Wind characteristics near ground in south-eastern coast area of China based on field measurement

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\textbf{ABSTRACT}

From the point of view of wind engineering, this paper discusses the wind characteristics of China’s south-eastern coast area near the ground based on field measurements. Five three-dimensional (3D) ultrasonic anemometers were installed at different heights on a transmission tower in Xiupu, Fujian province, which is a typical coastal landform in South-east China. These anemometers synchronously collected wind records. The wind data were sorted according to the strong wind criterion. The exponent of the mean wind speed and the turbulence intensity profile are provided based on the power law, and suggestions for code are given. The aerodynamic parameters of turbulence in the atmospheric boundary layer are given and used to evaluate the existing empirical models of 3D fluctuating wind speed, such as turbulence intensity, gust factor, turbulence integral length scale and power spectral densities. The provided results can be used by designers to improve the wind resistance of civil engineering projects in South-east China.

\textbf{1. Introduction}

China experiences frequent strong winds. This often results in collapse accidents in civil engineering projects, such as low-rise houses, transmission towers and long-span roofs (figure 1), especially in south-east coastal areas (Huang et al. 2010; Jin et al. 2010). To improve the wind resistance of civil engineering in these areas, it is urgent to reveal the characteristics of strong winds in the region and provide a model for wind flow.

Field measurement, including measurements of mean wind speed and fluctuating wind speed, is the most common method for study on wind characteristic. Li et al. (2009, 2010) and Tian et al. (2011) provided wind speed parameters according to wind data from ultrasonic anemometers on the 325 m meteorological tower in the downtown of Beijing. Gu et al. (2011) and Huang et al. (2014) have given landing typhoons parameters in the eastern coastal region of China. Shi et al. (2010) acquired the characteristics of strong wind in the eastern coast area of China, which is another district with serious wind disasters.

In the paper, wind parameters of the south-eastern coastal area of China, including the mean wind speed and fluctuating wind speed, are provided based on site-measurement data from 3D ultrasonic anemometers set on an 85 m high transmission tower.
2. Observation site and data sampling method

The chosen location for the observation was XiaPu, Fujian province, which is the region with the most serious wind disasters in China. The site, which is surrounded by small hills, is a typical southeastern coastal landform in China, as shown in figure 2.

Five 3D ultrasonic anemometers were mounted on a transmission tower at the 15, 27, 53, 67 and 82 m height levels in order to record wind speed data. The ultrasonic anemometers were set at the ends of steel cantilever beams on the tower facing the northeast direction in order to avoid the interference effect of the transmission tower according to the prevailing wind direction at the observation site. Five ultrasonic anemometers collected the wind speed data synchronously. The sampling frequency was 10 Hz.
The sampling data were carefully corrected before analysis in order to minimize the error of the ultrasonic anemometers. The following criteria were employed (Dai et al. 2008; Song et al. 2012):

1. remove any data that were kept invariable due to the failure of signal transmission or breaking down of instruments (stiff values),
2. remove any data that are not in conformity with the common statistical characters of the climate and lack of physical interpretation (wild points),
3. control data continuity of time and
4. control data continuity of space.

The ultrasonic anemometers recorded wind data in the north (from south to north), west (from east to west) and vertical (from bottom to up) directions synchronously, i.e. $u_x(t)$, $u_y(t)$ and $u_z(t)$. The averages are expressed as $U_x$, $U_y$ and $U_z$ (average time is 10 minutes, as specified in Chinese code (GB50009-2012)).

The wind attack angle in the vertical direction was very small in general. Therefore, the wind flow direction was considered to be equivalent to the horizontal direction (Xiang et al. 1996). The mean speed of the inflow wind $U$ can be calculated by the following equation:

$$U = \sqrt{U_x^2 + U_y^2}$$  \hspace{1cm} (1)

The horizontal wind angle $\varphi$ of the inflow wind can be calculated by the following equation:

$$\varphi = - \arccos\left(\frac{U_x}{U}\right) \cdot \text{sgn}(U_y) + 180^\circ$$  \hspace{1cm} (2)

where the unit is the degree and 0 degrees is defined as pointing directly south (figure 3), clockwise.

