International Journal of Fatigue 87 (2016) 71–80

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Evaluation of fatigue damage model predictions for fixed offshore wind turbine support structures

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ARTICLE INFO

Article history:
Received 26 July 2015
Received in revised form 28 December 2015
Accepted 4 January 2016
Available online 19 January 2016

Keywords:
Spectral fatigue analysis
Offshore wind turbine
Wide band process
Rainflow counting method
Akaike's information criterion

ABSTRACT

This work deals with the evaluation of the spectral fatigue damage prediction of a tripod offshore wind turbine support structure subjected to combined stochastic wave and wind – induced loads. The stochastic loadings are defined using the sea states based on a scatter diagram related to the North Atlantic. Further, the power spectral density of the hot spot stress is estimated accordingly. The prediction of fatigue damage is evaluated in several spectral fatigue damage models including the Rayleigh, Wirsching–Light, Tunna, $\alpha_{0.75,}$ Tovo and Benasciutti, Zhao–Baker, Rice and Dirlik models. Critical hot spot locations, which experience the most fatigue damage, are analysed based on the finite element method and the *S–N* fatigue damage approach. The time-domain solution based on the rainflow cycle counting method is assumed to be the "real" data and the model that best fits the fatigue damage of the wind turbine support structure is identified with the Akaike's Information Criterion.

1. Introduction

Although the fatigue damage is not the main cause of the catastrophic failure, but its effect on the cost of the maintenance of offshore wind turbine support structures cannot be overlooked [1]. Thus, an assessment of fatigue damage is necessary in order to aid the decision-making by means of the reliability-based assessment leading to an optimal balance between design and inspection planning with different safety measures [2].

In the present work, the fatigue damage assessment is carried out based on the spectral approach. The dynamic behaviour of a tripod offshore wind turbine (OWT) support structure is investigated under integrated loading conditions. Various probability distribution models are adopted to define long-term stress range distribution, which are formulated based on the assumption that the loading process is either narrow or wide banded. Considering the time-domain solution with the rainflow cycle counting (RFC) [3] method, which provides the most realistic result, a ranking study of identifying the best suited method to perform fatigue damage prediction, is performed based on Akaike's information criterion (AIC) [4].

The fatigue design methodologies that are used for offshore wind structures has benefited immensely from the experiences gained from the wind turbine industry [5] and offshore Oil & Gas industry [6].

The very initial studies [7,8] focused on developing the necessary design tools in time domain. Kühn [9] defined a general design methodology proposing the weighted quadratic superposition technique for a decoupled fatigue analysis, which was later improved by some applications given in [9–11].

With the introduction of powerful numerical tools [12] and the studies carried out for the verification of the existing codes [13], the tendency on the approach, used for the dynamic analysis of OWT structures, has turned into the integrated load and strength analysis. The sequential coupling approach [14] was applied to the strength assessment of a tripod OWT support structure. Recently, a number of studies [15–19] have been performed on a coupled fatigue analysis in the time domain for deep water fixed offshore wind turbines, concluding that the fatigue loading is found to be dominated by wind, especially the wind turbulence [20] with a relatively low contribution from hydrodynamic loads. However, Veldkamp and van der Tempel [21] stated that the contribution from hydrodynamic loads can differ in the higher sea states. For these states, the non-linear modelling of the wave loads may result in a more accurate approximation of the fatigue loads.

Currently, the design of the OWT support structure, with respect to fatigue, is based on the time-domain dynamic analysis. The fatigue loads are extracted directly from the load or stress time

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http://dx.doi.org/10.1016/j.ijfatigue.2016.01.007
0142-1123/

history by using the rainflow cycle counting method [22]. Some recommendations can be found in [13,23].

The non-linearity of the wind turbine operation accounting for the entire structural assembly of the turbine and dynamic control system is taken into account by the time domain analysis yet the solution may end up to be very complicated and time-consuming. The spectral fatigue damage analysis, performed in the frequency domain, can be considered as an alternative to the time domain approach.

The spectral fatigue damage assessment has been a very common practice for fixed offshore structures for quite some time and many studies may be found in the literature such as [24–26]. However, apart from the study from Wastling and Quarton [7], who addressed the load calculation of wind turbine, the spectral approach on fatigue damage calculation in the field of the offshore wind turbine, does not go a long way.

van der Tempel [27] developed a method for the fatigue design of the OWT support structure which takes into account both wind and wave–induced response, including the aerodynamic damping.

Yeter et al. [28] dealt with a spectral fatigue damage assessment of a tripod OWT under the combined wave and wind loading. A slightly different methodology was developed by employing the finite element method for the coupled dynamic analysis in the frequency domain, which indeed allowed to perform a more sophisticated response analysis by means of modelling the structure consisting welded tubular joints by using shell finite elements in FEA. Yeter et al. [29] analysed the fatigue reliability of the OWT support structure by using a limit state function based on the *S–N* approach including the uncertainties related to the structural response, induced load, material and fatigue life prediction method.

