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Feasibility of typhoon models and wind power spectra on response analysis of parked wind turbines

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SUMMARY:
Typhoon may induce severe damages to wind turbines in both eyewall and outer vortex regions, and accurate typhoon simulation is important for the wind turbine response estimation. In this research, wind fields in these two regions are reproduced by applying two-dimensional or three-dimensional models to simulate the mean wind speed, and von Karman spectrum or Kaimal spectrum for the fluctuating wind speed. The reproduced wind fields are used to calculate the typhoon-induced responses of parked wind turbines through time-domain analysis. In the eyewall region, two and three-dimensional models are found to underestimate the mean wind speed at hub height by about 6% and 3.5%, respectively, compared to the measured data, and the mean responses of the blade and the tower estimated with two-dimensional model are lower than those with three-dimensional model by 8~24%; taking the extreme responses with the measured spectrum as the benchmark, von Karman spectrum overestimates the extreme responses of the blade and the tower by 4~5% and 18~33% respectively, while Kaimal spectrum underestimates the extreme responses of the blade by 18~24% and overestimates the extreme responses of the tower by 16~29%. In the outer vortex region, the difference in mean responses between two and three-dimensional models is small and can be ignored; von Karman spectrum overestimates the extreme responses of the blade and the tower by 1~2% and 6~10% respectively, while Kaimal spectrum underestimates extreme responses of the blade by 6~20% and overestimates the extreme responses of the tower by 5~9%. As a result, it is recommended to apply three-dimensional model for the mean response estimation of parked wind turbines in the eyewall region, the two-dimensional model in the outer vortex region for less computation time, and the von Karman spectrum is suggested to be adopted for the extreme response in the whole typhoon field.

Keywords: typhoon wind simulating, three-dimensional model, spectrum model, wind turbine

1. INTRODUCTION

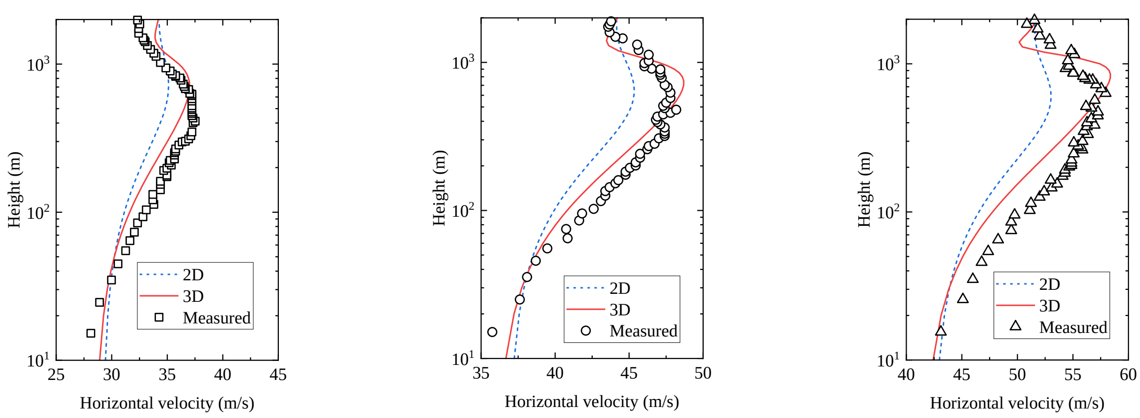
Typhoon risk has become the main factor restricting the wind power development in China and the US (Hallowell et al., 2018; Li et al., 2021), the two largest wind power markets in the world. Accurate simulation of typhoon wind field, especially in eyewall region, is important for estimating aerodynamic loads and responses of wind turbines. Typhoon mean wind profiles have been reproduced by measured data, power law and WRF-CFD method. Also, height-resolving model has been introduced in typhoon simulation to distinguish wind characteristics in different regions of the typhoon field and capture variations within the whole boundary layer (Wang et al., 2020, 2022). Some height-resolving models neglecting vertical advection to facilitate solution are called the two-dimensional typhoon models, and others considering the effect of vertical advection and obtaining similar supergradient wind with the observations are regarded as the three-dimensional typhoon models. However, these three-dimensional models have not been used for estimating the typhoon-induced response of wind turbine, and their differences compared with the two-dimensional models have not been revealed. Fluctuating characteristics of typhoon have been captured in terms of some key parameters, especially the wind power spectrum which markedly influences the vibration level of structures. Some full-scale measurements display that von Karman spectrum agrees well with along-wind spectrum of typhoon, while Kaimal spectrum is widely used in the design of wind turbine, even in typhoon condition (Gong and Chen, 2015; Kapoor et al., 2020). Also, some spectrum models for the measured typhoons have been built and show distinctions in different regions of the typhoon field. However, the differences of aerodynamic loads and responses of wind turbine estimated by various empirical and measured spectrum models have not been examined systematically.

In this paper, wind field simulation with height-resolving models and spectrum models are used to estimate response of parked wind turbine in different regions of the typhoon field. The methodologies of typhoon simulation are introduced in Section 2. The characteristics of reproduced typhoon fields are investigated in Section 3. In Section 4, the responses of wind turbine blade and tower located in different regions of the typhoon field are estimated and discussed considering various models. Finally, the appropriate wind field simulation models for response estimations of wind turbine in different regions of the typhoon field are recommended.

