Effectiveness of Tuned Liquid Column Dampers on Vibration Behavior of One-story Steel Structure under Harmonic Force and an Earthquake Record

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Abstract: Tuned Liquid Column Damper (TLCD) is a type of auxiliary mass system for dissipating the structural energy. This study considers the experimental performance of a one storey steel structure-TLCD system with various TLCD frequencies. A harmonic force was applied to each system and the optimum tuning ratio was measured. Afterward, an experimental study was carried out to consider the feasibility of implementing TLCD for an earthquake-excited structure and the response of the structure was examined. Attaching a TLCD at the top of a structure demonstrated a reduction of 19.4% and 29% in acceleration response when subjected to harmonic force and an earthquake record, respectively. A numerical study was proposed using finite element software for the system with the optimum tuning ratio excited by harmonic force and an earthquake record. The results of experimental works and finite element software were in good agreement.

Key words: seismic structural response, Tuned Liquid Column Damper.

INTRODUCTION

Mitigation of building structures has been a major concern amongst engineers. Vibration control devices can be categorized into active or passive systems and have been applied to prevent excessive vibrations. Active control systems require the supply of external time-varying control forces to resist the vibratory motion. The passive control systems do not have external power requirements.

Amongst passive systems, the use of damping devices has gained wide popularity in recent years. This is due their cost effectiveness and ease of installation. Furthermore, these damping devices do not change the intrinsic properties of the structures. Examples of dampers would include the Tuned Mass Damper (TMD) (Wargon, 1983), Petersen, 1980), Tuned Liquid Damper (TLD) (Modi and Welt, 1987), (Fujii et al., 1990), and the Tuned Liquid Column Damper (TLCD). In this paper the effectiveness of the TLCD as a damping device on a steel building structure is examined. Tuned Liquid Column Dampers (TLCDs) dissipate structural vibration by combined action involving the motion of the liquid mass in the tube, where the restoring force due to the gravity acting upon the liquid, and the damping effect as a result of the loss of hydraulic pressure due to the orifice(s) installed inside the container. Fig. 1 shows the schematic of a TLCD.

TLCD, as shown in Fig. 1, was first proposed by Sakai et al. (Sakai et al., 1989). The efficiency of TLCD for controlling wind-induced vibration was investigated by Xu et al. (Xu et al., 1992). A structure modeled as a lumped mass multi-degree of freedom system was analyzed. Samali et al. (Samali et al., 1992) did parametric studies by varying the TLCD characteristics. For a forty storey building under earthquake loading, the TLCD demonstrated a similar vibration suppression capacity as the TMD. Samali et al. (Samali et al., 1993) found the performance of the TLCD can be dependent on structural, damper, and excitation characteristics in general. Heo et al. (Heo et al., 2009) proposed a TLCD connected to the primary structure with spring and dashpot, which act as TMD in the transverse direction of the liquid motion and conducted forced vibration tests. In this study, an experimental work was conducted to find the optimum tuning ratio of a one-story steel structure-TLCD system with changing water elevation in TLCD when the system is subjected to a harmonic force. The efficiency of adding TLCD to structure with an optimum tuned ratio was subsequently considered when the structure-TLCD system was subjected to a Malaysian earthquake record. A new numerical model is also proposed with the aim of ANSYS software.
Methodology:

A. Experimental Work:

1. Preparation of Structure and TLCD:

The structure used in this study was a one-storey steel building. The structure was had a height of 1.0 m, dimensions of 0.8 m × 0.8 m, and a natural period of 0.67.

The TLCD was made from Perspex and filled with an incompressible liquid. The liquid had a density of 998 kg/m³, a viscosity of 0.001 kg/m.s, and a bulk modulus of 2.15×10⁹ kg/m.s² at 20 °C. Fig. 2 shows the structure-TLCD system.

2. Design Process:

The frequency of TLCD is calculated by using equation (1), which is dependent on gravitational acceleration (g) and the length of water measured from the centre line of tube (L).

\[
F = \frac{1}{2\pi} \sqrt{\frac{2g}{L}}
\]  

The frequency of the damper is tuned to a particular frequency of the structure so that when that frequency is excited the structure-TLCD system efficiency increases. For this reason, the tuning ratio is introduced. The tuning ratio is defined as the dominant frequency of the damper over the dominant frequency of the structure and is shown by \( \Upsilon \) (\( \Upsilon = \omega_d / \omega_s \)). In order to check the effects of tuning ratio, the height of the liquid inside the damper was adjusted for tuning ratios of 0.95, 1.0, and 1.04. In addition, another test was done with a damper that was tuned to the second dominant mode of structure. The TLCD used in this test was a simple TLCD without an orifice.
To record the acceleration response of a structure on the shake table, two accelerometers were used: one was attached to the shake table and the other was attached at the top of the structure. The acceleration-time graph of applied sinusoidal load is demonstrated in Fig. 3. In this graph, the acceleration peaks are at the frequencies where the resonance in the structure and the proposed TLCDs might occur.

