行政院國家科學委員會專題研究計畫　成果報告

子計畫五：側向與扭轉互制效應下高層建築之減振控制與風洞試驗

計畫類別：整合型計畫
計畫編號：NSC92-2211-E-032-022-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：淡江大學土木工程研究所

計畫主持人：吳重成

計畫參與人員：簡仕為、沈瑛璋

報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 93 年 11 月 22 日

行政院國家科學委員會專題研究計畫成果報告

側向及扭轉互制效應下高層建築之減振控制與風洞試驗(2/3)

計畫編號：NSC 91-2211-E-032-022

執行期限：92 年 8 月 1 日至 93 年 7 月 31 日

主持人：吳重成　淡江大學土木系

計畫參與人員：簡仕為、沈瑛璋　淡江大學土木系研究生

中文摘要

台灣近年來經濟急速起飛，建築物有愈蓋愈高的趨勢。由於結構物的高度增加，使得其勁度較一般建築為小，當受到風力擾動時，往往會造成過大的結構反應，尤其高層建築更為明顯，整個結構物來回振盪的結果，除了有安全上之顧慮外，也會造成使用人員不舒適及精密儀器之損壞。欲解決上述振動問題，研究發現結構控制可提供有效對策。本研究計劃提出對於具狹長型矩形斷面之高層建築，應用結構控制之抗風減振研究，目的在就抖振及渦散引起的側向及扭轉向互制之振動問題，以風洞試驗方式驗證結構控制（包括主動與被動控制）之可行性。92 年度（2/3）之內容重點有二：(i)建立調頻液柱阻尼器（TLCD）應用於具阻尼單自由度結構之最佳參數設計表；(ii)建構不同配置之調頻液柱阻尼器，進行元件性能之測試與校正，供設計應用之參考。

關鍵詞：高層建築、結構控制、調頻液柱阻尼器

Abstract

The economical development of Taiwan in the past decades has facilitated more and more construction of higher buildings in many urban areas where the space is highly limited. Because of their stiffness lessened, these buildings become more susceptible to wind excitation. Especially for high-rise buildings, the wind-induced responses, including displacement and acceleration on which building serviceability and comfort of occupants depend, are frequently excessive. In literatures, the use of structural control has been demonstrated to be efficient in reducing the wind-induced vibration for high-rise buildings. Therefore, the objective of this research is to investigate the applicability of structural control (active and passive control) through wind tunnel experiments to buildings with lateral-torsional motion under the excitation of buffeting and vortex shedding. The tasks in the 2nd year mainly include: (i) constructing design tables of optimal parameters for Tuned Liquid Column Damper (TLCD) applied on the damped SDOF structure; (ii) conducting member tests on different configurations of TLCD design to calibrate the parameters, such as frequency and head loss coefficient, for the reference of designers in the application.

Keywords: High-rise Building, Structural Control, Tuned Liquid Column Damper (TLCD)

1. Introduction

In the last decade, the idea of tuned liquid column damper (TLCD) for vibration suppression has been developed and its effectiveness was verified ([Sakai *et al*.(1989)], [Xu *et al*.(1992)], [Balendra *et al*.(1998)], *etc*.). Some design formulas have been provided in [Chang *et al*. (1998)] that basically assumes no damping in the structure. Although the negligence of structural damping in the optimization process provides simplicity in optimization, the results obtained may not represent the reality. As the application of TLCD to the industry becomes gradually popular, it is very desirable to provide design tables of the necessary parameters in a more realistic way such that the practitioners can use them as quick references in the designs. The contents in the first part of this paper will serve this purpose.

Since the design processes of TLCD and tuned mass damper (TMD) are similar, the mass ratio of the liquid mass versus structure mass shall be decided first as a *priori* before determining the frequency tuning ratio and head loss coefficient. Thus, the results in the design tables are presented in such a manner. The results presented are obtained for a single-degree-of-freedom damped structure under white noise wind excitation and comparisons are also made with those in [Chang *et al*. (1998)]. Furthermore, the cross-section ratio between the vertical and horizontal columns is regarded as a variable in the formulation to also scrutinize its optimal value for the best performance.

From literature review, it is found that the basic properties of TLCD, especially the head loss coefficient, have never been experimentally calibrated in a systematic manner. In order to provide designers more reliable information on the basic properties of TLCD, such as the natural frequency and head loss coefficient, the second part of this paper presents calibration results of TLCD properties using free vibration and harmonic forced vibration tests in the structural laboratory of Department of Construction Engineering, National Kaohsiung First University of Science and Technology. Comparisons are made between the experimentally calibrated results and the analytical results. Finally, a modified prediction formula for the head loss coefficient is proposed and suggested as the practical guideline for TLCD design.

2. Equation of Motion

The schematic diagram of a SDOF structure equipped with a TLCD under wind excitation is shown in Fig. 1. The variation of cross-section difference between horizontal and vertical columns of TLCD is considered for generality, and the head loss due to transition of cross-section difference in the vicinity of turn angle is negligible. By means of the energy principle associated with Lagrange's equations, the equations of motion of the structure and liquid surface motion of TLCD are expressed as ([Chang *et al*. (1998)])

$$M\ddot{x} + \rho A_h(2\nu L_v + L_h)\ddot{x} + \rho A_h \nu L_h \ddot{y} + C\dot{x} + Kx = F(t) \quad (1)$$

and

$$\rho A_h \nu L_e \ddot{y} + \rho A_h \nu L_h \ddot{x} + (1/2)\rho A_h \nu^2 \eta |\dot{y}|\dot{y} + 2\rho A_h g \nu y = 0 \quad (2)$$

, respectively, in which $\nu = A_v / A_h$ is the cross-section ratio of vertical versus horizontal columns; $L_e = 2L_v + \nu L_h$ is defined as the effective length; η is the head loss coefficient induced by flow passing through the orifice in the horizontal column; and *M*, *C*, *K* are the structural mass, damping and stiffness constants. If $\nu = 1$, then $L_e = L = 2L_v + L_h$ represents the total length of the liquid column. From Eq. (2), it is observed that the natural period and frequency of TLCD are $T_d = 2\pi\sqrt{L_e / 2g}$ and $\omega_d = \sqrt{2g/L_e}$, respectively.

