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Estimation of the Efficacy of Tuned Liquid Column Damper using Frequency Response Curves

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Abstract** - The Tuned Liquid Column Damper (TLCD) efficacy in the dynamic response control of structure has been investigated. The TLCD is a passive device that consists of a U-shaped tube filled with liquid columns that exhibit non-linear damping resulting from the hydrodynamic head loss observed inside the liquid column. In the present study, the response of a single degree of freedom (SDOF) system equipped with TLCD under the harmonic base excitation has been investigated. The parametric study includes estimates of maximum Displacement and maximum Acceleration using the non-linear coupled governing differential equation of motion. Mass ratio and length ratio in the frequency domain and varying base acceleration intensity was studied. This study aims to obtain the optimal combination of TLCD parameters' values, aiming to achieve the most optimized peak maximum response of the structure in the frequency domain. The results showed that the set of optimum parameters' values could be effectively applied in the design of TLCD in attenuating the dynamic response of structures.

Keywords - *Tuned Liquid Column Damper, Frequency Response Curves, Non-linear Damping, Mass Ratio, Base Acceleration.*

I. INTRODUCTION

In the present era, modern cities are growing fast, the shortage in land space and increasing population resulted in the construction of tall structures. The modernization in structural engineering and advanced construction technologies has led to lighter and flexible, tall structures and buildings vulnerable to dynamic loads like winds and earthquakes. The dynamic transverse loads on taller structures cause structural vibrations, which can become unacceptable from the serviceability, safety, and comfort point of view of the buildings' occupants. Structural design engineers and researchers worldwide face this challenge to attenuate the structural vibrations from the dynamic environmental loads like winds and earthquakes, and they are continuously working on finding the different kinds of structural systems that are robust and simple at the same time.

The dampers' installation was the conventional way of regulating the vibration of the structures, but it was effective. These can be used to mitigate the damaging impact of the structures induced by dynamic loads, which is accomplished by dissipating the structural vibration energy with the dampers mounted. The vibration control systems are broadly classified as Passive, Active, and Hybrid systems. This paper's study and research are focused in particular on a specific type of passive vibration control device called the Tuned liquid column damper (TLCD).

The Tuned liquid column damper consists of two vertical columns filled with a liquid whose vibration frequency is tuned to the structural natural vibration frequency, connected by a horizontal crossover duct of the same width and area forming a U-shaped type tube container, See Figure.1(a). The structure's vibration energy is dissipated through the damping effect produced by the headloss caused by the continuous flow motion of liquid through the two vertical columns and a horizontal crossover duct. The liquid kept typically is water, which can be advantageous in water supply and fire-fighting purposes. The tuned liquid column damper draws various advantages over other passive vibration control systems like Tuned mass dampers (TMD), Friction Dampers, Viscous Dampers, handling and installation, and easy liquid frequency tuning with structure, very few maintenance requirements, and lower cost.

Several past studies have contributed in the field of vibration control of structures using TLCD and other passive devices.TLCD was first proposed by Sakai et al. [1], which reduces wind-induced horizontal loads of tall structures. Xu et al. [2] investigated the efficiency of TLCD for controlling wind-induced vibration of a structure. The wind-induced vibration of towers was effectively controlled by TLCDs. Balendra et al. [3] studied the effectiveness of TLCD in controlling the wind-induced vibration of towers and in the suppression of wind-induced Acceleration of towers with different fundamental frequencies. Hitchcock et al. [4][5] first investigated the effects of the geometric configuration of liquid column vibration absorber (LCVA) without orifices and later, by performing experiments, observed the characteristics of rectangular-based bidirectional LCVAs (without orifices). The wind-induced vibration of a building was handled effectively using unsteady and non-uniform flow equations while studying the performance and effectiveness of an LCVA by Chang et al. [7]. The optimal parameters of a TLCD using a single degree of freedom system under the white noise excitations representing wind and seismic loadings are investigated by Yalla et al. [8].

The applicability of the TLCD for the seismic vibration control of short-period structures has been explored by Ghosh et al. [9]. In both the analytical and experimental results, the accurately tuned TLCD system could effectively reduce the dynamic response of the offshore platform system in terms of the vibration amplitude and the resonant frequency. Wong et al. [10] performed an analytical and experimental study and observed that the accurately tuned TLCD system could effectively reduce the dynamic response of the offshore platform system in terms of the vibration amplitude and the resonant frequency. Wu et al. [11] studied the optimization of TLCD with non-uniform cross-sections for application to an SDOF structure in a horizontal motion, facilitated by a non-iterative analytical response solution (closed-form solution) approach. Al-Saif et al. [12] proposed a modified TLCD as tuned liquid column ball damper (TLCBD) for structures vibrating at low frequencies, conducted a numerical study, and found a better vibration suppression capability of the proposed TLCBD compared to traditional TLCD. Chakraborty et al. [14] obtained optimum parameters of TLCD considering system parameters as uncertain bounded type under earthquake load by Robust Design Optimization approach. The vibration control of a structure by a TLCD with embossments is studied by Park et al. [15], the controlled performance of TLCD with embossments was found efficient and superior, compared to that of the conventional TLCD.

In this paper, a parametric study is conducted by varying some of the significant parameters of TLCD that are mass ratio and length ratio. The effect of varying the excitation base acceleration intensity on the structural response is also considered in the study. The frequency response curves are developed for the system to investigate the effectiveness of TLCD in attenuation of the dynamic response of the structure, subjected to an exciting harmonic base acceleration. This paper aims to obtain the optimal combination of TLCD parameters' values to achieve the most optimized peak maximum response of the structure in the frequency domain. The uncontrolled system's maximum peak response is compared with the controlled system's optimized maximum peak response in terms of the percentage response reduction of maximum peak Displacement and peak maximum Acceleration.

II. MATHEMATICAL MODELLING AND NUMERICAL STUDY

A. The Non-linear Coupled Governing Differential Equations of the Motion

The schematic diagram of a single degree of freedom (SDOF) structure equipped with a TLCD in horizontal motion is shown in Figure. 1(a). The equivalent Spring Mass System for this SDOF structure system equipped with TLCD can be idealized as shown in Figure. 1(b).