2. METHODOLOGY

2.1 Height-resolving model

The wind velocities at any position of typhoon field are derived by height-resolving models from the fluid momentum equation for air parcel, which are always solved with perturbation analysis or scale analysis for simplification. The models proposed by Meng et al. (1995) and Yang et al. (2021) are chosen to stand for the two-dimensional and three-dimensional model, respectively. The solution procedures of these two models are implemented in MATLAB, and the code validation is conducted with the measured data (Vickery et al., 2009) as shown in Fig. 1. The results distinctly present that the reproduced wind profiles by two models match well with those derived from the measured data, but the simulated wind profiles by the 3D model make a more realistic prediction of the supergradient wind when compared with the 2D model.



(a) (b) (c)

Figure 1. Validation of height-resolving models: vertical wind profiles with the mean boundary layer wind velocity corresponding to (a) 30-39, (b) 40-49 and (c) 50-59 m/s

2.2 Spectrum model

The empirical model proposed by Li et al. (2012), von Karman spectrum and Kaimal spectrum are adopted for fluctuating wind simulation of wind turbine, as shown in Fig. 2. The results show that Kaimal spectrum obviously underestimates the peak power density, while the peak frequency varies in different models.

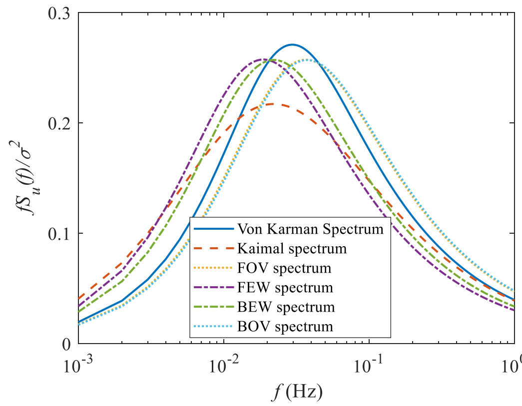


Figure 2. Comparison of different spectrum models

3. CHARACTERISTICS OF TYPHOON WIND FIELD

The wind field of Typhoon Hagupit (2008) making landfall in Guangdong province, China is reproduced by the height-resolving models and spectrum models. The maximum wind velocity occurs at radius r = 33.5 km, which can be called R_{max}. The circumferentially-averaged wind profiles at that position calculated by two-dimensional and three-dimensional models are shown in Fig. 3. It can be seen that the three-dimensional model obtains higher wind velocities and the maximum increasing ratio reaches almost 6%.

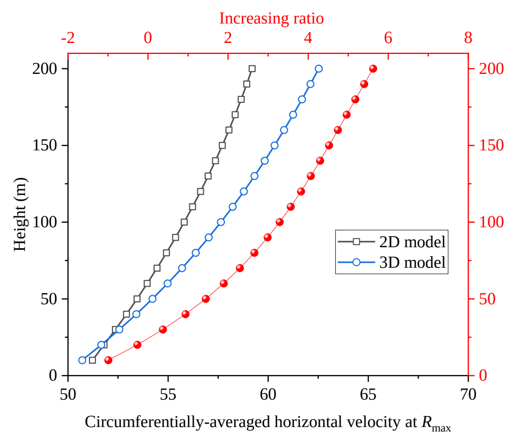


Figure 3. Circumferentially-averaged wind profiles at R_{max}

4. TYPHOON-INDUCED DYNAMIC RESPONSES OF WIND TURBINE

The blade root and tower base are the most unfavourable position of force and moment. As shown in Fig. 4, both flapwise and edgewise forces at blade root are lower with two-dimensional model. The maximum decreasing ratios reach 13.0% and 11.1%, respectively. Fig. 5 displays similar results for fore-after (FA) and side-to-side (SS) moment at tower base.

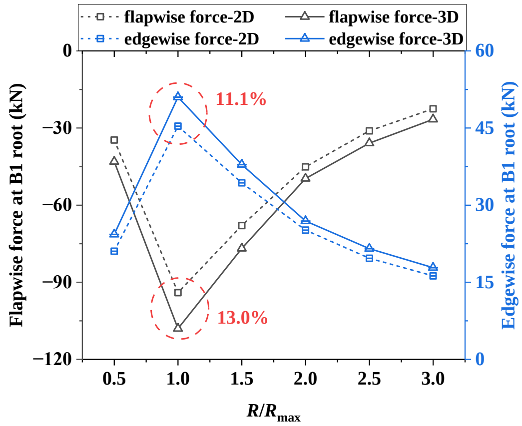


Figure 4. Flapwise and edgewise force at Blade 1 root

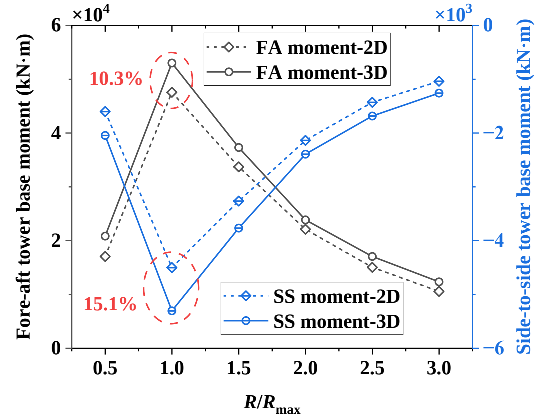


Figure 5. FA and SS Moment at tower base

5. CONCLUSIONS

It is recommended that three-dimensional model is applied for the response estimation of parked wind turbines in the eyewall region, two-dimensional model in outer vortex region for less computation time, and von Karman spectrum is used in the whole typhoon wind field.

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