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CHARACTERISTICS OF THE OFFSHORE EXTREME WIND LOAD PARAMETERS FOR WIND TURBINES DURING STRONG TYPHOON HAGUPIT

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Abstract: Observational data of the severe typhoon Hagupit are obtained by a 3-dimensional ultrasonic anemometer which is installed on a 100-meter-high meteorological tower located at an islet off the coast of Guangdong. The characteristics of the extreme wind load parameters for offshore wind turbines under the influence of extreme winds at severe typhoon intensity are analyzed. By comparing the observed data with the results derived from the International Electrotechnical Commission (IEC) standard 61400-1, the applicability of the methods computing extreme wind load parameters in the IEC standard are investigated under typhoon conditions. The results are as follows. (1) The changes of both the offshore extreme gust wind speeds and the extreme wind directions render a "M" shape bi-modal distribution with peak values in the eyewall region of Hagupit. (2) There are significant differences of amplitudes of the observed extreme operating gust wind speeds and extreme wind direction from the results calculated from the IEC standard. (3) The amplitudes of both the extreme operating gust wind speeds and the extreme directions exceed the upper limits of the IEC standard for three standard classes of wind turbines, and the values calculated by IEC standard are much significantly larger than the measured ones. (4) The observed extreme operating gust wind speeds are consistent with the results calculated by the IEC standard when wind turbines are under full or partial workload or cut-off conditions, although the amplitude of extreme wind directions calculated in terms of the IEC standard is larger than that of direct measurements. Measured extreme operating gust wind speeds sometimes exceed the IEC design criteria.

Key words: typhoon; offshore wind turbines; excessive workload; IEC standard

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1 INTRODUCTION

The external wind conditions are the dominant factors determining the workloads of wind turbines[1, 2], while the extremely strong winds in the wind farm are the basis for examining whether a certain class of wind turbine is suitable for operation in the region. Based on extreme wind speed and turbulence intensity, the IEC defined a set of criteria for categorizing wind turbines classes[3]. As shown in Table 1, where the reference wind speed V_{ref} is the mean wind speed averaged over 10 minutes with a probability of once in 50 years at the height of the wheel hub of the wind turbine, and the reference turbulence intensity I_{ref} is the expected value of the turbulence intensity when the 10-min. mean wind speed reaches 15 m/s at that height. Therefore, the extreme wind characteristics in the wind farm region will greatly affect the selection of wind turbines and have a direct impact on the construction costs and power generation efficiency for the wind farm.

Typhoons play an important role in development of wind energy resource in coastal and offshore China. When typhoon's intensity is relatively low (e.g. tropical storm), it is very favorable and beneficial for wind power generation. On the other hand, the strong

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winds of typhoons may result in serious damage to the wind farm. On the current capabilities and capacities of wind turbines against strong wind, about 55.5% of typhoons making landfall in China every year are beneficial to wind farm energy, while about 29.4% of them are damaging to the wind farm[4]. According to the historical meteorological data, all the maximum wind speeds in southeastern coastal China were recorded with typhoons[5, 6]. Therefore, the characteristics of extremely strong winds brought about by typhoons are fundamental in design and analysis of extreme workloads of wind turbines.

Table 1. Wind turbine classes recommended by IEC 61400-1[3].

Wind turbine class		I	II	III	S
reference wind speed V_{ref} (m/s)		50	42.5	37.5	
reference turbulence intensity I_{ref}	A	0.16	0.16	0.16	Values specified by the designer
	B	0.14	0.14	0.14	
	C	0.12	0.12	0.12	

In fact, the extreme wind condition parameters shown in Table 1 may not fully describe the response of wind turbines to extremely strong winds. Thus the criteria[3] recommended some detailed computational methods for extreme workload parameters of wind turbines under extreme wind conditions, including extreme operating gust, extreme direction change, extreme coherent gust with direction change, extreme wind shear and so on[3, 7]. For objective and accurate calculation and verification on the reliability of extreme wind condition parameters under particular weather condition in a particular area, it is absolutely necessary to acquire in-situ observations on strong winds of typhoons. With upgrade and improvement in our capacity to observe natural events, a number of representative strong typhoon cases have been observed with their strong wind characteristics in the near-surface boundary layer investigated over the past decades. For example, based on observations of a number of typhoons making landfall in Japan, Ishizaki examined the wind speed, turbulence intensity, power spectrum of typhoons, and found that there is a close correlation between the characteristics of typhoon wind conditions and the roughness of the underlying surface[8]; Cao et al.[9] studied the characteristics of fluctuating wind parameters, the probability density distribution of strong wind and the spatial cross correlation of the coherence function by using the wind conditions of the strong typhoon Maemi which was simultaneously observed by nine vane and seven ultrasonic anemometers at a height of about 15 meters above surface. Song et al.[10] examined the three-dimension characteristics of turbulence intensity, integral scale, power spectrum and attack angles over the typhoon region with ultrasonic anemometers and identified significant differences of turbulence characteristics between the typhoon centre and its periphery. However, negligible studies have been focused on the response parameters of wind turbines to extreme wind conditions under strong typhoon condition offshore. In this article, the observational data for Typhoon Hagupit, which were obtained by a 3D ultrasonic anemometer installed on a 100-meter-high meteorological tower located at offshore area of Bohe, Guangdong, were used to compute the response parameters to wind turbine workload under the extremely strong wind condition of Typhoon Hagupit. Before the computation, quality control, reliability verification and representativeness discrimination were performed on the original data. The results may be used to verify the applicability of the computational method as recommended by IEC for extreme workload parameters of wind turbines under strong typhoon conditions, and to find out the characteristics of impact of extremely strong wind on offshore wind turbines under typhoon conditions. It may be valuable for research and development in manufacturing wind turbines which can be installed at offshore wind farms in the future.

