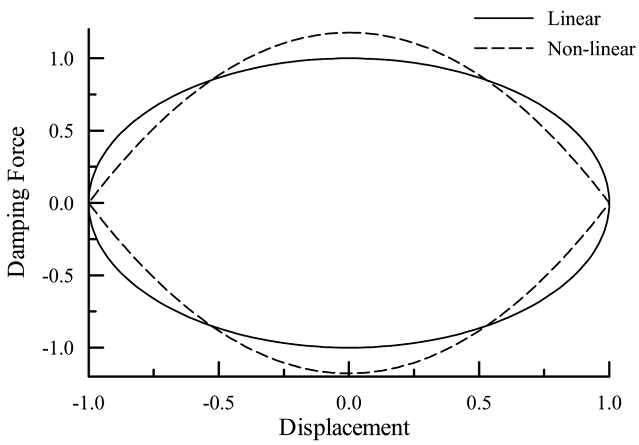

Fig. 3 Damping force-displacement diagram

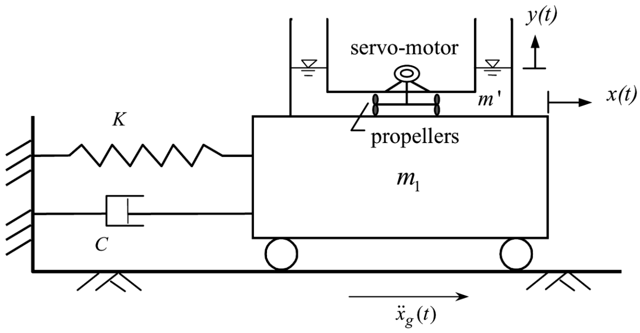

Fig. 4 A simple ATLCD system

this system with an ATLCD is subjected to a ground acceleration $\ddot{x}_g(t)$, the equation of motion can be written as (Chen and Ko 2003)

$$\begin{bmatrix} M & m'\alpha \\ m'\alpha & m' \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix} + \begin{bmatrix} C & 0 \\ 0 & c' \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix} + \begin{bmatrix} K & 0 \\ 0 & k' \end{bmatrix}\begin{Bmatrix} x \\ y \end{Bmatrix} = -\begin{Bmatrix} M \\ m'\alpha \end{Bmatrix}\ddot{x}_g + \begin{Bmatrix} 0 \\ 1 \end{Bmatrix}F_c(t) \tag{6}$$

where $M = m_1 + m'$, $F_c(t)$ represents the control force generated by the propellers.

The previous equation would be rewritten in a nondimensional form as

$$\begin{bmatrix} 1 & \alpha\mu \\ \alpha\mu & \mu \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix} + \begin{bmatrix} 2\eta\omega_p & 0 \\ 0 & 2\xi\omega_u\mu \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix} + \begin{bmatrix} \omega_p^2 & 0 \\ 0 & \mu\omega_u^2 \end{bmatrix}\begin{Bmatrix} x \\ y \end{Bmatrix} = -\begin{Bmatrix} 1 \\ \mu\alpha \end{Bmatrix}\ddot{x}_g + \begin{Bmatrix} 0 \\ 1/M \end{Bmatrix}F_c(t) \tag{7}$$

where

$$u = \frac{m'}{M}\ ,\ \eta = \frac{C}{2M\omega_p}\ ,\ \omega_p = \sqrt{\frac{K}{M}} \tag{8}$$

If $F_c(t) = 0$ in Eqs. (6) or (7), it becomes the case of a passive TLCD. The mass ratio μ and the length ratio α are usually pre-assigned and their ranges are usually μ = 0.5~2.0% and $\alpha \cong 0.8$ in practice. According to Hartog's method (Den Hartog 1962) based on the criterion that the amplitude of the steady-state dynamic response $x(t)$ of an undamped system (i.e., $C = 0$) with a TLCD shown in Fig. 4 under the harmonic ground excitation $\ddot{x}_g(t)$ in frequency domain is minimum, the formulas of the basic parameters i.e., the tuned frequency ω_u and the optimal damping ratio ξ of the TLCD can be achieved (Chen and Chao 2000) and given as

$$\omega_u = \omega_p(1 - 1.5\alpha^2\mu)^{1/2} \tag{9}$$

$$\xi = (\xi_1 + \xi_2)/2 \tag{10}$$

where ξ_1 or ξ_2 are functions of μ, α, and the tuned-frequency ratio f (where $f = \omega_u/\omega_p$) (Chen and Chao 2000).

It should be noted that the explicit formulas of the basic parameters for a damped system ($C \neq 0$) might be difficult to derive, however Eqs. (9) and (10) can provide good approximations as the initial values for a numerical iterative calculation.

Another method by Jacquot and Hoppe (Jacquot and Hoppe 1973) to determine these two parameters ω_u and ξ is based on minimizing the mean-square response of $x(t)$ under the white-noise random ground excitation $\ddot{x}_g(t)$. The mean-square response of a damped system with TLCD can be obtained by

$$E(x^2) = \int_{-\infty}^{\infty} |H(i\omega)|^2 S_{\ddot{x}_g}(\omega) d\omega \tag{11}$$

where $S_{\ddot{x}_g}(\omega)$ is the power-spectral density function of the ground excitation $\ddot{x}_g(t)$ and $H(i\omega)$ is the complex transfer function. The two parameters ω_u and ξ can be determined by

$$\frac{\partial R}{\partial \omega_u} = 0 \quad \text{and} \quad \frac{\partial R}{\partial \xi} = 0 \tag{12}$$

where R represents the effectiveness of the vibrational control, which is the ratio of the mean-square response of $x(t)$ with and without TLCD, when $R < 1.0$, the TLCD is effective for vibrational control.

In general the damping ratio of a prototype TLCD due to the friction between the water particle and the inner tube surface is much smaller than the optimal damping ratio of a TLCD calculated by Eqs. (10) or (12). Therefore additional damping is always necessary in order to achieve the optimal damping ratio of a TLCD. Two devices are suggested as follows: 1. The artificial orifices inside the horizontal tube, 2. The perforated cover plates at the openings of the vertical tubes. The damping of a TLCD with orifices or perforated cover plates is strongly dependent on the shape, size, number of orifices, or the perforated area ratio and the position of the cover plates. The latter seems to be simpler and efficient in practice.

The result of damping ratio from the model test can not be applied to the prototype directly. It can be predicted by a large-scaled model test or by engineering experience and judgement. Either the orifices or the perforated cover plates can adjust the damping ratio efficiently.