The bandwidth of the aerodynamic response is so wide that frequency domain methods generate far too conservative results for the fatigue damage estimation and to overcome this, a more convenient solution has to be applied. A number of different methods have been presented for that purpose in terms of using a correction factor [30–34], deriving equivalent stress in a closed form [35] and proposing more complicated statistical models to predict the long term stress distribution based on the statistical moments of the stress spectrum [36–38]. Benasciutti and Tovo [39] reviewed the fatigue analysis on wide band Gaussian stochastic process and a comparison of these methods has been reported in [40,41].

The objective of the present work is to determine which fatigue damage model performs better in the assessment of a welded tubular joint of an offshore wind turbine support structure, which involves the estimation of the combined the wind and wave – induced loads, structural response analyses in both time and frequency domain, the *S–N* hotspot stress and Palmgren–Miner's damage accumulation approaches.

The fracture mechanics approach [42] is oriented to predicting the behaviour of the cracked joints. A review of the historical development of crack propagation approach is given in [43,44]. Today, this approach is well established for the fatigue assessment of welded joints [45,46].

Fatigue damage assessment based on the *S–N* approach is design oriented and it can employ one of three approaches: nominal stress, hot spot stress and notch stress [47]. The hot spot stress approach is employed here. In the 1970s, the hot spot stress approach was developed under joint studies by the Classification Societies, offshore industry and research institutes [48] and successfully applied to tubular joints in offshore platforms [49,50]. Detailed recommendations for the fatigue stress assessment are given by IIW [47,51–53].

To design and analyse marine structures accounting for fatigue damage, the finite element method (FEM) together with the hot spot stress approach has become one of the most practical methods. Garbatov et al. [54] stated that the quantified local stress, on the vicinity of the structural singularities, depends very much on the structural idealisation, the utilised element types and the mesh subdivision. Some application of this approach has been reported in [2,55,56]. The most broadly accepted method, to estimate the accumulated fatigue damage, is the Palmgren linear cumulative damage rule [57].

In the scope of the present work, various probabilistic models to define the long-term stress distribution, accounting for both narrow and wide banded loading processes are studied and compared. Among these probabilistic models, the ones with fewer degrees of freedom are considered as the simplest models and the developed solutions to describe an assumed wide band process requires either a correction factor or more complex models in which more parameters are involved. The more parameters the models have, the higher uncertainties in the calculation are involved. Therefore the most suited model must be selected by weighting the models' ability to predict fatigue damage by their complexity.

The objective of the present work is not only to quantify the fatigue damage prediction by using different spectral fatigue damage models, but to provide a basis for the fatigue damage model evaluation and selection. For that purpose, fatigue damage is estimated through complicated multi-variable models along with a time domain solution and compared to each other by using the Akaike's information criterion. Consequently, a ranking between the investigated fatigue damage models are presented.

The Akaike's information criterion (AIC) is developed by Akaike [58] who proposed it as a tool for a model selection, evaluating the goodness of a statistical model in a series of breakthrough papers [4,59–61]. It is based on the concept of the negative entropy derived by Kullback–Leibler [62] as an information quantity (K–L distance) in which the measure for the discrepancy between the true model and the approximating model is given. Akaike developed a relationship between the K–L distance [63] and the maximum log-likelihood [64], which results in a certain AIC number. Given a data set, several competing models may be ranked according to their AIC, with the one having the lowest AIC being the best [64–67]. However, AIC may perform poorly if there are too many parameters in relation to the size of the sample, hence a modified criterion as called AIC_c was later proposed [68].

2. Spectral approach for fatigue analysis of OWT structures

It is always challenging for the designers to estimate the response at the resonance induced by exciting loads. Therefore, a vibration analysis is essential to define the structural natural frequencies and vibration modes so that the amplified fatigue load due to the resonance can be avoided. The frequency domain provides a solution using power spectral density functions related to input loading and structural response, which is often times much easier to obtain than a time history.

In the scope of this study, the dynamic analysis of wind turbine supporting structures modelled using the finite element method (FEM) is carried out. It is more efficient to perform the response analysis in the frequency domain instead of the time consuming transient dynamic analysis in time domain. Furthermore, the finite element analysis (FEA) based on frequency domain may reduce the complexity of this problem. The FEA is used to determine the relation between the load and stress in the structure by combining the power spectral density (PSD) of load with the transfer function of the unloaded structure. The predicted fatigue life is estimated assuming that the component is subjected to statistically-defined random stresses, which are simplified to be a stationary Gaussian process.

The spectral fatigue analysis is a straightforward approach based on several steps. With this approach, various orders of