AN ALTERNATIVE IMPLEMENTATION OF TUNED LIQUID DAMPER TO CONTROL SHORT PERIOD SEISMIC VIBRATION OF STRUCTURES

D.K Pandey[(1)], S.K. Mishra[(2)]

[(1)] *Research Scholar, IIT Kanpur,dkpandey@iitk.ac.in*
[(2)] *Associate Professor, IIT Kanpur, smishra @itk.ac.in*

Abstract

Conventional tune liquid damper (TLD) is generally employed to control the vibration of the long period structures. However, tuning of TLD to short-period structures possess difficulty due to its long period sloshing of the liquid inside the TLD. To overcome this difficulty, a new implementation of the TLD is proposed. In this study deepwater TLD is attached to the primary structure by a flexible base. Then the frequency of the impulsive mass of the liquid is tune by appropriately adjusting the properties of the flexible base. The proposed implementation is modeled by following the Housner linear sloshing model of the liquid storage tank. The optimal parameters of the damper are obtained by solving the equation of motions of the structure damper system numerically by subjecting the structure to a suit of recorded ground motions. The damper performance is further demonstrated by the conducting shake table test by adopting the optimized damper parameters obtained from the numerical study. The numerical and experimental study reveals that proposed implementation is efficient in reducing the vibration response of the short period structures.
Keywords: Tune liquid damper, Tune mass damper, short-period structures, vibration control, Deepwater TLD

1. Introduction

Conventional tune liquid damper is employed for the vibration control of long-period structures. The TLD consists of the liquid tank rigidly connected with the structure, and the frequency of the liquid sloshing is tuned with the fundamental frequency of the primary structure. Liquid sloshing, wave breaking of the liquid inside the liquid container are the primary source of the energy dissipation of the primary structure. The performance of the TLD to suppress the vibration of the structure is demonstrated by several researchers [1]–[4]. Some modifications to conventional TLD are also proposed to enhance the energy dissipation and hence damper performance. These damper modifications are briefly reviewed herein. The floating roof is employed in TLD to enhance energy dissipation [5]. Slopped bottom TLD is also proposed for the same [6]. Another modified TLD is employed by inserting a semicircular block in the TLD [7]. However, these conventional TLDs are employed for the vibration control of the long period structures. Banerji et al. [8] used a higher depth ratio of the TLD for suppressing the response of the short period structure. In another work, Banerji et al. [9] use a hybrid tune liquid mass damper (TMD), in which TLD is placed on the TMD. Ghosh et al. [10] proposed an alternative implementation in which tuned liquid column damper is attached by spring to the primary structure and the frequency of the whole damper is tuned with the fundamental frequency of the main structure. Recently Pandey et al. [11] proposed a compliant tune liquid damper in which shallow depth TLD is attached to structure by the flexible elastomeric pad to the primary structure. This flexible pad is used for tuning of the whole damper to the primary structure. Motivated from the works done by the Ghosh et al. [10] and the Pandey et al. [11] an alternative implementation of TLD is proposed in which TLD is attached to the primary structure by a flexible elastomeric pad and deep water depth is used contrary to the conventional shallow water TLD. In this implementation, the impulsive mass of the deep tank is tune with the primary structure by appropriately adopting the properties of the elastomeric pad. Two structures of the time period, 0.3 sec, and 0.5 sec are selected for the present study. The equation of motion of the structure damper system is derived by adopting the Housner linear sloshing model [12] of the deep-water tank. Six ground motions from three distinct hazard bines named as serviceability design earthquake (SDE), design basis earthquake (DBE) and maximum considerable earthquake (MCE). The damper parameters are optimized by solving the equation of motion numerically. The performance of the damper performance is obtained by employing the optimum parameters in the design of the damper and subjecting the structure to set of selected ground motions. The damper efficiency is further verified by conducting the shake table test by subjecting the structure to the set of selected ground motions.

2. Modeling of the damper

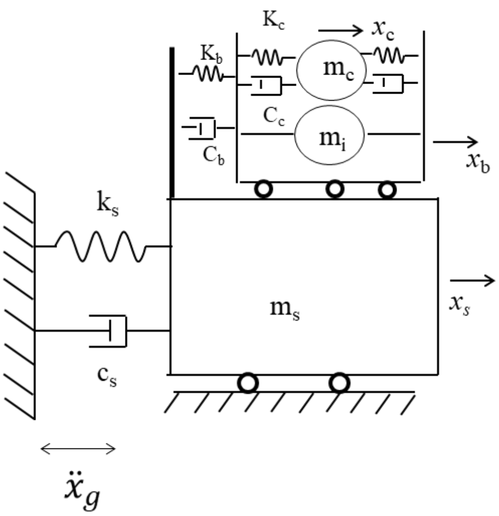

Fig. 1 – Schematic of the idealized model of the liquid and short period structure

