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Research Paper

Tuned Sloshing Damper in Response Control of Tall Building Structure

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The paucity of space and requirements of building infrastructure has driven us to explore for taller building systems. Also a large number of construction materials has emerged and are being used extensively in buildings. The usage of light weight high strength materials reduces the space requirement and also becomes economical. However, such structures have structurally become susceptible to the lateral loading generated due to wind or earthquake. Attempts are made to control the response of tall building systems by introducing control mechanisms in the form of active, passive or hybrid system. Usage of liquid storage tanks in tall building system in the form of a passive control device proves effective. Several works have been carried out in the past to understand the efficacy of such system, which popularly is known as tuned liquid dampers or tuned sloshing dampers (TSD). The present paper deals with the development of a numerical code to demonstrate the efficacy of such tuned sloshing damper considering fluid structure interaction effect.

Keywords: Sloshing; Damper; Response Control; Building, Passive System; Tuned Sloshing Damper (TSD)

Introduction

The paucity of space and the present trend towards tall buildings, the use of lightweight, high strength materials often accompanied by increased flexibility and a lack of sufficient inherent damping, increase their susceptibility to excitations such as due to wind, ocean waves or earthquakes. To reduce the risk of structural failures particularly during a catastrophic event it has become important to search for practical and effective devices for suppression of the vibrations generated due to such excitations. This has necessitated exploring mechanisms to suppress the vibrations of such tall buildings by some suitable devices. The devices used for mitigating structural vibration may be categorized according to their energy consumption as Passive, Active and Semi-active or Hybrid control systems. Several attemptsin the past have been made to evolve suitable types of structural control devices and derive their efficacies. These include works of Housner *et al*., 1997; Spencer Jr. and Sain, 1997; Soong and Spencer Jr., 2002 and Spencer Jr. and Nagarajaiah, 2003, amongst others.Passive control devices are systems which do not require external energy supply. Such systems are reliable since they are unaffected by power outages, which are common during natural calamities. Example of such system includes base isolation (using elastomeric and lead rubber bearings), energy dissipation devices such as metallic dampers, viscous dampers, friction dampers, tuned mass dampers, tuned liquid dampers etc. (Soong and Dargush, 1997; Kasai *et al*., 1998). Active control systems on the other hand involves considerable amount of external power to operate actuators that supply a control force to the structure. The control force is generated depending on the feedback of the structural response. These are more effective than passive devices because of their ability to adapt to different loading conditions and to control different modes of vibration. Examples of such systems include active mass dampers (AMDs), active bracing systems, etc. (Housner *et al*., 1994; Sakamoto *et al*., 1994).

Semi-active systems are viewed as controllable devices, with energy requirements less than typical active control systems since external power is only used to change device's properties such as damping

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or stiffness, and not to generate a control force. These function as passive devices in case of power failure. Examples of such systems include variable orifice dampers, electro-rheological dampers, magneto-rheological fluid damper, semi-active variable stiffness tuned mass damper (SAIVS-TMD) etc. (Symans and Constantinou, 1999). Hybrid control system utilizes the useful characteristics of both systems which implies the combined use of passive and active systems or passive and semi-active systems. The most common combinations are hybrid mass dampers (HMD), which combine tuned mass dampers with active actuators.

