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Directional effects on the reliability of non-axisymmetric support structures for offshore wind turbines under extreme wind and wave loadings

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ABSTRACT

In comparison with monopile support structures commonly used for offshore wind turbines (OWTs) in shallow water, fixed bottom support structures for deeper water such as jackets tend to lack axisymmetry and have different capacities when loaded in different directions. Design of such a structure may therefore benefit from consideration of the directional characteristics of loading. This paper focuses on a rational and efficient approach to assess the structural safety of jacket type OWTs under directionally dependent extreme environmental loads. The Incremental Wind–Wave Analysis (IWWA) framework is reviewed and used to assess capacity of jacket-type OWTs under directional environmental wind–wave conditions. The approach uses static pushover analysis of OWT jackets subject to combined wind and wave load patterns corresponding to increasing mean return periods (MRPs). The wind and wave conditions are calculated independently and assumed to occur simultaneously. The loading direction and jacket orientation are both included in the analysis. To illustrate the approach, metocean conditions at different sites along the U.S. Atlantic coast are obtained from the historical database of the National Oceanic and Atmospheric Administration (NOAA) Data Buoy Center. Two models are introduced for estimating the occurrence probability of wave direction, one of which directly uses the frequency of wave directions and the other uses a Gaussian kernel to represent the range of wave directions represented by given directional spectra. For each combination of wind–wave direction and structural orientation, an IWWA analysis gives the capacity in terms of the MRP conditions leading to formation of a fully developed plastic mechanism in the jacket. Those capacities, convolved with MRP models for loading intensity, yield direction-dependent structural reliabilities, and when those reliabilities are convolved with the probability density function for load direction, a total failure probability is obtained that accounts for wave directionality. Example analyses are conducted for an OWT supported by a four-leg jacket adapted from a design published as part of the European Union UpWind Project. Effects of extreme load directionality, structural orientation, structural geometry and site specification on the ultimate capacity of the jacket are carefully discussed.

1. Introduction

Renewable energy continues to contribute an increasing amount of energy to the global energy system and wind energy shows particular promise as a sustainable source of energy. It is planned that 20.0% of the electricity demand of the United States and 28.5% of the demand of the European Union will come from wind energy by 2030 [1,2]. The efficiency of offshore wind energy extraction will play a significant role in meeting these wind energy targets. Construction of offshore wind turbines (OWTs) requires different types of support structures for different water depths and geotechnical conditions, e.g. monopiles for shallow water up to 25–30 m, jackets and tripods for deep water (30–80 m depth) and floating platforms for water deeper than 80 m. Continued development of design and risk assessment techniques for such structures can play an important role in continuing to lower the overall cost of energy for offshore wind since the support structure can account for approximately 25% of the initial capital cost of an OWT [3].

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Most of the support structure types, except monopiles, are not axisymmetric. For example, a typical OWT jacket has 3 or 4 legs and a triangular or square cross-section. These kinds of non-axisymmetric support structures have different stiffness and capacity when loaded in different directions. The American Petroleum Institute (API) suggests that a minimum of 8 directional analyses are required for symmetrical, rectangular and square platforms, a minimum of 12 directions are required for tripod jackets, and even more additional directions are required for other unsymmetrical structures to ensure appropriate structural safety [4]. Further directional dependence comes from the fact that environmental loading intensity (e.g. wind speed and wave height) also varies with direction. Previous studies that assume wind and waves are unidirectional and load the support structure from a deterministic direction clearly cannot fully account for the directional dependence of capacity and loading that will influence the reliability of non-axisymmetric OWT support structures [5,6]. Neglecting the effect of directionality in the analyses of OWT support structures [7,8] surely does not allow for optimization of the structural orientation to minimize overall failure probability. In principal, it is possible that the structural orientation corresponding to minimum failure probability may not coincide with that which aligns the structural orientation with greatest capacity in the direction of most likely loading. Furthermore, it should be noted that the orientation of the support structure is essentially a free parameter in the design since the turbine is free to yaw and can face into the prevailing wind to maximize energy generation regardless of structural orientation. Therefore, a framework including the metocean conditions with directional dependences is valuable for risk and safety assessment of non-axisymmetric OWT support structures.