The linear sloshing model of liquid proposed by the Housner [12] is used for deriving the equation of motion of the liquid sloshing. The liquid inside the tank may be divided into two separate oscillating masses (impulsive mass and convective mass). Impulsive mass of liquid is the mass of the liquid, which is vibrating along with the water tank boundary. It is assumed that the tank wall is rigid. This assumption is valid for reinforced concrete water tanks. Convective mass is the sloshing mass of the liquid. The equation of motion of the structure damper system may be written as in the eq. (1) eq. (2) and eq. (3);

$$m_c \ddot{x}_c + m_c \ddot{x}_b + m_c \ddot{x}_s + c_c \dot{x}_c + k_c x_c = -m_c \ddot{x}_g \tag{1}$$

$$m_c \ddot{x}_c + m_b \ddot{x}_b + m_b \ddot{x}_s + c_b \dot{x}_b + k_b x_b = -m_b \ddot{x}_g \tag{2}$$

$$m_c \ddot{x}_c + m_b \ddot{x}_b + M \ddot{x}_s + c_s \dot{x}_s + k_s x_s = -M \ddot{x}_g \tag{3}$$

In which x_c, x_b and x_s are the displacement of the convective mass, damper base, and the structure relative to the ground. m_c, m_b and M are the mass of the sloshing mass, damper mass, and the mass of the structure inclusive of damper mass. m_c, m_b and M can be calculated as:

$$m_c = \alpha_c m_l \tag{4}$$

$$m_i = \alpha_i m_l \tag{5}$$

$$m_b = m_i + m_0 + m_c \tag{6}$$

$$M = m_s + m_b \tag{7}$$

where, m_l is the mass of the liquid, m_0 is the mass of container (assumed to be 10 percent of the liquid mass), α_c and α_i are the coefficients of the convective mass and the impulsive masses respectively and can be calculated as:

$$\alpha_c = \frac{0.264/\beta}{\tanh(\pi\beta)} \tag{8}$$

$$\alpha_i = \frac{\tanh(0.866/\beta)}{0.866/\beta} \tag{9}$$

β is the depth ratio of the liquid of the water to the length of the water tank. c_c, c_b and c_s are the viscous damping of the convective mass of liquid, elastomeric pad and the structure respectively. c_c, c_b and c_s maybe calculated by eq. (10), eq. (11) and eq. (12);

$$c_c = 2\varsigma_c m_c \omega_c \tag{10}$$

$$c_b = 2\varsigma_b m_b \sqrt{k_b / m_b} \tag{11}$$

$$c_s = 2\varsigma_s M \omega_s \tag{12}$$

ς_c, ς_b and ς_s are the viscous damping coefficient of the convective mass, elastomeric pad, and the structure, respectively. The damping ratio of the elastomeric pad is assumed to be 0.5 percent. k_c in eq. (13) and k_b in eq. (15) and k_s are the stiffness of convective mass, elastomeric pad, and the structure.

$$k_c = m_c \omega_c^2 \tag{13}$$

where: ω_c in eq. (14) is the linear sloshing frequency of the convective mass and given as the

$$\omega_c = \sqrt{(\pi\, g/\, L)\tanh(\pi\beta)} \tag{14}$$

$$k_b = m_b \omega_b^2 \tag{15}$$

where: ω_b in eq. (16) is the frequency of the elastomeric pad and given as the

$$\omega_b = \sqrt{\sum_{i=1}^{n_p} K_h \Big/ (m_i + m_0)} \tag{16}$$

where: K_h is the lateral stiffness of each elastomeric pad arranged in a parallel configuration to support the damper.
The equation defines the frequency ratio of the damper. (17);

$$\gamma_b = \omega_b / \omega_s \tag{17}$$

where: ω_s is the frequency of the primary structure. In the present implementation, the frequency of the impulsive mass of the liquid is tuned with the frequency of the structure. For tuning, the stuffiness of the elastomeric pad is chosen appropriately.

3. Selection of ground motion

The ground motions are selected from the SAC ground motion database. A total of six ground motions are selected for the present study. The ground motions are from three hazard bins named as the SDE, DBE, and MCE. The response spectra of the selected ground motions are shown in Fig. **2**. The details of the selected ground motions are listed in Table **1**. From Fig. **2**, it is observed from the figure that the mostly spectral peaks lie between 0.3 sec to 0.7 sec. It indicates that the selected ground motions are vulnerable to short period structures. The periods of the short period structure typically lies between, 0. 2 sec to 0.7 sec. It is also observed that some significant spectral ordinates lie after a period of 1 sec. The selection of the ground motions are based on their dominant frequency content, peak ground acceleration (PGA), peak ground velocity (PGV) and the PGV and PGA ratio.

