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The Discussion of Wind-induced Interference Effects of Large Cooling Towers Considering Wind Direction

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Abstract

The wind load is the control load of the cooling tower. The equivalent wind load is the most effective and popular way to assess the wind-induced vibration.

In practice, a wide range of surrounding buildings will change the wind direction, wind speed, wind profile, turbulence intensity and other parameters acting on the target tower completely, making the wind pressure distribution along with all the responses of the cooling tower totally different from the isolated case. Most researches on the vibration effect and the interference effect are independent, however, there remains relationship between the two.

The need to verify the correlation between the two effects becomes far more urgent when many super-large towers with complex arrangements and high designed wind speed are on the way. In this paper, an eight-tower rigid model pressure test along with finite element calculation are designed to study the distribution of wind-induced vibration effect and interference effect. The results show that the distributions of the two effects have different patterns: the maximum position of one may be the minimum of the other.

Introduction

Interference Index and Vibration Indexes

The interference effect is characterized by the interference factor:

$$I_{\mathrm{F}} = \frac{C_{multi}}{C_{isolate}} \quad (1)$$

where C_{multi} is the target parameter value under complex arrangements, while $C_{isolate}$ is that of the isolated case.

The vibration effect is generally characterized by the wind-induced vibration coefficient β:

$$\beta = \frac{C_{mean} \pm g \times \sigma}{C_{mean}} \quad (2)$$

where C_{mean} and σ are the mean value and the standard deviation of the target parameter, g is the peak factor.

The distribution of the wind-induced characteristics can be quite different between isolated tower and towers with complex arrangement. Under this circumstances, the interference and vibration indexes should not be defined as the ratio of values at each specific spot, but the ratio of the maximum values at each height. Using the indexes under these definitions, one can accurately obtain the design state of the multi-tower cases from the isolated tower state. To clarify the difference of the two definition, the factors in this research will be called interference/vibration index.

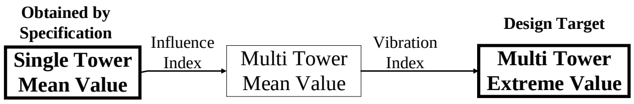


Figure 1. Work flow of the interference and vibration effect

Zhang[1] compared relevant specifications of China, Britain and Germany, regarding to the vibration effect and interference effect. In the Chinese Specification[2], the wind-induced coefficient is only related to the corresponding site category, while no interference factor is recommended. In German specifications, the analysis of the vibration effect is more refined, taking the gust wind effect and dynamic characteristics into consideration, with a recommended interference factor related to the spacing ratio, but the two effects are calculated separately. The British specification consider both effects together in one factor Φ, but it restricts the spacing ratio to be 1.5D, and wind-tunnel test shall be conducted when the height excesses 120 m. The differences in the specifications indicate that agreement hasn't been reached on how to combine the interference effect and the vibration effect.

<table>
<tr><th>Items</th><th>China</th><th>Britain</th><th colspan="2">Germany</th></tr>
<tr><td>Vibration Effect</td><td>Different β value according to site category only</td><td rowspan="6">φ consider the gust wind effect, dynamic characteristics and interference effects. The spacing is 1.5D only, and wind-tunnel test is recommended when the height excesses 120 m.</td><td colspan="2">φ considered the gust wind effect, dynamic characteristics</td></tr>
<tr><td rowspan="5">Interference Effect</td><td rowspan="5">The smallest spacing is recommended</td><td>L/D_m</td><td>F_I</td></tr>
<tr><td>≥4.0</td><td>1.0</td></tr>
<tr><td>=2.5</td><td>1.1</td></tr>
<tr><td>=1.6</td><td>1.3</td></tr>
<tr><td><1.6</td><td>Wind-Tunnel Test</td></tr>
</table>

Table 1. Specification of different countries regarding to vibration effect and interference effect

Which parameter should we use to assess the two effects? The specifications say nothing about this, which somehow encourages scholars to use different parameters when quantifying the effects.

Reference	Comparison Parameter
Sun[3]	Drag coefficient, lift coefficient, mean pressure distribution
Niemann[4]	Maximum tensile meridian force
Orlando[5]	Mean meridian force, mean hoop bending moment, maximum hoop and meridian normal stresses
Zhao[6]	Horizontal force coefficient, maximum shell displacement
Zhao[7]	Local buckling factor, circumference and meridian membrane force and bending moment, construction cost

Table 2. Different comparison parameters used to assess the interference effect

Systematically speaking, the selected parameters can be divided into three levels: load, response and structure cost:

- **load level:** the drag coefficient, the lift coefficient and the shape coefficient.
- **response level:** displacement, axial force and bending moment.
- **structure cost level:** reinforcement ratio, construction costs.

