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A comparative study of field measurements of the turbulence characteristics of typhoon and hurricane winds

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ABSTRACT

Tropical cyclones are referred to as typhoons and hurricanes in the South China Sea/North Pacific and the Atlantic Ocean, respectively. As the genesis of these storms results from different basins and latitudes, the wind field characteristics may differ in these storms and differ with the recommendations in current wind codes, which are mainly based on extratropical winds. In order to delineate any differences, based on wind data measured at fixed/deployable towers in four typhoons and three hurricanes, turbulent wind characteristics, e.g., turbulence ratio and intensity, integral scale, gust factor, peak factor, skewness and kurtosis, were comparatively investigated and compared with the recommendations in ASCE7-10. In this comparison, the influences of roughness length and mean wind speed on the turbulent wind characteristics were also examined.

1. Introduction

Each year, tropical cyclones (typhoons and hurricanes) impart major structural damage to property with attendant regional economic impact and loss of lives around the world (Kareem, 1985; Emanuel, 2003; McCullough et al., 2013; Munich, 2014). Strong winds and associated turbulent fluctuations in tropical cyclones are a major source of such damage. The salient features associated with these wind characteristics may depart from conventional boundary layer type winds in extratropical storms (Holmes, 2001; Tamura, 2009). Tropical cyclones are characterized by asymmetrical helical dominant flow structure and with associated convective mixing which may render their wind characteristics different from extratropical winds (Sharma and Richards, 1999). As upper level disturbances descend downwards, sudden changes in the wind speed and direction along the radial axis of the storm are experienced at the ground level. The downward transport of convective elements and horizontal momentum in higher level by downdraughts and boundary layer rolls also magnifies the wind speed and the variance of fluctuations in the surface (Powell et al., 1991, 1996; Bradbury et al., 1994; Wurman and Winslow, 1998; Sparks and Huang, 2001; Vickery and Skerlj, 2005; Li et al., 2012a, 2014). In light of the dominant features that are different from the extratropical storms, there is a need for better understanding of the turbulent wind characteristics and the flow structure in tropical cyclones.

Field measurements are the most direct and reliable approach to study turbulent features in tropical cyclones (Wilson, 1979; Amano et al., 1999; Xu and Zhan, 2001; Cao et al., 2009). To better understand turbulence mechanisms and flow structure characteristics in tropical cyclones, a number of field monitoring programs have been initiated in hurricane-prone areas, e.g., FCMP (Balderrama et al., 2011), WEMITE (Schroeder and Smith, 2003) and Stick-Net (Weiss and Schroeder, 2008). In China, a large number of wind observation towers and stations have been recently installed along the coastline of South China, where typhoons hit frequently each year, to quantify near-surface typhoon wind characteristics and the mechanism of typhoon wind induced loads on civil structures (Li et al., 2011a, 2011b; Song et al., 2012). In addition to these near surface observations, a large number of observations have also been made on structures to monitor wind field characteristics and structural response in tropical cyclones (Tamura et al., 1993; Xu and Zhan, 2001; Li et al., 2004, 2008).

Based on previous measurements, wind characteristics in tropical cyclones can be roughly summarized as (1) wind profile in tropical cyclones contains a jet-like structure with an logarithmic increase in wind speed to a maximum near 500 m, then followed by a gradual decrease with height (Franklin et al., 2003; Powell et al., 2003; Vickery et al., 2009; Giammanco et al., 2013); (2) turbulence intensities and integral length scales in tropical cyclone were found to be roughly greater than in extratropical storms (Choi, 1978; Sharma and Richards, 1999; Masters et al., 2010); however, some measurements suggested these two to be

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similar (Cao et al., 2009); (3) some observations suggested that gust factors in tropical cyclones were greater than in extratropical winds, and the difference was mainly attributed to the effects of the convective scale motions which occur infrequently and are more dominant in low wind speeds (Krayer and Marshall, 1992; Sparks and Huang, 2001; Vickery and Skerlj, 2005); (4) longitudinal wind velocity spectrum was noted in some studies to contain added energy at low frequencies as compared to extratropical winds (Powell and Houston, 1996; Schroeder and Smith, 2003; Yu et al., 2008), while most of the observations reported that the wind velocity spectrum in tropical cyclone winds was consistent with the von Karman spectrum (Xu and Zhan, 2001; Li et al., 2008), with the exception noted that spectrum in tropical cyclone contained additional energy in the high frequency range (Zhang, 2010; Li et al., 2012b, 2014). The potential reason for these inconsistent observations may in part be the complexity and transient nature of turbulent flow structure in tropical cyclone.

In addition to the differences of the configurations of the preceding observations, the basins and latitudes of the genesis of hurricanes and typhoons may also be a potential source of the variations in the turbulent wind characteristics in typhoons and hurricanes (Kareem, 1987). Through comparative studies of wind characteristics in typhoons, hurricanes, and the corresponding recommendations in ASCE7-10 (2010), it would be possible to better quantify the respective flow structures and address the need to better define the turbulent wind characteristics in typhoons and hurricanes for engineering applications.

In light of this background, this study undertakes delineation of the turbulent wind characteristics in typhoon/hurricane wind fields with potential implications on the performance of structures in typhoons and hurricanes. A comparative study of the turbulent wind characteristics using field measurements in four typhoons (Chanchu and Prapiroon in 2006, Nuri and Hagupit in 2008) and three hurricanes (Katrina, Rita and Wilma in 2005) were conducted. Turbulent wind characteristics, including turbulence ratio, aerodynamic roughness length, turbulence intensity, integral scale, gust factor, peak factor, skewness and kurtosis were investigated in detail and compared with the recommendations in ASCE7-10. Concluding remarks are offered in the end.