2 DATA AND METHODS

2.1 *The observational tower*

The observational data of Typhoon Hagupit were obtained by the 3D ultrasonic anemometer which was installed at a height of 60 meters over the meteorological tower offshore Bohe, Guangdong, about 4.5 km from the coast, as shown in Fig. 1.

The Bohe meteorological tower is a mast-type one fixed with cables, with a height of 100 meters, and located on Zhizai Island. The island is about 90 meters long and 40 meters wide, with the maximum height of 10 meters above sea level and major orientation in northeast-southwest direction. The meteorological tower was set up at the site of maximum height above the sea level (Latitude 21° 26' 20" , Longitude 111° 22' 25").

The Windmaster Pro 3D ultrasonic anemometer, manufactured by Gill, UK, is able to measure wind speeds up to 65 m/s, and is operational at data sampling frequencies up to 32 Hz. The actual data sampling frequency is 10 Hz. It was installed at the 60-meter height of the meteorological tower.

Fig. 1. Location of the 100-meter-high meteorological tower offshore Bohe, Guangdong.

2.2 *The observational data*

Typhoon Hagupit made landfall at the coastal region of Chencun in Maoming of Guangdong Province at 0645 (Beijing Standard Time, or BST, the same below) on September 24, 2008. The center of Hagupit passed over about 8.5 km southeast of the tower, as shown in Fig. 2. A maximum 10-minute mean wind speed of 45.9 m/s was observed by the ultrasonic anemometer at 60 meters of the tower (70 meters above sea level), with average maximum gust wind speed observed as 61.9 m/s over a course of 0.1 s. According to the duration of typhoon process and the extreme wind characteristics, the data for analysis were screened for the period from 0000 to 1500 BST on September 24, 15 hours in total.

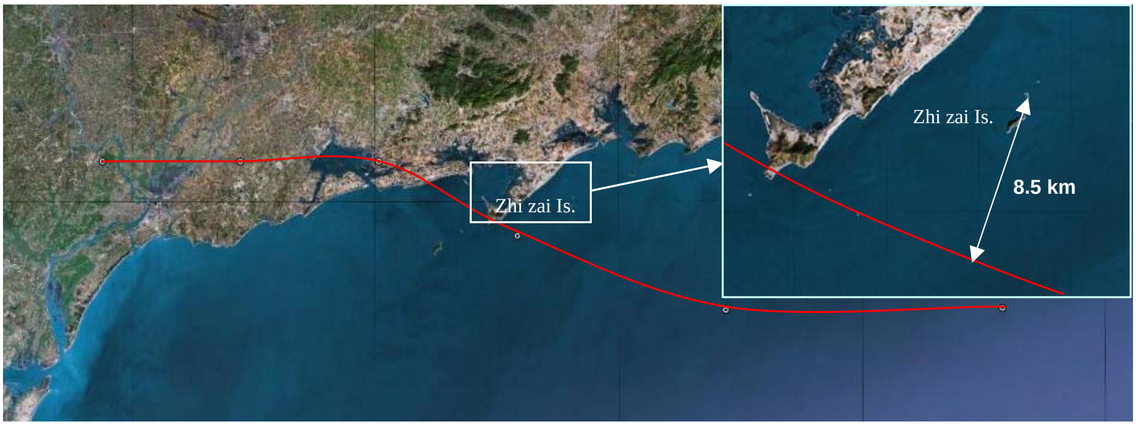


Fig. 2. Track of Typhoon Hagupit and the observational site.

2.3 *Data quality control and samples for analysis*

The observational data of Typhoon Hagupit were obtained by the 3D ultrasonic anemometer with high frequency sampling. The reliability of the data may be affected by precipitation during acquisition[11] due to the functional limitations of the equipment as typhoons are always accompanied by precipitation. Therefore, it is necessary to discriminate the accuracy and reliability of the data and reject invalid data according to the discrimination codes inherent in the ultrasonic anemometers used in the field measurements, and unreliable data due to relative unstable power supply during the typhoon process and other unidentified factors. The techniques used for quality control refer to some previous studies[12, 13].