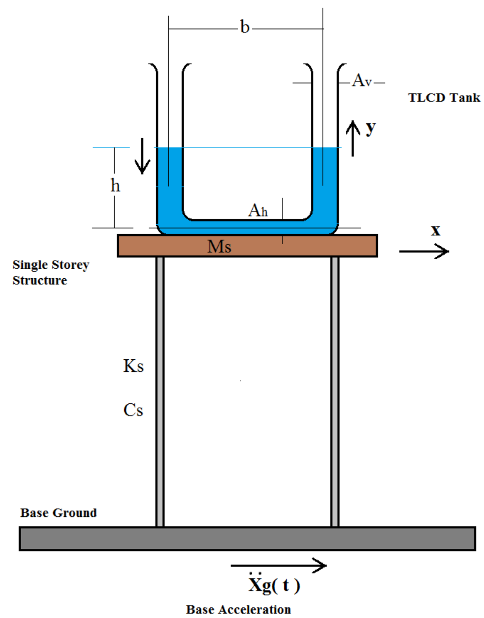

Figure. 1(a): Modeling of a single-story structure equipped with TLCD, idealized as SDOF system.

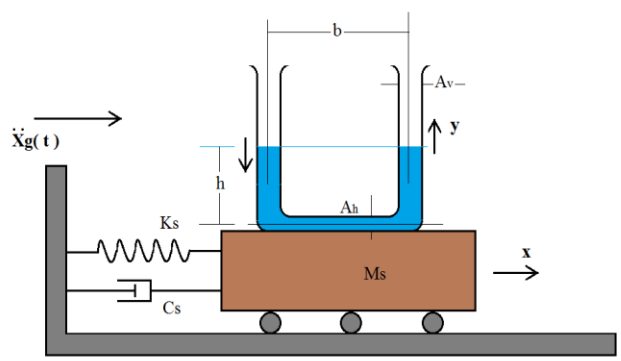

Figure. 1(b): An equivalent spring-mass system for SDOF structure system equipped with TLCD.

It is assumed that for TLCD, The fluid taken as the damper is incompressible (i.e., the flow rate is constant), depicting that water is a nice choice and the in-plane width of the TLCD vertical column cross-section is much smaller than its horizontal length. The sloshing effect on the liquid surface is considered negligible (when the structural frequency is as low as 0.5 Hz or even lower, which is very normal for high-rise structures, this is considered fulfilled.).

Using Lagrange's equations and energy principles, the coupled non-linear governing differential equations of motion for the structure and liquid motion in a TLCD can be expressed as [7]

$$(\mathbf{M_s} + \mathbf{M_d})\ddot{\mathbf{x}} + \mathbf{C_s}\,\dot{\mathbf{x}} + \mathbf{K_s}\,\mathbf{x} + \boldsymbol{\rho}\mathbf{Ab}\,\mathbf{y} = -(\mathbf{M_s} + \mathbf{M_d})\ddot{\mathbf{X}}_\mathbf{g}(\mathbf{t}) \quad \text{- (1)}$$

And

$$(\boldsymbol{\rho}\mathbf{AL_{ee}})\ddot{\mathbf{y}} + \left(\frac{1}{2}\right)\boldsymbol{\rho}\mathbf{A}\boldsymbol{\xi}\,|\dot{\mathbf{y}}|\dot{\mathbf{y}} + (\mathbf{2}\boldsymbol{\rho}\mathbf{Ag})\,\mathbf{y} + (\boldsymbol{\rho}\mathbf{Ab})\,\ddot{\mathbf{x}} = -(\boldsymbol{\rho}\mathbf{Ab})\ddot{\mathbf{X}}_\mathbf{g}(\mathbf{t}) \quad \text{- (2)}$$

In equations (1) and (2), '**x**' and '**y**' denote displacements of the structure and liquid surface, respectively. '**Ms**,' '**Cs**,' '**Ks**' are structural mass, damping and stiffness constant. '**b**' and '**h**' are horizontal and vertical column lengths, '**A**' is a cross-sectional area in horizontal and vertical columns, respectively, '**ρ**' is the density of the liquid, '**g**' is the acceleration due to gravity, '$\mathbf{L_{ee}} = (\mathbf{b} + \mathbf{2h})$' is defined as the effective length and '**ξ**' is head loss coefficient. (The headloss can be considered the overall headloss generated by flow motion in the liquid column). From Equation. (2), it is easily observed that the natural frequency of a TLCD is $\boldsymbol{\omega_d} = \sqrt{\frac{\mathbf{2g}}{\mathbf{Lee}}}$ rad/sec and the natural period is $\mathbf{T_d} = \mathbf{2\pi}\sqrt{\frac{\mathbf{Lee}}{\mathbf{2g}}}$ Seconds, accordingly. $\ddot{\mathbf{X}}_\mathbf{g}(\mathbf{t})$ is the base ground acceleration. The excitation frequency ratio (ω/ω_s) is the excitation frequency ratio to the structural natural frequency (ωs) controlled by varying external frequencies. The mass ratio (μ) is the ratio of the mass of the fluid damper (M_d) to the mass of the structure (M_s). The length ratio (α) of the liquid column damper is the ratio of the width of the horizontal portion (b) to the total length of the liquid column (L). The tuning ratio (f) is the ratio of the natural frequency of the damper (ω_d) to the natural frequency of the structure (ω_s).

The response reduction of the structure is defined as the ratio of the difference between uncontrolled structure responses and controlled structure to the uncontrolled structure's response. The percentage response reduction can be calculated as follows,

$$\textbf{Percentage Response Reduction} = \frac{(\mathbf{UCR} - \mathbf{CR})}{(\mathbf{UCR})}\,\boldsymbol{X}\,\mathbf{100}$$

Where UCR is an Un-controlled structural response quantity, and CR is a Controlled structural response quantity.

B. Numerical Study

For the study, a single degree of freedom (SDOF) system in the form of a spring-mass-damper system is considered and is equipped with TLCD.

The following values of parameters are considered in the study pertaining to the SDOF system:

(i) The mass of the structure (M_s) = 10,000 kg
(ii) The structural natural frequency (ω_s) = 12.566 rad/sec (Time Period = 0.5 sec)
(iii) The structural damping ratio is considered for the study is 2%.

The following range of the values of parameters is considered in the study pertaining to the TLCD:

(i) The mass ratio (μ) = 1% to 10%
(ii) The length ratio (α) = 0.4 to 0.9
(iii) The tuning ratio (f) = 1.0 (Tuned Condition)
(iv) The density of liquid 'ρ' = 1000 kg/m^3
(v) The acceleration due to gravity'g' = 9.81 m/s^2
(vi) The headloss coefficient here is taken as equal to 10.

