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Experimental study of controllable MR-TLCD applied to the mitigation of structure vibration

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Abstract. MR-TLCD (Magneto-Rheological Tuned Liquid Column Damper) is a new developed vibration control device, which combines the traditional passive control property with active controllability advantage. Based on traditional TLCD governing equation, this study further considers MR-fluid viscosity in the equation and by transforming the non-linear damping term into an equivalent linear damping, a solution can be obtained. In order to find a countable set of parameters for the design of the MR-TLCD system and also to realize its applicability to structures, a series of experimental test were designed and carried out. The testing programs include the basic material properties of the MR-fluid, the damping ratio of a MR-TLCD and the dynamic responses for a frame structure equipped with the MR-TLCD system subjected to strong ground excitations. In both the analytical and experimental results of this study, it is found that the accurately tuned MR-TLCD system could effectively reduce the dynamic response of a structural system.

Keywords: MR-TLCD; viscosity of MR-fluid; vibration mitigation; shaking-table testing on TLCD; magnetic power control

1. Introduction

TLCD (tuned liquid column damper) system is a device by utilizing the water sloshing power contained in a U-shape tube to reduce the vibrations of the main structure induced from environmental loadings. This device has been utilized in traditional civil structures such as the application to structures in Sakitama Bridge and Shin Yokohama Prince Hotel in Japan, where the effectiveness for the vibration reduction was also verified (Fujino and Sun 1993). TLCD was extended from TLD (tuned liquid damper) device, which is a container (not necessary a tube form) full of water that sloshes during the vibration of the main structure and then mitigates the vibration due to the phase difference of vibrations. TLD were widely discussed and studied in late 80s and early 90s (Fujino *et al.* 1988, 1992, Chaiseri *et al.* 1989). TLCD is a U-shape tube-like device that consists of water or similar liquid. The liquid passing through a small orifice opened at the center of cross section of the tube causes the hydraulic head loss of the liquid and then reduces the vibration of the main structure attached. Sakai *et al.* (1989) firstly studied the hydraulic head loss of the liquid induced from the orifice at the cross section that has damping effect. In the study for

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the application of the TLCD system to the tower type structure, Balendra *et al*. (1995) provided a relationship between the tower height and the opening ratio for the orifice. Won *et al.* (1996) also studied the application of TLCD system to the multi-degree-of-freedom structures by using random vibration analysis for the earthquake excitation.

Subsequently, many improvement ideas for the TLCD system have been proposed such as the variable orifice system or so called pressure control mechanism (Kareem et al. 1995) and the studies on the characteristics of variable cross section between the horizontal and vertical tube (Hichhock *et al*. 1997a, b, Gao and Kwok 1997). Gao and Kwok found from their numerical study that the increase of the cross section of horizontal tube might reduce the liquid column in the vertical tube and the optimal parameters could be obtained to reduce the amplification factor when the structure subjected to a harmonic vibration. In a recent study, a typical tension-leg type of floating platform (TLP) incorporated with a TLCD system was developed (Lee *et al.* 2006). The corresponding theoretical derivation and experimental verification were both performed. It was found that TLCD was an effective and economic means to reduce the wave induced vibrations of the floating offshore platform system. This study was further developed into an underwater form (UWTLCD) that may more effectively work and yet, reduce the burden weight on the platform system (Lee and Juang 2012). If necessary, the UWTLCD (underwater TLCD) can be designed to combine the buoyant device or pontoon system such that one device may have multipurpose function.

The effectiveness of TLCD to mitigate vibrations of structures induced from many kinds of excitations appears very encouraging, particularly during the resonant frequency vibrations. However, some drawbacks also exist in a TLCD system to limit its wider applications. The first disadvantage is its “tunable” but not “controllable” characteristic that defines its passive feature. The functionability of a TLCD system is solely determined in the design stage, where a TLCD is tuned to the best performance along with the dynamic characteristics of the main building. The second disadvantage is the low viscosity of the water in the TLCD tube that may slosh turbulently during a strong vibration and then lower its function. This phenomenon was also observed during the experimental test of this study. Therefore, some schemes to enhance the function of a TLCD system, particularly the efforts to make it an active damper were proposed in many ways such as the size of orifice was made controllably changeable (Haroun 1995) or the ratio of orifice opening to the cross section of the tube was made variable (Yalla 2001). The most impressive improvement that could improve both the controllability of a TLCD system and the stability of the fluid filled in the tube might be the development of a MR-TLCD system (Ni *et al.* 2004, 2005). The MR-TLCD (magneto-rheological TLCD) utilizing the sloshing power of a fluid with magnetic property to reduce the vibration of the main structure is a newly developed device that could effectively reduce the vibrations for many kinds of structure. The application of magneto-rheological (MR) properties in fluid could be found as early as in 1960s (Pappel 1965) when a MR-fluid was developed to control the flow-ability of liquid-fuel in rocket in outer-space missions. However, the research to utilize the controllable properties of a MR-fluid to apply to structural vibration mitigation did not appear until 2000s.

The direction of research for the application of MR-fluid may be divided into two parts, namely, the MR-damper and the MR-TLCD research. The research team of Jung and Choi (Jung *et al.* 2006, Choi *et al.* 2007) studied a MR damper-based smart passive control system for seismic protection of building structures. They proposed a system that a permanent magnet and a coil were designed to able to convert the kinetic energy of the relative motion between a building and a damper into electric energy to vary damping characteristics of the MR damper. A numerical study was carried out for smart base isolation system with MR damper (Fu *et al*. 2012). A smart base isolation system is an enhancement to a traditional isolation system - a rubber bearing base isolation system with MR damper. A similar study was also carried out for vibration control analysis of seismic response using MR dampers in the elevated highway bridge structures (Yan and Zhang, 2005).

The other application for the MR-fluid is the utilization of the fluid to a TLCD system as so-called MR-TLCD system. The most active group on the study of a MR-TLCD system can be credited to Ni and his team. Ni studied an optimal control system for wind-excited tall buildings by using semi-active MR-TLCDs in which he proposed a scheme of modeling and analysis of open-loop control for vibration mitigation of tall buildings (Ni *et al*. 2004, 2005). As we observed, although the results from the study for a MR-TLCD system were somewhat encouraging, more extensive studies are still needed such as problems related to the varieties of structures, interactions of fluid properties to the structural responses and the control scheme between the MR-fluid and the applied magnetic power. Experimental researches are also needed while most available studies are mainly focused on the theoretical developments and numerical analysis.

This study focuses on both the material properties and the application of the MR-TLCD to the structure. Based on traditional TLCD governing equation, this study further considers MR-fluid viscosity in the equation and by transforming the non-linear damping term into equivalent linear damping term a solution can be obtained. In order to find a countable set of parameters for the MR-TLCD system and to realize its applicability to structures, a series of experimental test were designed and carried out. The variation of free surface of the MR-liquid in the column was measured through high speed digital camera system and then analyzed to obtain the damping ratio. The MR-TLCD with optimum designed damping ratio corresponding to the main structure system then can be obtained. A shaking-table test was carried out subsequently for the structure equipped with MR-TLCD system. Comparisons for the mitigation performance among traditional TLCD, uncontrolled MR-TLCD and controlled MR-TLCD systems are also presented. In both the analytical and experimental results of this study it is found that the accurately tuned MR-TLCD system could effectively reduce the dynamic response of structural system in terms of both the maximum and average vibration amplitude induced from strong ground motion.

2. Theoretical derivation

In the theoretical background, the theorems for the traditional TLCD system were introduced firstly, and then the equations of motion for the response of a structure of single degree of freedom equipped with the TLCD system was presented. The magnification factors for the responses of the TLCD and the structure of the system were derived corresponding to various damping ratios. Subsequently,an optimum damping was obtained and accordingly used for the design of a MR-TLCD system, of which the related theoretical equations were also presented in this section.

