Estimating Wind-Induced Responses of the Sightseeing Tower of the West Taihu Lake, Changzhou

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Keywords: Wind-induced response, The sightseeing tower (Moon), Cross-wind, Along-wind.

Abstract. The wind tunnel test was carried out for the Sightseeing Tower of the West Taihu Lake, Changzhou in this study, and the equivalent static wind loads of the Moon Tower were obtained at different wind angles. Frequency-domain analysis was performed to reveal the wind-induced response dynamics. The distribution diagram of unfavorable equivalent static wind loads was worked out to provide reference for the design of the main structure.

Introduction

With the development of modern material technologies and construction techniques, a growing number of high-rise buildings have emerged, with large span, flexibility, lightweight, low damping, and hence a greater sensitivity to wind. For these buildings, wind load is an important design load. The damage and destruction of civil engineering structures caused by wind loads represent the major losses in a wind disaster. The extent of damage includes the destruction of roof, exterior wall systems, exterior glass coating and even the malfunction of the entire structure and lifeline facilities. Therefore, studies of the impact of wind on structures are essential to engineering structural design and calculations.

An Overview of the Moon Tower

The Moon Tower of the West Taihu Lake is located in the Moon Bay area of the West Taihu Lake in Changzhou, Jiangsu Province. It is 88m in total height, and the base is 4.2m high and 33m in diameter; the main body of the tower is 65.8m high and 6.85m in diameter, and the glass sphere on the top is 18m in diameter. The sightseeing platform at the bottom is 60m in diameter and has an absolute elevation of 3.70m. The roof terrace has an absolute elevation of 7.9m, which is 3.53m higher than that of the highest water level that is statistically possible every 50 years.

The structure of the Moon Tower of the West Taihu Lake has a large height-to-width ratio as well as low natural frequency and low damping. The structural vibration caused by the fluctuating wind load cannot be ignored, thus giving rise to the necessity of the wind-induced response analysis. However, the calculation methods for wind-induced vibration coefficient described in the current architectural design specifications are generally applicable to high-rise buildings with regular shapes. Therefore, on the basis of wind-induced response estimation, the wind-induced vibration coefficients of the Moon Tower were given in this study to facilitate a reasonable, safe and reliable wind resistant design of the structure.
Estimation of Wind-Induced Responses and Wind-Induced Vibration Coefficients

Definition of Wind Angles, Design Wind Load and Wind Load Coefficient

The definition of wind angles in the estimation of wind-induced responses is shown in Figure 2. The design wind load is set as 0.45kN/m², which is expected to occur every 100 years in Changzhou according to statistics.

Wind-Induced Response at 0-Degree Wind Angle

Figure 3. Displacement response spectrum of the top floor under fluctuating wind.

Figure 4. Contribution of vibration mode of each order to the wind-induced strain energy.

Figure 5. Wind-induced vibration response at 0 degree.
Figure 3 shows the fluctuating wind-induced response curves at 0-degree wind direction (X-axis direction) for the top floor of the sphere; Figure 4 shows the contributions of vibration mode of each order to the wind-induced response of the structure.

It can be seen that the first and second-order vibration modes make the greatest contribution to the structural response induced by fluctuating wind. The contribution of the first-order vibration mode is as high as 75%. The peak value appears near the frequency of 0.49Hz.

Figure 5 shows the equivalent static wind load-induced response at 0 degree, as well as the maximum wind-induced response under the action of equivalent static wind load plus fluctuating wind. It can be seen that under the action of equivalent static wind load alone, the cross-wind displacement is very small; but when the fluctuating wind is considered, the cross-wind displacement is large.

