MR Tuned Liquid Colum Damper (MR-TLCD) for Seismic Vibration Control

D. Roychowdhury [1], S. Gur [2, *]

[1] Department Civil and Environmental Engineering, Junior Research Fellow, Indian Institute of Technology Patna, Bihta, Patna-801106, India
[2] Department Civil and Environmental Engineering, Assistant Professor, Indian Institute of Technology Patna, Bihta, Patna-801106, India

Paper ID - 070468

Abstract

Seismic vibration control of flexible structure is an important aspect which mostly involves reduction of structure displacement via application of passive damper or mass dampers. Present study focuses on the seismic vibration control of flexible structure against random earthquake, through modified (using MR fluid) tuned liquid column damper (TLCD), known as the MR-TLCD. To this end, stochastic structural response analysis has been performed and results (structure displacement ratio and liquid displacement) are compared with conventional the TLCD. To establish the superior control efficiency of MR-TLCD over conventional TLCD, parametric study has been performed considering wide range of damper, structure, and earthquake loading parameters. Study results shows the existence of optimal value of tuning ratio, head loss coefficient, and yield shear strength of MR fluid of MR-TLCD which minimizes the structure displacement ratio, i.e. maximizes the control efficiency. Another important observation is that, for similar level of control efficiency MR-TLCD requires much less value of mass ratio than that of TLCD, and also at same time it keeps the liquid displacement much less compared to the TLCD, for same value of mass ratio. This aspect increases the applicability of MR-TLCD over TLCD for vibration control of the flexible structure. In comparison to the TLCD, MR-TLCD provides 17 % to 43 % higher structural displacement control efficiency and reduces liquid displacement by 14 % to 45 %.

Keywords: MR-TLCD, TLCD, Vibration Control, Stochastic Structural Response Analysis, Random Earthquake

1. Introduction

In the advent of rapid urbanization and to meet industrial requirement, the lack of proper land and sufficient space and above all, with the increasing cases of natural calamities, drives mankind to opt flexible, less weighted, lightly dammed slender structures as a sustainable solution. Due to the lack of sufficient space skyscrapers along with other tall structures have been constructed at a rapid pace for economic purposes. These tall structures are prone to earthquake and strong wind force, which can result in severe damage or even collapse if these forces' magnitudes are large and consistent. For such high storied residential building structures, these natural forces will severely affect the durability and will create maximum discomfort for residents staying at upper floors. As these structures are slender and longer period, thus there exists a continuous demand to reduce its oscillation via providing an efficient vibration control device, without affecting sustainability of the structures [1]. For this, many systems were developed in past that functions as damper utilizing their own masses or inertia force and damping force. Among different types of mass dampers, tuned mass damper (TMD) and liquid mass dampers (LMD) are widely used for the vibration control of structure [2]. But compared to the TMD, LMDs are easy to install, facilitate easy adjustment of liquid frequency and have low installation cost for new structure. Further, retrofitting to the existing structure with LMDs, makes it turned out as affective alternative to the TMD.

In LMD, the mass, damping and the restoring mechanisms are facilitated by varying the liquid (generally water) inside it. This liquid absorb vibration energy in same way the TMD does. However there exists two varieties of LMD based on the energy dissipation mechanism, like Liquid Slushing Damper (LSD) and Liquid Column Damper (LCD) [3,4]. The LSD acts on principle of slushing of liquid inside to dissipate the vibration energy and on the other hand the LCD works on principle of two things, one is the relative movement of liquid in U-shaped container and the structure and other is the passage of liquid through an orifice placed in horizontal part of the container as damping in order to dissipate the vibration energy [3,4]. Due to the little advancement on LCD, the tuned liquid column damper (TLCD) has been emerged for its cost effectiveness and easy installation. But it has disadvantage of high mass ratio and large liquid displacement, which makes it less efficient in passive vibration control. It works on only in unconstrained liquid displacement and it has been observed that for greater magnitude of earthquake it shows lesser performance due to large liquid displacement in column which results in spilling of liquid out of the container. So to control this aspect in design some limit in the liquid displacement in the column has been considered [5]. Thus to make this happen, along this line, tuned liquid ball column damper (TLCBD) emerged and this shows improvement in passive vibration control on TLCD [6–8].

Also the conventional TLCD is modified to the tuned liquid column gas damper (TLCGD) and used for seismic induced vibration reduction of offshore jacket platform [9–11].

In this context novel magneto-rheological tuned liquid column damper (MR-TLCD) came up as a newly proposed vibration control device, as a special class of TLCD with MR liquid [12–14]. Here, to make the TLCD control system more robust and efficient under wind or earthquake loading, MR liquid has been used which has the ability to change its viscosity under a certain magnetic field. Thus, MR-TLCD encompasses the combined benefit of tradition passive control property of TLCD and active control advantage of smart material (MR liquid) [12–16]. This makes control system more efficient in case of high magnitude earthquake and strong wind motion. MR liquid has nickel and iron particles inside it, which are affected by magnetic field. When there is strong motion in structure the magnetic field will generate flux accordingly, which eventually makes the liquid more viscous and thus helps it keeping in container column up to designed limit. In past some experimental and analytical studies had been conducted to determine optimal design parameters and response control efficiency of MR-TLCD under the wind, wave, and seismic loading, for building structures and jacket-type platform [16–18]. Previous study shows the improved control efficiency (reducing structure displacement) of MR-TLCD over TLCD, offers less liquid displacement alongside. Such aspects make MR-TLCD another alternative as well as more efficient control system than conventional TLCD, and thus can be used for effective design of structure.

This study focuses on the estimation of optimal design parameters and use them to determine the response (structure displacement and liquid displacement) for the MR-TLCD equipped building structure through the stochastic structural analysis process, and comparing the results with TLCD equipped structure. To this end, the optimal design parameter values of MR-TLCD and TLCD are estimated which maximizes the control efficiency. Next the parametric study has been performed using those optimal values of the design parameters of MR-TLCD and TLCD.

2. SDOF System with TLCD and MR-TLCD

This section provides the mathematical model for response analysis of single degree freedom (SDOF) system with the TLCD and MR-TLCD control system. It is important to note that, such type of mass dampers are designed to control any mode of multi-degree-of-freedom (MDOF) structure where modes are well separated frequency. Thus in many of the previous studies [4,5] SDOF systems are used to demonstrate control efficiency of liquid mass damper.

