# STRUCTURAL CONTROL USING MODIFIED TUNED LIQUID DAMPERS

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**ABSTRACT :**

This paper presents a numerical study for structural control using a modified configuration of the tuned liquid damper (TLD), which is a passive damper consisting of a solid tank filled with water used for controlling vibration of structures. The TLD damper relies on the sloshing of water inside it to dissipate energy. One characteristic of TLDs is that energy dissipation is greater when water sloshing is more. This characteristic has been utilized to design the modified TLD configuration, in which the TLD, instead of being rigidly connected to the floor, is elevated using a rigid rod connected to the floor by an appropriately designed torsion spring. This increases the base acceleration seen by the TLD and also introduces an additional in phase rotational motion, which increases the sloshing of water, and makes the TLD more effective in controlling structural response to earthquake and wind loads. In this present investigation, rectangular TLDs have been taken and liquid sloshing has been modeled using shallow water theory. This shallow water modeling of liquid sloshing has been used to investigate the response of the structure under harmonic base motions, with the standard TLD configuration. Numerical results have been compared with available experimental results to validate the TLD numerical model. This validated model is then used to study the effectiveness of the modified TLD configuration. Obviously, as the torsion spring approaches infinite rigidity, the modified TLD and standard TLD are the same. It is seen that, for a given structure TLD configuration, there exists an optimum value of the rotational spring stiffness, which is reasonably excitation independent, for which the effectiveness of the modified TLD is maximum. Thus the modified TLD configuration can be more effective as a structural control device than the standard TLD configuration.

**KEYWORDS:** Harmonic motion, Structural control, Passive device, Sloshing, Earthquake, Tuned liquid damper.

## 1. INTRODUCTION

The new generation civil engineering tall structures are flexible, weakly damped and light weight. Tuned liquid dampers are used to control the structural vibration in such structures. A tuned liquid damper (TLD) is essentially a rigid rectangular or a cylindrical liquid tank which is rigidly connected to the top of structure. The container may be a large tank or combination of many small tanks. The liquid, in general, is water. Lots of experimental and numerical research works (Modi *et al.* (1990), Tamura *et al.* (1995), Chaiseri *et al.* (1989), Fujino *et al.* (1992), Koh *et al.* (1994)) have been done over the past few years to illustrate the effectiveness of tuned liquid dampers (TLD) as a vibration control device for structures subjected to both harmonic and broad-band base excitations. Sun *et al.* (1992) developed a nonlinear model for a rectangular TLD which utilized the shallow water wave theory with consideration of wave breaking. Banerji *et al.* (2000) used the formulation suggested by Sun *et al.* (1992) and Chavan (2002) experimentally found discrepancies between experimental results and the results obtained by using the formulation suggested by Sun *et. al.* (1992) which is due to the shortcomings of the shallow water model in actual predicting the water surface caused by wave breaking. To overcome these shortcomings Samanta and Banerji (2006) used a different shallow water theory and two numerical schemes, the Lax finite difference method and the random choice method, to study the response of a single-degree-of-freedom structure, with an attached TLD, subjected to large amplitude harmonic base motions. It was seen that the newly used TLD model predicts better results than the earlier used TLD models used by Banerji *et al.* (2000). The Lax finite difference method also consistently predicts numerical results that are closer to the experimental results than other methods for harmonic base motions. This shallow water model of liquid sloshing has been used in this paper to investigate the response of the structure under harmonic base motions. A new TLD configuration has been proposed where the TLD is attached to the structure through a rotation spring and a rod.

## 2. ANALYTICAL FORMULATION

### *2.1 Formulation of TLD Equations*

Classical shallow water theory is used in this paper to simulate the sloshing of liquid in a rigid, rectangular TLD that moves in a coupled horizontal and rotational manner. Let $L$ and $B$ be the length and the width of the container, respectively, and suppose $h_0$ is the initially quiescent depth of the liquid within the container. The TLD's absolute horizontal motion is defined by $x_b$ while the corresponding rotational motion (clockwise direction) is specified by $\theta_b$. Here, $h$ is the (sloshing) liquid depth at distance x, v is the horizontal velocity of the liquid at x, relative to the base of the container. It is assumed that the liquid pressure is hydrostatic. The velocity profile is uniform at a vertical cross section. For this to be valid, the rotational motion, $\theta_b$, has to be small (say, below about 10 degrees). The governing equations are (Lu, 2001)

$$\frac{\partial h}{\partial t} + h\frac{\partial \mathrm{v}}{\partial x} + \mathrm{v}\frac{\partial h}{\partial x} = 0 \tag{2.1}$$

$$\frac{\partial \mathrm{v}}{\partial t} + \mathrm{g}\frac{\partial h}{\partial x} + \mathrm{v}\frac{\partial \mathrm{v}}{\partial x} + \frac{\partial^2 x_\mathrm{b}}{\partial t^2} - \mathrm{g}(\theta_\mathrm{b} - S) = 0 \tag{2.2}$$