3. Design curve of TLCD

The natural period of an open or closed TLCD of uniform cross-section can be given by Eq. (2). This equation can be rewritten as $l = (g'/2\pi^2)T_u^2$. If $g' = g$, it is the case for an open TLCD. Let $h_0 = 100$ cm, $P_0 = 1$ atm $= 1.013$ kg/cm^2, then g' defined by Eq. (2) for a closed TLCD is equal to

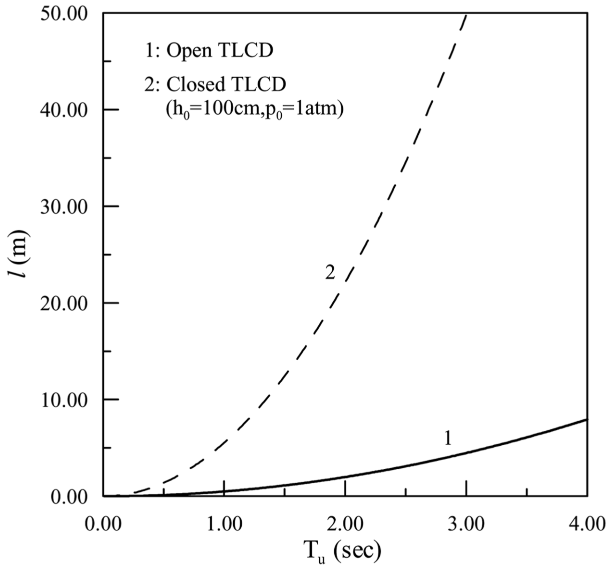

Fig. 5 Water length (l) vs. tuned period (Tu)

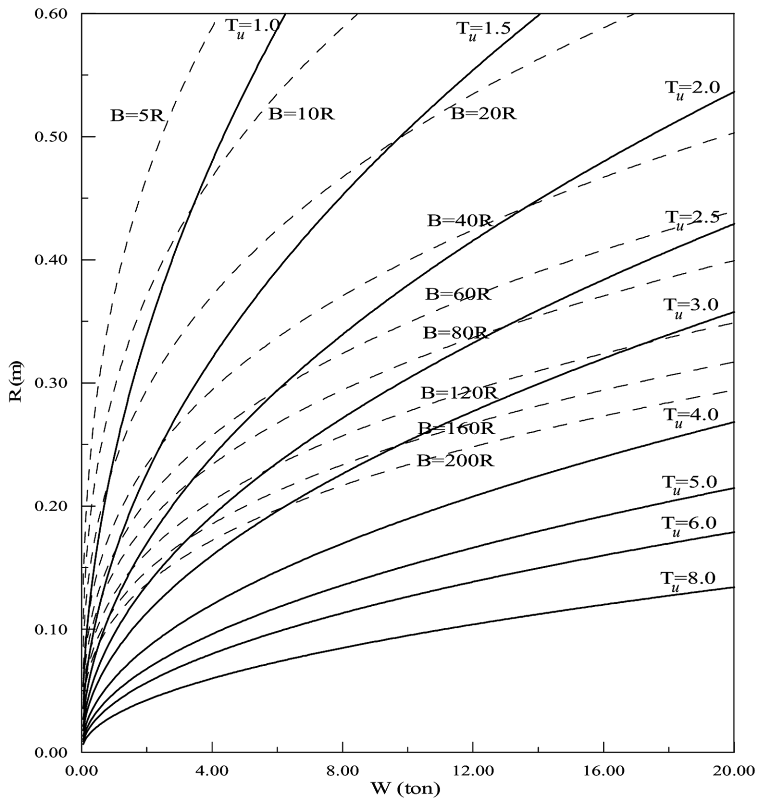

Fig. 6 Radius (R) vs. water weight (W) for a closed TLCD (h_0 = 100 cm, P_0 = 1 atm)

11.13 g. Therefore, the water 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 Fig. 5. 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 why a great number of the open TLCDs are usually used in practice, especially for large structures such as high-rise buildings. The relationship between the water weight W and the natural period of a TLCD can be given by $W = (\rho g g'/2\pi^2)AT_u^2$, where A is the cross-sectional area. With a circular cross-section of a TLCD of radius R for example, this equation can be rewritten as $R^2 = (2\pi/\rho g g' T_u^2)W$. The curves for R v.s W for a specific T_u are shown in Fig. 6 for a closed TLCD for the case of P_0 = 1.0 atm and h_0 = 100 cm. The equations of $B = \alpha l$ and $m = \rho A l$ can be reduced to the equation of $BR^2 = (\alpha/\pi\rho g)W$, this equation is also shown in Fig. 6 for α = 0.8 and B = 5~20R. The intersection of the solid and dashed curves in Fig. 6 gives the radius (R) and the water weight (W) of a closed TLCD for a specific period (T_u), and a specific ratio of B and R (α = 0.8).

4. The structural model of TLCD

The equation of motion of a single-degree-of-freedom system with a TLCD is given by Eq. (6). It is a mass-coupling system. The oscillation of the water surface of the vertical column of a TLCD is essentially a degree-of-freedom of motion; therefore the structural analysis of a multiple-degree-of-freedom structural system with one or several TLCDs can easily be carried out. According to Eq. (6) a TLCD can be modeled as a single-degree-of-freedom mechanism attached to a main system by a massless rigid bar with a lumped mass $4m'\alpha$ at its center and the pin connections at two ends as shown in Fig. 7. Due to the mass coupling effect of the rigid connection bar, the masses of the main system and the TLCD at the mass centers should be modified as $(M - m'\alpha)$ and $(1 - \alpha)m'$ as also shown in Fig. 7, respectively.

5. Semi-active TLCD

A given water head $y(t \le t_1)$ as shown in Fig. 8 is pre-set before an earthquake attack and released

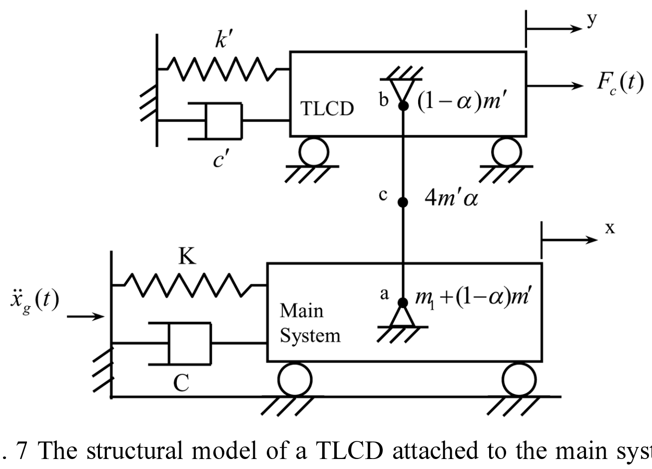

Fig. 7 The structural model of a TLCD attached to the main system

Fig. 8 A Pre-set of water head 1

at a proper time instant t_1 during the seismic excitation, hence enhancing the vibrational reduction of a structure significantly. This is a simple idea presented in this paper and referred to as a kind of semi-active TLCD. It is probably the simplest, economical, and effective way to control the seismic response of a structure, of course, the pre-set water level $y(t \leq t_1)$ denoted as y_1 and the released time t_1 will play two very important roles in practice. The latter seems to be more important and sensitive than the former. The system efficiency can deteriorate if the release time is not right. The choice of y_1 and t_1 should mainly depend on the maximum ground acceleration and the structural response which is to be suppressed. A simple control guide can be given as following: (1) A water head y_1 can be preset approximately twice as the maximum water elevation of a passive TLCD caused by designing maximum ground acceleration. (2) At the threshold of ground acceleration exceeds a certain percentage, say 50% for example, of the design maximum ground acceleration, it should get ready to release the preset of water level y_1. (3) The release of the pre-set of water head y_1 should be made at the time instant t_1 just when the motion of water level is opposite to the structural response, say the roof displacement of a building for example. In other words, the motions of the water level of TLCD and the roof displacement of a building should be out of phase with each other at time instant t_1, so the water motion can suppress the structural vibration effectively. More details will be given later by an example included in this paper. However, the control technique for this type of TLCD needs more research effort in future.