2.1 Modelling of SDOF system with MR-TLCD

Fig. 1 shows the mechanical model of SDOF system with an idealized TLCD and MR-TLCD device, subjected to horizontal ground motion. It has been assumed that the control system will dissipate significant part of the imparted seismic energy and reduce the displacement of structure. Thus the structure will behave as a linear elastic system. However, to suppress the excessive vibration of structure, liquid in TLCD or MR-TLCD, the system will undergo large displacement, showing nonlinear behavior. With the above
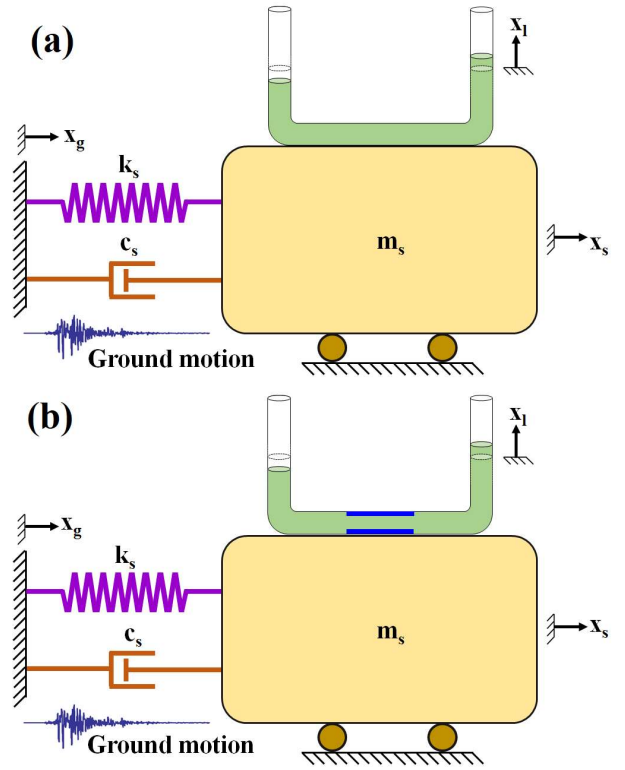

(a)

(b)

Fig. 1: SDOF system with (a) TLCD and (b) MR-TLCD

considerations the equation of motions of TLCD or MR-TLCD fluid and structure can be expressed as [4,8,12–14]

$$\ddot{x}_l + p\ddot{x}_s + \left(\frac{1}{L_e}\right)\left\{\left(\frac{\xi_l}{2}|\dot{x}_l|\right) + \left(\frac{c\tau_y}{\rho}\frac{L_p}{h}\frac{1}{|\dot{x}_l|}\right)\right\}\dot{x}_l + \left(\frac{2g}{L_e}\right)x_l = -p\ddot{x}_g \quad (1)$$

$$p\mu\ddot{x}_l + (1+\mu)\ddot{x}_s + 2\xi_s\omega_s\dot{x}_s + \omega_s^2 x_s = -(1+\mu)\ddot{x}_g \quad (2)$$

where, ρ is the density of the liquid, p is the length ratio (horizontal length to total length of the liquid column), μ is the mass ratio (mass of the liquid to the mass of the structure), c is a coefficient depends on the fluid velocity and varies between 2.07 to 3.07 [12–14] and taken as 2.1, τ_y is the developed yield shear stress in MR fluid due to magnetic field, h is the depth of MR liquid between fixed poles. For SDOF structure, ξ_s and ω_s are the damping ratio and frequency of the system, respectively. For the SDOF structure mass, damping, and stiffness is expressed through m_s, $c_s = 2\xi_s\omega_s m_s$, and $k_s = \omega_s^2 m_s$ respectively. The displacement, velocity, and acceleration of the liquid are denoted by x_l, $\dot{x}_l$, and $\ddot{x}_l$, respectively; and x_s, $\dot{x}_s$, and $\ddot{x}_s$ represents the SDOF structural system displacement, velocity, and acceleration respectively. The ground acceleration is denoted via $\ddot{x}_g$.

The frequency of the liquid column vibration is expressed as $\omega_l = \sqrt{2g/L_e}$. For design process of TLCD or MR-TLCD, this frequency of liquid vibration is normalized with the structure vibration frequency and express as tuning ratio $\gamma = \omega_l/\omega_s$. It is important to mention that, above Eq. (1) is related to the motion of MR fluid in MR-TLCD, and in absence of the magnetic field i.e. for $\tau_y = 0$ it will converge to the equation of motion of TLCD fluid.

2.2 Equivalent linearization of MR-TLCD

Here the nonlinear damping term in Eq. (1) is needs to be linearized before incorporation into the state-space formulation, and following equivalent linearization process as discussed below is used. The damping force provided by the MR-TLCD and by the equivalent linearized system can be expressed by Eq. (3) and Eq.(4) respectively.

$$F_d = \left(\frac{1}{L_e}\right)\left\{\left(\frac{\xi_l}{2}|\dot{x}_l|\right) + \left(\frac{c\tau_y}{\rho}\frac{L_p}{h}\frac{1}{|\dot{x}_l|}\right)\right\}\dot{x}_l \qquad (3)$$

$$\bar{F}_d = \left(\frac{2c_p}{L_e}\right)\dot{x}_l \qquad (4)$$

Here, c_p is the equivalent linearized viscous damping coefficient obtained from the non-linear viscous damping of MR-TLCD liquid.

According to the equivalent linearization method, to obtain c_p, the expectation of the square of error is minimized. Considering the external excitation as zero-mean stationary Gaussian process, the equivalent damping coefficient can be expressed as [17]

$$c_p = \frac{1}{\sqrt{2\pi}}\left[(\xi_l\sigma_{\dot{x}_l}) + \left\{\left(\frac{c\tau_y}{\rho}\frac{L_p}{h}\right)\frac{1}{\sigma_{\dot{x}_l}}\right\}\right] \qquad (5)$$

Here, $\sigma_{\dot{x}_l}$ is the root mean square (rms) value of liquid velocity in U-tube. Thus, for the stochastically linearized system, the equation of motion of the MR-TLCD or TLCD equipped structure can be rewritten in compact format as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{r\}\ddot{x}_g \qquad (6)$$

Here, for SDOF system with TLCD or MR-TLCD, different matrices are defined as; mass $[M] = \begin{bmatrix} 1 & p \\ p\mu & (1+\mu) \end{bmatrix}$; damping $[C] = \begin{bmatrix} \left(\frac{2c_p}{L_e}\right) & 0 \\ 0 & 2\xi_s\omega_s \end{bmatrix}$; and stiffness $[K] = \begin{bmatrix} \left(\frac{2g}{L_e}\right) & 0 \\ 0 & \omega_s^2 \end{bmatrix}$. The influence vector can be expressed as $\{r\} = \{0, 1\}^T$, and the displacement vector is given by $\{x\} = \{x_l, x_s\}^T$ and so the velocity and acceleration vector.

