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Incremental wind-wave analysis of the structural capacity of offshore wind turbine support structures under extreme loading

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ABSTRACT

Offshore wind turbine (OWT) support structures are subjected to non-proportional environmental wind and wave load patterns with respect to increases in wave height and with respect to wind and wave combined loading. Traditional approaches to estimating the ultimate capacity of offshore support structures are not ideally suited to analysis of OWTs. In this paper, the concept of incremental wind-wave (IWWA) analysis of the structural capacity of OWT support structures is proposed. The approach uses static pushover analysis of OWT support structures subject to wind and wave combined load patterns corresponding to increasing mean return period (MRP). The IWWA framework can be applied as a one-parameter approach (IWWA1) in which the MRP for the wind and wave conditions is assumed to be the same or a two-parameter approach (IWWA2) in which the MRPs associated with wind and wave conditions are related to a joint probability density function characterizing the wind and wave conditions at the site. Example calculations for monopile and jacket supported OWTs at Atlantic marine sites are performed under both one parameter and two parameters IWWA framework. The analyses illustrate that: the results of an IWWA analysis are site specific; and structural response can be dominated by either wind or wave conditions depending on structural characteristics and site conditions. Finally, reliability analyses for both examples excluding uncertainties in structural resistance are estimated based on their IWWA results and probabilistic models for site environmental conditions.

1. Introduction

In recent decades, offshore wind energy has been experiencing rapid worldwide development as an attractive renewable energy source [1]. Europe and Asia already have significant installed capacity on the order of gigawatts in Europe to hundreds of megawatts in Asia [2,3], and it is planned that 20% of the electricity demand of the United States will come from wind energy by 2030 [4]. Compared with onshore wind energy, offshore wind energy resources are emphasized both to exploit the tremendous potential of the offshore wind resource and mitigate the impact of wind turbines development on human populations [5]. The middle and northern Atlantic coast, the region in which offshore wind energy development will likely be focused in the U.S., is regarded as a natural place for offshore wind energy due to the large wind resource and short distance to population centers [6]. This paper introduces a novel method for assessing the structural capacity of fixed-bottom offshore wind turbine (OWT) support structures. The method accounts for varying load patterns that can affect OWT capacity due to non-proportional scaling effects of increased wind speed, wave height and their combinations. At this point in its development, the approach does not account for additional loads due to current or changes in mean water level. This approach, by accounting for variation in load pattern with increasing intensity of environmental conditions, contrasts with the approach typically used in seismic analysis of structures in which a single parameter, e.g. peak ground or spectral acceleration, can reasonably parameterize the seismic loading and the load distribution or pattern can be assumed to be constant with increasing acceleration. The approach described here is particularly useful for risk analysis of OWTs under extreme loading since current design practice attempts to ensure elastic response under design conditions.

To install wind turbines at marine sites, many configurations of offshore support structures are used. The monopile is the most common solution for OWTs in shallow water up to 25–30 m, and jackets are being investigated and proposed for the use of

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fixed-bottom turbines in deeper water (30–80 m depth) which promises to open up even more of the offshore wind resource [7,8].

Although movement towards offshore wind development is potentially transformative for the nation's energy portfolio, challenges become apparent almost at once: the Atlantic coast is at a considerable risk from severe hurricanes [9] and the environmental (wind and wave) loadings on OWTs lead to greater forces in the structure than those that would occur onshore, exacerbating the civil engineering problem [10–12]. Furthermore, the greater cost of OWTs means that analysis of the probability of failure under extreme loadings is even more important for OWTs than for onshore turbines.

Many studies have been carried out for load and response estimation for wind turbines with monopile and jacket foundation under uncoupled or combined wind and wave conditions from a given environmental model or measured data, e.g. Seidel et al. [13], Agarwal and Manuel [14], Jensen et al. [15], Haselbach et al. [16], Mardfekri and Gardoni [17] and Saha et al. [18]. These studies were mainly concentrated on dynamic time history simulation of support structures in the elastic or operational range of response. Ultimate capacity of OWTs has been seldom mentioned in the literature, yet an accurate prediction of capacity is needed to allow rational risk assessment.