2.1 Magnification factor for a SDOF system equipped with TLCD

The equation of motion for a typical TLCD system can be presented (Sakai *et al*. 1989, Lee and Juang 2012) as

$$\rho AL\ddot{y} + \frac{1}{2}\rho A\delta|\dot{y}|\dot{y} + 2\rho Agy = -\rho AB\ddot{x} \tag{1}$$

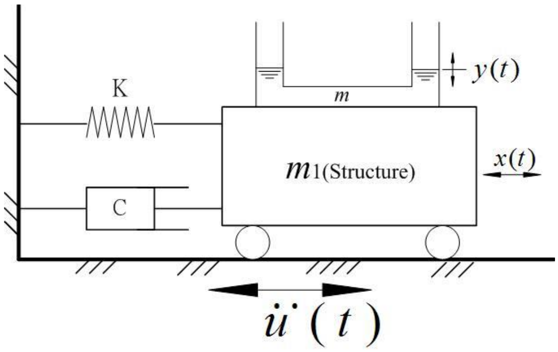


Fig. 1 A single degree of freedom system installed with TLCD

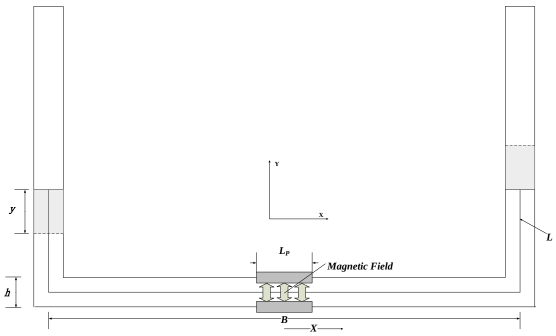


Fig. 2 MR-TLCD system with magnetic force control

where parameter *A* represents the inner area of cross section of the tube, *B* is the dimension of the horizontal portion of the tube, *g* is the gravitational constant, *L* is the total length of the liquid filled in the tube. Parameter ρ is the density of liquid filled in the tube and δ is the loss of water head. The displacement of the TLCD system is represented by *x* and *y* is the surface elevation of liquid in the tube. Their corresponding velocity and acceleration are denoted with dot and double dot overhead. The equation of motion can further be simplified by applying linearlization scheme to the second nonlinear term as

$$m\ddot{y} + c\dot{y} + m\omega_u^{\ 2} y = -m\alpha\ddot{x} \tag{2}$$

where $m = \rho AL$ is the mass of the liquid in the tube; $\alpha = \dfrac{B}{L}$ represents the length ratio between the horizontal part and the full length of the tube and damping coefficient $c = 2\xi\omega_u$, where ξ is the damping ratio and ω_u is the natural frequency, $\omega_u = \sqrt{2g/L}$. Now by installing the TLCD system on a primary structure of SDOF subjected to ground vibration $\ddot{u}$, the equation of motion can be modeled into a two degree of freedom system (Xue *et al*. 2000, Lee *et al*. 2006)

$$\begin{bmatrix} m & m\alpha \\ m\alpha & M \end{bmatrix}\begin{Bmatrix} \ddot{y} \\ \ddot{x} \end{Bmatrix}+\begin{bmatrix} c & 0 \\ 0 & C \end{bmatrix}\begin{Bmatrix} \dot{y} \\ \dot{x} \end{Bmatrix}+\begin{bmatrix} m\omega_u^2 & 0 \\ 0 & K \end{bmatrix}\begin{Bmatrix} y \\ x \end{Bmatrix}=\begin{bmatrix} -m\alpha \\ -M \end{bmatrix}\ddot{u}(t) \tag{3}$$

where M is the mass of main structure including the TLCD; K and C is the stiffness and damping coefficient of the main structure. After dimensionless application to coefficients of each term of the equation divided by mass M, the system of equation becomes

$$\begin{bmatrix} \frac{m}{M} & \frac{m}{M}\alpha \\ \frac{m}{M}\alpha & 1 \end{bmatrix}\begin{Bmatrix} \ddot{y} \\ \ddot{x} \end{Bmatrix}+\begin{bmatrix} \frac{c}{M} & 0 \\ 0 & \frac{C}{M} \end{bmatrix}\begin{Bmatrix} \dot{y} \\ \dot{x} \end{Bmatrix}+\begin{bmatrix} \frac{m}{M}\omega_u^2 & 0 \\ 0 & \frac{K}{M} \end{bmatrix}\begin{Bmatrix} y \\ x \end{Bmatrix}=\begin{bmatrix} -\frac{m}{M}\alpha \\ -1 \end{bmatrix}\ddot{u}(t) \tag{4}$$

Let $\frac{K}{M}=\omega_p^2$; $\frac{m}{M}=\mu^2$, then $C=2\eta\omega_p M$ and $c=2\xi\omega_u m$, where ω_p and η is the natural frequency and damping ratio of the main structure while ω_u and ξ is the frequency and damping ratio of TLCD. After rearrangement, a simplified equation system is obtained as

$$\begin{bmatrix} \mu^2 & \alpha\mu^2 \\ \alpha\mu^2 & 1 \end{bmatrix}\begin{Bmatrix} \ddot{y} \\ \ddot{x} \end{Bmatrix}+\begin{bmatrix} 2\xi\omega_u\mu^2 & 0 \\ 0 & 2\eta\omega_p \end{bmatrix}\begin{Bmatrix} \dot{y} \\ \dot{x} \end{Bmatrix}+\begin{bmatrix} \mu^2\omega_u^2 & 0 \\ 0 & \omega_p^2 \end{bmatrix}\begin{Bmatrix} y \\ x \end{Bmatrix}=\begin{bmatrix} -\mu^2\alpha \\ -1 \end{bmatrix}\ddot{u}(t) \tag{5}$$

If a harmonic excitation of frequency ω is input into the system, then the response of the system can be assumed as a harmonic form as

$$\begin{Bmatrix} y \\ x \end{Bmatrix}=\begin{Bmatrix} Y \\ X \end{Bmatrix}e^{i\omega t} \tag{6}$$

After carrying out the derivation for the responses and substituted back into Eq. (5) and solving for it, we may obtain a set of complex responses such that

$$\begin{Bmatrix} X \\ Y \end{Bmatrix}=\begin{Bmatrix} \dfrac{1-\gamma^2+2i\xi\gamma+\alpha^2\mu^2\gamma^2}{\omega_p^2\left[(1-\beta^2+2i\eta\beta)(1-\gamma^2+2i\xi\gamma)-(\alpha\mu\beta\gamma)^2\right]} \\ \dfrac{\alpha(1+2i\eta\beta)}{\omega_u^2\left[(1-\beta^2+2i\eta\beta)(1-\gamma^2+2i\xi\gamma)-(\alpha\mu\beta\gamma)^2\right]} \end{Bmatrix} \tag{7}$$

where $\beta=\frac{\omega}{\omega_p}$, $\gamma=\frac{\omega}{\omega_u}$ and $f=\omega_u/\omega_p$ is the ratio of frequency between the TLCD system and the primary (main) structure

The magnification factor defined as the amplitude of dynamic response to the static response δ_{st} for the main structure becomes a form as

