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Seismic Response Control of Structures using Liquid Column Vibration Absorber Considering Real Earthquake Ground Motions

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***Abstract*-- In this paper the performance of Liquid Column Vibration Absorber (LCVA) to mitigate structural vibrations considering different real earthquake time history data is investigated. To evaluate the significance of the parameters like mass ratio, frequency tuning ratio, length ratio, blocking ratio and area ratio, on the effectiveness of the LCVA for different earthquakes, a similar parametric analysis is performed using a time domain method. The result of the study shows that LCVA is very much effective in reducing the structural response to seismic excitations and the parameters play significant role in the performance of LCVA and some of them are also sensitive to the nature of the excitation.**

Keywords- Real earthquake time history; liquid column vibration absorber; vibration control; parametric study;

I. INTRODUCTION

Liquid dampers become more popular in recent days to reduce the seismic responses of structures, due to their low implementation cost, easier handling and low maintenance cost, and like other passive devices, they do not usually interfere with vertical and horizontal load paths. One of these devices, the Tuned Liquid Column Damper (TLCD), suppress the input energy by the combined action of the movement of the mass in the U-shaped container, the restoring force on the liquid due to gravity and the damping due to liquid movement through the orifices. Tuned Liquid Column Damper (TLCD), LCVA is one type of TLCD whose vertical cross section area is different from its horizontal cross sectional area. Sakai et al (1989) proposed the nonlinear mathematical expression of the TLCD. Watkins (1991) tested a different TLCD, the liquid column vibration absorber (LCVA). In recent years many experimental and theoretical studies have been carried out on the evaluation of LCVA performance in suppressing the structural vibrations. However most of them have investigated the performance of LCVA under sinusoidal loadings, wind excitations, and relatively few studies has been carried out on the seismic performance of LCVAs (Chang and Hsu 1998; Chakraborty et al. 2011).

In this paper the performance of Tuned Liquid Column Damper (LCVA) to control the earthquake induced structural vibrations is investigated using different past earthquake data. A similar parametric numerical analysis, involving the effects of the parameters like mass ratio, frequency tuning ratio, length ratio, and blocking ratio is carried out for different seismic time history data, using a time domain method (The Newmark-beta linear acceleration method) to deal with the nonlinearity of the governing equations, the variations of the different parameters are noted for different natures of the excitation. It is shown that the effectiveness of LCVA to reduce structural displacement and acceleration are very much dependent upon the nature of the earthquakes but overall it performs exceptionally well for all earthquakes. Although the parameters like mass ratio, frequency tuning ratio, length ratio, area ratio play significant role in the performance of LCVA and some of them are also sensitive to the nature of the excitation, few general conclusions are made in which the LCVA is more effective.

II. THE EQUATION OF MOTION OF STRUCTURE AND LCVA SYSTEM

A LCVA is a U-shaped liquid column tube whose vertical cross section area is different from its horizontal cross sectional area is attached to the top of a primary structure. A building is modeled as a SDOF structure and a LCVA is mounted on top of the primary structure as shown in Fig. 1. The horizontal and vertical cross section area, horizontal length, vertical height of liquid and the liquid mass density (generally water) are represented by A_h, A_v, B, h and ρ respectively. The total length of the liquid column is, L = (B+2h).The mass of the damper, $m_d = (\rho A_h B + 2\rho A_v h)$, ignoring the mass of the liquid container, which can be included within the mass of the primary structure.

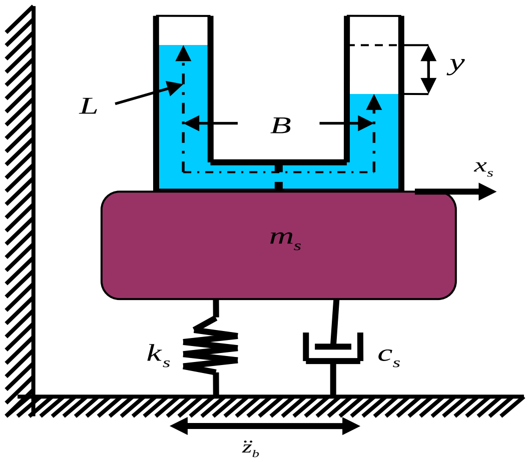

Fig.1: Simplified LCVA-structure system.

