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Seismic Response Reduction of Eccentric Structures Using Liquid Dampers

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1. Introduction

The installation of vibration absorbers on tall buildings or other flexible structures can be a successful method for reducing the effects of dynamic excitations, such as wind or earthquake, which may exceed either serviceability or safety criteria. Tuned liquid column damper (TLCD) is an effective passive control device by the motion of liquid in a column container. The potential advantages of liquid vibration absorbers include: low manufacturing and installation costs; the ability of the absorbers to be incorporated during the design stage of a structure, or to be retrofitted to serve a remedial role; relatively low maintenance requirements; and the availability of the liquid to be used for emergency purposes, or for the everyday function of the structure if fresh water is used (Hitchcock et al., 1997a, 1997b).

A TLCD is a U-shaped tube of uniform rectangular or circle cross-section, containing liquid. Vibration energy is transferred from the structure to the TLCD liquid through the motion of the rigid container exciting the TLCD liquid. And the vibration of a structure is suppressed by a TLCD through the gravitational restoring force acting on the displaced TLCD liquid and the energy is dissipated by the viscous interaction between the liquid and the rigid container, as well as liquid head loss due to orifices installed inside the TLCD container.

Analytical and experimental researches on this type of vibration reduction approach has been conducted, in which viscous interaction between a liquid and solid boundary has been investigated and used to control vibration (Sakai et al., 1989; Qu et al., 1993). Their experiments, defining the relationship between the coefficient of liquid head loss (as well as its dependence on the orifice opening ratio) and the liquid damping, confirms the validity of their proposed equation of motion in describing liquid column relative motion under moderate excitation. A variation of TLCD, called a liquid column vibration absorber (LCVA) has also been investigated, which has different cross sectional areas in its vertical and horizontal sections depending on performance requirements (Gao and Kwok, 1997; Yan et al., 1998; Chang and Hsu, 1998; Chang 1999). Yan et al. presented the adjustable frequency tuned liquid column damper by adding springs to the TLCD system, which modified the frequency of TLCD and expended its application ranges (Yan and Li, 1999).

Multiple tuned mass damper (MTMD) which consists of a number of tuned mass damper whose natural frequencies are distributed over a certain range around the fundamental frequency of the structure has been proposed and investigated (Kareem and Kline, 1995). The results showed that an optimized MTMD can be more efficient than a single optimized TMD and the sensitivity of a MTMD to the tuning ratio is diminished. A multiple tuned

liquid damper (MTLD) system is investigated by Fujino and Sun (Fujino and Sun, 1993). They found that in situations involving small amplitude liquid motion the MTLD has similar characteristics to that of a MTMD including more effectiveness and less sensitivity to the frequency ratio. However, in a large liquid motion case, the MTLD is not much more effective than a single optimized TLD and a MTLD has almost the same effectiveness as a single TLD when breaking waves occur. Gao et al analyzed the characteristics of multiple liquid column dampers (both U-shaped and V-shaped types) (Gao et al., 1999). It was found that the frequency of range and the coefficient of liquid head loss have significant effects on the performance of a MTLCD; increasing the number of TLCD can enhance the efficiency of MTLCD, but no further significant enhancement is observed when the number of TLCD is over five. It was also confirmed that the sensitivity of an optimized MTLCD to its central frequency ratio is not much less than that of an optimized single TLCD to its frequency ratio, and an optimized MTLCD is even more sensitive to the coefficient of head loss.

2. Circular Tuned Liquid Dampers

Circular Tuned Liquid Column Dampers (CTLCD) is a type of damper that can control the torsional response of structures (Jiang and Tang, 2001). The results of free vibration and forced vibration experiments showed that it is effective to control structural torsional response (Hochrainer et al., 2000), but how to determine the parameters of CTLCD to effectively reduce torsionally coupled vibration is still necessary to be further investigated. In this section, the optimal parameters of CLTCD for vibration control of structures are presented based on the stochastic vibration theory.

2.1 Equation of motion for control system

The configuration of CTLCD is shown in Fig.1. Through Lagrange principle, the equation of motion for CTLCD excited by seismic can be derived as

$$\rho A (2H + 2\pi R) \ddot{h} + \frac{1}{2} \rho A \xi |\dot{h}| \dot{h} + 2\rho A g h = -2\rho A \pi R^2 (\ddot{u}_\theta + \ddot{u}_{g\theta}) \quad (1)$$

where h is the relative displacement of liquid in CTLCD; ρ means the density of liquid; H denotes the height of liquid in the vertical column of container when the liquid is quiescent; A expresses the cross-sectional area of CTLCD; g is the gravity acceleration; R represents the radius of horizontal circular column; ξ is the head loss coefficient; $\ddot{u}_\theta$ denotes the torsional acceleration of structure; $\ddot{u}_{g\theta}$ is the torsional acceleration of ground motion.

Because the damping in the above equation is nonlinear, equivalently linearize it and the equation can be re-written as

$$m_T \ddot{h} + c_{Teq} \dot{h} + k_T h = -\alpha m_T R (\ddot{u}_\theta + \ddot{u}_{g\theta}) \quad (2)$$

where $m_T = \rho A L_{ee}$ is the mass of liquid in CTLCD; $L_{ee} = 2H + 2\pi R$ denotes the total length of liquid in the column; $c_{Teq} = 2m_T \omega_T \zeta_T$ is the equivalent damping of CTLCD; $\omega_T = \sqrt{2g/L_{ee}}$ is the natural circular frequency of CTLCD; $\zeta_T = \frac{\xi}{2\sqrt{\pi g L_{ee}}} \sigma_h$ is equivalent linear damping ratio

(Wang, 1997); $\sigma_{\dot{h}}$ means the standard deviation of the liquid velocity; $k_T = 2\rho Ag$ is the “stiffness” of liquid in vibration; $\alpha = 2\pi R / L_{ve}$ is the configuration coefficient of CTLCD.

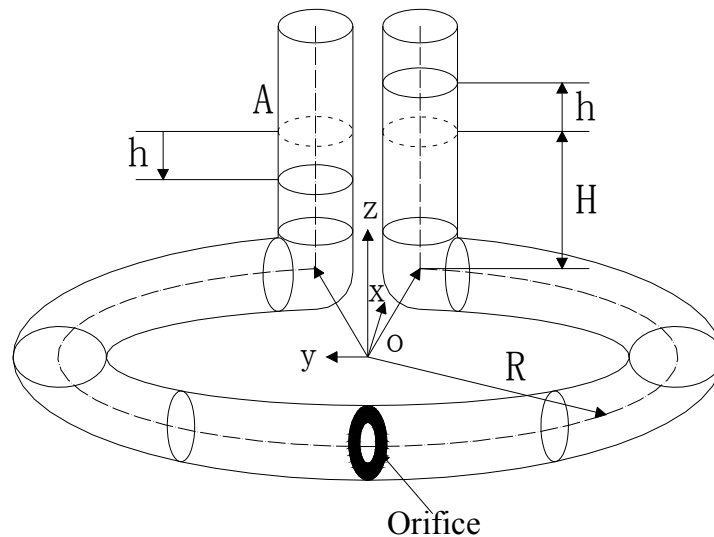


Fig. 1. Configuration of Circular TLCD

For a single-story offshore platform, the equation of torsional motion installed CTLCD can be written as

$$J_{\theta}\ddot{u}_{\theta} + c_{\theta}\dot{u}_{\theta} + k_{\theta}u_{\theta} = -J_{\theta}\ddot{u}_{g\theta} + F_{\theta} \quad (3)$$

where J_{θ} is the inertia moment of platform to vertical axis together with additional inertial moment of sea fluid; c_{θ} denotes the summation of damping of platform and additional damping caused by sea fluid; k_{θ} expresses the stiffness of platform; $\dot{u}_{\theta}$ and u_{θ} are velocity and displacement of platform, respectively; F_{θ} is the control force of CTLCD to offshore platform, given by

$$F_{\theta} = -m_T R (R\ddot{u}_{\theta} + R\ddot{u}_{g\theta} + \alpha\ddot{h}) \quad (4)$$

Combining equation (1) to (4) yields:

$$\begin{bmatrix} 1 + \lambda & \alpha\lambda / R \\ \alpha\lambda / R & \lambda / R^2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_{\theta} \\ \ddot{h} \end{Bmatrix} + \begin{bmatrix} 2\zeta_g\omega_{\theta} & 0 \\ 0 & 2\lambda\zeta_T\omega_T / R^2 \end{bmatrix} \begin{Bmatrix} \dot{u}_{\theta} \\ \dot{h} \end{Bmatrix} + \begin{bmatrix} \omega_{\theta}^2 & 0 \\ 0 & \lambda\omega_T^2 / R^2 \end{bmatrix} \begin{Bmatrix} u_{\theta} \\ h \end{Bmatrix} = - \begin{Bmatrix} 1 + \lambda \\ \alpha\lambda / R \end{Bmatrix} \ddot{u}_{g\theta} \quad (5)$$

where $\lambda = \frac{m_T R^2}{J_{\theta}}$ denotes inertia moment ratio. Let $\ddot{u}_{g\theta}(t) = e^{i\omega t}$, then

$$\begin{Bmatrix} u_{\theta} \\ h \end{Bmatrix} = \begin{Bmatrix} H_{\theta}(\omega) \\ H_h(\omega) \end{Bmatrix} e^{i\omega t} \quad (6)$$

where $H_\theta(\omega)$ and $H_h(\omega)$ are transfer functions in the frequency domain. Substituting equation (6) into equation (5) leads to

$$\begin{bmatrix} -(1+\lambda)\omega^2 + 2\zeta_s\omega_\theta i\omega + \omega_\theta^2 & -\alpha\lambda\omega^2 / R \\ -\alpha\lambda\omega^2 / R & -\lambda\omega^2 / R^2 + 2\lambda\zeta_T\omega_T i\omega / R^2 + \lambda\omega_T^2 / R^2 \end{bmatrix} \cdot \begin{Bmatrix} H_\theta \\ H_h \end{Bmatrix} = -\begin{Bmatrix} 1+\lambda \\ \alpha\lambda / R \end{Bmatrix} \quad (7)$$