Table 1 – Details of the ground motion selected for the present study

Sno	EQ. details	Magnitude	Dominant period (s)	PGA (g)
1	la14, Northridge, 1994	6.7	0.30	0.64
2	la17 Northridge, 1994	6.7	0.32	0.56
3	la18 Northridge, 1994	6.4	0.36	0.80
4	la24, Loma Prieta, 1989	7.0	0.72	0.46
5	la37, Palos Verdes (simulated)	7.1	0.68	0.70
6	la44, Imperial Valley, 1979	6.5	0.30	0.10

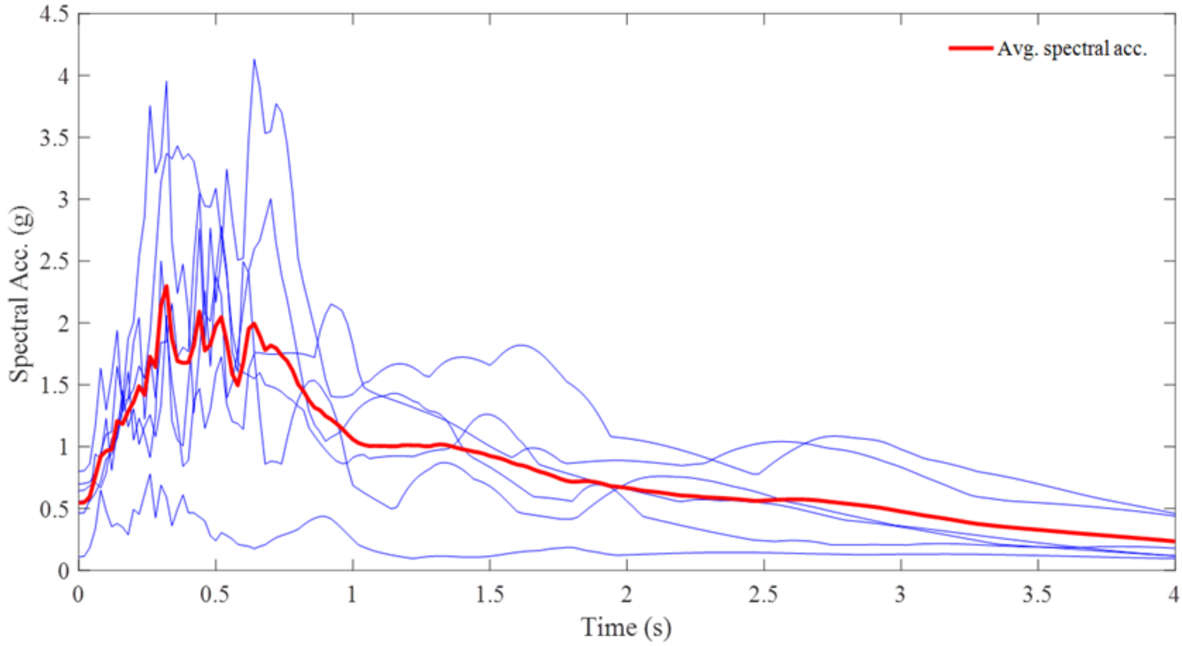

Fig. 2 – Acceleration response spectra of the selected ground motions

4. Selection of the damper parameters

The important parameters that need to be selected for the design of the proposed damper system are the frequency ratio, a damping ratio of the elastomeric pad, mass ratio, length of the water tank, depth ratio of the liquid. The frequency of the liquid sloshing is an important parameter to tune the tune liquid damper. This frequency is depending on the length of the liquid and the depth ratio of the liquid, as shown in eq. 14. However, for a short period structure, the required length of the liquid tank to tune the fundamental frequency of the liquid sloshing with the structure is not practically feasible, as the required length is minimal. To overcome this difficulty, tuning of long period liquid sloshing to short period structure, the sloshing frequency is left untuned, and a practically feasible length of the water tank of 0.5 m is chosen for the present study. The depth ratio is chosen as 0.6. This value is chosen because beyond this value (0.6), the depth ratio becomes insensitive to the fundamental sloshing frequency of the liquid. It is concluded from the previous studies (on passive tune damper systems) that the damper performance will enhance with the increase in the mass ratio. However, a significantly higher mass ratio of the damper may hamper the overall dynamic properties of the structure. Hence a value of the mass ratio is chosen as the 5 percent. The frequency ratio and the damping ratio of the elastomeric pads are optimized by subjecting the structure damper system to a set of selected ground motions. The RMS acceleration ratio, which is defined as the ratio of the RMS of the controlled acceleration to the RMS of the uncontrolled acceleration, is the objective of the optimization problem. The values of the frequency ratio and the damping of the elastomeric pad are chosen from the numerical search technique by minimizing the RMS acceleration ratio. The optimum value of the frequency ratio and the damping ratio of the elastomeric pad are obtained for each ground motion and then the average value of the frequency ratio and the damping ratio of the elastomeric pad (averaging among the ground motions) is representing the optimum values of the damper parameters. The variation of the optimum value of the frequency ratio and the damping ratio of the elastomeric pad is shown in fig 3(a) and fig 3(b) respectively and the corresponding peak acceleration ratio, defined as the ratio of the controlled peak acceleration to the uncontrolled peak acceleration and the RMS acceleration ratio is shown in fig 3(c) and 3(d) respectively. It is observed from the fig 3 (a) that the optimum frequency ratio is decreeing with an increase in the mass ratio for both the structures. It is also observed that the optimum frequency ratio of the 0.5 sec structure is slightly less than 0.3 sec structure. It is apparent from fig 3 (b) that the optimum damping ratio of the elastomeric pad is increasing with an increase in the mass ratio. It is also observed that the optimum value of the damping of the elastomeric pad is not changing significantly with change in the structure period. It is observed from fig 3 (c) and 3(d) that the efficiency of the structure is enhancing with an increase in the mass ratio however higher mass ratio of the damper may change the overall dynamic behavior of the primary structure. Hence a limiting value of the mass ratio of the 5 percent is chosen in the present study. The variation of the optimum parameters with a varying value of the damping of the structure is shown in fig 4(a) and fig 4(b) respectively and corresponding peak acceleration and the RMS acceleration ratio are shown in fig 4(c) and 4 (d) respectively. From fig 4 (a) and 4(b), it is observed that the optimum value of the frequency ratio damping ratio of the elastomeric pad is insensitive with the variation of the damping ratio of the structure at a lower damping value. However, at a higher value of the damping ratio of the structure, the optimum value of the damping of the elastomeric pad is decreeing.