A. The equation of motion of LCVA:

Due to the earthquake motion the structure-LCVA system is subjected to base acceleration $\ddot{z}_b$. If the relative horizontal displacement of SDOF system and the liquid surface displacement is represented by x and y, the equation of motion of liquid column will be

$$\rho A_h L_{ee}\ddot{y}+\frac{1}{2}\rho A_h \xi|\dot{y}|\dot{y}+2\rho g A_h y=-\rho A_h B(\ddot{x}+\ddot{z}_b) \quad (1)$$

Normalizing the above equation by liquid mass in the container, $\rho A_h L_{ee}$

$$\ddot{y}+\frac{\xi|\dot{y}|\dot{y}}{2L_{ee}}+\frac{2g}{L_{ee}}y+\rho\frac{L}{L_{ee}}\ddot{x}=-\rho\frac{L}{L_{ee}}\ddot{z}_b \quad (2)$$

Where $p=\frac{B}{L}$ is the length ratio. (Length ratio is the length of the horizontal portion of LCVA to its total length). Tuning ratio $\gamma=\frac{\omega_d}{\omega_s}$, where $\omega_d=\sqrt{\frac{2g}{L_{ee}}}$ is the frequency of the damper where $L_{ee}=L\{1+p(r-1)\}$ and ω_s is the frequency of the primary structure and area ratio $r=\frac{A_v}{A_h}$.

The co-efficient of head loss, ξ is determined using equation (3) (By Wu et al. 2005).

$$\xi=(-0.6\varphi+2.1\varphi^{0.1})^{1.6}(1-\varphi)^{-2} \quad (3)$$

Where φ is the blocking ratio.

B. The equation of motion of structure with LCVA

The equation of motion of primary structure with LCVA can be written as

$$(m_s+m_d)\ddot{x}+c_s\dot{x}+k_s x=-(m_s+m_d)\ddot{z}_b+r\rho A_h B\ddot{y} \quad (4)$$

Where, m_s, k_s, c_s are the mass, stiffness and damping of the primary structure.

Simplifying the above equation

$$(1+\mu)\ddot{x}+2\xi_s\omega_s\dot{x}+\omega_s^2 x+\frac{\mu p L}{L_{em}}\ddot{y}=-(1+\mu)\ddot{z}_b \quad (5)$$

Where, $\mu=\frac{(\rho A_h B+2\rho A_v h)}{m_s}$ (mass ratio) , $c_s=2\xi_s\omega_s m_s$ and $L_{em}=\left(\frac{B}{r}+2h\right)$.

From Eqns. (2) and (5)

$$\begin{bmatrix}(1+\mu) & \frac{\mu p L}{L_{em}}\\ \frac{pL}{L_{ee}} & 1\end{bmatrix}\begin{Bmatrix}\ddot{x}\\ \ddot{y}\end{Bmatrix}+\begin{bmatrix}2\xi_s\omega_s & 0\\ 0 & \frac{\xi|\dot{y}|}{2L_{ee}}\end{bmatrix}\begin{Bmatrix}\dot{x}\\ \dot{y}\end{Bmatrix}+\begin{bmatrix}\omega_s^2 & 0\\ 0 & \frac{2g}{L_{ee}}\end{bmatrix}\begin{Bmatrix}x\\ y\end{Bmatrix}=-\begin{Bmatrix}(1+\mu)\\ \frac{pL}{L_{ee}}\end{Bmatrix}\ddot{z}_b \quad (6)$$