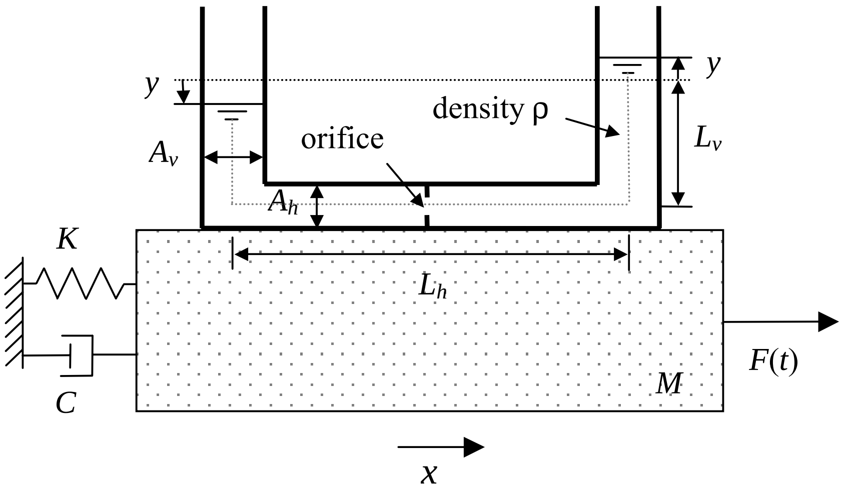

Fig. 1: SDOF Damped Structure Equipped with TLCD

3. Optimization for Finding Optimal Parameters

This section describes the steps of forming an optimization problem to find the proper parameters that can achieve the best performance using TLCD.

3.1 Damping for Situations under White Noise Wind

Under the situation that the wind excitation is a white noise type, according to [Xu *et al.*(1992)], the damping term $(1/2)\rho A_h \nu^2 \eta |\dot{y}|\dot{y}$ can be replaced by $\sqrt{2/\pi}\,\rho A_h \nu^2 \eta \sigma_{\dot{y}} \dot{y}$ by the equivalent linearization technique. In this way, a viscous damping form is used and the analysis can be simplified although it still depends on the standard deviation of $\dot{y}$, i.e. $\sigma_{\dot{y}}$.

3.2 Nondimensionalization

For conciseness of analysis and presentation, the equations of motion in Eqs. (1) and (2) are nondimensionalized before further derivation. The resulting forms of the nondimensionalized Eqs. (1) and (2) are expressed as

$$(1+\mu)\,\hat{x}'' + \mu m\,\hat{y}'' + 4\pi\xi\beta_1\hat{x}' + 4\pi^2\beta_1^2\hat{x} = \hat{F}(\hat{t}) \tag{3}$$

$$\hat{y}'' + n\hat{x}'' + \sqrt{2/\pi}\,\nu\, n\,\eta\sigma_{\hat{y}'}\,\hat{y}' + 4\pi^2\hat{y} = 0 \tag{4}$$

in which $\hat{x} = x/L_h$; $\hat{y} = y/L_h$; $\hat{t} = t/T_d$; $\hat{F} = F\,T_d^2\,/\,ML_h$; $\xi = C/2M\omega_s$ is the damping ratio of the structure; $\omega_s = \sqrt{K/M}$ is the natural frequency of the structure; $\beta_1 = \omega_s/\omega_d$ is the frequency tuning ratio of the structure versus TLCD; $p = L_h/L$ is the ratio of horizontal column length versus total column length; $\mu = \rho A_h(L_h + 2\nu L_v)/M$ is the mass ratio of the liquid versus the structure ; m and n are two parameters related to p and ν as $n = p/(1-p(1-\nu))$ and $m = \nu p/(\nu + p(1-\nu))$. Note that in Eqs. (3) and (4), the notation $'$ represents the differentiation with respect to the nondimensional time $\hat{t}$.

3.3 Stochastic Responses of Structure and TLCD Liquid Surface

By the substitution of the excitation with $\hat{F}(\hat{t}) = e^{i2\pi k\hat{t}}$ and the responses with $\hat{x} = \hat{X}\,e^{i2\pi k\hat{t}}$ and $\hat{y} = \hat{Y}\,e^{i2\pi k\hat{t}}$ in which $k = \omega/\omega_d$ into Eqs. (3) and (4), the frequency response functions $\hat{X}$ and $\hat{Y}$ due to $\hat{F}$ can be obtained as

$$T_{\hat{x}\hat{F}} = \hat{X} = [\,2\pi(1-k^2) + i\,\sqrt{2/\pi}\,\nu n\,\eta\sigma_{\hat{y}'}\,k]/2\pi G \tag{5}$$

$$T_{\hat{y}\hat{F}} = \hat{Y} = n\,k^2/G \tag{6}$$

in which

$$\begin{aligned} G = {} & [4\pi^2(1-k^2)(\beta_1^2 - (1+\mu)k^2) - 4\pi k^2\sqrt{2/\pi}\nu n\eta\sigma_{\hat{y}'}\xi\beta - 4\pi^2 k^4\mu\, m\, n] \\ & + i\,[\,8\pi^2\xi\beta_1 k(1-k^2) + 2\pi k\sqrt{2/\pi}\nu n\,\eta\sigma_{\hat{y}'}(\beta_1^2 - (1+\mu)k^2)\,] \end{aligned} \tag{7}$$

To compute the mean square of $\hat{x}$ in terms of the power spectrum of the nondimensional force $\hat{F}(\hat{t})$, the relation between the power spectra of $F(t)$ and $\hat{F}(\hat{t})$ is firstly constructed in the following, i.e.,

$$
\begin{aligned}
S_F &= \frac{1}{2\pi T}\,\mathrm{E}\left[\left|\int_0^{\infty} F(t)\,e^{-i\omega t}\,dt\right|^2\right] \\
&= \frac{1}{2\pi(\hat{T}\,T_d)}\,\mathrm{E}\left[\left|\int_0^{\infty} \frac{M\,L_2}{T_d^2}\hat{F}(\hat{t})\,e^{-i2\pi k\hat{t}}\,d\,(T_d\,\hat{t})\right|^2\right] \\
&= \frac{M^2 L_h^2}{T_d^3}\cdot\frac{1}{2\pi\hat{T}}\,\mathrm{E}\left[\left|\int_0^{\infty} \hat{F}(\hat{t})\,e^{-i2\pi kt}\,d\hat{t}\right|^2\right] \\
&= \frac{M^2 L_h^2}{T_d^3}\cdot S_{\hat{F}}
\end{aligned}
\qquad (8)
$$

in which T and $\hat{T}$ are the dimensional and nondimensional time duration, respectively. Thus, the mean square values of $\hat{x}$ can be derived by

$$
\mathrm{E}[\hat{x}^2] = \sigma_{\hat{x}}^2 = \int_{-\infty}^{\infty} S_F\,|T_{\hat{x}F}|^2\,d\omega = \int_{-\infty}^{\infty} \frac{M^2 L_h^2}{T_d^3} S_{\hat{F}}\cdot\left|\frac{T_d^2}{M\,L_h}\hat{X}\right|^2\cdot d\,(\omega_d k) = 2\pi S_{\hat{F}}\int_{-\infty}^{\infty}\left|\hat{X}\right|^2 dk \qquad (9)
$$

