Adaptive wind tunnel model tests for a large cooling tower considering the realistic wind environment

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ABSTRACT

The traditional wind tunnel model tests consider the theoretical atmospheric boundary layer (ABL) wind characteristics presented in Codes of Practice and publications as targets in simulating ABL flow fields. However, the theoretical knowledge might be inapplicable to a specific engineering case, since it is obtained by generalizing large quantities of measured data with simplifications and conservatism. To this end, adaptive wind tunnel model tests considering the realistic wind environment are proposed in this paper. According to the new simulation concept, field measurements for realistic ABL flow characteristics at the engineering sites should be undertaken before wind tunnel model tests, and wind tunnel model tests should then be formulated and conducted guided by field measurement results. Using a large cooling tower located in Xu-zhou, China as the engineering background, this paper proves that the adaptive wind tunnel model tests can lead to more reliable wind effects compared with those of the traditional simulation concept.

1. INTRODUCTION

As a mature technique applied in aviation industry, the wind tunnel model test was introduced into wind engineering research and design in 1960s. After Jensen (1958) proposed that the flow field simulated in the wind tunnel should be similar to the actual atmospheric boundary layer (ABL) flow field for wind engineering model tests, simulating ABL has become an indispensable test procedure. According to Cermak (1987), physical modeling to quantify wind effects for either wind-engineering design or research requires simultaneous similarity for two distinct physical phenomena. The initial consideration is similarity of the desired natural wind characteristics. When this requirement is satisfied, similarity of specific wind effects must then be considered. According to Eurocode 1 (1995), if wind tunnel model tests are carried out to evaluate

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To fulfill the task of simulating realistic ABL flow fields, passive simulation devices, including spires, roughness elements, grids and baffles, can jointly be used in wind tunnel model tests. It has been found that idealized flow fields can be obtained by adjusting the position and the number of some devices placed in the wind tunnel. According to Lopes, Gomes et al. (2008), the generation of the ABL was achieved in a short wind tunnel considering the mean velocity profile, the turbulence profile and spectra of the velocity fluctuations by means of a combination between triangular spires in the beginning of the tunnel’s working section and roughness elements distributed along the tunnel floor. According to Table 1 (Huang, Shi et al. 2001), different kinds of ABL flow fields are successfully simulated using passive devices in wind tunnels of Tongji University in China. Even in an open-jet 12-fan testing facility, spires and roughness elements are proven to be effective in simulating the suburban exposure wind flow (Fu, Chowdhury et al. 2014).

<table>
<thead>
<tr>
<th>Wind tunnel name</th>
<th>Size (m)</th>
<th>Wind speed range (m/s)</th>
<th>Built time</th>
<th>Simulated flow field type</th>
<th>Successfully simulated wind characteristics</th>
<th>Devices</th>
<th>Representative engineering services</th>
</tr>
</thead>
<tbody>
<tr>
<td>TJ-1</td>
<td>1.2 x 1.8 x 18</td>
<td>0.5-32.5</td>
<td>1991</td>
<td>Type B and C ABL flow fields</td>
<td>Mean wind speed profile, turbulence intensity profile, power spectral density for along-wind and vertical wind speed fluctuations</td>
<td>Grid and spires</td>
<td>Oriental pearl TV tower in Shanghai</td>
</tr>
<tr>
<td>TJ-2</td>
<td>3 x 2.5 x 15</td>
<td>0.5-68</td>
<td>1996</td>
<td>Type A, B, C and D ABL flow fields</td>
<td>Mean wind speed profile, turbulence intensity profile, power spectral density and turbulence integral scale</td>
<td>Baffle, spires, roughness elements</td>
<td>Jinmao tower in Shanghai</td>
</tr>
<tr>
<td>TJ-3</td>
<td>15 x 2 x 14</td>
<td>0.2-17.8</td>
<td>1994</td>
<td>Type A, B, C ABL flow fields and typhoon flow field</td>
<td>Mean wind speed profile, turbulence intensity profile and power spectral density</td>
<td>Baffle, spires, roughness elements and grid</td>
<td>Jiangyin bridge, Humen bridge, many stadiums and highrise buildings</td>
</tr>
</tbody>
</table>