From the above equation, the transfer function of structural torsional response can be expressed by

$$H_\theta(\omega) = \frac{[\lambda(1+\lambda) - \alpha^2\lambda^2]\omega^2 - 2(1+\lambda)\lambda\zeta_T\omega_T i\omega - \lambda(1+\lambda)\omega_T^2}{[-(1+\lambda)\omega^2 + 2\zeta_\theta\omega_\theta i\omega + \omega_\theta^2][-\lambda\omega^2 + 2\lambda\zeta_T\omega_T i\omega + \lambda\omega_T^2] - \alpha^2\lambda^2\omega^4} \quad (8)$$

Then, the torsional response variance of structure installed CTLCD can be obtained as

$$\sigma_{u_\theta}^2 = \int_{-\infty}^{\infty} |H_\theta|^2 S_{\ddot{u}_{g\theta}}(\omega) d\omega \quad (9)$$

If the ground motion is assumed to be a Gauss white noise random process with an intensity of S_0 and define the frequency ratio $\gamma = \omega_T / \omega_\theta$, the value of $\sigma_{u_\theta}^2$ can be calculated by

$$\sigma_{u_\theta}^2 = \frac{\pi S_0}{2\omega_\theta^3} \cdot \frac{2(1+\lambda)^4\zeta_T\gamma^4 + 2A_1\zeta_\theta(1+\lambda)^2\gamma^3 + 2\zeta_T(1+\lambda)^2(2B_1 + \alpha^2\lambda)\gamma^2 + 2C_1\zeta_\theta\gamma + 2\zeta_T(1+\lambda - \alpha^2\lambda)^2}{2(1+\lambda)^2\zeta_\theta\zeta_T\gamma^4 + 2A_1\zeta_\theta^2\gamma^3 + 4B_1\zeta_\theta\zeta_T\gamma^2 + 2D_1\zeta_T^2\gamma + 2\zeta_\theta\zeta_T} \quad (10)$$

where $A_1 = \alpha^2\lambda + 4\zeta_T^2(1+\lambda)$, $B_1 = (2\zeta_T^2 - 1)(1+\lambda) + 2\zeta_\theta^2 + \alpha^2\lambda$, $C_1 = 4\zeta_T^2(1+\lambda)^2 + \alpha^4\lambda^2$, $D_1 = 4\zeta_\theta^2 + \alpha^2\lambda$

2.2 Optimal parameters of circular tuned liquid column dampers

The optimal parameters of CTLCD should make the displacement variance of offshore platform $\sigma_{u_\theta}^2$ minimum, so the optimal parameters of CTLCD can be obtained according to the following condition

$$\frac{\partial \sigma_{u_\theta}^2}{\partial \zeta_T} = 0 \quad \frac{\partial \sigma_{u_\theta}^2}{\partial \gamma} = 0 \quad (11)$$

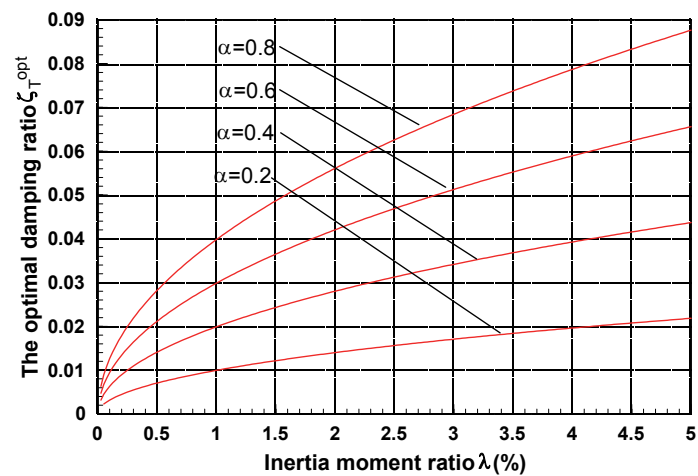
Neglecting the damping ratio of offshore platform ζ_θ and solving above equation, the optimal damping ratio ζ_T^{opt} and frequency ratio γ^{opt} for CTLCD can be formulized as

$$\zeta_T^{opt} = \frac{1}{2} \sqrt{\frac{\lambda\alpha^2(1+\lambda - \frac{5}{4}\lambda\alpha^2)}{(1+\lambda)(1+\lambda - \frac{3}{2}\lambda\alpha^2)}} \quad \gamma^{opt} = \frac{\sqrt{1+\lambda - \frac{3}{2}\lambda\alpha^2}}{1+\lambda} \quad (12)$$

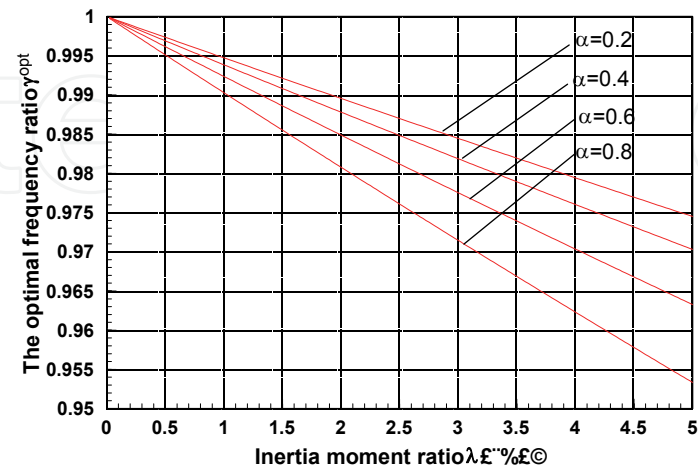
Fig. 2 shows the optimal damping ratio ζ_T^{opt} and optimal frequency ratio γ^{opt} of CTLCD as a function of inertia moment ratio λ ranging between 0 to 5% for $\alpha=0.2, 0.4, 0.6$ and 0.8 . It can be seen that as the value of λ increases the optimal damping ratio ζ_T^{opt} increases and the optimal frequency ratio γ^{opt} decreases. For a given value of λ , the optimal damping ratio ζ_T^{opt} increases and the optimal frequency ratio decreases with the rise of α . It can also be seen that the value of γ^{opt} is always near 1 for different values of α and λ in Fig.2. If let $\gamma = 1$ and solve $\frac{\partial \sigma_\theta^2}{\partial \zeta_T} = 0$, the optimal damping ratio of CTLCD ζ_T^{opt} is obtained as

$$\zeta_T^{opt} = \frac{1}{2} \sqrt{\frac{\lambda^2(a^2 + 1 + \lambda) + a^2\lambda(1 + \lambda)^2}{(1 + \lambda)^3}}$$

(13)



(a) The optimal damping ratio with inertia moment



(b) The optimal frequency ratio with inertia moment

Fig. 2. The optimal parameters of CTLCD with inertia moment ratio λ

The optimal parameters of CTLCD cannot be expressed with formulas when considering the damping of offshore platform for the complexity of equation (10), so we can only get numerical results for different values of structural damping, as shown in Table 1. Table 1 shows that for different damping of platform system, the optimal damping ratio of CTLCD increases and the optimal frequency ratio decreases with the rise of λ , which is the same as Fig. 2. Table 1 also suggests the damping of platform has little effect on the optimal parameters of CTLCD, especially on the optimal damping ratio ζ_T^{opt} .

	$\zeta_\theta = 0$		$\zeta_\theta = 1\%$		$\zeta_\theta = 2\%$		$\zeta_\theta = 5\%$	
	γ^{opt}	ζ_T^{opt}	γ^{opt}	ζ_T^{opt}	γ^{opt}	ζ_T^{opt}	γ^{opt}	ζ_T^{opt}
$\lambda = 0.5\%$	0.9951	0.0282	0.9935	0.0283	0.9915	0.0283	0.9832	0.0283
$\lambda = 1\%$	0.9903	0.0398	0.9881	0.0398	0.9856	0.0398	0.9755	0.0398
$\lambda = 1.5\%$	0.9855	0.0487	0.9829	0.0487	0.9799	0.0487	0.9687	0.0487
$\lambda = 2\%$	0.9808	0.0561	0.9778	0.0561	0.9745	0.0561	0.9622	0.0561
$\lambda = 5\%$	0.9533	0.0876	0.9490	0.0877	0.9442	0.0877	0.9278	0.0877

Table 1. The optimal parameters of CLTCD ($\alpha = 0.8$)

2.3 Analysis of structural torsional response control using CTLCD

The objective of dampers installed in the offshore platform is to increase the damping of the structural system and reduce the response of structure. To analyze the effects of different system parameters on the torsional response of structure, the damping of a platform structure with CTLCD is expressed by equivalent damping ratio ζ_e (Wang, 1997):

$$\zeta_e = \frac{\pi S_0}{2\omega_\theta^3 \sigma_\theta^2}$$

(14)

The relationships between ζ_e and different parameters of control system are shown in Fig. 3 to Fig. 7.