Damping is defined as the ability of the structure to dissipate a portion of the energy released during a dynamic loading event and thus one of the most important parameters that limit the response of the structures. Attachment of liquid tanks to the structure introduces capability of inducing damping in the system. The sloshing motion of the liquid that results from the vibration of the structure dissipates a portion of the energy release by the dynamic loading and therefore increases the equivalent damping of the structure. These tank devices are referred to as Tuned Sloshing Dampers (TSD). In general sloshing of liquid causes problem in tank devices, however, in this case the sloshing of liquid in tank is used to its advantage. The TSD system relies on the sloshing wave developing at the free surface of the liquid to dissipate a portion of the dynamic energy. The growing interest in liquid dampers is due to their low capital and maintenance cost and their ease of installation into existing and new structures. Thus TSD concept represents an excellent technique for up-grading the seismic resistance of both existing and new structures.The performance of TSD relies mainly on the sloshing of liquid at resonance to absorb and dissipate vibration energy of the structure. The full scale measurement of wind induced vibrations of two actual tall structures - Nagasaki Airport Tower (height 42 m) and Yokohama Marine Tower (height 101m) were carried out (Fuji *et al*., 1990). The displacements were reduced to about 40% upon installation of Tuned Sloshing Damper. Dynamic force frequency response function of TSD was also experimentally determined to study the effect of the TSD in which the natural frequency of the water inside the container was tuned to that of the structure. The mitigation of wind induced motion of buildings utilizing tuned sloshing dampers was studied (Ahsan Kareem, 1990). It was demonstrated by the authors that a sloshing damper can effectively reduce the motion of buildings when the fundamental sloshing and building frequencies are synchronized. A semi analytical model for TSD using a rigid rectangular tank filled based on shallow water wave theory was proposed (Sun and Fujino, 1992). The response of a SDOF structure fitted with a TSD was experimentally studied and it was found that TSD works satisfactorily for suppressing structural vibrations investigated The use of liquid dampers which are tuned to different vibration frequencies of a multi-degree-of-freedom structure was studied (Koh *et al*., 1994). It was observed by the authors that the position of the liquid damper has a significant effect on the vibration response. Takashi Nomura, 1994 employed Arbitrary Lagrangian-Eulerian (ALE) formulation to deal with the free surface motion of the liquid in TSD. Nonlinear interaction of liquid motion and structure motion was captured by the proposed computational method for the vortex-excited oscillation of a circular cylinder as well as a TSD-structure interaction problem. The full-scale measurements of the wind-induced responses of buildings to prove the efficiency of tuned liquid dampers (TLDs) was carried out (Tamura *et al*., 1995). The wind-induced responses of the buildings were measured before and after the installation of TLDs. Vibration perceived by occupants due to daily wind was significantly reduced. The TLD could reduce the acceleration responses during strong winds down to 1/2-1/3 of the response without the TLD, thus the habitability and serviceability of buildings were considerably improved. Ikeda and Nakagawa, 1997 studied the non-linear sloshing damper in a rectangular tank both analytically and experimentally. The water tank is attached to a structure to suppress the horizontal vibrations of the structure caused by a sinusoidal excitation. Quantitatively good agreement was obtained between the theoretical characteristics and the experimental results. Warnitchai and Pinkaew, 1997 proposed a new mathematical model of liquid sloshing in rectangular tanks, which include the effects of flow-dampening devices. This model can accurately represent the complex behaviour of liquid sloshing and, at the same time, is simple enough to be used in engineering calculations, and more importantly, the effects of flow-dampening devices can be analytically evaluated. Reed *et al*., 1999 numerically modelled the TLD as an equivalent tuned mass damper with non-linear stiffness and damping. These are determined such that the energy dissipation provided by the Non-linear Stiffness and Damping (NSD) is equivalent to that of the TLD. This NSD model captures the behaviour of the TLD system under a variety of loading conditions. Thus NSD model presented