III. NUMERICAL STUDY

For this study a building is modeled as a SDOF structure and a LCVA is mounted on top of the primary structure as shown in Fig. 1, used for the analysis. The properties of primary structure are m_s=3.0×10^5 kg, k_s=8.2247×10^6 N/m and damping ratio of structures, $\xi_s=2\%$.The structure has a natural frequency f1 =0.8333 Hz, which is tuned by frequency of the LCVA. To know the impact of seismic excitations on the performance of LCVA, some past earthquake ground motion records are selected for the analysis. The structure is analyzed twice, once without LCVA and again with a LCVA attached to the top, subjected to past earthquake ground motion records varying with different parameters. The structure without and with LCVA is subjected to previously selected past earthquake data of Park field earthquake (1966), EL-Centro earthquake (1940), Nepal earthquake (2015), and Eastern turkey earthquake (2011).for different mass ratios.

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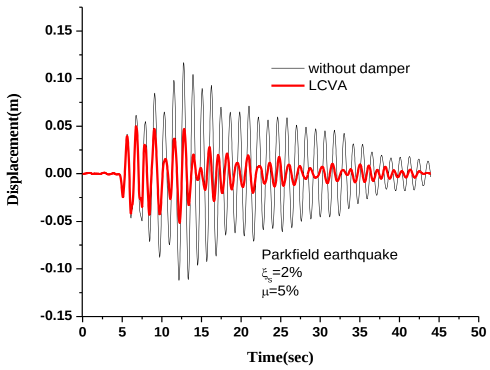
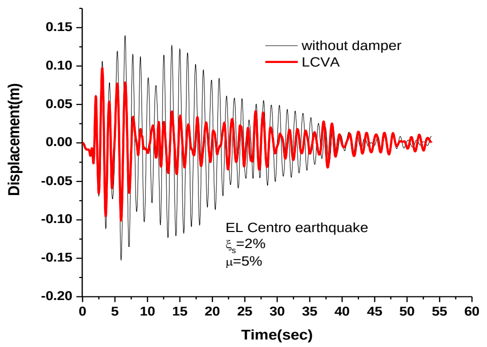
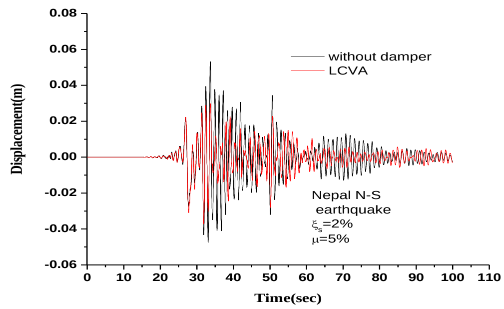
The variation of displacements of structures with time considering time history data of previously selected earthquakes using LCVA and without damper have been shown in Figs. 2 and Table-1, which shows the effectiveness of the damper in reducing peak structural responses for different mass ratios. The results show that the effectiveness of the LCVA to reduce the structural displacement very significant for some earthquake records and for some records the reductions are not that much effective. For 5% mass ratio and for Parkfield and Eastern turkey earthquake, the peak displacement reductions are 55.91% and 58.53% while for same mass ratio and for EL-Centro and Nepal earthquake data, the reduction are 33.79% and 29.94%.



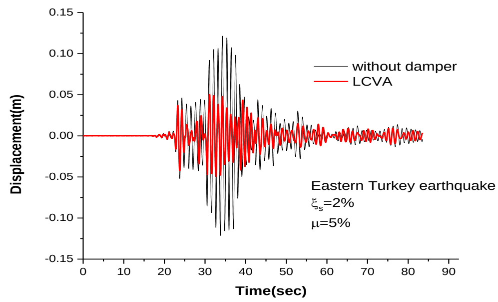
(a) Parkfield earthquake (1966).



(b) EL-Centro earthquake (1940).



(c)Nepal earthquake (2015).



(d) Eastern turkey earthquake (2011).

Fig. 2: Variation of displacement of structures considering real time history data of (a) Parkfield earthquake (1966), (b) EL-Centro earthquake (1940), (c)Nepal earthquake (2015),(d)Eastern turkey earthquake (2011), for Mass ratio = 5%, Damping ratio of structures=2% and, Length ratio=0.8.

