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Fatigue damage assessment of fixed offshore wind turbine tripod support structures

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ABSTRACT

The objective of this work is to carry out a fatigue damage assessment of a fixed offshore wind turbine support structure due to combined wave and wind – induced loading. Considering the operational mode of the wind turbine 3 loading conditions are identified and for each loading condition 4 critical regions located in different zones of the supporting structure are studied. The stress transfer function is obtained by carrying out dynamic finite element analysis in the frequency domain. A wave scatter diagram of the North Atlantic is used in order to account for the environmental effects. The stress transfer function is formulated such that a sufficient number of frequencies can be used in the Inverse Fast Fourier Transform with random phase angles in order to obtain the stress time histories. An up-to-date rainflow cycle counting method is adopted to count the total number of cycles related to stress range bins. The S–N approach is employed to estimate fatigue damage.

1. Introduction

A study of EWEA [1] stated that levelised cost of electricity (LCOE) of wind decreased 40% within the last two decades, which encourages the next generation offshore wind farms to be constructed further away from the shore. Deep water solution for offshore wind turbines requires building bigger and larger wind turbines in order to economise on the foundation and the power collection costs [2]. The increase in water depth, tower heights and rotor blade diameters increase the loads that result in stiffer foundations and support structures. Thus, the fatigue performance of welded connections is a design-driving criterion for the offshore wind turbine supporting structures, and the fatigue reliability assessment is necessary.

The main objective of this work is to investigate the existing approaches to estimate the fatigue damage of the most critical welded tubular joints of a tripod supporting structure. Three different approaches are considered to evaluate the fatigue damage for the models, created considering the tubular joint, its location on the support structure and the wind turbine performance-based loading condition.

The findings of this study create the bases of a fatigue reliability assessment in such way that the limit state function can be developed on a case by case basis (varying with joint type, location and loading condition), which covers the fatigue damage assessment approach that is seen fit for each particular fatigue-critical component of the structural system. Moreover, the specified reliability based formulation will aid to define an optimal planning of inspection and maintenance for the supporting structure in-service. The benefits of the reliability and risk based inspection and maintenance planning were reported by Straub et al. [3].

The influence of various environmental factors in the design of such structures has been discussed for the monopile structures in [4] and the tripod structures in [5]. These factors are to be taken into consideration when conducting the fatigue assessments.

Recently, a study, on the long-term coupled simulations in the time domain, was reported in [6], in which a reliability study of the offshore wind turbine components was also carried out. Furthermore, the fatigue reliability assessments were performed for different types of the supporting structures such as monopile, jacket and tripod in [7–10].

Through the years there have been many cycle counting methods developed, as described and recently updated by ASTM [11], to address the fatigue damage of wind turbine and support structures, which basically use the time history of either stress or strain [12]. Among these counting methods the rainflow cycle (RFC) counting method is the most preferred method and is accepted as a standard procedure [13].

In the fatigue damage assessment, the rainflow counting method is a time domain method that is used to determine the number of stress cycles with corresponding stress range and mean

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stress. If rigorously performed with a sufficient size time window, it is considered as the most accurate method for calculating the fatigue damage [14]. In order to obtain an accurate estimation of the fatigue damage a sufficient number of time simulations are to be performed.

The time domain simulation of complete turbine dynamics, wind and wave loading is a common practice. However, this solution requires a big amount of computational effort as far as the whole structural system is concerned. Therefore, here an alternative approach is offered, which is faster, simpler and considerably accurate for some particular welded tubular joints.

The approach applied starts with defining the loading input and continues with the dynamic response analysis of the offshore wind turbine supporting structure in the frequency domain. Subsequently, the stress response spectrum accounting for the stresses occurred due to combined wind and wave loading is derived, which will be then transformed into the time histories by the inverse Fast Fourier Transform [15]. The acquired time histories are used to count the stress cycles and once the stress range distribution is known the S–N approach is employed to estimate the fatigue damage.

The present approach is applied for 3 loading conditions considering 100% and 60% operational performance, and parking mode of the wind turbine. Based on the results of the static stress analysis using FEM there are 4 major hotspot regions observed in the structure, which are located around the intersection of the central column, the brace, the interior base and the pile tubular members. All these tubular joints are taken into consideration and the fatigue damage assessment is performed with respect to those hotspots and the loading conditions.

Yeter et al. [16] studied a similar structure and identified that the most critical hot spot occurs where the brace and central column intersect. Besides the zone covers this joint, there have been 2 other zones selected in order to study the fatigue damage assessment sensitivity with respect to combined wind and wave-induced loads.