here is an equivalent TMD representation of the TLD. An algorithm for updating the NSD damping and the stiffness coefficients in a time history analysis of a SDOF structural system has been provided. Kanok-Nukulchaiand Tam, 1999 proposed a Lagrangian displacement-based fluid element to model large amplitude free surface motion of nearly incompressible viscous fluids in a tank of rectangular cross-section under dynamic excitation for tuned liquid damper applications. The penalty method is employed to enforce the nearly incompressible characteristic of fluids. The effectiveness of the proposed model was verified by experimental results from the literature. The results show that the proposed non-linear fluid element can predict non-linear behaviors of large amplitude sloshing due to dynamic excitation, especially at near-resonant region.Yamamoto and Kawahara, 1999 presented a numerical study for structural control using a tuned TLD, which consists of solid tank filled with liquid. The authors demonstrated that the computed results are closer to the experimental ones. Banerji *et al*. (2000) carried out the study of the dynamic behavior of SDOF structure, rigidly supporting a rectangular TLD tank with shallow water. An attempt was made to define appropriate design parameters of the TLD that is effective in controlling the earthquake response of a structure through parametric studies. B. Nanda, 2010 had carried out a work on the application of tuned liquid damper for controlling structural vibration of buildings. The author made an exhaustive study and had demonstrated the efficacy of the tuned sloshing dampers. J Mondal, 2014 had carried out an experiment in the laboratory to demonstrate that the liquid sloshing helps in reducing structural vibration of framed structures. N K Rai *et al*., 2013 had attempted to reduce the response of existing buildings by carrying out retrofitting using tuned liquid dampers. The authors had demonstrated that liquid sloshing in tanks can help reducing the vibrational response of structures even when retrofitted in existing buildings. Tait *et al*. (2005) formulated both linear and non-linear numerical model of a TLD with slat screens. The nonlinear model of a TLD equipped with damping screens (Kaneko and Ishikawa, 1999) is presented. The non-linear sloshing response is postulated using shallow water theory (Lepelletier and Raichlen, 1988). A procedure to calculate the theoretical value of the force coefficient of a slat-type screen is presented and verified from experimental results and is applicable for both wind (small excitation) and earthquake (large excitation) loading.The non-linear model is capable of modelling a TLD equipped with multiple screens at various screen locations inside the tank. The non-linear model is also verified over a range of practical fluid depth to tank length ratio values. An experimental program is conducted to assess the applicability of the theoretically determined loss coefficient by a TLD during dynamic excitation. Frandsen, 2005 developed a fully non-linear 2-D σ-transformed finite difference solver based on inviscid flow equations in rectangular tanks. The fluid motion is described by non-linear potential flow equations allowing steep non overturning waves to be captured. Two-dimensional solutions are obtained using a finite-difference time-stepping scheme on adaptively mapped grids. The solver also removes the need for free-surface smoothing. The fluid model is coupled to an elastic support structure. The effectiveness of the TLD is discussed through prediction of coupling frequencies and response of the tank-structural system for different tank sizes, mass ratio between fluid and structure and tuning ratio. Bhattacharyya *et al*., 2006 had formulated a mixed Eulerian-Lagrangian finite element model to compute the non-linear sloshing amplitude of liquid in liquid filled rectangular and circular cylindrical containers subjected to sinusoidal base excitation. The solution is obtained by the Galerkin method. The fourth-order Runge-Kutta method is employed to advance the solution in the time domain. A re-gridding technique is applied to the free surface of the liquid, which eliminates the numerical instabilities without the use of artificial smoothening. This finite element method is used for computing the non-linear sloshing response of liquid in a two dimensional rigid rectangular tank with baffles and circular cylindrical container with annular baffle. Validity of the present model is checked by comparing available results for the tank without baffle. The effects of baffle parameters such as position, dimension, and numbers on the non-linear sloshing response are also examined.