The variation of structural acceleration with time considering time history data of Parkfield earthquake (1966), EL-Centro earthquake (1940), Nepal earthquake (2015), and Eastern turkey earthquake (2011), with LCVA and without damper are shown in Fig. 3 and Table-2. From Fig. 3 and Table-2 one can see that peak structural acceleration reduction capacity is not that much significant, this problem is important for acceleration sensitive component, such as non structural components, although this observation needs more extensive analysis for confirmation. The results also confirm that the effectiveness of the LCVA to reduce structural response is highly dependent upon the nature of the excitations but overall it performs exceptionally well for all earthquakes. From Figs. 2 and 3, it can also be seen that overall structural displacement and acceleration reduction capacity of LCVA is very good.

Table-1: Values of maximum displacement of structure without and with LCVA and corresponding effectiveness of LCVA taking structural damping=2%, frequency tuning ratio=1, blocking ratio=0.1 and length ratio=0.8

Earthquakes	Maximum displacement(m)					% Reduction			
	Without damper	With LCVA				With LCVA			
		Mass ratio				Mass ratio			
		1%	3%	5%	7%	1%	3%	5%	7%
Parkfield	0.1168	0.0997	0.0692	0.0515	0.0458	14.64%	40.75%	55.91%	60.79%
El -centro N-S	0.1524	0.1403	0.1189	0.1009	0.094	7.94%	21.98%	33.79%	38.32%
Nepal N-S	0.0531	0.0477	0.0392	0.0372	0.035	10.17%	26.18%	29.94%	34.09%
Eastern turkey	0.1213	0.0988	0.0659	0.0503	0.0457	18.55%	45.67%	58.53%	62.32%

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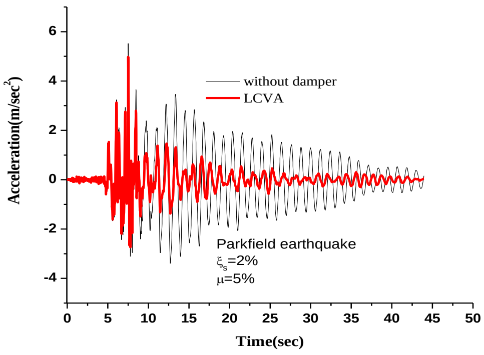
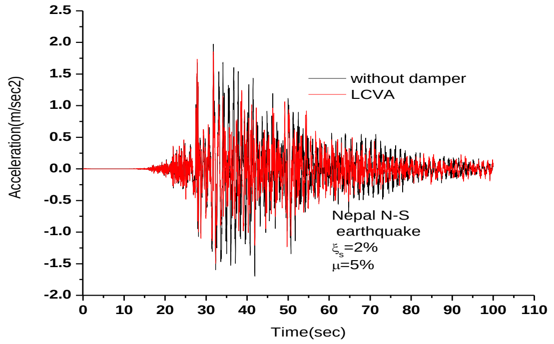
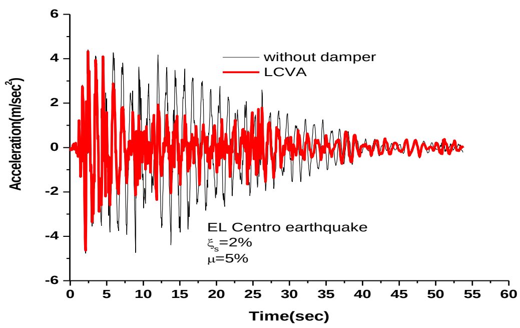


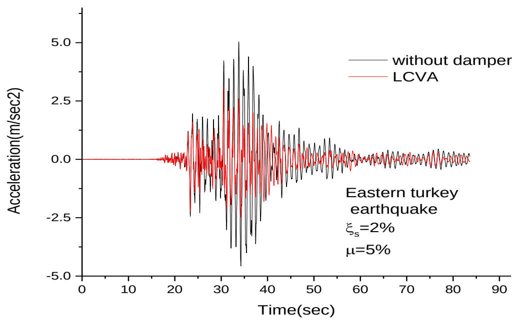
(a) Parkfield earthquake (1966).



