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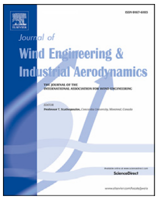

Field measurement and investigation of spatial coherence for near-surface strong winds in Southeast China

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ABSTRACT

With aid of structural health monitoring systems, the field measurements have been proceeded in a ready manner in recent years. This treatment, however, raises a question on the influence of complex terrain associated with engineering structures upon coherence analysis. An independent field measurement is thus still necessary for the analysis of spatial coherence. In the present paper, the field measurement of near-surface strong winds in Southeast China is carried out. For implementing the purpose, an observation array was built up in a typhoon-prone area. The wind characteristics of local site, the spatial coherence of wind field and statistics of decay parameters in exponential formats are investigated. It is revealed that decay parameters of the Davenport and Krenk models have a different relationship to vertical and lateral separations, which are positively and weakly correlated to vertical separation, respectively; while both negatively correlated to lateral separation. The statistics of decay parameters relies significantly upon the time period of velocity readings. Besides, there is a logical relationship between decay parameters and wind velocity, maintaining a consistency with the pioneering measured data in 1960s–1970s.

1. Introduction

With the increase of elevation and span of structures nowadays, higher safety standards, serviceability levels and economic demands are faced with challenges in the wind-resistant design of engineering structures. Investigation of spatial coherence of the wind field plays a critical step in the definition of wind loads (Zeng et al., 2017). Being a characteristic of wind field, spatial coherence describes the statistical dependence between components of turbulence in points separated in space. It affects the gust responses of slender structures sensitive to wind loads such as tall buildings, long-span bridges and power transmission towers.

As a modeling argument of spatial coherence of wind field, the coherence function was firstly defined to be the ratio of cross-spectral density and auto-spectral density of time series of wind velocity at two separated spatial points (Panofsky and McCormick, 1954). Davenport proposed the most widely-used coherence function in the exponential format, which is a function of elementary factors involving mean wind speed, separation distance between two spatial points, wave number and non-dimensional decay parameter (Davenport, 1961, 1967). Since then a variety of models in modified exponential formats have been proposed. Most of them are derived from Taylor's frozen turbulence hypothesis as to temporal homogeneity and spatial isotropy or anisotropy (Harris, 1970; Mann, 1994). Taking turbulence integral length scale into consideration, for instance, Krenk proposed a new model of spatial coherence (Krenk, 1996) and validated it together with Hansen (Hansen and Krenk, 1999). An isotropic turbulence theory based coherence formula was developed and validated through comparative studies against the classical exponential format in a design manual (Miyata et al., 2002). Using the theoretical formula, numerical simulations of spatial coherence of wind field was then proceeded in conjunction with the power spectral density of wind field (Zhu, 2015). Due to the intricate mechanism of spatial coherence of wind field, numerical simulations might miss some essential factors inherent in wind processes. Wind tunnel tests provide a more logical manner for the analysis of spatial coherence of wind field (Yasuaki et al., 2014; Yan and Flay, 2016). The argument of similarity ratio, however, is still a challenging issue correlated to wind tunnel tests. Bypassing this dilemma, field measurements are paid sufficient attention and underlie the validation of model parameters corresponding to local wind environments (Shiotani, 1975; Panofsky and Mizuno, 1975; Kristensen and Jensen, 1979; Chen and Letchford, 2006; Lothon et al., 2006;

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Li et al., 2013). A systematical summary focusing on the identification of decay parameters in the earlier period was drawn through reviewing a collection of experimental evaluations derived from the literature from 1961 to 1983 (Simiu and Scanlan, 1986; Solari, 1987).

In the last 30 years, the investigation of spatial coherence has become more targeted, which coincided with the application requirements. In the community of civil engineering, the build-up of health monitoring systems upon engineering structures such as tall buildings and long-span bridges provides platforms for the wind field measurements (Li et al., 2010). Toriumi et al. collected both typhoon and seasonal wind data from Ohnaruto Bridge and Akashi-Kaikyo Bridge in Japan, and investigated the effects of spatial correlation on gust responses (Toriumi et al., 2000). Miyata et al. investigated full-scale spatial correlation of the fluctuating wind field along the Akashi-Kaikyo Bridge during strong typhoons. Their findings indicated that the decay parameters show a weakly increasing trend with increase in horizontal separation and mean wind speed; while the mean value of the decay parameters slightly increases with separation when the separation of the two spatial points reaches a threshold (Miyata et al., 2002). Song et al. investigated the Macao Friendship Bridge during typhoon Nari, and found that both coherence function curves and decay parameters have significant differences from times during typhoon processes (Song et al., 2010). In the eye-wall of the typhoon, the horizontal spatial correlation is relatively stronger, and the correlation spectrum decays more slowly with frequency increase. Meanwhile, the minimum and maximum decay parameters in the coherence function model are 4.7 and 27.8, respectively (Song et al., 2010). Vigueras-Rodriguez et al. collected data from 72 turbines in an offshore wind farm and made a remark that the turbulence intensity should be considered in the analysis of longitudinal decay parameters; while the standard deviation of the fluctuating wind processes should be considered in the analysis of lateral decay parameters (Vigueras-Rodríguez et al., 2012). Fenerci et al. monitored the Hardanger Bridge in Norway and investigated the spatial coherence in several separation cases (Fenerci and Øiseth, 2016).

