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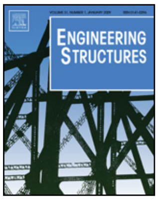

Long-term fatigue analysis of multi-planar tubular joints for jacket-type offshore wind turbine in time domain

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ABSTRACT

Long-term fatigue analysis of welded multi-planar tubular joints for a fixed jacket offshore wind turbine designed for a North Sea site in a water depth of 70 m is performed. The dynamic response of the jacket support structure due to wind and wave loads is calculated by using a decoupled procedure with good accuracy (Gao et al., 2010). Hot-spot stresses at failure-critical locations of each reference brace for 4 different tubular joints (DK, DKT, X-type) are derived by summation of the single stress components from axial, in-plane and out of plane action, the effects of planar and non-planar braces are also considered. Both a 2-parameter Weibull function and generalized gamma function are used to fit the long-term statistical distribution of hot-spot stress ranges by a combination of time domain simulation for representative environmental conditions in operational conditions of the wind turbine. A joint probabilistic model of mean wind speed U_w, significant wave height H_s and spectral peak period T_p in the northern North Sea is used to obtain the occurrence frequencies of representative environmental conditions (Johannessen, 2002). In order to identify the contributions to fatigue damage from wind loads, wave loads and the interaction effect of wind and wave loads, 3 different load cases are analyzed: wind loads only; wave loads only; a combination of wind and wave loads. The representative environmental condition corresponding to the maximum contribution to fatigue damage is identified. Characteristic fatigue damage of the selected joints for different models is predicted and compared. The effect of brace thickness on the characteristic fatigue damage of the selected joints is also analyzed by a sensitivity study. The conclusions obtained in this paper can be used as the reference for the design of future fixed jacket offshore wind turbines in North Sea.

1. Introduction

The role of wind energy in renewable energy utilization is becoming more and more important. During the last 13 years (1996–2009), the global cumulative installed capacity of wind energy increased with an average annual rate of 28.6% [1]. Compared with land-based wind energy, there is more available space, more stable and higher wind speed, and less visual disturbance and noise for offshore wind energy. So offshore wind technology is growing fast, e.g. a significant growth of the offshore wind energy in the years 2010–2015 is expected to be more than 40% [2] in Europe.

The support structure has been identified as a vital contribution to cost-effective installations especially in deep waters [3]. Up to now, offshore fixed wind turbines with monopile and tripod foundations are mainly used for shallow water depths of 20–30 m, while research work is ongoing for larger water depths like 40–100 m where jacket structures are commonly used in the oil and gas sector. Now, jacket substructures are at an early stage of their development for use in offshore wind and have a good potential to develop to an esteemed solution through further development of the industry and methods employed for mass fabrication and installation [3]. During 2006, two prototypes of the Repower 5 M (5 MW) wind turbine with jacket foundations have been installed in water depths of up to 45 m. These two turbines form a 'demonstrator' project to investigate the feasibility for a later offshore wind farm of 200 turbines [4].

For OWTs (Offshore Wind Turbines), the wind load will influence the dynamic response of jackets more significantly than traditional jacket platforms used in the offshore petroleum industry, and the load level of the fatigue loads as well as the number of load cycles to be considered is considerably higher. The number of load cycles generated from the rotor of a wind turbine within the design life-time of 20 years usually reaches more than 1×10^9 load cycles [5]. Therefore, the fatigue performance of welded connections is a design-driving criterion for many structural details of OWT (Offshore Wind Turbine) support structures. In several previous studies Klose and coworkers [5] did an integrated analysis of

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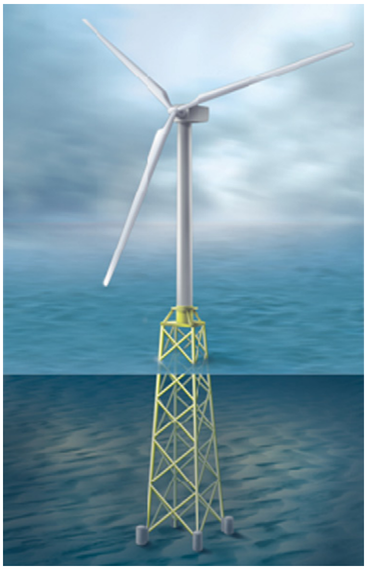

Fig. 1. Offshore wind turbine with jacket support structure (*Artists impression, Bjarne Stenberg/CeSOS, NTNU, Norway*).

wind turbine behavior and structural dynamics of a jacket support structure under combined wind and wave loads in time domain; Seidel and coworkers [6] used the sequential coupling and the full coupling methods to simulate offshore loads on jacket wind turbines, and validated these methods using measurement data from the DOWNVInD project; Gao and Moan [7] did the long-term fatigue analysis of offshore fixed wind turbines based on time domain simulations; Dong et al. [8] analyzed the fatigue reliability of jacket-type offshore wind turbine considering inspection and repair; however, in these previous works the long-term fatigue analysis of welded tubular joints was not performed, which is a very important issue for the design of jacket support structure of offshore wind turbine.

