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Design clustering of offshore wind turbines using probabilistic fatigue load estimation

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A B S T R A C T

In large offshore wind farms fatigue loads on support structures can vary significantly due to differences and uncertainties in site conditions, making it necessary to optimize design clustering. An efficient probabilistic fatigue load estimation method for monopile foundations was implemented using Monte-Carlo simulations. Verification of frequency domain analysis for wave loads and scaling approaches for wind loads with time domain aero-elastic simulations lead to 95% accuracy on equivalent bending moments at mudline and tower bottom. The computational speed is in the order of 100 times faster than typical time domain tools. The model is applied to calculate location specific fatigue loads that can be used in deterministic and probabilistic design clustering. Results for an example wind farm with 150 turbines in 30–40 m water depth show a maximum load difference of 25%. Smart clustering using discrete optimization algorithms leads to a design load reduction of up to 13% compared to designs based on only the highest loaded turbine position. The proposed tool improves industry-standard clustering and provides a basis for design optimization and uncertainty analysis in large wind farms.

1. Introduction

The offshore wind energy industry faces three important trends: (1) wind farms grow in size, (2) monopiles are installed in deeper water, and (3) cost reduction remains the most important challenge [1]. Part of the cost reduction must be realized from optimization of support structures for offshore wind turbines (OWTs). The governing support structures are monopiles as they cover 75% of the offshore wind market in 2013 [2]. Large offshore wind farms are predominantly located in deeper water (20–40 m) covering areas of several square kilometers (e.g. DanTysk with 80 OWTs (3.6 MW) covers ca. 70 km^2). Therefore, environmental site conditions, such as water depth and soil conditions, can easily differ significantly from one turbine position to another within large offshore wind farms. These variations lead to significant differences in fatigue loads on OWT support structures. Ideally, support structures should be optimized individually for each turbine position. In industry practice however, loads are often only evaluated for a limited number of design positions in the wind farm since load calculations are computationally demanding and cannot be performed for each position [3]. OWTs are then grouped into design clusters according to the design positions. For each cluster the preliminary support structure design is only performed once. It is assumed that the resulting load levels and structural designs can safely be carried over to all positions in the associated cluster. In order for this to hold, the design position must be the highest loaded location in the cluster. Thus, optimization of design clustering is necessary to reduce design conservatism and the cost of offshore wind energy.

Allocating OWTs to design clusters is typically performed in early project phases (preliminary design), making time-efficient approaches essential while load estimates are sufficient. In current industry projects turbines that are positioned in similar water depth and/or are expected to have similar first eigenfrequencies of the support structure are grouped into clusters [4]. Recently, Seidel [4] suggested an improved approach of clustering using a site parameter that also takes into account structural and hydrodynamic properties. This site parameter is however only suitable for wave load dominated designs. Thus, further work is needed to formulate turbine clustering as an optimization problem incorporating all important site specific information.

In detailed design and certification of OWT support structures a high number of load cases have to be assessed, which makes the

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computational effort for standard time domain fatigue load analysis significant [5,6]. Such simulations, although they are considered most accurate, are ill-suited for clustering optimization and probabilistic assessments. For these applications, load estimates are sufficient, as fast simulations are a necessity. Several approaches exist in literature to decrease computational costs of OWT load analysis, either using integrated analysis or wind-wave separate assessment.

A separate assessment of aerodynamic loads from time domain simulations combined with calculation of hydrodynamic loads in the frequency domain is suggested by Kuehn [7]. Later, van der Tempel [8] extends frequency domain analysis to wind-induced fatigue load calculation emphasizing the need to account for aerodynamic damping as the most important dynamic interaction [9]. In real systems, coupled wind and wave excitation leads to dynamic interaction between aerodynamic loads from the turbine rotor and hydrodynamic loads on the support structure. Aerodynamic damping describes an aerodynamic force that opposes the direction of turbine movement caused by changes in relative wind velocity on the blades due to tower movement in the wind direction (fore-aft mode) [10]. Ragan and Manuel [11] emphasize that spectra of structural response of wind turbines are often not narrow-banded and Gaussian due to rotor periodicity, hence stress ranges do not follow a standard Rayleigh distribution. They suggest to use the empirical Dirlik's method [12] to obtain stress range distributions from wind-induced load response spectra. In integrated methods, researchers propose to reduce the number of environmental conditions [13], number of simulation seeds, or simulation length [7]. For example, Zwick and Muskulus [13] suggest simplified fatigue load assessment based on statistical regression models to reduce the number of load cases for damage estimation.

