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Damage equivalent wind–wave correlations on basis of damage contour lines for the fatigue design of offshore wind turbines

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ABSTRACT

An adequate representation of the site-specific wind–wave joint distribution is essential for cost-efficient and reliable designs of offshore wind turbines. Therefore, the wind and wave climates are subjected to a correlation of wind and wave parameters for design purposes. These correlations are often based on a lumping of the directional wave climate and subsequent association of the lumped wave climate to the directional wind climate. Preservation of the hydrodynamic fatigue distribution from the full wave climate is an important aspect in the wind-wave correlation process which requires an adequate consideration of the dynamics from the offshore wind turbine. However, only a few wind-wave correlation methods exist for the fatigue design of offshore wind turbines and none of them take the dynamics of the full structure adequately into account. In this study a new wind-wave correlation method has been developed and introduced. The new method is based on the establishment of damage contour lines which are used to determine the sea-state parameters that ensure simultaneous compliance with damage equivalency criterions at different locations within the offshore wind turbine. This simultaneous damage equivalency throughout the structure together with the straightforward derivation of the corresponding damage equivalent sea-state parameters constitutes the novelty of the presented wind-wave correlation method.

1. Introduction

The fatigue design of offshore wind turbines (OWTs) is governed by dynamic responses from simultaneous aerodynamic and hydrodynamic loads. State-of-the-art methods to determine the corresponding design loads in a detailed design process is represented by integrated load calculations with aero-elastic tools under consideration of simultaneous wind and wave conditions as described e.g. by Ref. [17]. The establishment of these simultaneous wind-wave conditions requires a derivation of wind-wave joint parameters from a site- and project-specific met-ocean database. In practice the combined wind-wave parameters are established by a lumping of the wave climate and corresponding association to the wind climate, which hereinafter is denoted as wind-wave correlation. In this wind-wave correlation process it is very important to preserve the fatigue damages introduced from the underlying wind and wave climates in order to ensure a cost-efficient and reliable design. However, accurate wind-wave correlation methods for the fatigue design of OWTs do not exist and guidance is also missing in all relevant design guidelines, e.g. Refs. [4,8,11]. Hence, designers need to apply simplified correlation methods which do not necessarily capture the dynamics over the entire OWT and consequently introduces an uncertainty in the calculated fatigue design loads, in particular for hydrodynamically sensitive structures.

Passon & Branner showed in Ref. [18] that the lumping approach for the wave climate has a significant influence on the accuracy of calculated hydrodynamic fatigue loads. Furthermore, they introduced a damage equivalent lumping method for the wave climate that allows for preservation of the hydrodynamic fatigue damage distribution. However, this method does not consider a coupling of the lumped wave climate with the wind climate as required in the detailed design process of OWTs. Analogously to the wave lumping, the association of the wave climate with the wind climate has a significant influence on accuracy of the fatigue design loads.

Therefore, an improved wind-wave correlation method for the fatigue design of OWT is introduced in the present article. The new method allows for derivation of damage equivalent sea-state parameters, in terms of wave height and period, for each combination of wind speed, wind direction and wave direction. Here, the lumping of the wave climate and the connection to the wind

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Nomenclature

$\boldsymbol{D}^*$	unit damage matrix
$\boldsymbol{D}_s^*$	scaled unit damage matrix
$\boldsymbol{D}$	damage matrix
d	fatigue damage [−-]
p	probability [−]
v	hub height wind speed [m/s]
H_s	significant wave height [m]
T_p	peak period [s]
DCL	damage contour line
SCD	wave scatter diagram
OWT	offshore wind turbine

climate is performed simultaneously in one integral step. The corresponding sea-state parameters are determined from damage contour lines (DCLs) obtained for pre-established target damage levels at different locations within the OWT e.g. at mudline and tower top. Damage equivalency throughout the structure is ensured by selection of coinciding combinations of sea-state parameters from DCLs at different locations within the OWT.

