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Short-term fatigue analysis for tower base of a spar-type wind turbine under stochastic wind-wave loads

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Abstract

Due to integrated stochastic wind and wave loads, the supporting platform of a Floating Offshore Wind Turbine (FOWT) has to bear six Degrees of Freedom (DOF) motion, which makes the random cyclic loads acting on the structural components, for instance the tower base, more complicated than those on bottom-fixed or land-based wind turbines. These cyclic loads may cause unexpected fatigue damages on a FOWT. This paper presents a study on short-term fatigue damage at the tower base of a 5 MW FOWT with a spar-type platform. Fully coupled time-domain simulations code *FAST* is used and realistic environment conditions are considered to obtain the loads and structural stresses at the tower base. Then the cumulative fatigue damage is calculated based on rainflow counting method and Miner's rule. Moreover, the effects of the simulation length, the wind-wave misalignment, the wind-only condition and the wave-only condition on the fatigue damage are investigated. It is found that the wind and wave induced loads affect the tower base's axial stress separately and in a decoupled way, and the wave-induced fatigue damage is greater than that induced by the wind loads. Under the environment conditions with rated wind speed, the tower base experiences the highest fatigue damage when the joint probability of the wind and wave is included in the calculation. Moreover, it is also found that 1 h simulation length is sufficient to give an appropriate fatigue damage estimated life for FOWT.
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Keywords: Floating offshore wind turbine; Fatigue analysis; Rainflow counting; Cumulative fatigue damage; Axial stress; Tower base

1. Introduction

Due to energy shortage and stringent regulations on environmental pollution, recent decades have witnessed a huge development on the exploitation of renewable and clean energy sources such as wind, wave, tidal and solar. Among these potential energy sources, wind energy is most likely to be widely used in terms of technical and commercial aspects. At present, in China, the majority of wind turbines which have been utilized are bottom-fixed on land or in coastal areas. However, with the increasing size of bottom-fixed wind turbines, more space is needed and this is not practical on land. In addition, the locations of those bottom-fixed wind turbines are restricted by more concerns of visual and acoustic pollutions. Furthermore, in the coastal areas, the costs of bottom-fixed wind turbines rise sharply with increasing water depth. It is rather uneconomic for manufacturers and consumers to sustain the cost of large bottom-fixed wind turbines. As a result, a growing interest has shifted to Floating Offshore Wind Turbines (FOWTs) in recent years. Compared to bottom-fixed wind turbines, FOWTs are able to acquire more wind power since deep sea zones have much more stable and stronger wind speed but less considerations of limitations for siting. Currently, there are three main types of foundations for FOWTs under investigation and operation: spar-type, TLP-type and semi-submersible-type.

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Generally, a wind turbine under the cyclic loadings from wind and wave is expected to operate for over 20 years. During the design period for any types of wind turbines, fatigue damage is significantly known to be a critical problem. Adequate fatigue strength should be ensured by designers. Many studies have been conducted on cumulative fatigue damages and fatigue life predictions for bottom-fixed wind turbines. Long, Kühn and Tempel (Long and Moe, 2012; Kühn, 2001; Van Der Tempel, 2006) used frequency domain method for fatigue damage assessment of support structures of a wind turbine. Melchers (1987) developed a structural reliability methodology to assess the safety of offshore structures. Argyriadis and Klose, (2007) reported an integrated analysis of the fixed jacket wind turbine under combined wind and wave loads in time domain. They also did a detailed fatigue analysis of the tubular nodes on jacket using the loading derived by integrated analysis. Seidel et al., (2009) used data from the DOWNVInD project to validate the sequential coupling and the full coupling method for jacked wind turbines. Wei (Dong et al., (2011, 2012), finished a long-term fatigue analysis for four different types of tubular joints of fixed jacket offshore wind turbine in time domain. He also did a fatigue reliability analysis of jacket support structure based on the fracture mechanics analysis of crack growth and the corrosion-induced crack growth rate. Gao and Moan (2010) completed a long-term fatigue analysis of offshore fixed wind turbines based on time-domain simulations. Nevertheless, for those bottom-fixed wind turbines, substructures do not have 6 DOF body motions under integrated wind and wave loads, which means it is comparatively easy to get acceptably accurate loads and hot spot stresses. However, to a FOWT under integrated wind and wave loads, the equation of motion depends on many non-linear contributions including mooring line forces, aerodynamic and hydrodynamic forces and large displacements. This nature requires that the loads and stresses must be calculated at the updated position. Furthermore, due to the long natural period of a FOWT's motion, it is usually necessary to increase the simulation length to capture slowly varying response.