Eqns. 2.1 and 2.2 have to be solved in conjunction with the boundary conditions

$$\mathrm{v}\,|_{x=0} = \mathrm{v}\,|_{x=L} = 0 \tag{2.3}$$

and the appropriate initial conditions. If the liquid is at rest at time $t = 0$,

$$h\,|_{t=0} = h_0 \quad \text{and} \quad \mathrm{v}|_{t=0} = 0 \quad \forall x \in [0, L]. \tag{2.4}$$

S is related to $\tau_b$, by

$$S = \frac{\tau_b}{\rho g h} \tag{2.5}$$

where, $\tau_b$ the shear stress at the container's floor. The simplified expression for $\tau_\mathrm{b}$ is (Lu, 2001)

$$\tau_\mathrm{b} = \frac{\mu_l \mathrm{v}_{\max}}{h} \qquad \text{for} \quad z \le 0.7 \tag{2.6}$$

and

$$\tau_\mathrm{b} = \sqrt{\rho \mu_l \omega}\,\mathrm{v}_{\max} \qquad \text{for} \quad z > 0.7 \tag{2.7}$$

where ρ is the density of the liquid; $\mu_l$ is its dynamic viscosity (which is related to the kinetic viscosity, υ, by $\mu_l = \rho\upsilon$); $\omega$ is the circular frequency of the vibration, and $z$ is the liquid's dimensionless sloshing depth defined in (Lu, 2001). The TLD model is numerically solved by Lax finite difference scheme. Details of the solution procedure have been discussed by Samanta and Banerji (2006).

The total horizontal force that is exerted on the TLD's walls and floor due to the sloshing of the liquid (base shear force), $F$ is given by the following expression (Lu, 2001):

$$F = \frac{1}{2}\rho gB(h_R^2 - h_L^2) + \rho gBhSdx \tag{2.8}$$

The moment due to the liquid sloshing is given by (Sun *et al*, 1995)

$$M = -\frac{1}{6}\rho Ba_y(h_R^3 - h_L^3) - \int_0^L \rho Ba_y hxdx \tag{2.9}$$

The first part of the moment equation is due to the liquid sloshing forces acting on the end walls and the second part is due to the liquid sloshing forces acting on the bottom of the TLD tank. Here, $a_y$ is the acceleration of the liquid in the *y* direction. $h_L$ and $h_R$ *are* wave heights at the end wall on the left side and right side respectively.

### *2.2 Equation of Motion of Shear-beam Structure with TLD*

The equation of motion of such structure with TLD attached at it's top and subjected to horizontal ground motion can be written as

$$m_s \ddot{u}_x + c\dot{u}_x + ku_x = -m_s \ddot{u}_g + F \tag{2.10}$$

The base shear force, *F* is computed using Eqn. 2.8. The damping coefficient c is given by $c = 2\xi_s m_s \omega_s$, where $\xi_s$ is the damping ratio and $\omega_s$ is the natural frequency of the structure. The lateral stiffness and mass of the structure and are denoted by k and $m_s$, respectively, and $\ddot{u}_g$ is the ground acceleration.

### *2.3 Modified TLD Configuration*

In this paper a modified TLD configuration has been proposed. Here, the TLD is attached to the structure through a rotation spring and a rod. The schematic diagram of shear-beam structure, horizontal spring, damper, rod and the rotational spring is shown in Figure 1. The TLD is kept at the top of a rod of length *l*. The rod has been attached to the structure through a rotational spring.