The mean values of the dataset for this analysis were taken from the measurements for a time span of 10 minutes, while the extreme values were from 0.1 second mean records. After quality control, the data validity ratio, which is defined as the number of valid data divided by the total number of the data, exceeds 90%, satisfying the requirements for further study.

2.4 *Determination of representation of data for strong typhoon winds*

Typhoon belongs to a synoptic atmospheric vortex system consisting of mesoscale convective systems, with dramatic changes in both spatial and temporal distributions in winds, air pressure, temperature, humidity and other elements. From the cross-sections of circulations in the core, strong wind area near the eyewall, and in the periphery, significant difference may be found in characteristics of the three dimensional wind structure, turbulences characteristics and extreme wind conditions[10]. As the analysis on extreme workloads of wind turbines is focused on the strong wind characteristics in the strong wind area close to the typhoon eyewall, it is necessary to determine whether the strong wind near the typhoon eyewall was measured by the observational tower. According to the unique characteristics of typhoon vortex structure, two conditions should be satisfied simultaneously to judge whether strong wind areas near the typhoon center are observed: 1) the alterations of wind direction angles of the strong typhoon winds should be dramatic over the observing site; and 2) the time series of mean wind speeds exhibited a "M" shape, i.e., bi-modal distribution for the strong wind speeds with a trough between the two peaks, in which the wind speeds are less than 11 m/s (the area indicated near the typhoon eye)[14]. According to these criteria, the representativeness of the *t* observation data for the typhoon Hagupi was evaluated.

Figure 3 showed variations of the 10-minute mean wind speeds and directions obtained during Typhoon Hagupit at the 60-meter height of the meteorological tower. The two dotted lines indicated the moments when maximum wind speeds appeared before and after the typhoon center passed over the meteorological tower. The solid line denoted the moment when minimum wind speed in the typhoon centre appeared, i.e. the position of the typhoon centre. Fig. 3 also showed that the time series of 10-minute mean wind speeds during the strong wind (10-minute mean wind speeds over 17.2 m/s) process of Typhoon Hagupit exhibited bi-modal distribution with a minimum wind speed about 11.7 m/s between the two peaks. The wind directions of the strong winds were successively altered 182° clockwise. It is therefore able to be justified that the tower data represent some important strong wind characteristics of Typhoon Hagupit.

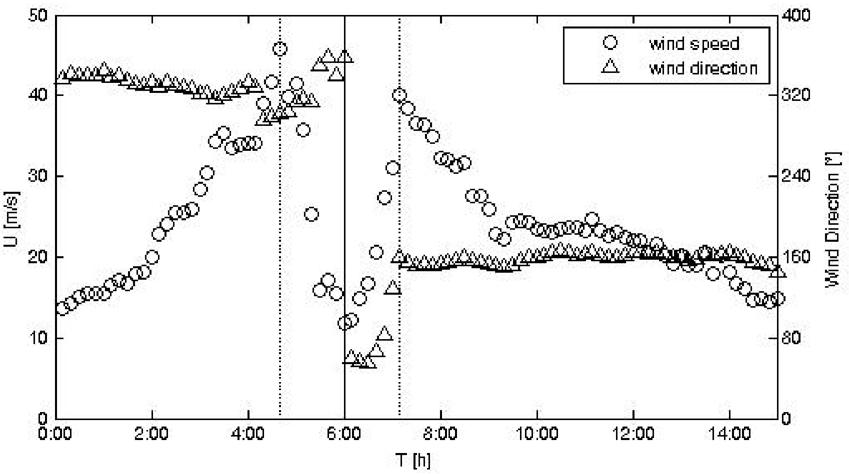


Fig. 3. Variations of 10-minute-mean wind speeds and directions at the 60-meter height obtained from the meteorological tower. (The dotted lines indicate the observation time of maximum wind speeds near the eyewall. The solid line shows the moment when minimum wind speed near the typhoon centre appeared. The small circles are for mean wind speeds and the triangles for wind directions.)

2.5 *Processing of three dimensional data*

The original measurements of wind speeds in three dimensions (3D), $u(t)$, $v(t)$ and $w(t)$, were taken as three sets of time-series in *x*, *y* and *z* axis of the coordinates system of the anemometer (not the real wind vectors). It is required to rotate the anemometer coordinates system by an angle of Φ to make sure that the measured velocity component $u(t)$ is consistent with the mean wind direction (i.e., latitudinal wind). The angle Φ is calculated as:

$$\Phi = tg^{-1}\left(\overline{v(t)}/\overline{u(t)}\right) \quad (1)$$

where $\overline{u(t)}$, $\overline{v(t)}$ are mean wind speeds in the 10-minute period. After coordinate transformation, the *x*, *y*, *z* in the new coordinates system represents the 3D wind speed and direction values in latitudinal $u(t)$, longitudinal $v(t)$ and vertical $w(t)$ directions. Finally, the real values of wind speed and wind direction are derived by synthesizing the values of the 3D components.