The following values of parameters are considered in the study pertaining to the base excitation of SDOF system equipped with TLCD:
Base acceleration function,

$$\ddot{\mathbf{X}}_\mathbf{g}(\mathbf{t}) = \mathbf{X}\,.\,\mathbf{sin}(\boldsymbol{\omega}\mathbf{t}) = \mathbf{C}\,.\,\mathbf{g}\,.\,\mathbf{sin}(\boldsymbol{\omega}\mathbf{t})$$

Where **X**= Acceleration Amplitude
C= Acceleration Intensity Factor = 0.001 to 0.005
g= Acceleration due to gravity

The equations (1) and (2) are modeled in the numerical computing software platform of Matlab and Simulink and is solved by a variable-step method with a maximum step size of 0.8, using the solver ODE45, which is an implicit form of Runge-Kutta Fourth Order numerical method as specified by the software. For the present study, the numerical solution is obtained for the time interval of (0 to 40 sec), with the system initially at rest. By varying the parameters and further developing the Frequency Response Curves in the frequency domain, the study results are obtained.

III. RESULTS AND DISCUSSION

The numerical study results were shown in terms of frequency response curves of maximum Displacement and maximum Acceleration for a given mass ratio and length ratio, and further pertaining to a given acceleration base intensity factor are presented. The frequency response curves are shown in Figure 3(a), Figure 3(b), Figure 4(a), Figure 4(b), Figure 5(a), and Figure 5(b).

The frequency response curves show the maximum response value of the controlled structure for a given particular excitation frequency ratio. The curve indicates a single peak value of the maximum response, found near the resonant frequency for uncontrolled structure. Whereas in the case of controlled structure, the two peaks were found, which indicates the existence of relative motion of liquid column in a tube with respect to that of the horizontal motion of the structure. The interest is in noting the peak values and understanding the maximum value of maximum response reached by the structure and then comparing the controlled structure and uncontrolled structure.

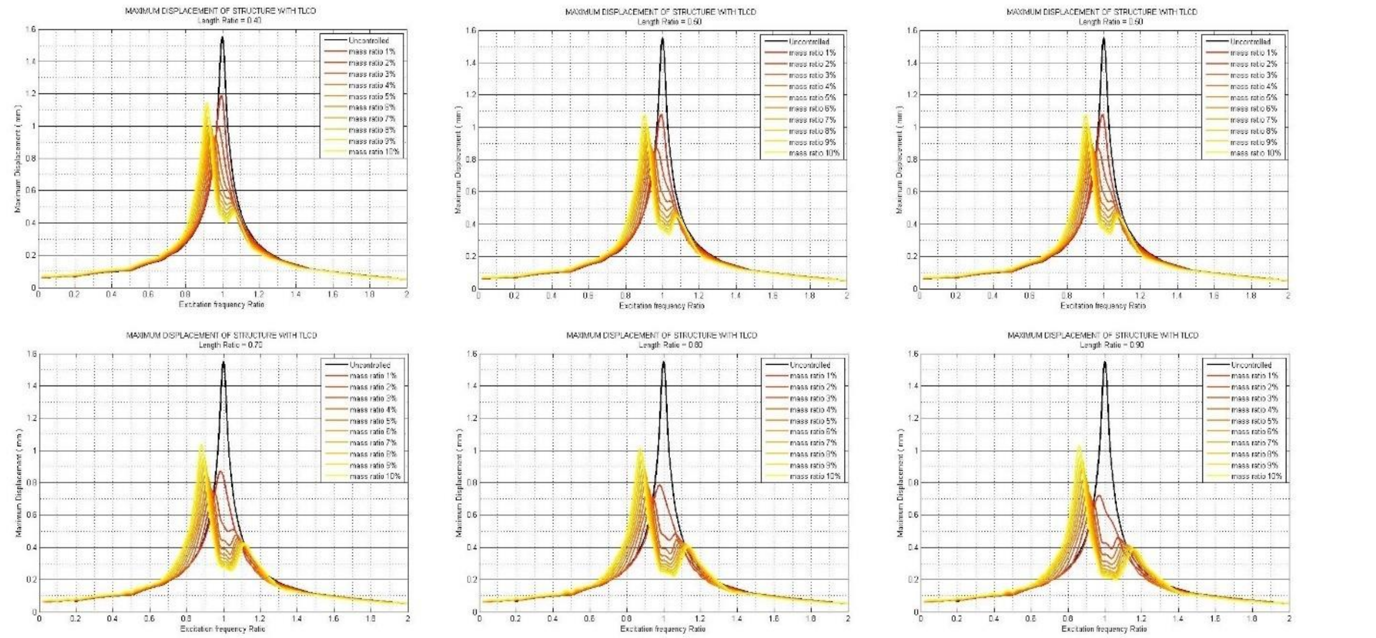

Figure 3(a): Frequency response curves for maximum Displacement of structure, for the base acceleration intensity factor 0.001.

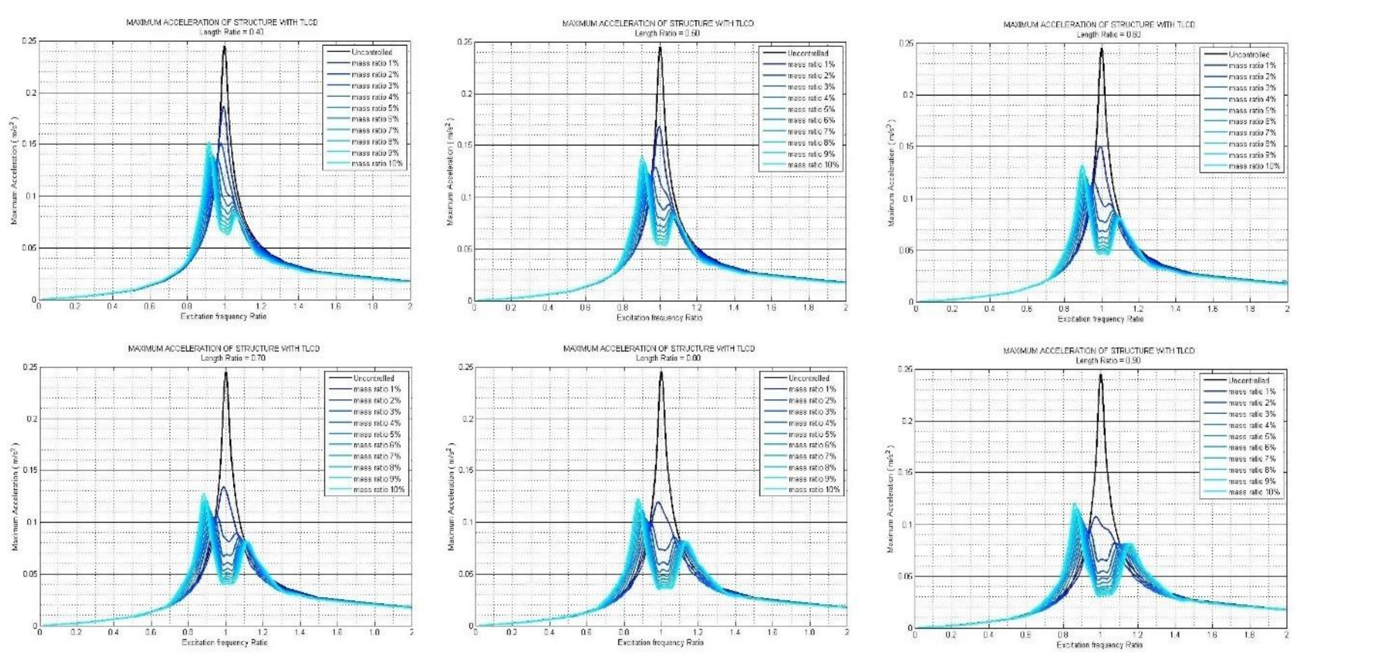

Figure 3(b): Frequency response curves for maximum Acceleration of structure, for the base acceleration intensity factor 0.001.