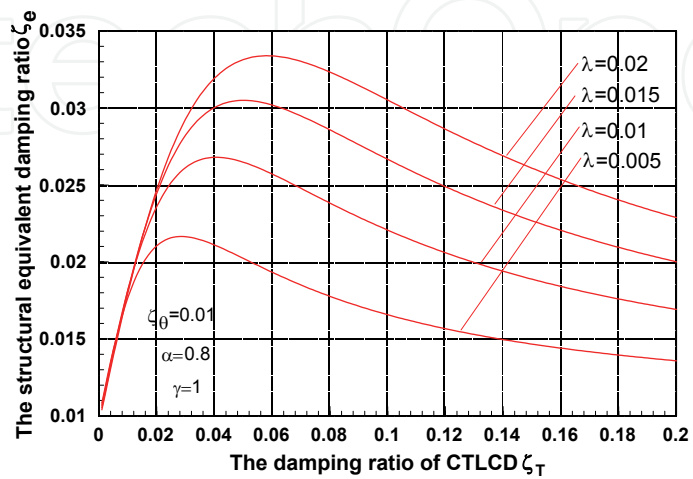


Fig. 3. The structural equivalent damping ratio with the damping ratio of CTLCD

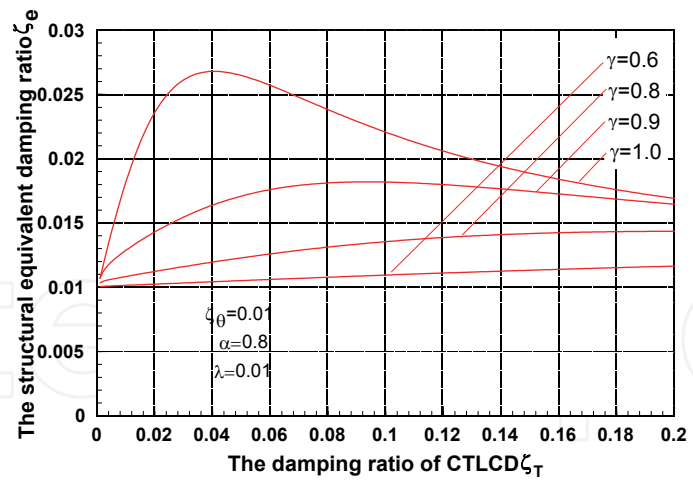


Fig. 4. The structural equivalent damping ratio with the damping ratio of CTLCD

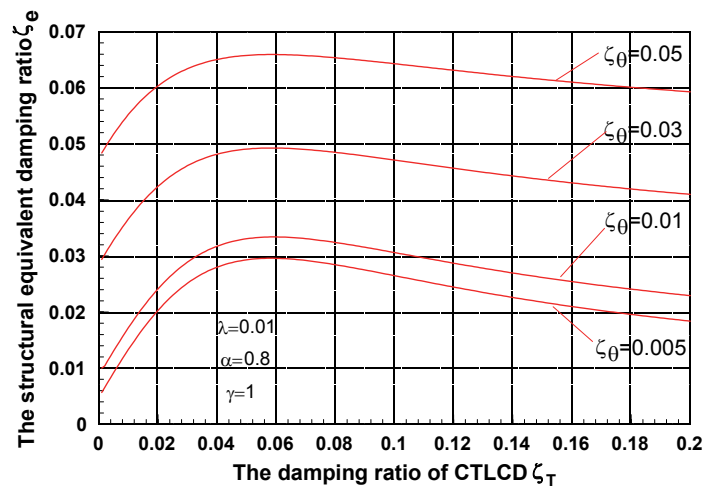


Fig. 5. The structural equivalent damping ratio with the damping ratio of CTLCD

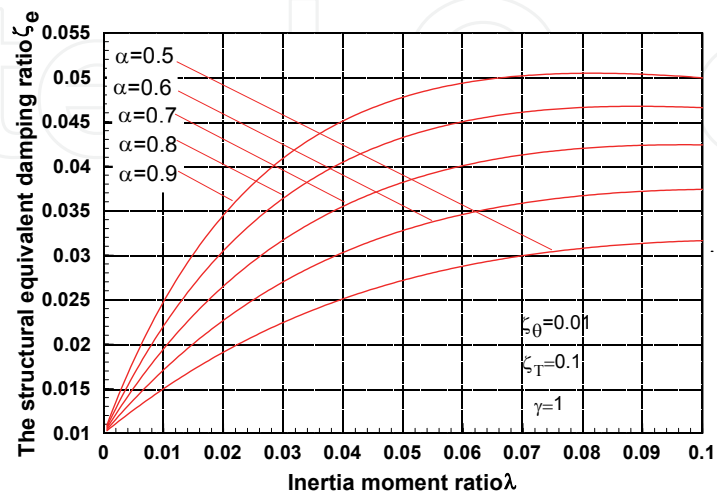


Fig. 6. The structural equivalent damping ratio with the inertia moment ratio

Fig. 3 shows the equivalent damping ratio of a platform structure ζ_e as a function of the damping ratio of CTLCD for $\lambda=0.005, 0.01, 0.015, 0.02$. It is seen from the figure that the equivalent damping ratio ζ_e increases rapidly with the increase of ζ_T initially, whereas it decreases if the damping ratio of CTLCD ζ_T is greater than a certain value.

Fig. 4 shows the equivalent damping ratio of a platform structure ζ_e as a function of the damping ratio of CTLCD for $\gamma =0.6, 0.8, 0.9, 1.0$. It is seen from the figure that the value of ζ_e increases with the rise of frequency ratio γ .

Fig. 5 shows the equivalent damping ratio of structure ζ_e as a function of the damping ratio of CTLCD for $\zeta_\theta=0.005, 0.01, 0.03$ and 0.05 . It is seen from the figure that as the rise of the damping ratio of structure ζ_θ , the equivalent damping ratio ζ_e increases.

Fig. 6 shows the equivalent damping ratio of structure ζ_e as a function of λ for $\alpha=0.5, 0.6, 0.7, 0.8$ and 0.9 . It can be seen from the figure that the damping ratio of structure ζ_e increases with λ initially. Whereas, the curve of ζ_e with λ will be gentle when the value of λ is greater than a certain value. It can also be concluded from the figure that the damping ratio of structure ζ_e increases with the rise of configuration coefficient α .

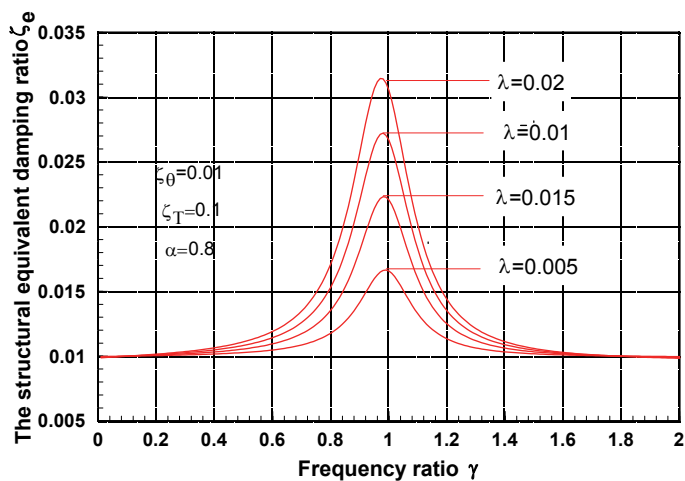


Fig. 7. The structural equivalent damping ratio with the frequency ratio

Fig. 7 shows the equivalent damping ratio of structure ζ_e as a function of frequency ratio between CTLCD and structure. It is seen from the figure that the value of ζ_e will be maximum at the condition of $\gamma=1$. So, the value of γ can be set to approximate 1 in the engineering application to get the best control performance.

2.4 Structural torsionally coupled response control using CTLCD

The torsional response of structure is usually coupled with translational response in engineering, so it is necessary to consider torsionally coupled response for vibration control of eccentric platform structure. In this paper, a single-story structure only eccentric in x direction is taken as an example, which means that the displacement in y direction is coupled with the torsional response of platform. The equation of torsionally coupled motion for the eccentric platform installed CTLCD can be written as

$$\begin{bmatrix} m_s & 0 \\ 0 & m_s r^2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_y \\ \ddot{u}_\theta \end{Bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{Bmatrix} \dot{u}_y \\ \dot{u}_\theta \end{Bmatrix} + \begin{bmatrix} K_y & K_y e_s \\ K_y e_s & K_\theta \end{bmatrix} \begin{Bmatrix} u_y \\ u_\theta \end{Bmatrix} = - \begin{bmatrix} m_s & 0 \\ 0 & m_s r^2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_{gy} \\ \ddot{u}_{g\theta} \end{Bmatrix} + \begin{Bmatrix} F_y \\ F_\theta \end{Bmatrix} \quad (15)$$

The above equation can be simplified as

$$\mathbf{M}_s \ddot{\mathbf{u}} + \mathbf{C}_s \dot{\mathbf{u}} + \mathbf{K}_s \mathbf{u} = -\mathbf{M}_s \ddot{\mathbf{u}}_g + \mathbf{F} \quad (16)$$

where m_s means the mass of platform together with additional mass of sea fluid; e_s is eccentric distance; u_y , $\ddot{u}_{gy}$ and K_y are the displacement, ground acceleration and stiffness of offshore platform in y direction, respectively; The control force $\mathbf{F}$ is calculated by

$$\begin{Bmatrix} F_y = -m_T(\ddot{u}_y + \ddot{u}_{gy}) \\ F_\theta = -m_T R(R\ddot{u}_\theta + R\ddot{u}_{g\theta} + \alpha \dot{h}) \end{Bmatrix} \quad (17)$$