The angle of the mean wind speed at the X-coordinate $\theta$ and the Y-coordinate $\eta$ (figure 4) can be calculated by the following equations:

$$\cos \theta = \frac{U_x}{U}$$  \hspace{1cm} (3)

$$\cos \eta = \frac{U_y}{U}$$  \hspace{1cm} (4)

Figure 3. Azimuth angle.
Thus, the fluctuating wind speed in the longitudinal, lateral and vertical directions can be calculated by the following equations, and the coordinate vectors are shown in figure 4.

\[
\begin{align*}
    u(t) &= u_x(t)\cos \theta + u_y(t)\cos \eta - U \\
    v(t) &= u_x(t)\cos \eta - u_y(t)\cos \theta \\
    w(t) &= u_z(t) - U_z
\end{align*}
\]

Then, the fluctuating wind parameters can be deduced by the time-history records of \( u(t) \), \( v(t) \) and \( w(t) \) based on random vibration theory.

### 3. Mean wind speed

Based on atmospheric turbulent theory, the atmospheric stability at any given moment can be classed as stable, unstable or neutral based on the air movement. Atmospheric stability is an important aspect of wind characteristics (Deaves & Harris 1982; Solari & Piccardo 2001). In wind engineering, the performance of structures in strong winds is a major problem, and the wind parameters should be deduced according to the strong wind record in which the atmospheric stability is neutral.

In this study, only 10% of the data were selected for analysis according to their wind speed \( U \), and the direction distribution of these samples is listed in table 1 (data with less than 1% probability of occurrence directions are listed in Others). Thus, wind records in ESE and SE were studied to obtain the wind characteristics of this area.

There have been several theoretical and empirical models, such as log law and power law, available for describing vertical distributions of mean wind speed (mean wind profile). The log law was originally derived for the turbulent boundary layer on a flat plate by Prandtl, and can be written as

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

![Figure 4. Coordinate vectors.](image)

| E   | ESE | SE | W   | WSW | NW | Others |
|-----|-----|----|-----|-----|----|--------|
| 13.3% | 32.7% | 33.7% | 14.6% | 3.2% | 2.2% | 0.3% |
where $U(z)$ is the mean wind speed at height $z$, $\kappa$ is Karman’s constant, $u_*$ is shear velocity and $z_0$ is roughness length.

Although the log law has a sound theoretical basis, some of its mathematical characteristics are problematic. To avoid some of these problems, wind engineers have often preferred to use the power law (Davenport 1965). The power law has no theoretical basis, but it is easily integrated over height. The power law has also been adopted by the Chinese code. It is written as follows:

$$U(z) = U(z_b) \left( \frac{z}{z_b} \right)^{\alpha}$$

(9)

where $z_b$ is the reference height, $U(z_b)$ is the mean wind speed and $\alpha$ is the exponent of the mean wind speed profile.

The fitting exponents according to the power law of all selected records are shown in figure 5. These results indicate that the power law can be used to describe the mean wind speed profile, which means that the air is neutral and there is classical turbulence in the atmosphere. Furthermore, the mean value of the fitting exponents in two directions is almost the same, indicating that the exponent $\alpha$ of the wind speed profile in this region is equal to 0.08. However, in Chinese code (GB50009-2012), the observation site is terrain A and the exponent $\alpha$ is 0.12. Therefore, in order to

Figure 5. Exponent of mean wind speed profile: (a) ESE direction (b) SE direction.
reinforce the wind-resistant properties of civil engineering in a region that frequently experiences strong winds, more accurate wind parameters are needed and wind observations should be enhanced.

4. Fluctuating wind speed

Fluctuating wind is induced by the wind irregularity and its intensity is variable at random over time. In this section, the fluctuating wind characteristics of the south-east coastal area, including turbulence intensity, gust factor, turbulence integral length scale and power spectral density, are investigated.

4.1. Turbulence intensity

Turbulence intensity $I_i(z)$ is the ratio of the standard deviation of the fluctuating wind velocity to the mean wind velocity in form. It represents the intensity of the fluctuating wind speed, and can be calculated by the following equation (Huang & Wang 2008):

$$I_i(z) = \frac{\sigma_i(z)}{U(z)} \cdot (i = u, v, w)$$

where $\sigma_i(z)$ is the standard deviation of the fluctuating wind speed at height $z$.

Table 2 presents the turbulence intensities at different heights. The values shown are the average values of the samples. These data show that as the height increases, the turbulent intensity in the longitudinal and lateral direction decreases, but the vertical value remains almost constant. In addition, the ratio of the longitudinal turbulence intensity and the lateral turbulence intensity is about 1.31 based on the measured data, which agrees with the result of 1.35 provided by other researchers (Pang et al. 2002).

