Tuned Liquid Dampers - A Critical Survey of Past Works

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Abstract--**Response controls of buildings with various forms of dampers have been a core area of study which was adopted to mitigate various natural hazards like wind and earthquake. Active, passive and hybrid dampers of various forms are mostly used in structures to make structures more resilient under these natural hazards. Tuned Liquid Dampers or TLD has been a common form of response controller and has undergone numerous modifications in its functionality and installation to reduce the structural vibrations during the event of an earthquake. Till date, several successful applications validated with experimental and numerical investigations have been presented on TLD. It has been observed through literature review that the effects of TLD in presence of unreinforced masonry infill were not studied and since the effect of masonry infill is significant on frame buildings, its importance cannot be ignored. Similarly, there is no comparative study on the parametric effects for the different proposed TLDs taken together. This can be investigated by researchers .**

Keywords-Dampers,TLD, Natural Frequency of Water, multi TLD, response control, sloshing.

I. INTRODUCTION

In recent trend there is a demand to construct tall buildings with light facades to minimize the space problem in urban areas. Often these buildings are relatively flexible structures, possessing quite low damping. Thus sensitivity of these structures to dynamic excitation has increased. Other than that it also led to increase various failure possibilities such as cladding partition, damage serviceability and occupant discomfort too. Therefore to ensure safer functional performance of tall structures it is essential to restrict the frequency of objectionable motion levels below the discomfort threshold. Various possibilities exist to achieve this goal. The most promising solution is to mitigate these problems is through the use of artificial damping devices, one of which Tuned Liquid Damper (TLD) concept is relatively a newer one. TLD, its name came from its operational use as because of it will be tuned to resonate with the main structures in out of phase from it. It is a type of motion activated under passive mechanism of supplemental damping system which is activated by the movement of structures and dissipates some part of the structural seismic input energy through its motion by Introducing extra force to the structure without any need of external power source.

In this paper a detailed study has been carried out to investigate the advances in tuned liquid dampers in the recent past and its applicability in buildings. This paper also presents a detailed report on various aspects of TLD, shortcomings in the past experiments and suggests a further improvement in the present scenario.

II. BACKGROUND

Since 1950s liquid dampers have been used in anti-rolling tanks for stabilizing marine vessels against rocking and rolling motions. In 1960s the same concept has been used as mutation dampers to control wobbling motion of a satellite in space. In the late 1970s TLD has started to be used in civil engineering. To reduce structural motion, Vandiver and Mitome(1979) used TLD to reduce the wind vibration of a platform, Mei(1978) and Yamamoto et.al.(1982) looked into structure wave interactions using numerical methods. In the early 1980s important parameters such as liquid height mass, frequency, and damping for a TLD attached to offshore proposed the use of a rectangular container completely filled with two immiscible liquids to reduce structural response to a dynamic loading. Modi& Welt(1988), Modi&Seto(1997), Kareem & sun (1987), Gardarsson(2001), Tamura &fujii(1995), Sun &Fujino(1989), Sun &Fujino(1992), Samanta&Banerji(2010), Olson(2001 were also among the first researcher who suggested the different types of TLD with suggested the different types of TLD with different properties of dampers utilizing liquid motion for civil engineering structures.

III. FUNCTIONALITY & VARIABILITY

The basic mechanism in TLD is that, damping originates in tuned liquid damper from energy dissipation through the action of internal fluid viscous force and from wave breaking. The amount of damping is dependent on amplitude of the fluid motion and wave breaking patterns. The motion inside the TLD sloshes at the side of wall of TLD tank which in turn produces a force opposite to the excitation direction.

And it is designed to have the same natural frequency of the structure, so that sloshing motion of fluid inside the TLD caused by the external excitation produces a sloshing force approximately anti-phase to the building motion. This in turn will help to mitigate the structural response in terms of story drift, floor response, amplitude, and roof displacements etc. of the building.