The new wind-wave correlation method presented in this article is an extension of the wave lumping method presented by Refs. [18,20]. Calculation examples including an assessment of the accuracy with respect to a full wave climate and alternative wave lumping methods complement the introduction of the new method. The met-ocean database of the Veja Mate Offshore Wind Farm project as established by Rambøll Wind is used for that purpose. The database comprises relevant met-ocean information in a high degree of detail and quality. Veja Mate is planned as a 400 MW offshore wind farm located at 40 m water depth within the German exclusive economic zone. The project is developed by Veja Mate Offshore Holding GmbH and their representative K2 Management GmbH with SWT-6.0-154 wind turbines from Siemens Wind Power A/S. Furthermore, the monopile type substructures are designed by Rambøll Wind.

2. Organization of wind–wave parameters for fatigue design purposes

Typically, detailed designs of OWTs are based on integrated load calculations under consideration of simultaneous wind and wave conditions. All relevant met-ocean parameters are commonly organized by primary parameters and associated parameters. Primary parameters form the general structure of the fatigue load cases and are defined a priori due to their project-specific but not site-specific character. The primary parameters used in this article are:

- Mean wind speed at hub height v.
- (Mean) wind direction φ_{wind}.
- (Mean) wave direction φ_{wave}.

Associated parameters are site-, project- and structure-specific and derived for the individual combinations of primary parameters. In the context of this article the relevant associated parameters are:

- Significant wave height H_s.
- Peak period T_p.
- Wind–wave joint probability of occurrence p.

Table 1 shows an organization for the relevant selection of primary and associated wind-wave parameters. The pre-defined

Table 1
Example structure of load case table parameters for one directional wind-wave combination used in the fatigue design of OWT.

v	φ_{wind}	φ_{wave}	H_s	T_p	p
2.5	30	120			
3.5	30	120			
…	…	…	…	…	…
31.5	30	120			
32.5	30	120			

primary parameters are filled in while the values of the associated parameters are left empty. Each line in the table represents one set of primary and associated parameters used for design load calculations note that e.g. a hub wind speed of 2.5 m/s represents wind speeds in the interval between 2.0 m/s and 3.0 m/s.

The calculation of the probabilities of occurrence p from wind distributions and wind-wave misalignment information is rather straightforward. Derivation of adequate wave parameters on the other hand is more complicated since a range of H_s-T_p combinations, described by wave scatter diagrams (SCD), or more properly denoted as wave scatter matrices, can occur for each set of the primary parameters mean wind speed, wind direction and wave direction. However, for practical applications typically only one unique H_s-T_p combination is associated to each individual set of primary parameters, mainly in order to limit the actual number of load simulations. Consequently a lumping of the directional, two-dimensional SCDs conditioned on the individual combinations of wind speed, wind direction and wave direction is required. This lumping and association of the wave climate with the wind climate constitutes the correlation of wind-wave parameters for fatigue design purposes. Unfortunately, detailed information on directional SCDs per set of primary parameters is often not available or disregarded for the sake of simplicity. In such cases the designer needs to complement the missing information on basis of simplifying assumptions which has an uncertain influence on the accuracy of design loads. However, this scenario is not addressed in the present article.

3. Correlation of wind-wave parameters for the fatigue design

Starting with the full wave climate described by directional SCDs comprising of $i = 1..n$ wave height classes $H_{s,i}$ and $j = 1..m$ wave period classes $T_{p,j}$ the wave lumping aims at the establishment of directional H_s-T_p relations with one representative peak period associated to each significant wave height or vice versa. Ref. [18] investigated various lumping approaches for the isolated wave climate and showed that fatigue damages can be significantly over- or underestimated if the lumping approach does not account for the dynamics of the structure and proper damage equivalency criterions.

Ref. [18] presented a new method allowing for lumping of wave heights on the given wave periods for all wave period classes $j = 1..m$ of an SCD resulting in a damage equivalent $H_{s,d,j}$-$T_{p,j}$ relation for the underlying full wave climate. Alternatively, the method can analogously be applied for lumping of wave periods on the given wave heights for all wave height classes $i = 1..n$ resulting in a damage equivalent $H_{s,i}$-$T_{p,d,i}$ relation. In both cases the fatigue damage distribution could be well preserved over $T_{p,j}$ or $H_{s,i}$ respectively. Both relations obtained by Ref. [18] are plotted for their omnidirectional reference case in Fig. 1. However, despite the fact that both relations represent the same SCD and reference conditions it can be seen that they do not coincide. Nevertheless, each relation ensured a very good preservation of the fatigue