The effect of load directionality on the operational response, ultimate capacity, fatigue performance, natural frequencies, etc. of offshore support structures has been the subject of some attention in the open literatures. Haver [9] studied the effect of wave directionality both for the quasi-static response and for the dynamic response of offshore jackets and stated that the extreme response is very sensitive to the platform orientation when all the sea states are assumed to approach from one direction. Bea et al. [10] highlighted the importance of the directional characteristics of the waves on the magnitude of measured deck forces, a loading that has been cited as the main reason for localized damage to the superstructure of oil platforms during hurricanes [11]. Li [12] further studied the directional effect of wind and wave loads on OWT jackets using a quasi-static pushover procedure and indicated that (i) the direction of the wind and wave force affects the structure's failure mechanism and ultimate strength significantly; (ii) the largest capacity of the jacket is attained when the jacket is oriented broadside to the dominant wave direction and the minimum capacity is attained when waves approach at 45° to the sides of a square plan jacket. Philippe et al. [13] found through modal analysis that natural modes for a particular floating OWT system are excited differently depending on the approaching direction of the waves. Mittendorf et al. [14] investigated the influence of directional irregular wave models on damage equivalent fatigue loads of OWTs and found that the consideration of the waves' directionality results in an approximate reduction of the observed fatigue loads of up to 20% compared to unidirectional models.

Many approaches have been developed to obtain directional environmental loading for analysis and design of non-axisymmetric offshore structures. One approach is specified in the API code [4] and recommends a wave height adjustment factor to account for the wave directionality in the Gulf of Mexico without the use of a directional and irregular nonlinear design wave. This is a simplified approach that allows an analysis to account for directional effects [15], but the development of the adjustment factors requires lengthy metocean monitoring and does not supply any probability information of the direction of approaching waves. A second approach to directional analysis is to generate a stochastic wave simulation that includes multidirectional waves corresponding to a directional wave spectrum [9,16–18]. This approach depends on the directional wave spectrum, which is always site-specific [19], and requires dynamic time history analysis which can be prohibitively time consuming when structural nonlinearities are to be included as well. A third approach to directional analysis borrows from both approaches and attempts to estimate possible directional extremes based on criteria obtained from existing sources of observed or simulated directional wave statistics [20,21]. Our study is based on the third type of approach to assess the directional intensities of OWT support structures.

This paper adds to the literature on directional effects for offshore structures by: using Incremental Wind–Wave Analysis (IWWA) [22] to assess structural capacity in a more accurate load-pattern dependent way; assessing directional effects for a realistic OWT jacket support structure; illustrating the approach with wave direction distributions and wind/wave intensity distributions derived from measured data from the U.S. coast; convolving wind/wave direction and intensity distributions to assess structural reliability as a function of jacket orientation.

2. Analysis framework

2.1. General configurations and assumptions

Fig. 1(a) shows the general configuration of a jacket-supported OWT that consists of the entire OWT assembly up to the bottom of the rotor–nacelle assembly (RNA). θ_{load} here refers in particular to the dominant wave direction, which dominates the failure of OWT jacket [22]. Since the jacket is a wave dominated structure (in the absence of yaw error) the wind is treated here as co-directional with the wave field. The structural configuration of the jacket is based on the model jacket defined in the European Union UpWind report [23], and the tower and RNA correspond to the widely disseminated National Renewable Energy Laboratory (NREL) 5-MW turbine [24]. Several simplifying assumptions regarding the loading conditions are made and these allow primary attention to be paid to the role of load directionality in governing the response of jacket-supported OWTs to extreme loading. First, the wind and wave loads are assumed to be co-directional without wind–wave misalignment. Second, perfect yaw control is assumed such that the turbine always faces directly into the wind and, as defined in Fig. 1(b), $\theta_{rotor} = \theta_{load}$, where θ_{rotor} is the direction of the RNA (i.e. the direction normal to the blade plane).

The Incremental Wind–Wave Analysis (IWWA) framework [22] provides an efficient nonlinear static approach to evaluate the capacity of OWT support structures subject to arbitrary combinations of wind and wave load. The approach, referred to as the IWWA1 procedure [22], combines independently evaluated wind and wave conditions at common mean return periods (MRPs). This approach neglects the correlation between wind and wave conditions and assumes that the MRPs of the wind and wave conditions are independent and the wind and wave conditions at equivalent MRPs occur simultaneously. Industry standards for offshore structures such as those published by API [4] and IEC [25] prescribe methods for determining wind and wave conditions from independent distributions. However, many papers have studied the effect of wind and wave correlation through FORM (First Order Reliability Method) [26] and IFORM (Inverse First Order Reliability Method) [27–29] and have highlighted that the assumption of independence is conservative and unrealistic under actual offshore