6. Propeller-controlled active TLCD

Two propellers along a geared shaft are installed inside the TLCD and are symmetrical with respect to the centre of the horizontal section as shown in Fig. 4. These two propellers are powered by a servomotor controlled by a computer to generate the control force. The propeller operating in a restricted water space inside a long tube has high efficiency and sensitivity. Furthermore, the impulsive-type control force generated by the propellers acting on the TLCD (as shown in Eq. (6)) and transferred to the main system directly through a mass-coupling mechanism (as shown in Fig. 7) could be more sensitive and effective than other type of mechanisms such as the spring/ dashpot device of a tuned mass damper. The propeller-controlled ATLCD was first presented and studied by the first author of this paper. The small-scale model test and application on the control of a five-story shear building to seismic excitation are included for verification and demonstration.

7. Experiments and comparisons

In order to show the vibrational-control performance of a passive or active TLCD, a small-scale model test is carried out. A simple pendulum-like platform with a uniform ATLCD is set up on a small-scale shaking table as shown in Fig. 9. This shaking table can only simulate the ground displacement, either harmonic or seismic, as the input to the platform. The wave gauge, displacement and velocity sensors are linked to a personal computer for data acquisition.

The horizontal length B is 160 cm, the still water height h is 16 cm, the diameter D is 4 cm, and the water weight is 2.42 kg, respectively, of the TLCD. The total weight of the platform including

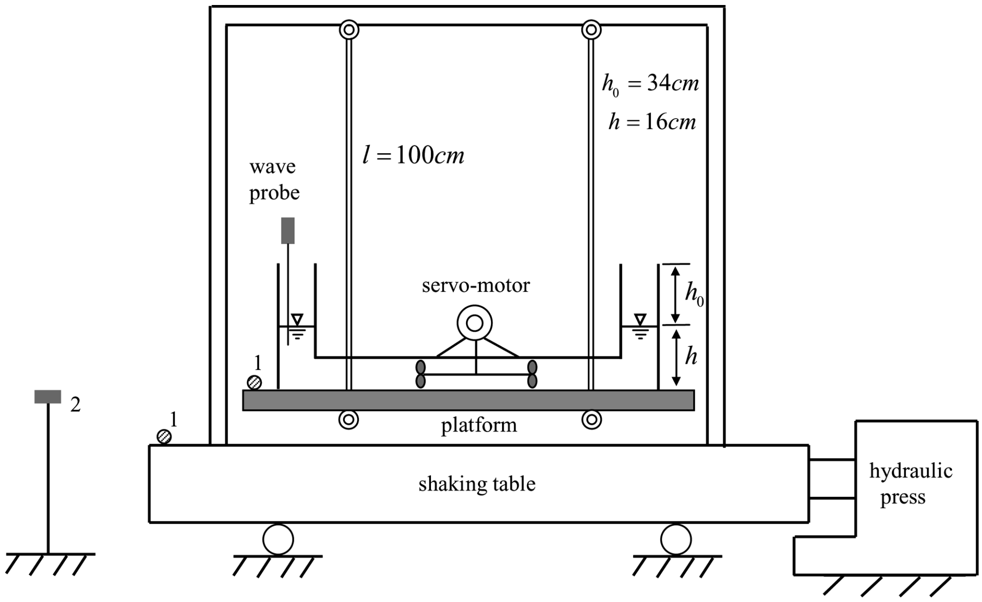

Fig. 9 A simple pendulum-like platform with ATLCD (1: accelerometer, 2: laser displacement sensor)

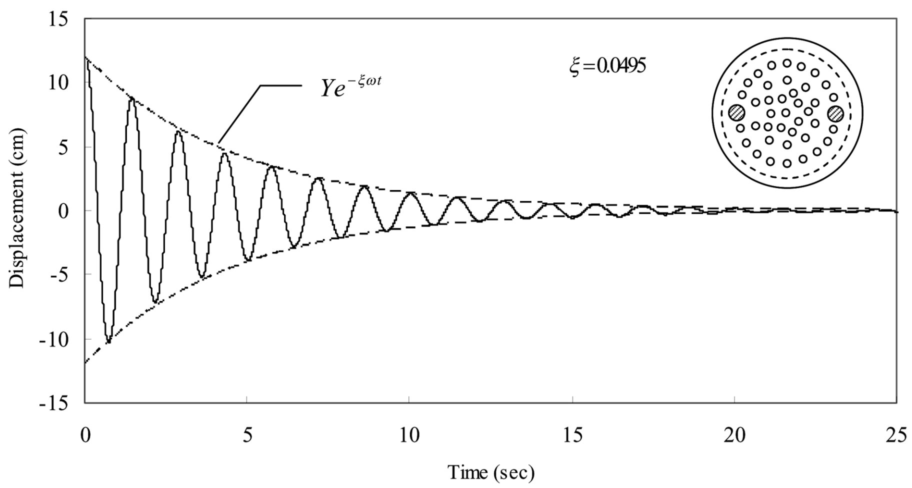

Fig. 10 Free vibration test (perforated area ratio 9.75%)

the ATLCD without water is 242 kg. The natural frequency is 3.213 rad/sec and the damping ratio is about 0.0032 measured by the free-vibrational test of this system without water. The tuned frequency and the optimal damping ratio of the TLCD calculated by Eqs. (9) and (10) are given as 3.197 rad/sec and 0.0508, respectively. A perforated cover plate with 9.75% of opening at each opening of the vertical column of TLCD is designed in order to achieve the optimal damping ratio of TLCD. The free-vibrational test by a preset of the water head y_1 = 12.5 cm (see Fig. 8) of TLCD with the perforated cover plates are shown in Fig. 10. The damping ratio of TLCD is about 0.0495 and it is slightly influenced by the different pre-sets of the water head.

In order to calibrate the relationship between the input voltage to the servo-motor and the output control force generated by a pair of two-blade propeller used in the model test, a pre-experiment is conducted. The experimental and the regressive results of the input voltage vs. the output water head Δy (or the maximum water head Δy_{max}) generated by the propellers are shown in Fig. 11 for