In the same manner, the mean square values of $\hat{y}$ and $\hat{y}'$ can be obtained and expressed as

$$
\mathrm{E}[\hat{y}^2] = \sigma_{\hat{y}}^2 = 2\pi S_{\hat{F}}\int_{-\infty}^{\infty}\left|\hat{Y}\right|^2 dk \qquad (10)
$$

and

$$
\mathrm{E}[\hat{y}'^2] = \sigma_{\hat{y}'}^2 = (2\pi)^3\,S_{\hat{F}}\int_{-\infty}^{\infty}\left|(ik)\hat{Y}\right|^2 dk \qquad (11)
$$

3.4 Performance Criterion

To find the optimal parameters for TLCD designs, the normalized mean square of the nondimensional structural response $\hat{x}$ is used as the performance criterion for optimization, which is defined as

$$
\mathrm{E}[\hat{x}^2]_{norm} = \mathrm{E}[\hat{x}^2]/\mathrm{E}[\hat{x}_0^2] = 32\pi^3\,\xi\beta_1^3\int_{-\infty}^{\infty}\left|\hat{X}\right|^2 dk \qquad (12)
$$

In Eq. (12), $\mathrm{E}[\hat{x}_0^2]$ represents the mean square of the nondimensional structural response without installing the TLCD device under white noise wind load, which can be expressed by

$$
\mathrm{E}[\hat{x}_0^2] = \frac{\pi S_F}{2\xi M^2\omega_s^3 L_h^2} = \frac{\pi S_{\hat{F}}}{2\xi\omega_s^3 T_d^3} = \frac{\pi S_{\hat{F}}}{2\xi\beta_1^3(2\pi)^3} \qquad (13)
$$

([Crandal and Mark (1963)]) Hence, a smaller $E[\hat{x}^2]_{norm}$ represents a better performance. Similarly, the normalized mean square of the nondimensional liquid surface response $\hat{y}$ can be also defined as

$$E[\hat{y}^2]_{norm} = E[\hat{y}^2]/E[\hat{x}_0^2] = 32\pi^3 \xi\beta_1^3 \int_{-\infty}^{\infty} \left| \hat{Y} \right|^2 dk \tag{14}$$

This quantity $E[\hat{y}^2]_{norm}$ shall be computed at the values of optimal parameters as the reference because it is practically important for the purpose of examining if the liquid surface displacement exceeds the height of the vertical liquid column.

Based on the formula provided in [Crandal and Mark (1963)] for stochastic analysis, the integrations in Eqs. (12), (14) and (11) can be further expressed as the closed forms, respectively, as

$$E[\hat{x}^2]_{norm} = 32\pi^4\xi\beta_1^3 \frac{(a_2a_3 - a_1a_4)/a_0 + a_3(b_1^2 - 2) + a_1}{a_1(a_2a_3 - a_1a_4) - a_0a_3^2} \tag{15}$$

$$E[\hat{y}^2]_{norm} = 32\pi^4\xi\beta_1^3 \frac{n^2}{a_1(a_2a_3 - a_1a_4) - a_0a_3^2} \tag{16}$$

$$E[\hat{y}'^2] = \sigma_{\hat{y}'}^2 = 8\pi^4 S_{\hat{F}} \frac{n^2(a_1a_2 - a_0a_3)/a_4}{a_1(a_2a_3 - a_1a_4) - a_0a_3^2} \tag{17}$$

in which

$$\begin{aligned} a_0 &= 4\pi^2\beta_1^2;\quad a_1 = 8\pi^2\xi\beta_1 + 2\pi\sqrt{2/\pi}\nu n\eta\sigma_{\hat{y}'}\beta_1^2; \\ a_2 &= 4\pi^2(1+\mu+\beta_1^2) + 4\pi\sqrt{2/\pi}\nu n\eta\sigma_{\hat{y}'}\xi\beta_1; \\ a_3 &= 8\pi^2\xi\beta_1 + 2\pi\sqrt{2/\pi}\nu n\eta\sigma_{\hat{y}'}(1+\mu); \\ a_4 &= 4\pi^2(1+\mu-\mu mn);\quad b_1 = (1/2\pi)\sqrt{2/\pi}\nu n\eta\sigma_{\hat{y}'} \end{aligned} \tag{18}$$

As observed from Eqs. (15)-(18), the computation of $E[\hat{x}^2]_{norm}$ and $E[\hat{y}^2]_{norm}$ requires the value of $\sigma_{\hat{y}'}$ that shall be obtained through iterations between Eq. (17) and (18). However, the convergence rate of such iterations is rather efficient.

3.5 Determination of Optimal Parameters η and β_1

As shown in Eqs. (15) and (18), the independent parameters for determining $E[\hat{x}^2]_{norm}$ include the structural damping ratio ξ, mass ratio μ, cross-section ratio ν, nondimensional power spectral density of the excitation $S_{\hat{F}}$, head loss coefficient η and damper frequency tuning ratio β_1. Since the structural damping ratio ξ and $S_{\hat{F}}$ are given, the choices of μ and ν are decided by the designer, the remaining two parameters for the optimization of performance criterion $E[\hat{x}^2]_{norm}$ are η and β_1.