* Note: ABL flow field types are defined by GB 50009-2001 (2002).
The passive method of simulating the ABL flow field in the wind tunnel is proven to be effective. However, the simulation targets are not necessarily the realistic natural wind characteristics of the specific engineering site. According to GB 50009-2001 (2002), Simiu and Scanlan (1996) and Holmes (2001), ABL flow fields are simply divided into four types according to the roughness length of the ground surface. Empirical formulae for the mean wind velocity profile are given for each flow field type based on on-site observations, but the turbulence intensity profiles are not definitively described. This is because that the roughness length varies in an interval for each terrain type which causes uncertainties to the turbulence intensity (Holmes 2001), and the turbulence intensity also depends on the mean wind speed which changes over time (Kozmar 2011). The practice of regarding a representative turbulence intensity profile as the simulation target for a type of ABL flow field in model tests (see, e.g., Xu, Yu et al. 2014, Lou, Zhang et al. 2015) is less reasonable. Besides, the practice of considering theoretical wind characteristics presented in Codes of Practice and publications as simulation targets is unreliable. The theoretical knowledge is obtained by generalizing large quantities of measured data with simplifications and conservatism, so they might be inapplicable to specific engineering cases. If it is possible, realistic turbulence intensity profile of the specific engineering site should be taken into account for wind tunnel model tests.

In this paper, a large cooling tower located in Peng-cheng electric power station in Xu-zhou, China is taken as the engineering background. Before its construction, anemometers were installed on the site for obtaining the actual wind environment information. Guided by field measurement results, adaptive wind tunnel model tests were formulated and conducted. After the construction of the large cooling tower, the realistic wind effects were obtained on the structure and compared with the model test results. The comparison demonstrates the usefulness of obtaining the realistic wind environment parameters for guiding the wind tunnel model test.

2. WIND ENVIRONMENT AT THE ENGINEERING SITE

2.1 Theoretical turbulence intensity profile

A 167-meter smooth-walled cooling tower was to be built in Peng-cheng power station, Xu-zhou, China. To its south, an adjacent cooling tower of the same size would be built, and there was an industrial complex to its west (see Fig. 1). To its north and east, there is no large interfering building, but a few mounds. According to the descriptions of terrain types given in Table 2 (Holmes 2001), the flow field at Peng-cheng electric power station is open terrain type, for which the roughness length is in between 0.01 and 0.05 m (see Table 2).
Table 2 Terrain types and roughness length

<table>
<thead>
<tr>
<th>Terrain type</th>
<th>Description</th>
<th>Roughness length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very flat terrain</td>
<td>Snow, desert</td>
<td>0.001~0.005</td>
</tr>
<tr>
<td>Open terrain</td>
<td>Grassland, few trees</td>
<td>0.01~0.05</td>
</tr>
<tr>
<td>Suburban terrain</td>
<td>Buildings 3-5m</td>
<td>0.1~0.5</td>
</tr>
<tr>
<td>Dense urban</td>
<td>Buildings 10-30m</td>
<td>1~5</td>
</tr>
</tbody>
</table>

According to Simiu and Scanlan (1996) and Holmes (2001), the following equation exists:

\[ U(z) = \frac{1}{k} u_* \ln \frac{z}{z_0} \]  

(1)

where \( z \) is the height above the surface, \( z_0 \) is the roughness length, \( u_* \) is the friction velocity, \( U(z) \) is the mean wind speed at \( z \) height, and \( k=0.4 \). The friction velocity \( u_* \) calculated for the site of Peng-cheng electric power station is 1.35~1.76 m/s.

According to Simiu and Scanlan (1996), the longitudinal turbulence intensity is defined as:

\[ I(z) = \frac{\sigma_u}{U(z)} \]  

(2)

where \( U(z) \) is mean wind velocity at elevation \( z \), and \( \sigma_u \) is root mean square value of \( u \). The longitudinal turbulence fluctuations can be written as:

\[ \sigma_u^2 = \beta u_*^2 \]  

(3)

where it is commonly assumed that \( \beta \) does not vary with height. Values of \( \beta \) suggested for structural design purposes on the basis of a large number of measurements are listed in Table 3 (Simiu and Scanlan 1996).
Table 3 Value of $\beta$ corresponding to various roughness lengths

<table>
<thead>
<tr>
<th>$Z_0$ (m)</th>
<th>0.005</th>
<th>0.07</th>
<th>0.3</th>
<th>1</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>6.5</td>
<td>6</td>
<td>5.25</td>
<td>4.85</td>
<td>4</td>
</tr>
</tbody>
</table>

By using the first-order exponential decay equation to fit data presented in Table 3, the following relation between $z_0$ and $\beta$ can be obtained:

$$\beta = 2.27 \exp\left(-\frac{z_0}{0.68}\right) + 4.05$$

(4)

According to Eqn. (4), the value $\beta$ for open terrain type is 6.29~6.16. Then, according to Eqn. (3), $\sigma_u$ for open terrain type is 3.39~4.37 m/s. Thus, the theoretical turbulence intensity profile for the site of Peng-cheng electric power station can be calculated using Eqn. (2). As is shown in Fig. 2, the theoretical turbulence intensity profile varies in the interval between the lower and upper envelopes due to the uncertainty of the roughness length.