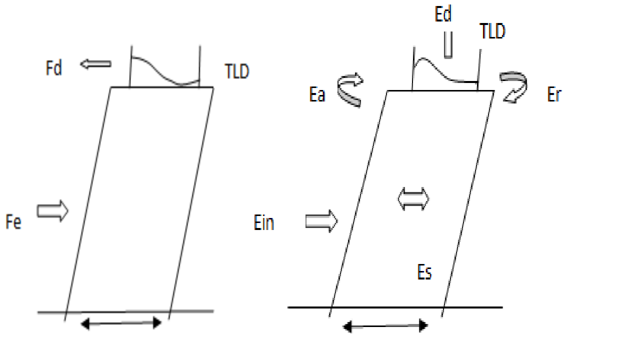


Fig. 1: Mechanism of the Motion damper (TLD). (a) Force Diagram (b) Energy Diagram

Figure 1 shows the mechanism of the motion damper or TLD representing the force and energy diagram.

The abbreviations are as: F_e=Excitation force,F_d =Resisting force by dampers,E_{in} =Energy input,E_a =Energy absorbed by dampers,E_d =Energy Dissipated by dampers, E_r=Energy Returned to structure, E_s=Structural Vibration Energy.

IV. TYPES OF TLD

Several types of TLDs are proposed during last two decades for utilizing the liquid damping mechanism effectively. A schematic diagram in figure 2 is presented to represent the various types of TLDs.

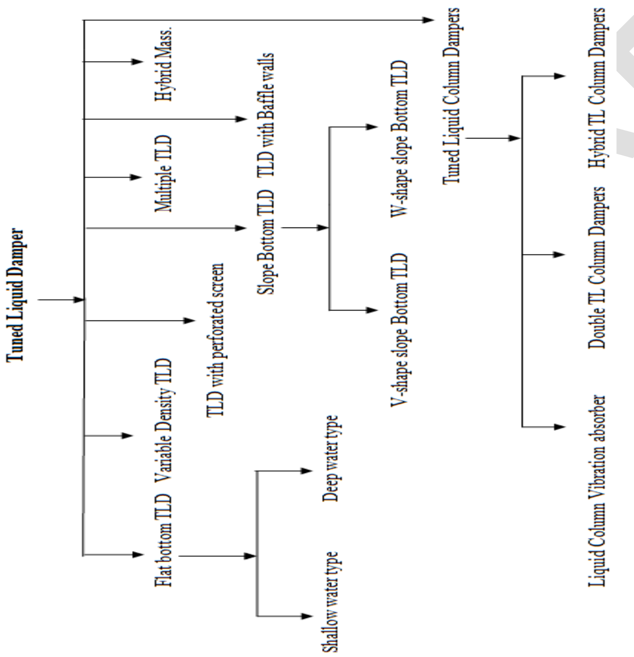


Fig. 2: Diagram showing the family of TLDs

A.Flat Bottom TLD :

Flat bottom TLD also called box type TLD. This type of TLD came in field first for reducing the structural vibration energy. These are generally of rectangular, square and circular type. Installed on the top most floor of the building. A TLD can be classified as shallow water type or deep water If this ratio is less than 0.15 it can be classified as shallow water type and for more than 0.15 it's called as deep water type. Shallow water type has a large damping effect for a small scale of externally excited vibration, but it is very difficult to analyse the system for a large scale of externally excited vibration as sloshing of water in a tank exhibits nonlinear behaviour. In case of deep water type the sloshing exhibits linear behaviour for a large scale of externally excited force.

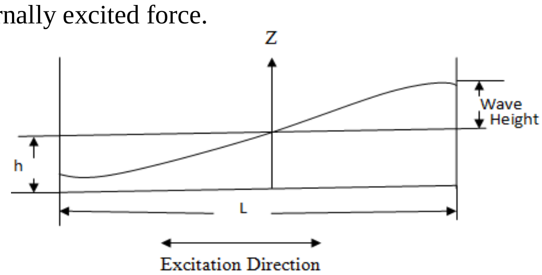
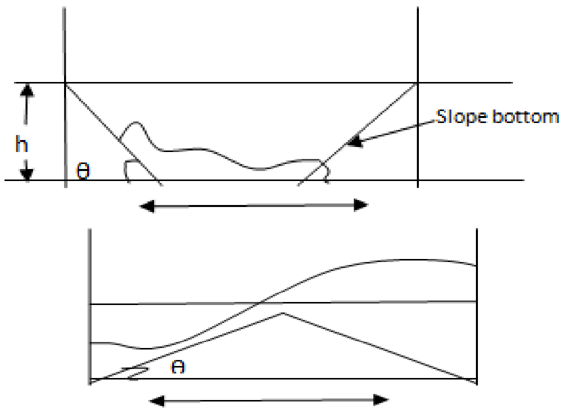