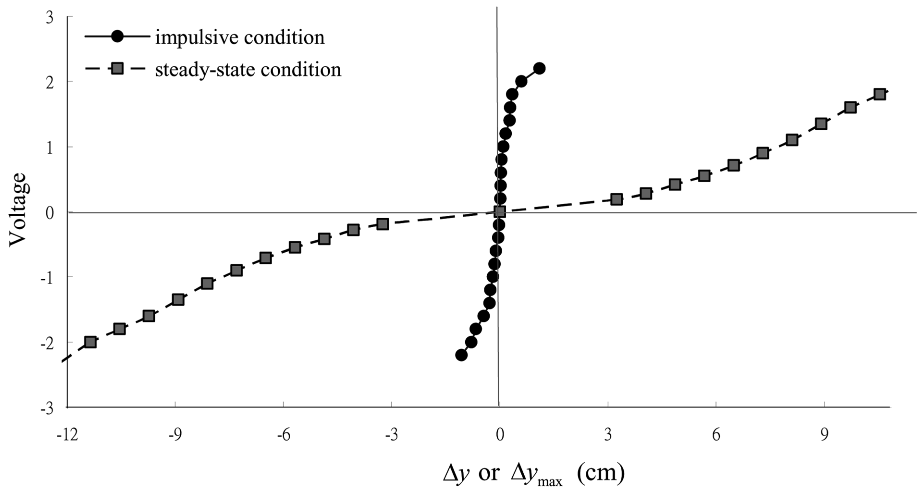

Fig. 11 The relationship between voltage and water head

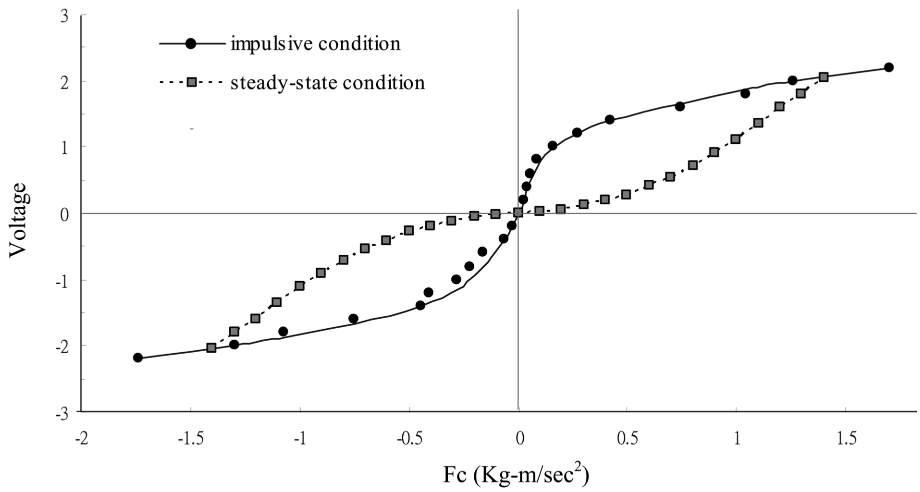

Fig. 12 The relationship between voltage and control force

the steady-state or the impulsive condition. Both the input voltage and the output control force are assumed as a step function, the control force F_c can be computed by $F_c = 0.5\rho g A_y \Delta y$ for the long-duration steady-state condition, or it can be computed from the relationship between the impulse and the change of momentum as $F_c \Delta t = m' \omega_u \Delta y_{\max}$ for the short-duration impulsive condition. The impulsive one is used to determine the control force F_c at each time step as shown in Fig. 12.

The steady-state harmonic responses of the platform and the water head of the passive or active TLCD in frequency domain and shown in Figs. 13 and 14. The dynamic responses controlled by ATLCD are determined in time domain by use of the space-state vector, the step-by-step calculation, and feedback optimal control theory (Chen and Ko 2003). The weighting coefficient R for the control force used to determine the optimal gain function (Chen and Ko 2003) is chosen as 1.0.

