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Tuned Liquid Damper

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Abstract - The aim of this paper is to show the effectiveness of a tuned liquid damper (TLD). TLD can be used in building structures to damp structural vibrations. A Tuned liquid damper is water confined in a container, usually placed on top of a building that uses the sloshing energy of the water to reduce the dynamic response of the system when it is subjected to excitation. The experimental setup models a building using PASCO beams and trusses and uses moveable base, powered by a motor, to simulate an earth quake. The sensor used in the experiment is an accelerometer that measures the acceleration at the top of the structure when subjected to vibrations in the presence and absence of a TLD. Vernier DAQ in conjecton with LabVIEW was used for data acquisition from the accelerometer. Frequency range around the resonant frequency (first natural frequency) was considered for excitation in both the cases. The outcome of the experiment was that the TLD effectively dampened the vibrations (up to 80% reduction in vibration) when excited and the dampening effect was found to be maximum around the resonance frequency. An attempt has also been made to theoretically model the system in the absence and presence of TLD.

Keywords: Vibration control, Tuned liquid Damper, Sloshing.

1. Introduction

Vibration control is an important aspect when designing buildings, especially if they are tall. Buildings can get subjected to substantial vibration due to wind and earthquakes. When an earthquake waves travel through the building, it is subjected massive forces, acceleration and displacement that makes the building highly unstable and eventually it collapses. Additionally, as modern skyscrapers are made tall using flexible beams, wind can cause significant swaying of the building. This repeated load cycles can induce fatigue into the beams and also can cause sea sick feeling for the residents living on top.

Mass damper, Liquid dampers, base isolators and other supplemental damping systems (SDSs) are among the various alternatives used to reduce the vibrations on the structures. This paper will focus on one of these methods, Tuned liquid Damper (TLD). A TLD is water confined in a container that uses the sloshing energy of the water to reduce the dynamic response of the system when the system is subjected to excitation. TLD has also been found to be very effective in cancelling vibrations caused due to wind.

Tuned Mass Dampers (TMDs) are the origin of TLDs. TMDs are implemented in most tall buildings to achieve vibration control since the 1950s. However, the more recent technology TLD, is a superior choice to tuned mass damper (TMD). TLD is more effective for absorbing low frequency vibrations produced due to wind, cost effective, requires less maintenance and easily implementable.

The objective of this paper is to experimentally verify that TLD can substantially damp vibrations in a building. Also, the modelling of TLDs and various methods of improving its performance have been explored.

2. Procedure

Pre-requisite to performing the experiment, a 4 story skeletal structure (Figure 1) was constructed, with the help of PASCO members (flexible and rigid). The flexible members were oriented in the direction of the base excitation. The entire structure rested on a slider mechanism which was also constructed using axles and other PASCO members (Figure 1). A transparent rectangular plexi glass container was placed on the top most floor which was effectively caged using the PASCO members to avoid any movement of the container with respect to the structure.

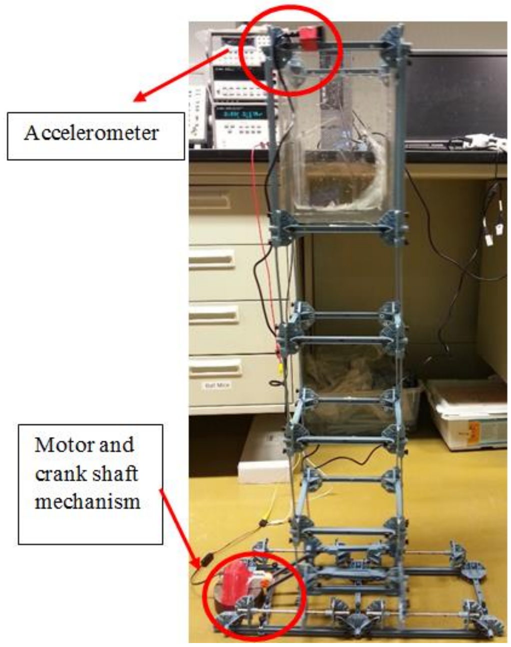

Fig. 1. TLD in effect with the help of sloshing energy of water.

A Vernier accelerometer (labVIEW supported), attached to the one of rigid members on the topmost floor, was used to measure the amplitude of the acceleration with the help of LabVIEW via the Vernier DAQ. A crank shaft mechanism was designed for the structure to be in conjunction with a Lego motor using Lego members. This was used to convert the motors rotational motion into translation motion. The Lego motor was powered by the variable voltage source that could provide voltage up to 12V.

