A variably baffled tuned liquid damper to reduce seismic response of a five-storey building

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Structural control is considered to be an efficient method to improve the seismic behaviour of buildings. Semi-active control methods have the reliability of passive systems, and at the same time offer the consistency and variability of active systems. In this method, structural responses decrease based on the change in damping properties or stiffness of the system. A tuned liquid damper (TLD) has low manufacturing, installation and maintenance costs. In this paper, a variably baffled TLD is proposed to reduce seismic response of structures and its behavior is evaluated under near- and far-field earthquakes. Damping of structural models can be changed using an efficient semi-active control algorithm, which acts by changing the angles of baffles. The results show that using these dampers in the semi-active control with an efficient design algorithm for changing the baffle angle improves seismic behaviour of the structural models and reduces the roof displacement. Consideration of the maximum roof displacement and its root mean squared value show that a TLD with variable baffles exhibits excellent performance under both near- and far-field earthquakes, while creating further response reduction under near-field earthquakes. However, the decreases of responses in angles of 0° and 20° are greater than those in angles of 50° and 70°.

Notation

- $c_a$: equivalent effective damping of tuned mass damper
- $c_v$: equivalent effective damping of tune liquid damper
- $f_s$: frequency of tuned mass damper (Hz)
- $H$: depth of the water in tuned liquid damper
- $k_s$: stiffness of tuned mass damper
- $k_v$: equivalent stiffness of tuned liquid damper
- $L$: length of tuned liquid damper
- $m_s$: mass of tuned mass damper
- $m_v$: equivalent mass of tuned liquid damper
- $n$: number of time steps in the time interval of excitation
- $Y_{RMS}$: root mean square of structural response (displacement, acceleration)
- $y_i$: structural response (displacement, acceleration)
- $\beta$: frequency ratio
- $\eta$: wave height
- $\zeta_a$: damping ratio tuned mass damper
- $\omega$: frequency of tuned liquid damper
- $\omega_a$: frequency of tuned mass damper

1. Introduction

The aim of structural control is to reduce structural vibrations by installing control devices and applying control forces to structures. Based on the need for external force, the structural control can be categorised into passive, active, semi-active or hybrid control (Symans and Constantinou, 1999). A semi-active control system may be defined as a system that typically requires a small external power source for operation (e.g. a battery) and utilises the motion of the structure to develop the control forces, the magnitude of which can be adjusted by the external power source. Control forces are developed based on feedback from sensors that measure the excitation and/or the response of the structure (Housner et al., 1997). A semi-active control system changes the damping or stiffness properties of the controlled structure to reduce structural responses. In contrast to active systems, these systems do not apply active forces, and they require an energy supply somewhat smaller than that of active systems, such that they can be fed just by a battery. This is crucial owing to the potential for power cuts during earthquakes (Housner et al., 1997).

The tuned liquid damper (TLD) is a passive mechanical damper designed to reduce unfavourable structural vibrations through liquid turbulence inside a rigid chamber. The TLD is a special case of a passive control device in which a liquid (water) is used as the energy dissipater. TLDs are categorised in two main groups according to the ratio of liquid depth to tank length: shallow and deep (i.e. if this ratio is less than 0.15 the TLD is shallow). The TLD is a rectangular or circular tank partially filled with water. Wave breaking, the tank geometry and its roughness, as well as water surface contamination are some aspects of the TLD energy dissipation mechanism (Kareem, 1993).

TLDs have been installed with success in several tall buildings to eliminate wind-induced vibrations (Tamura et al., 1992; Ueda et al., 1992). Sun et al. (1992) expanded a numerical model to consider interaction between the TLD and its controlled...
structure and present two coefficients for the wave refraction. Both coefficients were calibrated using experimental methods. This model was expanded by Koh and co-workers for arbitrary excitations (Koh et al., 1994).