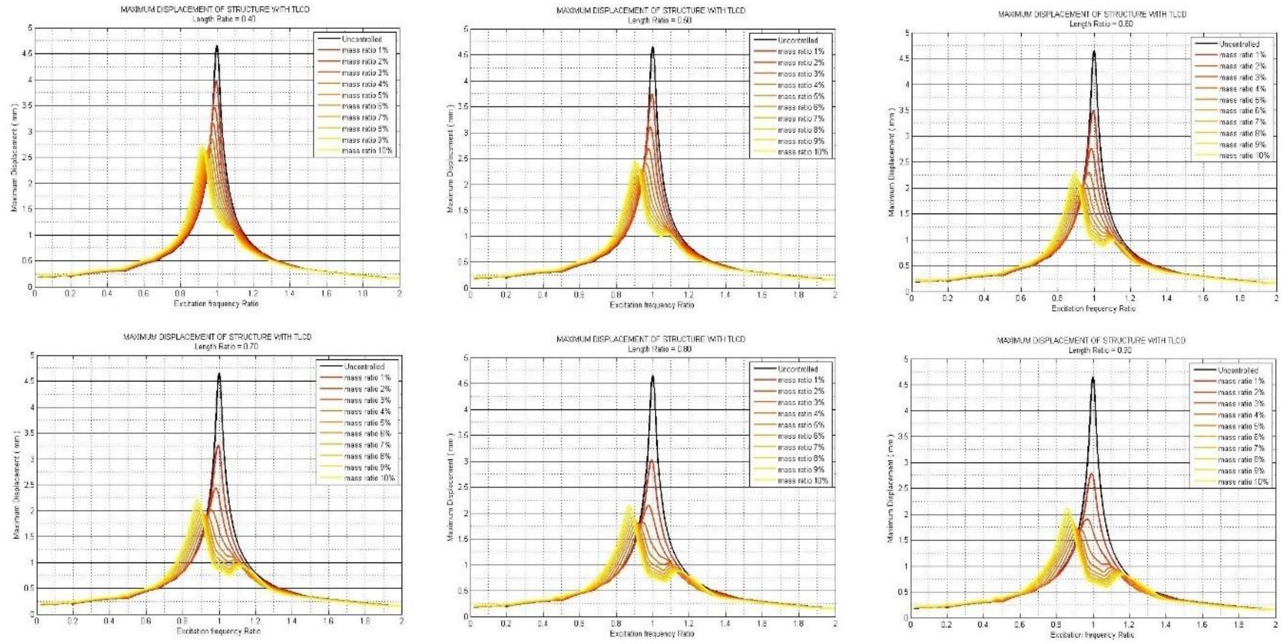

Figure 4(a): Frequency response curves for maximum Displacement of structure, for the base acceleration intensity factor 0.003.

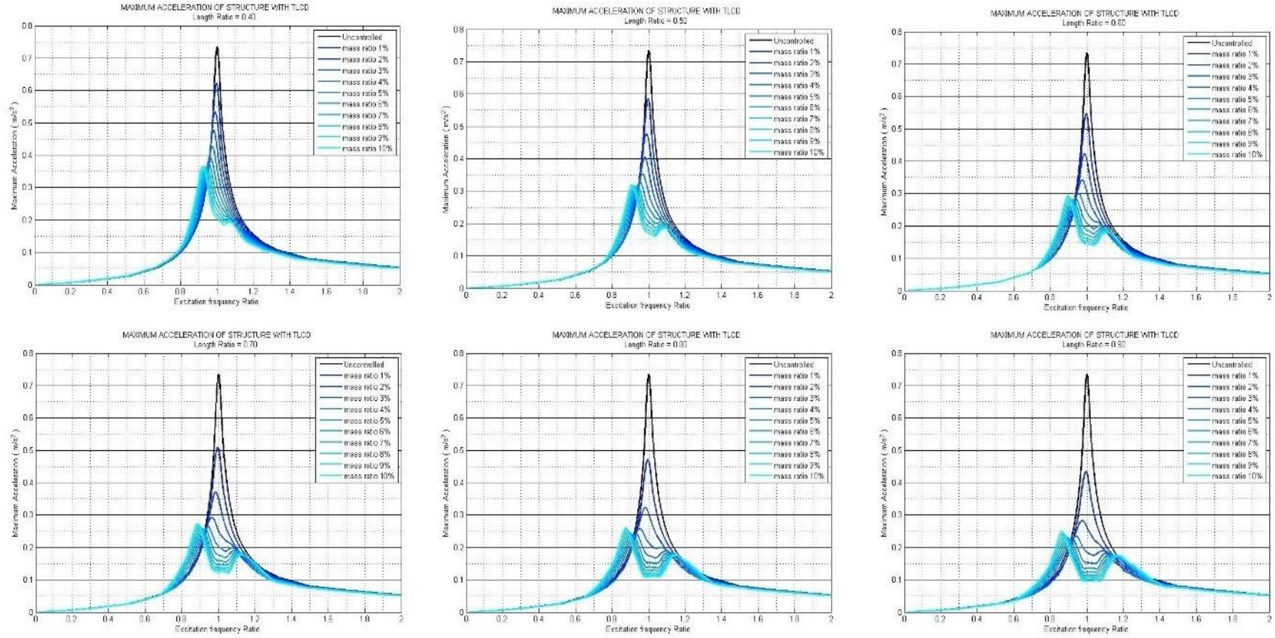

Figure 4(b): Frequency response curves for maximum Acceleration of structure, for the base acceleration intensity factor 0.003.