(c)Nepal earthquake (2015).



(b) El Centro earthquake (1940).



(d) Eastern turkey earthquake (2011).

Fig. 3: Variation of acceleration of structures considering real time history data of (a) Parkfield earthquake (1966), (b) EL-Centro earthquake (1940), (c) Nepal earthquake (2015), (d) Eastern turkey earthquake (2011), for mass ratio=5%, Damping ratio of structures=2%, Length ratio=0.8.

Table-2: Values of maximum acceleration of structure without and with LCVA and corresponding effectiveness of LCVA taking structural damping=2%, frequency tuning ratio=1, blocking ratio=0.1 and length ratio=0.8

Earthquakes	Maximum structural acceleration(m/sec^2)					% Reduction			
	Without damper	With LCVA				With LCVA			
		Mass ratio				Mass ratio			
		1%	3%	5%	7%	1%	3%	5%	7%
Parkfield	5.5168	5.4011	5.1822	4.9794	4.7919	2.10%	6.07%	9.74%	13.14%
El -centro N-S	4.7706	4.7439	4.6915	4.6403	4.5903	0.56%	1.66%	2.73%	3.78%
Nepal N-S	1.9749	1.9625	1.912	1.8542	1.7878	0.63%	3.18%	6.11%	9.47%
Eastern turkey	5.0328	4.3143	3.4387	3.1175	2.9669	14.28%	31.67%	38.06%	41.05%

Mass ratio is the most important parameter influencing the effectiveness of LCVA in reducing the structural displacement. Mass ratio can be defined as the ratio of the mass of the damper to the mass of structure. It is evident from Table-1 and Fig. 4 that LCVA with higher mass ratio is more effective in suppressing the structural displacement. To incorporate higher mass and to maintain the liquid column shape the LCVA can consist of small diameter tubes of same length, as the natural frequency of LCVA depends only on its length.

Much higher value of mass ratio is not effective as they add to the inertial load on the structure due to base excitations. Also a higher mass ratio is impractical due to the space requirements.

And much higher mass ratio also increases the overall loading in structures, in real life applications. In the range of mass ratio 0.05 to 0.07 LCVA can effectively reduce the structural displacements without hampering the overall loading conditions.

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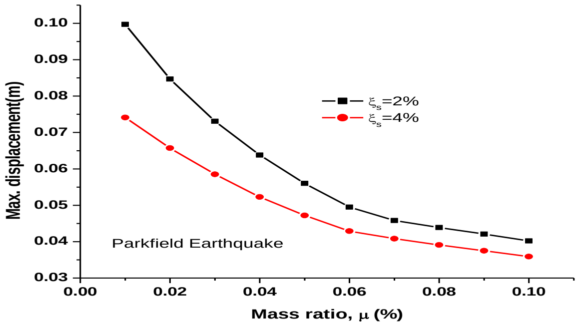
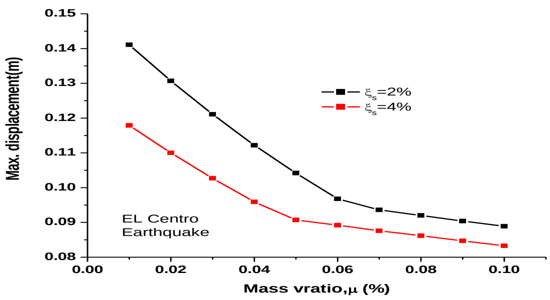
Fig. 5 shows the influence of length ratio in peak liquid and structural displacement. If the value of length ratio is increased gradually the value of maximum structural displacement is gradually reduced, and the liquid displacement is increasing.



(a) Parkfield earthquake (1966).