The TLD is a damper with low manufacturing and maintenance costs that is motivated by the slightest motion in a structure. The equations of a system equipped with a TLD are similar to those of a system equipped with a tuned mass damper (TMD). The design procedure of a TMD is basically applicable to TLDs. Damping is provided by friction of the fluid against the tank walls. As the performance of the gravity force is in essence a reversible mechanism, the secondary system has some frequency properties that can be harmonised with the structure, optimising its behaviour criteria (Tondl et al., 2000). Similarly to a TMD system, a TLD system can reduce the response of the main system by modifying its frequency response function. In a TLD the secondary mass is liquid and the damping forces are established through the motion of the liquid through viscosity, wave breaking and/or damping screens in the TLD (Tait et al., 2004a, 2004b, 2005a). Tait and co-workers used honeycomb sheets to increase the energy dissipation in TLDs (Tait et al., 2005b).

As previously stated, low manufacturing and maintenance costs are the main advantages of this damper. TLD systems can provide dual-function capability to be used as emergency fire water storage. Although a certain level of threshold excitation is required to activate a TMD, using a liquid in the TLD eliminates this limitation. In other words, the liquid used in TLDs can be effectively mobilised at all levels of structural motion (Islam, 2012).

In this paper, the objective is to examine the behaviour of a TLD with variable baffles and the feasibility of its use in semi-active control of structural responses due to near- and far-field earthquakes. Therefore, in this research an experimental model of the proposed damper is used to passively control the responses of a two-dimensional (2D) frame. The frame in this study is similar to the five-storey structure examined by Zahrai et al. (2012).

2. Variably baffled TLD (VBTLD)

To use a TLD as a damper applicable in various vibrational situations, a number of researchers – including Tait et al. (2004a, 2004b, 2005a, 2005b), Love and Tait (2010) and Zahrai et al. (2012) – have used TLDs incorporating some slight manipulations. Tait and co-workers placed some perforated plates inside the tank of the liquid damper to increase the system damping (Tait et al., 2005b). Love and Tait (2010) also studied the effects of different states of these perforated plates. Moreover, Zahrai et al. (2012) used tunable baffles inside a rectangular tank. Their TLD, which is intended for use in this study, is schematically shown in Figure 1.

3. Replacement of VBTLD with equivalent TMD parameters

To model the VBTLD, as previously stated, the equations in Sun et al. (1992) were used as follows. The objective is to find the effective mass, \( m_v \), the equivalent effective damping, \( c_v \), and the effective frequency, \( \omega_a \), of a TLD. According to the studies of Sun and co-workers, to represent the mass and damping of a TLD, it is possible to use the following equations

1. \[
m_v = m_a \frac{1 - \beta^2}{(1 - \beta^2)^2 + (2\xi_a \beta)^2}
\]

2. \[
c_v = c_a \frac{\beta^4}{(1 - \beta^2)^2 + (2\xi_a \beta)^2}
\]

where \( \beta = \omega/\omega_a \), \( \omega_a = \sqrt{k_a/m_a} = 2\pi f_a \), \( \xi_a = c_a/(2m_a\omega_a) \) and subscripts ‘a’ and ‘v’ refer to the TMD and the TLD, respectively.

Equivalent stiffness is calculated by

3. \[
k_v = m_v \omega_a^2
\]
in which $m_c$ is from Equation 1 and $\omega$ is determined using the study of Zahrai et al. (2012) based on the period of the damper in each direction of baffles.

4. The numerical model

Zahrai et al. (2012) examined a passive model of the damper with an orifice over this structure. In this study, a benchmark five-storey building structure is used; this structure has been utilised in the Sydney Technological University, Australia and adopted by the International Association for Structural Control. The structure can have a maximum of five storeys with different heights (Al-Dawod et al., 2000). The building steel frame has an overall height of 3.6 m and two bays, each 0.75 m wide, with beams of $75 \times 75 \times 4$ mm hollow steel sections. The building mass, including the additional mass to the fourth and fifth floors, is 550 kg. Finally, the frequency of the model is 1.4 Hz.