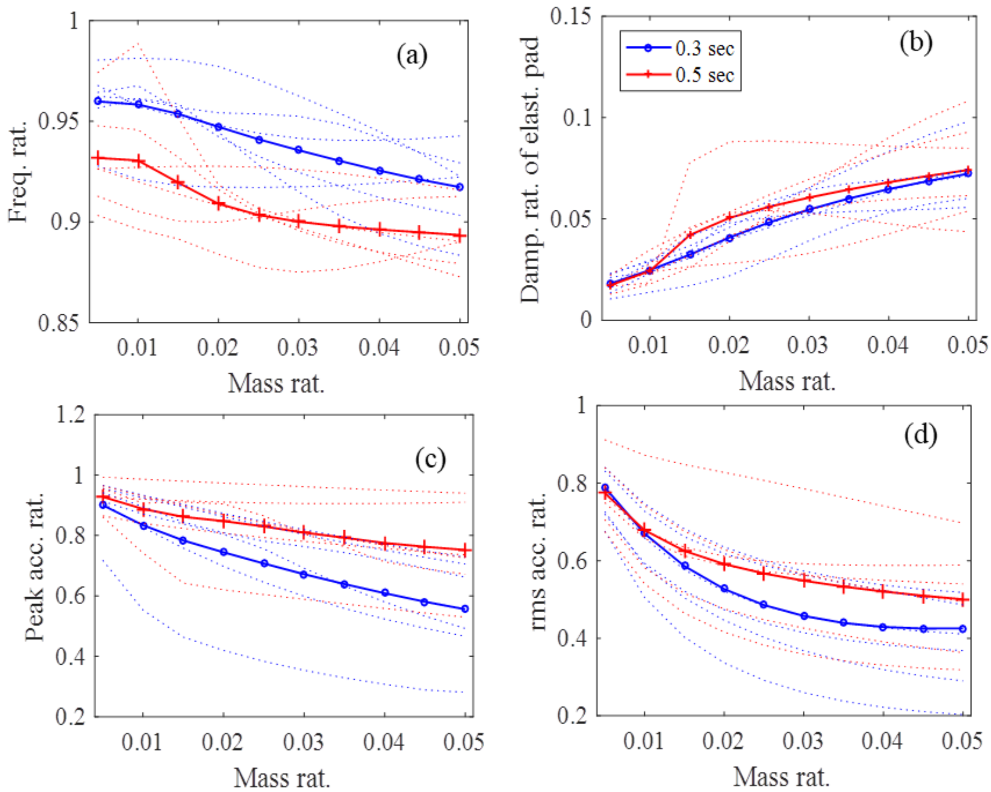

Fig. 3 – The optimum values of the (a) frequency ratio (b) damping ratio of the elastomeric pad and corresponding (c) peak acceleration ratio (d) RMS acceleration ratio for varying level of the mass ratio

Table 2 – Adopted dampers and the structure parameter

Sno.	Structure parameters		Damper parameters			
	Time period (s)	Damp. rat. (percent)	Mass ratio (percent)	Frequency ratio	Damp. rat. of elasto. pad (percent)	Length of the tank (m)
1	0.3	1	5	0.95	5	0.56
2	0.5	1	5	0.925	5	0.56

The control efficiency of the damper is compromised by increasing the damping ratio of the structure. This trend is in line with the other studies performed on the passive tune vibration control devices are adopted to judge the performance of the damper. It may be noted that the present optimization is performed for the set of ground motion. Hence optimum value may vary in actual. A detailed study may be required for general optimization. This study is restricted to in finding the optimum value of the damper parameters for a set of ground motions. The detailed study on optimization may carry out in full research paper. Based on the observation obtained from the above discussion, the following parameters of the damper (selected to judge the performance of the damper) are listed in table 2.