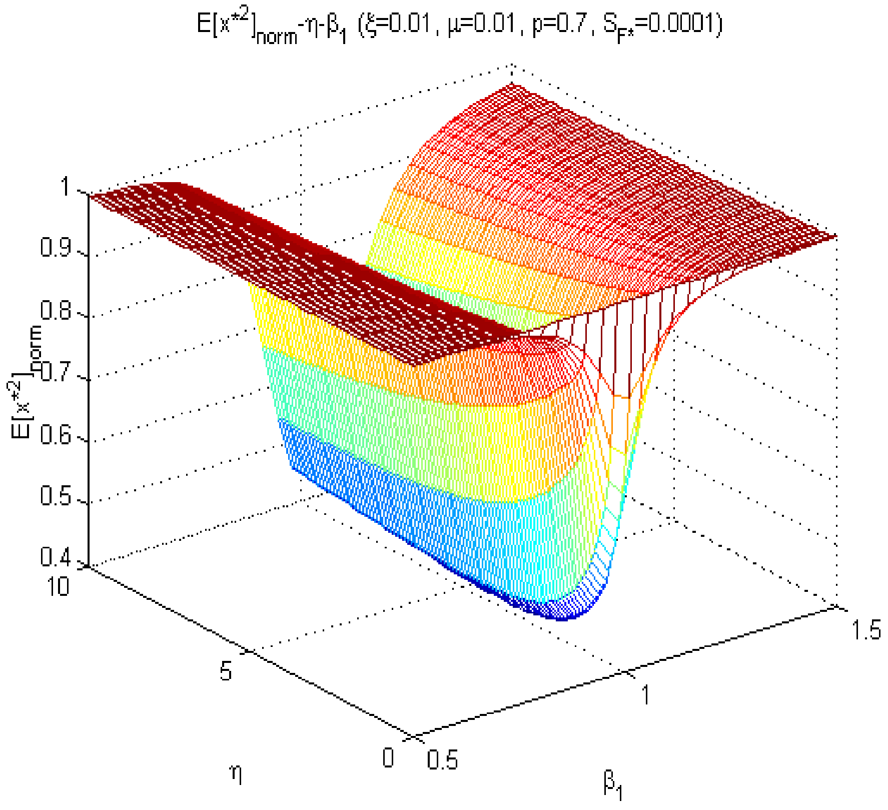

Fig. 2: Distribution Surface of $E[\hat{x}^2]_{norm}$ on the η- β_1 Plane

As shown in Fig. 2 is the 3-D distribution surface on the η-β_1 plane for $\xi=10^{-2}$, $S_{\hat{F}}=10^{-4}$, $\mu=10^{-2}$ and $\nu=1$. A numerical optimization technique such as the gradient method can be used to allocate the η_{opt} and β_{1opt} that correspond to the minimal $E[\hat{x}^2]_{norm}$, and therefore the design tables such as Tables 1~3 can be constructed. In Tables 1~3, η_{opt} , β_{1opt} and the corresponding values of $E[\hat{x}^2]_{norm}$ and $E[\hat{y}^2]_{norm}$ are tabulated for the situations of $\nu=1$ and different combinations of ξ, μ and *p*. Since it is observed from Fig. 2 that the performance $E[\hat{x}^2]_{norm}$ is not sensitive with η varied within the vicinity of η_{opt}, the lower and upper values of η corresponding to 5% degradation from the best performance are also tabulated in Tables 1~3, expressed as "95%" under the same columns of η_{opt}. From the numerical results, the effect of $S_{\hat{F}}$ on η_{opt} has been observed and the relation is constructed as shown in Tables 1~3. Such a relation can also be observed by the co-occurrence of $\eta\sigma_{\hat{y}'}$ in Eq. (18) and the linear relation of $\sigma^2_{\hat{y}'}$ and $S_{\hat{F}}$ in Eq. (17). As observed from Tables 1~3, the better performance occurs as $p=L_h/L$ is larger. Additionally, the extensive numerical results further demonstrate the effect of different values of ν on the minimal $E[\hat{x}^2]_{norm}$. It is found that under the same ξ, μ, p and $S_{\hat{F}}$, the minimal $E[\hat{x}^2]_{norm}$ is smallest at $\nu=1$, as shown in Fig. 3. This indicates that using uniform cross-sections for the liquid columns is the best choice.

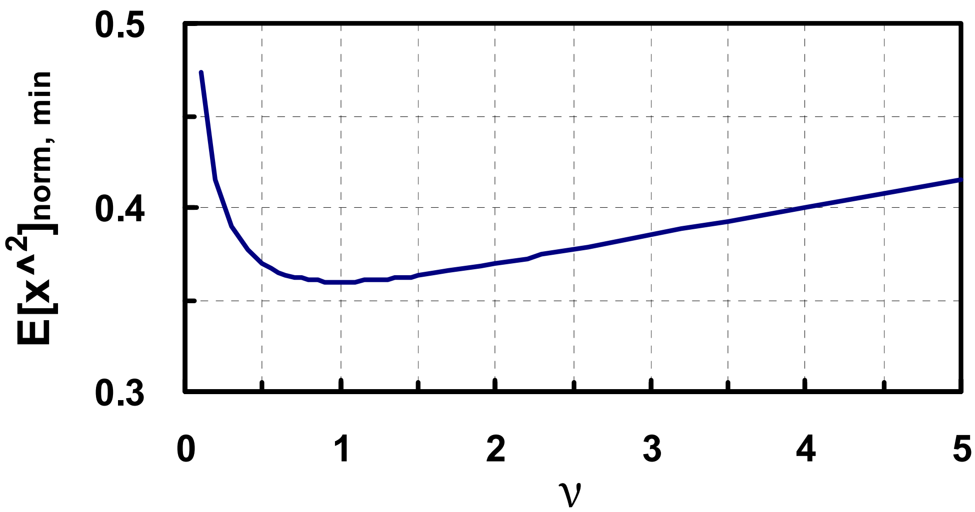

Fig. 3: Effect of ν on the minimal $E[\hat{x}^2]_{norm}$ (ξ=0.01, μ=0.01, p=0.8, $S_{\hat{F}}=10^{-4}$)

Table 1: Optimal Parameters for TLCD Designs (ν=1, ξ=0.01)

p	$\frac{1}{\beta_{1opt}}=\frac{\omega_d}{\omega_s}$	$\eta_{opt}(\times\sqrt{10^{-4}/S_{\hat{F}}})$ 95% ~ 100% ~ 95%	$E[\hat{x}^2]_{norm}$	$E[\hat{y}^2]_{norm}$
ν=1, ξ=0.01, μ=0.01				
0.5	0.9942	1.702 ~ 3.474 ~ 7.445	0.490	20.626
0.6	0.9939	1.853 ~ 3.623 ~ 7.369	0.437	18.954
0.7	0.9935	1.987 ~ 3.771 ~ 7.398	0.395	17.478
0.8	0.9931	2.110 ~ 3.918 ~ 7.482	0.360	16.184
0.9	0.9926	2.225 ~ 4.063 ~ 7.597	0.330	15.047
ν=1, ξ=0.01, μ=0.02				
0.5	0.9886	3.983 ~ 7.545 ~14.769	0.392	8.776
0.6	0.9880	4.323 ~ 7.955 ~15.033	0.345	7.885
0.7	0.9873	4.632 ~ 8.351 ~ 15.396	0.308	7.146
0.8	0.9865	4.917 ~ 8.731 ~ 15.805	0.278	6.527
0.9	0.9856	5.183 ~ 9.096 ~ 16.234	0.253	6.004
ν=1, ξ=0.01, μ=0.03				
0.5	0.9831	6.528 ~ 11.979 ~ 22.557	0.340	5.242
0.6	0.9823	7.083 ~ 12.697 ~ 23.246	0.296	4.657
0.7	0.9812	7.589 ~ 13.383 ~ 24.017	0.263	4.185
0.8	0.9800	8.055 ~ 14.030 ~ 24.814	0.236	3.798
0.9	0.9788	8.490 ~ 14.648 ~ 25.614	0.214	3.475
ν=1, ξ=0.01, μ=0.04				
0.5	0.9778	9.261 ~ 16.677 ~ 30.701	0.305	3.619
0.6	0.9766	10.048 ~ 17.735 ~ 31.872	0.265	3.193
0.7	0.9753	10.765 ~ 18.734 ~ 33.097	0.234	2.854
0.8	0.9738	11.426 ~ 19.675 ~ 34.325	0.209	2.580
0.9	0.9721	12.040 ~ 20.564 ~ 35.526	0.189	2.353
ν=1, ξ=0.01, μ=0.05				
0.5	0.9725	12.141 ~ 21.586 ~ 39.134	0.280	2.710
0.6	0.9711	13.172 ~ 23.006 ~ 40.827	0.242	2.379
0.7	0.9695	14.110 ~ 24.337 ~ 42.541	0.213	2.119
0.8	0.9676	14.975 ~ 25.586 ~ 44.224	0.190	1.910
0.9	0.9655	15.776 ~ 26.760 ~ 45.851	0.172	1.738