3 ANALYSIS ON EXTREME WORKLOAD PARAMETERS OF WIND TURBINES

Extreme operating gusts and extreme direction changes are the two important parameters in calculation of extreme wind workload parameters of the wind turbines. According to the wind turbine models deployed in current large-scale wind farms and their installation height, the basic parameters for wind turbines were chosen: 70 meters for rotor diameter D of the selected wind turbines, and 70 meters (base height above the sea level) for the hub height Z_{hub}.

3.1 *Extreme operating gusts*

3.1.1 CALCULATION METHODS

Extreme operating gusts of wind turbines are defined as the parameter representing the effect of gust wind speed on a particular class of wind turbine in a particular base time interval at the hub height of wind turbines. This parameter involves a wind gust with probability of once a year, which is related to the wind turbines operating conditions and closely associated with the wind turbines sustainable working conditions. IEC[3] recommended the formula for calculating extreme operating gust wind speed, at a specified height Z, with probabilities of once a year or 50 years, as follows.

$$V(Z,t) = \begin{cases} V(z) - 0.37V_{gust} \sin(3\pi t/T)(1-\cos(2\pi t/T)) & 0 \le t \le T \\ V(Z) & otherwise \end{cases} \quad (2)$$

At the height of Z, extreme operating gust wind speed $V(Z,t)$ is a function of time period t, with its maximum period T given as 10.5 seconds. In Eq. (2), $V(Z)$ represents 10-minute mean wind speed at height Z, while V_{gust} means the maximum amplitude of changes of gust wind speeds, with a period of 10.5 seconds, at 10-minute intervals. Theoretically, parameter V_{gust} should be obtained from field measurements. However, due to difficulties in obtaining high-frequency wind data, IEC[3] recommended empirical formulas for this parameter.

$$V_{gust} = \{1.35\times(V_{e_1} - V_{hub})\} \quad (3a)$$

$$V_{gust} = \left\{3.3\times\left(\frac{\sigma_1}{1+0.1\times(\frac{D}{\Lambda_1})}\right)\right\}. \quad (3b)$$

Eqs. (3a) and (3b) are used for calculating extreme operating gusts for recurrence periods of 1 year and 50 years, respectively. In Eq. (3b), σ_1 means the normalized difference of latitudinal component of velocity. For wind turbines in the three standard categories A, B and C, as given by the IEC[3] standard, the values of σ_1 are calculated by Eq. (4), subjected to the parameters unique to the categories of the wind turbines, as given in Table 1.

$$\sigma_1 = I_{ref}\times(0.75V_{hub}+b); \quad b = 5.6m/s \quad (4)$$

where I_{ref} is the reference turbulence intensity (Table 1).

In assessing suitability of a class of wind turbines in an area with particular wind characteristics, σ_1 should be calculated from the observational data. In calculating V_{gust} with Eq. (3), σ_1 can be taken as the standard deviation of the observed latitudinal wind speeds at time interval of 0.1 second against 10.5 seconds. The V_{hub} is 10-minute mean wind speed at the height of 70 meters, while D is the rotor diameter (taken as 70 m), and Λ_1 the parameter of turbulence scale, defined by the following expression[3]:

$$\Lambda_1 = \begin{cases} 0.7z & z \le 60m \\ 42m & z \ge 60m \end{cases} \quad (5)$$

Extreme wind direction change is defined as the maximum amplitude of changes of wind directions at time intervals of every 6 seconds, with a recurrence period of *N* (*N*=50) years. Theoretically, the wind direction angle θ_e in every 6 seconds should be calculated by the observational data. However, due to difficulties in obtaining data with high-frequency sampling, the IEC[3] recommended the following formulas:

$$\theta_e = \pm 4\arctan\left[\frac{\sigma_1}{V_{hub}\times(1+0.1\times(\frac{D}{\Lambda_1}))}\right] \quad (6)$$

According to the IEC[3], the parameter of extreme wind direction change $\theta(t)$ can be obtained by

$$\theta(t) = \begin{cases} 0^\circ & t<0 \\ \pm 0.5\theta_e(1-\cos(\pi t/T)) & 0 \le t \le T \\ \theta_e & t > T \end{cases} \quad (7)$$

where in Eq. (7), t is the time interval during which the amplitude of changes of wind direction may be determined; T is the characteristic time interval for wind turbines to respond to the wind direction changes, taken as $T = 6$s.