![Fig. 3: Acceleration-time graph of sinusoidal load](image)

After obtaining the optimum tuning ratio, a Malaysia seismic record in Kuala Lumpur was chosen as the shaking table input for the properly tuned structure-TLCD system and the acceleration response of the system was measured. This earthquake had a PGA of 0.024g. Fig. 4 shows the seismic acceleration record in Malaysia.

![Fig. 4: Earthquake acceleration record in Malaysia](image)

The characteristics of the TLCD models used in this experimental work are mentioned in Table 1. In this table, hv is the height of the water from base of TLCD, and the length ratio is the ratio of the horizontal column length to the total length of the tube.

<table>
<thead>
<tr>
<th>Model</th>
<th>Frequency of TLCD</th>
<th>Period</th>
<th>Tuning Ratio(ϒ)</th>
<th>Length of Horizontal Tube (B)</th>
<th>hv</th>
<th>Liquid Length</th>
<th>Length Ratio</th>
<th>Mass of Damper</th>
<th>Mass Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLCD86</td>
<td>1.406</td>
<td>0.71</td>
<td>0.95</td>
<td>0.12</td>
<td>86</td>
<td>252</td>
<td>0.4</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>TLCD73</td>
<td>1.482</td>
<td>0.67</td>
<td>1.00</td>
<td>0.12</td>
<td>73</td>
<td>226</td>
<td>0.45</td>
<td>1.9</td>
<td>1.6</td>
</tr>
<tr>
<td>TLCD63</td>
<td>1.55</td>
<td>0.64</td>
<td>1.04</td>
<td>0.12</td>
<td>63</td>
<td>207</td>
<td>0.48</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>TLCD33</td>
<td>1.85</td>
<td>0.54</td>
<td>Tuned with 2ed mode</td>
<td>0.12</td>
<td>33</td>
<td>145</td>
<td>0.69</td>
<td>1.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**B. Analytical Process:**

Analytical work was conducted with the finite element software called ANSYS. TLCD was modeled to verify that the frequency of the damper was the same as what was calculated in theory. Then, a properly tuned structure-TLCD system was simulated, in which the tuning ratio was obtained from the results of experimental work. Fig. 5 shows the model of TLCD in ANSYS and water movement in modal analysis.
The fluid was modelled using FLUID 79, which defined by four nodes having two degrees of freedom at each node and with translation in the nodal x and y directions. Degrees-of-freedom of the element in the interaction surface are coupled with the adjacent node-degree-of-freedom of the tank wall in the normal direction of the tank wall. The FLUID 79 element only supports lumped mass matrix and the reduced method is used for the modal analysis. The reduced method works with only the master degrees of freedom. The finite element analysis is used to obtain the sloshing frequency of the laboratory models of tanks that were used in the experimental work. The experimental and numerical results are compared.

A 2-D model of a steel structure with an attached damper at its top is shown in Fig. 6.

**RESULTS AND DISCUSSION**

**A. Experimental Work:**

*Acceleration Response Due to Harmonic Load:*

The response acceleration graphs of TLCD-structure systems are shown in Fig. 7. Table 2 shows the maximum response acceleration of TLCD-structure systems.
Table 2: Maximum Acceleration Response of structure-TLCD systems subjected to Harmonic Force

<table>
<thead>
<tr>
<th>Type of System</th>
<th>Maximum Acceleration (m/s²)</th>
<th>Acceleration Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STR.</td>
<td>1.68</td>
<td>-</td>
</tr>
<tr>
<td>STR. +TLCD33</td>
<td>1.48</td>
<td>8</td>
</tr>
<tr>
<td>STR. +TLCD63</td>
<td>1.53</td>
<td>4.3</td>
</tr>
<tr>
<td>STR. +TLCD73</td>
<td>1.29</td>
<td>19.3</td>
</tr>
<tr>
<td>STR. +TLCD86</td>
<td>1.3</td>
<td>19</td>
</tr>
</tbody>
</table>

As is obvious in Fig. 7, the acceleration graph of structure-TLCD systems are like the graph of a structure alone until the 6th second; then they separate and continue. This could be due to the effects of frequencies of the TLCD after the 6th second, which are dominant after that point.