Fatigue load calculations contain significant uncertainties commonly addressed with safety factors in the design standards [6,14]. Insight on the effect of uncertainties on EFLs improves the understanding of the actual structural reliability. A brief overview of existing work on probabilistic fatigue assessment of wind turbines is given by Yeter [15] and Veldkamp [16].

In this paper, a design clustering method for OWTs was developed using probabilistic fatigue load estimation. The fatigue load estimation method uses frequency domain analysis to calculate wave loads and a scaling approach for wind loads on monopile-based OWTs. Uncertainties in input data and model assumptions are analyzed through Monte-Carlo simulations (MCS). The focus is on uncertainties in the load calculation model, while structural response and damage is determined deterministically. The load estimation tool was verified with fully integrated, aero-elastic time domain simulations. Due to computational efficiency, fatigue loads can be calculated site specific for every turbine location within the wind farm. This makes turbine clustering a discrete optimization problem.

This paper provides a novel approach of optimization of turbine clustering. Additionally, probabilistic assessments give insight on how uncertainties in load calculation can alter allocation of turbines to clusters. This paper is organized as follows. Section 2 outlines the developed fatigue load estimation method, its model assumptions and verification. A summary of the probabilistic load assessment is presented in Section 3. Section 4 focuses on clustering optimization by discussing problem formulations and solution approaches using brute-force and discrete optimization algorithms. Section 5 demonstrates the established clustering optimization method for an realistic wind farm example of 150 monopile-based OWTs in a water depth range of 30–40 m exposed to typical North Sea conditions.

2. Method for fatigue load estimation

2.1. Approach

The developed method calculates dynamic structural response of OWT support structures to site specific aero- and hydrodynamic loading. Fatigue loads for shear forces and bending moments are estimated for distinct output locations of the support structure (mudline and interface) for each turbine position in the wind farm. The term “interface” refers to a structural node between tower bottom and top of the monopile. Loads are assessed as equivalent fatigue load (EFL) which is a constant-amplitude load range that would cause an equivalent amount of damage as a variable-amplitude load time series F_i for a specified number of load cycles N_k (cf. Equation (1)). N_i are the number of cycles, T_{sim} is the simulation time, T_{life} is the lifetime, and m is a material parameter from the SN-curve of welded steel.

$$EFL = \left(\sum_{i=1}^{n} \frac{N_i}{N_k} \cdot \frac{T_{life}}{T_{sim}} \cdot F_i^m \right)^{1/m} \quad (1)$$

The method is based on three core elements (cf. Fig. 1): (1) calculation of wave-induced EFLs in the frequency domain, (2) scaling of wind-induced EFLs from a time domain reference case, and (3) combination of wind-wave EFLs with direct quadratic superposition [7]. The execution time for one simulation case is in the order of seconds.

Wave-induced fatigue loads: The estimation of wave-induced fatigue loads in the frequency domain is summarized in the following. Full details of the method are given in Ref. [17]. Hydrodynamic loads are obtained from Morison equation using wave kinematics power spectral densities based on JONSWAP wave spectra. The drag force in Morison equation is linearized by using the first term of a Fourier series expansion as suggested by Borgman [18]. Modal analysis is performed on a finite element model of the OWT support structure to synthesize transfer functions using the modes in the frequency range of interest at the desired input and output degrees of freedom.

To account for the dynamic interaction between wind and waves, aerodynamic damping (damping ratio ca. 1.5–8%) is superimposed to structural, hydrodynamic and soil damping (damping ratio ca. 1%) in the synthesis of transfer functions. Aerodynamic damping is a function of wind speed, rotor speed, and mode shape. It is determined turbine-specific with modal analysis from a fully coupled, non-linear aero-elastic model. The aerodynamic damping force acts in opposite direction to wave excitation forces on the support structure in case that wind and waves are unidirectional (assuming no yaw misalignment). Therefore, aerodynamic damping is largest for the first mode (fore-aft) and aligned wind and waves, while the damping effect reduces for wind-wave misalignment and higher structural modes.

The finite element model describes foundation and tower with Timoshenko beam elements, rotor-nacelle-assembly as an equivalent concentrated mass on top of the tower, and soil with distributed linear springs according to a realistic reference design (further details are given in Ref. [17]). In order to minimize computational effort, transfer functions are generated for a moment-equivalent wave force at MSL only instead of using distributed transfer functions along the monopile wave-action zone. The distributed wave loads are integrated to MSL and weighted with the first mode shape in order to avoid overestimation of the equivalent load. Structural response is determined by combining transfer functions with input hydrodynamic loading. Wave-induced EFLs are finally obtained from the response spectra with Dirlik's method [12].