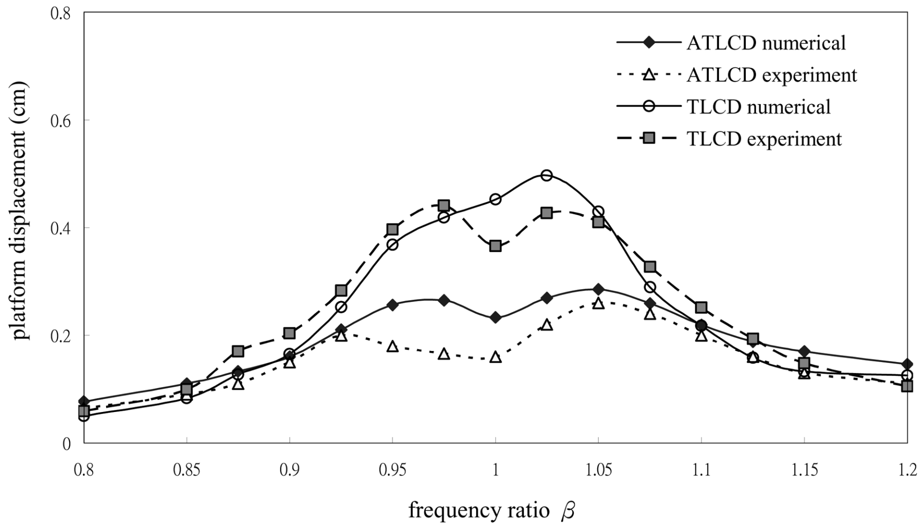

Fig. 13 The steady-state harmonic response of the platform

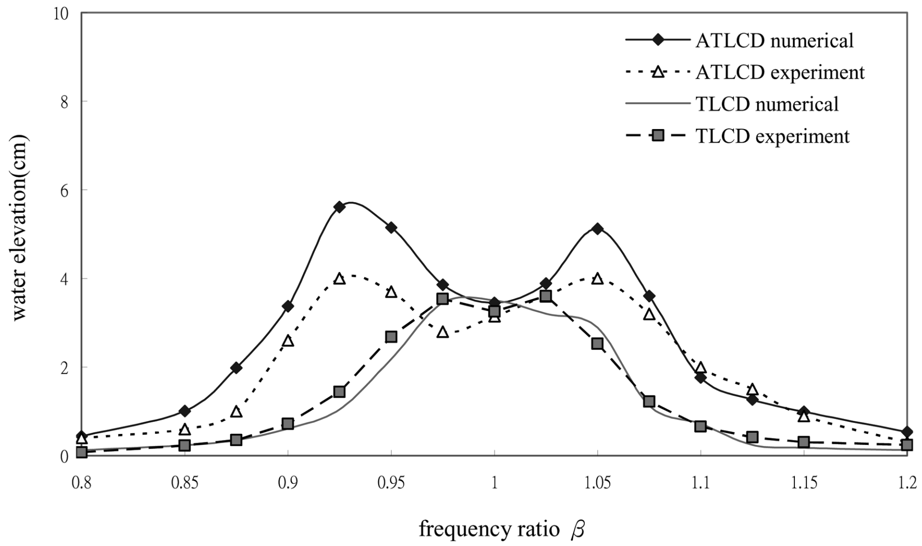

Fig. 14 The steady-state harmonic response of the water elevation

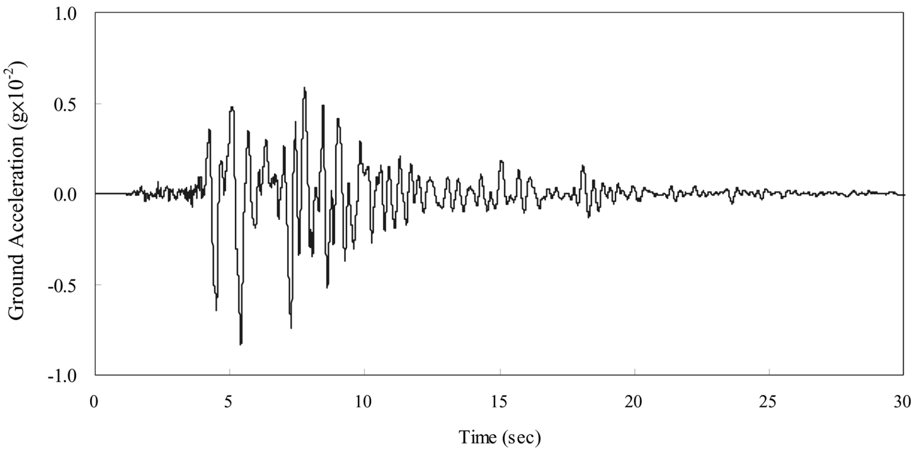

Fig. 15 The 1/100 ground acceleration record of Kobe earthquake

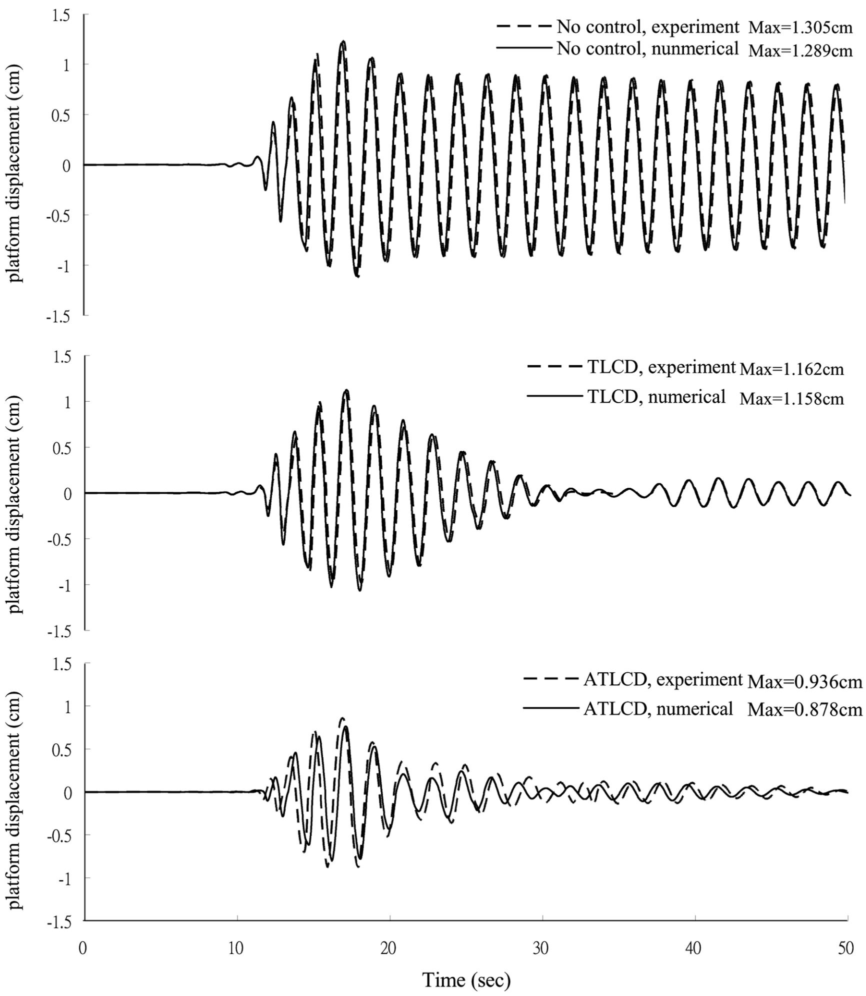

Fig. 16 The seismic responses of the platform

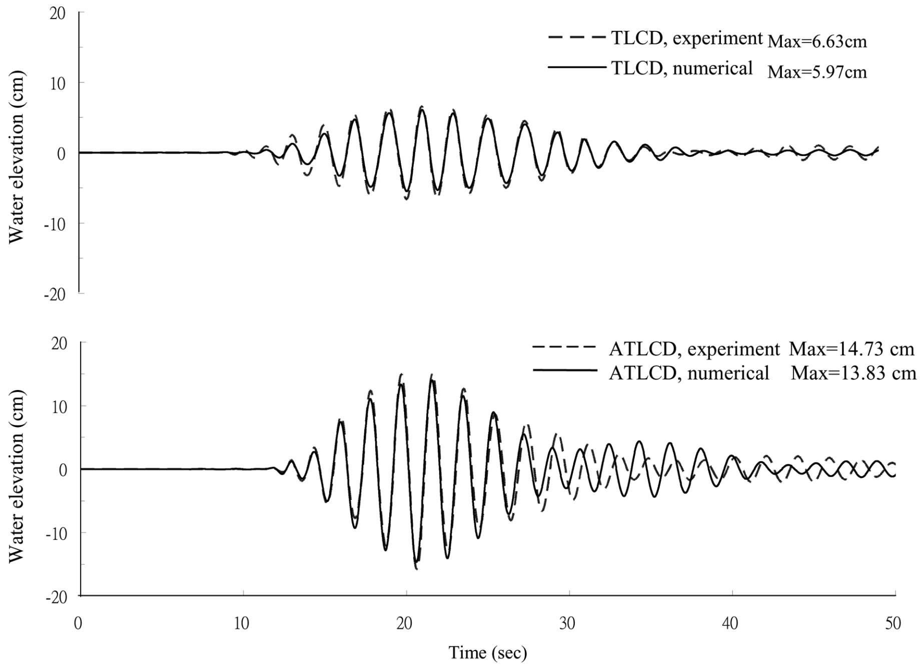

Fig. 17 The seismic responses of the water elevation

Both the experimental and analytical results look quite consistent. The analytical result of water head of the passive TLCD is slightly larger than the experimental one (the active TLCD without power). This is probably due to the additional damping component from the water flow through the propellers.

1% of the Kobe earthquake ground acceleration record is shown in Fig. 15 as the input excitation to the same structural model. The seismic responses of the platform and the water elevation of TLCD are shown in Figs. 16 and 17. The response of the platform without control is also shown. As we can see, both the experimental and analytical results of the seismic responses are also consistent. The water motion inside the active TLCD is much more pronounced than that inside the passive one.

Example : Vibrational control of a five-story shear building to earthquake.