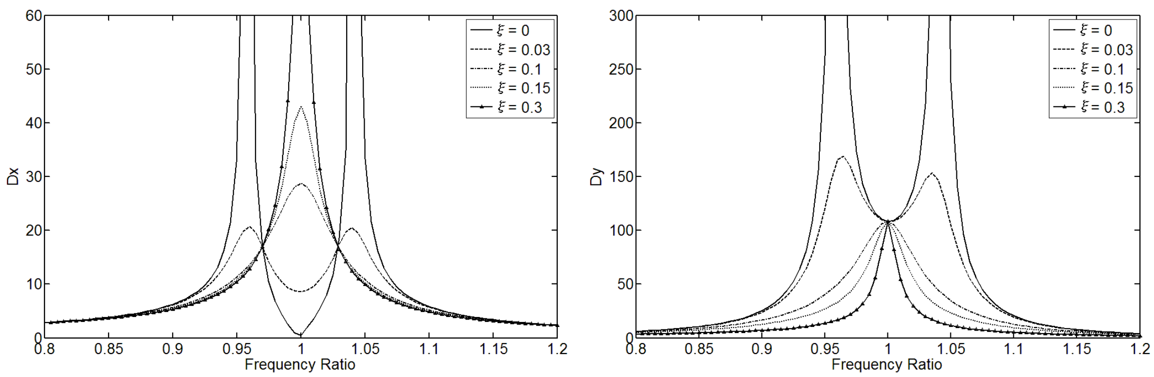
$$D_X = \frac{|X|}{\delta_{st}} = \left| \frac{(1-\gamma^2+\alpha^2\mu^2\gamma^2)+i(2\xi\gamma)}{\left[(1-\beta^2)(1-\gamma^2)-(\alpha\mu\beta\gamma)^2+i(1-\beta^2)(2\xi\gamma)\right]} \right|$$

$$= \left\{ \frac{(1-\gamma^2+\alpha^2\mu^2\gamma^2)^2+(2\xi\gamma)^2}{\left[(1-\beta^2)(1-\gamma^2)-(\alpha\mu\beta\gamma)^2\right]^2+\left[(1-\beta^2)(2\xi\gamma)\right]^2} \right\}^{\frac{1}{2}} \tag{8}$$

Similarly, the magnification factor for the fluid motion of the TLCD can be presented as

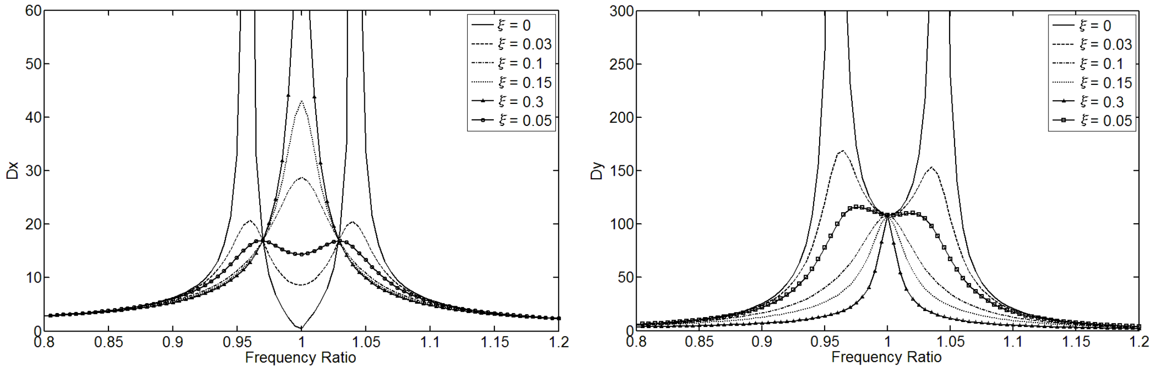
$$D_Y = \left\{ \frac{\alpha^2}{\left[(1-\beta^2)(f^2-\beta^2)-(\alpha\mu\beta^2)^2\right]^2+\left[(1-\beta^2)(2\xi f\beta)\right]^2} \right\}^{\frac{1}{2}} \tag{9}$$

A set of curves for the magnification factor of both primary structure and the TLCD are obtained corresponding to various damping factors ξ as shown in Fig. 3(a) and 3(b), where parameters of the TLCD are determined based on the testing model such that μ^2 = 0.0123; α = 0.733. Some significant differences between these two figures are observed. For the magnification factor of primary structure as shown in Fig. 3(a), two points located on the side evenly larger or smaller than the resonant frequency are always crossed by the curves of magnification factors with various damping ratio. It is obvious that any value of magnification factor lower than these two points will be in the range of optimum damping. On the other hand, as shown in Fig. 3(b), there is only one point crossed by curves for the magnification factor of TLCD that is on the frequency resonant to the primary structure. Secondly, as is observed in Fig. 3(b), corresponding to a larger damping ratio, the mitigation factors always become smaller, but however, for the response of main structure as shown in Fig. 3(a), the reduction of mitigation effect seems not corresponding to the variation of damping ratio. In the case of 30% damping ratio, the response in the resonant frequency seems not able to be suppressed effectively.



(a) with various damping ratio (D_X) (b) with designed damping ratio (D_Y)

Fig. 3 Magnification factor for the structure



(a) with various damping ratio (D_X) (b) with designed damping ratio (D_Y)

Fig. 4 Magnification factor for the structure

To find an optimum value of damping ratio that is effective on both the structure and the damper system, ξ is presented as a function of magnification factor and parameters of structure properties by rewriting equation (8) into an equation such that a square of the damping ratio as

$$\xi^2 = \frac{\left[(1-\beta^2)(f^2-\beta^2)-(\alpha\mu\beta^2)^2\right]^2 D_X^2 - (f^2-\beta^2+\alpha^2\mu^2\beta^2)^2}{(2f\beta)^2 - \left[(1-\beta^2)(2f\beta)\right]^2 D_X^2} \tag{10}$$

It appears that after application of related structure parameters for the determined value of μ and α, which is obtained from the proposed testing structural system, and solving Eq. (10) for the damping ratio, ξ = 5.02%. The magnification factors for both the main structure and the TLCD are shown in Figs. 4(a) and 4(b), respectively. The magnification factor are clearly under control as shown in the figure, where the magnification factors for both the main structure and TLCD response are both well below the crossed point in the vicinity of resonant frequency. Therefore, in the following testing set-up for the design of MR-TLCD, a similar damping ratio was proposed and tested.

2.2 Damping ratio for a MR-TLCD system

For a typical TLCD damper filled with viscous fluid, the governing equation can be modified as (Sakai 1989; Ni et al. 2004, 2005)

$$\rho AL\ddot{y} + \frac{1}{2}\rho A\delta|\dot{y}|\dot{y} + \frac{c_v\tau_y AL_p}{h}\frac{\dot{y}}{|\dot{y}|} + 2\rho gAy = -\rho AB\ddot{x} \tag{11}$$

It is noticed that the influence due to the viscosity of magneto-rheological fluid is presented in the third term of the equation while the other terms are similar to a traditional TLCD without orifice. The influence of the magneto-rheological fluid in a TLCD system relates to the yielding shear stress induced by the magnetic field τ_y ; the magnetic field influence range of the tube L_P ; the height of the fluid in the vertical tube h; the velocity coefficient c_v and the area of cross section of the tube.