3.1.2 CHARACTERISTICS OF OFFSHORE EXTREME OPERATING GUSTS

Figure 4 showed time series of the maximum amplitude of gust of latitudinal wind speeds at time intervals of 10.5 seconds, obtained at the height of 70 meters above sea level during the 15 hours Typhoon Hagupit passing over the Bohe meteorological tower. Fig. 4a described the parameters derived directly from field measurements, while Fig. 4b provided the results calculated by Eq. (3b) in the IEC standard. Fig. 4a also displayed that there were characteristics of both rise and fall in amplitude for gust wind speeds, which were involved in the change of amplitude of the latitudinal maximum gust from field measurements. However, evaluation and assessment for wind turbines need to consider only the characteristics of rise in amplitude of gust. Fig. 4b demonstrates only the rise in amplitude of wind speeds, which reveals bi-modal distribution characteristics in the strong wind area near the typhoon eyewall. The maximum operating gust wind speed from direct field measurements was 17.6 m/s, close to 17.3 m/s calculated by Eq. (3b).

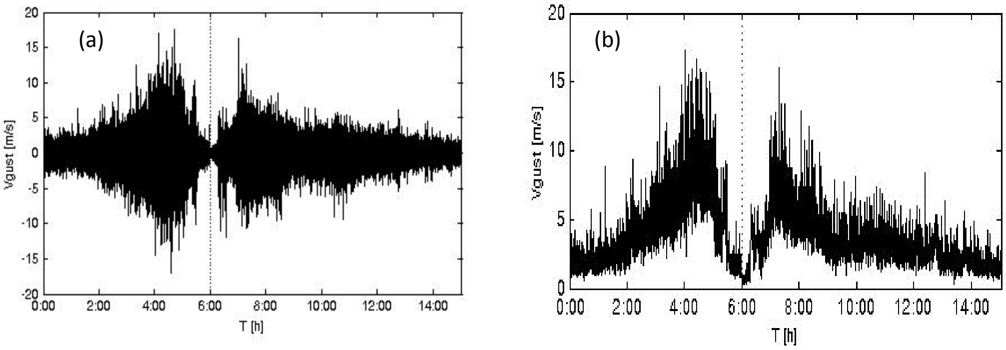


Fig. 4. Time series of V_{gust} from typhoon Hagupit (The dashed line marks the moment typhoon center passing over the meteorological tower. a: the measured results; b: the results calculated by IEC.

The IEC provided changes of standard V_{gust} values with respect to increase of mean wind speeds for design of the three standard classes of wind turbines (noted as class A, B, and C, respectively. The same is true below), as described by the three straight lines in Fig. 5. In order to investigate the applicability of Eq. (3b) in the IEC standard and variations of V_{gust} under the typhoon conditions, comparative analyses were carried out for the values of V_{gust} derived from field measurements against those from the Eq. (3b). It showed that the observed V_{gust} experiences maximum increase of amplitude of gust winds with a period of 10.5 seconds in every 10 minutes sub-sample (noted by the triangles in Fig. 5). The maximum values of V_{gust} are calculated by Eq. (3b) using the observed latitudinal velocity component data, where V_{gust} was taken as the maximum standard deviation of the observed latitudinal wind speeds at time interval of 0.1 second against 10.5 seconds in every 10 minutes sub-sample (noted by the hollow circles in Fig. 5).

Figure 5 shows that the trend of the observed V_{gust} is consistent with that from the IEC. However, both of the results exceeded the upper limits for design of the three standard classes of wind turbines given by the IEC. Among the V_{gust} values calculated by the IEC formula, 8.9% of the total samples (10 minutes for a sample unit) exceeded the standard design value for class A wind turbines, 17.8% for class B, and 33.3% for class C, respectively. In contrast, only about 3.3% samples of the directly observed V_{gust} values exceeded the standard design value for class A wind turbines, 8.9% for class B, and 20.0% for class C, respectively.

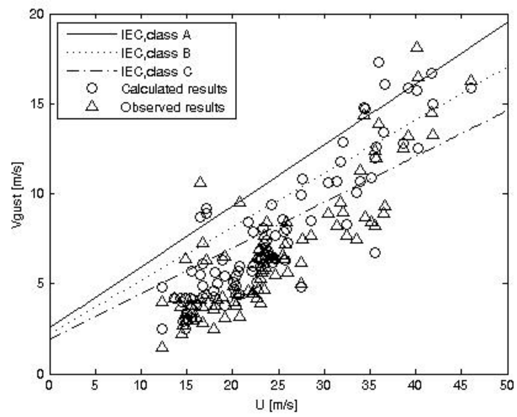


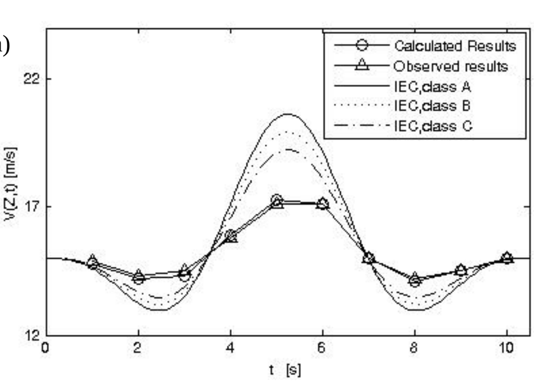
Fig. 5. Variations of the maximum V_{gust} in every 10-minute time interval with a period of 10.5 s for typhoon Hagupit. (The solid, dotted and dashed lines represent the upper limits of V_{gust} values for design of classes A, B and C wind turbines, respectively; the circles indicate the V_{gust} values calculated by the IEC formula, while the triangles stand for the observed V_{gust}).