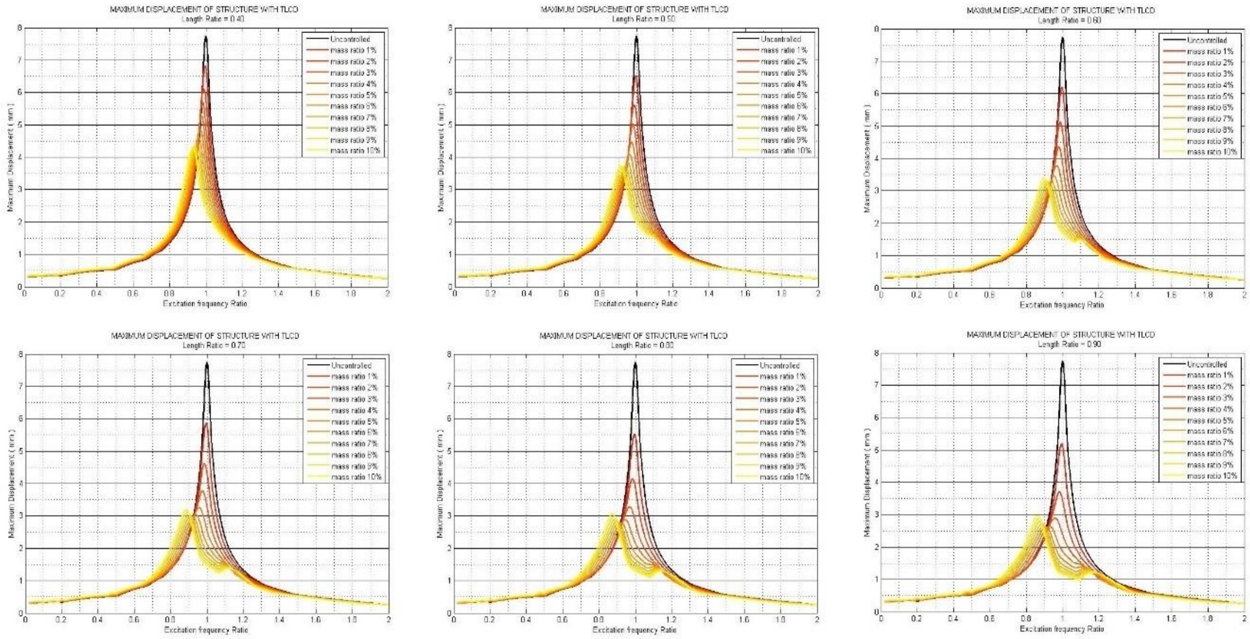

Figure 5(b): Frequency response curves for maximum Displacement of structure, for the base acceleration intensity factor 0.005.

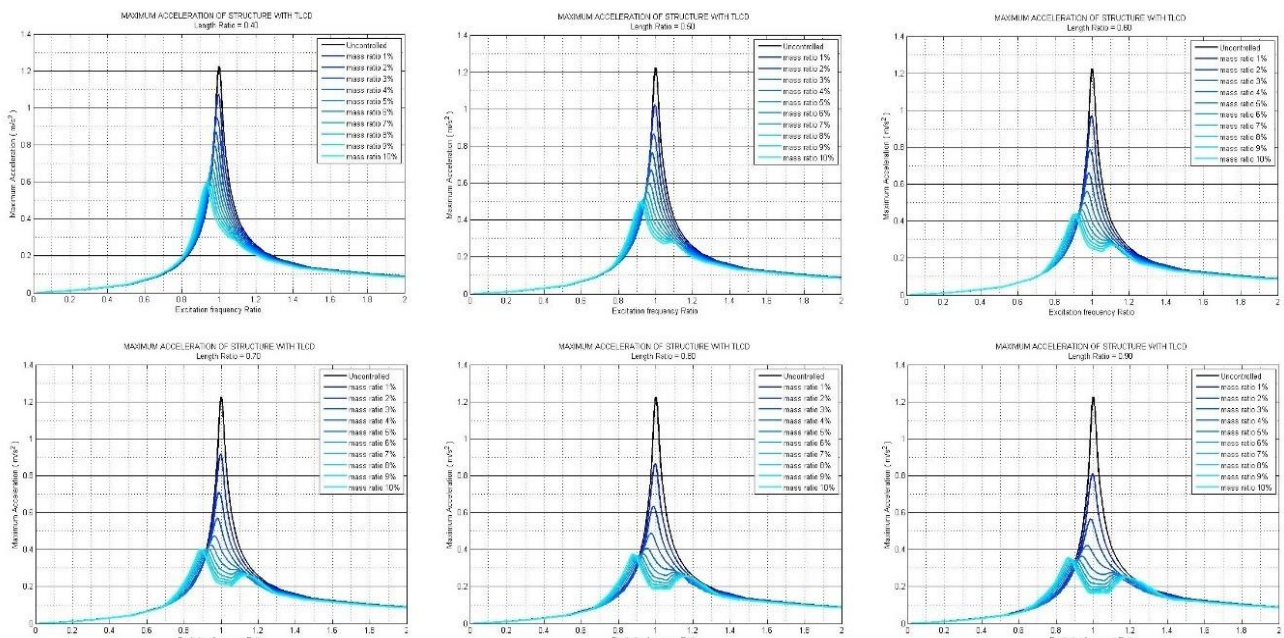

Figure 5(b): Frequency response curves for maximum Acceleration of structure, for the base acceleration intensity factor 0.005.

A. Effect of Mass Ratio

It was found that for a given length ratio, as the mass ratio increases, the peak maximum response value of the structure decreases until a specific mass ratio is reached, further the peak maximum response value of structure starts increasing beyond this specific mass ratio, this specific mass ratio at the point of inflection of curve is referred to as optimum mass ratio. This phenomenon is observed in both the maximum peak Displacement and peak maximum acceleration response of the structure.

The values of optimum mass ratios obtained from the study are given in Table 1a.and Table 1b.for different length ratios and base acceleration intensity factors. Figure 6(a), Figure 6(b), Figure 6(c) shows the graph of peak maximum displacement quantity of the structure obtained from frequency response curves versus the mass ratio corresponding to a particular length ratio. Similarly, Figure 7(a), Figure 7(b), Figure 7(c) shows the graph of peak maximum acceleration quantity of the structure obtained from frequency response curves versus the mass ratio corresponding to a particular length ratio. The study reveals the existence of optimum mass ratio at which optimum peak maximum response of the structure can be achieved in the mass ratio domain. The optimum peak maximum response is the minimum of all the maximum peak response of structure for a given length ratio and occurs at a unique mass ratio, referred to as an optimum mass ratio. The choice of mass ratio in the design of TLCD for controlling the maximum peak response could prove to be very significant and essential for the engineers and researchers working across the world in this discipline.