![Fig. 2 Upper and lower envelopes of the theoretical turbulence intensity profile in open terrain](image)

2.2 Actual turbulence intensity profile

Before the construction of the two-grouped cooling towers, a two-dimensional (2D) propeller anemometer, a three-dimensional (3D) ultrasonic anemometer and a vane are arranged at the engineering site at 20-meter height in 2007 (see Fig. 3). For the 2D propeller anemometer, measured data are the wind speed and the wind direction in the horizontal plane. The 3D ultrasonic anemometer can record full oncoming flow information, including wind speed, azimuth angle and elevation angle, which is more preferable in use under normal weather conditions. However, the performance of the 3D anemometer is likely to be adversely affected by rainwater, and 2D anemometer is used as 3D anemometer’s substitute on rainy days.
The field measurements for the realistic flow field information last for over one year. A huge amount of wind speed samples has been obtained, from which records with constant strong winds are selected and processed. They are divided into 10-min data segments, and the turbulence intensities and the corresponding mean wind speeds are calculated for each segment. Fig. 4 illustrates some representative results, which suggests that turbulence intensity tends to decrease as the mean wind speed increases, which accords with Quan, Wang et al. (2013). The longitudinal turbulence intensity measured at 20-meter height is in [0.006, 0.25], and the mean value is 0.027 which is much smaller than the theoretical turbulence intensity calculated at the same height.
Using Eqn. (2), the turbulence profiles are calculated based on measured data. A comparison between measured and theoretical turbulence intensity profile envelopes made in Fig. 5 suggests that the upper envelope for measured turbulence intensity profiles is close to the theoretical value, but the lower envelope for measured turbulence intensity profiles is close to the vertical axis, which is significantly smaller than the theoretical value. Thus, it can be concluded that the oncoming flow at Peng-cheng electric power station is highly uncertain, as the measured flow characteristic varies in an extremely wide interval. The flow with negligible free-stream turbulence and the theoretical open terrain ABL turbulent flow can be approximately regarded as the two extremes of the realistic oncoming flow in terms of the turbulence intensity.

![Fig. 5 Measured and theoretical turbulence intensity profile envelopes](image)

### 3. ADAPTIVE WIND TUNNEL MODEL TESTS

Without the realistic oncoming flow information, traditional wind tunnel model tests rely solely on the theoretical knowledge, which might lead to unrealistic results. Considering the field measurement findings (see Sec. 2.2), the model tests for Peng-cheng cooling tower are adaptively formulated and presented in this section, which include the following steps: First, the uniform flow field with negligible free-stream turbulence is simulated in the wind tunnel, and the corresponding wind effects are regarded as the lower limit value; Second, the traditional ABL turbulent flow field for open terrain is also used, and the wind effects obtained in the flow field are regarded as the upper limit value; Third, the final result is obtained by averaging the upper and the lower limits.
3.1 Model test in uniform flow field with negligible free-stream turbulence

The wind tunnel model test is carried out in TJ-3 atmospheric boundary layer (ABL) wind tunnel at Tongji University, Shanghai. It is a closed circuit rectangular cross-section wind tunnel, wherein the size of the test zone is 15m in width, 2m in height and 14m in length. The test wind speed can be continuously controlled in a range from 1 to 17.6m/s. In uniform flow field, the non-uniformity of wind speed in test zone is less than 1%, the turbulence is less than 0.5% and the average flow deviation angle is less than 0.5°.