Fig. 3: Schematic Diagram of a Tuned Liquid Damper

B.Slope Bottom TLD:

Slope bottom TLD came into existence for mitigating the drawbacks associated with box type TLD. This concept originated from the sea shore phenomenon. It is well known that a sloping beach is an effective energy dissipater. The majority of ocean waves are dissipated along the shores, especially due to wave breaking. Other features associated with the slope bottom tank is that, Since the run-up height amplification is greater for the sloping beach than the vertical wall, wave motion in the TLD becomes more nonlinear than the box shape TLD and a greater horizontal force might be created with less water mass. Beating phenomenon also can mitigate through slope bottom TLD.



- V-shape and W-shape slope bottom of TLD

Fig. 4: Slope bottom TLDs

C.Multiple TLD:

Multiple TLD is another variety of TLD in which number of TLD is attached together filled with the same depth of water whose natural frequency are distributed over a certain range around the fundamental natural frequency of the structure. Its easy to make a TLD multiple by employing the slightly different depths of liquid and no additional effort to increase the damping of water sloshing to the optimal value isrequired.

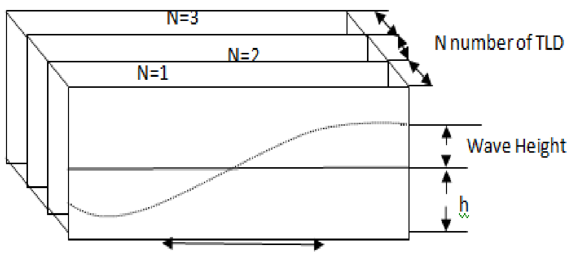
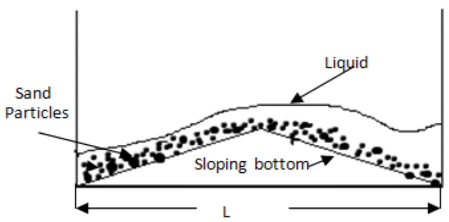


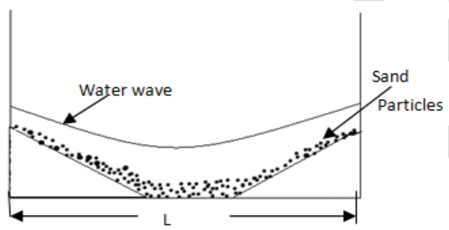
Fig. 5: Multiple TLD

D.Variable Density:

The main function of TLD with variable density is to increase the density of liquid by adding additional substances. For solving the light density limits, slow set in motion of water & continuous wave motion of water (Beating) problems this type of TLD has proposed.



- W-Shape Slope Bottom of TLD with variable density



- (b) v-shape slope bottom of tld with variable density

Fig. 6: TLDs with variable density

E. Slat screen TLD:

A perforated slat screen is used in TLD for minimizing the off tuning effect & to make suitable for wide range of excitation frequency. A slat screen is made of a number of slats, height of slats and total solid area of the screen is S_s=n.D_s. The solidity ratio of the screen S= S_s/h.

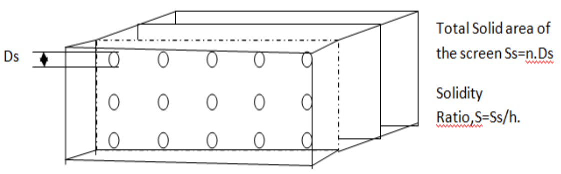


Fig. 7: TLD with Slat Screen

F. Hybrid Mass TLD:

The TLD is known to dissipate more energy when water sloshing is greater , which happens when the TLD base is subjected to a large amplitude motion for utilizing this characteristics the TLD is connected to a secondary mass that is attached to the primary structure through an appropriately designed spring system. Which is called hybrid mass TLD since there are both a secondary mass and a liquid dampe$_r$.

