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Buffeting response analysis of offshore wind turbines subjected to hurricanes

Gholamreza Amirinia*, Sungmoon Jung

Department of Civil and Environmental Engineering, Florida A & M University – Florida State University, College of Engineering, Tallahassee, FL 32310, USA

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ABSTRACT

The objective of this paper is to investigate the effects of newly observed hurricane turbulence models on offshore wind turbines by considering unsteady aerodynamic forces on the tower and wind-wave-soil-structure interaction. The specific goals were analyzing the tower and blade structural buffeting responses, the low cycle fatigue during different hurricane categories, and extreme value of the short term responses. To achieve these goals, first, the recent observations on hurricane turbulence models were discussed. Then a new formulation for addressing unsteady wind forces on the tower was introduced and NREL-FAST package was modified with new formulation. Results showed that recently observed turbulence models resulted in larger structural responses and low cycle fatigue damage than existing models. In addition, extreme value analysis of the short term results showed that the IEC 61400-3 recommendation for wind turbine class I was conservative for designing the tower for wind turbine class S subjected to hurricane; however, for designing the blade, IEC 61400-3 recommendations for class I underestimated the responses.

1. Introduction

Investigation of hurricanes during last decade showed that hurricanes have different turbulence characteristics from regular high winds (Caracoglia and Jones, 2009; Jung and Masters, 2013; Li et al., 2012; Schroeder and Smith, 2003; Yu et al., 2008). These differences in the turbulence energy models affect the structures by changing the buffeting response characteristics or causing low cycle fatigue. In this regard, special structures such as offshore wind turbines in hurricane prone regions need to be studied more for safety and economical aspects (Amirinia and Jung, 2017, 2016; Amirinia et al., 2015; Gong and Chen, 2015).

Observations and analysis of hurricane surface winds revealed that turbulence spectrum of hurricane winds differs from that of non-hurricane high winds (Balderrama et al., 2011; Caracoglia and Jones, 2009; Gong and Chen, 2015; Jung and Masters, 2013; Li et al., 2012; Schroeder and Smith, 2003; Yu et al., 2008). Li et al. (2012) and Caracoglia and Jones (2009) showed that in the hurricane, the higher turbulence frequencies have higher level of energy; however, Schroeder and Smith (2003), Yu et al. (2008), and Jung and Masters (2013) showed that hurricane spectrum has higher level of energy in low frequencies. Different turbulence energy models affect structures differently, while the mean wind speed and turbulence intensity are identical between models. In this regard, mean responses of structures subjected to regular high winds and hurricane winds are comparable, whereas, the buffeting responses are different. Because of these differences in buffeting responses, conditions such as structural integrity and low cycle fatigue subjected to different hurricane turbulence models should be investigated.

Various studies in recent years have been conducted to investigate hurricane effects on wind turbines. Han et al. (2014) reviewed the characteristics of tropical cyclones and their probable effects on the wind turbines. Guo et al. (2014) compared existing wind shear and turbulence spectrum models in standards for wind turbine analysis during hurricane and showed that different models result in different responses. Kim and Manuel (2014) used conventional Kaimal et al. (1972) turbulence model and a coupled wind-wave approach for analyzing offshore wind turbines. They explored hurricane induced loads on offshore wind turbines with consideration of nacelle yaw and blade pitch control. After that, Kim et al. (2016) studied effects of hurricane Ike (2008) and hurricane Sandy (2008) on an offshore wind turbine. They considered the conventional Kaimal et al. (1972) wind spectrum and addressed effects of yaw misalignment and blade azimuthal angle on the responses. All the mentioned studies addressed an important issue in the analysis of offshore wind turbines subjected to hurricanes, however, all of them used existing turbulence models for

* Corresponding author.
E-mail address: gamirinia@fsu.edu (G. Amirinia).

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simulating the hurricane. To this end, there is a need for studying the effects of recent observations of hurricane turbulence models on the wind turbines.

The duration of the hurricane compared to structural design life is short. Hence, large turbulent forces in a short period of time are exerted on the structure. In this case an accurate low cycle fatigue analysis is necessary for determining the structural integrity during hurricane. By referring to the differences in turbulence spectrum models, the buffeting responses of the structures subjected to the various hurricane turbulence models are important in terms of low cycle fatigue analysis. Li et al. (2014) studied wind buffeting forces on fatigue analysis of the wind turbine foundation. Tibaldi et al. (2015) investigated the operating wind turbine fatigue based on a linear model. Lee et al. (2013) applied a numerical method to study the wake turbulence impacts on wind turbine fatigue. By reviewing previous studies and new findings about hurricane turbulence models, the low cycle fatigue analysis of the offshore wind turbines should be studies carefully to investigate the effect of newly observed and presented models.

IEC (6140)0-1 (2005) and IEC (6140)0-3 (2009) have recommendations for different wind turbine classes and load cases; however, for special events such as hurricane, they introduced wind turbine class S which the design variables should be defined by the designer. In order to compare the short term responses of the wind turbine subjected to hurricane with IEC (6140)0-1 (2005) and IEC (6140)0-3 (2009) recommendations, an extreme value analysis is necessary. Several studies has been conducted on extreme value analysis which considered various methods and approaches (Kim and Manuel, 2013, 2014; Kim et al., 2016). By considering the importance of new hurricane turbulence models on buffeting responses, an accurate extreme value analysis is necessary for comparing the short term results with IEC (6140)0-3 (2009) recommendations. An accurate extreme value analysis and comparison with existing recommendations also assist to consider important issues in designing wind turbines class S.