For the nonlinear expression in the second term of the equation of motion, a linearlization scheme was performed by applying an equivalent damping coefficient $\boldsymbol{c_d}$ for the second and third term in the equation so that Eq. (11) could be rewritten into a form as

$$\rho AL\ddot{y}+c_d\dot{y}+2\rho Agy=-\rho AB\ddot{x} \tag{12}$$

To minimize the error induced from the linearlization process, a difference between Eqs. (11) and (12) can be found as ε and presented as

$$\varepsilon=\frac{1}{2}\rho A\delta\left|\dot{y}\right|\dot{y}+\frac{c_v\tau_y AL_p}{h}\frac{\dot{y}}{\left|\dot{y}\right|}-c_d\dot{y} \tag{13}$$

By minimizing the difference ε using the least square method such as E[ε^2] the mean value of square of the difference, the equivalent damping coefficient $\boldsymbol{c_d}$ can be found from following differentiation

$$\frac{d(E\left[\varepsilon^2\right])}{dc_d}=0 \tag{14}$$

After substitution of Eqs. (13) into (14), the equivalent damping coefficient c_d is found as

$$c_d=\sqrt{\frac{2}{\pi}}\rho A\delta\sigma_{\dot{x}}+\sqrt{\frac{2}{\pi}}\frac{c_v\tau_y AL_p}{h\sigma_{\dot{x}}} \tag{15}$$

The equivalent-damping ratio can be presented as a ratio between the damping coefficient and the critical damping as

$$\xi_d=\frac{c_d}{2\rho AL\omega_d}=\frac{1}{2\sqrt{\pi gL}}\left(\delta\sigma_{\dot{x}}+\frac{c_v\tau_y L_p}{\rho h\sigma_{\dot{x}}}\right) \tag{16}$$

where $\sigma_{\dot{x}}$ is the standard deviation of fluid velocity in the tube. After realization for the parameters presented in Eq. (16) from experimental tests, the equivalent-damping ratio ξ_d is ready to be obtained. Since the damping ratio has been proposed to be 5.02%, during the optimum design process for a two-degree freedom of system for a main structure equipped with a damper system, by applying parameters in Eq. (16), a series of MR-TLCD were designed and tested.

3. Testing for viscosity property of MR-fluid and damping ratio for MR-TLCD

In addition to the dimensions of the device, the influential parameters to the damping ratio of a MR-TLCD will mainly be the properties of the magneto-rheological fluid (MR-fluid), including viscosity, density and the applied magnetic field influence on the fluid. The base liquid applied in a MR-TLCD device is magneto-rheological fluid (MR-fluid). Basically, it is composed of silicate oil of various viscosities and iron-particles with size about 7 μ m. The viscosity of the MR-fluid will be influenced by the strength of the magnetic power and the content-fraction of iron-particles mixed in the fluid. In terms of the composition of a MR-fluid, the most important parameters are the content fraction of the iron-particles in the fluid and the viscosity of the fluid. Therefore, in order to understand the variation of viscosity property of MR-fluid that contains various percentages of iron-particles subjected to controlled magnetic forces, experimental tests were designed and performed by measuring the viscosity of the fluid and the damping ratio of MR-TLCD.

3.1 Viscosity testing for MR-Fluid

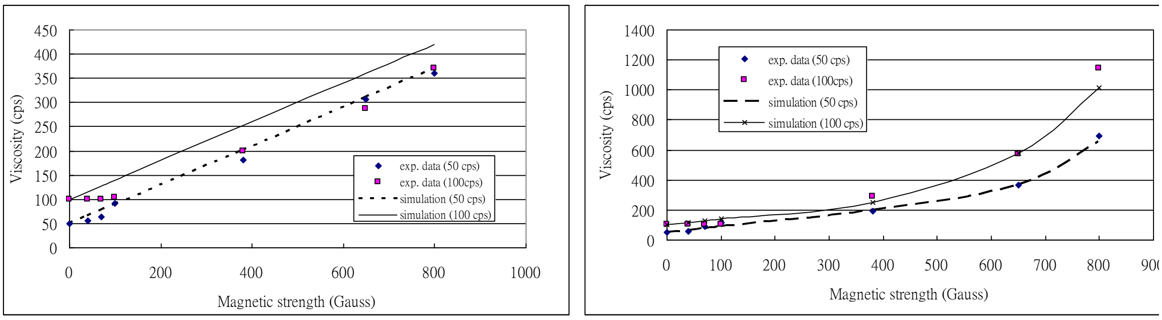
For the viscosity test, three levels of percentage of iron-particles, namely, 0%, 10% and 20% (in terms of weight ratio) are contained in the MR-fluid for each level of designed viscosity. The MR-fluid was originally designed with two levels of viscosity, which are 50 cps and 100 cps (centipoises, 1 cps = 1 MPa · s). The MR-fluid containing various iron-particles was tested for the variation of its viscosity when magnetic force was applied in various levels of strength up to 800 Gauss.

Shown in Figs. 5(a) and 5(b) are the test results of variation of viscosity for MR-fluid subjected to various magnetic forces, where 10% and 20% iron-particle are contained in the fluid, respectively. It shows that corresponding to the increase of applied magnetic strength, the viscosity of the MR-fluid will increase. However, when the content of iron-particle is 0%, no matter how strong the magnetic power is applied, the viscosity of the fluid remains unchanged. It also shows that when the content-fraction of iron-particles is larger, the influence on the viscosity by magnetic power becomes more significant.

For the fluid with 10% content-fraction of iron-particle as shown in Fig. 5(a), the increase ratio of the viscosity seems to be in a linear relationship with respect to the increase of the magnetic power. A linear relationship between viscosity variation and the applied magnetic strength is obtained from the curve-fitting scheme as

$$f = 0.4x + f_0 \tag{17}$$

where f is the viscosity and f_0 is the original initial viscosity before the application of magnetic power while x is the applied magnetic strength. Observed from Fig. 5(a), the variation of viscosity is not significantly influenced by the initial value. Therefore, Eq. (17) may appropriately represent the viscosity variation for an MR-fluid with 10% iron-particle content corresponding to the increase of magnetic power up to 800 Gauss.



(a) with 10% iron-particle (b) 20% iron-particle

Fig. 5 Viscosity variation for MR-fluid subjected to various magnetic forces

Shown in Fig. 5(b) is the variation of the experimental data of the viscosity that increases nonlinearly corresponding to the magnetic power increment, when the content-fraction of the iron-particle is 20% in the fluid. Simulations were also performed for the viscosity varied with respect to the magnetic power for this case while the initial value is 50 cps and 100 cps, respectively. In the simulation, for low magnetic strength, the viscosity of MR-fluid is linearly corresponding to the increase of magnetic power, but however, in the high magnetic strength (> 650 cps), the variation of viscosity is nonlinearly related to the magnetic power as a cubic polynomial function as

$$f = \begin{cases} 0.4x + f_0, & x < 650cps \\ 1.06x - 0.0031x^2 + 0.0000034x^3, & x \geq 650cps \end{cases} \tag{18}$$

As shown in Fig. 5(b), the solid-line and dash-line are corresponding to the MFR-fluid with initial viscosity of 50 cps and 100 cps, respectively, where a good agreement to the experimental result is shown in the figure.

3.2 Damping ratio testing for MR-TLCD

The damping ratio of the MR-TLCD composed of various percentages of iron-particles and viscosities of fluid was tested when various magnetic forces were applied to the horizontal section of the tube. During the test, the free surface level of MR-fluid was measured when the MR-TLCD was subjected to a harmonic excitation of frequency ω. Shown in Fig. 6 is the actual variation of free surface of MR-fluid in a TLCD during the tests, where four consecutive images of the fluid level from high-speed camera were shown. The variation of the fluid surface levels was drawn into figures corresponding to time eclipsed.

The variation in free surface level related to the damping property of the fluid can be presented as

$$y(t) = Ye^{-\omega_n \xi t}\cos(\omega_d t) \tag{19}$$

where Y is the initial level of the free surface of fluid, ω_n is the natural frequency of the MR-TLCD; ξ the damping ratio. Parameter ω_d is the damped frequency of the system such that $\omega_d = \omega_n\sqrt{1-\xi^2}$. Typical time histories of free surface variation for fluid with various particle contents and viscosities were tested. The magnetic power with strengths varied from 0 Gauss to 240 Gauss was applied as a control force that would change the viscosity as was shown in Fig. 5. A list of parameters for the damping-ratio test of MR-TLCD system are shown in Table 1.

