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ScienceDirect

Energy Procedia 80 (2015) 151 – 158

Energy Procedia

12th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2015

Probabilistic fatigue analysis of jacket support structures for offshore wind turbines exemplified on tubular joints

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Abstract

The design of offshore wind turbines is usually based on the semi-probabilistic safety concept. Using probabilistic methods, the aim is to find an advanced structural design of OWTs in order to improve safety and reduce costs. The probabilistic design is exemplified on tubular joints of a jacket substructure. Loads and resistance are considered by their respective probability distributions. Time series of loads are generated by fully-coupled numerical simulation of the offshore wind turbine. Especially the very high stress ranges that rarely occur during a period with constant conditions are decisive for the fatigue design. The peak-over-threshold method is applied to find the probability distribution of the very high stress ranges. The method of maximum-likelihood estimation is used to determine the parameters of the underlying generalized Pareto distribution. Further analysis shows that especially the number of the very high stress ranges, scattering for different time series, has a significant impact on the resulting fatigue damage.

Peer-review under responsibility of SINTEF Energi AS

Keywords: offshore wind energy; jacket substructure; tubular joints; fatigue design; probabilistic analysis; peak-over-threshold method; generalized Pareto distribution

1. Introduction

Jackets are commonly used substructures of offshore wind turbines (OWTs) with a rated power of at least 5 MW for sites with water depths as from 25 m. During their life time, OWTs and the used substructures are stressed by

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Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2015.11.417

fatigue loads caused by wind, operation, and sea state. Especially the welded tubular joints of jackets are highly stressed due to their complex geometry.

The design of support structures is usually based on the semi-probabilistic safety concept, as defined in standards such as DNV-OS-J101 [1]. Instead, the probabilistic safety concept can be applied for an improved design of jacket substructures [2]. For that purpose, adequate and accurate description of the stochastical behavior of load effects, loads, and resistance shall be available. Predictions of loads acting on the OWT are commonly derived from numerical simulations. The aim is to find an advanced design of OWTs by applying probabilistic safety concept. Hence, cost of support structures for OWTs can be reduced. In general, probabilistic design of OWTs still is a topic of research [3] [4].

2. Fatigue design of offshore wind turbines

2.1. Semi-probabilistic design

Within the semi-probabilistic safety concept, cf. e.g. DNV-OS-J101 [1], characteristic values of loads S_k and resistance R_k are chosen as specific quantiles of their respective probability distributions. Uncertainties of the characteristic values are covered by load and material factors, γ_f and γ_m. The resulting design value for the load S_d must not exceed the design value of the resistance R_d. This general limit state to be fulfilled is given by Eq. (1). Load and material factor can be adapted in order to cover certain safety levels and consequence classes of failure.

$$S_d = \gamma_f \cdot S_k \le \frac{R_k}{\gamma_m} = R_d \tag{1}$$

When considering fatigue, the characteristic value R_k of the S-N curve is defined as the mean value minus two-times the standard deviation of the underlying distribution of the detail category $\Delta\sigma_c$ for the endurance of $2 \cdot 10^6$, cf. DNVGL-RP-0005 [5]. The stress ranges (loads) are found by numerical simulation of OWTs affected by environmental conditions as defined in design load cases, cf. e.g. IEC 61400-3 [6]. The statistical combination of the parameters describing these conditions usually is stated in the design basis of the planned OWT. The fatigue damage is calculated by applying Palmgren-Miner's rule,

$$D_{fat} = \sum_i \frac{n(\Delta\sigma_i)}{N_{Ri}(\Delta\sigma_i)} \le \eta \tag{2}$$

where n is the number of stress ranges with the value $\Delta\sigma$, and N_R is the corresponding endurance for the stress range. The accounted fatigue damage D_{fat} shall not exceed a certain value of the usage factor η, as named in DNVGL-RP-0005 [5]. Its value depends on the accessibility of the structural member for inspections.

For the semi-probabilistic fatigue design as required by IEC 61400-3 [6], only six numerical simulations of the OWT with a duration of ten minutes and different wind seeds and sea states are required for each wind speed being considered. Recent studies on the joints of a jacket structure [7] with a 5 MW wind turbine by Zwick and Muskulus [8] show that an error of up to 12% for fatigue loads can occur with a probability of 1% for simulations with a total duration of 60 minutes, resulting in an overestimation of the fatigue life by up to 29%.

2.2. Probabilistic design

For safety verification when using the probabilistic safety concept, the probability that the loads are greater than the resistance must not exceed a predefined value for the probability of failure. A value for the probability of failure of 10^{-4} for unmanned OWTs represents the normal safety class, as stated in DNV-OS-J101 [1]. Generally, target reliabilities shall be chosen such that they "commensurate with the consequence of failure" [1].

When applying the probabilistic design, all possible load scenarios are to be considered. Considering the high number of environmental conditions for all possible operational states of OWTs during the life time, the required