Table 2: Optimal Parameters for TLCD Designs (ν=1, ξ=0.02)

ν=1, ξ=0.02, μ=0.01				
p	$\frac{1}{\beta_{1opt}}=\frac{\omega_d}{\omega_s}$	η_{opt} ($\times\sqrt{10^{-4}/S_{\hat{F}}}$) 95% ~ 100% ~ 95%	$E[\hat{x}^2]_{norm}$	$E[\hat{y}^2]_{norm}$
0.5	0.9939	1.658 ~ 4.465 ~ 13.532	0.691	24.965
0.6	0.9936	1.658 ~ 4.527 ~ 12.137	0.640	24.274
0.7	0.9931	2.015 ~ 4.607 ~ 11.366	0.595	23.413
0.8	0.9927	2.157 ~ 4.699 ~ 10.913	0.555	22.491
0.9	0.9922	2.284 ~ 4.796 ~ 10.642	0.520	21.569
ν=1, ξ=0.02, μ=0.02				
0.5	0.9882	4.041 ~ 9.205 ~ 22.596	0.592	11.790
0.6	0.9876	4.429 ~ 9.468 ~ 21.476	0.538	11.130
0.7	0.9868	4.767 ~ 9.749 ~ 20.940	0.492	10.483
0.8	0.9859	5.070 ~ 10.035 ~ 20.714	0.454	9.876
0.9	0.9850	5.346 ~ 10.322 ~ 20.668	0.421	9.318
ν=1, ξ=0.02, μ=0.03				
0.5	0.9827	6.694 ~ 14.219 ~ 32.002	0.532	7.438
0.6	0.9818	7.296 ~ 14.737 ~ 31.177	0.478	6.911
0.7	0.9807	7.828 ~ 15.264 ~ 30.933	0.434	6.429
0.8	0.9794	8.308 ~ 15.786 ~ 30.996	0.397	5.996
0.9	0.9780	8.750 ~ 16.297 ~ 31.234	0.366	5.611
ν=1, ξ=0.02, μ=0.04				
0.5	0.9773	9.533 ~ 19.445 ~ 41.634	0.489	5.321
0.6	.9760	10.364 ~ 20.254 ~ 41.154	0.437	4.893
0.7	0.9746	11.102 ~ 21.056 ~ 41.251	0.394	4.515
0.8	0.9730	11.773 ~ 21.838 ~ 41.649	0.359	4.184
0.9	0.9712	12.390 ~ 22.593 ~ 42.208	0.330	3.895
ν=1, ξ=0.02, μ=0.05				
0.5	0.9720	12.516 ~ 24.844 ~ 51.451	0.457	4.089
0.6	0.9705	13.586 ~ 25.969 ~ 51.360	0.406	3.732
0.7	0.9688	14.542 ~ 27.063 ~ 51.836	0.365	3.424
0.8	0.9668	15.411 ~ 28.126 ~ 52.598	0.331	3.158
0.9	0.9646	16.210 ~ 29.140 ~ 53.506	0.303	2.929

Table 3: Optimal Parameters for TLCD Designs (ν=1, ξ=0.03)

p	$\frac{1}{\beta_{1opt}} = \frac{\omega_d}{\omega_s}$	η_{opt} ($\times\sqrt{10^{-4}/S_{\hat{F}}}$) 95% ~ 100% ~ 95%	$E[\hat{x}^2]_{norm}$	$E[\hat{y}^2]_{norm}$
ν=1, ξ=0.03, μ=0.01				
0.5	0.9937	1.475 ~ 5.456 ~ 24.934	0.793	25.076
0.6	0.9933	1.730 ~ 5.430 ~ 20.020	0.750	25.295
0.7	0.9928	1.937 ~ 5.443 ~ 17.400	0.710	25.156
0.8	0.9923	2.112 ~ 5.479 ~ 15.826	0.673	24.801
0.9	0.9917	2.264 ~ 5.531 ~ 14.809	0.640	24.316
ν=1, ξ=0.03, μ=0.02				
0.5	0.9879	3.892 10.863 34.440	0.707	12.692
0.6	0.9872	4.366 10.979 30.489	0.657	12.410
0.7	0.9863	4.761 11.145 28.288	0.612	12.026
0.8	0.9854	5.102 11.338 26.970	0.573	11.599
0.9	0.9844	5.406 11.547 26.154	0.538	11.162
ν=1, ξ=0.03, μ=0.03				
0.5	0.9823	6.612 16.457 45.113	0.651	8.325
0.6	0.9813	7.310 16.775 41.533	0.598	7.997
0.7	0.9801	7.902 17.145 39.589	0.552	7.639
0.8	0.9788	8.423 17.539 38.496	0.512	7.281
0.9	0.9773	8.892 17.943 37.893	0.478	6.938
ν=1, ξ=0.03, μ=0.04				
0.5	0.9768	9.527 22.210 56.079	0.609	6.115
0.6	0.9755	10.458 22.769 52.803	0.555	5.804
0.7	0.9740	11.258 23.375 51.124	0.509	5.492
0.8	0.9723	11.968 23.997 50.285	0.470	5.194
0.9	0.9704	12.611 24.619 49.930	0.436	4.916
ν=1, ξ=0.03, μ=0.05				
0.5	0.9714	12.590 28.099 67.201	0.576	4.792
0.6	0.9699	13.762 28.927 64.233	0.522	4.508
0.7	0.9680	14.779 29.793 62.844	0.477	4.235
0.8	0.9660	15.685 30.661 62.287	0.438	3.983
0.9	0.9637	16.507 31.515 62.205	0.405	3.752

4. Example of TLCD Design

To demonstrate the use of design tables, a 75-story building in the numerical example of [Chang et al. (1998)] is used for the TLCD design. The 1st mode properties of the building are M = 4.61x10^7 N sec^2/m, C = 1.04x10^6 N sec/m (ξ=1%) and K = 5.83x10^7 N/m ($\omega_s = 0.179 \cdot 2\pi$ rad/second). The power spectral density of the excitation S_F is 7.73 x10^9 N^2 second/rad. For better performance, ν=1 and a larger p=0.7 are suggested herein. The step-by-step design procedure of TLCD is stated as follows:

(I) By choosing the mass ratio μ=0.01, the inverse of frequency tuning ratio $1/\beta_{1opt} = \omega_d / \omega_s$ is 0.9935 according to Table 1. Therefore, the total length of TLCD, L, is 15.73m following $\omega_d = \sqrt{2g/L} = \omega_s \cdot (1/\beta_{1opt})$=1.117 rad/second. The horizontal length L_h can be also obtained as 11 m.

