Aerodynamic Across-wind Response according to Damping Ratios of a Tall Building Using Tuned Liquid Column Damper

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ABSTRACT

Tuned liquid column damper (TLCD) is more advantageous in terms of space than TLD for instance in the installation on the actual building. The aeroelastic experiment installation of TLCD, however, it is more difficult to relate the natural frequency of scale model of TLCD to aeroelastic model and the evaluation of wind control performance. Aeroelastic experiment is achievable only for low damping ratio. This study installs TLCD with different lengths of horizontal pipes at the top floor of aeroelastic model, which is similar to the actual structure. Through aeroelastic experiment at different damping ratios, the vibration response (displacement) in across-wind direction establishment is important in order to figure out the vibration of the wind control effects to damping rate changes.

Keywords: Tuned liquid column damper, aeroelastic experiment, damping ratio, across-wind direction

Introduction

The emergence of high-strength structural member and development of structural analysis technology have greatly improved design and construction technology. According to the rate at which tall buildings are build compared to smaller structures for a more efficient space utility within a limited space. Buildings increase in flexibility with taller heights and the damping ratio. High-strength material decreases so that vibration response by wind load increases. The vibration response induces anxiety and migraine to residents in severe cases affecting their stability and survival. Many researches on wind vibration control using various methodologies in countries across the world have emerged. Key methods include changing the form of the structure to be aerodynamically robust in order to improve habitability and serviceability of tall buildings against wind vibration and reducing their response by increasing damping of structure by installing passive-form auxiliary damping devices (TMD, TLD TLCD)[Gao. H.(1997)]. The cases of installing auxiliary damping device rather than changing the form of the structure have increased due to the influence of usable space of buildings. TLCD (tuned liquid column damper) is more valuable in terms of space than TLD when it comes to installation on the actual building. Most tests on TLCD for instance the numerical methods or the proposal of the equations of motion of pendulum type[Chang. C.C(1998)], which simplifies TLCD-structural type and simple performance tests conducted. This is through installing in the middle of TLCD with different porosity and experimental equation[Balendra. T, Wang. C. M, Rakesh. G(1999)].

Excitation amplitude is proposes to predict head loss coefficient. Besides the wind-induced vibration, response supported by the wind load another study conducted through Xu, Kwok. Since late 1990s, the reduction effects of wind-induced vibration response due to the
wind load conducted only for aeroelastic model tests, with TLD installed above the highest floor in the aeroelastic model that is similar to the actual model[You K. P, Kim Y. M(2004)]. The aeroelastic experiment with installation of TLCD is difficult to similarize the natural frequency of scale model of TLCD and aeroelastic model. There is almost no evaluation of wind control performance and aeroelastic experiment is only achievable for low damping rates[You J. Y(2012)]. This experiment finds the direct response value by reproducing the behavior of the building in relation to wind through installing the wind tunnel elastic model, which implements the actual structure with the vibration characteristics of the building. In relation to this, the study has installed TLCD with different lengths of horizontal pipes at the top floor of aeroelastic model that is similar to the actual structure for comparative analysis to damping ratio of actual structure. Through aeroelastic experiment at different damping ratios, the wind-induced vibration response(displacement) in across-wind direction has to be in place in order to figure out the vibration control effect according to damping rate changes.

Wind Tunnel Test

The wind tunnel test for aeroelastic experiment conducted using the boundary layer wind tunnel device owned by boundary layer wind tunnel lab of Chonbuk National University. The cross-section of measurement unit of wind tunnel is an open-type wind tunnel device with width of 2.1m, height 1.7m, length 18m, and total length 27m, and wind speed range of 0.3m/s~12m/s. The experiment was conducted at suburban area($\alpha=0.15$) with turbulence intensity of 10% at model height as for the wind flow within the wind tunnel in order to generate across-wind vibration relatively more easily. It measured measurement points(z) at a 2cm interval up to 10 cm, at a 5cm interval up to 80cm, and at a 10cm interval up to 100cm from the measurement reference point.

Picture 1 shows the overall view of the wind tunnel testing device. Fig 1 displays the vertical distribution of mean wind speeds and turbulence intensity by height in a suburban area formed in the wind tunnel. The power spectrum of lateral component of turbulence at height of 40cm in suburban area($\alpha=0.15$) is also indicated in Fig. 2 the direction of the wind normal to the front face of the aeroelastic model has a zero angle of attack as shown in Fig. 3.