In this paper, the main objectives were investigating the effects of recently observed hurricane models on structural responses and low cycle fatigue of offshore wind turbines. In addition, to compare the short term analysis with existing IEC (6140)0-3 (2009) recommendations and proposing extra consideration for special conditions such as hurricane, an extreme value analysis was carried out. For these purposes, first, the recent observations on hurricane turbulence models were discussed. Next, the buffeting wind loads on the wind turbine structure were mentioned and a new formulation for addressing unsteady wind forces on the tower was introduced (Amirinia and Jung, 2016). This new formulation was later used to modify NREL-FAST (Jonkman and Buhl, 2005) for analysis. At next step, according to recent findings about hurricane winds, hurricane wind and wave fields were simulated based on the Saffir-Simpson hurricane wind scale (Simpson and Saffir, 1974). Then, to investigate the effects of various hurricane turbulence models on the wind turbine structures, the modified NREL-FAST (Jonkman and Buhl, 2005) in previous sections was used to analyze structure-wind-wave-soil interaction of the NREL-5 MW wind turbine (Jonkman et al., 2009). Finally, the structural responses and low cycle fatigue analysis were presented and discussed. At the end, an extreme value analysis was carried out on the short term results and extreme responses were compared with IEC (6140)0-3 (2009) recommendations for 50-years return period load case for extra design consideration.

2. Hurricane turbulence models

The wind turbulence spectrum represents the energy distribution in turbulent wind (Li et al., 2012). The total energy of turbulent flows can be expressed as superposition of eddies (Yu et al., 2008). Big eddies which represent small wave numbers or low frequencies, supply the most energy content of turbulent flow; whereas, small eddies with high wave numbers in high frequencies dissipate the gained energy (Kaimal et al., 1972; Tieleman, 1995; Yu et al., 2008). This gain and dissipation are connected to each other with an inertial subrange where the influence of viscosity is small. According to the equilibrium, the gain and dissipation of energy should be equal which made Kolmogorov's hypothesis as Eq. (1) as:

$$E(k) = a\varepsilon^{2/3}k^{-5/3} \tag{1}$$

where ε represents energy dissipation, k is wave number, and a is a universal constant. Earlier studies investigated wind turbulence spectrums for non-hurricane winds (Davenport, 1961; Kaimal et al., 1972; Tieleman, 1995; Von Karman, 1948). Kaimal et al. (1972), based on series of experiments, showed that all spectra reduce to a limited family of curves which fit a single universal curve in inertial subrange but spread out in low frequencies. They proposed a formula for wind spectrum as shown in Eq. (2):

$$\frac{nS_u}{\sigma_u^2} = \frac{21.\,6f}{(1 + 33f)^{5/3}} \tag{2}$$

where $f = nz/U(z)$ represents the normalized frequency, n is the frequency, S_u is the spectral density of the longitudinal velocity fluctuation at height z, and σ is the standard deviation of longitudinal velocity fluctuation. Hurricane field data observations during the last decade revealed that turbulence spectrum of the hurricane boundary layer winds is different from those of non-hurricane high-winds. Schroeder and Smith (2003), Yu et al. (2008), and Jung and Masters (2013) showed that compared to non-hurricane spectral models, hurricane spectrums had higher energy content in low frequencies. The formula derived for hurricane wind turbulence spectrum (Yu et al., 2008) with high amount of energy in low frequencies was presented as:

$$\frac{nS_u}{\sigma_u^2} = \frac{1}{\beta}\times\frac{p_1f^2 + p_2f + p_3}{f^3 + q_1f^2 + q_2f + q_3} \tag{3}$$

where $\sqrt{\beta} = \sigma/u^*$ is the turbulence ratio, u^* represents the friction velocity, and p_i and q_i are constants proposed by Yu et al. (2008) as shown in Table 1.

On the other hand, Li et al. (2012) and Caracoglia and Jones (2009) based on series of observations, presented an opposite results that higher frequencies contained larger amount of energy rather than low frequencies. Li et al. (2012) provided spectrum models for their observation with high amount of energy in high frequencies as:

$$\frac{nS_u(n)}{\sigma_u^2} = \frac{16.\,66f}{1.\,72 + 237.\,24f^{5/3}} \tag{4}$$

Table 2 summarizes the spectrum models presented by mentioned researchers and used in this paper. In addition, Fig. 1 shows the difference between recent observed models and the spectrum introduced by Kaimal et al. (1972).

Some relevant discussion can be found in the meteorological and engineering literature to understand the large variation in hurricane spectra. Wind spectra can be affected by various parameters such as upstream roughness (Yu et al., 2008). It is been observed that spectral values water surface and sea are higher than those of onshore regions. Also for open exposures, the spectral energy contents in lower observatory anemometers are more than those in higher observatory devices (Yu et al., 2008). Moreover, the low frequency range of spectrum depends on the atmospheric stability (Kaimal et al., 1972; Tieleman, 1995; Yu et al., 2008), hence for increased instability, the

Table 1
Coefficients of Yu et al. (2008) spectrum.

Spectra	p_1	p_2	p_3	q_1	q_2	q_3
10 m, Over Land	−0.9999	3.112	1.159e-4	18.64	1.188	3.35e-3
10 m, Over Sea	−0.00598	0.1544	1.055e-5	0.4458	0.06486	9.754e-5

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