The experiment consisted of two parts

1) Free vibration (to find natural frequency of the structure): Under free vibration (absence of TLD), the motor was disconnected from the experimental apparatus and the structure was excited freely like that of a cantilever beam. The to and fro acceleration of the structure due to flexible members and base excitation was recorded in lab view using the accelerometer.

2) Forced vibration: The forced vibration was conducted by running the motor at voltages ranging from 3V to 8V, in steps of 0.5V. It was performed in the presence and absence of TLD so as to show the effectiveness of the TLD in dampening the dynamics of structure due to base excitation. In the presence of TLD, 500g of water was added inside the plexiglass container. In the absence of TLD, 500g of sand was added, so as to keep the mass consistent in both the cases.

3. Methodology

3.1 Modelling the Building

The slender beams used in the building have been modelled using Euler's beam bending theorem. As a consequence, the lateral bending in a one sided cantilevered beam has the stiffness value

$$k = \frac{3EI}{l^3} \tag{1}$$

where, E= modulus of elasticity of the material

I=Second moment of area of the cross section, for rectangular cross section, $I = \frac{1}{12}bh^3$

l=height of the beam.

If the beam is cantilevered at both ends (in terms of civil engineers, welded at both ends), then the stiffness increases by 4 times and is given by

$$k = \frac{12EI}{l^3} \tag{2}$$

In the model used, each floor was supported by 4 beams (each cantilevered/welded at both ends) and thus the equivalent stiffness was 4 times the value given in equation (2). Thus, if a single floor was modelled, then the resulting differential equation would be:

$$m\ddot{x} + c\dot{x} + kx = f \tag{3}$$

where, m=mass of the floor
c=dampening coefficient
k=equivalent stiffness, i.e. $k = \frac{48EI}{l^3}$
f=external applied force

If the model is extended to multiple floors (which in this case is 4), then similar number of coupled differential equations will be obtained. They are stated (under forced vibration) as follows:

$$m\ddot{x_1} + 2c\dot{x_1} + 2kx_1 = c\dot{x_2} + kx_2 + k * a * \cos(\omega t) - c * a * \sin(\omega t)$$
$$m\ddot{x_2} + 2c\dot{x_2} + 2kx_2 = c\dot{x_3} + kx_3 + c\dot{x_1} + kx_1$$
$$m\ddot{x_3} + 2c\dot{x_3} + 2kx_3 = c\dot{x_4} + kx_4 + c\dot{x_2} + kx_2$$
$$M\ddot{x_4} + c\dot{x_4} + kx_4 = c\dot{x_3} + kx_3 \tag{4}$$

where, ω=frequency of the periodic input
a=amplitude of the input

For the given setup, the parameters are given in table 1. Substituting these constants in the equation set (4), the eigenvalues (and the corresponding natural frequencies) can be calculated. The four natural frequencies were 1.6 Hz, 8.4 Hz, 14.9 Hz, 19.5 Hz.

Table 1. Various parameters of the building.

l	0.13404 m
b	0.01016 m
h	0.0026 m
E	$2.29 * 10^9$ Pa
m	0.162 kg
M	1.27 kg

3.2 Modelling the Liquid

For accurately capturing the motion of sloshing water in a vibrating tank, nonlinear functions must be employed. If the conventional spring mass formula given in equation (3) is used for modelling liquid sloshing behavior, then all the constants m, k and c will no longer be constants, but rather functions of displacement i.e $m(x)$, $k(x)$ and $c(x)$. Most often, the numerical modelling is coupled with CFD (Computer Fluid Dynamics) software simulations and/or actual experimental setup simulations to obtain various curve fits for m, k and c as functions of x. This is could be further complicated if water is confined in a complex geometry.