It is assumed that the damping matrix in Equation (16) is directly proportional to the stiffness matrix, that is

$$\mathbf{C}_s = a\mathbf{K}_s \quad (18)$$

where the proportionality constant a has units of second. The proportionality constant a was chosen such that the uncoupled lateral mode of vibration has damping equal to 2% of critical damping. This was to account for the nominal elastic energy dissipation that occurs in any real structure (Bugeja *et al.*, 1997). The critical damping coefficient c_c for a single degree-of-freedom (SDOF) system is given by

$$c_c = 2m_s \omega_y \quad (19)$$

where $\omega_y = \sqrt{K_y / m_s}$ is natural frequency of the uncoupled lateral mode. From the equation (18) and (19), the constant a is determined by

$$a = \frac{0.02 \times 2m_s \sqrt{K_y / m_s}}{K_y} \quad (20)$$

Combining the Equation (2) and (15), the equation of motion for torsionally coupled system can be written as

$$\begin{bmatrix} 1 + \mu & 0 & 0 \\ 0 & 1 + \frac{\mu R^2}{r^2} & \frac{\alpha \mu R}{r^2} \\ 0 & \alpha \mu R & \mu \end{bmatrix} \begin{Bmatrix} \ddot{u}_y \\ \ddot{u}_\theta \\ \ddot{h} \end{Bmatrix} + \begin{bmatrix} a\omega_y^2 & a\omega_y^2 e_s & 0 \\ \frac{a\omega_y^2 e_s}{r^2} & a\omega_\theta^2 & 0 \\ 0 & 0 & 2\mu\zeta_T \omega_T \end{bmatrix} \begin{Bmatrix} \dot{u}_y \\ \dot{u}_\theta \\ \dot{h} \end{Bmatrix} + \begin{bmatrix} \omega_y^2 & \omega_y^2 e_s & 0 \\ \frac{\omega_y^2 e_s}{r^2} & \omega_\theta^2 & 0 \\ 0 & 0 & \mu\omega_T^2 \end{bmatrix} \begin{Bmatrix} u_y \\ u_\theta \\ h \end{Bmatrix} = - \begin{bmatrix} 1 + \mu & 0 \\ 0 & 1 + \frac{\mu R^2}{r^2} \\ 0 & \alpha \mu R \end{bmatrix} \begin{Bmatrix} \ddot{u}_{gy} \\ \ddot{u}_{g\theta} \end{Bmatrix} \quad (21)$$

where $\mu = m_T / m_s$ is a ratio between the mass of CTLCD and the mass of structure; $\omega_\theta = \sqrt{k_\theta / (m_T r^2)}$ denotes the natural frequency of the uncoupled torsional mode. The following assumptions are made in this paper: $\ddot{u}_{gy}$ and $\ddot{u}_{g\theta}$ are two unrelated Gauss white noise random processes with intensities of S_1 and S_2 , respectively; H_{yy} , $H_{y\theta}$, $H_{\theta y}$ and $H_{\theta\theta}$ are transfer functions from $\ddot{u}_{gy}$ to u_y , $\ddot{u}_{g\theta}$ to u_y , $\ddot{u}_{gy}$ to u_θ and $\ddot{u}_{g\theta}$ to u_θ , respectively. Then, the displacement variance of structure can be obtained by

$$\begin{aligned}\sigma_{u_{yy}}^2 &= S_1 \int_{-\infty}^{\infty} |H_{yy}|^2 d\omega & \sigma_{u_{y\theta}}^2 &= S_2 \int_{-\infty}^{\infty} |H_{y\theta}|^2 d\omega \\ \sigma_{u_{\theta y}}^2 &= S_1 \int_{-\infty}^{\infty} |H_{\theta y}|^2 d\omega & \sigma_{u_{\theta\theta}}^2 &= S_2 \int_{-\infty}^{\infty} |H_{\theta\theta}|^2 d\omega\end{aligned}\quad (22)$$

where $\sigma_{u_{yy}}$ and $\sigma_{u_{y\theta}}$ are displacement variances in y direction caused by the ground motion in y direction and θ direction, respectively; $\sigma_{u_{\theta y}}$ and $\sigma_{u_{\theta\theta}}$ are displacement variances in θ direction caused by the ground motion in y direction and θ direction, respectively. So, the equivalent damping ratios of structure are given as

$$\zeta_{eyy} = \frac{\pi S_1}{2\omega_y^3 \sigma_{u_{yy}}^2} ; \zeta_{ey\theta} = \frac{\pi S_2 r^2}{2\omega_y^3 \sigma_{u_{y\theta}}^2} ; \zeta_{e\theta y} = \frac{\pi S_1}{2\omega_y^3 r^2 \sigma_{u_{\theta y}}^2} ; \zeta_{e\theta\theta} = \frac{\pi S_2}{2\omega_y^3 \sigma_{u_{\theta\theta}}^2} \quad (23)$$

where ζ_{eyy} and $\zeta_{ey\theta}$ are equivalent damping ratios in y direction caused by the ground motions in y direction and θ direction, respectively; $\zeta_{e\theta y}$ and $\zeta_{e\theta\theta}$ are equivalent damping ratios in θ direction caused by the ground motions in y direction and θ direction, respectively. Then, the total equivalent damping ratio ζ_{ey} in y direction and $\zeta_{e\theta}$ in θ direction can be defined as

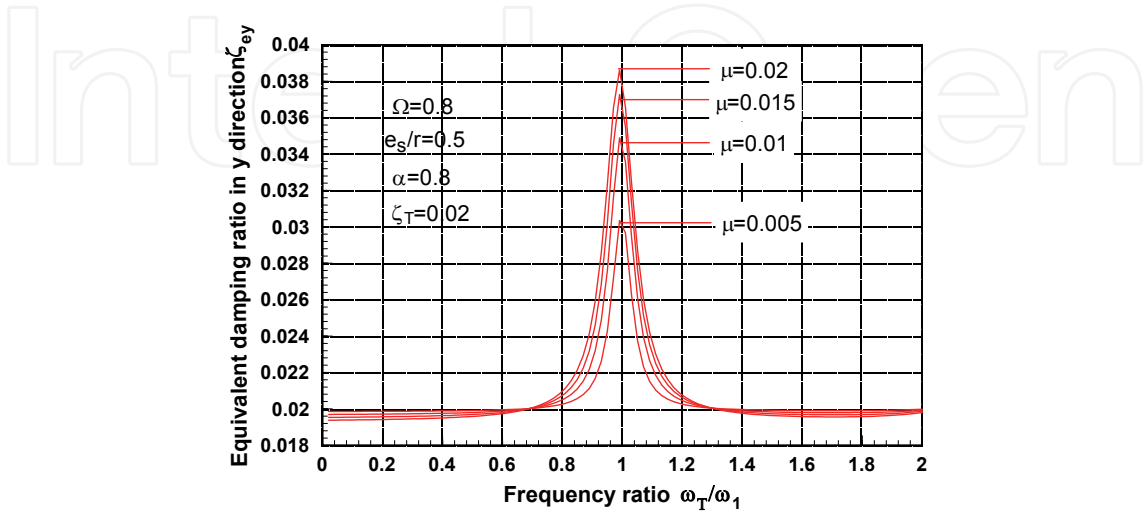
$$\begin{aligned}\zeta_{ey} &= \zeta_{eyy} + \zeta_{ey\theta} \\ \zeta_{e\theta} &= \zeta_{e\theta y} + \zeta_{e\theta\theta}\end{aligned}\quad (24)$$

Define $\Omega = \omega_\theta / \omega_x$ as the frequency ratio between the uncoupled torsional mode and uncoupled translational mode and ω_1 as the first frequency of torsionally coupled structure. The relationships of equivalent damping ratio ζ_{ey} and $\zeta_{e\theta}$ with parameters of control system are shown in Fig. 8 to Fig. 11.

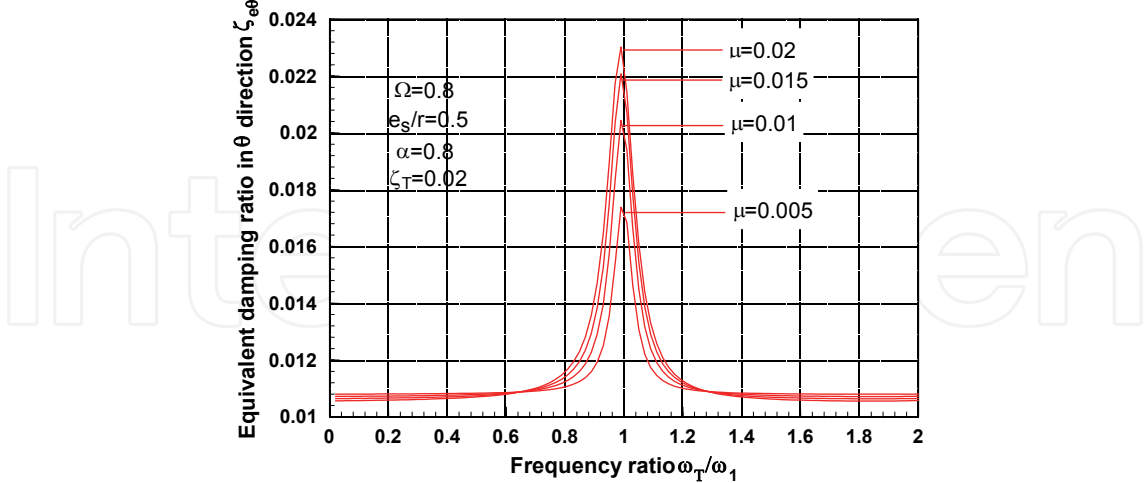
Fig. 8 shows the equivalent damping ratio ζ_{ey} and $\zeta_{e\theta}$ as functions of frequency ratio ω_T / ω_1 for mass ratio $\mu = 0.005, 0.01, 0.015$ and 0.02 . It is seen from the figure that the values of ζ_{ey} and $\zeta_{e\theta}$ are maximum when the value of frequency ratio ω_T / ω_1 is approximate 1. The Fig. 8 also suggests that damping ratio ζ_{ey} and $\zeta_{e\theta}$ increase with the rise of mass ratio μ .