Pushover analysis with material and geometrical nonlinearities is an efficient approach to evaluate nonlinear behavior and ultimate capacity of offshore structures [19] and has been recommended by industry standards [20]. Although pushover analysis techniques are well developed for offshore oil and gas platforms, that framework is not ideally suited to analysis of OWTs. First, traditional pushover analysis assumes that the lateral loading can be parameterized by a single variable and assumes that the lateral loading distribution or pattern remains constant as the load parameter is scaled up. This assumption does not hold for OWTs since wind and wave loads on the structure are imperfectly correlated [21] and wave loads are non-proportional with an increase in wave height [22]. This variability of the load pattern with increasing loading intensity leads to a dependence between the load intensity and the capacity [23,24]. The simplest way to understand this load pattern variability is that a taller wave, even if generating the same base shear as a shorter wave, will generate greater base moment due to the greater moment arm associated with the greater wave height. Second, extreme conditions which only appear at longer return period can contribute significantly to the lateral load in ways that could not be accounted for if a shorter return period load were simply scaled up as in a traditional pushover analysis. For example, wave-in-deck forces arise when the wave height is such that the wave interacts with the deck of a jacket structure [25]. A recent study of capacity analysis of oil and gas jacket platforms has introduced the idea of Incremental Wave Analysis (IWA), which arrives at capacities for jackets and accounts for load pattern variation with wave height [26]. This paper extends the idea of IWA to include the wind loads that act on an OWT and describes a new approach to fixed-bottom OWT capacity analysis called Incremental Wind-Wave Analysis (IWWA).

The remainder of this paper is organized as follows: The IWWA framework is introduced as a general approach in both single and double parameter versions in which the wind and wave loading intensities are scaled by a single parameter or two joint parameters; specific methods for calculating wind and wave loads on OWTs used in the examples are summarized; two example support structures, a monopile and a jacket, are introduced and site environmental conditions are specified; the results of IWWA analysis are presented for both structures and those results are discussed; finally, the main conclusions of the paper are summarized.

2. Incremental wind-wave analysis framework

The incremental wind-wave analysis (IWWA) framework provides a systematic and efficient approach to evaluate the capacity of OWT support structures subject to arbitrary combinations of wind and wave load. Dynamic effects of wind and wave loads, such as wind turbulence, wave irregularity, wave-structural interaction, time-dependent variance of loading direction and amplitude, etc., that require time history analysis would affect the operational and ultimate results. The question of dynamic versus static capacity estimation has ever been addressed by Golafshani et al. [26] for offshore oil and gas support structures and they found, for two different example platforms, that the difference between the dynamic and static results was either negligible (less than 0.5%) or approximately 14% such that the static analysis provided a conservative estimate. The difference is dependent on the dynamic behavior of the platform. Dynamic effects have been neglected here to provide initial insights into the load pattern dependence of OWT support structure capacity and because of the large computational demands of the multiple nonlinear time history analyses required for an analogous dynamic approach. In this section two forms of the IWWA framework are described in general terms, one–called: IWWA1–in which a scalar hazard measure is used for combined wind and wave loading and one–called: IWWA2–in which separate hazard measures are used for the wind and wave loading. Although the scalar, single-parameter IWWA has significant limitations due to the assumption that wind and wave conditions at equivalent, independently estimated return periods occur simultaneously, it is still described first followed by the vector-valued two-parameter IWWA to provide maximum clarity and accessibility of the methods.

2.1. Single-parameter IWWA

Consider an OWT support structure that occupies a space denoted by $S \subset \mathbb{R}^3$, has material properties $M(x)$ where $x \in S$ gives a position in the structure, and subject to point and distributed loading $L(x;\text{wind},\text{wave})$, where $x \in \partial S$ denotes a point on the surface of the structure. For the purposes of developing the IWWA framework, the support structure is assumed to be fully fixed at the mudline and consist of the entire OWT assembly up to the bottom of the rotor-nacelle assembly (RNA). In the single parameter IWWA the environmental conditions are parameterized by the mean return period (MRP) of the wind and wave conditions so that the loading can be expressed as $L(x;\text{MRP})$ and to maintain a direct connection to the probabilities of occurrence of the environmental conditions. In principle, any method for estimating the wind and wave conditions at various MRPs can be used in the IWWA framework including approaches such as the inverse first order reliability method (IFORM) that generates a contour in the probability space corresponding to an MRP for a set of combinations of wind and wave conditions. Here the joint pdf of the wind and wave conditions is just that, but the independently assessed return periods have been substituted for the wind speed and wave height to maintain a closer connection to the probabilities of occurrence of the wind and wave conditions. The specific approach used here is developed as follows: (1) We calibrate the probability models for wind and wave based on the historical database from the NOAA data buoy center, annual maxima selected from hourly measurements of the wind speed at 5 m elevation $W_s\ (60\ \text{min},\ 5\ \text{m})$ and significant wave height H_s; (2) We adjust those values to correspond to 1-min wind speeds at 90m elevation $W_s\ (1\ \text{min},\ 90\ \text{m}) = 1.608 W_s\ (60\ \text{min},\ 5\ \text{m})$ or extreme waves $He = 1.87 H_s$; (3) We develop independent joint probability models for these annual maxima of the 1-minute wind and extreme wave