In our experimental case, water was confined in a simple rectangular container. In existing literature, there are various linear models which predict the natural frequency of water in rectangular containers, provided that the amplitude of sloshing is within certain limits. At high water amplitudes, the linear models are no longer valid, since various nonlinearities enter the system, such as wave breaking and slamming (instead of sloshing). In this paper, a rather simple approach has been taken to model the system. Linear theory existing in literature has been used to find the natural frequency of water confined in rectangular, which is given by (Abramson, 1966):

$$\omega = \frac{1}{2*\pi} sqrt\left(\frac{g\pi}{a}\tanh\left(\frac{\pi h}{a}\right)\right) \tag{5}$$

where, ω=the natural frequency of sloshing in Hz
h=height of the water in the container
a=the length of the container in the direction of excitation
The dampening factor was also modelled linearly using the equation [3]:

$$\zeta = sqrt\left(\frac{\nu}{a^{\frac{3}{2}}\sqrt{g}}\right) \tag{6}$$

where, ν=kinematic viscosity of the liquid
Equations (5) and (6) are only valid for shallow water cases (cases when $\frac{h}{a} > 0.15$)

When one observes the motion of water in a confined container, some layers of water move (the layers on top), while other layers (at bottom) stay still. Literature defines the non-moving layer of water as dead or inactive mass, while the moving layers as active mass (Yalla, 2001). Expressed mathematically:

$$m_{tot} = m_a + m_i \tag{7}$$

Where, m_{tot}=the total amount of water in the tank
m_a=active mass of water in the tank
m_i=inactive mass of water in the tank

There exists a linear theory as well for defining the amount of active water in the system (Abramson, 1966), however this theory turns invalid even at low amplitudes of excitation. Thus, using visual inspection, an estimate of the active mass was made. Once the natural frequency is known using equation (5) and the active mass is known using CFD or experimental methods, the equivalent stiffness and the dampening coefficient can be found out using:

$$k_{equ} = m_a * \omega^2 \tag{8}$$

$$c_{equ} = 2\zeta\sqrt{k_{equ} * m_{equ}} \tag{9}$$

Using these equivalent constants, the liquid equation can be coupled with the equation set given in (4) in which the first 3 equations remains the same, while the fourth equation is modified and coupled with a new equation as given below.

$$\begin{gathered}(M + m_i)\ddot{x_4} + (c + c_{equ})\dot{x_4} + (k + k_{equ})x_4 = c\dot{x_3} + kx_3 + c_{equ}\dot{x_5} + k_{equ}x_5 \\ m_a\ddot{x_5} + c_{equ}\dot{x_5} + k_{equ}x_5 = c_{equ}\dot{x_4} + k_{equ}x_4\end{gathered} \tag{10}$$

3.3 Simulation

Matlab was used to simulate the system behavior in presence and absence of TLD by solving the equation sets (4) and (10) using the built in numerical differential equation solver 'ode 45'. The displacement of the top floor (x_4) at each exciation frequency was obtained. The x_4 amplitudes at steady state was divided by the input amplitude to obtain $\frac{output}{input}$ ratio at each frequency. The result of the simulation is plotted in Figure 2.

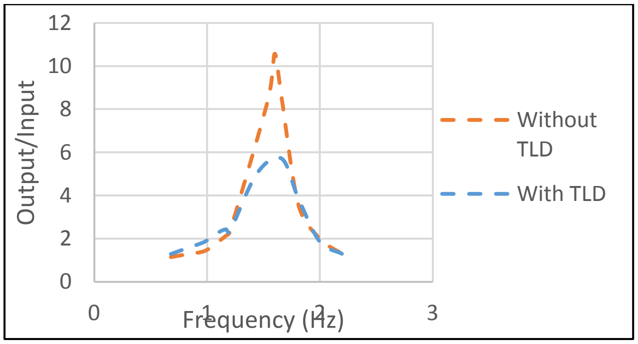

Fig. 2. $\frac{Output}{Input}$ ratio obtained through numerical simulations.

4. Experimental Results

4.1 Free Vibration Test

Free vibration test was performed without the presence of the TLD, to obtain the values of 'c' and the natural frequencies of the building. On performing the free vibration tests, Figure 3 was obtained. From FFT of this data, the first two natural frequencies were observed as ω_n = 1.59 Hz, 8.52 Hz . These values closely matched the values obtained in theory, which gave ω_n = 1.60 Hz, 8.4 Hz.

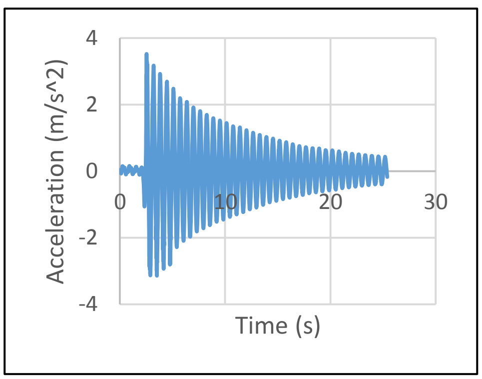

Fig. 3a. Time response.