**Wind-Induced Responses of the Structure at All Wind Angles**

<table>
<thead>
<tr>
<th>Wind angle</th>
<th>X-axis Direction</th>
<th>Y-axis Direction</th>
<th>Resultant Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average wind-induced displacement (Unit: m)</td>
<td>Maximum wind-induced displacement (Unit: m)</td>
<td>Average wind-induced displacement (Unit: m)</td>
</tr>
<tr>
<td>0 degree</td>
<td>-0.0229</td>
<td>-0.0412</td>
<td>0.0006</td>
</tr>
<tr>
<td>15 degrees</td>
<td>-0.0235</td>
<td>-0.0405</td>
<td>0.0017</td>
</tr>
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<td>30 degrees</td>
<td>-0.0235</td>
<td>-0.0421</td>
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<td>-0.0168</td>
<td>-0.0306</td>
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</tr>
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<td>-0.0067</td>
<td>-0.0203</td>
<td>-0.0107</td>
</tr>
<tr>
<td>75 degrees</td>
<td>0.0055</td>
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<tr>
<td>90 degrees</td>
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<td>0.0636</td>
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</tr>
<tr>
<td>105 degrees</td>
<td>0.0108</td>
<td>0.0450</td>
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</tr>
<tr>
<td>120 degrees</td>
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<td>0.0359</td>
<td>-0.0195</td>
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<td>135 degrees</td>
<td>0.0099</td>
<td>0.0332</td>
<td>-0.0206</td>
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<td>165 degrees</td>
<td>0.0096</td>
<td>0.0182</td>
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<td>180 degrees</td>
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<td>0.0181</td>
<td>0.0010</td>
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<td>195 degrees</td>
<td>0.0091</td>
<td>0.0181</td>
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<tr>
<td>210 degrees</td>
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<td>0.0283</td>
<td>0.0204</td>
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<tr>
<td>225 degrees</td>
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<td>0.0298</td>
<td>0.0191</td>
</tr>
<tr>
<td>240 degrees</td>
<td>0.0107</td>
<td>0.0317</td>
<td>0.0190</td>
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<td>255 degrees</td>
<td>0.0115</td>
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<td>0.0144</td>
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<td>285 degrees</td>
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<td>300 degrees</td>
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<td>315 degrees</td>
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<td>330 degrees</td>
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</tr>
<tr>
<td>345 degrees</td>
<td>-0.0224</td>
<td>-0.0427</td>
<td>-0.0005</td>
</tr>
</tbody>
</table>

The wind loading deformation diagrams of the structure under the corresponding maximum wind-induced response at different wind angles are shown below.

The maximum displacements along X (0 degree) and Y (90 degree) directions at different wind angles are given in Table 1.

Note: In $\sqrt{X^2 + Y^2}$, X and Y represent the wind-induced displacements in X-axis and Y-axis directions, respectively.

As shown in Table 1, the winds with the angles of 90 degrees, 210 degrees and 330 degrees are the most unfavorable to the structure.
The three moons are arranged evenly around the center of the Moon Tower at an interval of 120 degrees. Therefore, the peak values of equivalent static wind loads and wind-induced structural responses occur also at an interval of 120 degrees. According to rotational symmetry, it can be known that the most unfavorable wind angle of 0 degree is equivalent to 120 degrees and 240 degrees.

Wind-Induced Vibration Coefficients and Equivalent Static Wind Loads in Along-Wind Direction

The wind-induced vibration coefficients of nodal displacement of the Moon Tower were calculated according to the results of the wind-induced response analysis in 3.3 and the equation (22).

Figure 7 shows the wind-induced vibration coefficients of nodal displacement in the along-wind direction at 0 degree (i.e. X-axis direction), and Figure 8 shows the wind-induced vibration coefficients of nodal displacement in the along-wind direction at 90 degrees (i.e. Y-axis direction).

As shown in the figures, the wind-induced vibration coefficients at the nodes with larger wind-induced response amplitude are similar, and these nodes play a critical role in structural design. At 0 degree, the wind-induced vibration coefficient of the entire structure can be 1.80, while at 90 degrees the wind-induced vibration coefficient of the entire structure is 2.4.
Then according to rotational symmetry and the above analysis results, the along-wind vibration coefficients at some typical angles can be obtained:

1. At 0, 120 and 240 degrees, the along-wind vibration coefficient of the structure is \( \beta = 1.8 \);
2. At 90, 210 and 330 degrees, the along-wind vibration coefficient of the structure is \( \beta = 2.4 \).

The along-wind vibration coefficients of the structure at other angles can be obtained through linear interpolation.

In actual practice of structural design, the standard value of along-wind equivalent static wind load of the main structure is calculated as follows:

\[
\max_{w} \beta \cdot C \cdot \mu \cdot \omega \cdot \psi \cdot M \cdot a
\]

In the formula, \( \beta \) is the along-wind vibration coefficient of the structure; \( \mu \) is the design wind load value in Changzhou, which is 0.45kPa, as determined according to the occurrence frequency of once every 100 years; \( \omega \) is the height variation coefficient of wind load at the top of the Moon Tower (at 88m height), and \( \omega = 2.26 \) according to the landform; \( \mu \) is the average block wind load coefficient at the top of the Moon Tower.