Different interference factors will be defined according to the selection of different parameters. The wind-induced vibration coefficient is usually obtained from the wind-tunnel test of aerodynamic model or the wind-tunnel test of rigid model combined with the calculation based on the FEM. The wind-induced vibration coefficient of the German specification mainly come from Niemann's aerodynamic wind-tunnel test, during which the meridian force was used to define the wind-induced vibration coefficient. Ke[8] and Zou[9] defined the coefficient using the displacement in the aerodynamic model test. Zou compared the wind-vibration coefficient based on displacement with the wind-vibration coefficient of Chinese and German specifications, the trend and value are basically the same. In this paper, the criteria of displacement, shell circumference/meridian stress/moment are examined.

Wind-tunnel Test and Finite Element Calculation

This paper focuses on interference effect and vibration effect among typical eight-tower arrangements. The research can be divided into 2 steps: (1) wind tunnel tests were performed on a rigid model for various cases and wind pressure data around the tower surface were measured (internal pressure is also recorded for calculation); (2) finite element analyses of a cooling tower model were carried out to calculate structure response.

The Design of the Wind-Tunnel Test

A series of wind tunnel tests were carried out on a rigid model to obtain the time series of the pressure data. The tests were performed in the TJ-3 atmosphere boundary layer wind tunnel at Tongji University in Shanghai, China. The testing section is 15m wide×2m high. A 1:300 reduced-scale model of a 185 m-high cooling tower together with the multi-tower arrangement was designed. The rigid model was made of organic glass, which barely vibrates under wind load. There were 12×36=432 pressure taps on the external surface of the tower shell, 12 layers along the meridian height, 36 taps arranged evenly around the circumference for every layer, which can be seen in Fig 2; pressure taps were also arranged on the internal surface, where the layers along the meridian direction was halved.

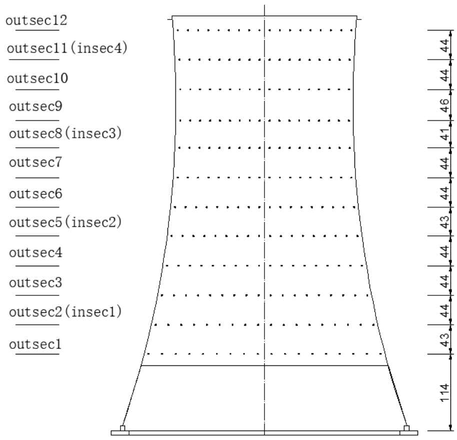


Figure 2. Pressure tap arrangement

The surrounding terrain is set to be Type B according to the Chinese Load Code (GB50009-2012), with the mean and turbulence wind profiles shown in Fig 3. The sampling frequency was set at 300Hz, with the sampling duration of 60 seconds. To simulate Reynolds number effects (mean pressure distribution profile of the rib-free case according to Chinese specification[2]), 36 ribs were pasted uniformly around the circumference. The ribs were 1.0 mm wide and 0.7 mm thick, and stretched from bottom to top. The operating wind speed is 8 m/s.

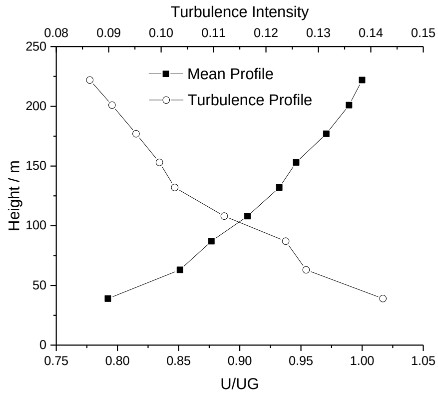
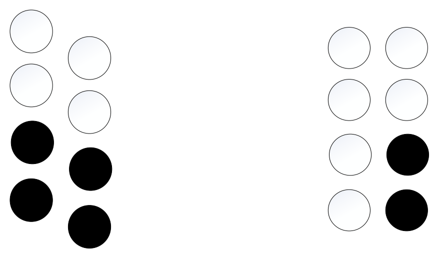


Figure 3. Mean wind profile and turbulence profile

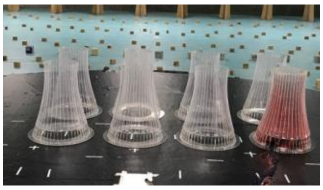
The FEM calculation in the 2nd step is amazingly time-assuming, so this paper fix the center-to-center distance between adjacent towers to be 1.5D, under which circumstances the results can be compared to the Britain specification where the distance is also fixed to 1.5D. Two typical arrangement: rhombic and triangular was chosen, which are shown in Fig 4. Pictures of the arrangements are also taken in the wind tunnel, which can be seen in Fig 5.



a) Rhombic Arrangement b) Triangular Arrangement

Figure 4. Multi-tower Arrangement Design

Wind direction ranged from 0° to 315°, with the increments of 45°. Thanks for the geometric symmetry of tower combination, not all towers were targeted as observed tower.