From the number of samples of V_{gust} exceeding the upper limits for design of the three classes of wind turbines (Fig. 5), it is found that for about 14.4% (in total for the three classes of turbines) the IEC samples V_{gust} is greater than the observed V_{gust} value when the tangential speed of the wind turbines is below 25 m/s. Furthermore, the observed V_{gust} value does not exceed the design limit for class A wind turbine when the wind speed is less than 25 m/s. However, when the wind speed is greater than 25 m/s, there are 45.6% samples of IEC V_{gust} exceeding the standard design limits for all three classes of the wind turbines, while there are only 22.2% of the observed V_{gust} values exceeding the design limits. In other words, the formula recommended by IEC overestimates V_{gust} under typhoon conditions, and the greater the wind speed, the higher deviation the overestimation.

Under various operating conditions, there should be a variety of strategies to design wind turbines in order to accommodate with extreme wind conditions. Considering the characteristics of response of the wind turbines to extreme gusts, wind speed samples were screened from the data of Typhoon Hagupit for the conditions that wind turbines may be operated in full capacity, cut-off or have to be shut down with wind speeds once in a couple of years, and were taken as characteristic wind speeds for different operating conditions. Applying the observed V_{gust} and IEC V_{gust} into Eq. (2), the extreme operating gust wind speed $V(Z,t)$ is obtained and compared with the theoretical curves of $V(Z, t)$ for the three standard classes of wind turbines under different operating conditions.

Figure 6 illustrated that variation of the extreme operating winds, which were under the influences of characteristic wind speeds corresponding to operating conditions of wind turbines, is consistent with that of IEC[3].

(a)



(b)

(c)

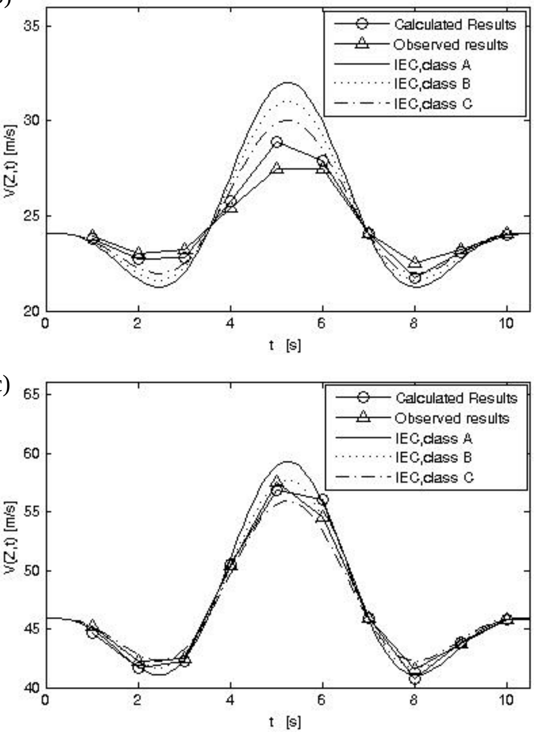


Fig. 6. Comparison between the curves of extreme operating gusts of typhoon Hagupit and the standard curves of the three standard classes of wind turbines under different conditions (a: the condition of rated wind speed, b: the cut-off wind speed, c: the extreme wind speed; the circles mark the IEC $V(Z,t)$ and the triangles mark the observed $V(Z,t)$).

Figures 6a & 6b showed that the extreme operating gust wind speeds ($V(Z,t)$) under the influences of Typhoon Hagupit are greater than the standard values of three classes of wind turbines given by IEC in the time ranges of 1–3.5 s and 7–10 s, when the wind turbines were in full operation (with wind speed limit of 15 m/s) and should be cut off (wind speed limit of 24.1 m/s). By examining the 10-minute mean wind speed of 45.9 m/s (about once in 35 years, the maximum wind speed of Typhoon Hagupit did not reach the magnitude with a recurrence period of 50 years) from the observational dataset, it is found that the IEC $V(Z,t)$ are generally consistent with the observed $V(Z,t)$.

3.2 *Changes of extreme wind direction*

3.2.1 COMPARISON OF THE VARIATION CHARACTERISTICS OF THE OBSERVED WITH THOSE DERIVED FROM IEC FORMULA

Figure 7 provides variations of amplitude of wind direction changes θ_e every 6 seconds. Fig. 7a showed the observed results, while Fig. 7b presented the θ_e calculated by the IEC Eq. (6), with σ_1 the standard deviations of the measured wind speeds in time interval of 0.1 s against 6 s.