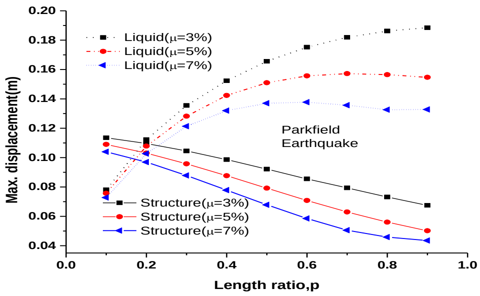


(b) EL-Centro earthquake (1940).

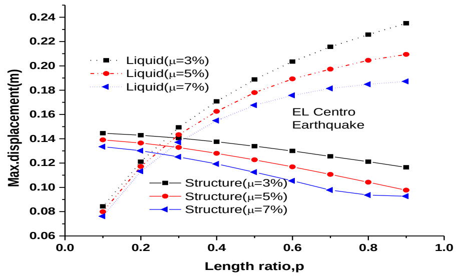
Fig. 4: Variation of maximum Displacement of structures with mass ratio for 2% and 4% damping ratio of structure considering real time history data of (a) Parkfield earthquake (1966), (b) EL-Centro earthquake (1940).

With a higher length ratio LCVA can reduce the maximum structural response more efficiently. This is because the mass of the horizontal part of the LCVA is the only effective mass of LCVA acting on the structure. However length ratio is limited by the liquid displacement bounded values, cause with higher increase of the liquid displacement there is the chance of being out of tuned as a result the efficiency of the LCVA will reduce.

Fig. 6 shows that with increase in blocking ratio the liquid displacement is decreasing while the structural displacement is increasing. Though the coefficient of head loss is depend upon the blocking ratio but the higher value of blocking ratio is not considerable as with increase the blocking ratio the movement of liquid will decrease as a result energy dissipation by movement of liquid mass will decrease.

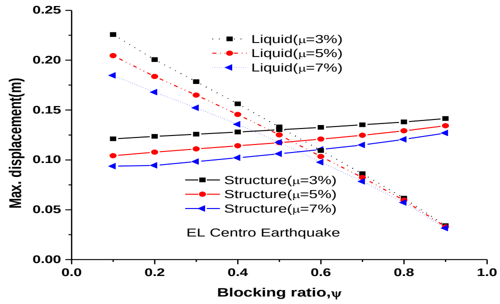


(a) Parkfield earthquake (1966).

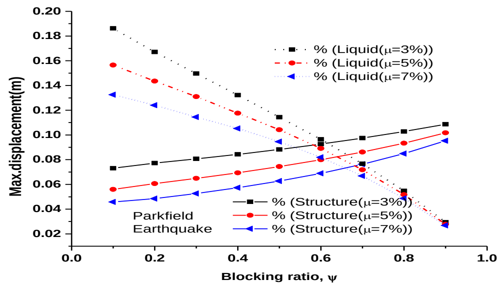


(b) EL-Centro earthquake (1940).

Fig 5: The influence of length ratio on the maximum displacement of structure and liquid for 3% and 5% and 7% mass ratio considering real time history data of (a) Parkfield earthquake, (b) EL-Centro earthquake



(a) Parkfield earthquake (1966).

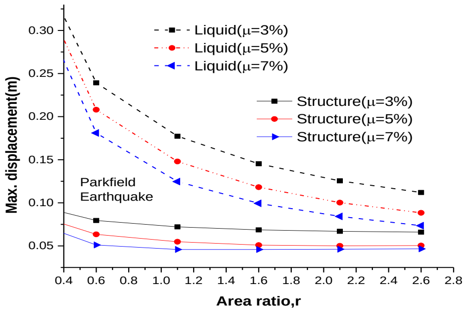


(b) EL-Centro earthquake (1940).