The study by Sun et al. (1992) is used as shown in Table 1 to model the fluid damper in Opensees. For each orientation of baffles according to Equations 1 and 2 and using the values in Table 1, equivalent stiffness, mass and damping are determined. The mass and the viscous spring defined in Opensees are utilised according to each baffle angle. The stiffness and damping of the viscous spring are equal to the equivalent stiffness and damping values. The damper is placed in the roof of the structure.

In this study, four near-field earthquake records of the Loma Prieta, Imperial Valley, Northridge and Kobe earthquakes are utilised. In addition to the near-field records, two far-field records, from the Kern County and Northridge earthquakes, are also utilised. Input excitations are selected from recorded strong ground motions of the next generation attenuation (NGA) library (Peer, 2015). Six earthquake records are selected for this study and their characteristics are summarised in Table 2. This ensemble of ground motions involved four near-field and two far-field ground motions.

The important issue here, however, is the tuning of the TLD. According to the study by Zahrai et al. (2012), to tune the TLD, it is enough to adjust the structural frequency between the frequencies of the damper when the TLD baffles are fully open and fully closed. They concluded that the damper in this situation has the best performance. Bearing this in mind, they used a TLD with rotating baffles for a five-storey building model. In the current study, the TLD with variable baffles and the controlled structure have characteristics exactly the same as those used by Zahrai et al. (2012) to overcome the optimisation problem. It should also be mentioned regarding the re-adjustment of the damper after rotation of the baffles that, because the period of the structure is between the damper periods in the fully open and fully closed baffle positions, significant changes will not occur in the initial tuning. In fact, if the TLD is tuned properly at first, the baffle rotation does not make too much change to its initial tuning.

The numerical model studied here is validated using results of the research conducted by Zahrai et al. (2012) investigating a three-dimensional (3D) experimental model. With respect to the symmetry of their model, torsional displacements (rotation) of the roof due to the 1940 El-Centro earthquake were negligible. Hence, considering the same stiffness and section properties, structural responses of the 2D numerical model of the present study under the 1940 El-Centro earthquake are compared with those of the previous study. The results show good agreement with those of the 3D experimental model, and the best performance of the damper is at the angle of 70° for the 2D numerical model. Furthermore, at the baffle angle value of 0°, both the experimental and numerical models achieve their peak displacement response.

5. Numerical results of VBTLD in passive and semi-active control scenarios

In this study, the objective is to determine whether the TLD with baffles rotating in each time step of an input excitation can perform better than a TLD with non-rotating baffles. To this end, first a TLD with fully open baffles (0°) embedded on a five-storey building model is excited and responses are determined. Then, the baffle angle is changed to 20° and the structure–damper model is stimulated according to earthquake records. Figure 2 compares the roof displacement of the five-storey building model in two such situations. Similarly, for different angles of baffles up to 70°, structural responses are determined as shown in Figure 3.
Finally, having identified the best response at each angle, the lowest has been selected and specified as a response that can happen in a semi-active control process (see Figure 4).

As stated earlier, according to Zahrai et al. (2012), the baffle angle of 70° is the best situation; however, Figure 5 exhibits the semi-active control scenario can perform better, especially when considering the structure under different earthquakes with various characteristics.

In Figure 3, it can be seen that at the beginning of the time interval of 12 to 14 s, before 12.5 s, the angle of zero has the best performance and at 12.5 s the angle of 70° has the best performance. At approximately 13 s, it can be observed that the angle of 70° decreases the structural response more until about 14 s, when the zero angle of the baffles will have a better performance. Hence, it can be understood that if the angle of the baffles is changed according to an appropriate method during the excitation, a better behaviour would be observed for the structure. In other words, it is possible to effectively reduce the displacement response of the structure. As can be observed in the figures, the diagram corresponding to the semi-active control has also been plotted, which shows the least responses. Indeed, if the baffles could be rotated with an appropriate mechanism during the excitation, it would be possible to reduce the structural displacement and the time history diagram of the displacement would approach the semi-active control response. In the following, the results of the structural
Figure 4. Displacement–time history of the roof under the Kobe earthquake for different baffle angles compared to the case with semi-active control.

Figure 5. Displacement–time history of the roof under the Kobe earthquake for 70° as baffle angle compared to semi-active control.