The turbulence intensity profile reveals variation of the fluctuating wind turbulence intensity as the height increases. Similarly, to the mean wind speed, the fitting results of the longitudinal intensity profile are given in figure 6.

These results show that the minus power law can be used to describe the turbulence intensity profile. Because the mean wind speed in the denominator of equation (10) satisfies the power law, the standard deviation of the longitudinal fluctuating wind velocity in the member stays the same. The fitting exponents of the two directions are concentrated on $-0.13$, which means that the exponent $\alpha$ of the turbulent intensity profile in this region is equal to $-0.13$.

| Height | $I_u$ | $I_v$ | $I_w$ |
|--------|-------|-------|-------|
| ESE    |       |       |       |
| 15 m   | 0.17  | 0.14  | 0.08  |
| 27 m   | 0.15  | 0.13  | 0.08  |
| 53 m   | 0.14  | 0.11  | 0.09  |
| 67 m   | 0.14  | 0.11  | 0.09  |
| 82 m   | 0.14  | 0.11  | 0.09  |
| SE     |       |       |       |
| 15 m   | 0.17  | 0.11  | 0.08  |
| 27 m   | 0.15  | 0.12  | 0.09  |
| 53 m   | 0.13  | 0.09  | 0.08  |
| 67 m   | 0.12  | 0.08  | 0.07  |
| 82 m   | 0.11  | 0.08  | 0.08  |
The profile of the turbulence intensity in Chinese code (GB50009-2012) and Japanese code (AIJ-RLB-2004) is defined as follows:

\[ I_u(z) = I_{u,10} \left( \frac{z}{10} \right)^{-\alpha} \]  

\[ I_u(z) = I_{u,10} \left( \frac{z}{10} \right)^{-\alpha - 0.05} \]

where \( I_{u,10} \) is the longitudinal turbulent intensity at the height of 10 m.

This shows that the relationship between the mean wind speed profile exponent and the turbulence intensity coincides with Japanese code. These results can provide future reference for code modification.

4.2. Gust factor

In many international design codes on wind load, the peak gust wind speed is used for cladding design purposes. The gust factor, \( G_t(z) \), is the ratio of the maximum gust speed to the mean wind speed.
speed within a specified period. In this study, each period was three seconds, which is common

\[
G_u(z) = 1 + \frac{\max(u_{tg} = 3.0(z))}{U(z)} 
\]

(13a)

\[
G_v(z) = \frac{\max(v_{tg} = 3.0(z))}{U(z)} 
\]

(13b)

\[
G_w(z) = \frac{\max(w_{tg} = 3.0(z))}{U(z)} 
\]

(13c)

where \(\max(u_{tg} = 3.0(z))\), \(\max(v_{tg} = 3.0(z))\) and \(\max(w_{tg} = 3.0(z))\) are the largest wind speeds over duration of \(t_g\) (3.0 s in this paper) in the longitudinal, lateral and vertical directions at height \(z\), respectively.

Table 3 displays the gust factor at different heights. The data displayed are the average values of the samples. It can be observed that the variation with height of the gust factor is almost the same as that of turbulence intensity. Ishizaki and Choi found the relationship between the three parameters based on the actual measured data. Cao et al. (2009) further summarized the findings into the following expression, which provides estimates of gust factors:

\[
G_i(z) = 1 + aI_i^b(z)\ln(T/t_g) \quad (i = u, v, w) 
\]

(14)

where \(T\) is the averaging period for the mean wind speed and \(t\) is the gust duration (in this paper, \(T\) is 600 s (Holmes 2007) and \(t_g\) is 3 s); \(a\) and \(b\) are the parameters based on field measurement. \(a = 0.62\) and \(b = 1.27\) were suggested by Choi, but \(a = 0.50\) and \(b = 1.00\) were suggested by Ishizaki (Cao et al. 2009).

Based on equation (14), figure 7 provides the relationship between gust factor and turbulence intensity in three directions at the height of 53 m. According to this figure, \(a\) is 0.39, 0.41 and 0.45 in the longitudinal, lateral and vertical directions, respectively, and \(b\) is 1.0 in all three directions, which agrees with Ishizaki’s suggestion.

### 4.3. Turbulence integral length scale

The turbulence integral length scale is a critical measurement of the eddy average size that reflects the spatial correlation of the fluctuating flow speed. The larger the turbulence integral length scale is, the stronger the spatial correlation is.