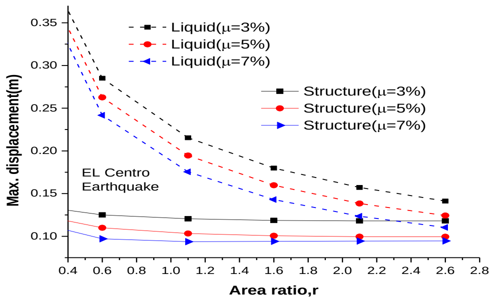
Fig. 6: The influence of blocking ratio on the maximum displacement of structure and liquid for 3%, 5% and 7% mass ratio considering real time history data of (a) Parkfield earthquake, (b) EL-Centro earthquake

Moreover from Fig. 5 and Fig. 6 it can be concluded that in the range of length ratio 0.7 to 0.8 and blocking ratio 0.1 to 0.3 the LCVA is more efficient.

Fig. 7 shows that with increase in area ratio the liquid displacement as well as the structural displacement is decreasing. As the liquid and structural displacement decreasing, the efficiency of LCVA will increase and there is less chance of being out of tuned and could be a possible advantage when headroom is restricted. From Fig. 7 it can be concluded that in the range of area ratio 1.5 to 2 the LCVA is more efficient.



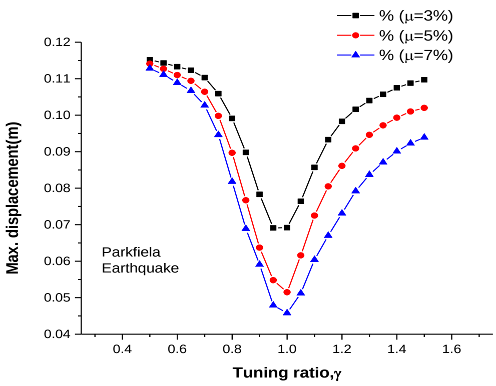
(a) Parkfield earthquake (1966).



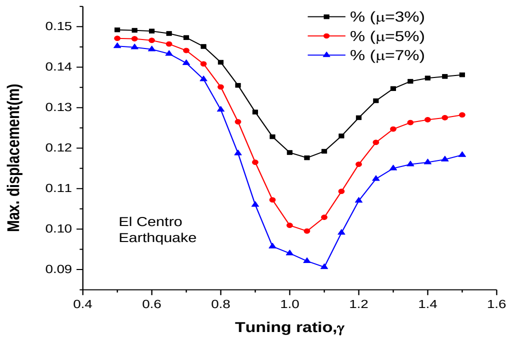
(b) EL-Centro earthquake (1940).

Fig. 7: The influence of area ratio on the maximum displacement of structure and liquid for 3%, 5% and 7% mass ratio considering real time history data of (a) Parkfield earthquake, (b) EL-Centro earthquake

It is very important that LCVA should be tuned properly with the structural frequency for better performance. The optimal tuning ratio not only depends upon the mass ratio and the damping of structure but also depends upon the nature of the excitations. Although the influence of the tuning ratio on the effectiveness of the damper is different for different earthquake nature, and slightly change with the change of mass ratio, still, it can be seen from Fig. 6 that in the range of tuning ratio, γ 0.9 to 1.1 the LCVA is more efficient in controlling the structural response.



(a) Parkfield earthquake (1966).



(b) EL-Centro earthquake (1940).

Fig. 8: Variation of max. Displacement of structures with tuning ratio for 2% damping ratio and 3%, 5% and 7% mass ratio considering real time history data of (a) Parkfield, (b) EL-Centro earthquake.

IV. CONCLUSIONS

The result of the study shows that with the proper design parameters LCVA is efficient to reduce peak structural displacement due to the seismic excitations while the peak acceleration reduction capacity is comparatively less, but overall structural displacement and acceleration capacity is very efficient. The study also shows that the parameters play significant role in the performance of the LCVA and some of the parameters are also sensitive to the nature of the excitations, some similarities is found in the nature of the behavior of the damper due to different type of earthquake excitations, which is very helpful in designing the damper for real life applications. Although the structural displacement and acceleration reduction capacity of LCVA are highly depends on the nature of the excitation but overall it performs exceptionally well for all earthquakes, by standing out the maximum structural displacements and also rapid response decay. This is very beneficial in real life, by enhancing occupants comfort and safety in flexible building with low intrinsic structural damping.

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