Table 1 Parameters for the damping ratio test

parameter	value	parameter	value
ω_n	5.11 rad/s	L	0.75 m
L_p	0.01 m	B	0.55 m
ρ	1200 kg/m^3	c	3.07
Y	0.1 m	h	0.05 m
A	0.0025 m^2		

Fig. 6 The consecutive images for the variation of free surface of MR-fluid under test

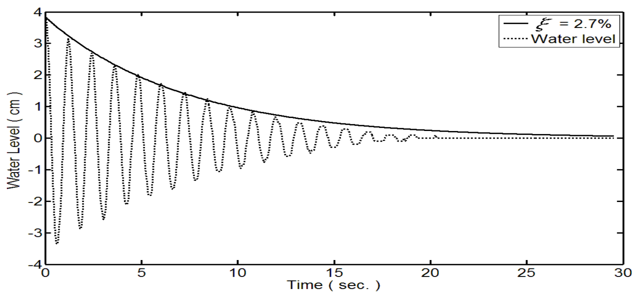


Fig. 7 Free vibration of traditional TLCD

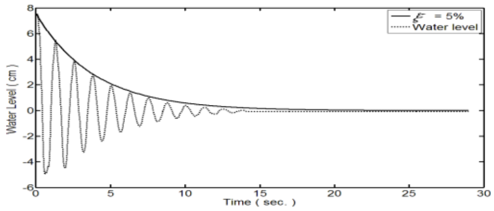
In addition to testing groups for the MR-TLCD, a reference test for a traditional TLCD system with only water in tube was carried out and the test results were shown in Fig. 7. It appears to be that the water without addition of iron-particles and additional viscosity has the lowest damping ratio $\xi = 2.7\%$.

The experimental results for three sets of MR-TLCD system tested under various magnetic powers were shown in Figs. 8-10, respectively, where fluid contained with various fractions of iron-particle and viscosities is taken into consideration. For set-1 MR-TLCD as presented in Fig. 8, the content of iron-particle in the fluid is 10% and the viscosity of fluid is 10 cps. For set-2 MR-TLCD as presented in Fig. 9, the content of iron-particle in the fluid is 20% while the viscosity of fluid is 50cps. For set-3 MR-TLCD as presented in Fig. 10, similarly, the content of iron-particle is 20% but the viscosity of the fluid is 100 cps.

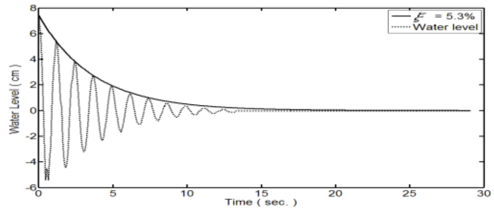
Fig. 8(a) shows the response of 10% iron-particle, 10 cps MR-fluid without any magnetic force control while Figs. 8(b) and 8(c) are responses for the MR-fluid subjected to 40 Gauss and 60 Gauss magnetic force, respectively. For the fluid slightly modified with little MR-properties (10% iron-particle and 10cps viscosity) as observed in Fig.8, compared to Fig. 7, the damping ratio is about double that of TLCD. In this testing case for MR-TLCD, the damping is slightly increased when the magnetic force is applied such that increased from 5.0% to 5.3% when 40 Gauss magnetic force is applied and increased by 5.5% when 60 Gauss is applied.

Similarly, Fig. 9(a) is the response of free vibration for the MR-TLCD for the 20%, 50 cps fluid without any magnetic force control while Figs. 9(b) and 9(c) are responses for the 20%, 50cps fluid subjected to 40 and 60 Gauss magnetic force, respectively. Compared to Fig. 7 for a TLCD response, the damping ratio is significantly increased even without application of a magnetic power. When the magnetic force is applied, the damping ratio slightly increased from 11% to 12% when 40 Gauss magnetic force is applied and increased to 12.5% when 60 Gauss is applied.

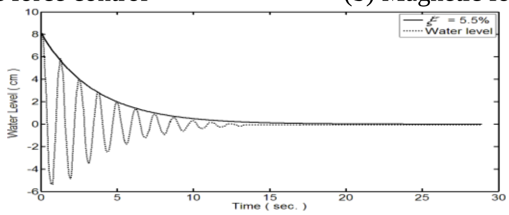
Result shown in Fig. 10(a) is the case without any control of magnetic force, while Figs. 10(b) and 10(c) are controlled by 60 Gauss and 240 Gauss magnetic force, respectively. The damping ratio was raised to 23% from 19% when the controlled magnetic force was increased to 60 Gauss than the one without magnetic force control. It is noticed from the cases shown in Figs. 8 and 9 that the influence from small magnetic force is minor in terms of raising the damping of a MR-TLCD system, but however, as was shown in the viscosity test for MR-fluid, the viscosity can be significantly raised when the strength of the magnetic force was enhanced. Therefore, in this case, as was shown in Fig. 10(c), the controlled magnetic force was largely raised to 240 Gauss and the damping ratio of the MR-TLCD is also significantly raised to 29%, which is 52.6% increment.



(a) Without magnetic force control

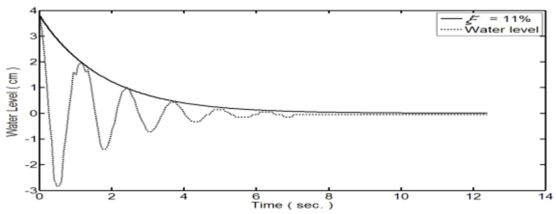


(b) Magnetic force control - 40 Gauss

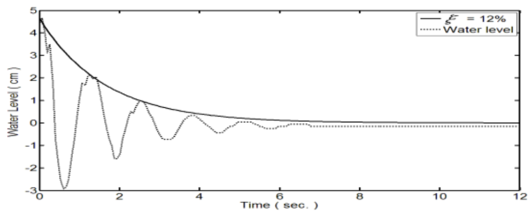


(c) Magnetic force control - 60 Gauss

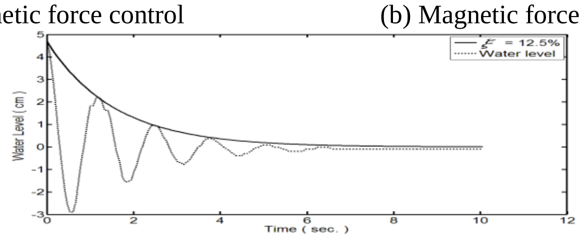
Fig. 8 Free vibration of MR-TLCD with/without magnetic force control (10%, 10cps)



(a) Without magnetic force control

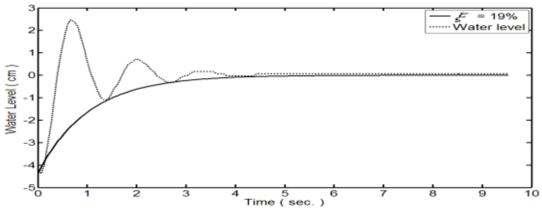


(b) Magnetic force control - 40 Gauss

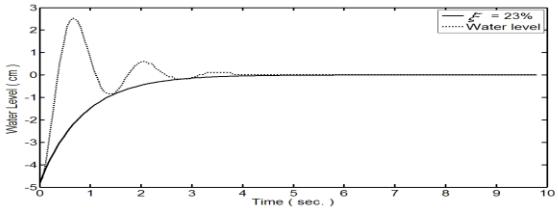


(c) Magnetic force control - 60 Gauss

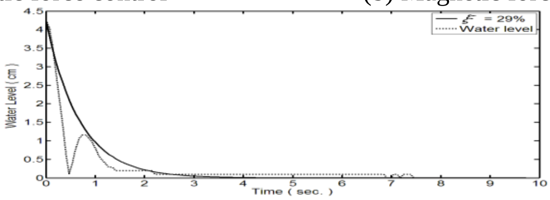
Fig. 9 Free vibration of MR-TLCD with/without magnetic force control (20%, 50cps)