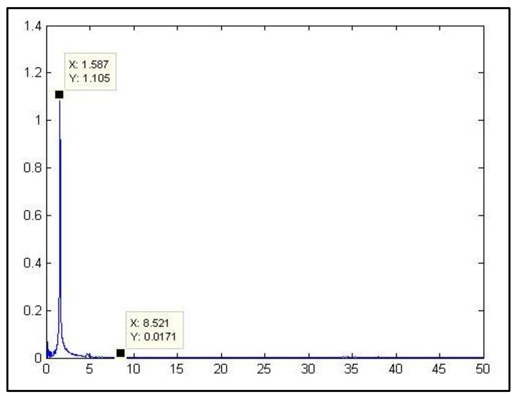

Fig. 3b. FFT of the time response.

4.2 Forced Vibration Tests

As mentioned in the procedure, forced vibration tests were performed by varying the voltage to the motor (between 3V to 8V). The case of 5.5 V and 6 V (voltage around the resonant frequency) are shown in Figure 4 and 5.

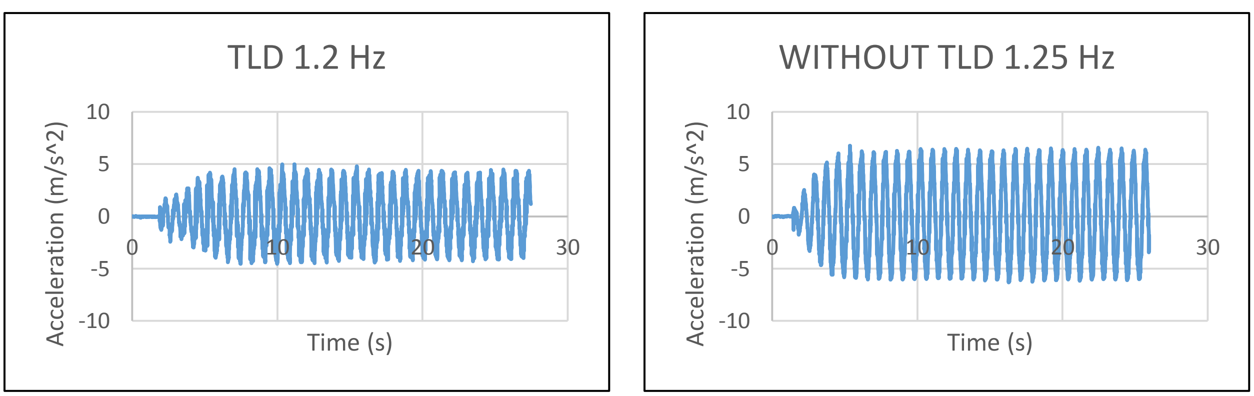

Fig. 4. Response with and without TLD at 4.5 V.

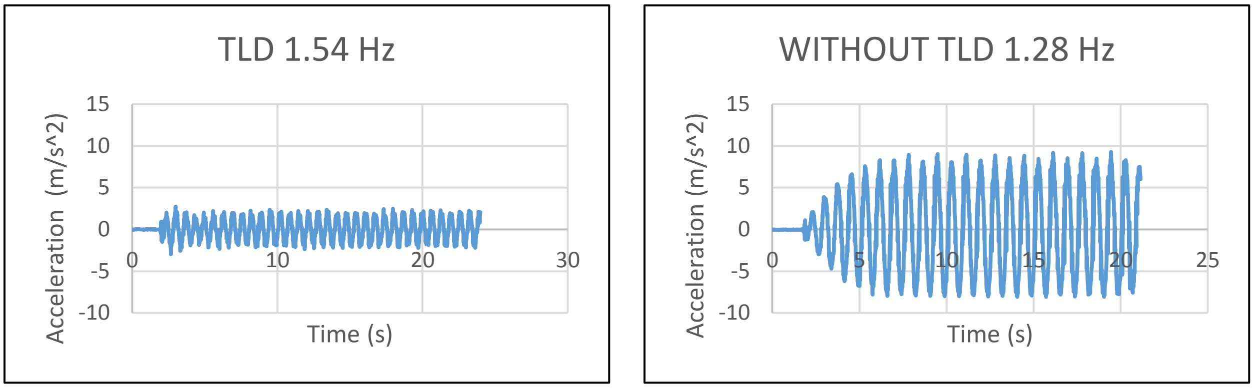

Fig. 5. Response with and without TLD at 5 V.