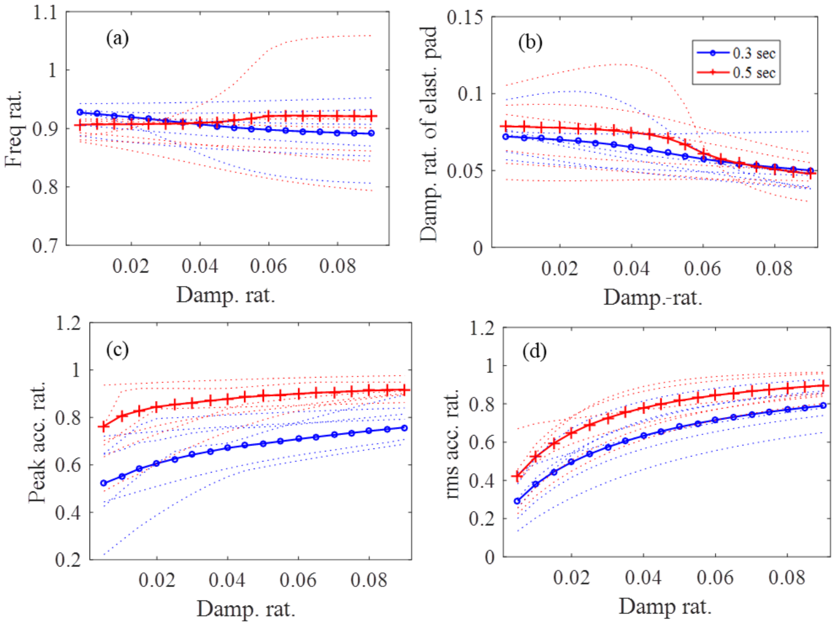

Fig. 4 – The optimum values of the (a) frequency ratio (b) damping ratio of the elastomeric pad and corresponding (c) peak acceleration ratio (d) RMS acceleration ratio for varying level of the damping ratio

5. Performance of the damper

Table 3 – Efficiency of the proposed damper system

Sno.	EQ. no.	Structure period (s)	Peak acc. (m/s^2)			r.m.s acc. (m/s^2)		
			Uncontro.	Contro.	Effici. (%)	Uncontro.	Contro.	Effici. (%)
1	la14	0.3	23.13	19.15	17.21	4.43	2.24	49.40
		0.5	15.25	14.37	5.72	3.23	2.21	32.01
2	la17	0.3	24.95	8.60	65.53	5.36	1.26	76.39
		0.5	15.10	11.17	26.02	3.03	1.23	59.51
3	La18	0.3	25.86	20.12	22.20	5.31	2.09	60.76
		0.5	31.20	25.71	17.58	8.00	2.40	69.99
4	la24	0.3	10.30	5.99	41.79	2.68	1.47	44.92
		0.5	20.30	14.13	30.41	6.83	4.56	33.23
5	la38	0.3	17.79	10.77	39.47	3.12	1.66	46.84

Sno.	EQ. no.	Structure period (s)	Peak acc. (m/s^2)			r.m.s acc. (m/s^2)		
			Uncontro.	Contro.	Effici. (%)	Uncontro.	Contro.	Effici. (%)
		0.5	26.32	13.77	47.67	4.99	2.53	49.26
6	la44	0.3	6.83	3.11	54.52	1.26	0.51	59.94
		0.5	2.92	2.33	20.10	0.65	0.42	35.87