Fig. 9 shows equivalent damping ratio ζ_{ey} and $\zeta_{e\theta}$ as functions of mass ratio μ for configuration coefficient $\alpha = 0.5, 0.6, 0.7$ and 0.8 . It is seen from the figure that the values of ζ_{ey} and $\zeta_{e\theta}$ increase initially and approach constants finally with the rise of mass ratio μ .

It can also be concluded that the values of ζ_{ey} and $\zeta_{e\theta}$ both increase with the rise of configuration coefficient α .

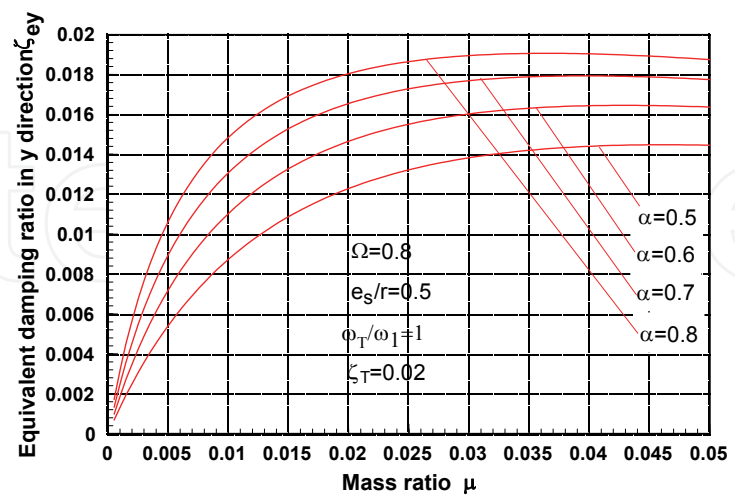


(a) Equivalent damping ratio in y direction

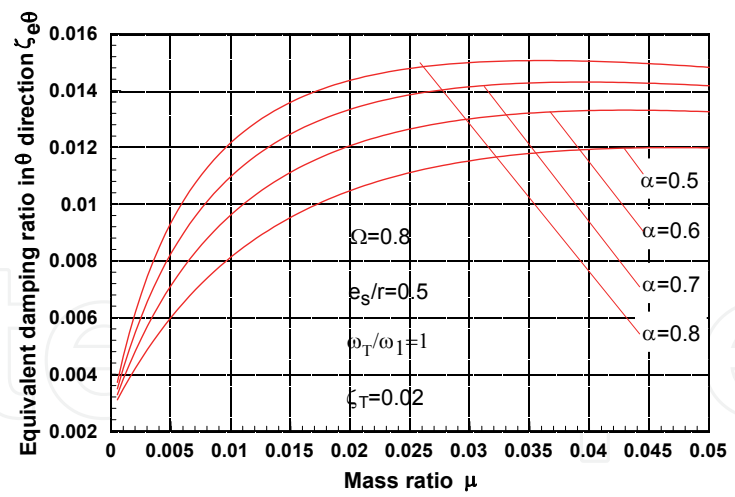


(b) Equivalent damping ratio in θ direction

Fig. 8. Equivalent damping ratio of structure with frequency ratio ω_T / ω_1

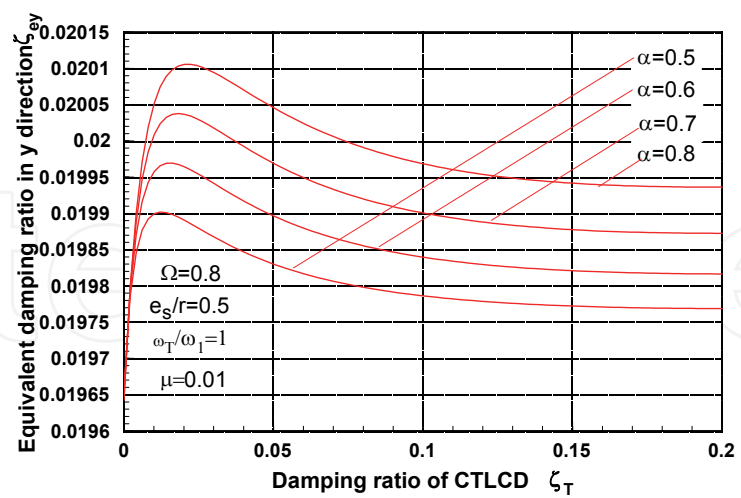


(a) Equivalent damping ratio in y direction

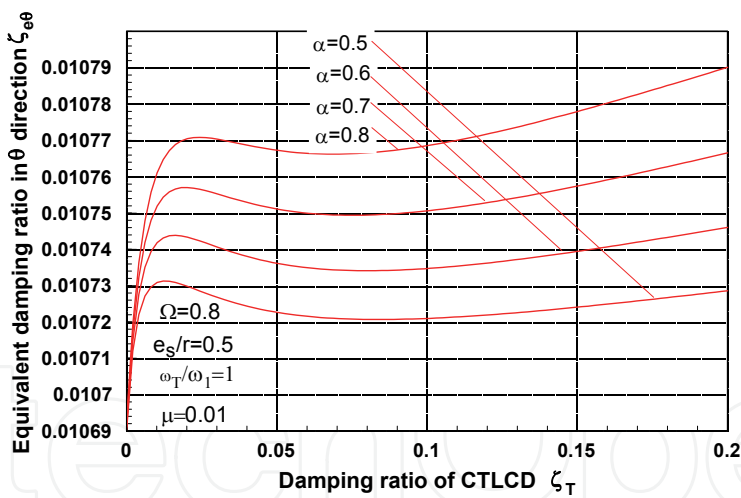


(b)Equivalentnet damping ratio in θ direction

Fig. 9. Equivalent damping ratio of structure with mass ratio μ



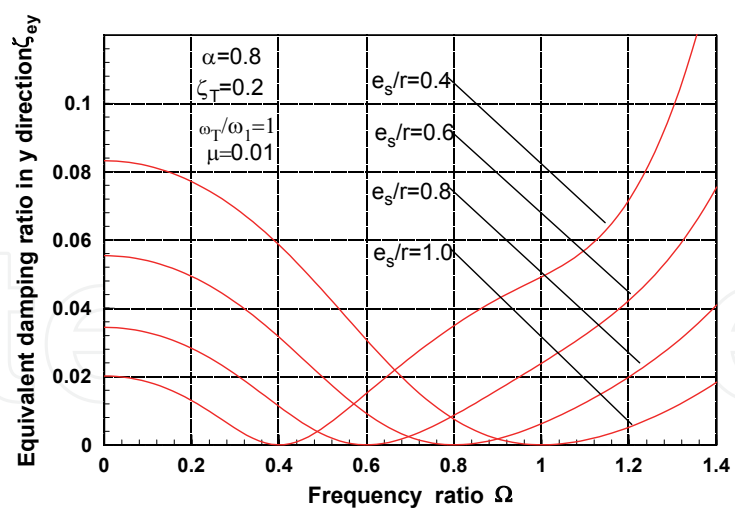
(a) Equivalent damping ratio in y direction



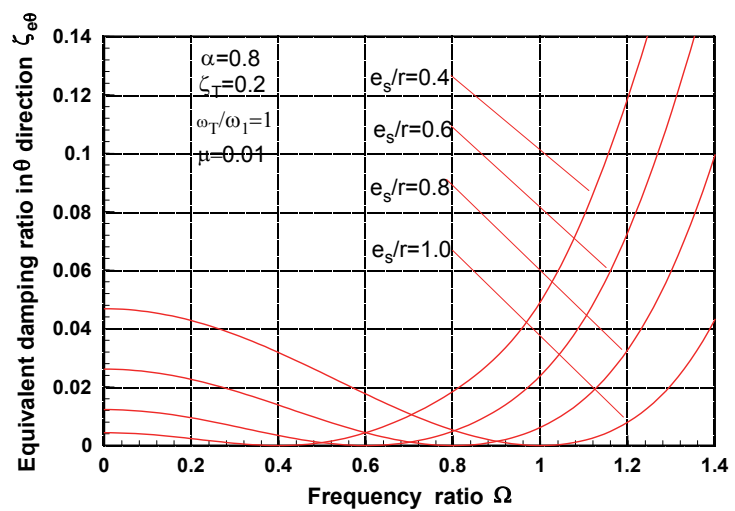
(b) Equivalent damping ratio in θ direction

Fig. 10. Equivalent damping ratio of structure with damping ratio ζ_T

Fig. 10 shows equivalent damping ratio ζ_{ey} and $\zeta_{e\theta}$ as functions of damping ratio ζ_T for $\alpha = 0.5, 0.6, 0.7$ and 0.8 . It is seen from the figure that the values of ζ_{ey} and $\zeta_{e\theta}$ rapidly increase initially with the rise of ζ_T ; whereas, after a certain value of ζ_T , ζ_{ey} will decrease to a constant and $\zeta_{e\theta}$ decrease first, then increase gradually.