Tuned Sloshing Dampers can be broadly classified into two categories, shallow-water and deep-water dampers based on the ratio of the water depth to the tank length in the direction of motion. The TSD system relies on the sloshing wave developing at the free surface of the fluid to dissipate a portion of the dynamic energy. The growing interest in liquid dampers is due to their low capital and maintenance cost and their ease of installation into existing and new structures. Thus TSD concept represents an excellent technique for up-grading the seismic resistance of both existing and new structures.

The liquid tank attached to the structure, undergoes sloshing motion that results from the vibration of the structure, dissipates a portion of the energy released by the dynamic loading and therefore increases the equivalent damping of the structure.

In the present paper, dynamic characteristics of an idealised building structure in 2-D form are studied when attached with tuned liquid filled tank as passive damper under dynamic excitation. The two systems, liquid system and the structural system in Fig. 1 are studied in uncoupled form. The coupling between the two systems is achieved through iterations.

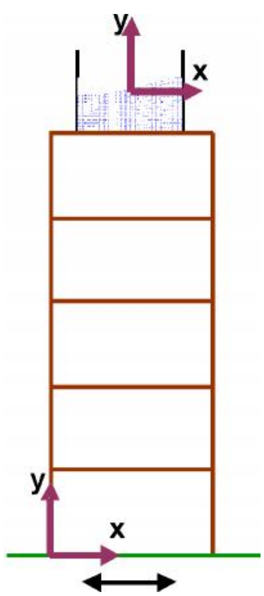


Fig. 1: Structure and fluid system

Theoretical Formulation

A rigid container of width L containing incompressible and inviscid liquid subjected to horizontal oscillation is considered. The stationary liquid height is **h** and $\boldsymbol{\eta}$ represents the free surface sloshing elevation. Fluid domain $\boldsymbol{\Omega}$ is bounded by the free surface $\mathbf{S_1}$ and fluid-solid boundary interface $\mathbf{S_2}$. Solid boundary consists of tank wall and tank bottom as shown in Fig. 2.

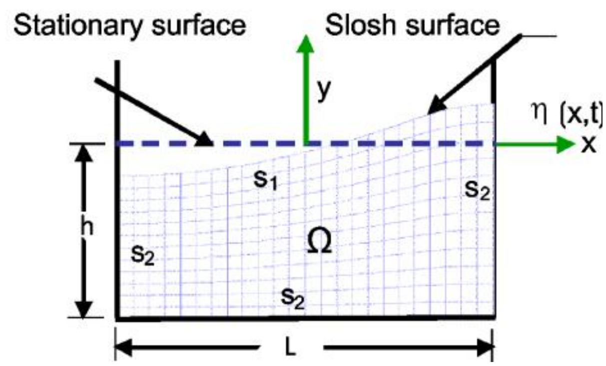


Fig. 2: Liquid sloshing in rigid tank

Governing Equation

Considering the liquid as inviscid and incompressible, and flow irrotational, governing equation may be written by Laplace equation in $\boldsymbol{\Omega}$ as:

$$\nabla^2\phi = 0 \tag{1}$$

where, $\prod(x, y, t)$ is the velocity potential. However, in a moving tank the total velocity potential $\prod$ may be split into two parts, potential function $\prod_t$ due to tank motion and disturbed potential function $\prod_s$ due to fluid motion.

$$\phi = \phi_t + \phi_s \tag{2}$$

For the tank moving in horizontal direction in vertical plane, $\prod_t$ may be expressed as

$$\phi_t = x \cdot \dot{x}_{st} \tag{3}$$

Expressing Laplace equation in terms of $\prod_s$

$$\nabla^2\phi_s = 0 \tag{4}$$

Boundary Conditions

In a rigid container, solution of Laplace equation must satisfy the boundary condition

$$\frac{\partial \phi_s}{\partial n} = 0 \qquad \text{on } S_2 \tag{5}$$

where *n* is the unit normal vector drawn outwardly to the solid boundary

$$\left.\frac{\partial\phi_s}{\partial x}\right|_{x=\pm L/2} = 0\ ; \quad \left.\frac{\partial\phi_s}{\partial y}\right|_{y=-h} = 0 \text{ on } S_2 \qquad (6)$$

In Eulerian form Kinematic and Dynamic Boundary conditions on free liquid surface are

$$\frac{\partial\phi_s}{\partial y} = \frac{\partial\eta}{\partial t} + \frac{\partial\phi_s}{\partial x}\cdot\frac{\partial\eta}{\partial x} \quad \text{on } S_1 \qquad (7)$$

Kinematic B.C

$$\frac{\partial\phi_s}{\partial t} + \frac{1}{2}\cdot\nabla\phi_s\cdot\nabla\phi_s + g\cdot\eta + x\cdot\ddot{x}_{st} = 0 \quad \text{on } S_1 \qquad (8)$$