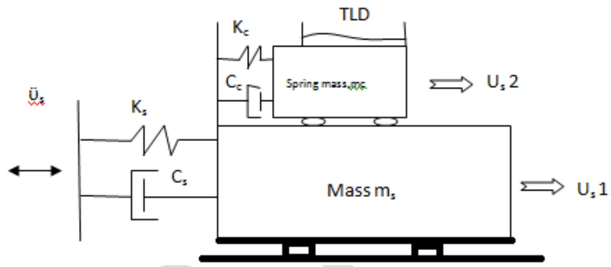


Fig. 8: Hybrid mass liquid damper

G. Baffle Wall TLD:

TLD with baffles are used to compensate the effect of probable mistuning of the TLD & to make the TLD more controllable.

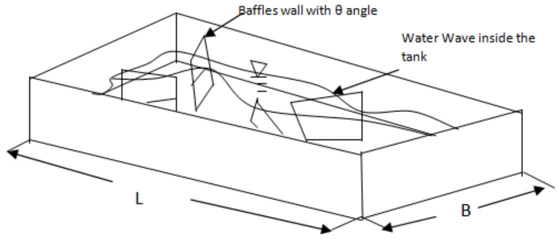


Fig. 9: TLD with baffle walls

H. Tuned Liquid Column Dampers(TLCD):

Tuned Liquid Column Dampers dissipates structural vibration by combined action involving the motion of the liquid mass in the tube, where the restoring force is due to the gravity action upon the liquid and the damping effect as a result of loss of hydraulic pressure due to the orifices installed inside the container.

As a damper TLCD system offers few advantages over other damping devices, including TSDs , such as

- TLCD can take any arbitrary shape, for which it can be fitted to an existing structure easily,
- Unlike mathematical model, which quantitatively defines the dynamics of TLCD can be formulated.
- We can control the damping capacity of TLCD through controlling orifice opening. This allows us to actively control the damping in TLCD system , and
- We can tune the frequency of a TLCD by adjusting the liquid column in the tube.

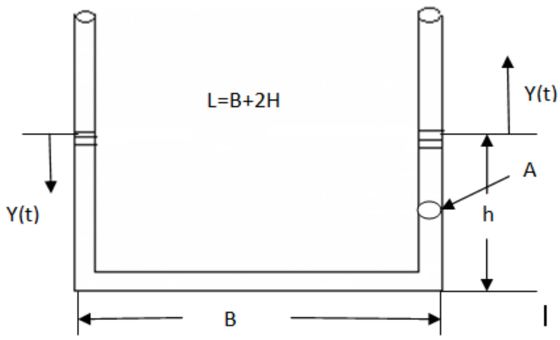


Fig. 10 : Tuned Liquid Column Damper

V. ADVANCEMENTS IN TLD TILL DATE

In this section, reviews on few remarkable researches on tuned liquid dampers are presented. It presents the modifications, advancements, alterations carried out with TLD for better performances in buildings by researchers

K.Fuji, Y.Tamura (1990) found that TSD is an effective for reducing the structural response on gusty days in towers & it depends on the amplitude of vibration. Author has calculated the frequency response function by the lumped mass system using the TSD frequency response function.

$Ho(w)=-(w/w_o)^2.(1/M_o).(1/(1-(w/w_o)^2+i2h_o(w/w_o)+(w/w_o)^2.$ € $(m_j/M_o)H_j(w))$
Where,

Where, Ho(w)= Frequency response function of a structure with TSDs,$w_{o=}$ Natural frequency of the structure,h_o= Damping ratio of the structure,M_o= Generalized mass of the structure,$H_j(w)$= Frequency response function of a TSD(Accel/Force),m_j=Mass of the TSD,j= Number of TSDs

Kareem, (1990) Conducted his study on TSD for reduction of wind induced motion. A finite element model was investigated the performance of liquid motion including the effect of free surface nonlinearity, viscosity and energy dissipation. Author gave conclusion that TSD imparts a additional damping to the system. It dissipates structural vibration through viscous action of fluid & wave breaking. Can be used in tall buildings, towers, bridges and in offshore platform also.