The wind speed at the model top height is regarded as the reference wind speed, which is measured by a system composed of a pitot tube and a micromanometer. The wind pressures on the tower model are obtained using a pressure measurement system composed of a DSM3000 electronic pressure scanning valve, a PC machine and a self-programming signal acquisition system, whose sampling frequency is 312.5Hz. The data length at each pressure measurement point in each run is 6000. The 1:200 scaled pressure measurement model is made of synthetic glass, which ensures its strength and rigidity. Its prototype is the 167-meter high Peng-cheng cooling tower. 12×36 measurement points are arranged along the meridian and circumferential directions, respectively. The model in uniform flow field is shown in Fig. 6, and the distribution of the measurement points is presented in Fig. 7.
To simulate the high Reynolds number (Re) effects, 8 types of surface roughness are set up on the model. For each surface roughness condition, pressure measurement tests are conducted under 4 wind speeds (6m/s, 8m/s, 10m/s and 12m/s). Thus, the data for a total of 32 (8×4) cases are obtained. To avoid the end effects, the 8th circumferential section which is closest to the throat of the tower model is chosen as the characteristic section. By processing data obtained on the 8th section, it can be found that only 5 within the 32 cases can successfully re-simulate the actual static characteristics of the prototype cooling tower in the reduced-scale model with lower Re. This can be proved from a good fitting of the two mean wind pressure distributions based on the model test and the full-scale measurement (Niemann 1971), respectively (see Fig. 8 (a)). The five cases are regarded as valid simulation cases, and the dynamic wind effects for the valid simulation cases are presented in Fig. 8 (b).
3.2 Model test in traditional open terrain ABL turbulent flow field

Using triangular spires and roughness elements, the traditional ABL turbulent flow field for open terrain is simulated for the test. Fig. 9 suggests that all simulated flow field characteristics are close to the targets (Simiu and Scanlan 1996, Holmes 2001). In Fig. 9, the power spectral density is measured at 1 m height, and the simulated turbulence integral scale at that height is around 0.3 m.

The model in traditional ABL turbulent flow field is shown in Fig. 10, and the wind tunnel model test and the data processing are undertaken in the same way as those conducted in uniform flow field. The obtained results presented in Fig. 11 suggest that 5 valid simulation cases exist. The static wind effects for the 5 cases are all close to the full-scale measurement result (see Fig. 11 (a)), but the fluctuating wind pressure distributions are different (see Fig. 11 (b)).
4. FULL-SCALE MEASUREMENTS FOR WIND EFFECTS ON PENG-CHENG COOLING TOWER

After the model tests, the full-scale wind effects are further measured on Peng-cheng cooling tower, which are employed to see whether the underlying problem with the traditional wind tunnel model test is mitigated.

4.1 Setup for full-scale measurements

During Peng-cheng cooling tower’s construction in 2009, 36 transducers are evenly installed around the tower’s throat section at 130-meter high (see Figs. 12 and 13). Besides, another transducer is arranged inside a cabin, which provides static reference pressure for measurements presented in this paper.
The wind pressure transducers used are piezoresistive ones, whose dimensions are: 13cm in length, 5cm in width and 3cm in depth (see Fig. 14). The transducers’ maximum measured value is ±2.5kPa (corresponding to 63m/s wind speed). Their maximum sampling frequency and precision are 100Hz and 1/1000 maximum range, respectively.

Before installed on the prototype tower, the transducer is tested in TJ-2 wind tunnel of Tongji University for its performances. It is found that when oncoming flow speed is greater than 15m/s, the noise to signal ratio for the transducer is kept below 5% (see Fig. 15 (a)). Besides, it is shown that the signal produced by the transducer agrees with those obtained using high-precision electronic pressure scanivalve in 0-6Hz frequency domain (see Fig. 15 (b)). These prove that both static and dynamic performances of the transducer are agreeable.
The whole full-scale measurement campaign lasts from 2010 to 2015 on a 2-3 times of intensive test per year basis. In each time, we predict the occurrence of the strong wind scenario based on a local meteorological center’s weather-forecast. Equipments are set up before the arrival of the strong wind, and 24-hours simultaneous recordings for wind and wind-induced pressures are then conducted which usually continue for 1 to 2 weeks long. In the huge amount of data measured, those obtained from Nov. 28, 2011 to Dec. 12, 2011 are found to be most representative.

The daily predominate wind direction and the daily representative 10-min mean wind velocity obtained from Nov. 28 to Dec. 12 in 2011 are shown by Fig. 16 and Fig. 17, respectively (the mean wind velocities are obtained at 20-meter high and converted to the corresponding values at 130-meter high using the power law formula of mean wind profile). As can be seen from Fig. 17, only wind speeds for Nov. 29 and Dec. 8 exceed 12m/s, which represent valid strong wind scenarios. However, the wind directions on the two days are quite different. On Nov. 29, the oncoming flow is from due east, but it is from due north on Dec. 8 (see Fig. 16). Since some transducers installed on the tower’s north surface are found ineffective, complete fluctuating wind pressure distribution can only be obtained on Nov. 29. Besides, the upstream terrain is smooth, and there are no obvious interference effects caused by neighboring cooling towers or buildings with respect to the specific wind direction of Nov. 29. As a result, the wind-induced pressures recorded on Nov. 29 in 2011 should be used.
4.2 Validation of model test results using full-scale wind effects