The maximum acceleration responses of structure-TLCD systems are demonstrated in Table II. As can be seen, using TLCD causes a reduction of the acceleration response of a system. Adding TLCD33 and TLCD63 did not show significant reductions, which were 8% and 4.3%, respectively. This means that tuning the damper frequency to the second mode of a structure does not have considerable effects on the response reduction of structures. In a STR.+TLCD73 system, in which the tuning ratio is 1.0, the maximum reduction of acceleration occurred around 19.3%. Increasing the tuning ratio to 1.05 by raising the water height to 86 mm showed the same reduction acceleration as STR.+TLCD73. As a result, the optimum tuning ratio was equal to 1.0, in which the maximum reduction of the acceleration response occurred. Thus, increasing the water height does not have a considerable effect on system efficiency.

Acceleration Response Due to Harmonic Load:

A Malaysian earthquake record load was imposed on the structure. The maximum acceleration response of a properly tuned structure-TLCD under earthquake excitation is shown in Table 3 and compared with the structure alone. As can be seen, the acceleration response of the structure subjected to the Malaysian Earthquake Load was reduced up to 25% by adding a TLCD.

Table 3: Acceleration response of a structure-TLCD system excited by earthquake load STR.

<table>
<thead>
<tr>
<th>Maximum Acceleration Response (m/s²)</th>
<th>STR. +TLCD73</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92</td>
<td>0.69</td>
<td>25%</td>
</tr>
</tbody>
</table>

B. Analytical Results:

1. TLCD Modeling:

A TLCD was modeled in ANSYS software as shown in Fig. 5. The frequency of TLCD was checked to be similar to the theory, which was 1.49 for TLCD73.

2. Acceleration Response of a Structure-TLCD System due to Harmonic Force in ANSYS LCD Modeling:

The acceleration and displacement response of a structure modeled in ANSYS when sinusoidal force was imposed to the structure is shown in Table 4. The acceleration and amplitude responses versus time graph are shown in Fig. 8.

Table 4: The acceleration response of a structure with and without Tuned TLCD due to Harmonic Force

<table>
<thead>
<tr>
<th>Type of System</th>
<th>Maximum Acceleration (m/s²)</th>
<th>Acceleration reduction (%)</th>
<th>Maximum Displacement of Structure (m)</th>
<th>Amplitude Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>STR.</td>
<td>1.65</td>
<td>-</td>
<td>0.019</td>
<td>-</td>
</tr>
<tr>
<td>STR. +TLCD73</td>
<td>1.30</td>
<td>21%</td>
<td>0.015</td>
<td>21%</td>
</tr>
</tbody>
</table>

A properly tuned TLCD was attached to the top of the structure, reducing both the acceleration and displacement responses of the structure by 21%. There is an ignorable difference between finite element modeling and experimental work, which can be due to two-dimensional modeling of the structure and TLCD in ANSYS.

3. Acceleration Response of a Structure-TLCD System due to Earthquake Excitation in ANSYS:

A Malaysian recorded earthquake time history was imposed to the structure. The maximum response acceleration of the structure, as well as the maximum displacement of the structure with and without a damper, is shown in Table 5.
Fig. 8: (a) Acceleration response (Ax) versus Time graph (b) Displacement responses (Ux) versus Time when sinusoidal force was imposed to the structure

Table 5: The acceleration Response of a structure-TLCD system due to Malaysian earthquake record by ANSYS software

<table>
<thead>
<tr>
<th>Models</th>
<th>Maximum Acceleration in ANSYS (m/s²)</th>
<th>Acceleration Response Reduction</th>
<th>Maximum Displacement of Structure (m)</th>
<th>Displacement Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Str.</td>
<td>0.89</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Str-TLCD73*</td>
<td>0.63</td>
<td>30%</td>
<td>0.008</td>
<td>20%</td>
</tr>
</tbody>
</table>

As can be seen, attaching a TLCD at the top of the structure caused a reduction of 30% in acceleration. The displacement of the structure was reduced 20% as well. Hence, adding TLCD is an effective way to decrease displacement and acceleration of structures under earthquake excitation.

Conclusion:

An experimental work conducted to obtain an optimum tuning ratio by attaching TLCDs with different frequencies on the top of a one-story steel structure and subjecting it to a sinusoidal load. The tuning ratio of 1.0 was considered the optimum value for this structure, with such a load in which the maximum reduction of acceleration response occurred. A Malaysian recorded earthquake was imposed on a properly tuned structure-TLCD system and a considerable reduction in acceleration response was shown. The analytical model of this system was done using ANSYS software. According to analytical work, the acceleration and amplitude response of the structure were reduced with the addition of a TLCD. The results of experimental works and finite element software were in good agreement and the small difference found could be due to two dimensional modeling of the TLCD-structure system in ANSYS.

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