L. M. Sun, (1992)Has studied Nonlinear model for rectangular TLD by using the shallow water wave theory with considering effect of liquid damping. Analytical & experimental both studies had performed for checking the efficiencies. Different basics equations has been derived by Navier Stokes equation & continuity equation. Boundary conditions for solving those equations are also stated in his work. Fr accounting the breaking waves two

- coefficientscda&cfr from experiments data sets has been found out. And lastly Author concluded that TLD is very satisfactory for suppressing structural vibration. A modified TLD model can predict the structural response very well even in the presence of breaking waves. The suggested equations are-

$$F_w = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\frac{\pi h}{L}}$$

$$\lambda = \frac{1}{\eta + h}\frac{1}{\sqrt{2}}\sqrt{w\nu}(1 + \frac{2h}{b} + S)$$

$$Cda = 0.57\sqrt{\frac{\varepsilon h w_w}{\nu}}A$$

cfr=1.05
Where,

Fw=Fundamental natural frequency of liquid sloshing according to linear shallow water wave theory,G=Acceleration due to gravity,L=length of the tank in the direction of liquid motion,H=Width of tank,λ=Damping coefficient,Ƞ=Height of water wave above still water,H=Height of still water,V= Kinematic viscosity,W= Angular excitation frequency,B= Width of the tank,S=Surface contamination factor(Used S=1),Cda&cfr= wave breaking coefficients,Cda=is used when the wave height exceeds the water depth h(Ƞ>h),Xs max.=Maximum displacement experienced by the structure at the location of the TLD.

V. J. Modi, (1997) TSD by numerical simulation it can able for suppressing the amplitude over 85% at resonance based on the nonlinear dissipative as well as dispersive shallow water model.

Reed and Gardarsson(1998)Presented a study on TLD by both experimentally and the tank is robust in dissipating energy over a wide frequency range preferably for large amplitude excitation. Design damper frequency must be tuned at the value lower than that of the structural frequency. The base shear force induced by the liquid sloshing is given here-

$$F_b = \frac{1}{2}\rho g b[hr^2 - hi^2]$$

where p = density,*g* =gravity,*b*=tank width, *hi* =wave height at the end wall on the left side and
hr=wave height at the end wall on the right side.

Relation between Excitation Frequency *f* and wave propagation speed *S*

$$F = \frac{S}{2L}$$

Where,L=length of the tank And the propagation speed S of the breaking wave

$$S = \sqrt{\frac{g}{2}\frac{hl}{hi}(hi + hl)}$$

hl =is the total water depth immediately behind the wave front,hi=water depth.

Banerji(2010) Numerical studies has been conducted on

TLD for both actual ground motions & sets of artificial ground motions for SDOF . The normalized equations of motion of structure with TLD is

$$\ddot{u}_s + 2\xi_s w_s \dot{u}_s + w_s 2u_s = ag + \frac{F}{m_s}$$

$$w_s = \frac{2\pi}{T_s}$$

Where, F=Base shear force.

.

It was observed that TLD gives good agreement for dissipating the structural response as the ground excitation amplitude increases. The TLD is less sensitive towards variation in the values of its parameters for larger mass & depth ratios. It was also concluded that the optimum value of depth ratio is about 0.15 & mass ratio is about 4%.

M.J.Tait, (2008)A nonlinear numerical model based on shallow water wave theory is found to accurately predict the efficiency & robustness for a number of structure-TLD systems in random excitation. Mass ratio has greater influence that depth ratio for increasing the effective damping.

Young-Moon kim(2006) Studied TLD & TLCD experimentally , found that TLCD was more effective control vibration than TLD. The different natural frequency are-

$F_w = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\frac{\pi h}{L}}$ for rectangular &square water tank (1)

$F_w = \frac{1}{2\pi}\sqrt{\frac{1.841\,g}{R}\tanh\frac{1.841\,h}{R}}$ for circular water tank

$F_w = \sqrt{\frac{2g}{L}}$ for TLCD water tank.