In recent years, many investigations have been conducted on the accurate calculations of loads and stresses on FOWTs. Ma et al., (2015) studied the dynamic responses of a spar-type wind turbine known as the OC3-Hywind concept by numerical simulation code *FAST* in time domain, and she provided a good procedure to obtain the loads on floating wind turbines. Bachynski (2014) compared the results of dynamic responses from fully-coupled nonlinear time domain analysis and simplified linear frequency domain analysis for four concepts of tension leg platform wind turbine. Additionally, based on the loads and stresses, the fatigue analysis of a semi-submersible wind turbine was also carried out. Kvittem and Moan, (2015a) estimated the tower base's bending moment and the short-term tower fatigue damage for a semi-submersible wind turbine in frequency domain and compared the results to a study based on a fully coupled, nonliner time-domain analysis. Kvittem (2014), Kvittem and Moan (2015b), also did a coupled time domain analysis for a semi-submersible wind turbine by SIMO/RIFLEX with an extension of TDHill and estimated the accuracy of narrow band approximation for fatigue which was proposed by Gao and Moan (2008). Besides, Kvittem investigated the selection of the parameters (simulation duration, number of random realizations and bin sizes for discretization of joint wind and wave distribution) in fatigue damage calculations. Haid et al., (2013) examined appropriate simulation lengths for load analysis of offshore floating wind turbine and did a sensitivity analysis. His investigations showed that the procedure used for counting the half cycles is more important than the simulation length itself.

This paper deals with the short-term fatigue analysis of a spar-type wind turbine tower under stochastic wind and wave loads. The loads (axial force, flapwise bending moment and edgewise bending moment) at the tower base can be calculated by the non-liner aero-hydro-servo-elastic tool *FAST*. Tower base is simplified as a thin-walled cylinder, which means the axial stress of the tower base can be obtained using a simple formula. Rainflow counting method is applied to the time series of axial stress for the number of stress cycles (corresponding to different mean stresses and stress ranges). According to the specific S-N curve and Miner's rule, the fatigue cumulative damages at the different positions of tower base under stochastic wind-wave loads are available.

In brief, four key issues are going to be investigated in this work:

(1) The comparisons of response spectra and statistical properties for axial stress and fatigue damages at different tower base positions.
(2) The effects of simulation length on the results of FOWT fatigue analysis.
(3) The influence of misaligned wind and wave conditions on fatigue damage of the tower base.
(4) The property of the structural fatigue damage under wind-only and wave-only.

In this paper, the models of a spar-type FOWT and corresponding loads are introduced firstly. Then the fatigue damage procedures and the joint wind and wave distributions are illustrated. Furthermore, the specific load cases are defined according to the key issues to be investigated. Based on that, all the results of the axial stress and the short-term fatigue damage are discussed in details.

As the key component connecting wind turbine and floating platform, it is vital to acquaint with the fatigue properties of tower base under the stochastic wind-wave loads which can provide useful information for the tower design of FOWTs.

2. The spar-type floating wind turbine and the loads in consideration

The fatigue strength is conducted for a NREL offshore 5 MW baseline wind turbine, which is supported by a spar-buoy. This type is well known as ‘Hywind’ (Fig. 1). Jonkman et al., (2009) is an internationally recognized FOWT

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