B. Effect of Length Ratio

By increasing the length ratio with consideration of the optimum mass ratio, the decrease in the structure's peak maximum response is observed. The length ratio of 0.9 showed the most percentage response reduction in the structure's peak maximum response among the other length ratios for a given base acceleration intensity factor. This is depicting that as the length ratio increases, and one can obtain a more optimized mass ratio at which more reduction in the maximum peak response of the structure can be achieved. Table 2 provides the set of length ratio and the mass ratio at which optimum peak maximum response of the structure is observed from among the range of parameters considered in the study.

Table 1a: Optimum Peak Maximum Displacement Value of the Structure equipped with TLCD (Controlled Structure), obtained from Frequency Response Curve and Percentage Response Reduction of Peak Maximum Displacement of Structure.

Base Acceleration Intensity Factor	**Length Ratio**	**Optimum Peak Maximum Displacement Value (mm)**	**Mass Ratio Corresponding to the Optimum Peak Maximum Displacement Value**	**Excitation Frequency Ratio Corresponding to the Optimum Peak Maximum Displacement Value**	**Un-controlled Peak Maximum Displacement (mm)**	**% Response Reduction of Peak Maximum Displacement**
0.001	0.4	0.9270	0.04	0.953	1.5511	40.24
0.001	0.5	0.8392	0.03	0.953	1.5511	45.90
0.001	0.6	0.7888	0.03	0.941	1.5511	49.15
0.001	0.7	0.7360	0.02	0.949	1.5511	52.55
0.001	0.8	0.7052	0.02	0.941	1.5511	54.54
0.001	0.9	0.6806	0.02	0.935	1.5511	56.13
0.002	0.4	1.7617	0.05	0.951	3.1015	43.20
0.002	0.5	1.5702	0.04	0.951	3.1015	49.37
0.002	0.6	1.4321	0.04	0.939	3.1015	53.83
0.002	0.7	1.3371	0.03	0.943	3.1015	56.89
0.002	0.8	1.2582	0.03	0.933	3.1015	59.43
0.002	0.9	1.2061	0.03	0.923	3.1015	61.11
0.003	0.4	2.6045	0.07	0.939	4.6521	44.02
0.003	0.5	2.2751	0.06	0.937	4.6521	51.10
0.003	0.6	2.0513	0.05	0.935	4.6521	55.91
0.003	0.7	1.8999	0.04	0.937	4.6521	59.16
0.003	0.8	1.7777	0.04	0.923	4.6521	61.79
0.003	0.9	1.6963	0.03	0.933	4.6521	63.54
0.004	0.4	3.4513	0.09	0.931	6.2028	44.36
0.004	0.5	2.9768	0.07	0.933	6.2028	52.01
0.004	0.6	2.6585	0.06	0.931	6.2028	57.14
0.004	0.7	2.4421	0.05	0.929	6.2028	60.63

0.004	0.8	2.2827	0.05	0.916	6.2028	63.20
0.004	0.9	2.1552	0.04	0.921	6.2028	65.25
0.005	0.4	4.2975	0.10	0.927	7.7534	44.57
0.005	0.5	3.6788	0.08	0.931	7.7534	52.55
0.005	0.6	3.2639	0.07	0.925	7.7534	57.90
0.005	0.7	2.9779	0.06	0.921	7.7534	61.59
0.005	0.8	2.7741	0.05	0.923	7.7534	64.22
0.005	0.9	2.6109	0.05	0.910	7.7534	66.33

Table 1b: Optimum Peak Maximum Acceleration Value of the Structure equipped with TLCD (Controlled Structure), obtained from Frequency Response Curve and Percentage Response Reduction of Peak Maximum Acceleration of Structure.

Base Acceleration Intensity Factor	**Length Ratio**	**Optimum Peak Maximum Acceleration Value (m/s^2)**	**Mass Ratio Corresponding to the Optimum Peak Maximum Acceleration Value**	**Excitation Frequency Ratio Corresponding to the Optimum Peak Maximum Acceleration Value**	**Un-controlled Peak Maximum Acceleration (m/s^2)**	**% Response Reduction of Peak Maximum Acceleration**
0.001	0.4	0.1333	0.04	0.955	0.2448	45.57
0.001	0.5	0.1207	0.03	0.955	0.2448	50.68
0.001	0.6	0.1107	0.03	0.945	0.2448	54.78
0.001	0.7	0.1045	0.03	0.939	0.2448	57.33
0.001	0.8	0.0988	0.03	0.929	0.2448	59.64
0.001	0.9	0.0945	0.02	0.939	0.2448	61.41
0.002	0.4	0.2487	0.06	0.943	0.4896	49.21
0.002	0.5	0.2187	0.06	0.935	0.4896	55.33
0.002	0.6	0.1977	0.05	0.931	0.4896	59.62
0.002	0.7	0.1832	0.04	0.933	0.4896	62.59
0.002	0.8	0.1724	0.04	0.921	0.4896	64.78
0.002	0.9	0.1634	0.03	0.927	0.4896	66.64
0.003	0.4	0.3600	0.09	0.929	0.7344	50.99
0.003	0.5	0.3121	0.07	0.931	0.7344	57.51
0.003	0.6	0.2795	0.06	0.927	0.7344	61.94
0.003	0.7	0.2570	0.05	0.927	0.7344	65.01
0.003	0.8	0.2396	0.05	0.916	0.7344	67.38
0.003	0.9	0.2262	0.05	0.904	0.7344	69.20
0.004	0.4	0.4708	0.10	0.925	0.9792	51.92
0.004	0.5	0.4045	0.08	0.929	0.9792	58.69
0.004	0.6	0.3592	0.08	0.914	0.9792	63.32
0.004	0.7	0.3263	0.07	0.912	0.9792	66.68
0.004	0.8	0.3024	0.06	0.910	0.9792	69.12
0.004	0.9	0.2847	0.05	0.912	0.9792	70.92
0.005	0.4	0.5870	0.10	0.931	1.2240	52.05
0.005	0.5	0.4962	0.10	0.916	1.2240	59.46
0.005	0.6	0.4354	0.09	0.912	1.2240	64.43
0.005	0.7	0.3938	0.08	0.906	1.2240	67.82
0.005	0.8	0.3639	0.07	0.902	1.2240	70.27
0.005	0.9	0.3410	0.06	0.902	1.2240	72.14

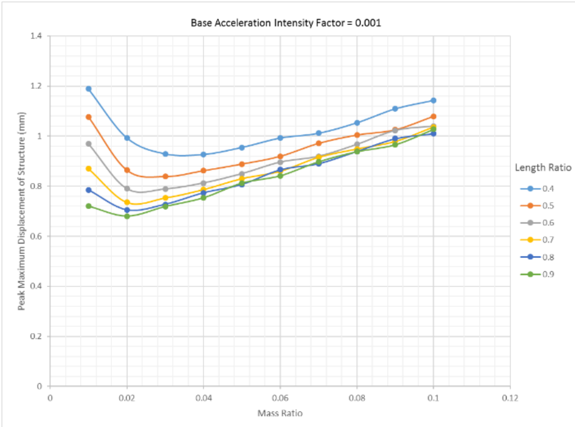

Figure 6(a): Peak maximum Displacement of the structure for various mass ratios and length ratios, corresponding to the base acceleration intensity factors of 0.001