DMF=$(((r^2-\beta^2)^2+(2\xi_a r\beta)^2)/([(r^2-\beta^2)(1-\beta^2)-(r^2\beta^2\mu)]^2+(2\xi a\, r\beta)^2(1-\beta^2-\beta^2\mu)^2))^{1/2}$

Where,

$(M = \frac{m_t}{m_s})$ Mass ratio , $(R = \frac{f_t}{f_s})$ tuning ratio, $(B = \frac{f}{f_s})$structure-excited frequency ratio, ξ_a =Damping Ratio of TLD

$Fw' = Fw/(m_w W^2 A)$

$\eta'max = \eta max/h$

Where, DMF=Dynamic magnification factor,Fw'=Base shear force,η'max=Height of waves,Fw=Base shear force calculated from load cell after deducting the inertia force of empty tank,$m_{w=}$mass of water in the tank,W=Excited frequency of shaking table,A=Amplitude of shaking table,ηmax=Water Height Measured from wave gauge.

Hong-Nan Li (2000) presented simplified simulating calculation formulas for TLD by the use of Navier-Stakes Equation of fluid. This has been solved by volume of fluid. The dynamic liquid pressure equations have derived in his work which is very beneficial for reducing the dynamic response of the structure. Relative formulas given below are taken by the stated literature.

1. When $h/A = 0.4$ ($0.6\text{ m} \le A \le 5\text{ m}$):

$$F_m = \alpha\{\pm 2{,}221.6A^{2.2537}(T/T_w) \mp 1{,}594.2A^{2.6662}\}$$

$$(0.8 \le T/T_w \le 1.15)$$

$$F_m = \alpha\{\pm 0.002014A^{-2.193} \mp 0.01587A^{-2.1484}(T/T_w)^{-20}\}^{-1}$$

$$(1.15 \le T/T_w \le 1.4)$$

$$\alpha = 0.9622e^{-0.0357A}a_m^{0.9975+0.0103A} \quad (a_m \le 1\text{ m/s}^2)$$

2. When $h/A = 0.5$ ($0.6\text{ m} \le A \le 5\text{ m}$):

$$F_m = \alpha\{\pm 2{,}675.9A^{2.181}(T/T_w) \mp 1{,}976.8A^{2.1752}$$

$$(0.8 \le T/T_w \le 1.2)$$

$$F_m = \alpha\{\pm 0.001143a^{-2.1931} \mp 0.01324A^{-2.16944}(T/T_w)^{-20}\}^{-1}$$

$$(1.2 \le T/T_w \le 1.4)$$

$$\alpha = 0.63459e^{-0.0342A}a_m^{1.10126A^{0.0117}} \quad (a_m \le 1.5\text{ m/s}^2)$$

Gardarsson, (2001)Presented an experimental study on 30^0slope bottom tuned liquid damper. In this study Author concluded that Slope bottom TLD Behave like softening spring which mitigate the beating problem. The proposed type is effective when it is tuned slightly higher than the structures fundamental response frequency.

Olson, Reed (2001)Extended the Slope bottom study to evaluate the appropriate Slope bottom data for structural engineering context. The natural frequency of water estimated from Lamb's equation is modified with wetted perimeter. And lastly it has found that with modified length parameter Lamb's equation for natural frequency of water f slope bottom gives close estimate.

$$F_w = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L1}\tanh\frac{\pi h}{L1}}$$

Where,$L1 = L0 + (\frac{2ho}{\sin\theta})$

Where, g= Acceleration due to gravity, L1=Wetted perimeter length of slope surface,h=width of the tank.

Xin, Chen (2009)Different types of slope bottom with variable density (by using sand) was examine on 3storey frame building both experimentally and numerically. They have found that variable density with w-shape bottom is consistently more effective in mitigating both the storey drift and floor acceleration of building than V-shaped bottom, and much more effective than box TLD under strong earthquake. Because of increased damping and reducing mass in the suspended state the Density variable TLD(DVTLD) can step up the decaying process of free vibration after the cessation of an external excitation .