Dynamic B.C

In Lagrangian form, equations may be written as

$$\frac{dx}{dt} = \frac{\partial\phi_s}{\partial x};\quad \frac{dy}{dt} = \frac{\partial\phi_s}{\partial y} \quad \text{Kinematic B.C} \qquad (9)$$

$$\frac{d\phi_s}{dt} = -\left[\left(\frac{1}{2}\right)\cdot\left(\nabla\phi_s\cdot\nabla\phi_s - 2\cdot\frac{\partial\phi_s}{\partial y}\cdot\frac{\partial\eta}{\partial t}\right) + g\cdot\eta + x\cdot\ddot{x}_{st}\right]$$

Dynamic B.C

(10)

Finite Element Formulation

Initial Impulse Condition

Initially the flow starts with a small horizontal tank velocity. Calling this as an initial impulse condition, based on linear theory

$$\phi = 0\ ; \quad \eta = 0$$

on free surface (11)

$$\phi = \phi_t + \phi_s \quad \& \quad \phi_t = x\cdot\dot{x}_{st}$$

$$\phi_s = -x\cdot\dot{x}_{st}(0)\ ; \quad \eta = 0$$

on free surface (12)

where $\dot{x}_{st}(0)$ is initial small tank velocity.

For finite element analysis entire fluid domain is discretized using four noded quadrilateral elements.

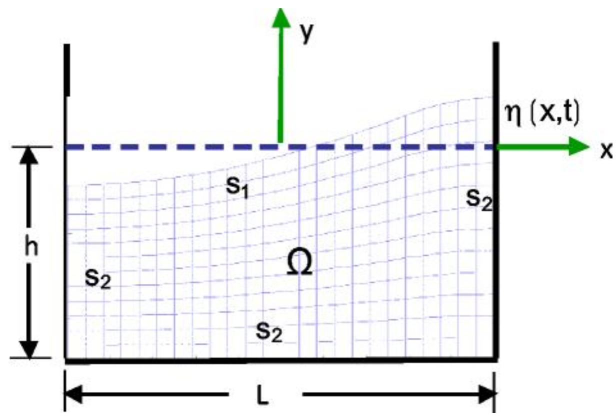


Fig. 3: Finite element model of liquid sloshing

As discussed earlier to start with, initial condition may be taken as

$$\phi_s = -x\cdot\dot{x}_{st}(0)\ ; \quad \eta = 0$$

on free surface (13)

With the known velocity potential at free surface nodes Laplace equation is solved to obtain unknown nodal velocity and pressure satisfying the boundary conditions.

Finite Element Solution of Laplace Equation

Spatial discretization of Laplace equation is done by means of Galerkin weighted residual technique.

$\prod_s$ is approximated as

$$\phi_s \simeq \tilde{\phi}_s = \sum_{i\in n} N_i\bar{\phi}_i \qquad (14)$$

Applying Galerkin'sprinciple

$$\iint N_i\cdot\left(\frac{\partial^2\tilde{\phi}_s}{\partial x^2} + \frac{\partial^2\tilde{\phi}_s}{\partial y^2}\right) dx\cdot dy = 0 \qquad (15)$$

Assuming **n** is the total number of nodal points of the discretized liquid domain and n_d be the number of nodes corresponding to the free surface boundary, the unknown nodal values is given by $n–n_d$, also equal to the number of equations resulting from Galerkin's approximation.