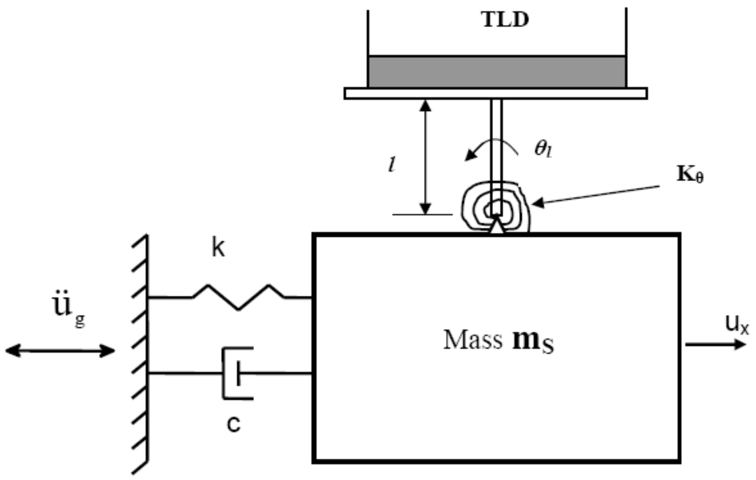


Figure 1 Schematic diagram of a shear-beam structure with the modified TLD configuration

The coupled motion caused by the rotation and translation may enhance or degrade the TLD's performance depending on the position of the TLD with respect to the centre of rotation. A single story structure with rotational spring and TLD has two degrees-of-freedom, the horizontal motion of the structure and the rotation of the rod. Therefore, the equations of motion of such structure subjected to horizontal ground motion, can be written as

$$\begin{bmatrix} (m_s+m_t) & -m_t.l \\ m_t & -(m_t.l+(J_1+J_2)/l) \end{bmatrix}\begin{Bmatrix} \ddot{u}_x \\ \ddot{\theta}_l \end{Bmatrix}+\begin{bmatrix} C & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} \dot{u}_x \\ \dot{\theta}_l \end{Bmatrix}+\begin{bmatrix} K & 0 \\ 0 & -K_\theta/l \end{bmatrix}\begin{Bmatrix} u \\ \theta_l \end{Bmatrix}=\begin{Bmatrix} F-\ddot{u}_g(m_s+m_t) \\ F+M/l-\ddot{u}_g m_t \end{Bmatrix} \tag{2.11}$$

where $u_x$ is the horizontal displacement relative to the ground and $\theta_l$ is the rotation of the rod with respect to the vertical axis in the anti-clock wise direction, respectively. Furthermore, $m_s$ is the lumped mass at the top of the structure and $m_t$ is the lumped mass at the bottom of the TLD. $J_1$ and $J_2$ are the mass moment of inertia of the mass at the top of the rod and the rod, respectively, $l$ is the length of the rod, and $\ddot{u}_g$ is the ground acceleration. C, K, $K_\theta$ are the damping of the structure, stiffness of the structure and the stiffness of the rotational spring respectively. The terms F and M denote the component of the sloshing force and the moment, respectively.

The equation of motion of such structure is coupled with TLD equations and all these equations must be solved simultaneously to get the response of the structure. The TLD equations (Eqn. 2.1 and 2.2) are first solved using Lax finite difference scheme to obtain base shear force (*F*) and moment (*M*). *F* and *M* are computed using Eqn. 2.8 and 2.9. Then these are used to obtained structural response using Eqn. 2.11. In this paper, Eqn. 2.11 has been solved using Newmark-β average acceleration method for multi-degree of freedom systems.

## 3. RESULTS

Investigations were conducted to study the dynamic behavior of a structure with TLD when subjected to harmonic ground motion. The harmonic ground motion is defined by its excitation frequency and amplitude of ground motion. Since the harmonic ground motion consists of a single frequency, the analysis of structure with TLD will provide an understanding of the behavior of the structure-TLD system for this kind of ground motion. It also gives a general idea of how the structure would behave when it is subjected to more realistic earthquake ground motions.

### *3.1 Results for Shear-beam Structure with TLD*

The classical shallow water theory that has been discussed above in section 2 is used here to idealize the liquid motion in a TLD. The effect of wave breaking is automatically taken into account in the TLD formulation. Numerical results have been compared with experimental results (Chavan, 2002). A typical comparison of experimental and theoretical results is shown in Figure 2. Normalized peak acceleration of structures for different excitation frequency ratio $\beta$ (which is the ratio of the frequency of the sinusoidal excitation $f_e$ and fundamental natural frequency of structure $f_w$), is presented for different mass ratios $\mu$, which is the ratio of the mass of the water to the mass of structure. Both small and large excitation levels are considered. Here, $A_0$ denotes the displacement amplitude of the sinusoidal excitation. Good agreement is generally observed between experimental and theoretical results for various mass ratios in various structures.