The response of the system over the whole excitation range is presented in Figure 6.

From the experimental data shown in Figures 4 and 5, one can distinguish the transient and steady state response. The average amplitude of the steady conditions was divided by the input and this is plotted in Figure 6, which gives the frequency response of the system.

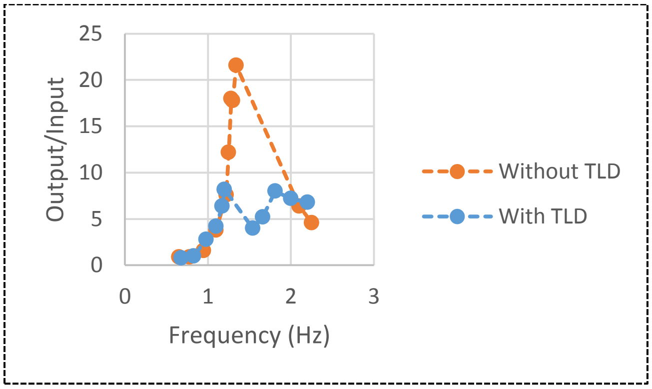

Fig. 6. $\frac{Output}{Input}$ ratio obtained through experimental data.

5. Discussion

From the experimental results provided in Figure 6, it can be seen that the objective of dampening displacement and acceleration of the structure with the help of a TLD, was met. As can be seen from the same Figure, the maximum effect of dampening occurs around the resonant frequency (first natural frequency) of the building and as we move away from the resonant frequency, the effect of the damper decreases. The TLD has minimal effect on the higher frequencies of the building since they are not very destructive.

From the Figure 4, it can be seen that without TLD, there is a single peak; while in the presence of TLD, split peaks are obtained. Split peaks are a common phenomenon in TMD systems and various literatures have reported this (Mellichamp).

On comparing the experimental and theoretical results (Figure 2 and 6), the case in the absence of TLD (which is just the building itself) has been modelled quite accurately. The first two natural frequencies predicted by the model, were observed in the system. However, the modelling of the coupled system (in the presence of TLD) does not coincide very much with the experimental results. This is primarily due to using a low accuracy model in the liquid equation. This can be improved by curve fitting m, k and c as functions of x. In some of the models, additional constants are included to further match the model with experiments (Yalla, 2001). In actual design problems, these curve fits are made either through

CFDs or through experiments (Hardware In Loop, HIL).

The efficiency of TLD depends on various parameters like the liquid used, container geometry, amount of liquid, usage of baffles, etc. Generally water is chosen as the liquid and baffles are not used in shallow water TLD (when $\frac{h}{a} > 0.15$) cases. If the geometry is confined to rectangle, then the only tuning parameter is the amount of water. In this experiment, only one case was run (TLD containing water with 500g). The study of how the amount of water influences the efficiency will be a subject of future research. However, a few points can be certainly made regarding tuning. As with TMDs, even TLDs would act best when the sloshing frequency of water would be close to the resonant frequency of the building. Along with that, $\frac{water\ mass}{building\ mass}$ would play a key factor for optimizing the amount of water.

Regarding geometry of the container, Tuned liquid column dampers (TLCD) have been found to have better efficiency than TLDs. This has been explained due to fact that the content of inactive/dead mass is lower in the case of TLCDs (De Souza et al., 2006). This model could be used for such future study.

6. Conclusion

The experiment performed, showed the efficiency of the Tuned Liquid damper in dampening the acceleration and displacement of structure when the structure's base was excited. From the theoretical and experimental results obtained it was confirmed that TLD was most effective when the structure was excited at resonance frequency of the structure, reducing the $\frac{output}{input}$ ratio from 22 to 4 (80% reduction in vibration). Theoretical model was successful in modelling the behavior of the building but fell short in modelling the behavior of water. This was due to using a low accuracy model for modelling water and improvement in this regard, will be the scope of further study. To summarize, TLD is a relatively simple method of vibration control and this has been verified by the performed experiments.

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