In the stated literature the horizontal control force Fj(t) applied to the jth floor of the building by a slope bottom TLD is equal to the resultant of the fluid dynamic pressures on the left and right walls of the flat bottom TLD tank, and expressed by

Where, ρ= Water density,$\ddot{x}_j(t)$ =Relative acceleration on the jth floor with respect to the base of the building, $\ddot{x}_g(t)$ =Ground acceleration at the base of the building, $\dot{y}(t)$ =First modal acceleration of water sloshing,H=Maximum water depth,L=Length of tank.

Fujino,&Sun (1993)Conducteda study on multiple TLD experimentally by forced excitation experiment and on MTLDs-structure interaction experiment. Through experiment he found that An MTLDs with proper frequency band width does not lose its efficiency even for off-tuning in frequency. Various parametric formulas are presented there-

$f_o = f_N + \frac{f_1}{2}$ Central frequency

$\Delta_R = (f_N - \frac{f_1}{f_0})$ Frequency band width

$B_i = ((f_i + 1) - f_i)$ Frequency Spacing

$\Delta_y = \frac{f_s - f_0}{f_0}$ Off-tuning parameter

Where,f_i= Natural sloshing frequency of the ith individual TLD, f_1 and f_N=Lowest and the highest f_i, N= Number of TLDs,f_s=Natural frequency of the structure,f_{TLD}=Natural frequency of TLD, h and ν=Liquid depth and kinematic viscosity.

Banerji&Samanta (2011)In this work Author presented hybrid mass TLD for increasing the base acceleration amplitude and concluded that effectiveness of HMLD depends on the relative stiffness of the secondary mass spring system used for making the model hybrid compared to the stiffness of the primary system. HMLD found 20% - 60% more effective for reducing the structural response in both large amplitude excitation and broad band earthquake ground motions.

Zahrai, Abbasi(2012)Studied TLD with rotable baffles for compensate the effect of probable mistuning of the TLD and also for making the TLD more controllable. Aexperimental investigation was carried out on five story frame building with TLD rotable baffles subjected by 21different harmonic and with 2scaled down earthquake excitation. After the experiment Author gave the conclusion is that the best performance can achieved when the angle of baffles are $0^0<\theta>90^0$. The effectiveness of the baffles Is more strong against the Kobe earthquake than the El-Centro earthquake. With baffles increases the flexibility of the TLD under random excitations and also cover the mistuning effects.

VI. SHORT COMINGS & SCOPE FOR FURTHER ENHANCEMENT IN TLDs

In real life applications the TLD and structure are never perfectly tuned. As because of its very difficult in assessing structure exact natural frequency beforehand, and TLD natural frequency is also amplitude dependant.

- In real life applications the TLD and structure are never perfectly tuned. As because of its very difficult in assessing structure exact natural frequency beforehand, and TLD natural frequency is also amplitude dependant.
- Linear Structural model and TLD behavior does not give proper agreement for practical application. For knowing health monitoring, condition assessment, and damage detection of TLD-structural system nonlinear model idealization needed.
- Optimal angle for sloped bottom TLDs, for minimal structure response very crucial to investigate. As liquid run-up decreases the liquid damping also decreases and Depending upon the slope angle the run-up heights generated.
- For practical TLD installations, the spaces available are extremely limited. That prevents the TLD designer from installing a fully rectangle or cylindrical TLD.
- No difference in the response reduction has been found in structure with and without during the first few periods of oscillation, until the sloshing force inside the TLD builds up.

VII. CONCLUSION

As observed from the detailed study of tuned liquid dampers from its inception, it is clearly noted that TLD has been an efficient form of damper which has been successfully implemented as a device of response control in buildings by numerical and experimental studies. This has also been reported that, TLDs are less expensive and do not require any external power to operate, rather they can be used for additional purposes like swimming pool and fire fighting. But, the TLDs that were investigated had several shortcomings and need to be investigated to be more practically applicable in buildings. Those shortcomings are discussed in the present study which may be considered in the future and carry forward for further modifications and hence better optimized results.

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