Figure 7a shows that the observed θ_e values did not show evident fluctuation during the Typhoon Hagupit process. The maximum values of the fluctuation occurred in the area of strong winds (near the typhoon eyewall). Further comparison shows that although the trends of the values are basically consistent with their peak values in the strong wind areas, significant differences in their magnitudes, i.e. the maximum observed θ_e, were 28° , much smaller than the 41.5° derived from the IEC formula. Moreover, the average value of the observed θ_e was 2.4° , in comparison with the 9° of IEC. In this sense, the IEC methods might have significantly overestimated the amplitude of changes in extreme wind directions under typhoon conditions.

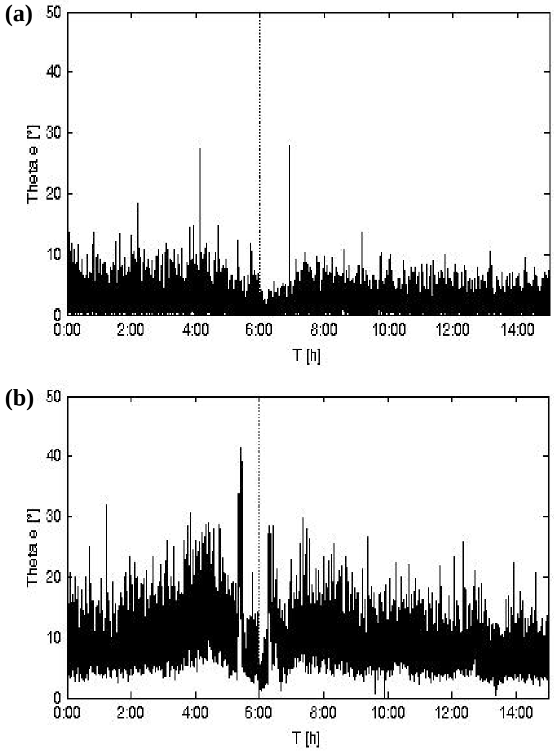


Fig. 7. Time series of the extreme wind directions θ_e at 6-second intervals. a: the observed θ_e; b: the IEC θ_e. The dotted line indicates the moment when the lowest wind speed near the typhoon center appeared.

3.2.2 COMPARISON OF EXTREME WIND DIRECTION CHANGES UNDER HAGUPIT WITH IEC STANDARD FOR DESIGN OF WIND TURBINES

Figure 8 shows the changes of the maximum values of θ_e in 6 s with mean wind speeds in every 10-minute sampling period during the strong Typhoon Hagupit. The three curves represent the standard θ_e values for design of the three classes of wind turbines (i.e. classes A, B and C, respectively) as stipulated in the IEC standard, under different conditions of strong wind speeds. The hollow circles represented the maximum θ_e values in every 10-minute sampling period, calculated by eq. (6) of IEC. And the hollow triangles denoted the observed θ_e values.

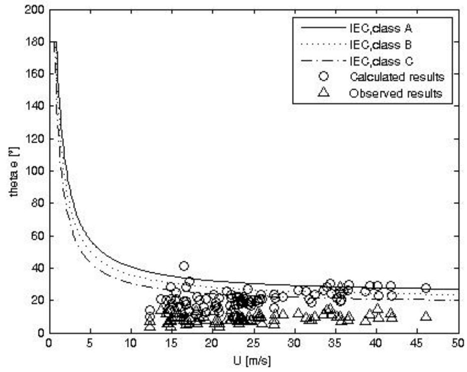


Fig. 8. Time series of maximum values of θ_e in every 10-minute sampling period.

It is found that the observed θ_e values never exceeded the criteria for design of the class A wind turbines. However, only one sample of the observed θ_e was found to exceed the design limit for class B and C wind turbines. Comparatively, in 7.8%, 17.8%, and 27.8% of the total samples for the class A, B and C wind turbines, respectively, θ_e values calculated by the IEC formula exceed the design limits.

By choosing the wind speed samples from the observations of Typhoon Hagupit with the conditions for the wind turbines in full operation, cut-off and occasional shutdown with a probability of once in many years, and applying the observed θ_e and the calculated θ_e values by Eq. (6), respectively, into Eq. (7), the parameters of extreme wind direction changes $\theta(t)$ with respect to period t were obtained and compared with the theoretical $\theta(t)$ for the three standard classes (A, B and C) of wind turbines under different operating conditions (Fig. 9).