### *3.2 Results for Modified TLD Configuration*

The TLD model described in section 2.3 has been used here to obtain the response for modified TLD attached with a shear-beam structure. The properties of different structures and the attached TLDs are given in Table 3.1. Structures of different natural frequencies are taken to examine the effectiveness of modified-TLD system over the TLD-structure systems. A typical peak structural acceleration for case-3 structure is plotted against a dimensionless rotational stiffness parameter in Figure 3. This dimensionless rotational stiffness parameter is given by

$$\text{Dimensionless rotational stiffness parameter} = K_\theta / K.l^2 \tag{3.1}$$

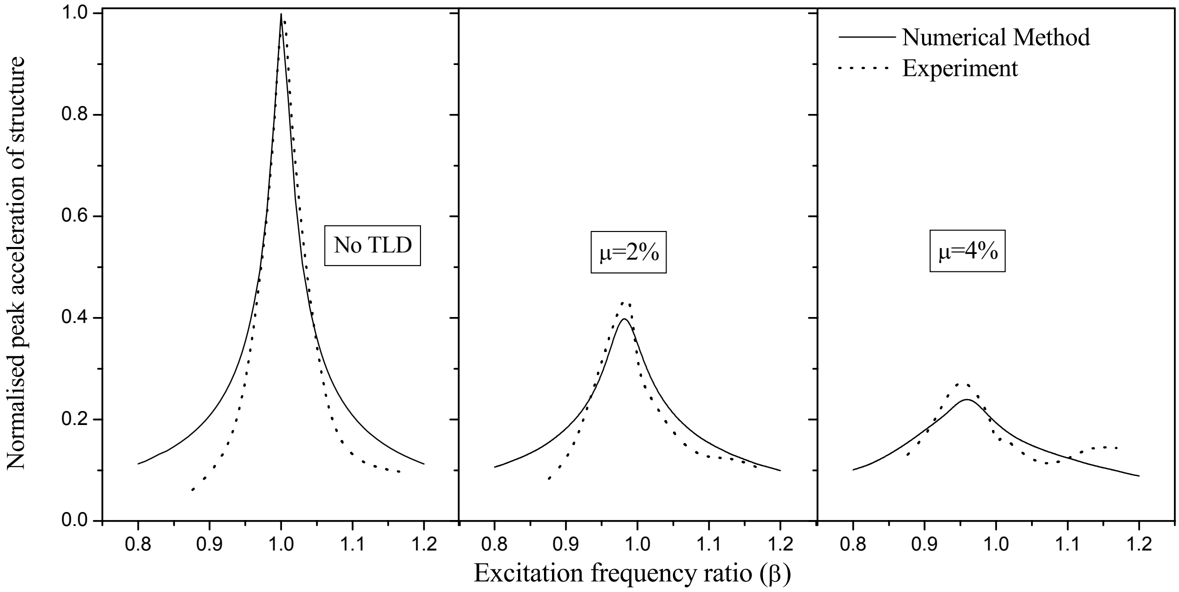


Figure 2 Spectrum of normalized peak accelerations for different mass ratios
(Natural frequency of structural, $f_s$=1.37 Hz; structural damping, ζ= 1.24; Δ= 0.143, $A_0$=1 mm)

Table 3.1 Structural properties and TLD parameters

| Structure Type | | Case -1 | Case - 2 | Case - 3 | Case - 4 | Case - 5 |
|---|---|---|---|---|---|---|
| Mass [Kg] | | 145.8 | 121.8634 | 1476.225 | 3080.025 | 4730.625 |
| Structural Time Period [s] | | 1.0 | 1.25 | 1.5 | 1.8 | 2.0 |
| Structural Damping (%) | | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Tank Size | Length, L [mm] | 360 | 563 | 810.64 | 1167.3 | 1441.1 |
| | Width, B [mm] | 150 | 50 | 300 | 300 | 300 |
| Depth Ratio ( $\Delta = h_0/L$ ) | | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| Mass Ratio ( μ = mass of water / mass of structure ) | | 2%, 4% | 2%, 4% | 2%, 4% | 2%, 4% | 2%, 4% |

