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Spectral characteristics of surface-layer turbulence in the North Sea

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Abstract

According to IEC 61400-1 and IEC 61400-3 standards, the wind load on the rotor-nacelle assembly of offshore wind turbines should be estimated from the Kaimal or Mann spectral models, unless site-specific full-scale measurements are available. The Kaimal spectral model was developed in a flat and homogeneous onshore site and its applicability in offshore environment, e.g. the North Sea, where a number of wind turbines are in operation, is not thoroughly documented. The present paper utilizes the wind data recorded on the offshore platform FINO 1 in 2007 and 2008 to study the single-point auto-spectral and cross-spectral densities of wind turbulence. It investigates the validity of the Kaimal model, the Mann spectral model, the IEC Kaimal model and the one proposed in the NORSOK standard N-003. The latter standard is developed by the Norwegian petroleum industry for the design of offshore structures. Time series of 1 h duration are considered and a simple non-stationary wind model based on a time-varying fluctuating mean is used to increase the number of samples that can be treated as stationary.

For wind velocities ranging from $14\,\mathrm{m\,s^{-1}}$ to $28\,\mathrm{m\,s^{-1}}$, a good agreement is observed between the Kaimal spectra and the measured ones, although the power spectral density of the wind fluctuations is larger than predicted for reduced frequencies below 0.04. The Mann spectral model showed a good agreement with the measured spectra. At the altitude of 80 m, we found in average $\Gamma = 3.7$, $\alpha\epsilon^{2/3} = 0.04\,\mathrm{m^{4/3}s^{-2}}$ and $L = 70\,\mathrm{m}$. Finally, the NORSOK spectrum agrees fairly well with the measured one if a Charnock coefficient of 0.011 is used.

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Keywords: Surface-layer turbulence, FINO 1, Wind spectra, Full-scale measurements, Offshore wind

1. Introduction

The dynamic wind load on wind turbines is commonly modelled in the time domain using the wind spectral models provided by IEC 61400-1 [1]. These include the models by Kaimal et al. [2] and Mann [3], the parameters of which have been fitted to the Kaimal spectral model. The latter model was developed for a flat and homogeneous onshore site, and its applicability in offshore environment is little documented, especially for the North Sea. Few spectral models have been designed using offshore measurements. Among them is the wind spectrum currently used in the NORSOK standard [4] and developed based on field measurements in Sletringen (Frøya municipality), which is an island located ca. 110 km West of Trondheim in Norway.

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The offshore platform FINO 1, located 45 km North of Borkum in Germany, provides continuous measurements of offshore wind since 2003 [5]. Until now, the data collected have been used to describe the turbulence intensity [6], to study the wind velocity profile over the sea [7], turbulent fluxes [8, 9] and the wind coherence [10]. The platform has also been utilized to investigate the applicability of wind lidar technology to measure turbulence statistics [11, 12]. As shown in a short review by Kettle [13], no in-depth analysis of the single-point auto-spectral and cross-spectral densities of the wind fluctuations has however been conducted.

Based on the wind data recorded on the offshore platform FINO 1 in 2007 and 2008, the present paper assesses the applicability of the Mann spectral model, the Kaimal spectral model and the NORSOK spectrum to model the surface-layer wind turbulence in offshore environment, under neutral and near-neutral atmospheric stability. The study is organized as follows: firstly, a review of measurements of offshore wind spectra during the last thirty years is presented. Secondly, the measurement site is briefly introduced as well as an overview of the wind conditions recorded in 2007 and 2008. Thirdly, the wind spectra estimated from the measurement data for the three wind components are compared to the Mann and the Kaimal spectral models. For the along-wind component, the comparison also includes the NORSOK spectrum and the IEC Kaimal spectrum. The discussion focuses on the challenges associated with the study of the spectral characteristics of offshore wind.

2. Instrumentations and methods

2.1. A review of offshore wind spectra

At the end of the 70s, Naito [14, 15] conducted early measurements of the spectral characteristics of offshore wind in Japan, 1 km from the coast and up to 15 m above sea level. These measurements remain a rare case where the three wind components were measured offshore (Table 1). In 1985, based on the measurements of Smith [16], Kareem [17] proposed an empirical wind spectrum for the along-wind component derived from Kaimal et al. [2] that was better suited for modelling the dynamic wind loads in offshore environment. In 1988, Ochi et al. [18] reviewed the different wind spectra measured the decade before and showed that they were similar in the high frequency domain but displayed significant differences in the low frequency range, which highlights the need to use site-specific spectra to better model wind loads on offshore structures. In the 90s, the spectral characteristics of wind were studied on the Norwegian coast by Andersen and Løvseth [19–21] and are currently used in NORSOK Standard [4]. More recently, the de Maré and Mann [22] assessed the Mann turbulence model in the Baltic Sea for wind velocities ranging from $8\,\mathrm{m\,s^{-1}}$ to $12\,\mathrm{m\,s^{-1}}$. The present paper complements their study by considering larger wind velocities and a higher measurement altitude.

In the present study, the along-wind, across-wind and vertical wind component are denoted u, v and w, respectively. The wind component $i = \{u, v, w\}$ is a random process that can be split up into a mean part, $\bar{i}$, and a fluctuating part with zero mean, i'. By definition, $\bar{v} = \bar{w} = 0\,\mathrm{m\,s^{-1}}$ [23], leading to the following relations:

$$u = \bar{u} + u' \tag{1}$$

$$v = v' \tag{2}$$

$$w = w' \tag{3}$$

Table 1. Review of full-scale measurements of offshore wind spectral densities.

Reference	Location	Wind component(s)	Velocity range	Averaging time
Naito [14, 15]	Sagami Bay	u, v, w	$2\,\mathrm{m\,s^{-1}} < \bar{u} < 19\,\mathrm{m\,s^{-1}}$	27 min
Smith [16], Kareem [17]	Atlantic NW	u	$6\,\mathrm{m\,s^{-1}} < \bar{u} < 22\,\mathrm{m\,s^{-1}}$	40 min
Eidsvik [24]	Norwegian Sea	u	$2\,\mathrm{m\,s^{-1}} < \bar{u} < 36\,\mathrm{m\,s^{-1}}$	20 min
Andersen and Løvseth [21]	Norwegian Sea	u	$15\,\mathrm{m\,s^{-1}} < \bar{u} < 27\,\mathrm{m\,s^{-1}}$	40 min
de Maré and Mann [22]	Baltic Sea	u, v, w	$8\,\mathrm{m\,s^{-1}} < \bar{u} < 12\,\mathrm{m\,s^{-1}}$	30 min
Present study	North Sea	u, v, w	$14\,\mathrm{m\,s^{-1}} < \bar{u} < 28\,\mathrm{m\,s^{-1}}$	60 min