2.3 Stochastic Model Earthquake

In the present study, a stochastic model of ground motion, namely Kanai-Tajimi model is adopted for simulation process [19]. This Kanai-Tajimi model is well known to simulate the stochastic stationary ground motion where a white noise bed rock motion is filtered through a linear filter representing the characteristics of soil/ ground between structure and bed rock. The coloured noise produced in this process will provide power spectral density function (PSDF) of Kanai-Tajimi model as defined by [8,19]

$$S(\omega) = S_0 \frac{\left[(\omega_f^2)^2 + (2\xi_f\omega_f\omega)^2\right]}{\left[(\omega_f^2-\omega^2)^2 + (2\xi_f\omega_f\omega)^2\right]} \qquad (7)$$

where, ω_f and ξ_f are characteristic frequency and damping of the soil strata, and S_0 is the spectral intensity of white noise from bed rock motion. The filter frequency is normalized by the structure fundamental vibration mode frequency and expressed as normalized filter frequency $(\text{i.e. } \lambda = \omega_f/\omega_s)$.

Therefore, assuming the modelling of ground motion, represented via Kanai-Tajimi PSDF, as a stationary process, the filter equations are expressed as [4,8,20]

$$\ddot{x}_f + 2\xi_f\omega_f\dot{x}_f + \omega_f^2 x_f = -\ddot{w} \qquad (8)$$

$$\ddot{x}_g = (\ddot{x}_f + \ddot{w}) = -(2\xi_f\omega_f\dot{x}_f + \omega_f^2 x_f) \qquad (9)$$

where, x_f, $\dot{x}_f$, and $\ddot{x}_f$ are the displacement, velocity, and acceleration of ground, respectively; and $\ddot{w}$ is the intensity of white noise at the bed rock with power spectral intensity S_0. Note past studies [21,22] showed that, in presence of large damping in the system leads to same maximum values of responses from the stationary and non-stationarity earthquake model, which is also the case in this present study. Thus, stationary model of earthquake is adopted here.

2.4 Stochastic Response Analysis

The stochastic analysis presented herein is based on the assumption that both excitation and responses are the Gaussian stationary stochastic process. Based on stationary process assumption, substituting the Kanai-Tajimi model of ground motion $(\ddot{x}_g)$ i.e. Eq. (9) into the equation of motion i.e. Eq. (6) and rearranging it, the equation of motion of TLCD or MR-TLCD equipped structure can be written for the state space formulation as [4,8,20]

$$\{\ddot{x}\} = -[M]^{-1}[C]\{\dot{x}\} - [M]^{-1}[K]\{x\} + \{r\}(2\xi_f\omega_f\dot{x}_f + \omega_f^2 x_f) \qquad (10)$$

Combining Eq. (10) and (8), the state space equation of motion can be written as [4,8,20]

$$\frac{d}{dt}\{Y\} = [A]\{Y\} + \{w\} \qquad (12)$$

where, $[A]$ is the augmented system matrix (provided in appendix), $\{Y\}$ is the motion state vector for the TLCD or MR-TLCD equipped structure, and $\{w\}$ is the excitation vector containing the terms quantifying the intensity of the rock bed white noise. The state vector $\{Y\}$ and the excitation term $\{w\}$ are expressed as [4,8,20]

$$\{Y\} = \left\{\{x\}\ x_f\ \{\dot{x}\}\ \dot{x}_f\right\}^T \qquad (13)$$

$$\{w\} = \left\{\{0\}\ 0\ \{0\}\ -\ddot{w}\right\}^T \qquad (14)$$

In stochastic analysis, the covariance of response quantities is estimated assuming the sate response vector as the Markovian process. The evolution equation for the covariance matrix $[V]$ of the state vector $\{Y\}$ can be obtained by solving the first order differential equation as given below [4,8,20]

$$\frac{d}{dt}[V] = [A][V]^T + [V][A]^T + [P] \qquad (15)$$

Response statistics of the derivative process (such as $\{\ddot{x}\}$) is estimated through below expression [4,8,20]

$$[\dot{V}] = [A][V][A]^T + [P] \qquad (16)$$

where, $[P]$ is the matrix containing seismic intensity terms of bed rock white noise excitations. Different elements of the response covariance matrix $[V]$ and excitation matrix $[P]$ are given by the $V_{ij} = E[Y_iY_j]$ and $P_{ij} = E[w_iw_j]$, respectively. Following the excitation vector $\{w\}$, the matrix $[P]$ has all zero terms, except the last diagonal term as $2\pi S_0$ (provided in appendix).

Although the equivalent linearization is applied to represent the nonlinear damping force of TLCD and MR-TLCD, but both the systems show nonlinear characteristics. Thus, to obtain the convergence in solution, Eq. (15) and (16) are solved iteratively. The rms value of any response parameter is obtained from the covariance of the response as

$$\sigma_{Y_i} = \sqrt{V_{ii}} \qquad (17)$$

Control efficiency of the liquid mass dampers such as TLCD or MR-TLCD are commonly expressed in terms of ratio of displacement of controlled to uncontrolled structures, as adopted in this study, and expressed by

$$R_{x_s} = \sigma_{x_s}^c / \sigma_{x_s}^{uc} \qquad (18)$$

Here, R_{x_s} provides the normalized displacement response of structure (i.e. ratio of the controlled to uncontrolled structures displacement). In this present study, normalized displacement of structure (R_{x_s}) with the rms liquid displacement (σ_{x_l}) is estimated, as presented in subsequent sections.

3. Numerical Study

Present section provides the results of the stochastic response analysis of SDOF system equipped with TLCD or MR-TLCD. During simulation process, at any time one parameter is varied over a wide range and other parameters are kept at their default values. Default values of different parameters are adopted in this study are tuning ratio = 0.95, head loss coefficient = 0.75, yield shear strength of MR fluid = 50.00, mass ratio = 3.00 %, length ratio = 0.70, magnetic section length ratio = 0.35, structure time period = 2.00 s, structure damping ratio = 1.00 %, seismic intensity = 0.05 m²/s³; and normalized ground frequency = 4.50.