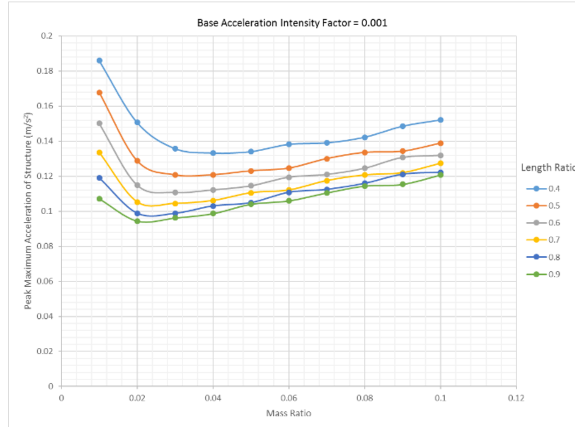

Figure 7(a): Peak maximum Acceleration of the structure for various mass ratios and length ratios, corresponding to the base acceleration intensity factors of 0.001

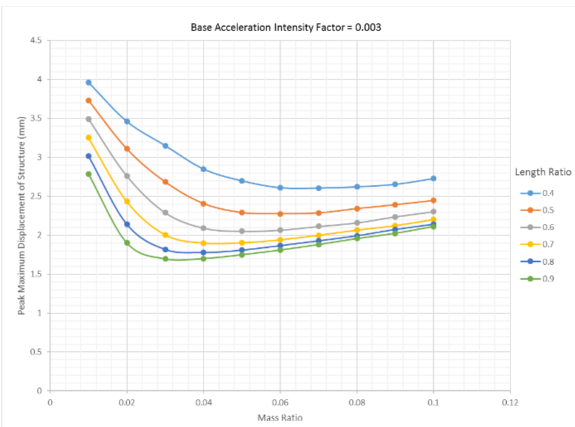

Figure 6(b): Peak maximum Displacement of the structure for various mass ratios and length ratios, corresponding to the base acceleration intensity factors of 0.003

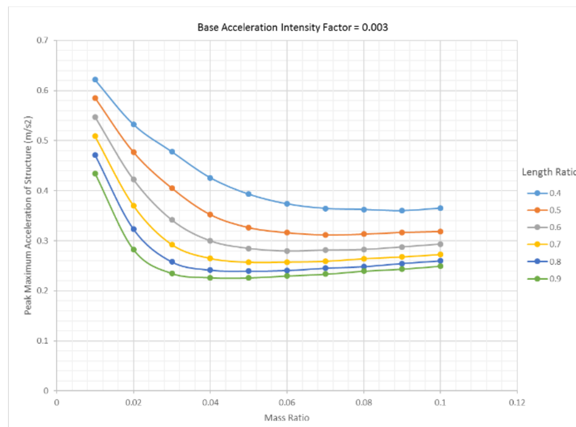

Figure 7(b): Peak maximum Acceleration of the structure for various mass ratios and length ratios, corresponding to the base acceleration intensity factors of 0.003

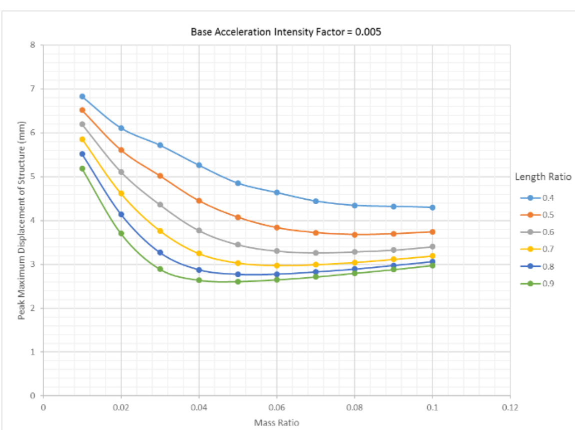

Figure 6(c): Peak maximum Displacement of the structure for various mass ratios and length ratios, corresponding to the base acceleration intensity factors of 0.005

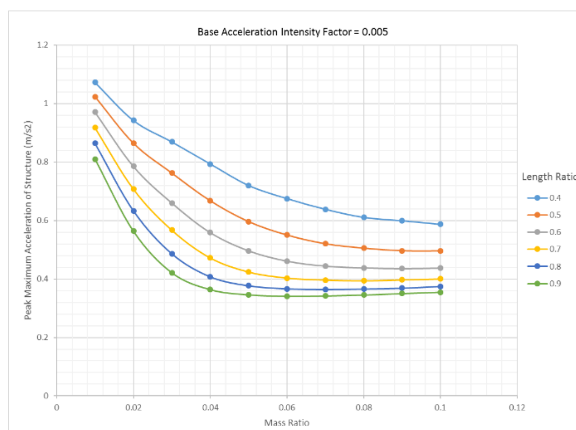

Figure 7(c): Peak maximum Acceleration of the structure for various mass ratios and length ratios, corresponding to the base acceleration intensity factors of 0.005

C. Effect of Base Acceleration Intensity Factor

The base acceleration intensity factors intensify the response of the structure. The structure equipped with TLCD and the structure equipped without TLCD both situations experience an increase in response; however, one of the major findings in the current study is the percentage response reduction in the structure's maximum peak response. It is observed that the percentage response reduction in the maximum peak response of the structure remains almost stagnant while showing some gradual increase in its magnitude as the base acceleration intensity factor is increased. The overall results are summarized and are depicted in **Figure 8(a), Figure 8(b), Figure 9(a), and Figure 9(b).** These figures realize the significant variation of the structure's maximum peak response with varying the base acceleration intensity factor for displacement response and acceleration response of the current study.

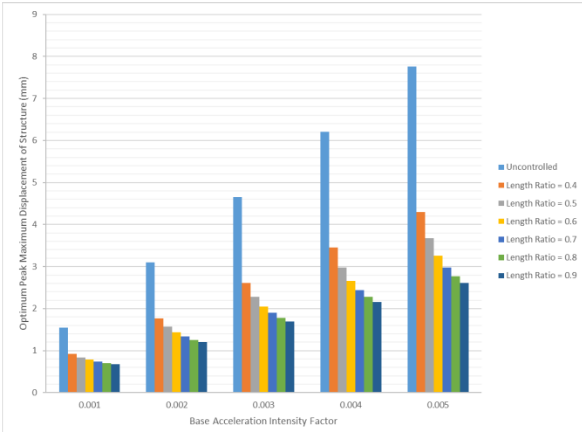

Figure 8(a): Optimum Peak maximum Displacement of the structure for different length ratios and base acceleration intensity factors.