Figure 6. Displacement–time history of the roof under the Northridge earthquake for different baffle angles compared to the case without damper.
analysis under the record of a far-field earthquake, the Northridge earthquake, are presented in Figures 6 and 7. In these figures the displacement–time history of the roof is plotted at different time intervals.

The acceleration response–time history also shows that the rotating baffles can improve the structural behaviour. Figure 8 shows the acceleration–time history of the roof due to the Loma Prieta near-field earthquake. As can be observed, at different times of the excitation, the damper with different baffle orientation has better performance. In the eighth second of the excitation, the angle of 70° provides the minimum acceleration for the structure, while in about 8·3 s, first the angle of zero and then the angle of 20° create more efficient responses. This demonstrates that, in the same way as for the displacement response, rotation of baffles can enhance the performance of the structure in terms of acceleration as well.

The results of the research are tabulated as follows. In Tables 3–8, the maximum displacement of the roof and the root mean square (RMS) value of the roof displacement are presented. As the maximum response occurs only at one moment, it is not sufficient to examine the liquid dampers from solely the viewpoint of their effect on reduction of the maximum response. Hence, the RMS value of the structural responses was used during the analyses (Equation 4). This criterion will be used to evaluate the enhancement of the responses.

\[
Y_{\text{RMS}} = \sqrt{\frac{\sum_{i=1}^{n} y_i^2}{n}}
\]

where \(y_i\) is the structural response (displacement, acceleration…) and \(n\) is the number of time steps in the time interval of excitation.

As can be observed in the tables, the use of this damper in semi-active control causes reduction in both maximum and RMS displacements compared to that of passive control. In Tables 3–6, the results of the near-field earthquake records, and in Tables 7 and 8, the results of the far-field earthquake records are presented.

The results of the analyses show that rotating baffles in semi-active control improve the damper overall behaviour. The
tables also show that the semi-active control results when compared with various baffles’ angles are closest to those of the damper with a baffle angle value of 70°. This is because of the increased contact area of the fluid with the baffles owing to the increased curvature of flow lines. As stated in the previous study (Zahrai et al., 2012), further reduction of structural responses in this situation leads to greater similarity between the results for this angle and those for semi-active control.

Table 3. The response results of the structure under the Kobe earthquake and percentage of response reduction in the semi-active control

<table>
<thead>
<tr>
<th>Baffles angle</th>
<th>0</th>
<th>20</th>
<th>50</th>
<th>70</th>
<th>Semi-active</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum roof displacement: m</td>
<td>1.68 x 10^{-1}</td>
<td>1.58 x 10^{-1}</td>
<td>1.57 x 10^{-1}</td>
<td>1.54 x 10^{-1}</td>
<td>1.52 x 10^{-1}</td>
</tr>
<tr>
<td>RMS of the displacement: m</td>
<td>3.36 x 10^{-2}</td>
<td>3.21 x 10^{-2}</td>
<td>2.89 x 10^{-2}</td>
<td>2.79 x 10^{-2}</td>
<td>2.53 x 10^{-2}</td>
</tr>
<tr>
<td>Reduction of the maximum roof displacement: %</td>
<td>9.52</td>
<td>3.80</td>
<td>3.18</td>
<td>1.3</td>
<td>—</td>
</tr>
<tr>
<td>Reduction of the RMS of roof displacement</td>
<td>24.70</td>
<td>21.18</td>
<td>12.46</td>
<td>9.32</td>
<td>—</td>
</tr>
</tbody>
</table>
Consideration of these tables suggests that the reduction in the RMS of displacement is greater than the maximum displacement because of the inherent performance of TLD. Fluid dampers, as a result of fluid turbulence and energy loss from wave propagation, cause further reduction of structural response in the range of excitation and relative to the maximum value. In other words, this performance squeezes the time history of responses and decreases the maximum response lower than the RMS response. As the results show, rotating baffles under the near-field earthquakes in the vicinity of zero angle, open baffles, has caused the most reduction in responses, whereas under the far-field earthquakes a baffle angle of 20° provokes the greatest reduction. This is due to the impulsive nature of near-field earthquakes. Thus, turning the baffles and their near-closed state causes curvature of the flow lines and wave propagation, as well as increasing the damping coefficient of the damper. This coefficient in an angle value of zero is less than for semi-active control. Therefore, the results of baffle rotation show a greater decrease than that of the zero angle.