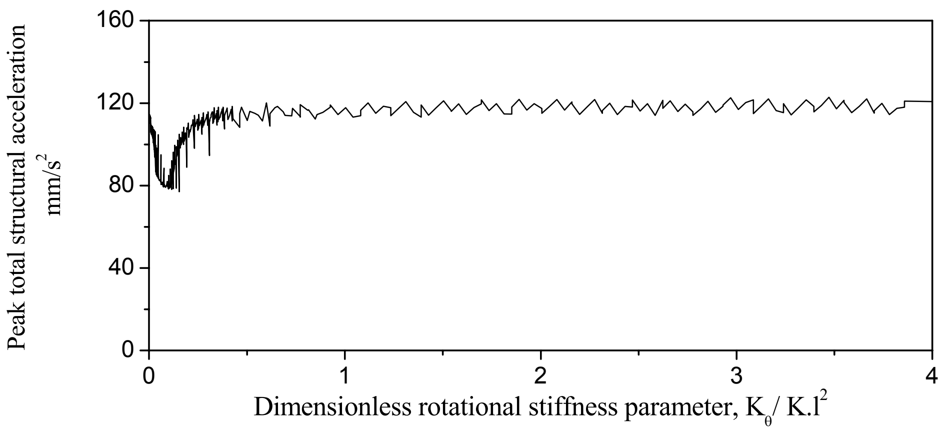


Figure 3 Effect of dimensionless rotational stiffness parameter on peak total structural acceleration response for Case-3 structure and frequency ratio, β=0.90

Rod lengths ($l$) of 200-2000mm are taken for different rotational stiffness ($K_\theta$), and it is seen that the dimensionless rotational stiffness parameter given in Eqn. 3.1 governs the behavior rather than the individual parameters. Further, a minimum value of rotation stiffness ($K_\theta$) is required for the system to be stable. For a certain optimum value range of the dimensionless rotational stiffness parameter there is a significant decrease in the structural response (Figure 3). Actually, for these stiffness parameter values, the lateral and rotational motions of the TLD are in phase and the TLD motions are significantly enhanced leading to significantly increased sloshing. Thus the TLD becomes more effective in these situations. As the rotational stiffness parameter is increased beyond this optimum value range, the effectiveness of the modified TLD decreases, because the connection between TLD and structure becomes rigid and TLD tends to move along with the structure, as it does for the standard TLD configuration. When the rotational stiffness ($K_\theta$) becomes almost rigid, the effectiveness of modified-TLD system becomes similar to TLD-structure systems with no rotational spring and rod. Therefore, the response of the structure can be reduced by a significant amount, if the dimensionless rotational stiffness parameter is properly chosen for that particular structure, as shown in Figure 4, where a typical time history of the structural acceleration is plotted for case-5 structure with excitation frequency ratio $\beta = 0.95$.

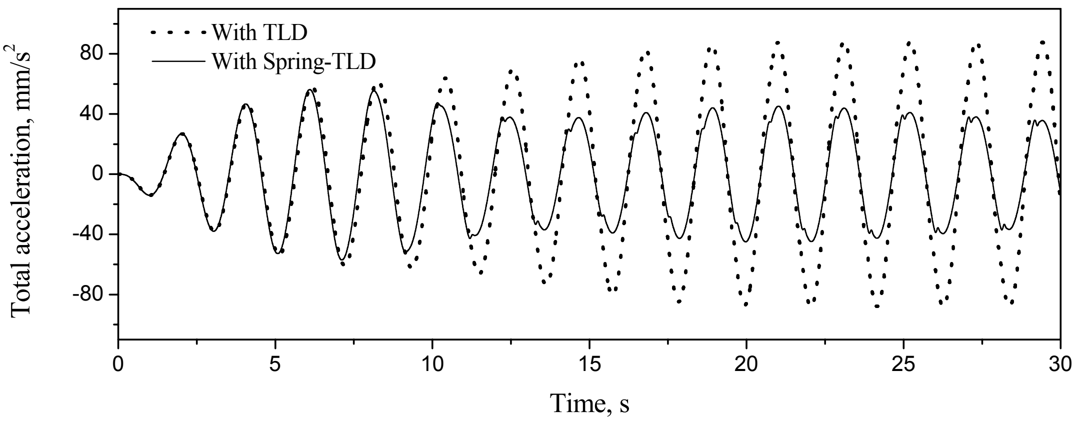


Figure 4 Total structural acceleration time histories for frequency ratio $\beta$= 0.95 and mass ratio $\mu$=2% for Case-5 structure ($T_n$ =2.0 s)