![Fig.1 Vertical distribution of average wind speed and turbulence intensity](image1.jpg)

![Picture.1 Overall view of the actual wind tunnel experiment device.](image2.jpg)
Aeroelastic Experiment

Gimbal device

In aeroelastic model test, gimbal that maintains X direction and Y direction degree of freedom of vibration model is used this composes of spring that assigns rigidity, damping device that assigns damping, detection device of response and support device that supports this. The frame that supports gimbal should have heavy weight because it should not vibrate within measured frequency range even if the model vibrates. In order to have mass \( m \), damping coefficient \( c \) and rigidity \( k \) the dynamic characteristics of actual building expressed in gimbal by law of similarity as they are, mass \( m \) was taken from model mass, damping coefficient \( c \) from damping device that used silicon oil with different viscosity to adjust damping ratio and rigidity \( k \) from device like spring.

Spring that adjusts rigidity, totally 4 coil springs with the same modulus of elasticity is used with two in X direction and two in Y direction. Damping device composes of a circular damping plate installed at the bottom of gimbal used to change the damping ratio of structure. This device uses Silicon oil below circular damping.

There are two methods of measuring model vibration namely the method of installing strain gauge at the copper plate of X direction and Y direction linked to coil spring and the method of using non-contact type optic laser displacement meter. For measurement that is, more precise optic laser displacement meter (LK-2101) in the measurement.

The gimbal below, call for free vibration test at top layer of model, and after natural frequency and damping ratio of the model obtained. It further clarifies the aeroelastic wind tunnel assessment done on wind tunnel. Picture 2 shows the appearance of gimbal and picture 3 and 5 the detailed appearance of gimbal by parts. Picture 6 shows the appearance of gimbal installed within wind tunnel.

![Picture. 2 The appearance of gimbal](image)

![Picture. 3 X-axis and Y-axis of gimbal](image)
Similarity Condition and Aeroelastic model

In order to find out the characteristics of vibration response the experiment objective model was produced so TLCD may be installed at top layer by applying 1/200 scale with the ratio of long side to short side (Depth/Breadth). In case of such aeroelastic model, the vibration characteristic of building is accurately achievable only if similarity requirement is attainable. As such, the modeling building vibration characteristics is to match three parameters like non-dimensional frequency, mass ratio and damping ratio etc to actual object. Such similarity requirement is possible through changing expression according to the method of modeling experiment model. Specifically, mass ratio indicates that if fluid density is the same experiment and actual object, generalized mass is one third of length scale cube, and the similarity parameter on building elasticity, a parameter that combines structure elasticity and wind speed as non-dimensional frequency in general, and represents the relationship of wind speed, model scale and natural frequency scale. The expressions Eq. (1) and Eq. (3) clearly Illustrates the correlation of the three parameters.

\[
\text{Mass: } \left( \frac{n_j \cdot b}{\rho B^2 h} \right)_M = \left( \frac{M_j}{\rho B^2 h} \right)_p
\]

(1)

\[
\text{Natural frequency: } \left( \frac{n_j \cdot b}{V} \right)_M = \left( \frac{n_j \cdot B}{vV} \right)_p
\]

(2)

\[
\text{Damping ratio: } (\xi_j)_M = (\xi_j)_p
\]

(3)
Where

\[ v, V = \text{representative wind speeds} \]
\[ \rho = \text{air density} \]
\[ v, V = j^{th} \text{modal masses of the model and the prototype structure, respectively} \]
\[ b, B = \text{widths of the model and the prototype structure, respectively} \]
\[ h, H = \text{heights of the model and the prototype structure, respectively} \]
\[ \xi_j = j^{th} \text{modal damping ratio; and the subscripts } M \text{ and } P \text{ denote the model and the prototype structures, respectively} \]

The law of similarity of actual object and model of structure the subject of this study depicts in Table 1. Since when determining the scale of model, appearance the wind direction area of model should be less than 5% of wind tunnel cross-section area, measure taken so this aeroelastic model of 3.89% shall fall within less than 5% blockage factor. The natural frequency of aeroelastic model was set to 3Hz so TLCD water tank installation is mandatory. Table 2 shows the dimension and mass of aeroelastic model with the ratio of long side to short side (Depth/Breadth) 3. There are totally nine types of TLCD models for installation at top layer of aeroelastic model, and experiment done so the natural frequency of TLCD model is set to the same value as the natural frequency(3Hz) of aeroelastic model, so it may become 1.5% and 3.0% generalized mass of aeroelastic model. Table 3 shows the specification of TLCD model installed in aeroelastic model. Picture 7 shows TLCD model with different horizontal pipe lengths, and Picture 8 shows aeroelastic experiment installed within the wind tunnel.