The turbulent vortex can be assumed to move at the mean speed. Thus, the fluctuating wind speed \(u_1(x_1, t + \tau)\) can be defined as \(u(x_1 - x, t)\), where \(x = U \cdot \tau\). This assumption is known as
Taylor’s hypothesis, and can be expressed as the following formulation (Simiu & Scanlan 1992):

\[
L_i(z) = \frac{U(z)}{\sigma_i^2(z)} \int R_i(z, \tau) d\tau. \quad (i = u, v, w)
\]  

(15)

where \(R_i(z, \tau)\) is the correlation function (Lutes & Sarkani 2004) of the fluctuating wind speed at height \(z\).
Table 4 lists the average values of the turbulence integral length scales. As Table 4 demonstrates, it is difficult to provide an empirical model of the turbulence integral length due to its discrete. Figure 8 also indicates that the integral length of the turbulence does not have an obvious relationship with the turbulence intensity.

4.4. Power spectra

The energy distribution of the fluctuating wind speed in the frequency domain can be clearly expressed in the form of a power spectra $S_i(n)$, which is an important indicator to describe the wind field characteristics. Power spectra provide the distribution of the turbulence with frequency, and the standard deviation $\sigma_i$ can be determined by the integration of $S_i(n)$ over all the frequencies (Ou & Wang 1996) as follows:

$$\sigma_i^2(z) = \int S_i(z, n)dn \ (i = u, v, w)$$

where $n$ is frequency and $S_i(z, n)$ is the power spectra of the fluctuating wind speed at the height $z$.

Many different mathematical forms have been used to express $S_{i,z}(n)$ in meteorology and wind engineering. The most common of these is the von Karman form. This may be written in several ways, and equations (17) and (18) are a commonly used non-dimensional form (Lawson 2001)

$$\frac{nS_{u,z}(n)}{\sigma_u^2(z)} = \left[ 1 + 70.8 \left( \frac{nL_u(z)}{U(z)} \right)^2 \right]^{5/6}$$

$$\frac{nS_{i,z}(n)}{\sigma_i^2(z)} = \frac{4 nL_{i}(z) \left[ 1 + 755.2 \left( \frac{nL_{i}(z)}{U(z)} \right)^2 \right]^{11/6}}{\left[ 1 + 283.2 \left( \frac{nL_{i}(z)}{U(z)} \right)^2 \right]} \ (i = v, w)$$

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**Table 4. Turbulence integral length scale at different heights.**

| Height | $L_u$  | $L_v$  | $L_w$  |
|--------|--------|--------|--------|
| ESE    | 115 m  | 99.3 m | 22.5 m |
| 27 m   | 124 m  | 97.9 m | 35.1 m |
| 53 m   | 150 m  | 101 m  | 42.2 m |
| 67 m   | 143 m  | 97.6 m | 46.2 m |
| 82 m   | 134 m  | 93.8 m | 50.9 m |
| SE     | 104 m  | 76 m   | 21.4 m |
| 27 m   | 114 m  | 80.2 m | 37 m   |
| 53 m   | 112 m  | 67 m   | 44.5 m |
| 67 m   | 123 m  | 62.5 m | 46.1 m |
| 82 m   | 123 m  | 65.2 m | 51.2 m |

**Figure 8.** Relationship between integral length and turbulence intensity.
Figure 9 shows that the fluctuating wind speed spectra measured at the height of 53 m generally agree with the Karman spectra, and the results for each other height were identical. Though there is some discrepancy at high frequencies \( \frac{nL_e}{U(z)} > 0.5 \) due to background noise, the measured spectra can be used to describe the fluctuating wind speed spectra characteristics.

Figure 9. Power spectra at 57 m height level.
5. Conclusions

This paper presents the wind parameters of the south-east coastal region of China drawn from five ultrasonic anemometers installed at five height levels on a transmission tower. The conclusions that can be drawn from this study are summarized as follows.

1. The exponent $\alpha$ of the wind speed profile is equal to 0.08, and the exponent of the turbulence intensity profile is equal to $-0.13$ based on wind records, which differs from Chinese Code. The relationship between the two exponents is in conformity with that provided by Japanese Code.

2. The relationship between the gust factor and the turbulence intensity agrees with Ishizaki’s suggestion.

3. It is difficult to provide an empirical model of the turbulence integral length due to its discrete in full scale.

4. The measured power spectra coincide with the experimental model provided by Von Karman.

These conclusions can be used by future designers to improve the wind resistance of civil engineering projects in the coastal region of South-east China. They can also provide a basic reference for modification of codes.

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