Wind-Induced Vibration Coefficients and Equivalent Static Wind Loads in Cross-Wind Direction

The analysis results of wind-induced vibration responses at all wind angles show that the displacement caused by the equivalent static wind load of the structure in the cross-wind direction are very small, while the fluctuating wind-induced response and extreme response are large. In such case, it is not suitable to use the wind-induced vibration coefficient to express cross-wind equivalent static wind load, since the average equivalent static wind load is 0, which is mainly the equivalent component corresponding to fluctuating wind load.

The cross-wind vibration response spectrum at the top of the structure at 0 degree shows that a significant peak appears at the natural frequency is 0.49Hz. This indicates that the inertial force of the structure controls the cross-wind vibration. In other words, the first-order vibration mode plays the dominant role. Therefore, the cross-wind equivalent static wind load can be expressed through the inertial force of the cross-wind induced vibration of first-order mode as follows:

\[
\{ F \} = a \cdot \{ \omega \} \cdot \{ M \} \cdot \{ \psi \}
\]

In the formula, \( \{ M \} \) and \( \{ \psi \} \) represent the mass matrix and the first-order mode function, respectively; \( \{ \omega \} \cdot \{ M \} \cdot \{ \psi \} \) represents the shape function for the inertial force of the first-order mode, and \( a \) is the proportionality coefficient.

Under the action of cross-wind equivalent static wind load \( \{ F \} \), the cross-wind displacement of the structure is the same as the analysis results in 3.3, according to which the proportionality coefficient in the formula (2) can be calculated.

According to the analysis results in the above section, the wind at 90 degrees is most unfavorable for the structure. In this paper, cross-wind equivalent static wind loads at 0 and 90 degrees are mainly analyzed to benefit the structural design. The cross-wind equivalent static wind loads can be worked out by integrating the equivalent wind loads at all nodes of each floor obtained through formula (2).

Cross-Wind Equivalent Static Wind Load at 0 Degree. At 0 degree, as shown in Table 1, the maximum cross-wind displacement is 0.0336m, and the cross-wind equivalent static wind load (i.e. the Y-axis direction) can be obtained according to formula (2) (as shown in Figure 9).
Figure 10 shows the comparison between the responses of the Moon Tower at all heights to the equivalent static wind load and the numerical value in cross-wind direction. It can be seen that the two are in good agreement.

Figure 9. Cross-wind equivalent static wind load at 0 degree.

Figure 10. Comparison between the response to the equivalent static wind load and the actual wind-induced response at 0 degree.

Cross-Wind Equivalent Static Wind Load at 90 Degrees. At 90 degree, as shown in Table 1, the maximum cross-wind displacement is 0.0636m, and the cross-wind equivalent static wind load (i.e. the X-axis direction) can be obtained accordingly (as shown in Figure 11).

Figure 11. Cross-wind equivalent static wind load at 90 degrees.

Figure 12. Comparison between the response to the cross-wind equivalent static wind load and the actual wind-induced response at 90 degrees.

Conclusions
Based on the wind tunnel test, the wind load pressure duration of the Moon Tower is obtained. Frequency-domain analysis is adopted to analyze wind-induced response dynamics and equivalent static wind loads of the Moon Tower on the West Taihu Lake at different wind directions. The unfavorable equivalent static wind load distribution is worked out for the design of the main structure. The main conclusions and suggestions are as follows:

1. According to the analysis of wind-induced vibration, the winds at 90 degrees, 210 degrees and 330 degrees are most unfavorable to the structure, and these three wind directions are symmetric around the three axes of the center;
2. The along-wind vibration coefficient of the entire structure at 0 degree is 1.8, while that at 90 degrees is 2.4;
(3) The cross-wind equivalent static wind loads at the two typical unfavorable wind angles of 0 and 90 degrees are given, and the extreme values of actual dynamic response are in good agreement with the responses to the equivalent static loads;

(4) In actual design, along-wind equivalent static wind loads and cross-wind equivalent static wind loads should be taken into consideration, and the effects of cross-wind and along-wind responses should be combined according to the provisions of Clause 8.5.6 of Load Code for the Design of Building Structures (2012). That is, 

\[ S = \sqrt{(0.6 S_A)^2 + S_C^2}, \]

where \( S_A \) and \( S_C \) represent along-wind and cross-wind wind load effects, respectively.

Acknowledgements

This article is sponsored by Special Fund of Fundamental Scientific Research Business Expense for Higher School of Central Government (Projects for young teachers) in 2014 (Fund No.ZY 20140204).

References