(a) Without magnetic force control



(b) Magnetic force control - 60 Gauss



(c) Magnetic force control - 240 Gauss

Fig. 10 Free vibration of MR-TLCD with/without magnetic force control (20%, 100cps)

4. Shaking table test for structure equipped with MR-TLCD

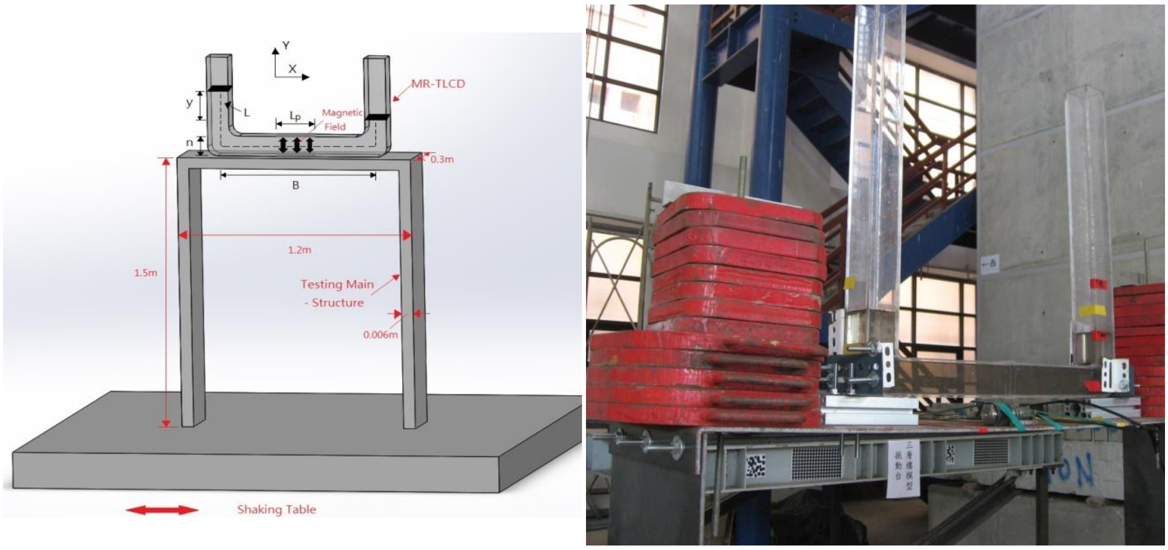
The main purpose for the shaking table test is to find the response mitigation effectiveness of MR-TLCD to the primary structure and the comparison to traditional TLCD during an excitation similar to ground motion, which may be induced from earthquake, traffic impact or operation of machines. In the following presentations, as proposed, two sets of amplitude of ground motions are applied, namely 0.25mm and 0.50mm and therefore, the testing results are divided into two parts and discussed as follows.

4.1 Testing set-up of shaking table test

A SDOF structural system was designed such that an one-bay steel frame with lumped mass on the top was equipped with a TLCD or MR-TLCD system. This SDOF structure equipped with MR-TLCD was installed at a shaking table to test. The testing sequence includes following investigations: (1) response for structure without any damping devices; (2) response for structure equipped with TLCD; (3) response for structure equipped with MR-TLCD but without magnetic force control; (4) response for structure equipped with MR-TLCD and with magnetic force control. The shaking-table is located at NKFUST, Taiwan, of which the table area is 3 m×3 m with 10-ton load capacity. The table-equipped actuator has capacities of 15-ton maximum output force, 1G maximum acceleration and 250 mm maximum stroke. A schematic drawing showing the testing set-up of a frame-structure equipped with MR-TLCD ready to be tested on the shaking-table is presented in Fig. 11(a). Fig. 11(b) is the photograph showing the complete testing set-up installed in the structure testing lab.

In order to find the mitigation effect during the resonant vibration, the primary structure was designed to be soft enough to have natural frequency that is close to the one for a TLCD or MR-TLCD system. During the pretest run, observed from the free vibration time-history and corresponding spectrum, the natural frequency of the primary structure the SDOF steel frame system was obtained as 0.85 Hz while the frequency of the MR-TLCD is 0.814 Hz.

A damping ratio close to ξ = 5% was proposed, as was found in the analysis of magnification factor, for both the TLCD and MR-TLCD system without control of magnetic force and therefore, an MR-fluid with 10% content of iron-particle and 10 cps viscous fluid was utilized for the MR-TLCD in the test. After application of 60 Gauss magnetic force control for the MR-TLCD, the damping ratio may raise to 5.5% as was tested previously for the MR-TLCD properties. The applied excitation of shaking-table is harmonic in a series of nine frequencies from 0.65 Hz to 0.97 Hz, with increment of 0.04 Hz for each test-run and two amplitudes of displacement 0.25 mm and 0.50 mm are applied. A typical time-history of ground motion for the shaking table and the corresponding spectrum were presented in Fig. 12, where the excitation frequency is 0.85 Hz along with 0.25 mm stroke of the actuator.



(a) Schematic drawing of the testing set-up (b) Photograph showing the complete set-up in the lab

Fig. 11 The testing set-up of the system for shaking-table test

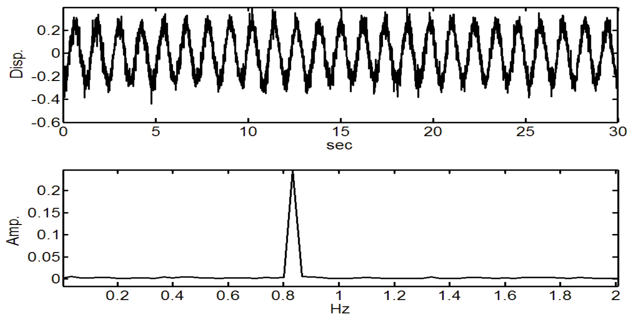


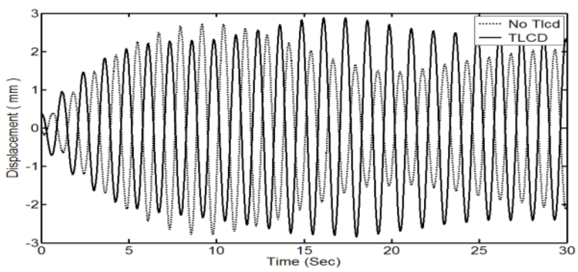
Fig. 12 Typical time history and corresponding spectrum for ground excitation from shaking table (0.25 mm stroke and 8.5 Hz frequency)

4.2 Experimental results for structure equipped with MR-TLCD system subjected to 0.25 mm ground excitation

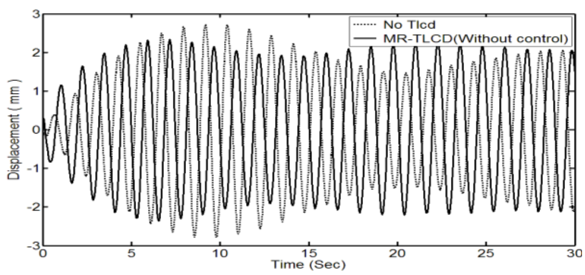
Fig.13 shows the comparison for displacement responses of the structure, where Fig. 13(a) is the response comparison for a system with or without TLCD, (b) is the response comparison for a system with or without MR-TLCD (no controlled magnetic force) and (c) presents the comparison for a system with or without MR-TLCD, which is controlled by magnetic force. The applied frequency for the ground motion is 0.81 Hz. As was presented from Figs. 13(a)-13(c), the response of the structure equipped with TLCD is obviously larger than the one without TLCD system while the systems equipped with MR-TLCD that was either controlled by magnetic force or not show some mitigation in the responses of early stage.