Although a body of research has been carried out for revealing the essence associated with decay parameters of coherence models, the challenging issue still remains open due to the intricate mechanism behind decay parameters. It is recognized in previous studies that the decay parameter of exponential format representing spatial coherence models hinges upon a series of ingredients (Yan et al., 2013), such as mean wind speed, turbulence intensity, roughness length, separation distance, wind angle and even temperature. With aid of structural health monitoring systems, field measurements for investigation of decay parameters have proceeded in a ready manner in recent years. This treatment, however, poses a question on the coherence analysis, in that the logical quantification of roughness length is extremely difficult due to the complex terrain associated with most engineering structures. The early observations at towers were mostly implemented in areas of open plains; although the integrity and accuracy of such measured data may be in doubt due to lack of instrumental sensitivity. Independent field measurements are thus still necessary for the analysis of spatial coherence.

In the present paper, field measurements of near-surface strong winds in Southeast China were carried out, where an observation array consisting of four towers and twelve ultrasonic anemometers were employed. The wind characteristics of local site and the spatial coherence in function of decay parameters are investigated. The remaining sections are arranged in this paper as follows. Section 2 discusses the details of field measurement based wind characteristics of the local site, including atmospheric thermal stability, turbulence intensity, turbulence integral length scale and turbulent spectrum. The classical spatial coherence models and the identification of decay parameters of vertical and lateral coherence are detailed in Section 3. In Section 4 the statistical analysis of decay parameters for vertical and lateral coherence is discussed. The relevance of the decay parameters to velocity readings and mean wind speed is investigated as well. Concluding remarks are included in Section 5.

2. Field measurement based wind characteristics of local site

2.1. Observation array

For the purpose of investigation of near-surface strong natural winds, a wind observation array was built up in Dadeng Island in Southeast China in January 2015, a typical typhoon-prone area. Dadeng Island covers an area of 13.2 square kilometers and features a countryside landscape characterized by farmland, scrub, trees and low-rise buildings, in the center of which the observation array is located, as shown in Fig. 1. The observation array is adjacent to lots of trees with heights of around 10 m, and these trees may cause large turbulence when the air flow comes from certain directions.

Fig. 2 shows the layout of the observation array and the ultrasonic anemometers used for the field measurements. It is seen that the observation array consists of twelve ultrasonic anemometers (Gill WindMaster and WindMaster Pro) deployed on four towers, which are labelled P1, P2, P3 and P4, respectively, from the North to the South. The towers P1 and P4 are 20-m high; the towers P2 and P3 are 40-m high. The four towers are separated by distances of 30 m, 90 m and 60 m, respectively, in a horizontal line. With these separations, the horizontal separations between spatial points of the wind field can be defined to be 30 m (towers P1 and P2), 60 m (towers P3 and P4), 90 m (towers P2 and P3), 120 m (towers P1 and P3), 150 m (towers P2 and P4) and 180 m (towers P1 and P4).

Four Gill WindMaster Pro ultrasonic anemometers were installed at 30 m and 40 m heights on towers P2 and P3. Eight Gill WindMaster ultrasonic anemometers were installed at 10 m and 20 m heights on towers P1, P2, P3 and P4. The sampling frequency of the ultrasonic anemometers was set to 10 Hz. Besides, twelve type 109 temperature probes were deployed on the towers, which were located at the same elevations on the ultrasonic anemometers. Six sets of data acquisition units and power supplies were placed on platforms on the towers 8-m from the ground. The sampling frequency of temperature probes was set to 1 Hz. All these instruments were calibrated before they were shipped from abroad. There are two manners for data storage and data acquisition. One is the manual collection on-site bimonthly from the platforms of towers; the other is the remote access of data server in local office room with wire transmission from the data acquisition units on the towers. The measurement data were monitored and checked for one week after the observation system was troubleshot.

2.2. Recorded wind data

The ultrasonic anemometers output the measured wind speeds as horizontal components in the N-S, and E-W directions, labelled as U_{NS}, U_{EW}, respectively, and as a vertical component, labelled as U_V. The relationship between the coordinate system of the anemometer and the geographic coordinate system is shown in Fig. 3(a). $U_{NS}{}^{+}$ denotes horizontal wind component blowing from South to North, and $U_{EW}{}^{+}$ denotes horizontal wind component blowing from East to West. The horizontal mean wind speed $\overline{U}_H$ and mean wind angle θ in a time period can be derived from the following equations:

$$\overline{U}_H = \sqrt{\overline{U}_{NS}^2 + \overline{U}_{EW}^2} \tag{1}$$

$$\theta = \begin{cases} 360 - \arccos\dfrac{\overline{U}_{NS}}{\overline{U}_H}, & \text{if } \overline{U}_{EW} > 0 \\ \arccos\dfrac{\overline{U}_{NS}}{\overline{U}_H}, & \text{if } \overline{U}_{EW} < 0 \end{cases} \tag{2}$$

where $\overline{U}_{NS}$, $\overline{U}_{EW}$ denote the mean values of recorded wind speeds U_{NS}, U_{EW} in a time period, respectively; the horizontal mean wind angle θ is defined as the angle from North clockwise to the direction that the air