(a) Equivalent damping ratio in y direction



(b) Equivalent damping ratio in θ direction

Fig. 11. Equivalent damping ratio of structure with frequency ratio Ω

Fig 11 shows equivalent damping ratio ζ_{ey} and $\zeta_{e\theta}$ as functions of frequency ratio Ω for $e_s/r=0.4, 0.6, 0.8$ and 1.0 . It is seen from the figure that the values of ζ_{ey} and $\zeta_{e\theta}$ are approximate zero for the structure with Ω near to e_s/r ; for the structure $\Omega < e_s/r$, the values of ζ_{ey} and $\zeta_{e\theta}$ decrease with the rise of frequency ratio Ω and increase with the rise of e_s/r ; for the structure with $\Omega > e_s/r$, the values of ζ_{ey} and $\zeta_{e\theta}$ increase with the rise of frequency ratio Ω and decrease with the rise of e_s/r .

3. Torsionally coupled vibration control of eccentric buildings

The earthquake is essentially multi-dimensional and so is the structural response excited by earthquake, which will result in the torsionally coupled vibration that cannot be neglected. So, the torsional response for structure is very important (Li and Wang, 1992). Previously, Li et al. presented the method of reducing torsionally coupled response by installing TLCDs in structural orthogonal directions (Huo and Li, 2001). Circular Tuned Liquid Column

Dampers (CTLCD) is a type of control device sensitive to torsional response. The results of free vibration and forced vibration experiments showed that it is effective to control structural torsional response (Liang, 1996; Hochrainer, 2000). However, how to determine the parameters of CTLCD to effectively reduce torsionally coupled vibration is still necessary to be further investigated.

3.1 Equation of motion for control system

The configuration of TLCD is shown in Fig. 12(a). According to the Lagrange theory, the equation of motion for TLCD excited by seismic can be derived as

$$\rho A(2H + B)\ddot{h} + \frac{1}{2}\rho A\xi|\dot{h}|\dot{h} + 2\rho Agh = -\rho AB(\ddot{u} + \ddot{u}_g) \quad (25)$$

where h is the relative displacement of liquid in TLCD; ρ means the density of liquid; H expresses the height of liquid in the container when the liquid is quiescent; A denotes the cross-sectional area of TLCD; g is the acceleration of gravity; B represents the length of horizontal liquid column; ξ is the head loss coefficient; $\ddot{u}$ and $\ddot{u}_g$ mean the acceleration of structure and ground motion, respectively

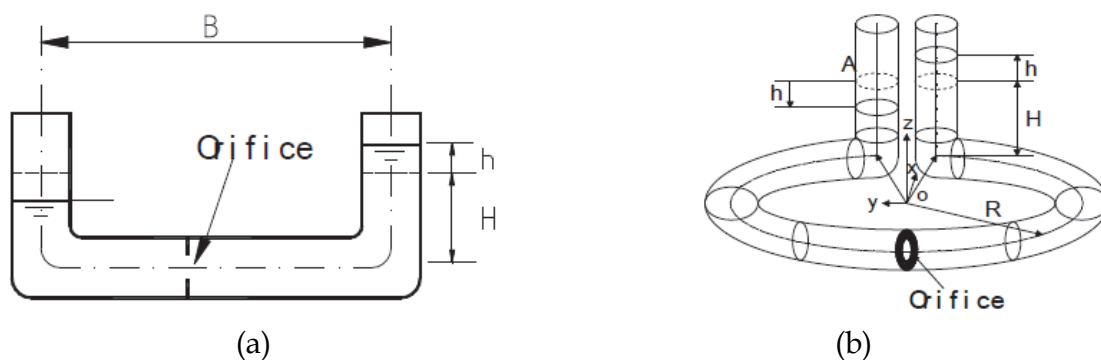


Fig. 12. Configuration of Liquid Column Dampers

The shape of CTCD is shown in Fig. 12(b). In the same way, the equation of motion for CTLCD is derived as

$$\rho A(2H + 2\pi R)\ddot{h} + \frac{1}{2}\rho A\xi|\dot{h}|\dot{h} + 2\rho Agh = -2\rho A\pi R^2(\ddot{u}_\theta + \ddot{u}_{g\theta}) \quad (26)$$

Two TLCDs are set in the longitudinal direction and transverse direction of n -story building, respectively, and a CTLCD is installed in the center of mass, as shown in Fig.13. The equation of motion of system excited by multi-dimensional seismic inputs can be written as

$$[M_s]\{\ddot{u}\} + [C_s]\{\dot{u}\} + [K_s]\{u\} = -[M_s][E_s]\{\ddot{u}_g\} + \{F_T\} \quad (27)$$

Where, $[M_s]$, $[C_s]$ and $[K_s]$ are the mass, damping and stiffness matrices of the system with dimension of $3n \times 3n$, respectively. $\{u\}$ means the displacement vector of the structure,

$\{u\} = \{u_{x1} \cdots u_{xn} \ u_{y1} \cdots u_{yn} \ u_{\theta 1} \cdots u_{\theta n}\}^T$; $[E_s]$ is the influence matrix of the ground

excitation; $\{\ddot{u}_g\} = \{\ddot{u}_{xg} \quad \ddot{u}_{yg} \quad \ddot{u}_{\theta g}\}$ is the three-dimensional seismic inputs; $F_T = \{0 \quad \dots \quad F_x \quad 0 \quad \dots \quad F_y \quad 0 \quad \dots \quad F_\theta\}$ is the three-dimensional control vector, where

$$\begin{aligned} F_x &= -m_{Ttot}(\ddot{u}_{xn} + \ddot{u}_{xg}) - \alpha_x m_{Tx} \ddot{h}_x + (m_{Tx} l_{1y} + m_{Ty} l_{2y})(\ddot{u}_{\theta n} + \ddot{u}_{\theta g}) \\ F_y &= -m_{Ttot}(\ddot{u}_{yn} + \ddot{u}_{yg}) - \alpha_y m_{Ty} \ddot{h}_y - (m_{Tx} l_{1x} + m_{Ty} l_{2x})(\ddot{u}_{\theta n} + \ddot{u}_{\theta g}) \\ F_\theta &= (m_{Tx} l_{1y} + m_{Ty} l_{2y})(\ddot{u}_{xn} + \ddot{u}_{xg}) - (m_{Tx} l_{1x} + m_{Ty} l_{2x})(\ddot{u}_{yn} + \ddot{u}_{yg}) \\ &\quad + \alpha_x m_{Tx} l_{1y} \ddot{h}_x - \alpha_y m_{Ty} l_{2x} \ddot{h}_y - (m_{Tx} r_1^2 + m_{Ty} r_2^2 + m_T R^2)(\ddot{u}_{\theta n} + \ddot{u}_{\theta g}) - \alpha_\theta m_T R \ddot{h}_\theta \end{aligned} \quad (28)$$

where (l_{1x}, l_{1y}) means the location of the TLCD in x direction; (l_{2x}, l_{2y}) means the location of the TLCD in y direction; $r_1^2 = l_{1x}^2 + l_{1y}^2$; $r_2^2 = l_{2x}^2 + l_{2y}^2$.

Combining Equation (1) to (3), the equation of motion for the control system can be written as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = -\mathbf{M}\mathbf{E}\ddot{\mathbf{u}}_g \quad (29)$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices of the combined and damper system. Although the damping of the structure is assumed to be classical, the combined structure and damper system represented by the above equation will be non-classically damped. To analyze a non-classical damped system, it is convenient to work with the system of first order state equations

$$\dot{\mathbf{Z}} = \mathbf{A}\mathbf{Z} + \mathbf{B}\ddot{\mathbf{u}}_g \quad (30)$$

where

$$\mathbf{Z} = \begin{Bmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \end{Bmatrix}, \quad \mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{E} \end{bmatrix} \quad (31)$$

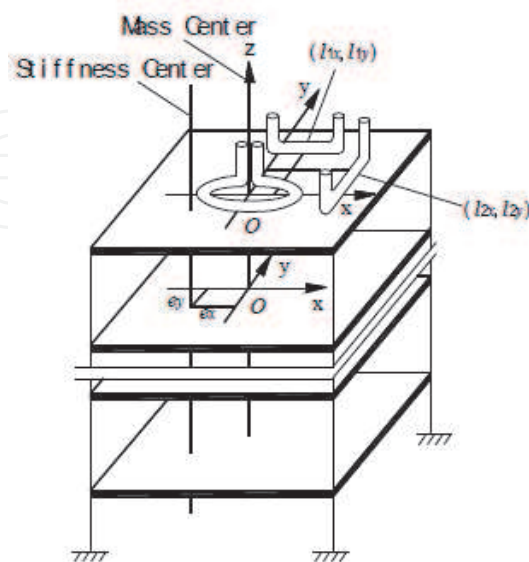


Fig. 13. An eccentric structure with liquid Dampers

3.2 Dynamical characteristics of the structure

The structure analyzed in this paper is an 8-story moment-resisting steel frame with a plan irregularity and a height of 36m created in this study and shown in Figure 14 and Figure 15(Kim, 2002). The structure has 208 members, 99 nodes, and 594 DOFs prior to applying boundary conditions, rigid diaphragm constrains, and the dynamic condensation. Applying boundary conditions and rigid diaphragm constraints results in 288 DOFs. They are further reduced 24 DOFs by the Guyan reduction of vertical DOFs and the rotational DOFs about two horizontal axes.

The static loading on the building consists of uniformly distributed floor dead and live load of 4.78 Kpa and 3.35 Kpa, respectively. A total lateral force (base force) of 963 KN is obtained and distributed over the structure using the equivalent linear static load approach. Each floor shear force is distributed to the nodes in that floor in proportion to nodal masses.