Fig. 2 (a1) to (c1) show the effect of the variation of tuning ratio, head loss coefficient, and yield shear strength of MR fluid on the rms displacement ratio of the structure. Fig, 2 (a1) to (b1) show that, for both TLCD and MR-TLCD, there exists a combination of optimal values of the tuning ratio $\left(\gamma_{opt} = 0.95\right)$ and the head loss coefficient $\left(\xi_{l_{opt}} = 0.75\right)$ which minimizes structure displacement ratio. Similarly, Fig. 2 (c1) shows that, for MR-TLCD, an optimal value of yield shear strength of MR fluid $\left(\tau_{y_{opt}} = 50.00\right)$ maximizes the displacement control efficiency. At this optimal point, MR-TLCD reduces the rms displacement of structure by 43 %, compare to the TLCD controlled structure. Fig. 2 (a2) to (c2) show the variation of rms liquid displacement with varying tuning ratio, head loss coefficient, and MR fluid yield shear strength. With varying tuning ratio (Fig. 2 (a2)) rms liquid displacement changes non-monotonically, and at the optimal tuning ratio, the rms liquid displacement becomes maximum. However, with increasing value of head loss coefficient and MR fluid yield strength (Fig. 2 (b2) and (c2)), the rms value of liquid displacement decreases monotonically. Here, at the optimal input parameter case, MR-TLCD reduces the rms value of liquid displacement by 45 % than TLCD.
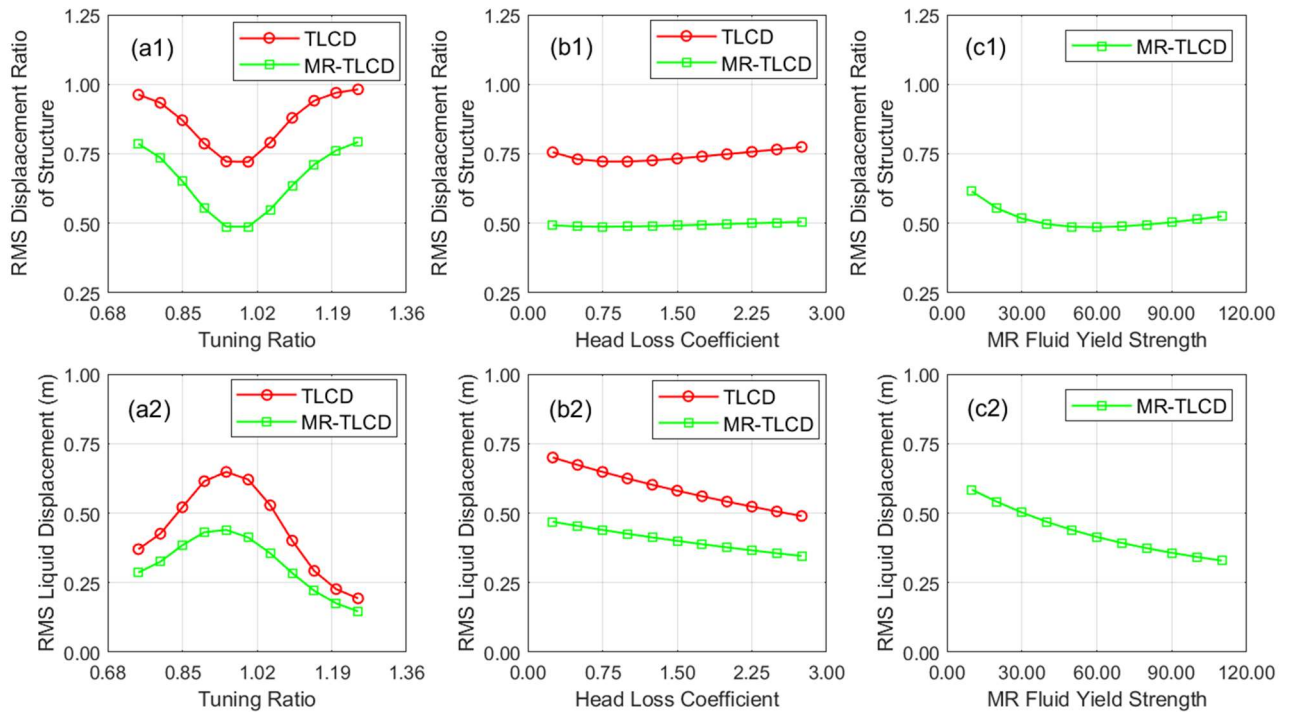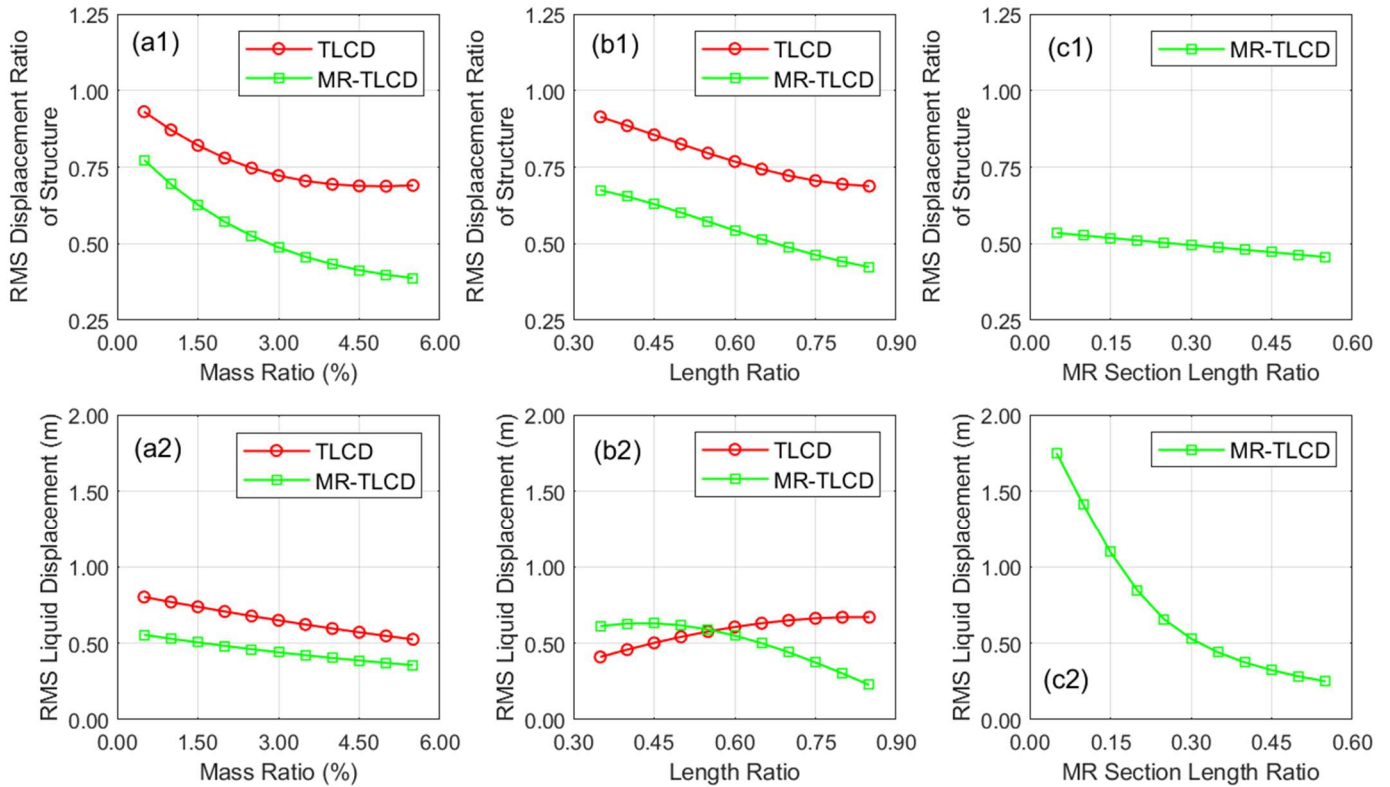