The mass and the dynamic properties of a five-story shear building without TLCD or TMD are given in Tables 1 and 2. A TLCD or TMD is installed on the roof of this building. The structural model with TLCD is shown in Fig. 18. The water mass of TLCD is assumed to be 2% of the total mass of the building; therefore the masses at points a, b, and c on the roof as shown in Fig. 18 are 123200 、3200 and 51200 kg, respectively. The damping ratio of this building without control is

Table 1 The mass of a five-story shear building

Floor	1F	2F	3F	4F	5F	Total
Mass×10^3(kg)	200	180	160	140	120	800

Table 2 Natural frequencies and mode shapes of the five-story shear building without TLCD

		Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Natural Freq. (rad/sec)		5.1377	13.2047	20.5391	26.2989	30.0782
Mode Shape	1F	1.0000	1.0000	1.0000	1.0000	1.0000
	2F	2.0150	1.3985	0.3672	−0.7567	−1.6445
	3F	2.9470	0.8089	−1.0199	−0.5214	1.7093
	4F	3.6886	−0.5058	−0.7259	1.3559	−1.2507
	5F	4.1241	−1.6719	1.0560	−0.7676	0.4776

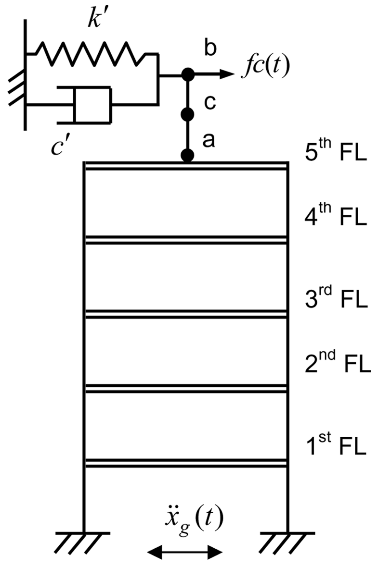

Fig. 18 Five-story shear building with TLCD

Table 3 The parameters of TLCD or TMD for the five-story building

Mass Ratio	Length Ratio (α)	Tuned Frequency Ratio		Optimal Damping Ratio	
		TMD	TLCD	TMD	TLCD
2%	0.8	0.976	0.990	8.62%	6.95%

Table 4 Natural frequencies and mode shapes of the five-story shear building with TLCD

Mode		Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Natural Freq. (rad/sec)		4.68	5.52	13.14	20.45	26.24	30.07
Mode Shape	1F	1.00	1.00	1.00	1.00	1.00	1.00
	2F	2.03	1.99	1.41	0.38	−0.74	−1.64
	3F	3.02	2.88	0.83	−1.01	−0.54	1.70
	4F	3.89	3.51	−0.48	−0.76	1.35	−1.23
	5F	4.52	3.78	−1.66	1.02	−0.72	0.44
	Water level	19.95	−19.94	1.57	−0.87	0.60	−0.36

assumed to be 2% for all vibrational modes. The important parameters, the tuned frequency and the optimal damping ratio, of TLCD or TMD are determined based on the fundamental mode of this building by Hortog's method and the results are given in Table 3. Since the design of the TLCD or TMD is based on the fundamental mode of this building, the fundamental mode will be split into two vibrational modes if a TLCD or TMD is attached to this building. The natural frequencies and mode shapes of this building with TLCD are given in Table 4. The natural frequencies of the first

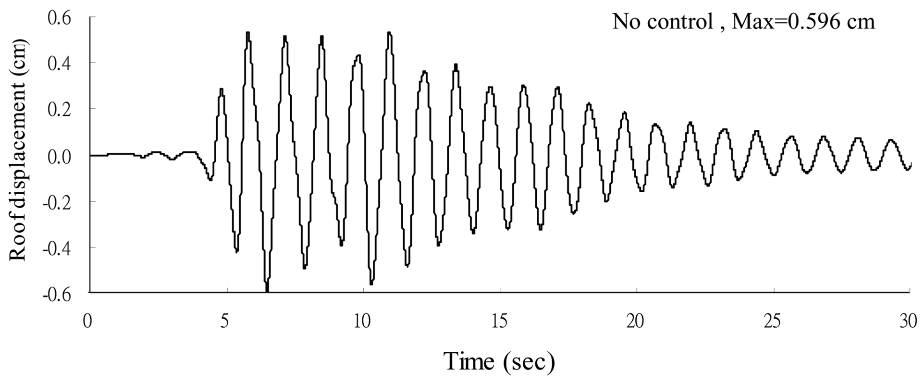

Fig. 19 Roof displacement without control

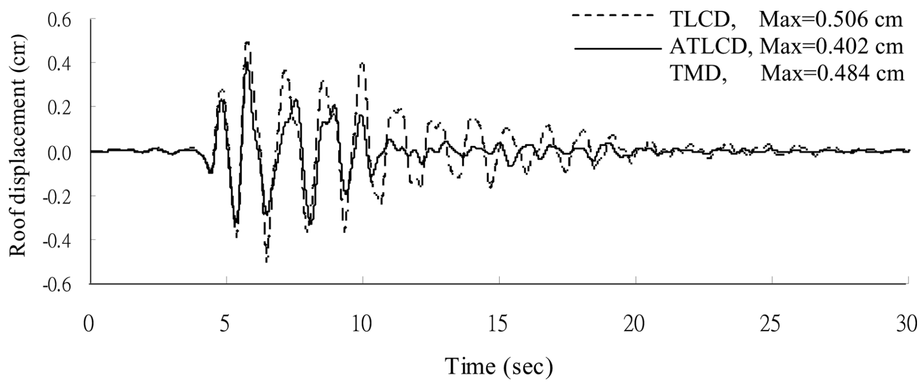

Fig. 20 Roof displacement under control

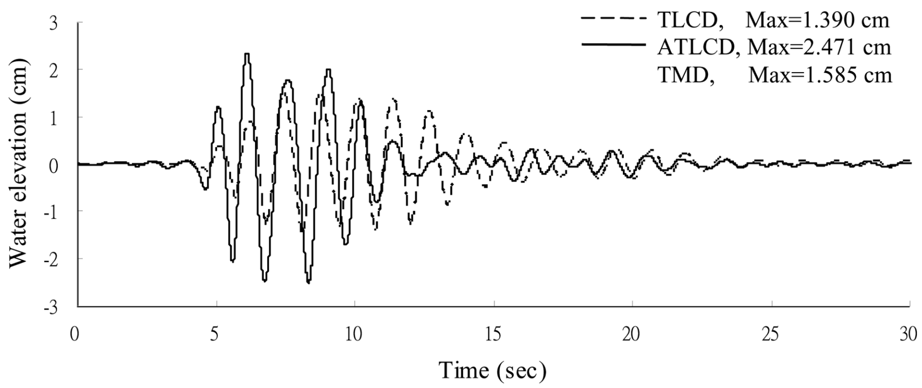

Fig. 21 Water elevations

and third modes of this building with TLCD or TMD are used to establish the Rayleigh damping matrix (Clough and Renzien 1993). The dynamic response are determined in time domain (Chen and Ko 2003). The building is subjected to the 1/100 ground acceleration of Kobe earthquake as shown in Fig. 15. The roof displacements are shown in Figs. 19 and 20. The water elevation of TLCD is shown in Fig. 21. The maximum responses controlled by TMD are also given in Figs. 20