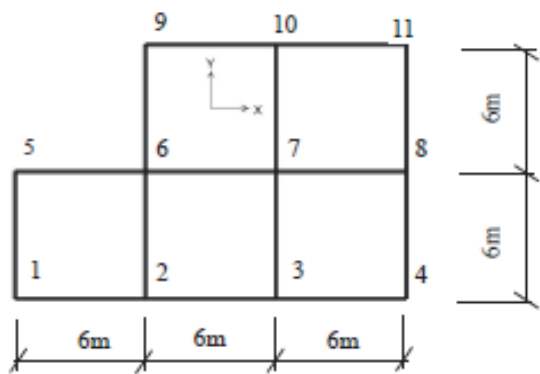


Fig. 14. Plan of the structure

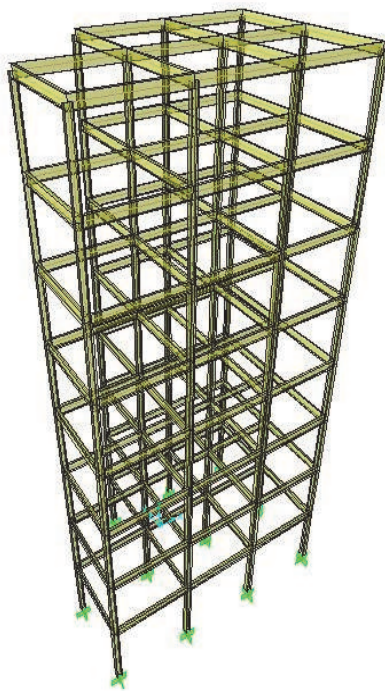


Fig. 15. FEM figure of the structure

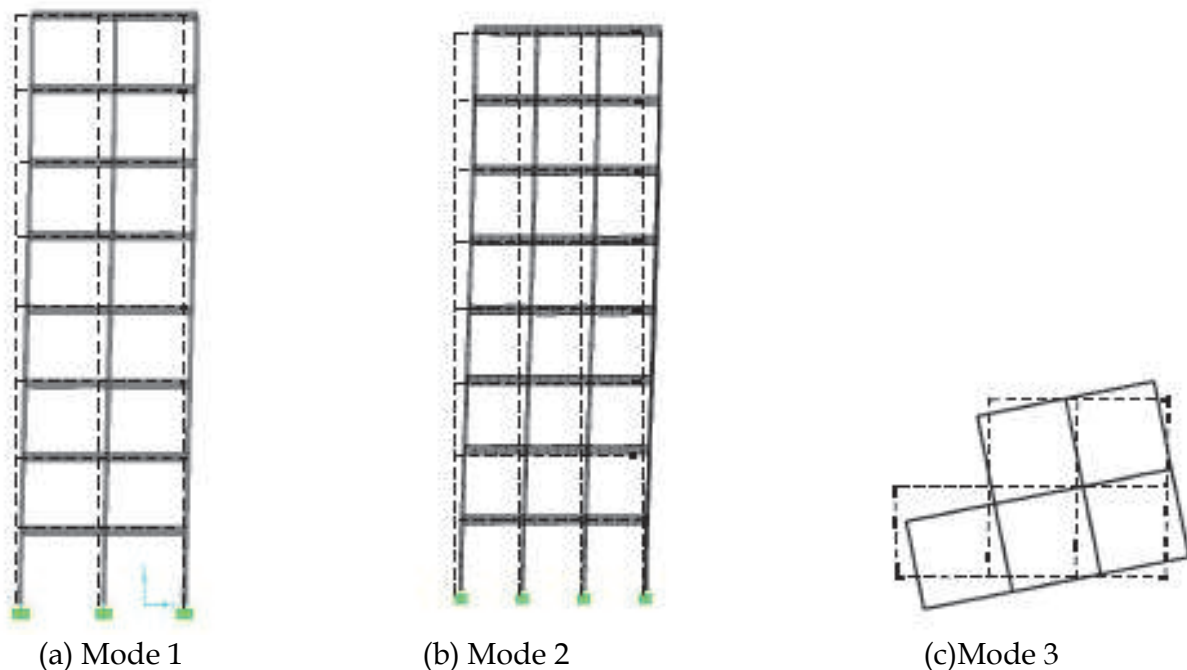


Fig. 16. The first three modes of the structure

Because of plan irregularity substantially more translational and torsional coupling effect is expected in this example. Figure 16 shows the first three modes of vibrations: (a) mode 1 with a frequency of 0.57 Hz, (b) mode 2 with a frequency of 0.72 Hz, (c) mode 3 with a frequency of 0.75 Hz.

3.3 Optimization of the damper parameters

To reduce the torsionally coupled vibration of the 8-story eccentric buildings, two TLCDs are respectively installed on the top story of the structure along x and y direction and one CTLCD on the mass center of the top story. Hence, there are many parameters of the control system to be optimized. The focus of the paper is how to optimize the parameters of liquid dampers to effectively control the dynamical responses of structures. Genetic Algorithm (GA) provides a general framework for the optimization of complicated systems, which is independent of specific areas and robust for the types of problems. In this section, parameters of liquid dampers are optimized by use of GA.

The following form of performance function is used, primarily because it is easy to evaluate the responses of structures

$$f_2 = 1 - \frac{\sqrt{\sum_{i=1}^n (d_x^2 + d_y^2 + d_\theta^2)_{i,\text{controlled}}}}{\sqrt{\sum_{i=1}^n (d_x^2 + d_y^2 + d_\theta^2)_{i,\text{uncontrolled}}}} \quad i = 1, 2, 3, \dots, n \quad (32)$$

where, d_x , d_y and d_θ are the drifts of a story in x , y and torsion direction.

Both, the stochastic model and the design response spectra have been used to define the base input motion. For the stochastic model, the ground motions in x and y directions are described by two identical but uncorrelated zero-mean stationary processes with power spectral density function $\Phi_I(\omega)$ of the Kanai-Tajimi form:

$$\Phi_l(\omega)=\frac{1+4\beta^2\left(\frac{\omega}{\omega_g}\right)^2}{\left[1-\left(\frac{\omega}{\omega_g}\right)^2\right]^2+4\beta^2\left(\frac{\omega}{\omega_g}\right)^2}S_0$$

(33)

The parameters of this function are: $\omega_g = 5\pi$, $\beta = 0.5$, $S_0 = 0.01$.

As mentioned before, two TLCDs and one CTLCD are installed at the top of the building. The objective of the study is to design the optimum parameters of these dampers that would maximize the performance function stated earlier. The possible ranges for the design parameters are fixed as follows:

1. Mass ratio, μ : The mass ratio is defined as the ratio of the damper mass to the total building mass. It is assumed that each damper ratio can vary in the range of 0.1 percent to 1 percent of the building mass. Thus the maximum mass of the damper system consisting of three dampers could be as high as 3 percent of the building mass.
2. Frequency tuning ratio, f : The frequency ratio for each damper is defined as the ratio its own natural frequency to the fundamental frequency of the building structure. Here it is assumed that this ratio could vary between 0-1.5.
3. Damping ratio, d : This is a ratio of the damping coefficient to its critical value. It is assumed that this ratio can vary in the range of 0-10 percent.
4. Damper positions from the mass center, l_x in x axis and l_y : in y axis: It is assumed that l_x can vary between -8 and 5 meters and l_y can vary between -4 and 3 meters

The optimization process starts with a population of these individuals. For the problem at hand, 30 individuals were selected to form the population. The probability of crossover and mutation are 0.95 and 0.05, respectively. The process of iteration is determined to be 300 steps. The final optimum parameters for the two optimum design criteria are given in Table 2.

	Performance Criteria i (f1=0.47769)		
	TLCD in x direction	TLCD in y direction	CTLCD
μ	0.008519	0.0095655	0.0014362
f_r	1.2334	0.96607	1.1137
d_r	0.053803	0.061988	0.052886
l_x	-7.38	0.45567	—
l_y	-6.479	-2.2431	—

Table 2. The optimal parameters of liquid dampers

3.4 Seismic analysis in time domain

The parameters of liquid dampers on the 8-story building structure have been optimized in the previous section and the results are listed in the Table 2. The control results of liquid dampers on the building are analyzed in time domains in this section. The El Centro, Tianjin and Qian'an earthquake records are selected to input to the structure as excitations, which represent different site conditions.