Fig. 2: Variation of the rms structure displacement ratio with respect to the (a1) tuning ratio, (b1) head loss coefficient, and (c1) MR fluid yield strength. Variation of the rms liquid displacement with respect to the (a2) tuning ratio, (b2) head loss coefficient, and (c2) MR fluid yield strength.

Fig. 3 shows the variation of the rms displacement ratio of structure (in Fig. 3 (a1) to (c1)) and the rms liquid displacement (in Fig. 3 (a2) to (c2)) under varying mass ratio, length ratio, and length ratio of the magnetic section. Here, Fig. 3 (a1) and (a2) show the variation of rms displacement ratio of structure and liquid displacement, respectively, with varying wide range of mass ratio. It is observed that, for both responses, the curve shows downward trend i.e. the values of both rms structure displacement and rms liquid displacement monotonically decreases with increasing mass ratio, for both TLCD and MR-TLCD. For rms structure displacement, the variation shows nonlinearity in contrary to the curve that shows almost linear behaviour for rms liquid displacement. It has been observed that, the MR-TLCD shows better structure displacement control efficiency over TLCD. Noteworthy that, even at very less mass ratio, MR-TLCD offers less rms displacement of structure and rms liquid displacement than TLCD. Thus for same control efficiency, the requirement of mass ratio is less for MR-TLCD than TLCD and therefore increases its applicability. Next, Fig. 3 (b1) and (b2) show the variation of rms displacement ratio of structure and liquid displacement with varying length ratio. Fig. 3 (b1) shows the monotonic variation (decreases linearly) of rms displacement ratio of structure with increasing length ratio, for both TLCD and MR-TLCD. Here also the MR-TLCD equipped SDOF structure shows less rms displacement i.e. a better control efficiency over the TLCD. But Fig. 3 (b2) shows opposite trend in rms liquid displacement, i.e. for TLCD the rms liquid displacement increases with increasing length ratio, while for MR-TLCD this variation is decreasing in nature. However at a length ratio of almost 0.55, the two curve cross each other, and show rms liquid displacement for both TLCD and MR-TLCD as almost 0.55m. Thus for MR-TLCD, to have less rms liquid displacement than TLCD, a critical length ratio need to be provided. Note that, the cause for opposite trend in the rms liquid displacement curves in Fig. 3 (b2) is due to the higher damping force in the MR-TLCD, as produced via strong magnetic field imposed around the horizontal part of damper. Fig. 3 (c1) and (c2) shows the variation of rms displacement ratio of structure and rms liquid displacement, respectively, for MR-TLCD with varying MR-section length ratio (i.e. the length of the magnetic section to the total length of the liquid column). Fig. 3 (c1) shows the rms structure displacement ratio decreases monotonically (almost linearly) with the increasing MR-section length ratio, however the variation is very less. Whereas, Fig. 3 (c2) shows significant variation of rms liquid displacement, which decreases drastically with the increasing MR-section length ratio. Such response behaviour of MR liquid is due to the presence of magnetic field, where with the increasing length of magnetic section the effect of magnetic field increases on MR liquid and thereby increases the damping which finally reduces the liquid displacement. Therefore, as per Fig. 3 MR-TLCD shows higher control efficiency than TLCD, and provided less liquid displacement.4
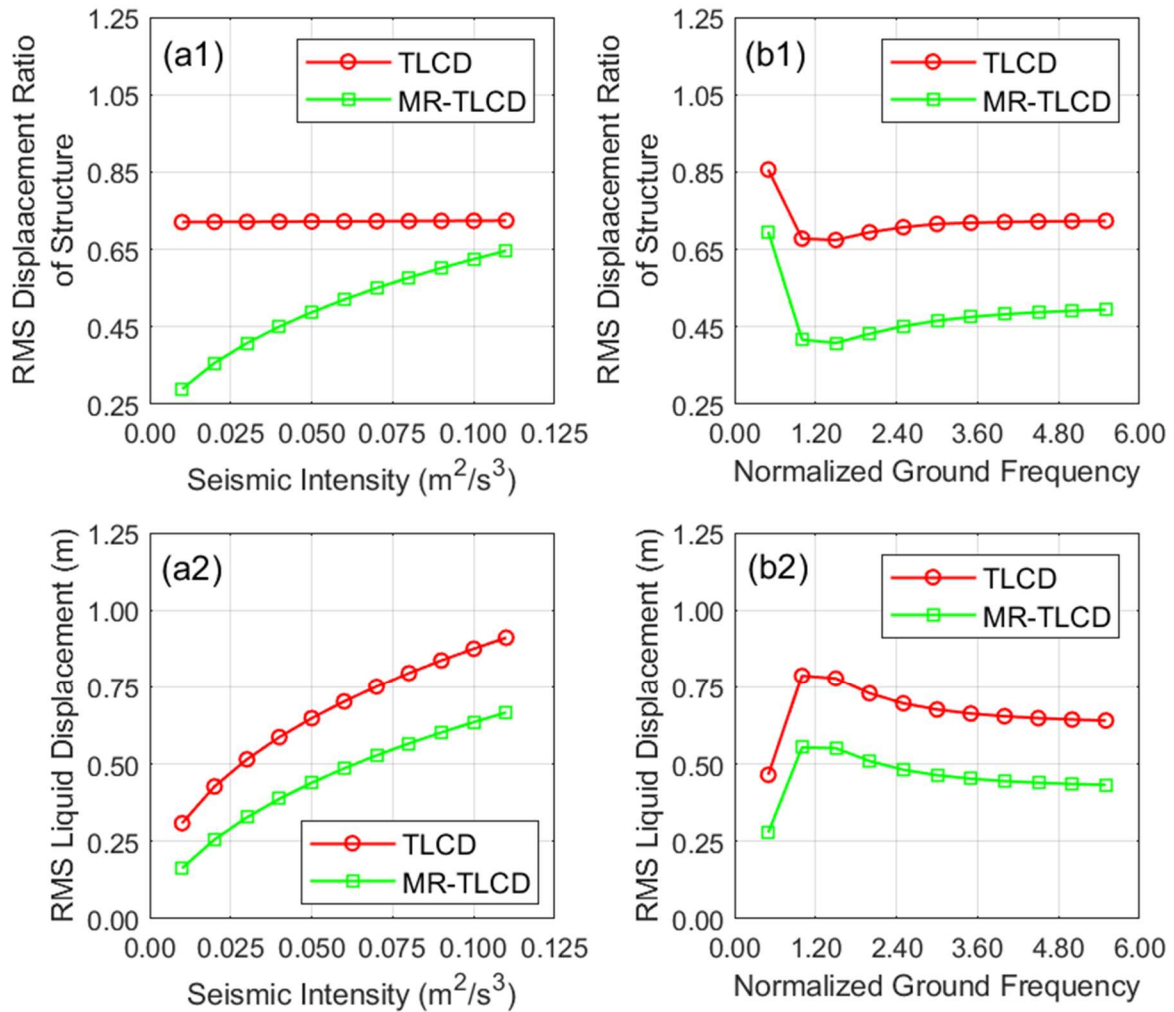