To evaluate the performance of the damper with rotating baffles, the RMS displacement of the first floor and the RMS acceleration of the roof are investigated. Tables 9 and 10 present the results obtained. As reflected in Tables 9 and 10, rotation of the baffles in semi-active control reduces the RMS displacement of the first floor, and this reduction is greater for near-field earthquakes in comparison with far-field earthquakes. Also as presented in the tables, Kobe earthquake has the greatest reduction of the response compared to the passive control, which for the angle value of zero is equal to 25%. In this excitation, the RMS response decreases by 9.25% compared to passive control with the angle value of 70°, which is the best performance in passive control. The results show that, in addition to the roof displacement response, VBTLD can effectively decrease the first floor displacement response.

As is well known for semi-active control, in addition to the reduction of displacement response, reduction of the acceleration response is important. In this study, the effect of variable baffles on the RMS acceleration response of the top floor is also investigated. The results presented in Table 9 for Northridge far-field earthquake demonstrate that the semi-active control reduces the RMS roof acceleration response by 20%; this value for Kobe earthquake in Table 10 is about 25%. The study on the acceleration results illustrates that the efficiency of the damper in building structures subjected to near-field earthquakes is superior to that for far-field earthquakes. In other words, the VBTLD has better performance under the near-field earthquakes.
As observed in Figure 9 for Kern County earthquake the RMS acceleration response in the various floors of the structure is reduced in semi-active control. This means that the rotation of the baffles during semi-active control can effectively decrease the structural responses in middle storeys as well as in the roof and first storey.

6. Conclusion

In this study, the behaviour of a TLD with variable baffles in the semi-active control of a five-storey steel frame was examined. For this study, four near-field and two far-field earthquake records were used to excite the frame. The liquid depth inside the damper was considered to be 42 mm, which is equivalent to a mass percentage of 1%.

Investigation of the numerical results shows that the rotation of the baffles during the excitation leads to the enhancement of structural responses, that is, a reduction of the maximum and RMS of roof displacement, the RMS of first floor displacement and the RMS of roof acceleration. However, this reduction is lower for the baffle angles of 50° and 70° due to the curving of the streamlines inside the damper and increase of the damping coefficient for these angles.

The results of this study and examination of time history diagrams of the frame displacement show that by designing an appropriate algorithm for rotating the baffles, it is possible to improve the dynamic behaviour of structures and reduce the displacement response, which is only possible in a semi-active control algorithm. Hence, exploiting an appropriate algorithm, the damper can be used semi-actively and structural displacement responses can be reduced with a change in the baffles angle. Investigation of the displacement demands reveals that semi-active control with this type of damper leads to further reduction of the RMS of the roof compared to the maximum roof displacement.

Based on numerical results, the maximum reduction in the maximum roof displacement occurred in the far-field record of the Northridge earthquake in semi-active control relative to an angle value of 20°. Examination of the maximum roof displacement reduction at the angles of 50° and 70° showed that a higher reduction was observed in near-field earthquakes than in far-field ones, indicating better efficiency under near-field earthquakes.

With respect to roof RMS displacements, under the near-field earthquakes, a reduction in the range of 6–25% was observed, in which the maximum reduction was associated with zero angle of the baffles in the Kobe earthquake. Under the far-field earthquakes, a similar reduction range of 6–23% was observed. In addition, the roof RMS acceleration showed a response decrease range of 5–25% and 3–20%, respectively, under the near- and far-field earthquakes.

In addition, the examination of this parameter at angles of 50° and 70° in the near- and far-field earthquakes indicated the higher efficiency of the TLD with variable baffles under near-field earthquakes.

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Enayati and Zahrai

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