The structural response without liquid dampers subjected to earthquake in x , y and θ directions are expressed with x_0 , y_0 and θ_0 , respectively. Also, the response with liquid

dampers subjected to earthquake in x , y and θ directions are expressed with x , y and θ , respectively. The response reduction ratio of the structure is defined as

$$J = \frac{x_0 - x}{x_0} \times 100\%$$

(34)

The maximum displacements of the structure and response reduction ratios are computed for three earthquake records and the results listed from Table 3 to Table 5. It can be seen

Story Number	x_0 (cm)	x (cm)	J (%)	y_0 (cm)	y (cm)	J (%)	θ_0 (10 ⁻⁴ Rad)	θ (10 ⁻⁴ Rad)	J (%)
1	0.57	0.53	6.14	1.18	0.99	15.94	1.71	1.56	8.77
2	1.11	1.03	7.24	2.28	1.94	15.12	3.30	3.04	7.88
3	1.77	1.58	10.71	3.43	2.96	13.73	5.02	4.61	8.17
4	2.38	2.04	14.20	4.30	3.76	12.59	6.42	5.87	8.57
5	2.98	2.54	15.01	4.95	4.39	11.34	7.62	6.90	9.45
6	3.48	3.03	12.77	5.64	4.69	16.76	8.50	7.46	12.24
7	4.03	3.67	8.86	6.58	4.89	25.64	10.05	8.63	14.13
8	4.37	4.06	7.00	7.10	5.47	22.98	10.96	9.63	12.14

Table 3. Maximum displacements of the structure (El Centro)

Story Number	x_0 (cm)	x (cm)	J (%)	y_0 (cm)	y (cm)	J (%)	θ_0 (10 ⁻⁴ Rad)	θ (10 ⁻⁴ Rad)	J (%)
1	2.49	1.85	25.64	2.10	1.83	12.57	4.67	4.22	9.64
2	4.91	3.66	25.49	4.05	3.52	13.03	9.14	8.25	9.74
3	7.71	5.78	25.06	6.30	5.48	13.12	14.21	12.73	10.42
4	10.26	7.69	24.98	8.36	7.23	13.59	18.83	16.75	11.05
5	12.77	9.58	24.97	10.36	8.90	14.08	23.21	20.60	11.25
6	14.79	11.09	24.97	11.98	10.27	14.25	26.55	23.56	11.26
7	16.88	12.66	24.96	14.10	12.13	13.91	30.45	27.05	11.17
8	17.98	13.51	24.89	15.22	13.41	11.90	32.44	29.02	10.54

Table 4. Maximum displacements of the structure (Tianjin)

Story Number	x_0 (cm)	x (cm)	J (%)	y_0 (cm)	y (cm)	J (%)	θ_0 (10 ⁻⁴ Rad)	θ (10 ⁻⁴ Rad)	J (%)
1	0.11	0.10	6.91	0.10	0.091	6.93	0.132	0.12	4.10
2	0.19	0.17	6.57	0.19	0.16	16.00	0.25	0.24	1.25
3	0.23	0.21	6.66	0.28	0.22	24.60	0.39	0.38	2.82
4	0.24	0.21	11.48	0.38	0.28	25.86	0.51	0.50	1.45
5	0.29	0.22	23.54	0.48	0.36	24.89	0.63	0.61	1.40
6	0.34	0.26	24.76	0.56	0.43	23.54	0.72	0.70	2.20
7	0.39	0.34	14.17	0.70	0.54	21.70	0.83	0.79	4.45
8	0.43	0.39	8.15	0.77	0.62	19.47	0.93	0.87	5.60

Table 5. Maximum displacements of the structure (Qian'an)

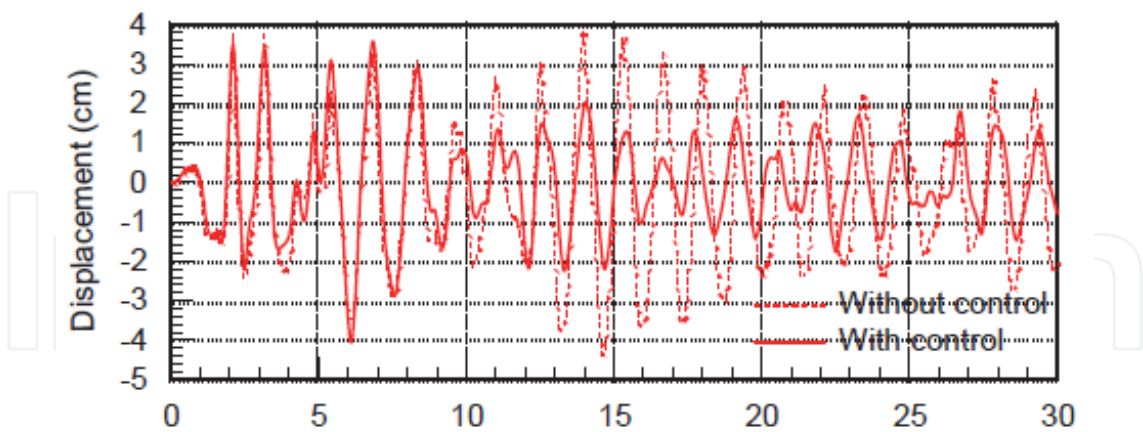


Fig. 17. Time history of the displacement on the x direction of top floor (El Centro)

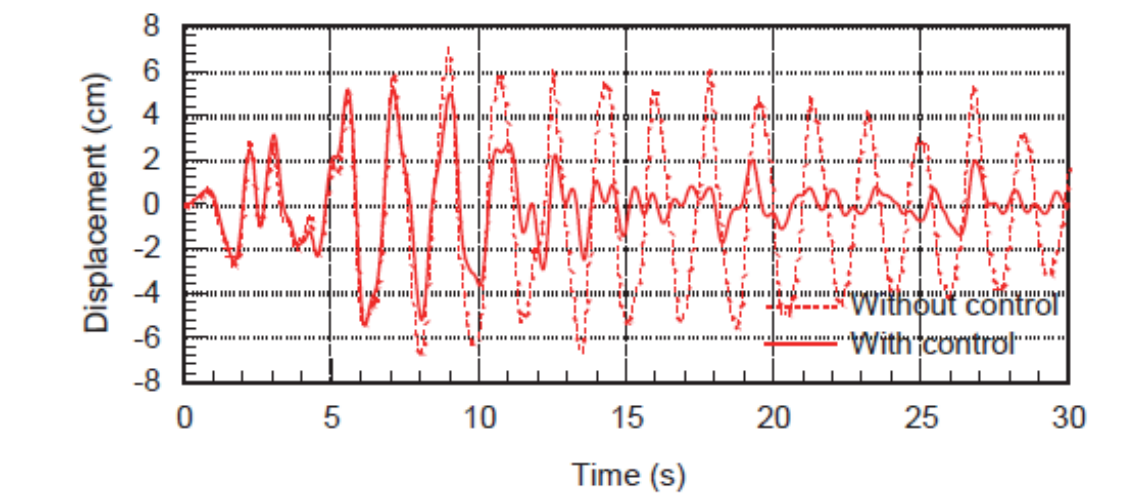


Fig. 18. Time history of the displacement on the y direction of top floor (El Centro)

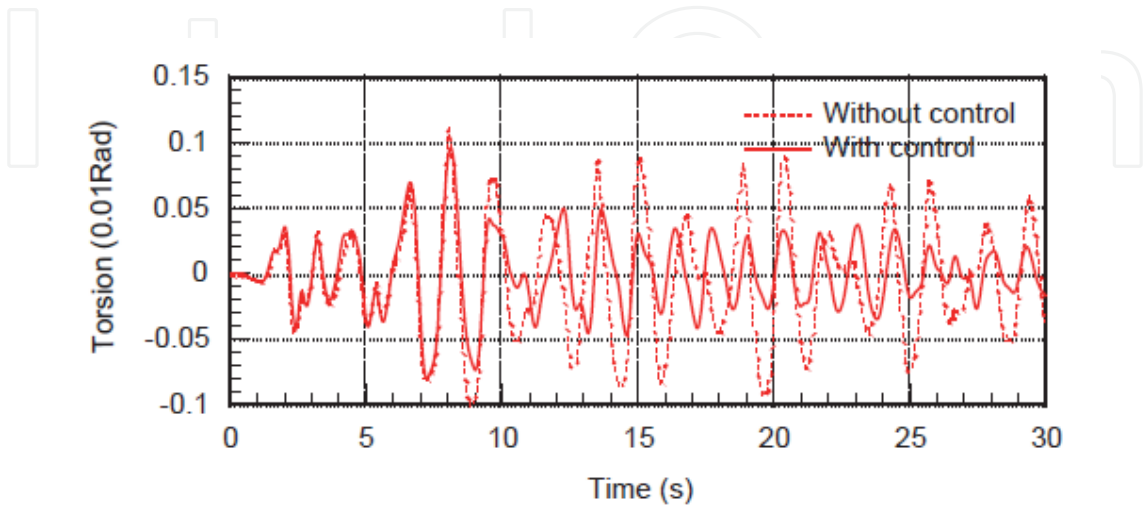


Fig. 19. Time history of the torsional displacement of top floor (El Centro)

from the tables that the responses of the structure in each degree of freedom are reduced with the installation of liquid dampers. However, the reduction ratios are different for the different earthquake records.

The displacement time history curves of the top story are shown from Fig. 6 to Fig. 8 and acceleration time history curves in Fig. 17 to Fig. 19 for El Centro earthquake. It can be seen from these figures that the structural response are reduced in the whole time history.

4. Conclusion

From the theoretical analysis and seismic disasters, it can be concluded that the seismic response is not only in translational direction, but also in torsional direction. The torsional components can aggravate the destroy of structures especially for the eccentric structures. Hence, the control problem of eccentric structures under earthquakes is very important. This paper focus on the seismic response control of eccentric structures using tuned liquid dampers. The control performance of Circular Tuned Liquid Column Dampers (CTLCD) to torsional response of offshore platform structure excited by ground motions is investigated. Based on the equation of motion for the CTLCD-structure system, the optimal control parameters of CTLCD are given through some derivations supposing the ground motion is stochastic process. The influence of systematic parameters on the equivalent damping ratio of the structures is analyzed with purely torsional vibration and translational-torsional coupled vibration, respectively. The results show that Circular Tuned Liquid Column Dampers (CTLCD) is an effective torsional response control device. An 8-story eccentric steel building, with two TLCDs on the orthogonal direction and one CTLCD on the mass center of the top story, is analyzed. The optimal parameters of liquid dampers are optimized by Genetic Algorithm. The structural response with and without liquid dampers under bi-directional earthquakes are calculated. The results show that the torsionally coupled response of structures can be effectively suppressed by liquid dampers with optimal parameters.

5. Acknowledgment

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