Presented in Figs. 14(a)-14(c) are same responses for the structure when the applied frequency of the ground motion raises to 0.85 Hz that is resonant to the frame structure. It is observed clearly that the responses for the structure without any damping device are significantly magnified along with time when ground motion was applied. However, when the damping devices are equipped on the structure, the responses are significantly reduced. The mitigation effect seems to be slightly better for structure equipped with MR-TLCD system in the later stage of vibration.

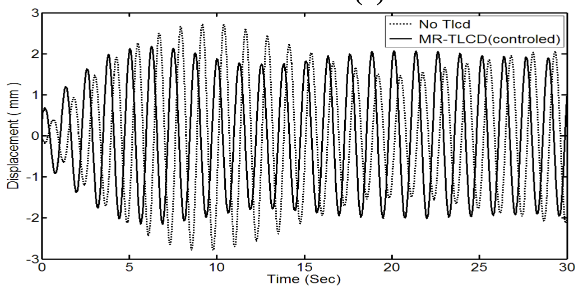
Fig. 15 shows comparisons of responses for the structure subjected to 0.89 Hz ground motion. Again, the displacement responses of the structure are mitigated by either TLCD or MR-TLCD devices. The difference for the mitigation effect between the TLCD and MR-TLCD with or without magnetic force control is in the middle stage of vibration, during which the TLCD seems to have better effect for the displacement reduction.



(a) Structure with and without TLCD

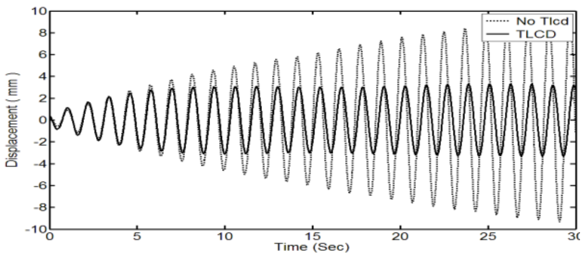


(b) Structure with and without MR-TLCD

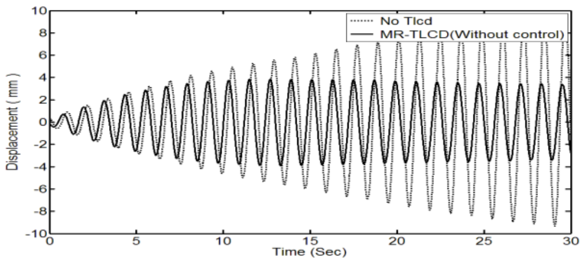


(c) Structure with and without controlled MR-TLCD

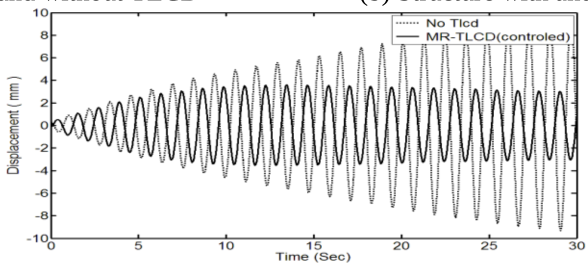
Fig. 13 Comparison of displacement response (0.81 Hz, 0.25mm excitation)



(a) Structure with and without TLCD

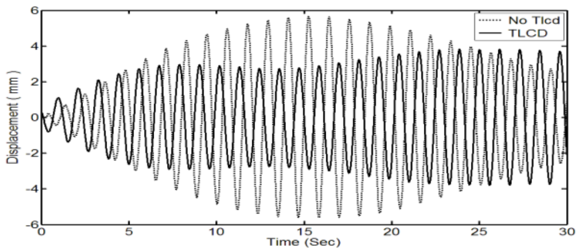


(b) Structure with and without MR-TLCD

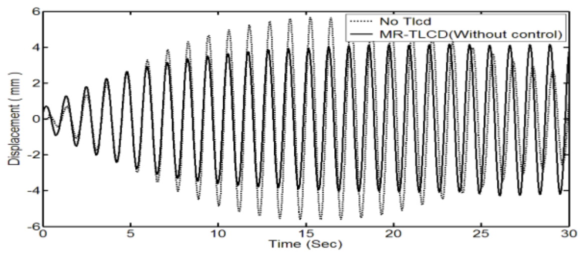


(c) Structure with and without controlled MR-TLCD

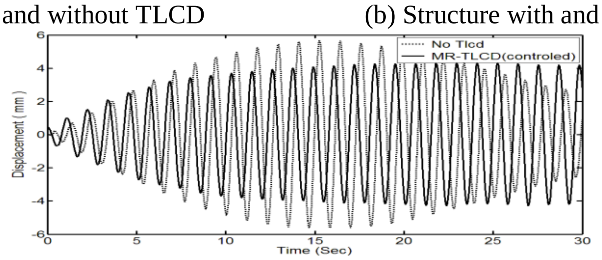
Fig. 14 Comparison of displacement response (0.85 Hz, 0.25 mm excitation)



(a) Structure with and without TLCD



(b) Structure with and without MR-TLCD



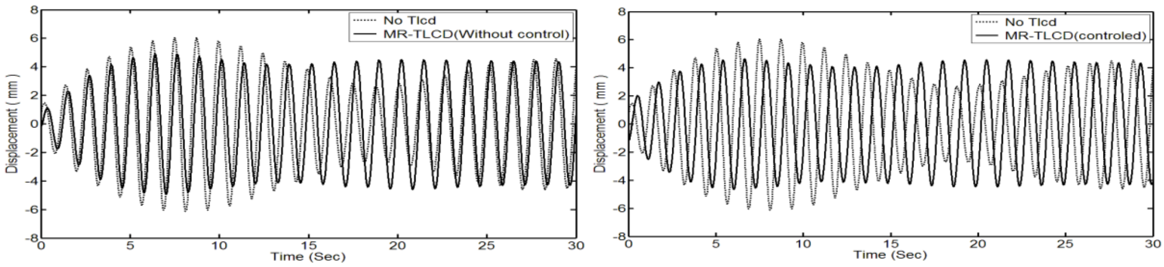
(c) Structure with and without controlled MR-TLCD

Fig. 15 Comparison of displacement response (0.89 Hz, 0.25 mm excitation)

4.3 Experimental results for structure equipped with MR-TLCD system subjected to 0.50 mm ground excitation

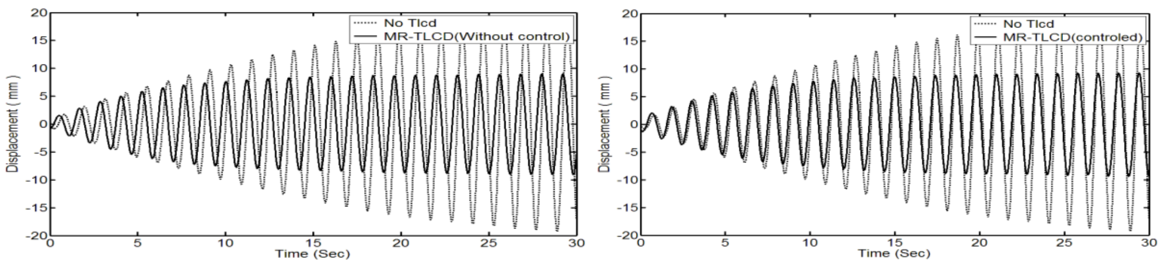
Due to a turbulence from the heavy sloshing of water in the TLCD tube when 0.50 mm ground excitation was applied to the structural system, experimental test for the structure equipped with TLCD was not able to be carried out. Therefore, the comparison for the responses will be for the structures equipped with MR-TLCD, while the magnetic control force will be applied on-and-off alternatively. As was shown in Figs. 16(a) and 16(b) represent the response comparison for structures equipped with either uncontrolled MR-TLCD or controlled MR-TLCD, respectively, when the frequency of applied excitation is 0.81 Hz. It appears that the mitigation effect from MR-TLCD, whether it is controlled by the magnetic force or not, is not impressed during the whole excitation. In the later exciting stage, the responses seemed to be slightly magnified.