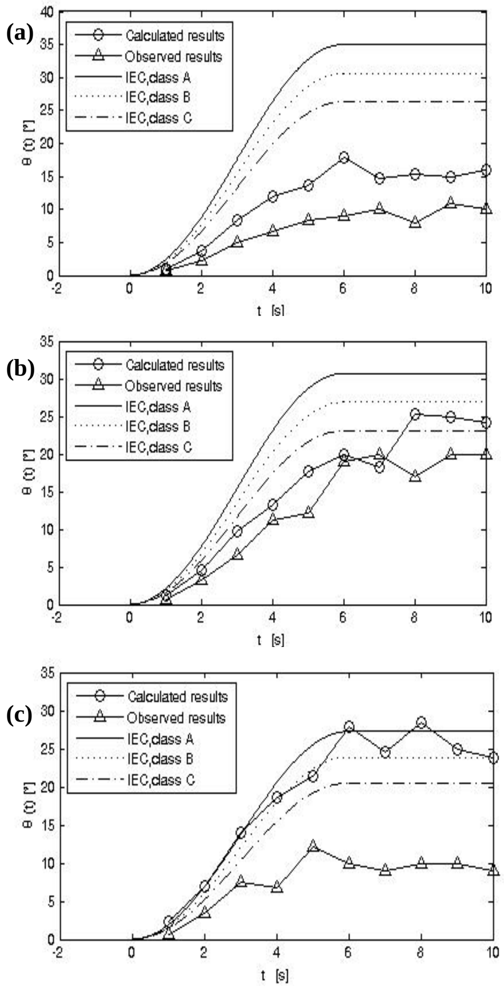


Fig. 9. Direction change of extreme winds of typhoon Hagupit and the standard curves of the three standard classes of wind turbines under different conditions (circles: IEC $\theta(t)$; triangles: observed $\theta(t)$).

Figure 9 showed that the trend of extreme wind direction changes corresponding to operating wind conditions of the wind turbines was in general consistency with those of the IEC standard, with an evident feature that the latter is larger than the former. Nevertheless, the observed amplitudes of extreme wind direction changes are less than those of the design criteria given by IEC for the three standard classes of wind turbines in any time intervals. Furthermore, the extreme direction change parameters calculated by the IEC formula exceed the IEC design criteria for wind turbines in the conditions of cut-off and shutdown.

4 CONCLUSIONS AND DISCUSSION

Using the observational data of Typhoon Hagupit obtained by the 3D ultrasonic anemometer installed on the 100-meter-high meteorological tower located in an offshore area of Guangdong, analyses were carried out on the characteristics of the two extreme workload parameters of extreme operating gusts and extreme wind direction changes for the wind turbines under strong typhoon conditions. By comparing the results derived directly from observations with those derived from the IEC formula, and by examining the applicability of the IEC design criteria for the three classes of wind turbines under various operating conditions associated with typhoon influences, conclusions are mainly drawn as follows.

(1) According to the analysis of the observational data, it is found that both the offshore extreme operating gust wind speeds and the amplitudes of extreme direction changes with respect to time exhibited an "M" shape bi-modal distribution. The maximum rise of the observed extreme operating gusts is 17.6 m/s, and the maximum amplitude of extreme direction changes is 28° , both of which are associated with the design of wind turbines, and both of their peak values appeared in the strong wind area near the eyewall of Typhoon Hagupit.

(2) Comparisons between the parameters of extreme operating gusts and the amplitude of extreme wind direction changes that were calculated by the IEC formula and those derived from the observation reveal good agreements on the trend with respect to wind speed and period. However, the magnitude of the parameters is larger by using IEC formula than by field observation.

(3) The observation shows that with the increase of mean wind speeds during the typhoon process both the extreme operating gust winds and the amplitude of extreme wind direction changes exceed the upper limits for design of the three classes of wind turbines according to the IEC standard. And the values of the parameters calculated by the IEC formula are generally greater than the observed ones, and the larger the wind speeds, the greater the change of amplitude.

(4) Under various operating conditions when the wind turbines were in full operation, cut off and shut down, there was a general consistency between the variations and the values of the extreme operating gust winds with respect to period, calculated by the IEC methods, and derived from observation. However, the amplitudes of extreme wind direction changes are significantly larger than those derived from observations. In comparison with the criteria given by the IEC standard for design of the three classes of the wind turbines, the observed extreme operating gust winds exceeded the criteria in the time intervals 1–3.5 s and 7–10 s. Nevertheless, it is not the case for the amplitudes of extreme wind direction changes.

(5) As implied by the observation, the characteristics of the extreme workload parameters for offshore wind turbines should not be applicable over land or other sorts of underlying surfaces. The characteristic parameters calculated by the IEC

formula for extreme wind conditions under the influences of an offshore strong typhoon are larger than the design criteria given by IEC. Since the IEC standard 61400-1 is the result of large quantity of typhoon cases, it should be cautioned to use the standard in some special situations, such as strong typhoons. In addition, the conclusions in this article need to be verified further with more cases of strong typhoons that are newly observed.

Only two parameters on extreme operating gust winds and extreme wind direction changes are discussed here because of limitation of length. The applicability of other parameters given by IEC will be discussed in the next article.

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