Table 1. The law of similarity of actual body and aeroelastic model

<table>
<thead>
<tr>
<th>Section</th>
<th>Prototype</th>
<th>Aeroelastic model</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height(m)</td>
<td>160</td>
<td>0.8</td>
<td>1/200</td>
</tr>
<tr>
<td>Crosssection(m²)</td>
<td>403.7(11.6mx34.8m)</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Volume(m³)</td>
<td>64592</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>Natural frequency(Hz)</td>
<td>0.3</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Density (kg/ m³)</td>
<td>120</td>
<td>120</td>
<td>1</td>
</tr>
</tbody>
</table>

Table. 2 Dimension and mass of aeroelastic model

<table>
<thead>
<tr>
<th>Aspect ratio</th>
<th>Breadth(cm)</th>
<th>Depth(cm)</th>
<th>Height(cm)</th>
<th>Frequency</th>
<th>Mass(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5.8</td>
<td>17.4</td>
<td>80</td>
<td>2.91(Hz)</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table. 3 Specification of TLCD model installed in aeroelastic model

<table>
<thead>
<tr>
<th>Horizontal Length</th>
<th>Water mass</th>
<th>Mass Ratio(%)</th>
<th>Model freq.(mm)</th>
<th>TLCD Freq.(mm)</th>
<th>TLCD Model Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>25mm</td>
<td>5.6</td>
<td>1.5</td>
<td>2.91</td>
<td>2.9</td>
<td>25HM1</td>
</tr>
<tr>
<td>30mm</td>
<td>5.6</td>
<td>1.5</td>
<td>2.91</td>
<td>2.9</td>
<td>30HM1</td>
</tr>
<tr>
<td>35mm</td>
<td>5.6</td>
<td>1.5</td>
<td>2.91</td>
<td>2.9</td>
<td>35HM1</td>
</tr>
</tbody>
</table>
Free vibration tests

Once calibration of gimbal X-axis, Y-axis, and adjustment of spring are complete, free vibration tests runs to check to see if the natural frequency of experiment subject for each axis remains at target value. Through multiple repeated tests, this is possible, particularly through measurement of the natural frequency at vibration level. The change by amplitude of natural frequency stays at minimal level. Free vibration test checks the damping constant. This analyzes waveform obtained through free vibration of model in place where no vibration occurs, and after adjustment of all the values to remain in specified range through adjustment of damping device. The natural frequency and damping ratio of aeroelastic model is obtain respectively with the use of expressions Eq. (4) and Eq. (5) both of which involve logarithmic decrement by free vibration.

\[
\xi = \frac{1}{2m\pi} \ln \frac{a_l}{a_{l+m}} \quad (4)
\]

\[
f = \frac{m}{T_{l+m} - T_l} \quad (5)
\]

where

- \(m\) = the number of oscillations
- \(T_l\) = the time at the peak amplitude of the \(l\)th vibration
- \(T_{l+m}\) = the time at the maximum, amplitude of the \((l+m)\)th vibration
- \(a_l\) = the peak amplitude of the \(l\)th oscillation
- \(a_{l+m}\) = the peak amplitude of the \((l+m)\)th oscillation

Fig. 4 shows the time history of free vibration for the two axes (X-axis and Y-axis) of aeroelastic vibration model, and Picture 9 the appearance of free vibration test of aeroelastic model on top of gimbal. To change damping ratio, 3 types of silicon oils, KF96-500CS, 1000CS and 3000CS is used, and the numbers by silicon oil names represent the magnitude of viscosity. CS a unit of dynamic viscosity indicates cSt, and 1cSt becomes 1mm/s. Picture 10 shows the appearance of four silicons installed on the damping plate of gimbal, and Table 4 the natural frequency and damping ratio for X-axis and Y-axis by the change of silicon oil viscosity. The more oil viscosity, the higher damping ratio, and natural frequencies were all the same except for 3,000CS. Table 5 shows the natural frequency and damping ratio of the case where mutually different nine TLCDs installation on top layer of aeroelastic model. Overall the more the length and mass of horizontal tube increase, the natural frequency decreases, but damping ratio increases.
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Fig. 4 Time history of the building for model (Y-direction)

(a) X-axis  
(b) Y-axis

Picture. 9 Appearance of free vibration test of aeroelastic model on top of gimbal

Picture. 10 Appearance of 4 silicons installed on the damping plate of gimbal
Table 4. Natural frequency and damping ratio by the change of silicon oil viscosity