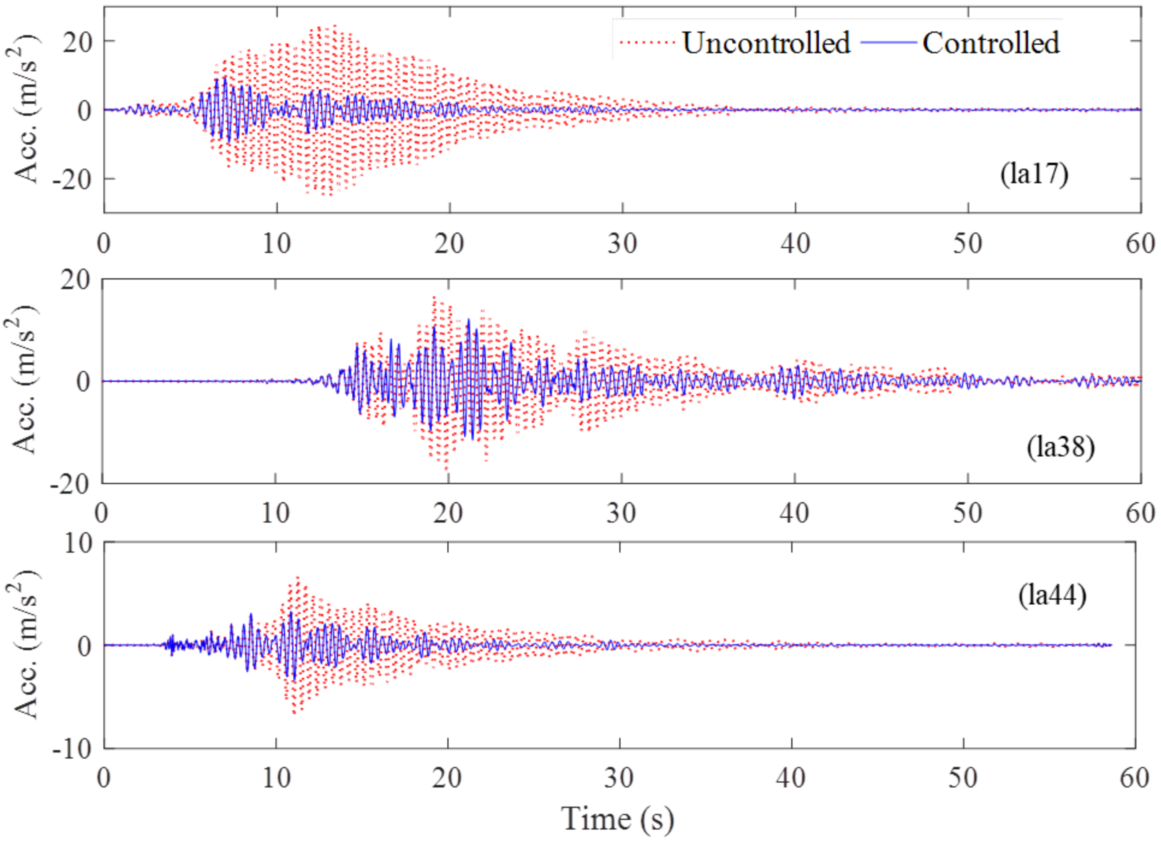

Fig. 5 – The acceleration time history of the structure subjected to (a) la17, (b) la38 and (c) la44

The damper preference is judged by conducting a numerical and experimental study. The parameters of the damper are adopted herein is listed in table 2. The numerical demonstrated of the damper performance is performed by solving the equation of motion of the structure damper system numerically by following the Newmark beta average acceleration method. The time step of the numerical integration is adopted sufficiently small to avoid numerical instability in the integration scheme. The performance of the damper in suppressing the RMS and peak acceleration is listed in Table **3**. The acceleration time histories of the three ground motion are also shown in fig. 5(a), fig. (5b) and the fig.5(c). From fig.5, it is observed that the present damper system significantly suppressing the structure response. It is observed from Table **3** that the performance of the damper is better for suppressing the RMS acceleration response in comparison to the peak acceleration response. It is observed that the maximum peak acceleration reduction is 65.53 percent and the maximum reduction in RMS acceleration is 76.39 percent. The minimum peak acceleration response reduction is 5.72 percent and is for the ground motion la14. The primary response parameter of the interest in the present study is acceleration, as acceleration is sensitive to the short period structures. However displacement of the structure is also an important quantity. Significant response reduction is also achieved in reducing the displacement response of the structure as well. However the summary of the displacement response reduction is not listed just for brevity. However displacement time histories of the structure subjecting to three ground motions same as used for the demonstration of the acceleration response reduction of the structure are shown in fig 6(a), fig 6(b) and the fig 6(c). It is observed from the fig (6) that the present system is efficient in reducing in displacement response as well.