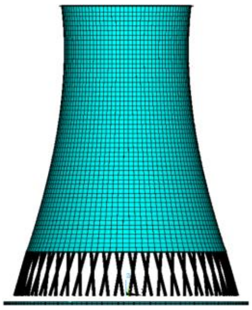
a) Rhombic Arrangement b) Triangular Arrangement

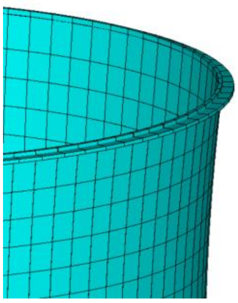
Figure 5. Multi-tower Arrangement in the wind-tunnel

Finite Element Calculation

The time-history of the wind-induced response analysis of the cooling tower is conducted via transient dynamic analysis in the famous finite element software ANSYS. The input data is the load signal, while the output data is the displacement or other outputs, such as stress, strain, etc. Through the transient dynamic analysis function, the displacement response time of each node according to the wind load can be obtained.

However, due to the limited number of test equipment, the wind pressure taps cannot cover all the node of the model. Therefore, the POD method is employed to interpolate 12 × 36 = 432 measurement data to the wind pressure time history data of 55 × 96 = 5280 loading points.





a) FEM Model Outline b) Details of the Rigid Ring

Figure 6. Finite Element Model

The test object is a concrete tower, and the damping ratio is set to be 5% according to Chinese specification.

Results

Based on the time history data, the interference and vibration indexes are calculated, together with the combination index. For simplicity, only several important results are listed below.

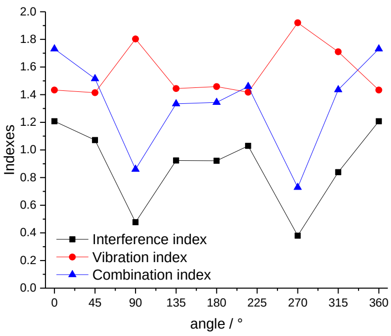


Figure 7. Indexes of displacement along circumference (Rhombic Arrangement Tower#1 0° 134.5 m height)

Fig 7 shows the indexes of displacement along circumference of one case. As shown in Fig 7, the interference and vibration indexes have totally opposite trend, and the trend of the combination of the two somehow resembles that of the interference index. This is a general phenomenon among most cases.

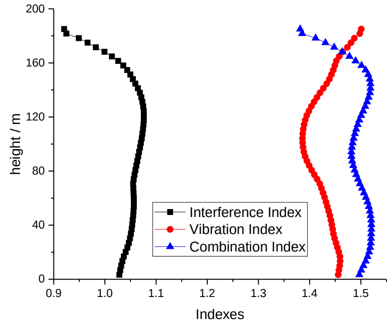


Figure 8. Indexes of displacement along height (Rhombic Arrangement Tower#1 45°)

Fig 8 shows the indexes of displacement along meridian of one case. It can be seen that the regulations along circumference and meridian are the same.

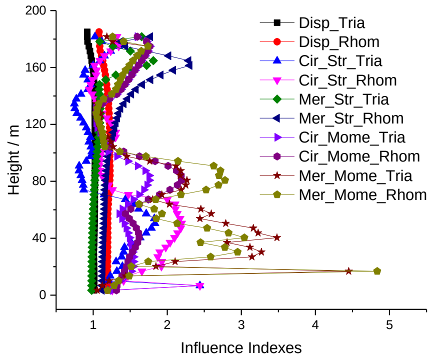


Figure 9. Interference indexes of different criteria under triangular and rhombic arrangements (Disp – Displacement, Tria- Triangular, Rhom- Rhombic, Cir – Circumference, Mer – Meridian, Str – Stress, Mome- Moment)

Fig 9 shows the interference indexes of different criteria under both arrangements, the displacement interference index is rather stable, while the meridian moment indexes yield the largest at the part below 90 m, and the meridian stress indexes yield the largest at the top part. Also, the index calculated under triangular arrangement is generally smaller than that under rhombic arrangement.

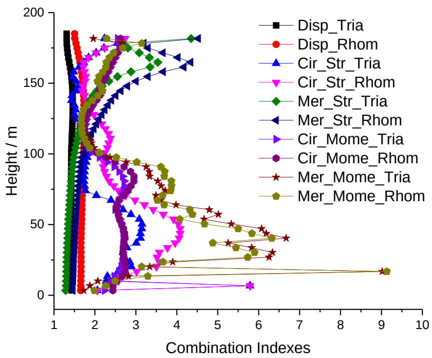


Figure 10. Combination indexes of different criteria under triangular and rhombic arrangement

Fig 10 shows the combination indexes of different criteria under both arrangements. The regulations of the combination index are almost the same as that of the interference index.