On Nov. 29 in 2011, six groups of 10-min wind pressure samples with mean wind speed in between 11.3 and 16.4 m/s (at 130-meter high) are produced by transducers installed on Peng-cheng cooling tower. After data processing, the fluctuating wind pressure distributions obtained are compared with those of two early field measurement campaigns in history (Ruscheweyh 1976, Sageau 1979) and one model test study (Davenport and Isyumov 1996) in Fig. 18. It is obvious that the basic tendencies of those distributions are the same. All of the curves in Fig. 18 can be divided into three regions: windward region (0-40 degree), side region (40-120 degree) and wake region (120-180 degree). In windward region, the fluctuating wind pressure coefficients decrease with the increase of angle. In side region, the fluctuating wind pressure coefficients first increase and then decrease with the increase of angle, reaching the peaks at the angles between 80 and 100 degrees. In wake region, the fluctuating wind pressure coefficients decrease and then remain stable at a certain value. However, it is obvious that the results on Peng-cheng cooling tower are smaller than those on cooling towers of smaller sizes over the full half-circle. It is suspected that the differences have resulted from the discrepancy of the turbulence intensity of the oncoming flow.

In addition, Fig. 18 compares the fluctuating wind pressure distributions measured on Peng-cheng cooling tower with the results obtained by wind tunnel model tests under uniform flow. It can be found that the model test results are approximately the lower envelopes of the full-scale measurement results, which supports the practice of regarding wind effects obtained in uniform flow field as the lower limit value (see Sec. 3).
Fig. 18 Fluctuating wind pressure distributions obtained by full-scale measurements and wind tunnel model tests under uniform flow

Fig. 19 equally compares the fluctuating wind pressure distributions measured on Peng-cheng cooling tower with the results obtained by wind tunnel model tests under traditional ABL turbulent flow. It can be found that the model test results are approximately the upper envelopes of the full-scale measurement results, which also supports the practice of regarding wind effects obtained in ABL turbulent flow field as the upper limit value (also see Sec. 3).

Fig. 19 Fluctuating wind pressure distributions obtained by full-scale measurements and wind tunnel model tests under turbulent flow

By using a mathematical conversion method (Zhao, Cheng et al. 2012), the model test results obtained under uniform and turbulent flows are averaged. A comparison made in Fig. 20 indicates that the averaged model test result is very close to the full-scale measurement results. Due to discretization errors, the averaged model test result might vary in a range, which is shown in Fig. 20. Coincidentally, most realistic
fluctuating wind pressure coefficients fall into the variation range. These prove that the average value of the two wind tunnel model test results is the reasonable final result, and it can be applied to the full-scale condition.

Fig. 20 Fluctuating wind pressure distributions obtained by full-scale measurements and the average value of the two wind tunnel model test results

5. CONCLUSIONS

(1) Theoretical knowledge and field measurement results both indicate that the turbulence intensity profile cannot be definitively described for each terrain type. This is because the turbulence intensity depends on the roughness length and the mean wind speed, which both vary in intervals.

(2) The turbulence intensity measured at Peng-cheng power station varies in a wider range than the theoretical value, and the lower envelope for measured turbulence intensity profiles is extremely low compared with the theoretical one. These suggest that there exist possibilities that theoretical ABL flow characteristics presented in Codes of Practice and publications might not be applicable to a specific engineering case. A reasonable explanation is that theoretical results are obtained by generalizing large quantities of measured data, and simplifications and conservatism are usually included in generalization.

(3) With measured wind environment information at hand, wind tunnel model tests can be adaptively formulated considering the realistic ABL flow characteristics. By comparing wind effects obtained from model tests and full-scale measurements, this paper proves that the adaptive model tests lead to more reliable results. Thus, it is suggested that if possible, field measurements for wind environments at specific engineering sites should be undertaken before wind tunnel model tests.

(4) The fluctuating wind pressure distributions obtained by wind tunnel model tests under traditional open terrain ABL turbulent flow are approximately the upper envelopes of the full-scale measurement results. This suggests the conservativeness of the
traditional model tests.

(5) The fluctuating wind pressure coefficients on Peng-cheng cooling tower are found to be much smaller than those measured on other cooling towers over the full half-circle. It is assumed that the differences have resulted from the discrepancy of the turbulence intensity of the oncoming flow. So, occasionally, wind effects obtained from one engineering case cannot be simply generalized to another without knowing the oncoming flow information.

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