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Cross-wind fatigue analysis of a full scale offshore wind turbine in the case of wind–wave misalignment

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ABSTRACT

Wind–wave misalignment is often necessary to consider during the design of offshore wind turbines due to excitation of side–side vibration and the low aerodynamic damping in that direction. The measurements from a fully instrumented 3.6 MW pitch regulated-variable speed offshore wind turbine were used for the estimation of the side–side fatigue loads at the tower bottom. The joint wind–wave distribution and the distribution of the wind–wave misalignment angles were considered. The side–side fatigue at the tower bottom and the damping from site measurements are presented as function of the misalignment angles. A model of the same wind turbine was set-up and simulations with the aero-hydro-servo-elastic code HAWC2 were performed to investigate the effect of damping on the side–side fatigue. Turbulent wind field, irregular waves and flexible soil are used in the simulations based on site-measurements. The aim of the current study is to examine the sensitivity of the side–side fatigue to the wind–wave misalignment and different values of additional offshore damping in the system. It was found that the additional offshore damping of the physical system may be higher than what is typically used in offshore wind turbine sub-structure design, due to the low sensitivity of the measured side–side fatigue loads to the misalignment angle. Choice of an accurate damping value implemented in the model during the design of the wind turbine sub-structure can lead to material and cost savings.

1. Introduction

Cross-wind fatigue on offshore wind turbine monopile support structures due to wave loading misaligned with the wind can become a significant design driver, because of the low aerodynamic damping experienced in this direction. According to the DNV guidelines for offshore structures [1], the misalignment between the wind and wave directions should be included in the design if misalignment conditions are present in the site of installation. However, these cross-wind fatigue loads are difficult to predict due to uncertainty in the overall system damping. The choice of a conservative damping value can result in over-dimensionalization of the substructure, high estimated fatigue loading and a design which is not economically feasible. In Ref. [2], the cross-wind aero-elastic damping is examined, and the sensitivity of the cross-wind loads to the damping, especially during wind–wave misalignment, is highlighted. In the same study, measurements from offshore wind turbines at Horns Rev 1 and the Burbo offshore wind farms, were used to estimate the damping and a logarithmic decrement δ of about 10% was found (excluding aerodynamic damping). This analysis gave indications that the actual damping on offshore wind turbines is more than what is typically used in design calculations ($\delta = 6\%$) [2]. In Ref. [3], the logarithmic decrement considering only the non-aerodynamic damping (structural-, hydrodynamic-, soil-damping) is estimated as 14–15% (2.25% damping ratio).

The effect of misalignment angles on the fatigue of the structure is examined in Ref. [4]. A study conducted by Fischer et al. [5] considering all load cases described in IEC 61400-3 [6] and misalignment angles from 0° to 360° demonstrated the importance of wave directionality during the design process. The bending moment in the fore–aft direction was 30% higher in the case of waves perpendicular to the wind, while the side–side loading is 5 times larger when compared to aligned wind and wave results. In Ref. [7], the equivalent loads and fatigue damage at the tower and monopile bottom were examined for different cases of wind–wave misalignment, considering both linear and non-linear waves. The effect of misalignment on the simulated fatigue, including the probability density function of misalignment angles has

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been investigated in Ref. [8]. For a misalignment distribution with a peak close to 0° the fatigue damage in the tower bottom was increased by 3.6% between the misaligned and the collinear cases. For the case where the highest probability of occurrence is for an angle of 60° the increase in the fatigue damage is up to 15%. An increase in the fatigue damage accumulation due to waves perpendicular to the wind direction is also reported in Ref. [9], where a non-linear irregular wave model is implemented in the analysis.

In the current study the target is to investigate the sensitivity of the cross-wind fatigue loading to the different wind–wave misalignment angles, for various values of the net damping of the system. In the analysis the misalignment distribution is considered. The outline of this paper is as follows: firstly the site and the measurements calibration are described in Sections 2 and 3. Secondly the joint wind–wave distribution and the misalignment distribution based on site observations are presented in Section 4. Thirdly the calculation of the damage equivalent loads of the measured cross-wind vibration at the tower bottom for each wind–wave bin and misalignment sector are discussed. Finally the sensitivity of the cross-wind fatigue to the different misalignment angles, for different damping values is examined.