The purpose of this paper is to carry out a long-term fatigue analysis of the welded tubular joints of a fixed jacket offshore wind turbine designed for a North Sea site in a water depth of 70 m (as shown in Fig. 1). The main idea is to investigate how the long-term distribution of hot-spot stress ranges can be represented by analytical functions like the Weibull distribution and the generalized gamma distribution, which is usually necessary for reliability analysis of welded tubular joints and developing simplified methods for practical design. Four tubular joints (DK, DKT, X-type) are selected for use in the fatigue damage analysis which represent different conditions with respect to geometry and location (as shown in Fig. 7). A joint probabilistic model of mean wind speed, significant wave height and spectral peak period in the northern North Sea is used to simulate the environmental loads and totally 400 environmental conditions (wind/sea states) are considered. Hot-spot stresses at the brace toe and the brace saddle locations of each reference brace–chord intersection are obtained. Totally 60 different locations are analyzed and one critical hot-spot location of each joint with respect to most cumulative fatigue damage is selected as the delegate in this study. The long-term statistical distribution of hot-spot stress ranges are fitted by using a 2-parameter Weibull function and a generalized gamma function respectively by combination of time domain simulation for representative sea states in operational condition of the wind turbine. Due to the natural uncertainties associated with the inherent variability of the physical process, e.g. wave elevation, wind speed, the uncertainties exist in the long-term distribution of wind- and wave-induced hot-spot stress ranges, e.g. the uncertainties of the two parameters defining the Weibull distribution. In order to reduce the statistical uncertainties in the long-term distribution of hot-spot stress ranges caused by the stochastic processes of wind and wave, 20 simulations are performed for each short term environmental condition, which are usually used in the stochastic analysis of dynamic response of structures. More details can be found in [10]. Furthermore, in order to identify the contributions to fatigue damage from wind loads, wave loads and interaction of wind and wave loads, 3 different load cases are considered: wind loads only; wave loads only; a combination of wind and wave loads. Contribution to fatigue damage from each short-term environmental condition is calculated and the representative environmental condition corresponding to the maximum contribution to fatigue damage is identified. Characteristic fatigue damage of the selected joints for different models is also predicted and compared. The effect of brace thickness on the characteristic fatigue damage of the selected joints is also analyzed by a sensitivity study.

2. Probabilistic model of wind and waves

For OWTs, the environmental loads are induced by wind, waves, currents and in some cases floating ice. Accurate estimation of these loads, especially for wind loads, are very important not only for the design of OWT structures but also for wind power forecasting and applying control strategies. The International Electro-technical Commission (IEC) has issued the 61400-3 standard [11], which defines 32 different design load cases for ultimate analysis and 9 different design load cases for fatigue analysis. Proper combination of wind and wave loads needs to be addressed for design purposes, preferably in an integrated analysis. However, detailed information of wind, waves and currents needs to be collected and predicted at the specified wind farm sites before we do a dynamic response analysis of OWTs.

In this paper, we mainly consider the normal operation condition of wind turbine, which is also defined as the design load case DLC 1.2 in IEC 61400-3 [11]. A joint probabilistic model of mean wind speed U_w, significant wave height H_s and spectral peak period T_p in the northern North Sea is used to obtain the occurrence frequencies of different sea states, which is suggested by Johannessen [12]. The probability model is obtained by using the data of simultaneous wind and wave measurements covering the years 1973–1999 from the northern North Sea. Wind is characterized by 1-h mean wind speed at 10 m above the average sea level and described by the 2-parameter Weibull distribution, as given in Eq. (1):

$$F\left(U_w\right) = 1 - \exp\left[-\left(\frac{U_w}{A_w}\right)^{B_w}\right] \tag{1}$$

where A_w is the scale parameter of the Weibull distribution, and B_w is the dimensionless shape parameter of the Weibull distribution. However, for wind turbines, the wind speed at the nacelle height is of interest. The wind speed is therefore extrapolated to the nacelle height using a power law of 0.14 in this study. The turbulence intensity is fixed to 0.15 in all of the short-term simulations of time-varying wind speed and the Mann model [13] is used to generate the turbulent wind field. The turbulence intensity is an important factor which has a significant influence on the calculation results of wind loads and structural responses. Different standards give different magnitudes of the turbulence intensity depending on the relative roughness and altitude parameters, as shown in Fig. 2 [9]. Compared with the curve for offshore or low turbulence, the turbulence intensity of 0.15 is higher than that of GL standards but is a reasonable approximation of the IEC standards. Further validation and assessment of wind conditions should be performed through monitoring measurement