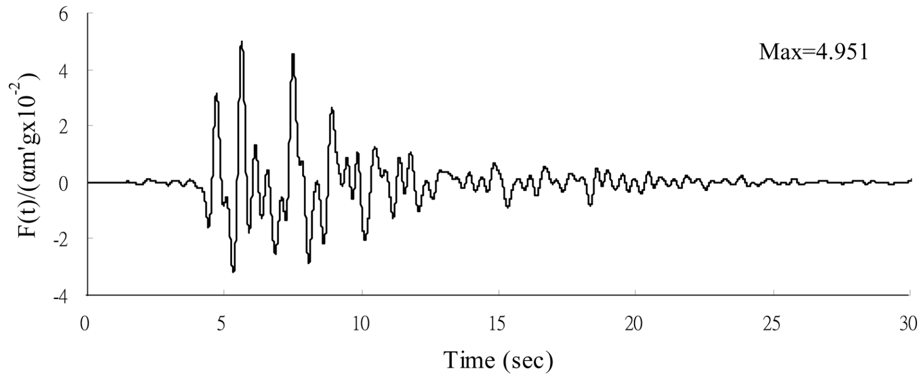

Fig. 22 Control force

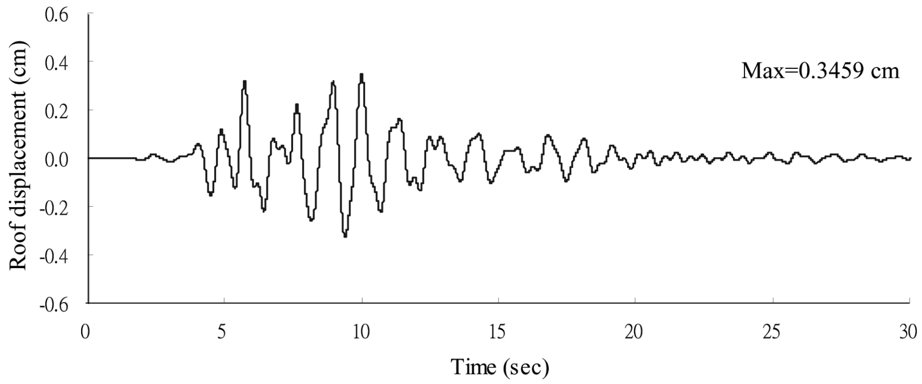

Fig. 23 Roof displacement (TLCD, $y(t \le t_1)$ = 3 cm at t_1 = 3.8 sec)

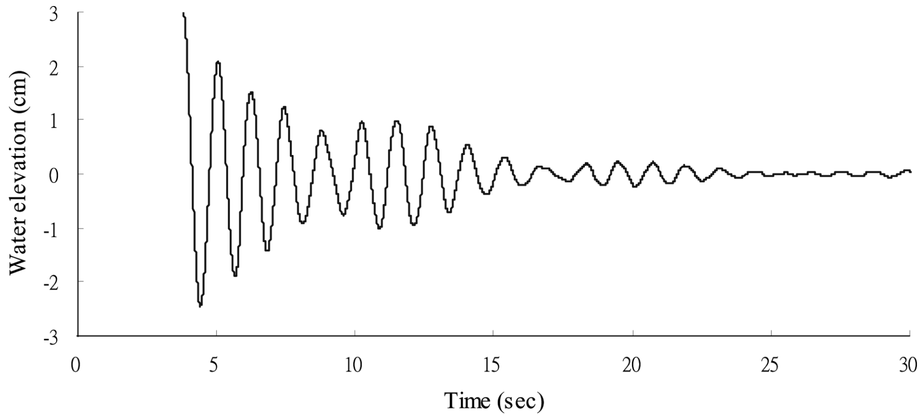

Fig. 24 Water elevation (TLCD, $y(t \le t_1)$ = 3 cm at t_1 = 3.8 sec)

and 21 for comparison. The results show that TLCD and TMD have the significant vibrational-control ability. The control force generated by the propellers of the ATLCD is calculated by the Feedback Optimal Control Theory and the result is shown in Fig. 22. The weighting coefficient R for the control force used to determine the optimal gain function (Chen and Ko 2003) is chosen as 3.0×10^{-6}. If a given water head $y(t \le t_1) = y_1 = 3$ cm is pre-set before earthquake attack and released at $t_1 = 3.8$ sec after the seismic excitation, the responses of the roof displacement and the water level are shown in Figs. 23 and 24. As we can see, the pre-set of the water head and released at a proper time can result a significant vibrational control. Fig. 25 shows the influence of the pre-set of the water head y_1 ($y_1 = 1{\sim}5$ cm) released at the same time instant $t_1 = 3.8$ sec on the maximum roof displacement. It can be seen that the maximum roof displacement is not very sensitive to the variation of y_1. Fig. 26 shows the influence of the releasing time t_1 ($t_1 = 0{\sim}4$ sec) on the maximum roof displacement for a constant pre-set of water head $y_1 = 3$ cm. It can also be seen that the maximum roof displacement is very sensitive to the variation of t_1. The result could be worse if the releasing time t_1 is not right. The releasing time t_1 at each trough of the wave as shown in Fig. 26 shows that the motion of the water level is out of phase with the roof displacement as shown in Fig. 19. Therefore the releasing time t_1 at each trough of the wave of Fig. 26 gives a better control of the roof displacement. The pre-set of the water head should be released before the time instant

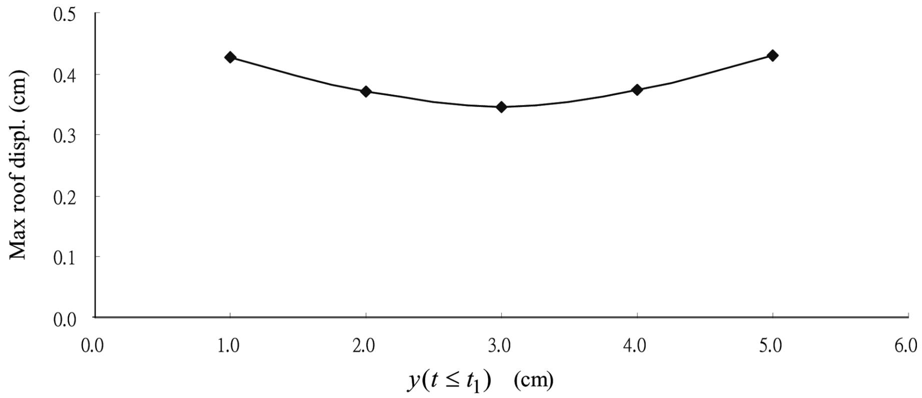

Fig. 25 Maximum roof displacement (TLCD, $y(t \le t_1) = 1{\sim}$ 5 cm at $t_1 = 3.8$ sec)

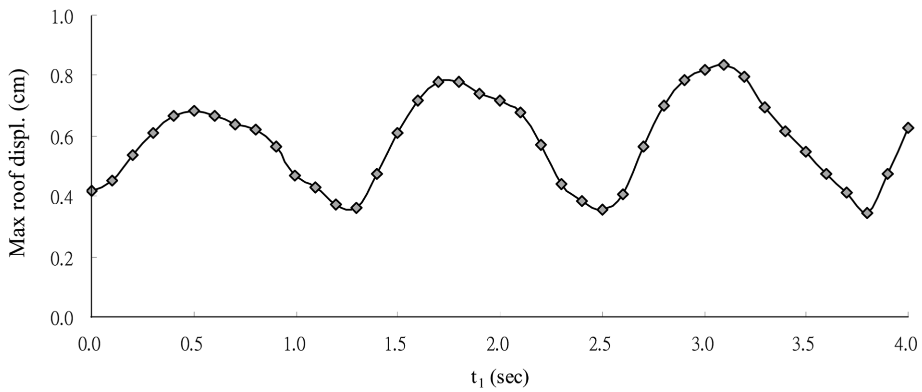

Fig. 26 Maximum roof displacement (TLCD, $y(t \le t_1) = 3$ cm at $t_1 = 0{\sim}4$ sec)