Applying appropriate boundary condition and known velocity potential $\prod_d$ at free surface nodes, the resulting equation becomes

$$\int N_i \cdot \frac{\partial \tilde{\phi}_s}{\partial n}\ ds \ = \iint \nabla N_i \sum_{j \in n \setminus n_d} \nabla N_j \bar{\phi}_j \ \ dx \cdot dy \ \ + \iint \nabla N_i \sum_{j \in n_d} \nabla N_j \bar{\phi}_{d\,j} \ \ dx \cdot dy \qquad (i \in n \setminus n_d) \qquad (16)$$

$$[K]\{\bar{\phi}\} = \{f\}$$

where $\{\bar{\phi}\}$ is the vector of unknown nodal nalues (17)

$$K_{ij} = \iint \left(\frac{\partial N_i}{\partial x} \sum_{j \in n \setminus n_d} \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \sum_{j \in n \setminus n_d} \frac{\partial N_j}{\partial y} \right) dx \cdot dy \qquad (18)$$

$$\iint \left(\frac{\partial N_i}{\partial x} \sum_{j \in n_d} \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \sum_{j \in n_d} \frac{\partial N_j}{\partial y} \right) \cdot \ \bar{\phi}_{dj} \ dx \cdot dy \qquad (19)$$

F-S Interaction Model

The two systems, fluid system and the structural system are studied in decoupled form. The two systems are iterated in the sense that fluid system will experience the floor response and in turn fluid system will exert hydrodynamic sloshing force on the structure.

The equation of motion of the structure being solved for a fluid-structure interaction problem is:

$$[M]\ \{\ddot{u}_{st}\} + [C]\ \{\dot{u}_{st}\} + [K]\{u_{st}\} = F_e + F_d \qquad (20)$$

Where, M is mass matrix of the structure, C is damping matrix of the structure, K is the stiffness matrix, u_{st} is nodal displacement vector.

F_e is the excitation force vector, for earthquake excitation; $F_e = -[M]\{l\}\ \ddot{x}_g$ l is the influence vector of the structure subjected to ground excitation. F_d is the total hydrodynamic sloshing force due to sloshing in tanks, $F_d = \sum_{i=1}^{N_d} \{m_i\}\ F_i$

F_i is the hydrodynamic sloshing force due to sloshing of TSD at ith floor, N_d is the number of liquid damper installed over the storeys, m_i is the influence vector for the liquid damper situated at ith floor.

$\ddot{x}_g$ is ground acceleration.

Stiffness matrix K and consistent mass matrix M for the given multi-degree freedom structure is determined. Damping matrix C of the structure is derived from *Rayleigh damping* which considers mass and stiffness-proportional damping for the case of classical damping.

Natural frequencies and the natural mode shapes of vibration are obtained by performing the free vibration analysis of the structural system.

Incorporating the damping term in Dynamic boundary condition

$$\frac{d\phi_s}{dt} = -\left[\begin{array}{l} \left(\frac{1}{2}\right) \cdot \left(\nabla\phi_s \cdot \nabla\phi_s - 2 \cdot \frac{\partial \phi_s}{\partial y} \cdot \frac{\partial \eta}{\partial t} \right) \\ + g \cdot \eta + x \cdot \ddot{x}_{st} + \mu.\phi_s \end{array} \right] \qquad (21)$$

μ is the damping coefficient in the damping term $\mu.\phi_s$, which primarily takes into account the damping effect due to sloshing of the liquid.

$\ddot{x}_{st}$ is the base acceleration induced in the tank due to structure response which is same as the floor acceleration, to which the TSD is rigidly connected to. Thus $\ddot{x}_{st}$ can be obtained as $\{m\}^T.\{\ddot{u}_{st}\}$.

Calculation of Sloshing Force

Hydrodynamic sloshing force is obtained by integrating the hydrodynamic pressure over the tank projected area, which in turn acts on the structure as base shear force.

$$F \ = \ b \left\{ \begin{array}{l} \int_{-h}^{\eta_1} p(L/2, y, t) dy - \\ \int_{-h}^{\eta_2} p(-L/2, y, t) dy \end{array} \right\} \qquad (22)$$

Where η_1 and η_2 are the free surface sloshing elevation at the two side walls of the tank, and $p(L/$

2,y,t) and $p(-L/2, y, t)$ are the liquid pressures at $x = \pm L/2$. b is breadth of tank, the dimension in other orthogonal direction. The convergence in the solution is achieved by an iterative procedure both for structural displacement and the pressure developed in the liquid.