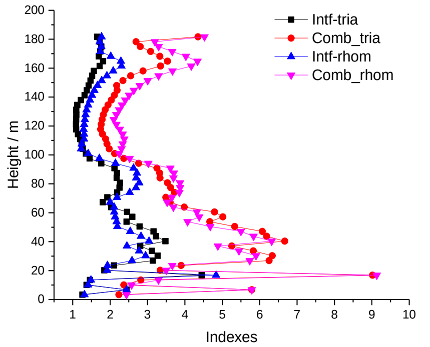


Figure 11. Comparison of the envelope of the interference and combination indexes under two different arrangements

As shown in Fig 11, the envelope of the two indexes have similar trend, but the interference index is more stable above 20 m, and the combination index has an uprush above 160 m. The equivalent vibration index calculated using the envelope values is shown in Fig 12. The value in two regions (below 40 m and above 160 m) are relatively large.

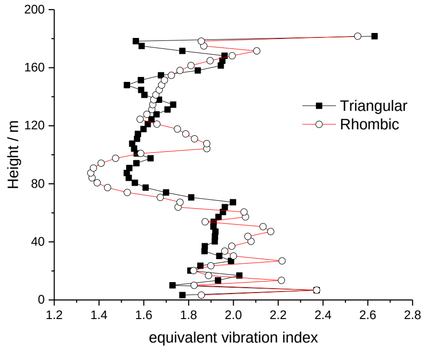


Figure 12. Equivalent vibration index calculated by the envelope of influence and combination indexes

Conclusions

Wind-tunnel test on rigid model together with the FEM calculation has been conducted to investigate the wind-induced response of complex-arranged tower groups. The main conclusions are as follows:

- **Interference Effect and Vibration Effect:** the two effects are represented by interference and vibration effect. To accurately assess these two effects, five criteria are examined. Among which the index of displacement is the most stable and smallest one, and the meridian moment indexes yield the largest at the part below 90 m, and the meridian stress indexes yield the largest at the top part.

- **The Connection between the Two:** the tendencies of the two indexes are quite different, which makes sense because they have totally different mechanism. Also, the tendency of the combination index resembles that of the interference index.

- **Recommendation:** when combined, these two factors should share the same case and wind attack angle, otherwise the final amplification factor may be exaggerated.

Acknowledgments

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References

[1] Zhang J F, Yao-Jun G E, Zhao L. Comparisons of Nominal Values of Wind Loads on Hyperboloidal Cooling Towers[J]. *Journal of Architecture & Civil Engineering*, 2011.

[2] GB/T 50102-2003, Code for Design of Cooling for Industrial Recycled Water[S].

[3] T.F. Sun, Z.F. Gu. Interference between wind loading on group of structures [J]. Journal of Wind Engineering and Industrial Aerodynamics,54:213-225, 1995.

[4] H.J. Niemann, H.D. Kopper. Influence of adjacent buildings on wind effects on cooling towers [J]. Engineering Structures, 20:874-880, 1998.Rosenhead, L. (editor) *Laminar Boundary Layers* Oxford, Clarendon Press, 1963.55

[5] M. Orlando. Wind-induced interference effects on two adjacent cooling towers [J].Engineering Structures, 23:979-992, 2001.

[6] L. Zhao, X. Chen, S.T. Ke, Y.J. Ge. Aerodynamic and aero-elastic performances of super-large cooling towers [J]. Wind and Structures, 19:443-465,2014.

[7] L. Zhao, X. Chen, Y.J. Ge. Investigations of adverse wind loads on a large cooling tower for the six-tower combination [J]. Applied Thermal Engineering,

[8] Ke S, Zhao L, Ge Y, et al. Wind tunnel test on aeroelastic model of large hyperbolic cooling towers and features of wind-induced response[J]. Jianzhu Jiegou Xuebao/journal of Building Structures, 2010, 31(2):61-68.

[9] Zou Y. Study on Wind Effects and Wind-Tunnel Test Method for Super Large Cooling Towers Group[D]. Hunan University, 2013

[10] Dong R, Zhao L, Yao-Jun G E, et al. Investigation of surface roughness and its influence to flow dynamic characteristics of hyperbolic cooling tower[J]. Acta Aerodynamica Sinica, 2013, 31(2):250-259.

[11] Lienhard, J.H. Synopsis of lift, drag, and vortex frequency data for rigid circular cylinders[R]. Bulletin 300， 1966

[12] Chen Z. Wind engineering of bridge [M]. Beijing: China Communications Press, 2005.