2. Measurements and data

2.1. Field measurements sites and instruments

A number of wind observation towers have been built along the coastline of southern China where typhoons hit frequently each year after year. Data obtained during the passage of four typhoons and three hurricanes are examined in this paper.

Typhoon Chanchu (0601) was simultaneously recorded at the Red Bay Tower (RBT) and the Oubian Tower (OT) in South China. RBT is a 60 m high tower located in the Red Bay peninsula connected to the mainland on the SSW side. The RBT is deployed in open flat terrain with uniform roughness within a radius of around 500 m from the tower location, farther away it is exposed to sea surface in the N and S direction. In the NE-E directions, the distance from the RBT to the coastline is greater than 1 km, and in the range from 500 m to the coastline, there are some trees, one-story houses and small mountain lower than 30 m high. In the directions from 270 degree to 315 degree, the distance from the RBT to the coastline is greater than 1.5 km, and there are some trees and small mountains in this direction. The detailed expose of the RBT is shown in Fig. 1a. The RBT is a triangular lattice tower with width of each side of 0.6 m. Two 3-D ultrasonic anemometers (WindMaster™ Pro, Gill Instruments Limited) were installed on two 1.5 m long cantilevers in the east side of the tower to collect data with the sampling frequency of 4 Hz at 10 m and 60 m height, respectively. In this study, all towers used to measure the typhoon wind data in South China have the same structure system; and anemometers on the towers were installed on a 1.5 m long cantilever but at different heights and directions for different towers, as shown in Fig. 2. For brevity, the structure system and the setups of towers will not specify for other towers in the following parts. The effects of flow distorted by the mast is insignificant (Britter et al., 1979; Wieringa, 1989; Kaimal and Finnigan, 1994). The wind speed range of the WindMaster™ Pro anemometer is between 0 and 65 m/s with the resolution of 0.01 m/s and the accuracy of smaller than 1.5% of RMS at 12 m/s. The wind direction range is between 0° and 359° with the resolution of 0.1° and the accuracy of 2° at 12 m/s. Two propeller anemometers (Model 05103L, R.M. Young Company, USA) were installed on two cantilevers in the west side of the tower at 10 m and 60 m height to collect wind data at 1 Hz. The output wind speed range of the propeller anemometer is 0–100 m/s, and its distance constant is 2.7 m 63% recovery for wind speed and 1.3 m 50% recovery for wind direction, respectively. At 30 m height, a 2-D ultrasonic (WindSonic, Gill Instrument Limited) was installed on a cantilever to collect data at 4 Hz. The wind speed range of the WindSonic anemometer is 0–60 m/s with the resolution of 0.01 m/s and the accuracy of ±2% at 12 m/s. The wind direction range is 0–359 degree with resolution of 1° and accuracy of ±3° at 12 m/s.

OT is a 70 m high tower located on Haishan Island. In the E-S-SW directions, it is exposed to open water; in other directions, it is exposed to relatively flat land terrain covered by grasses and sparse small trees within 2-km distance, as shown in Fig. 1b. One 3-D ultrasonic anemometer (HD2003, Delta Ohm Srl, Italy) was installed at 10 m height in the east side of the tower with data acquired at 1 Hz. The wind speed range of the HD2003 sonic anemometer is between 0 and 60 m/s with the resolution of 0.01 m/s and the accuracy of ±1% of reading. The wind direction range is between 0° and 360° with the resolution of 0.1° and the accuracy of ±2°. At 5 m height, one 3-D ultrasonic anemometer (CSAT3, Campbell Science, Inc., USA) was installed in the east side of the tower to collect data at 10 Hz. The wind speed range of the CSAT3 sonic anemometer is between 0 and 65.535 m/s with the resolution of 0.001 m/s of RMS. The wind direction range is between 0° and 360° and the accuracy of ±0.7° at 1 m/s for horizontal wind. One RM Young 52203 rain gauge was installed at 0.5 m height on the east side of the tower. A 1-WIRE thermometer (Dallas Semiconductor Corp, USA) was buried at 0.1 m under the ground about 3 m away at the east side of the tower.

Typhoon Prapiroon (0606) was recorded on the Bohe Tower (BT), a 10 m high tower located on a bulge on the seacoast of Diancheng, Maoming, Guangdong province, as shown in Fig. 1c. The observation station is exposed to the sea surface in directions between 45° and 225° (clockwise). In NW-N directions, it is exposed to open flat terrain with uniform roughness within a radius of about 500 m from the tower location. In the W direction, it is sea surface in a distance of 3 km from the OT station. In the direction between 225° and 270°, there is a small island at a distance of around 4 km from the OT station; and within 0.5-km distance, it is open flat terrain. A 3-D sonic anemometer (HD2003, Delta Ohm Srl., Italy) was installed in the east side of the tower at 10 m height and data was collected at 1 Hz, and one 3-D ultrasonic anemometer (CSAT3, Campbell Science, Inc., USA) was installed on a cantilever at 5 m height in the east side with the data collected at 10 Hz. Two RM Young 05106 propeller anemometers were installed on another two cantilevers in the west side of the tower at 5 m and 10 m. The dynamic response characteristics of the RM Young 05106 propeller anemometers are the same as RM Young 05103L anemometer. A RM Young 52203 rain gauge was installed at 0.7 m height around 3 m away at the west side of the tower. A 1-WIRE thermometer (Dallas Semiconductor Corp, USA) was buried at 0.1 m under the ground about the 3 m away at the SW side of the tower.