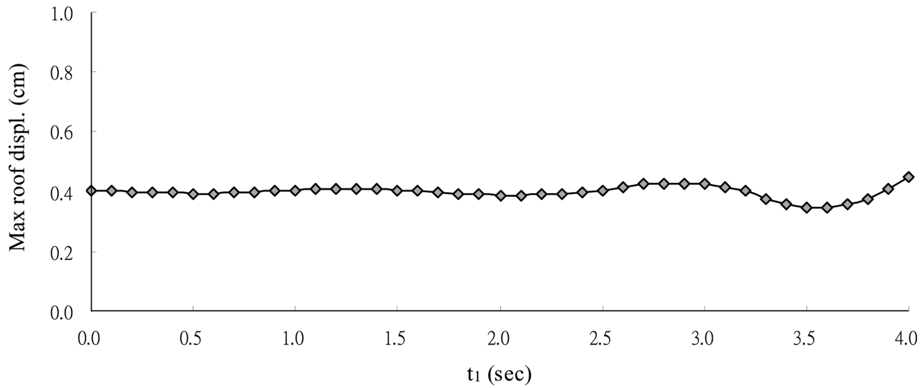

Fig. 27 Maximum roof displacement (ATLCD, $y(t \leq t_1)$ = 3 cm at t_1 = 0~4 sec)

when the maximum displacement occurs. However the control technique for the proper releasing time is not an easy job up to now, it should depend on both the time histories of input earthquake and the output structural response. It needs more research efforts in the near future. Fig. 27 shows the influence of the pre-set of the water head on the maximum roof displacement controlled by the active TLCD. The pre-set of the water head has almost no influence on the control performance of ATLCD. It means that the control ability of TLCD has its upper limit, and beyond the limit it is hard to improve the control performance any further.

The tuned frequency of the TLCD is 5.086 rad/sec, and the water length of the open uniform TLCD is 0.758 m. This dimension is not suitable for the practical engineering design, so the closed TLCD should be an alternative. Let h_0 = 1 m and P_0 =1.013 kg/cm^2, then g' = 11.13 g. Hence the water length is 8.44 m, the cross section area 1.89 m^2, and the water mass 16000 kg of a closed TLCD for this example. We may use five identical closed TLCDs for this example, and each one has the following properties: h_0 =100 cm, p_0 = 1 atm, R = 34.7 cm, and l = 8.44 m. This example illustrates the fact that the closed TLCD could provide a better design condition than the open one.

8. Conclusions

Some conclusions would be drawn from this study and given as follows:

(1) The natural period of an open TLCD can be adjusted by only changing the water length, but for a closed TLCD it can be adjusted by changing the water length, air pressure and volume of the air chamber. Therefore the closed TLCD is more flexible in practical applications.

(2) The tuned frequency and the optimal damping ratio of TLCD can be determined based on the fundamental mode of a building by use of the Hartog's method or the Jacquot and Hoppe's method.

(3) The mass of a TLCD is about 1~2% of the first-mode generalized mass of a building, and the length ratio α can be assumed 0.8 for a uniform TLCD, in practice.

(4) The additional damping is always necessary in order to achieve the optimal damping ratio of a TLCD. Two devices are suggested: (1) The artificial orifices inside the horizontal tube, and (2) The perforated cover plates at the openings of the vertical tubes. The latter one seems to be more simple and efficient in practice.

(5) The proposed structural model of a TLCD (see Fig. 7) can be employed very easily and effectively for the structural analysis of a building with one or several TLCDs by use of the finite-element method.
(6) The pre-set of water head and its properly releasing time of TLCD will result the significant vibrational control, however the control technique of the properly releasing time should need more research work in future. This control technique is effective for earthquake-induced vibration, but in-effective for wind-induced vibration.
(7) It has also been studied in this paper that the pre-set of the water level can not improve the performance of ATLCD significantly.
(8) An active TLCD is effective to control both the earthquake-induced and windinduced vibrations.
(9) The propeller operating in a restricted water space inside a long tube has high efficiency. The control performance of a propeller-controlled active TLCD has been primarily studied to be excellent. Therefor the various applications of the propeller-controlled active TLCD would be an important topic of future research.
(10) The passive, semi-active, and active TLCDs would have the following advantages: (1) simple structure, (2) easy manufacture, installation, and maintenance, (3) no need to change the structural system of a structure, (4) space saving, and (5) excellent performance in vibrational control; therefore it might have high potential in various applications for the vibrational control. This is also one important goal for future research.

Acknowledgements

The authors gratefully acknowledge the financial support of this research from the National Science Council, the Republic of China.

References

Balendra, T., Wang, C.M. and Cheong, H.F. (1995), "Effectiveness of tuned liquid column dampers for vibration control of towers", *Eng. Struct.*, **17**(9), 668-675.

Chen, Y.H. and Chao, C.C. (2000), "Optimal damping ratios of TLCDs", *Struct. Eng. Mech.*, **9**(3), 227-240.

Chen, Y.H. and Ko, C.H. (2003), "Active tuned liquid column damper with propellers", *Earthq. Eng. Struct. Dyn.*, **32**, 1627-1638.

Clough, R.W. and Renzien, J. (1993), *Dynamics of Structures*, McGraw-Hill, 2nd Edition, New York.

Den Hartog, J.P. (1962), *Mechanical Vibrations*, McGraw-Hill, 4th Edition, 93-106.

Gao, H., Kwok, K.S.C. and Samali, B. (1999), "Characteristics of multiple tuned liquid column dampers in suppressing structural vibration", *Eng. Struct.*, **21**, 316-331.

Hitchcock, P.A., Kwok, K.C.S., Watkins, R.D. and Samali, B. (1997), "Characteristics of Liquid Column Vibration Absorbers (LCVA)-I, II", *Eng. Struct.*, **19**, 126-144.

Jacquot, R.G. and Hoppe, D. (1973), "Optimal random vibration absorber", *J. Eng. Mech. Div.*, ASCE, **99**, 612-616.

Lewis, E.V. (1989), *Principles of Naval Architecture*, 2nd Edition, Vol. III, Chapter VIII, 126-133.

Sakai, F., Takeda, S. and Tamaki, T. (1989), "Tuned liquid column damper-new type device for suppression of building vibrations", *Proc. of International Conf. on Highrise Building*, 926-931, Nanjing, China.

Sun, K. (1994), "Earthquake responses of buildings with liquid column dampers", *Proc. of the Fifth U.S.*

National Conf. on Earthquake Engineering, (Chicago, U.S.A.), **2**, 411-420.

Won, A.Y.J., Piers, J.A. and Haroun, M.A. (1996), "Stochastic seismic performance evaluation of tuned liquid column dampers", *Earthq. Eng. Struct. Dyn.*, **25**, 1259-1274.

Xue, S.D., Ko, J.M. and Xu, Y.L. (2000), "Tuned liquid column damper for suppressing pitching motion of structure", *Eng. Struct.*, **23**, 1538-1551.

Yalla, Swaroop K. and Kareem, Ahsan. (2000), "Optimum absorber parameters for tuned liquid column dampers", *J. Struct. Eng.*, ASCE, **126**(8), 906-915.