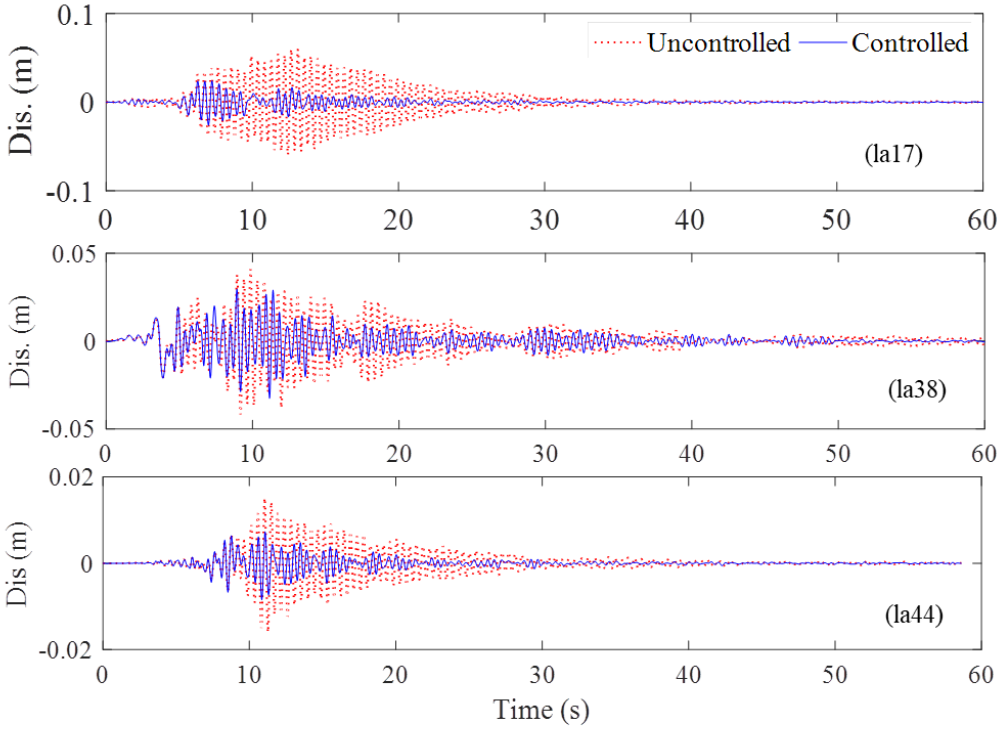

Fig. 6 – The Displacement time history of the structure subjected to (a) la17, (b) la38 and (c) la44

6. Experimental study

The experimental study is performed by conducting the shake table test to verify the damper performance. The shake table available in the structural engineering laboratory IIT Kanpur is used for the present study and is shown in fig 6. The shake table is of payload capacity of the 5kN. The frequency range of the operating of the table is 50 Hz. The model structure used for the experimental study is shown in fig 7. The identified damping ratio and fundamental time period of the model is 2.7 percent and the 0.299 sec. The mass of the model is 100 kg. The damper is attached at the top of the structure as shown in fig 8. The mass ratio (ratio of the mass of the whole damper and the mass of the structure) adopted as the 5 percent. The tank weight is 0.6 kg and the mass of the water inside the tank is 4.4 kg. The coupon test is conducted to judge the shear modulus of the elastomeric pad. The size of the elastomeric pad is 21 mm ×11 mm × 50 mm. The total number of the elastomeric pad required for adequate tuning of the damper is four. These elastomeric pads placed in a parallel arrangement. With this, the tuning ratio of the impulsive mass of the damper is 0.933. A total of six ground motions (same as the numerical demonstration) are used for the experimental demonstration. The performance of the damper is demonstrated through the story wise variation of the peak acceleration normalized by the base acceleration as shown in fig. (9). The control response is contrasted with the uncontrolled response. It is observed that the proposed damper system is effective in reducing the peak acceleration among the stories of the structure. It is also observed that the response reduction is more towards the higher stories. The damper performance in reducing structural vibration is shown in fig 9(a), fig 9(b), fig 9(c), fig 9(d), fig 9(e) and fig 9(f).