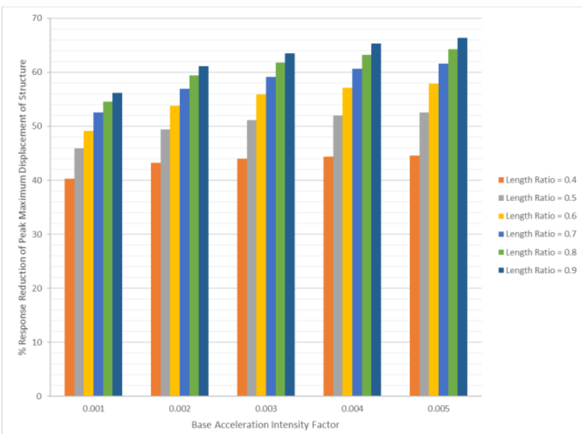

Figure 8(b): Percentage response reduction of the maximum peak Displacement of the controlled structure with respect to the uncontrolled structure for various length ratios and base acceleration intensity factors.

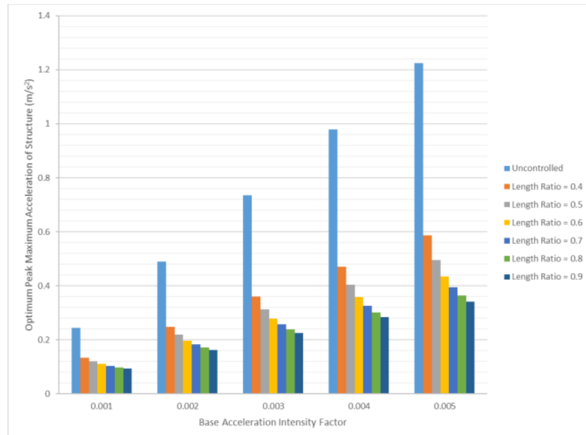

Figure 9(a): Optimum Peak maximum Acceleration of the structure for different length ratios and base acceleration intensity factors.

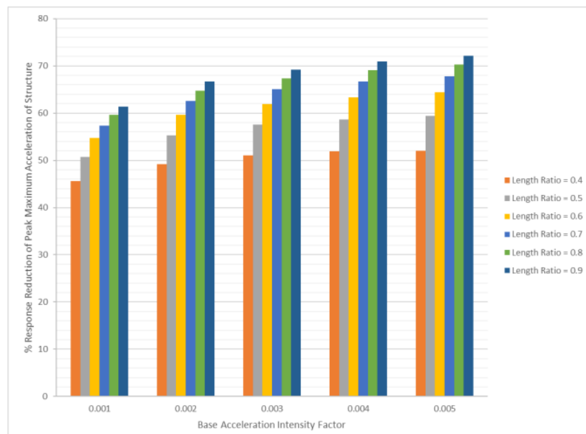

Figure 9(b): Percentage response reduction of the peak maximum Acceleration of the controlled structure with respect to the uncontrolled structure, for various length ratios and base acceleration intensity factors.

Table 2: The current study's most optimum parameter set for dynamic response control of the structure.

Base Acceleration Intensity Factor	Length Ratio	Mass Ratio	Optimum Displacement Value (mm)	Un-controlled Displacement (mm)	% Response Reduction Of Displacement
0.001	0.9	0.02	0.6806	1.5511	56.13
0.002	0.9	0.03	1.2061	3.1015	61.11
0.003	0.9	0.03	1.6963	4.6521	63.54
0.004	0.9	0.04	2.1552	6.2028	65.25
0.005	0.9	0.05	2.6109	7.7534	66.33
Base Acceleration Intensity Factor	**Length Ratio**	**Mass Ratio**	**Optimum Acceleration Value (m/s^2)**	**Un-controlled Acceleration (m/s^2)**	**% Response Reduction Of Acceleration**
0.001	0.9	0.02	0.0945	0.2448	61.41
0.002	0.9	0.03	0.1634	0.4896	66.64
0.003	0.9	0.05	0.2262	0.7344	69.20
0.004	0.9	0.05	0.2847	0.9792	70.92
0.005	0.9	0.06	0.3410	1.2240	72.14

IV. CONCLUSIONS

The Tuned Liquid Column Damper (TLCD) efficacy in the dynamic response control of structure is investigated for harmonic base excitation to the structure, aiming to control dynamic response quantities. The structure's response with TLCD is obtained in terms of maximum Displacement and maximum Acceleration by solving the non-linear coupled governing differential equation of motion of the system numerically.

An intensive parametric study is conducted to investigate the dynamic characteristics of a structure equipped with TLCD and understand the response of a structure subjected to harmonic base excitation. Varying some of the significant parameters of TLCD, namely, mass ratio and length ratio, in the frequency domain and the excitation base acceleration intensity, the response of the controlled system and the uncontrolled system is obtained and compared to study the effects of parameters contributing towards the dynamic response control of structures.

The Frequency Response Curves (FRC) are developed for the system provides an overall insight into the behavior of the system response in the frequency domain. The study focuses on the maximum peak response of Displacement and Acceleration of structure and their optimization to get a minimum peak maximum response of the system, and this also contributes to the peak dynamic response control of structures using a passive device TLCD. Based on the trends of results obtained, the following conclusions are drawn:

1. There is a value of mass ratio at which the controlled structure's peak maximum response is at minimum.
2. The increase in the length ratio improves the reduction in the optimum peak maximum response of the controlled structure.
3. The percentage response reduction observed in the study with varying base acceleration intensity factor considers the validity and efficacy of the set of optimum mass ratio and length ratio in attenuating the optimum peak maximum response even at the increase in base acceleration intensity factor for dynamic response control of the structure subjected to harmonic base excitation.
4. The set of optimum parameters obtained from Table 2 gives the engineers and researchers choice of parameters to control the structure's peak dynamic response and could be useful in the design of TLCD.
5. The maximum percentage response reduction of maximum peak Displacement is obtained as 66.33 % at a mass ratio of 5% and length ratio of 0.9 for a base acceleration intensity factor of 0.005. The maximum percentage response reduction of peak maximum Acceleration is obtained as 72.14 % at a mass ratio of 6% and length ratio of 0.9 for a base acceleration intensity factor of 0.005.
6. TLCD is the best choice among the passive devices that significantly contributes to the dynamic response control of structure and prove to be an excellent device with minimalistic requirements once if the optimum parameters are appropriately selected.

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