Fig. 3: Variation of the rms structure displacement ratio with respect to the (a1) mass ratio, (b1) length ratio, and (c1) length ratio of MR fluid section. Variation of the rms liquid displacement with respect to the (a2) mass ratio, (b2) length ratio, and (c2) length ratio of MR fluid section.

Fig. 4 shows the variation of the rms displacement ratio of structure (in Fig. 4 (a1) to (b1)) and the rms liquid displacement (in Fig. 4 (a2) to (b2)) under varying structure time period and damping ratio of structure. Fig. 4 (a1) and (a2) show variation of the rms displacement ratio of structure and liquid displacement with varying time period of structure, respectively, for both MR-TLCD and TLCD. In Fig. 4 (a1), for MR-TLCD, curve shows almost linearity in response, while for TLCD, it is nonlinear in nature. However compare to the TLCD, MR-TLCD shows better control efficiency in retaining the low variation rate of rms structure displacement. For TLCD equipped structure, up to time period 1.7 s, the rms displacement ratio shows little variation and after that it continuously increases with increasing time period of SDOF structure. In Fig. 4 (a2), the curve denoting the rms liquid displacement of MR-TLCD and TLCD, which shows non-linearity in variation. For both of the cases, the rms liquid displacement increases with the increasing time period of SDOF structure. Further, for both the control system, at low level of time period of structure, rate of variation in the liquid displacement is much more than the higher time period of structure. Also in this case, MR-TLCD shows much better