2. Site description

A 3.6 MW Siemens pitch regulated-variable speed wind turbine with a 107 m rotor is installed at the Walney Offshore Wind farm 1 (Fig. 1a). The wind turbine is located at the west coast of England, 15 km from the shore, in the Irish Sea and has been fully instrumented for load measurements. The turbine is mounted on a monopile structure at a water depth of 26 m. Strain gauges and accelerometers are installed at 4 different heights throughout the whole length of the tower (4 gauges per height). The sampling rate of the data acquisition system is 35 Hz. The data has been obtained from the wind turbine manufacturer (Siemens Wind Power) and DONG Energy and is presented in this paper in normalized terms. A nacelle mounted cup-anemometer provides wind speed measurements in time series of 10 min and a buoy installed close to the foundation measures the wave characteristics every 30 min (including significant wave height, peak crossing period and wave direction). Turbine yaw angles, blade pitch angles and power production are obtained as 10 min averages from the SCADA data. The mean yaw angle provided by the SCADA data was used to estimate the wind direction and the mean wave direction from the buoy are compared to identify cases of wind–wave misalignment (Fig. 1b).

3. Measurements calibration

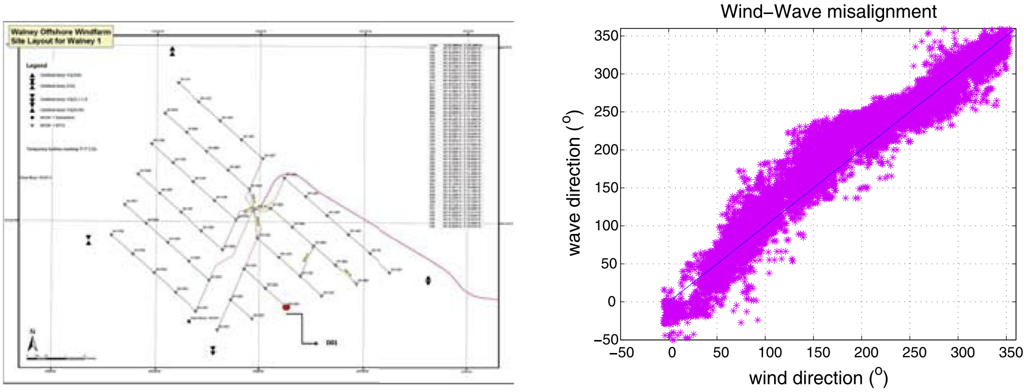
Before the post-processing of the measurements a calibration of the raw data from the strain gauges is required. The time series data are divided up into files each corresponding to 10 min of measurements and the signals are in voltage. Four strain gauges are installed per height placed one across from the other at 150°–330° for the measurement of the North–South and 60°–240° for the East–West bending (Fig. 3a). In the same figure, the sign of the moments from the coordinate system definition is also presented. The tower measurements were calibrated using the mass and offset center of gravity of the nacelle, where the nacelle is slowly rotated 360° around the yaw axis. Fig. 2 presents the coordinate system of the support structure used for the measurements calibration, along with the location of the nacelle center of gravity (CoG). The moment induced by the nacelle weight is defined as a negative moment in the x direction. The subscript T denotes tower. The offset of the CoG creates a moment, which is captured by the strain gauges during the yaw test as a sinusoidal curve. Fig. 3b presents an example of the strain signal versus the yaw angle.

The range of the sinusoidal curve from the yaw test is equal to twice the expected moment due to the nacelle weight. This allows the gain of the bridge to be estimated as shown in Eq. (1a). The bridge offset is the mean value of the sinusoidal curve, calculated by Eq. (1b). $min(V)$ denotes the minimum strain value in voltage observed during the test, $Mass_{nacelle}$ is the mass of the nacelle, g is the acceleration due to gravity, d is the distance of the nacelle center of gravity (CoG) from the tower axis and $range(V)$ is the range of the sinusoidal curve in voltage. The transformation to the rotating system that follows the wind turbine is performed through Eq. (2), where α is the angle between the strain gauge position and bridge north (30°) and y is the yaw angle at each time step.

$$gain = \frac{2 \cdot Mass_{nacelle} \cdot g \cdot d}{range(V)}, \tag{1a}$$

$$offset = -Mass_{nacelle} \cdot g \cdot d - gain \cdot min \tag{1b}$$

$$\begin{aligned} M_{x,rot} &= M_{NS}\cos(\alpha - y) - M_{EW}\sin(\alpha - y) \\ M_{y,rot} &= M_{NS}\sin(\alpha - y) + M_{EW}\cos(\alpha - y) \end{aligned} \tag{2}$$



(a) Outline of Walney Offshore Wind farm 1 (DONG Energy).

(b) Wind-wave misalignment in the site.

Fig. 1. Walney offshore wind farm 1.