(II) By using Eq. (8), $S_{\hat{F}}$ = 5.35x10^{-6} can be obtained. According to Table 1, η_{opt} = $3.774 \cdot \sqrt{10^{-4}/5.35 \cdot 10^{-6}}$ = 16.31. Therefore, $E[\hat{x}^2]_{norm}$ = 0.395 and $E[\hat{y}^2]_{norm}$ = 17.48 are obtained.

(III) Check if the liquid surface displacement exceeds the vertical column length. By Eq. (13), $E[\hat{x}_0^2]$ is 3.318x10^{-6}. Therefore, $E[\hat{y}^2]$=$E[\hat{y}^2]_{norm}$ x $E[\hat{x}_0^2]$= 5.8x10^{-5}, $\sigma_y^2 = E[\hat{y}^2] \cdot L_h^2$ = 7.02x10^{-3} m^2 and σ_y = 0.084m. Since the vertical column length of the TLCD is L_v=(L-L_h)/2=2.365m, which is much more than five times of σ_y, this design is feasible.

(IV) By $\mu = \rho A(L_h + 2L_v)/M$ (water ρ=997 Nsec/m^4), the cross-section A=29.4 m^2 is thus determined.

5. Comparisons of Optimal Parameters with [Chang et al. (1998)]

In [Chang et al. (1998)], the parameter η_{opt} is determined under the assumption that the structure has no damping (ξ=0) and the tuning ratio β_1=1. By following the previous formulations in Eqs. (15) and (18), and setting the first η derivative of $E[\hat{x}^2]_{norm}$ equal to zero as well as letting ξ=0 and β_1=1, η_{opt} can be obtained as

$$\eta_{opt} = \sqrt{2}(\pi)^{3/2} \frac{1}{\nu\, n\, \sigma_{\hat{y}'}} \sqrt{\frac{\mu(\mu + m\, n)}{1+\mu}} \qquad (19)$$

Unlike the expression in [Chang et al. (1998)], η_{opt} in Eq. (19) is rewritten in terms of the mass ratio μ and the horizontal length ratio p (m and n are functions of p) for convenience in the practical design. As Shown in Table 4 is the comparisons of the optimal parameters and performances of the TLCD design for the same building (two cases with ξ=0.01 and ξ=0.05) used in Section 4. Note that in these designs, the horizontal liquid column length L_h is kept to be 12 m and the cross-section area A is 88.5 m^2.

Table 4: Comparisons of Optimal Parameters with [Chang et al. (1998)]

ν=1, ξ=0.01, μ=0.0298, p=0.774, $S_{\hat{F}} = 4.40\text{x}10^{-6}$			
	$1/\beta_{1opt}$	η_{opt}	$E[\hat{x}^2]_{norm}$
[Chang et. al. (1998)]	1.000	67.528	0.250
This Paper	0.980	65.593	0.243
ν=1, ξ=0.05, μ=0.0298, p=0.774, $S_{\hat{F}} = 4.40\text{x}10^{-6}$			
	$1/\beta_{1opt}$	η_{opt}	$E[\hat{x}^2]_{norm}$
[Chang et. al. (1998)]	1.000	102.158	0.677
This Paper	0.979	99.019	0.673

6. Experimental Calibration of TLCD Properties

From literature review, it is found that the basic properties of TLCD, especially the head loss coefficient, have never been experimentally calibrated in a systematic manner. In order to provide designers more reliable information on the basic properties of TLCD, such as the natural frequency and head loss coefficient, this section presents calibration results of TLCD properties using free vibration and harmonic forced vibration tests in the structural laboratory of Department of Construction Engineering, National Kaohsiung First University of Science and Technology. Four differently configured groups of TLCDs with uniform cross-section as shown in Fig. 4 are designed. To examine if the size of liquid mass has effects on the basic properties, each configured group contains three TLCDs that has cross-sections of 15cmx15cm, 30cmx15cm and 45cmx15cm, respectively. Since the damping of TLCD is mainly produced by energy dissipating mechanism while the flow passes through the orifice located in the middle of the horizontal column, four different orifice areas with area blocking ratios (ψ) of 20%, 40%, 60% and 80%, respectively, are used in each configured group to calibrate the corresponding head loss coefficient η. The detail dimensions of each configured group are listed in Table 5, in which *D* represents the amplitude of the table displacement while harmonic forced vibration tests are tested.

Firstly, the four configured groups of TLCD are sequentially placed on the shake table. The natural frequencies of TLCD are calibrated for each group by recording the response of the free vibration tests, in which the liquid surface movement is excited by driving the shake table at a frequency close to the resonance frequency and then suddenly ceasing its motion. As shown in the upper part of Table 6 is the natural frequencies thus measured for each group. It is found that the size of liquid mass does not have effect on the natural frequency. From Table 6, it is concluded that the analytical natural frequency $\omega_d = (2g/L)^{1/2}/2\pi$ (Hz) is reliable because the errors between the measured and predicted frequencies are as small as less than 2%.

Secondly, to calibrate the head loss coefficient, the forced vibration tests are performed for each group by driving the shake table at various frequencies, and hence the liquid response is recorded. The head loss coefficients are calibrated by comparing the measured amplitude responses of the liquid displacement and those from the analytic formula. Because the excitation is harmonic, the analytic formula is derived from Eq. (2) with ν being set to 1, *x* being substituted by $D\sin\omega t$ and the damping term being replaced by a viscous damping $\rho A_h(4/3\pi)\eta\varphi_y\,\omega\dot{y}$, in which φ_y represents the amplitude of *y*. By the same nondimensionalization procedure as mentioned in the earlier section, the amplitude of $\hat{y}$ can be thus solved as

$$\varphi_{\hat{y}} = \left[\frac{-2\pi^2(1-k^2)^2 + \left(4\pi^4(1-k^2)^4 + k^8(8/3\ \eta\, p)^2\, 4\pi^2\gamma^2\right)^{1/2}}{k^4(8/3\ \eta\, p)^2}\right]^{1/2} ; \qquad \gamma = p\,D/L_h \quad (20)$$