Here the objective is not only to detect the hotspots and their severity, as done in the paper just referred, but also to define a proper approach to the fatigue damage assessment. For instance, for some hotspots a special care must be given, resulting in the application of more sophisticated approach for the damage assessment. However, for less critical hotspots the use of a simplified approach may be reasonable and enough, without having overestimated fatigue damage.

2. Fatigue analysis in time domain

In the time domain analysis the response of the structure is expressed as a stress or strain time history and the fatigue damage occurs as an outcome of the stress or strain reversals in the time history, which is known as cycles. As far as the fatigue damage calculation is concerned, the stress range and mean stress associated with it are the most significant matters.

A simple description of how the fatigue damage accumulates on a structural component is given by Wöhler [17], which is recognized as the basis for the fatigue analysis of wind turbine support structure. The Wohler's equation assumes that each cycle of constant stress range, $\Delta\sigma$, causes a particular amount of damage, and that damage increases linearly with the number of stress cycles applied, N until it reaches an anticipated failure level. The damage induced in any single cycle is proportional to the stress range amplitude raised to the mth power, where m is a material parameter. A second material parameter a is proportional to the number of cycles a material can withstand before failure. If N_f is defined as the number of cycles of failure, the Wohler's equation may be expressed as:

$$N_f \Delta\sigma^m = \tilde{a} \quad (1)$$

The fatigue strength descriptors, $\log\tilde{a}$ and m varies with the types of S–N curves. The work here uses two different S–N curves given by DnV [18] for T/Y joint type as illustrated in Fig. 1. The first one is for the sea water environment with a cathodic protection (SN1) in which $\log\tilde{a}$ and m are 11.764 and 3, respectively. The latter one is for the free corrosion condition i.e. without cathodic protection (SN2) in which $\log\tilde{a}$ and m 11.687 and 3 respectively. The one slope S–N curve for the cathodic protection is used, which keeps the results on the safe side for calculated fatigue lives, as also recommended by DnV [18]. The choice of using two different S–N curves is based on the fact that the offshore wind turbine support structure is assumed to spend 15 years under the cathodic protection and the rest of 25 years in-service is spent without cathodic protection.

It has been a common practice using the S–N curve regarding the cathodic protection for the components located around the splash zone of offshore structures. Nevertheless, the corrosion is an important deterioration mechanism and depending on the corrosion severity, the provided coating protection may fail before the end of the service life. Therefore, the joints subjected to corrosive environment may fracture earlier than the ones located in a non-corrosive environment.

The fatigue damage accumulated from each stress cycle can be calculated from the relevant S–N curve based on the assumption of the linear damage accumulation, expressed as:

$$D_{total} = \sum_{i}^{N_t} \frac{n_i}{N_{f,i}} \quad (2)$$

where N_t is the total number of stress cycles, n_i is number of constant amplitude stress range cycles $\Delta\sigma_i$ in block i, and $N_{f,i}$ is the number of cycles to failure at constant stress range $\Delta\sigma_i$. The fatigue damage is assumed to occur when the damage ratio D_{total} exceeds unity.

The number of cycles to failure at the specific stress range must be taken from the universal S–N curves that are designed for the related structural detail. For the number of cycles occurred in time history a cycle counting method must be used. In the present work, the stress cycles are rainflow counted [19].

2.1. Cycle counting methods

The environmental and operational loads acting on an offshore wind turbine create a fluctuating stress time history and through counting these stress cycles, this time history can be expressed as a long-term stress distribution. Some counting methods are reported with different algorithms to deal with this complex time

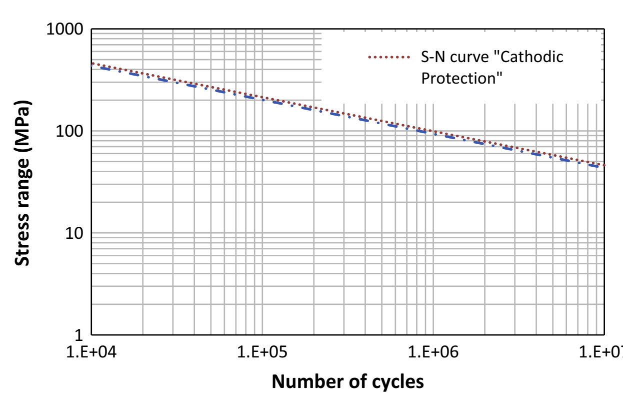

Fig. 1. S–N curves regarding tubular joints.