liquid displacement reduction efficiency over the TLCD and thus beneficial to be used for a wide range of time period of structure. Next, Fig. 4 (b1) shows that the variation of the rms displacement ratio of structure with varying damping ratio of structure, and the variation shows linearity in both of cases. However for TLCD, rms displacement ratio shows increasing trend with increasing damping ratio of structure, whereas for MR-TLCD this trend is opposite in nature i.e. decrease with increasing damping ratio of structure. This signifies the fact that, with increasing damping ratio of structure TLCD loses it control efficiency, whereas MR-TLCD retains its superior control efficiency. Also for a wide range of structure damping ratio, MR-TLCD offers better control efficiency over TLCD in reducing the structure displacements. Fig. 4 (b2) shows the variation in liquid displacement with varying damping ratio of structure and both of the curves for TLCD and MR-TLCD show steady and linear reduction of liquid displacement with increasing damping ratio of structure. Here also, MR-TLCD shows higher efficiency to reduce liquid displacement than the conventional TLCD.
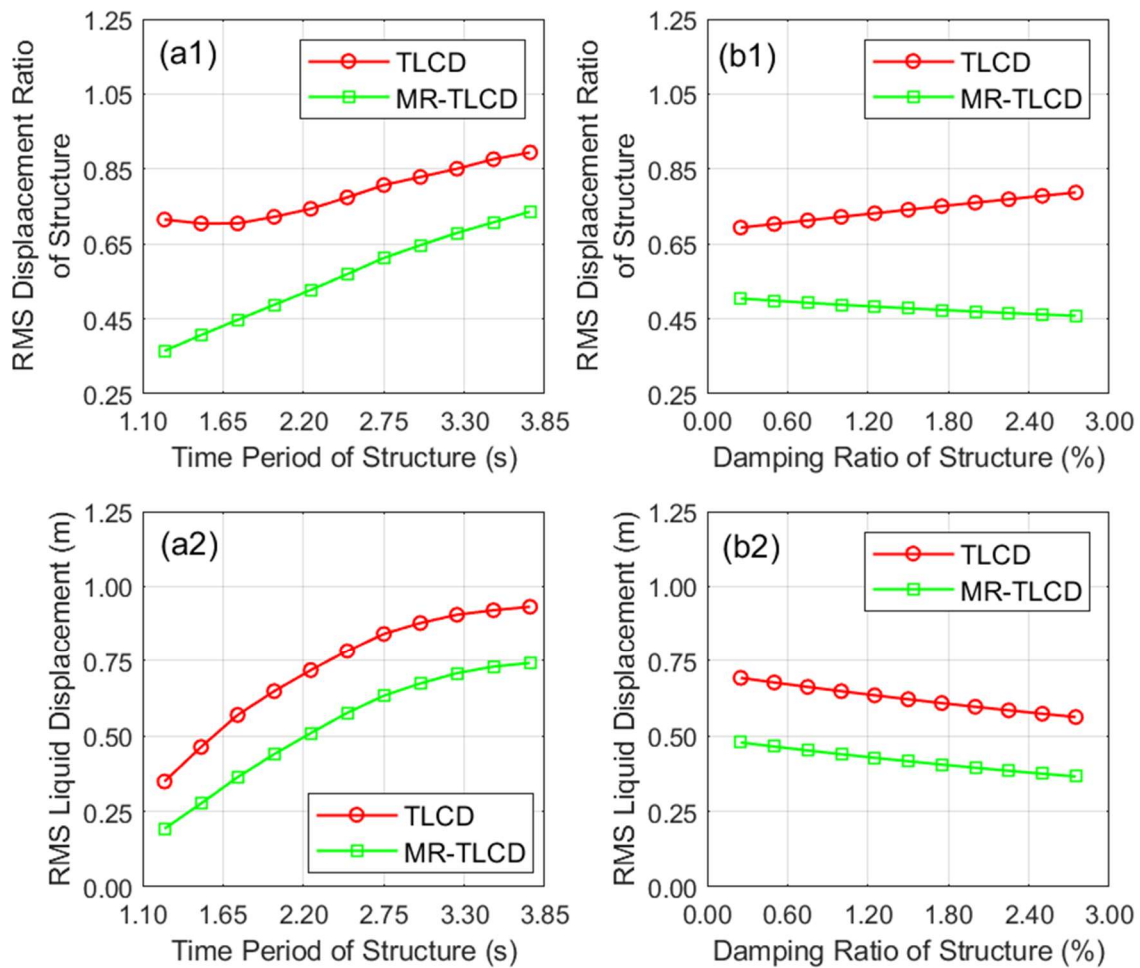
Fig. 4: Variation of the rms structure displacement ratio with respect to the (a1) structure time period and (b1) structure damping ratio. Variation of the rms liquid displacement with respect to the (a1) structure time period and (b1) structure damping ratio.

Fig. 5: Variation of the rms structure displacement ratio with respect to the (a1) seismic intensity and (b1) normalized ground frequency. Variation of the rms liquid displacement with respect to the (a1) seismic intensity and (b1) normalized ground frequency.

Fig. 5 shows the variation of the rms displacement ratio of structure (in Fig. 5 (a1) to (b1)) and the rms liquid displacement (Fig. 5 (a2) to (b2)) under the varying seismic intensity and normalized ground frequency. Fig. 5 (a1) and (a2) show variation of rms displacement ratio of structure and the liquid displacement under varying seismic intensity respectively for both TLCD and MR-TLCD. Here, Fig. 5 (a1) shows almost no variation of rms displacement ratio of the structure for TLCD under varying seismic intensity. This describes the insensitivity of the TLCD to reduce the rms displacement ratio as both the uncontrolled and controlled (via the TLCD) SDOF structure influenced equally by the seismic intensity. In contrary, MR-TLCD shows significant variation in rms structure displacement ratio under varying seismic intensity and it increase non-linearly with increasing seismic intensity value. Fig. 5 (a2) shows that the rms liquid displacement of TLCD and MR-TLCD increases non-linearly with increasing seismic intensity. It is also clear from Fig. 5 (a2) that, while the rms displacement of liquid varies, MR-

TLCD shows much higher reduction than TLCD. Next, Fig. 5 (b1) and (b2) show the effect of variation of normalized ground frequency on the response parameters i.e. rms displacement ratio of structure and rms liquid displacement, respectively, for both TLCD and MR-TLCD. From Fig. 5 (b1), studying the nature of the curves for both TLCD and MR-TLCD, it has been found that, initially the value decreases and at the normalized ground frequency almost near to 1.00, the rms displacement ratio of structure reaches to its lowest value and then it again increases and reaches a constant value. This happens because of the resonance phenomena which occurs when the normalized ground frequency become 1.00. Thus the, rms displacement ratio of structure reaches its lowest value, and after the ground frequency moves far from the structural frequency, the rms displacement ratio of structure stabilizes. It is noteworthy to mention here that, MR-TLCD keeps rms displacement ratio of structure lower than what TLCD does and thus proves much better control efficiency. In contrast to Fig. 5 (b1), Fig. 5 (b2) shows an opposite trend in the rms liquid displacement,

for both TLCD and MR-TLCD; i.e. at first the rms liquid displacement reaches to it maximum value and then it decreases before it stabilizes to a constant value at higher value of the normalized ground frequency. This happened because of same resonance factor, as explained previously. Here also it is seen that, the MR-TLCD offers much better reduction in the liquid displacement than the conventional TLCD. Thus from the above results, it is clear that compare to the TLCD, MR-TLCD provides much better structural displacement control efficiency in conjunction with the lower value of liquid displacement.

4. Conclusion

Present study focuses on the performance assessment of MR-TLCD for seismic vibration control of flexible structure, and compares with the results with TLCD. To this end a SDOF structure with control system of MR-TLCD and TLCD is adopted, stochastic structural analysis has been carried out against the random earthquakes. As response output, two quantities, i.e. rms structure displacement ratio and rms liquid displacement are measured. This study results demonstrated the presence of a set of optimal design parameters of MR-TLCD and TLCD, i.e. the tuning ratio, head loss coefficient, and shear strength of MR fluid which minimizes the rms structure displacement ratio. Next, those optimal values of the design parameters are used for the detail parametric study. In every case of the parametric study, compare to the TLCD, MR-TLCD provide superior control efficiency (i.e. the less displacement of the structure), as well as lower level of liquid displacement. It has been found that the MR-TLCD improves the rms structure displacement control efficiency up to maximum 43 % over the TLCD, and reduces the rms liquid displacement by maximum 45 % over the TLCD. Another important observation of this study is that, for similar level of rms displacement control efficiency, MR-TLCD requires less mass ratio than TLCD, and produces less value of liquid displacement. Taken together all of the above mentioned aspects, MR-TLCD shows superior control efficiency over the convention TLCD, as well as an added benefit of less mass ratio requirements. Thereby, for the seismic hazard mitigation, it increases the applicability of MR-TLCD over the conventional TLCD. Finally, all these facts helps designer to design a sustainable, light weight, tall and flexible building structure.