For each configured group, by adjusting the head loss coefficient η in Eq. (20) to proper values, the amplitude of $\hat{y}$ versus *k* is plotted together with the experimental data to fit each other, as denoted by the solid curves shown in Fig. 5. The head loss coefficients thus calibrated are listed in the lower part of Table 6. As observed in these results, it is found that the head loss coefficient is neither affected by different size of liquid mass nor by different configurations (different *p*). It is only significantly affected by the area blocking ratio ψ in the orifice, as demonstrated by the well-known formula

$$\eta = (\psi + 0.707\psi^{0.375})^2(1-\psi)^{-2} \quad (21)$$

that is originally used to predict η in many literatures. However, the head loss coefficients calibrated from the measured data do not correlate well with Eq. (21). Therefore, a modified prediction formula that correlates well with the experimental data is constructed by keeping the same form as Eq. (21) but revising some coefficients. The resulting formula of η is expressed as

$$\eta = (-0.6\psi + 2.1\psi^{0.1})^{1.6}(1-\psi)^{-2} \quad (22)$$

The comparison of Eq. (21), Eq. (22) and the experimentally calibrated data of η is illustrated in Fig. 6. It is suggested that the modified prediction formula of η in Eq. (22) shall provide as a valuable practical guideline for TLCD design to the engineers.

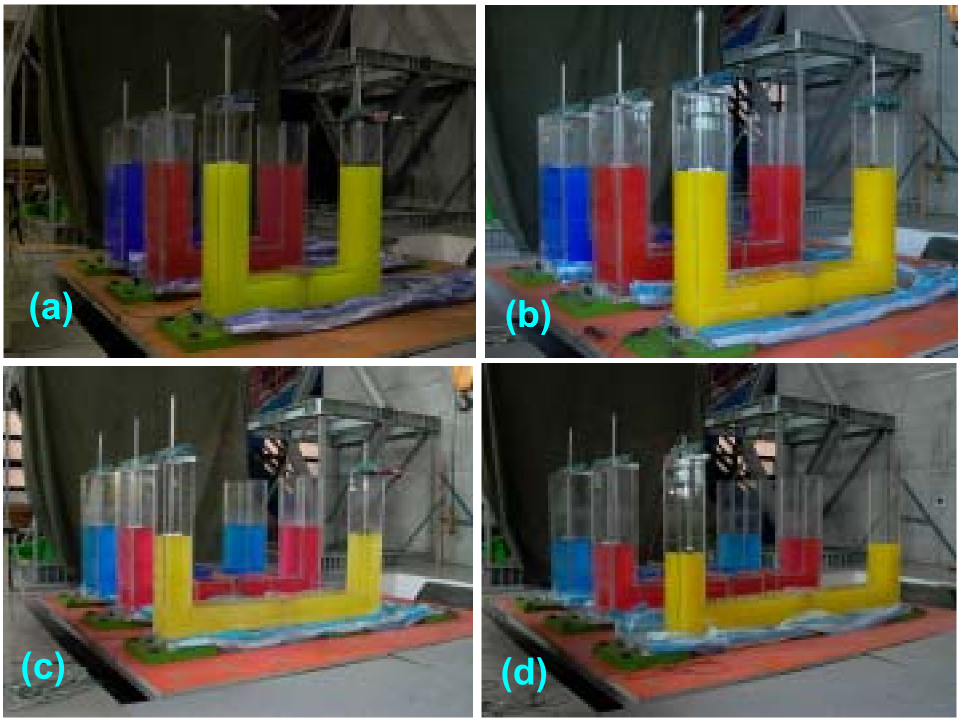

Fig. 4: Four Configured Groups of TLCDs on the Shake Table: (a) Configured Group I; (b) Configured Group II; (c) Configured Group III; (d) Configured Group IV.

Table 5: Dimensions of Configured Groups of TLCD

	Configured Group			
	I	**II**	**III**	**IV**
L_h (cm)	85	115	145	175
L_v (cm)	63.75	57.5	48.33	37.5
A_h (= A_v) (cm^2)	15x15 30x15 45x15	15x15 30x15 45x15	15x15 30x15 45x15	15x15 30x15 45x15
Blocking Ratio ψ (%)	20, 40, 60, 80	20, 40, 60, 80	20, 40, 60, 80	20, 40, 60, 80
$p=L_h/L$	0.4	0.5	0.6	0.7
$L= L_h+2\ L_v$ (cm)	212.5	230	241.67	250
$\omega_d =(2g/L)^{1/2}/2\pi$ (Hz) (Predicted)	0.4836	0.4648	0.4535	0.4459
D	4 cm	4 cm	4 cm	4 cm

Table 6: Calibrated Results from TLCD Property Tests

	Configured Group			
	I	**II**	**III**	**IV**
Natural Frequency ω_d (Hz) (Error w.r.t. Predicted)	0.4923 (1.8%)	0.4727 (1.7%)	0.4595 (1.3%)	0.4516 (1.3%)
Head Loss Coefficient η				
Blocking Ratio ψ=20%	3.96	3.55	3.40	3.40
Blocking Ratio ψ=40%	6.10	5.80	5.70	5.55
Blocking Ratio ψ=60%	12.80	12.40	12.50	12.00
Blocking Ratio ψ=80%	54.50	54.00	59.00	56.00