Parametric studies are carried out to observe the effect of slosh damping in the response of the structural system. The parameters studied are the tuning ratio, ratio of sloshing frequency to modal frequency of structure, mass ratio, ratio of mass of damper to structure, water depth ratio, ratio of stationery liquid height to length of the tank etc. A five storeyed building with overhead water tank as TSD is considered for the parametric investigations. Properties of the beams and columns are uniform throughout the storeys. First modal frequency for the considered structure is 6.2 rad/sec. TSD will be used to suppress the first vibration mode of this building subjected to ground excitation. Tuning the fundamental sloshing of the overhead water tank (as TSD) to the first modal frequency of the building gives the length of the tank as 0.8 m in the direction of the excitation. Fig. 4 shows the details of the building considered for parametric studies.

For the parametric investigation to determine the optimal TSD parameters the building is subjected to harmonic ground excitation.

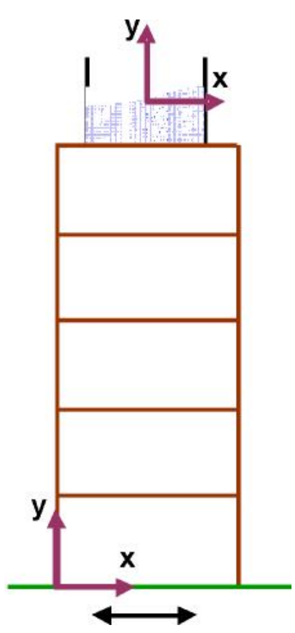


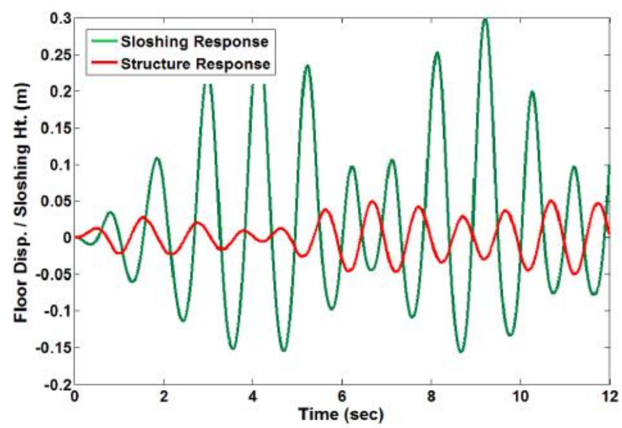
Fig. 4: Test Structure for the parametric investigation

$$\ddot{u}_g = -x_0 \,.\, \omega_e^{\,2} .\, \sin(\omega_e \,.t);$$
$$\text{where } x_0 = 0.007m; \; and \; \omega_e = 6.2 \; rad/\text{sec}$$

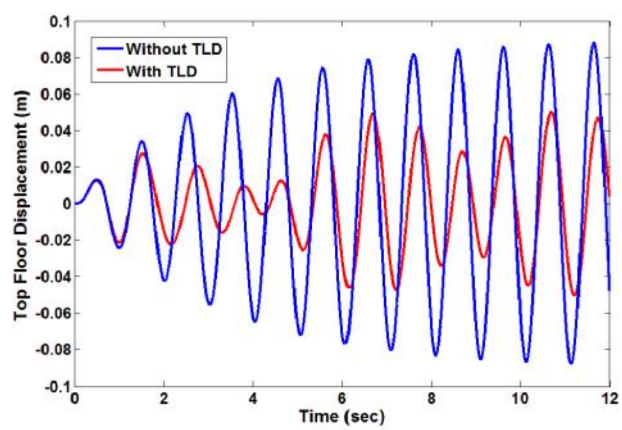
Thus the three frequencies namely structure modal frequency, sloshing frequency and the excitation frequency are kept synchronized

Fig. 5(A) shows the displacement of the top floor of the building for a mass ratio of 1.5. Fig. 5(B) shows the displacement of the structure and the sloshing displacement. The phase difference of the two displacements is quite distinct.