<table>
<thead>
<tr>
<th>Viscosity</th>
<th>Aspect ratio (D/B)</th>
<th>Natural frequency</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Y- axis</td>
<td>Y- axis</td>
</tr>
<tr>
<td>NO silicon</td>
<td>2.91</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>500cs</td>
<td>2.91</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>1000cs</td>
<td>2.91</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td>3000cs</td>
<td>2.92</td>
<td>1.64</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Natural frequency and damping ratio of the case where mutually different 9 TLCDs are installed on top layer of aeroelastic model

<table>
<thead>
<tr>
<th>Viscosity</th>
<th>TLCD Types</th>
<th>Across- wind direction (Y-direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Natural frequency (Hz)</td>
</tr>
<tr>
<td>No Silicon</td>
<td>No-TLCD</td>
<td>2.87</td>
</tr>
<tr>
<td></td>
<td>25mm</td>
<td>2.76</td>
</tr>
<tr>
<td></td>
<td>30mm</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td>35mm</td>
<td>2.79</td>
</tr>
<tr>
<td>500cs</td>
<td>No-TLCD</td>
<td>2.87</td>
</tr>
<tr>
<td></td>
<td>25mm</td>
<td>2.76</td>
</tr>
<tr>
<td></td>
<td>30mm</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td>35mm</td>
<td>2.79</td>
</tr>
<tr>
<td>1000cs</td>
<td>No-TLCD</td>
<td>2.87</td>
</tr>
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<td></td>
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</tr>
<tr>
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<tr>
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<td>2.87</td>
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<tr>
<td></td>
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<td>2.76</td>
</tr>
<tr>
<td></td>
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<td>2.77</td>
</tr>
<tr>
<td></td>
<td>35mm</td>
<td>2.79</td>
</tr>
</tbody>
</table>

**Experiment Result and Analysis**

In aeroelastic vibration model test using wind tunnel totally three TLCD models with varying length ($L_h=25$mm, $L_h=30$mm, $L_h=35$mm) of horizontal tubes and 4 different damping ratios (0.71, 0.81, 1.02, 1.64) in the middle of top layer of aeroelastic model were installed. To find out the effect of reduction of lateral direction vibration response (displacement) in mutually different TLCD test model. Experimental investigation was conducted for spectrum analysis value and displacement response, at 15 wind speed points within wind speed range of 1.13m/s ~ 4.52m/s for across-wind direction (Y-direction) at wind angle 0 centering on low wind speed where vortex excitation occurs. The measurement data measured 5 times for 4096 measurement data values with sampling frequency of 500Hz.

**Dimensionless Displacement Response**

Figure 5~8 shows the dimensionless displacement response according to change in lengths of horizontal pipe of TLCD ($L_h=25$mm, $L_h=30$mm, $L_h=35$mm) at different damping ratios. The case without viscosity or with viscosity of 500CS as the horizontal pipe length increased, the displacement vibration response decreases. For reduced wind speed 2.61 with
vortex excitation the case of no viscosity saw at most over 38% of decrease in maximum displacement response at horizontal pipe length $L_h=35\text{mm}$ compared to the case with no TLCD. The case of viscosity of 500CS saw at most over 47% decrease at horizontal pipe length $L_h=35\text{mm}$ and the case of viscosity 1000CS saw at most over 50% decrease at horizontal pipe length $L_h=30\text{mm}$. For viscosity 3000CS, it decreased at most below 10% for all horizontal pipe lengths compared to the case without TLCD.

**Dimensionless Spectral analyses**

Figure 9 shows the displacement spectrum result at different damping ratios at wind speed 1.30m/s where the maximum peak is measured. Regardless of horizontal tube length, maximum displacement spectrum appears clearly near natural frequency 2.91, and with spectrum appearing largest when TLCD is not installed. For a smaller damping ratio, the spectrum analysis result appeared largest and as the damping ratio increased, the size of displacement spectrum appeared smaller.
Conclusions

After installing TLCD with different length of horizontal pipe on top of aeroelastic model with side ratio of three, to find the across-wind vibration reduction effect according to damping ratio, aeroelastic response analysis is important and the following conclusion was drawn.

1) For all the other viscosities except for 3000cs, most saw a decrease in displacement response in low-speed reduced wind speed when TLCD installation at the top floor compared to the case without the installation.
2) Dimensionless displacement response decreased as damping ratio increased and the amount of decrease by TLCD was mostly decreasing.
3) For smaller damping ratios, the spectrum analysis result appears larger and for greater damping ratios, the size of displacement spectrum appears smaller.

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References