The response comparisons during the resonant excitation are presented in Fig. 17 when a 0.85 Hz ground excitation is applied. It shows that the response of structures can effectively be suppressed by both uncontrolled MR-TLCD and controlled MR-TLCD when the excitation of ground motion is resonant to the natural frequency of the primary structure. Fig. 18 presents the comparison of structural responses when the frequency of excitation is 0.89 Hz. The suppression of the response only occurred at the early loading stage.



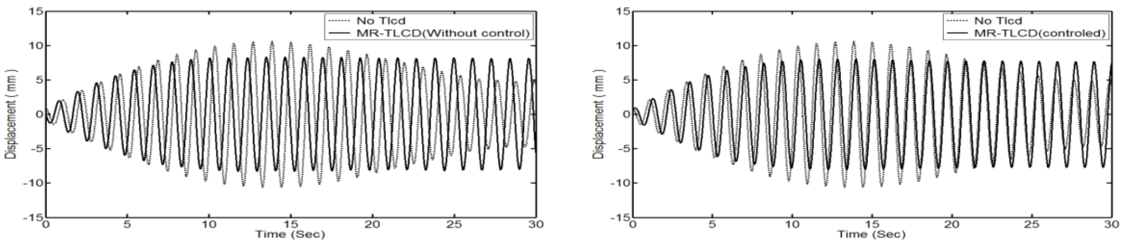
(a) Structure with and without MR-TLCD (b) Structure with and without controlled MR-TLCD

Fig. 16 Comparison of displacement response (0.81 Hz, 0.50 mm excitation)



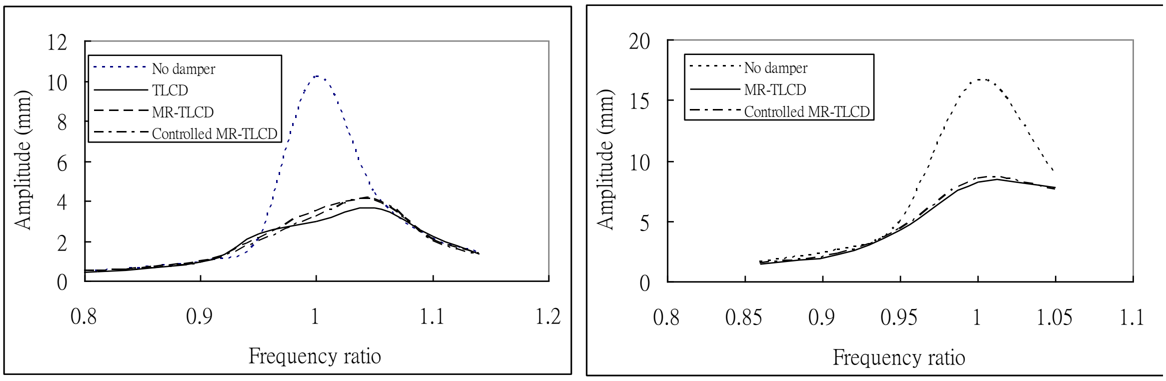
(a) Structure with and without MR-TLCD (b) Structure with and without controlled MR-TLCD

Fig. 17 Comparison of displacement response (0.85 Hz, 0.50mm excitation)



(a) Structure with and without MR-TLCD (b) Structure with and without controlled MR-TLCD

Fig. 18 Comparison of displacement response (0.89 Hz, 0.50mm excitation)



(a) Responses to 0.25 mm ground motion (b) Reponses to 0.50 mm ground motion

Fig. 19 Response comparison in average of highest 1/5 amplitudes corresponding to ground excitation frequency

4.4 Discussions for the mitigation effectiveness of structure equipped with MR-TLCD system

For the 0.25 mm stroke testing series, the displacement responses for the structure equipped with TLCD, uncontrolled MR-TLCD and controlled MR-TLCD are listed in Table 2 and compared to the responses of structure without installation of any damping devices. An average of the largest 1/5 displacement response data during each run of the test were considered as a typical response in this study. Similarly, Table 3 lists the average of the largest 1/5 data for the displacement responses of structure equipped with MR-TLCD with or without magnetic control-force when the loading stoke is 0.5 mm during the ground excitation. Accordingly, two graphs were drawn for the responses with respect to the frequency ratio of the excitation force to the natural frequency of the primary structure as was shown in Figs. 19(a) and 19(b).

Table 2 The average of maximum 1/5 displacement response (0.25 mm stroke)

frequency ratio	freq. of ground motion (Hz)	average of maximum 1/5 displacement (mm)			
		No TLCD	TLCD	MR-TLCD	MR-TLCD (60 Gauss control)
0.76	0.65	0.351	0.344	0.342	0.347
0.81	0.69	0.468	0.465	0.462	0.453
0.86	0.73	0.659	0.666	0.661	0641
0.91	0.77	1.049	1.081	1.055	1.018
0.95	0.81	2.051	2.387	2.094	1.933
1.00	0.85	10.186	2.969	3.449	3.161
1.05	0.89	4.404	3.660	4.006	4.051
1.10	0.93	2.082	2.205	2.022	1.987
1.14	0.97	1.407	1.344	1.326	1.294

Table 3 The average of maximum 1/5 displacement response (0.50 mm stroke)

frequency ratio	freq. of ground motion (Hz)	average of maximum 1/5 displacement (mm)		
		No TLCD	MR-TLCD	MR-TLCD (60 Gauss control)
0.86	0.73	1.6269	1.487	1.4439
0.91	0.77	2.5646	2.3042	2.2568
0.95	0.81	4.8312	4.3488	4.266
1.00	0.85	16.6179	8.2375	8.4733
1.05	0.89	8.815	7.8376	7.5171

From the comparison of responses corresponding to frequency ratio as shown in Fig. 19, it is clear that the best effect of response mitigation for the structural response occurs at the resonance when the vibration frequency is close to the natural frequency of the structure. The type of the damping device such as TLCD system, MR-TLCD without or with magnetic force control, seems to not significantly affect the mitigation effect. A MR-TLCD system with/out control of magnetic force shows a slight better effect than TLCD system when the vibration is away from the resonant frequency.

5. Conclusions

As was presented and discussed in the experimental results, some conclusions and suggestions may be addressed as follows:

1. The damping of MR-TLCD system will be influenced by the viscosity of the fluid and the magnetic force, but nevertheless, the application of the magnetic force may further influence the viscosity of the fluids.

2. When the vibration stroke is large, the water sloshing in the TLCD system will become dramatically large and then the damping device may become malfunctioned. However, because the MR-TLCD can take larger vibration stroke due to its higher viscosity in fluid, it can have better performance for a structure subjected to larger ground excitation.

3. During the resonant vibration state, among TLCD, MR-TLCD (uncontrolled) and MR-TLCD (controlled) three types of damper systems, TLCD has the better performance.

4. However, if the frequency ratio shifts away from resonant one, then the TLCD system may magnify the responses while the MR-TLCD system, no matter if it is controlled or not, would still have the mitigation effect.

Improvements for the further researches are recommended as follows. Due to the limitation from testing facilities that the application of the magnetic power is not large enough, a magnetic source with stronger power will be required to observe a better mitigation effect for the ME-TLCD system. Secondly, a test to a multi-degree of freedom structure equipped with ME-TLCD system will be suggested and compared to a SDOF system.

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