In the present model, water depth ratio (h/L) is kept in the range of 1-2. Parametric investigations



A



B

Fig. 5: Response of structural system with and without Tuned Sloshing damper. Column height = 4m, beam length = 8 m, damping ratio = 5%, EI beam = 17.5e-4 kNm^2, EI column = 27.9e-4 kNm^2, Beam crossectional area = 0.12m^2, Column crossectional area = 0.24m^2, UDL on beam = 40 kN/m

Table 1: Performance of TSD against varying water depth

Water depth ratio (h/L)	0.8	1.0	1.25	1.50	1.75	2.0
Mesh size	12x12	12x12	14x12	16x12	18x12	20x12
Top floor displacement (m)	0.0477	0.0475	0.0488	0.0502	0.0512	0.0521
Percentage reduction	47	47.2	45.7	44.2	43.1	42.1

Table 2: Performance of TSD against varying mass ratio

Mass Proportions %	5^{th} =100% 4^{th} =0 %	5^{th} =90% 4^{th} =10 %	5^{th} =80% 4^{th} =20 %	5^{th} =70% 4^{th} =30 %	5^{th} =60% 4^{th} =40 %
Top Floor Displacement (m)	0.0475	0.0471	0.0481	0.0491	0.05
Percentage Reduction	47.2	47.7	46.6	45.4	44.4

Other parameters assumed in the study are: Structure Damping = 5%; Mass Ratio = 2%; Tuning Ratio = 1; Water Depth Ratio = 1; Top Floor Displacement without TSD = 0.09 m

have been carried out to analyse the performance of TSD with the varying water depth ratios. For the varying water depth ratios inherent damping in the structure is kept 5% and the mass ratio as 2% keeping the water tank at the top floor (i.e. 5^{th} floor). Table 1 indicates the percentage reduction in the displacement of the top floor for different water-depth ratio, with the following parameters: Structure Damping = 5%; Tuning Ratio = 1; Mass Ratio = 2%; Top Floor Displacement without TLD = 0.09 m.

A parametric study was undertaken to study the effect of mass proportioning on the displacement of the building structure. Accordingly the mass was distributed between two floors instead of lumping at one floor. Table 2 indicates the percentage reduction in floor displacement due to the mass distribution in two floors.

Concluding Remarks

Maximum percentage reduction in the response of the structure as top floor displacement was obtained for water depth ratio equal to 1. Increasing the water depth ratio from 1 to 2 caused the gradual decline in the effectiveness of the overhead water tank as damper, but still water depth of 2 provided a significant amount of percentage reduction in the top floor displacement as 42.1%. This implied that the water depth ratio in the range of approximately 1.0-1.5 may provide appreciable amount of mitigation up to 44%.

Investigations carried out for the varying mass proportion showed that TSD maintained its performance quite effectively even after proportioning the damper mass as 100-0, 90-10, 80-20, 70-30, and 60-40 % over the top two storeys. In the present case of five storey structure under harmonic ground excitation maximum percentage reduction of 47.7% in the response of the structure as top floor displacement was observed for mass proportioning of 90% at 5^{th} floor and 10% at 4^{th} floor. It was also observed that tuned water tank performs effectively as a damper even for the mass proportioning of 60% at 5^{th} floor and 40% at 4^{th} floor providing a percentage reduction of 44.4 in the structure top floor displacement.

Significant performance of deep-water TSD with varying mass proportion implied that if enough top floor space is not available for the installation of TSD one can carry out the proportioning of the damper mass in the upper storeys for multi-storeyed buildings. Also from the structure design point of view instead of lumping the mass at the top storey proportioning of damper mass in the upper storeys will reduce the increase in the stresses in the structural members due to the addition of the damper mass.

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