References

1. EI -Khoury O, Adeli H. Recent Advances on vibration control of structures under dynamic loading. Archives of Computational Methods in Engineering, 2013; 20: 353-360.

2. Xu BYL, Samali B, Member A, Kwok KCS. Control of along - wind response of structures by mass and liquid dampers. Journal of Engineering Mechanics, 1992; 118(1): 20-39.

3. Ghosh A, Basu B. Seismic vibration control of short period structures using the liquid column damper. Engineering Structures, 2004; 26(13): 1905-1913.

4. Gur S, Mishra SK, Bhowmick S, Chakraborty S. Compliant liquid column damper modified by shape memory alloy device for seismic vibration control of structures. Smart Materials and Structures, 2014; 23: 105009.

5. Chakraborty S, Debbarma R, Marano GC. Performance of tuned liquid column dampers considering maximum liquid motion in seismic vibration control of structures. Journal of Sound and Vibration, 2012; 331(7): 1519-1531.

6. Al-Saif KA, Aldakkan KA, Foda MA. Modified liquid column damper for vibration control of structures. International Journal of Mechanical Sciences, 2011; 53(7): 505-512.

7. Chatterjee T, Chakraborty S. Vibration mitigation of structures subjected to random wave forces by liquid column dampers. Ocean Engineering, 2014; 87(1): 151-161.

8. Gur S, Roy K, Mishra SK. Tuned liquid column ball damper for seismic vibration control. Structural Control and Health Monitoring, 2015; 22: 1325-1342.

9. Mousavi SA, Bargi K, Zahrai SM. Optimum parameters of tuned liquid column-gas damper for mitigation of seismic-induced vibrations of offshore jacket platforms. Structural Control and Health Monitoring, 2011; 20(3): 422-444.

10. Hochrainer MJ, Fotiu PA. Design of coupled tuned liquid column gas dampers for multi-mode reduction in vibrating structures. Acta Mechanica, 2018; 229: 911-928.

11. Hokmabady H, Mohammadyzadeh S, Mojtahedi A. Suppressing structural vibration of a jacket-type platform employing a novel Magneto-Rheological Tuned Liquid Column Gas Damper (MR-TLCGGD). Ocean Engineering, 2019; 180: 60-70.

12. Wang JY, Ni YQ, Ko JM, Spencer BF. Semi-Active TLCDs Using Magneto-Rheological Fluids for Vibration Mitigation of Tall Buildings. Advances in Building Technology, 2002; 1: 537-544.

13. Ni TQ, Ying ZG, Wang JY, Ko JM, Spencer BF. Stochastic optimal control of wind-excited tall buildings using semi-active MR-TLCDs. Probabilistic Engineering Mechanics, 2004; 19(3): 269-277.

14. Wang JY, Ni YQ, Ko JM, Spencer BF. Magneto-rheological tuned liquid column dampers (MR-TLCDs) for vibration mitigation of tall buildings: Modelling and analysis of open-loop control. Computer and Structures, 2005; 83(25-26): 2023-2034.

15. Colwell S, Jakob A. Experimental investigation on the MR-TLCD for vibration control of slender structures. Proceedings of ISMA 2006: International Conference on Noise and Vibration Engineering, 2006; 3: 1395-1406.

16. Sankar S, Chakraborty A. Development of semi-active vibration control strategy for horizontal axis wind turbine tower using multiple magneto-rheological tuned liquid column dampers. Journal of Sound and Vibration, 2019; 457: 15-36.

17. Cheng CW, Lee HH, Luo YT. Experimental study of controllable MR-TLCD applied to the mitigation of structure vibration. Smart Structures and Systems, 2015; 15(6): 1481-1501.

18. Sankar S, Chakraborty A. Optimal design of semiactive MR-TLCD for along-wind vibration control of horizontal

axis wind turbine tower. Structural Control and Health Monitoring, 2018; 25(2): 1-18.

19. Kanai K. Semi-empirical formula for the seismic characteristics of ground. Bulletin of the Earthquake Research Institute, University of Tokyo, 1957; 35: 309-324.

20. Mishra SK, Gur S, Chakraborty S. An improved tuned mass damper (SMA-TMD) assisted by a shape memory alloy spring. Smart Materials and Structures, 2013; 22: 095016.

21. Jangid RS. Equivalent linear stochastic seismic of isolated bridges. Sound and Vibration, 2008; 309: 805-822.

22. Lu Z, Liao Y, Huang Z. Stochastic response control of particle damper. Journal of Sound and Vibration, 2020; 481: 115439.

Appendix

Detail of the augmented system matrix used in Eq. (12) for stochastic analysis is

$$[A] = \begin{bmatrix} [0]_{(n,n)} & \{0\}_{(n,1)} & [I]_{(n,n)} & \{0\}_{(n,1)} \\ \{0\}_{(1,n)} & 0 & \{0\}_{(1,n)} & 1 \\ -[M]^{-1}_{(n,n)}[K]_{(n,n)} & \omega_f^2\{r\}_{(n,1)} & -[M]^{-1}_{(n,n)}[C]_{(n,n)} & 2\xi_f\omega_f\{r\}_{(n,1)} \\ \{0\}_{(1,n)} & -\omega_f^2 & \{0\}_{(1,n)} & -2\xi_f\omega_f \end{bmatrix}$$

where, n is the degree of freedom of the structure with the control system and for the TLCD or MR-TLCD it is $n = 2$.

The power spectral density matrix for the rock bed seismic motion is expressed as

$$[P] = \begin{bmatrix} [0]_{(n,n)} & \{0\}_{(n,1)} & [0]_{(n,n)} & \{0\}_{(n,1)} \\ \{0\}_{(1,n)} & 0 & \{0\}_{(1,n)} & 0 \\ [0]_{(n,n)} & \{0\}_{(n,1)} & [0]_{(n,n)} & \{0\}_{(n,1)} \\ \{0\}_{(1,n)} & 0 & \{0\}_{(1,n)} & 2\pi S_0 \end{bmatrix}$$