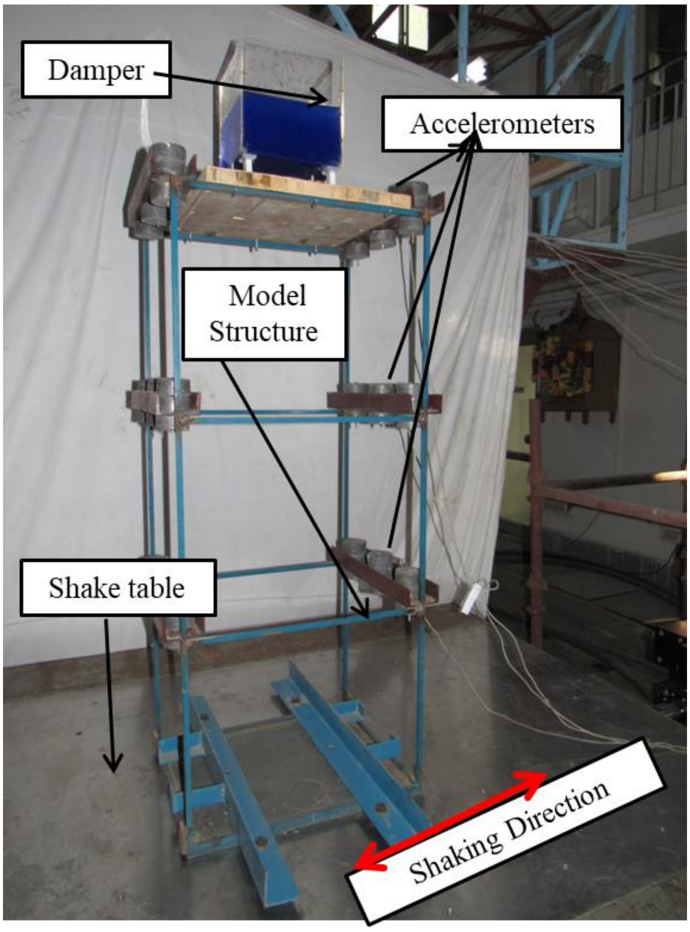

Fig. 7 – Model structure and damper

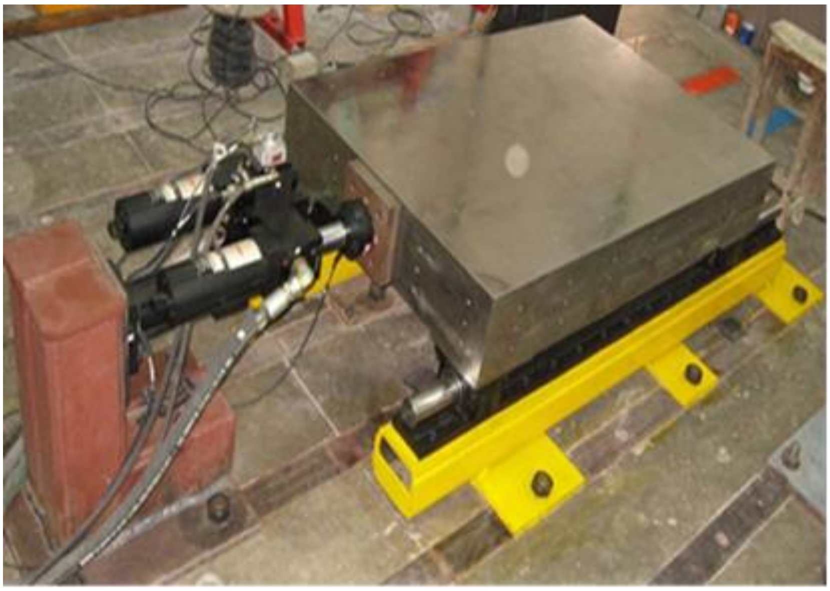

Fig. 8 – Shake table test facility available at IIT Kanpur

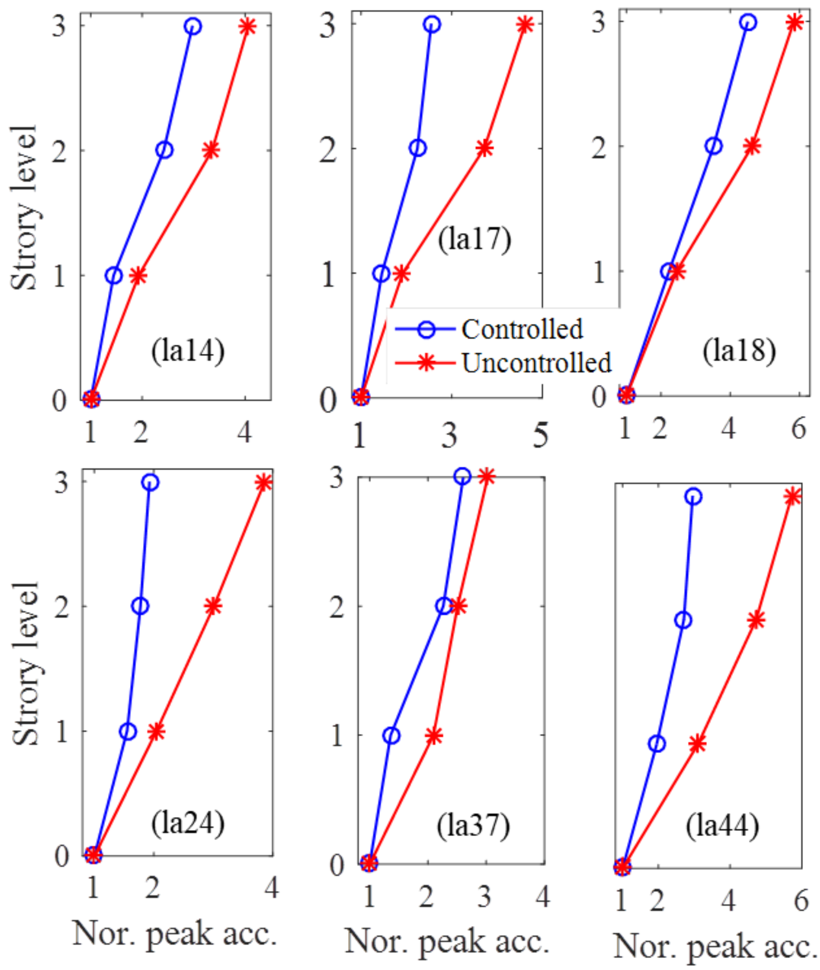

Fig. 9 – Story-wise variation of the normalized uncontrolled and controlled peak acceleration of the structure when subjected to (a) la14, (b) la17 (c) la 18 (d) la 24 (e) la 37 and (f) la37

7. Conclusions

A new implementation on the tuned liquid damper is proposed to tune the damper to a short period structure. Two short-period structures are considered. The equations of the motion of the structure damper system are derived and solved numerically to obtain optimum damper parameters. The damper performance is demonstrated in reducing the structural acceleration by adopting the optimum damper parameters and employing a set of selected ground motions. From the numerical demonstration, it is concluded that the proposed structure damper system is effective in reducing the response. The numerical efficiency is further verified by conducting the shake table test. It is concluded that the proposed damper system is effective and robust in reducing the structural acceleration among all the stories.

8. References

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