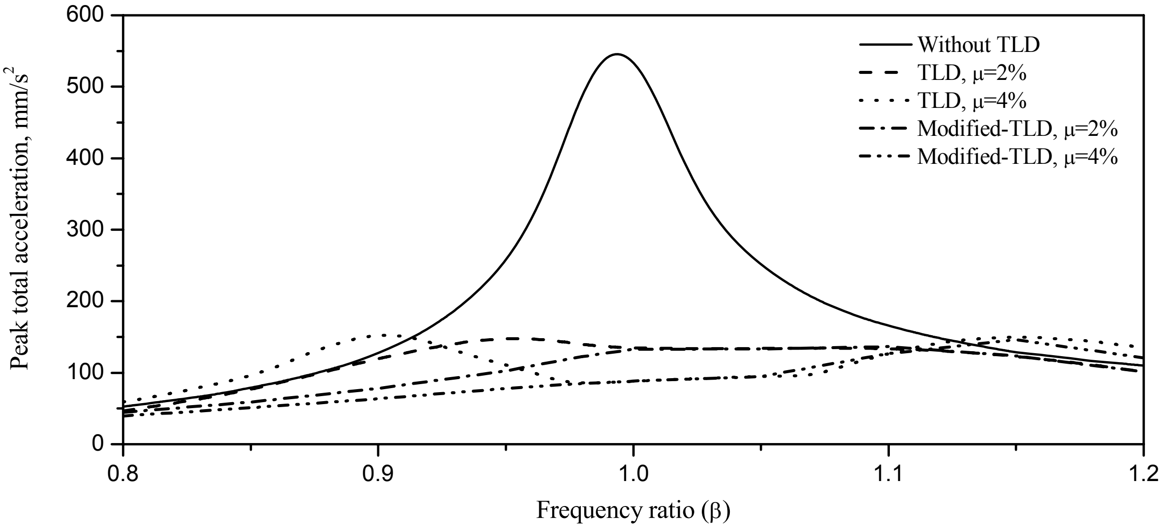


Figure 5 Variation of peak total acceleration with frequency ratio ($\beta$) for different TLD configurations and mass ratios for Case-3 structure with peak base displacement amplitude of 1 mm

In Figure 5 peak total accelerations are plotted for different frequency ratios (β) for $T_n$=1.50 s structure. It is seen that modified-TLD systems are mostly effective for excitation frequency ratios less than 1.1. Reduction of peak acceleration in different structures for frequency ratio β = 0.95, are shown in Table 3.2. From the present investigation it has been found if the dimensionless rotational stiffness parameter is properly chosen, i.e. it takes its optimum value, the modified TLD configuration is more effective in response reduction during base motions than the standard TLD configuration. It is significantly more effective for flexible structures ($T_n \geq 1.50$ s) with frequency ratios in the range of 0.85-0.95.

Table 3.2 Reduction of peak acceleration in different structures for frequency ratio, β = 0.95

| Structure Type | | | Case -1 | Case - 2 | Case - 3 | Case - 4 | Case - 5 |
|---|---|---|---|---|---|---|---|
| Structural Time Period [s] | | | 1.0 | 1.25 | 1.5 | 1.8 | 2.0 |
| Peak Acceleration [mm/s$^2$] | | | 527.54 | 373.50 | 255.31 | 139.12 | 125.38 |
| Percentage reduction in peak acceleration [%] | With TLD | μ = 2% | 22.94 | 36.06 | 39.00 | 21.36 | 29.79 |
| | | μ = 4% | 47.70 | 58.42 | 56.54 | 42.33 | 46.16 |
| | With modified-TLD | μ = 2% | 26.41 | 38.34 | 59.77 | 45.51 | 54.48 |
| | | μ = 4% | 47.70 | 58.67 | 69.41 | 59.86 | 64.92 |

## 4. SUMMARY AND CONCLUSIONS

A study on the effectiveness of a TLD in controlling the response of structure is carried out for harmonic excitations. The results show that a properly designed TLD can significantly reduce response of structures. It is found that the shallow water theory used for modeling the TLD liquid sloshing is good in predicting actual structural response.
A modified TLD configuration has been proposed, where the TLD is connected to the structure through a rotational spring and rigid rod system. The effectiveness of such a configuration has been studied for harmonic base excitations. This modified configuration has been found to be more effective as a structural control device than the standard configuration, where the TLD is rigidly connected to the structure. The effectiveness is definitely dependent on the stiffness of the rotational spring. For sinusoidal excitation, the proposed modified TLD configuration with an optimum rotational spring stiffness has been found to be significantly more effective than the standard TLD configuration for relatively flexible structures and for the frequency ratios (β<1.1) that provide the major contribution to structural response, with the TLD characteristics being the same for both configurations.

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