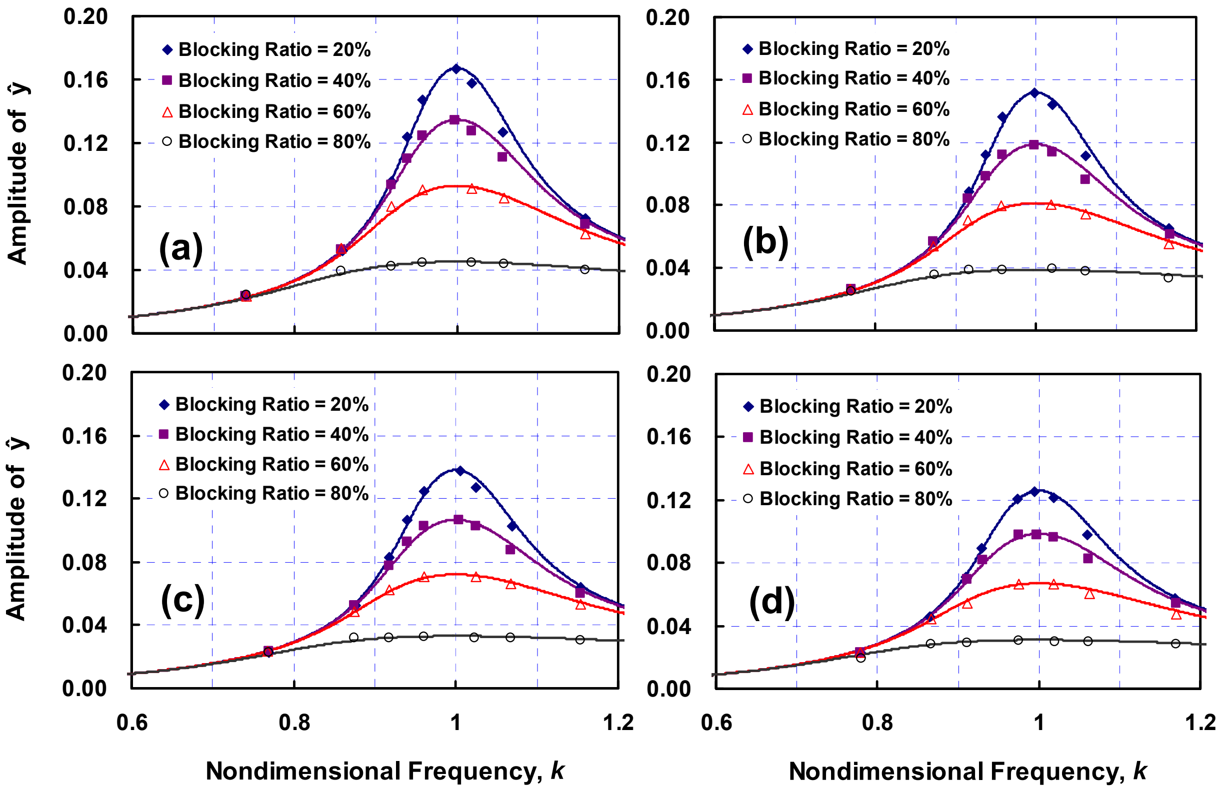

Fig. 5: Experimental Results of Amplitudes of $\hat{y}$ for Each Configured Group of TLCD in Forced Vibration Tests: (a) Configured Group I; (b) Configured Group II; (c) Configured Group III; (d) Configured Group IV.

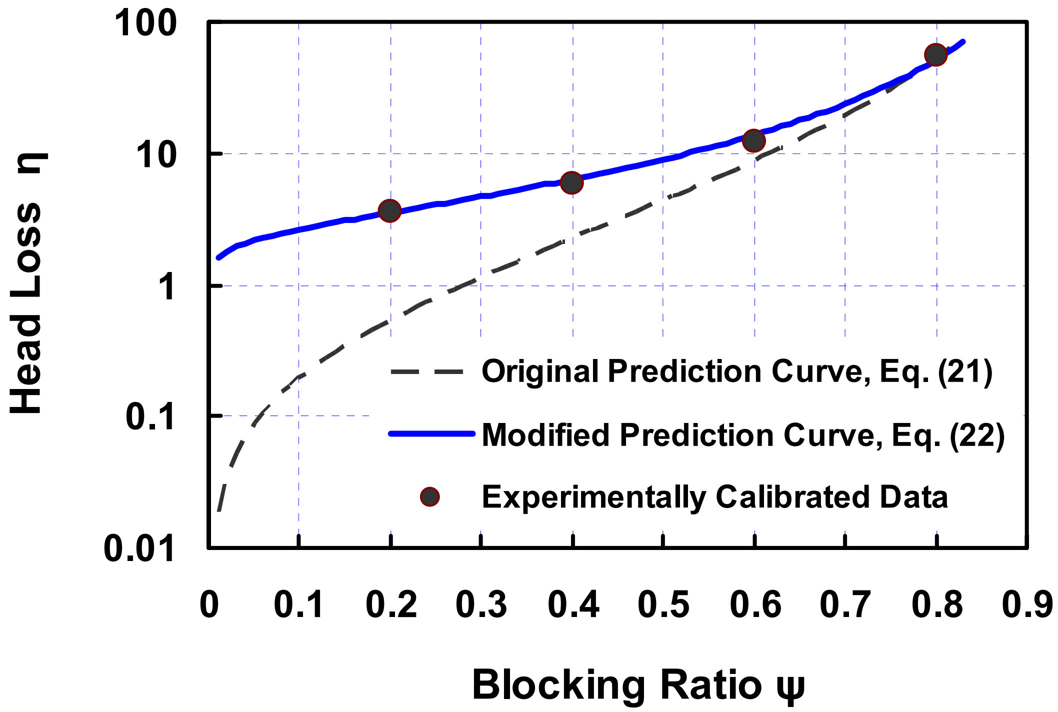

Fig. 6: Comparison of head loss coefficients

7. Summaries

The optimal tuning ratio, β_{1opt}, and head loss coefficient, η_{opt} are numerically obtained through the minimization of the normalized response of a structure equipped with a TLCD. It is found that using uniform cross-section is the best choice. Design tables are constructed for the practical references of designers and a design example of using these design tables has been demonstrated. The optimal parameters and performances are compared with the close form formula in [Chang et al. (1998)] and the difference is found insignificant from the practical point of view. Note that, in this paper, the expression of η_{opt} in [Chang et al. (1998)] has been rewritten as Eq. (19) in terms of the mass ratio for the convenience in practical designs.

The extensive calibration results of TLCD properties using free vibration and harmonic forced vibration tests have been presented and the comparisons are made with the analytical results. From comparison, it is found that the analytical formula for natural frequencies is validated, while the original prediction formula for head loss coefficients does not correlate well with the calibrated results. Therefore, a modified prediction formula for the head loss coefficient is finally proposed and suggested as the practical guideline for TLCD design.

Acknowledgments

This research is financially supported by National Science Council of Taiwan under the grant number NSC92-2211-E-032-022.

References

[1] Balendra, T., Wang, C.M., Rakesh, G., “Effectiveness of TLCD Various Structural Systems”, *Eng. Struct.*, Vol. 21, pp. 291-305, 1998.

[2] Chang, C.C. and Hsu, C.T., “Control Performance of Liquid Column Vibration Absorbers”, *Eng. Struct.*, Vol. 20, No. 7, pp. 580-586, 1998.

[3] Crandal, S.H. and Mark, W.D., *Random Vibration in Mechanical Systems*, Academic Press, San Diego, CA, 1963.

[4] Sakai, F., Takaeda, S., Tamaki, T., “Tuned Liquid Column Damper-New Type Device for Suppression of Building Vibration”, *Proc. Int. Conf. On High-rise Building*, Nanjing, China, pp. 926-931, 1989.

[5] Xu, Y. L., Samali, B. and Kwok, K. C. S.,”Control of Along-wind Response of Structures by Mass and Liquid Dampers”, *ASCE J. of Eng. Mech.*, Vol. 118, No. 1, pp. 20-39, 1992.