Marine Structures 48 (2016) 15–32

Contents lists available at ScienceDirect

Marine Structures

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

Modified environmental contour method for predicting long-term extreme responses of bottom-fixed offshore wind turbines

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A R T I C L E I N F O

Article history:
Received 9 October 2015
Received in revised form 26 February 2016
Accepted 29 March 2016
Available online 12 May 2016

Keywords:
Environmental contour method
Inverse first order reliability method
Offshore wind turbines
Long-term extreme response
Statistical extrapolation

A B S T R A C T

Predicting extreme responses is very important in designing a bottom-fixed offshore wind turbines. The commonly used method that account for the variability of the response and the environmental conditions is the full long-term analysis (FLTA), which is accurate but time consuming. It is a direct integration of all the probability distribution of short-term extremes and the environmental conditions. Since the long-term extreme responses are usually governed by very few important environmental conditions, the long-term analysis can be greatly simplified if such conditions are identified. For offshore structures, one simplified method is the environmental contour method (ECM), which uses the short-term extreme probability distribution of important environmental conditions selected on the contour surface with the relevant return periods. However, because of the inherent difference of offshore wind turbines and ordinary offshore structures, especially their non-monotonic behavior of the responses under wind loads, ECM cannot be directly applied because the environmental condition it selects is not close to the actual most important one.

The paper presents a modified environmental contour method (MECM) for bottom-fixed offshore wind turbine applications. It can identify the most important environmental condition that governs the long-term extreme. The method is tested on the NREL 5 MW wind turbine supported by a simplified jacket-type support structure. Compared to the results of FLTA, MECM yields accurate results and is shown to be an efficient and reliable method for the prediction of the extreme responses of bottom-fixed offshore wind turbines.

1. Introduction

Long-term analysis is very important for determining both life-time fatigue damage and extreme structural responses of offshore wind turbine designs. The full long-term analysis integrates the product of the probability of the environmental

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http://dx.doi.org/10.1016/j.marstruc.2016.03.003

conditions and the corresponding short-term response probability distribution (extreme probability, fatigue damage, etc.) to calculate the life-time result.

Due to the large number of environmental conditions to be included, the full long-term analysis is not efficient or economical. Thus, many simplification methods are used for the fatigue and extreme prediction. The simplified methods are either improving the efficiency of simulations or reducing the number of environmental conditions for the integration. For fatigue, there are methods for efficient probability integral evaluation such as perturbation approach, asymptotic approximation [1], or univariate dimension-reduction method [2], etc. For fatigue damage, frequency-domain analysis can also be used instead of the more costly time-domain simulations [3]. For extreme analysis, there are simplified methods such as estimating the extreme responses by combining the extremes under each single environmental load, such as [4–6].

The analysis can also be simplified by reducing the environmental cases. This is especially effective for extreme analysis because the long-term extreme is affected by very few environmental conditions. The environmental contour method (ECM) [7] is such an approach based on the Inverse first order reliability method (IFORM) [8], which uses a single short-term environmental condition with the desired return period. It is initially used in offshore structure design and is now also included in the design for land-based and offshore wind turbines. Different from ordinary offshore structures, wind turbines operate or park under varying wind speed. Thus, it has been found by [9–12] that the method is not suitable for many offshore wind turbines. The paper will show that the modified environmental contour method (MECM) can still be applied for bottom-fixed offshore wind turbines and find the long-term extreme response efficiently with accuracy.

The paper introduces MECM and its implementation. A case study on the NREL 5 MW wind turbine [13] supported by a simplified 92-m jacket-type support structure [14] with water depth of 79 m is conducted. The wind turbine is pitch-regulated with cut-in, rated, and cut-out wind speed of 3 m/s, 11.4 m/s and 25 m/s respectively. The environmental conditions are based on a site located in central North Sea, labeled as site 15 in [15]. The environmental parameters considered are mean wind speed, significant wave height, spectral peak period while the turbulence intensity of the wind speed is assumed to be constant as 0.15.

2. Full long-term analysis (FLTA)

The full long-term analysis (FLTA) is a straight forward method for calculating the long-term extreme response probability distribution. It is an accurate approach because it considers all the environmental conditions, which is also why it is not very economical. The results of the full long-term analysis are used as benchmark to determine the performance of other simpler long-term extreme analysis methods.

The FLTA calculates the long-term result by directly integrating all environmental parameters and the corresponding short-term response probability functions. There are many ways for short-term analysis by using extremes (maxima of each time period), local peaks, or up-crossing rates, etc. [16]. If using the short-term extremes, the long-term extreme can be found by Eq. (1), where F stands for the cumulative distribution function (CDF) and s is the environmental condition that satisfies Eq. (2). $f_S(s)$ is the probability density function (PDF) of s. $F_X^{LT}(\xi)$ and $F_{X|S}^{ST}(\xi|s)$ are the long-term and short-term CDF of the extreme values of the response X, respectively.

$$F_X^{LT}(\xi) = \int F_{X|S}^{ST}(\xi|s) f_S(s) \mathrm{d}s \tag{1}$$

$$\int f_S(s) \mathrm{d}s = 1 \tag{2}$$

In this study, the 1-h short-term extremes probability distribution is used. The 1-h short-term extremes probability distribution is calculated based on the maximum responses of 10-min periods by assuming each 10-min period is independent. Since mean wind speed, significant wave height and spectral peak period are the variables for the environmental condition, Eq. (1) can be rewritten as Eq. (3), where U_w, H_s, T_p are mean hub-height wind speed, significant wave height, and spectral peak period respectively. $F_{X_{1-hr}}^{LT}(\xi)$ is the long-term 1-h extreme CDF of response X and $F_{X_{1-hr}|U_w,H_s,T_p}^{ST}(\xi|u,h,t)$ is the short-term 1-h extreme CDF of response X under environmental condition (u,h,t).

$$F_{X_{1-hr}}^{LT}(\xi) = \iiint F_{X_{1-hr}|U_w,H_s,T_p}^{ST}(\xi|u,h,t) f_{U_w,H_s,T_p}(u,h,t) \mathrm{d}u\mathrm{d}h\mathrm{d}t = \sum F_{X_{1-hr}|U_w,H_s,T_p}^{ST}(\xi|u,h,t) f_{U_w,H_s,T_p}(u,h,t)\Delta u \Delta h \Delta t \tag{3}$$

For 50-year long-term results, one can either find ξ such that $F_{X_{1-hr}}^{LT}(\xi) = 1/(50\cdot 365.25\cdot 24)$, or find the 50-year 1-h extreme probability distribution $[F_{X_{1-hr}}^{LT}(\xi)]^{50\cdot 365.25\cdot 24}$ and calculate its most probable value as the result.

The FLTA is used in design of offshore structures and wind turbines, often with some simplification such as reducing the number of environmental parameters. The disadvantage of the method is that it requires a large number of simulations to cover all the environmental conditions. For most requirements, only the high exceedance probability (50-year or 20-year, etc.) is of interest, which means that only the tail part of the long-term extreme CDF is important. This implies that most of the environmental conditions included are not contributing to the result of the long-term extreme. If the most important environmental conditions are preserved while the unimportant ones are ignored, the FLTA will still give the same result.