Simplified Fatigue Assessment of Offshore Wind Support Structures Accounting for Variations in a Farm

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1 Introduction

Provided the significant contribution of support structures to the capital expenditures of offshore wind, optimisation schemes are often developed to address the need for tailored design of different structures in one farm. A crucial aspect of them is, among others, the Fatigue Limit State (FLS)[1234] .To this direction, research is conducted on the response of the structure to cyclic loading in the frequency-domain[567] . However, the complexity and the need for advanced software (finite element and/or aero-elastic codes) often limit the flexibility. As a consequence, the design process is not facilitated significantly.

The focus of this study is principally placed on the impact that variations in an offshore wind farm (OWF) have on the support structures, particularly on their resistance to cumulative damage caused by wind and wave loading. The vital requirement is therefore that the procedure is computationally affordable to ensure applicability for the early design phase of multiple structures. The goal of this study is to develop such a procedure.

2 Approach

The approach relies on an acknowledged limitation: simplified estimation of FLS at several locations in the farm should not be a standalone process. Therefore, a detailed analysis of a reference support structure in the farm serves as a starting point on the basis of which the influence of site variations can be captured. Effectively, the analysis is structured on two foundations: the reference structure and the new structure at another location, with extrapolated behaviour. The desired speed-up is achieved by conducting the meticulous assessment only at the reference position which is then followed by quick estimations at the locations of interest (Fig.1). To increase the reliability of the outcome, correction factors are extracted from the reference position and applied to the new locations.

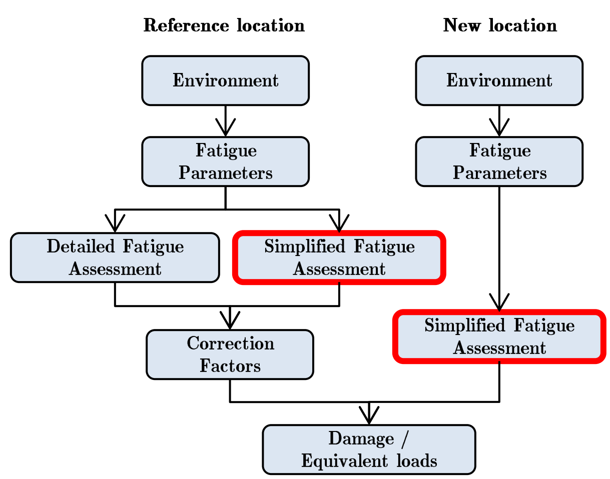

Figure 1. Model for quick FLS estimations at different locations in an OWF

The first step in this study is the development of a suitable method for the simplified FLS estimation, outlined in red in Fig.1. The aim for this method is to be simpler and faster than a full frequency domain analysis. The developed method is benchmarked against time domain simulations, to assess its performance. Subsequently, the simplified fatigue assessment is implemented in the procedure shown in Fig.1, where the simplified method is used to extrapolate the detailed fatigue assessment of the reference structure to other structures in the farm. The procedure is then applied in a case study, in which the fatigue damage in various support structures in the wind farm is assessed. The results of this assessment are compared with results from time domain simulations to determine the effectiveness of the procedure.

3 Main Body of Abstract

The development of a method for the quick FLS assessment is the core block of Fig.1 (outlined in red). With the structural response specified by the local environmental parameters and dynamics, it predicts the lifetime fatigue damage of the monopiles under cyclic loading. The requirement for low complexity compared to conventional frequency-domain analysis is achieved by the following steps:

- identification of dynamic load components of the excitation
- analytical calculation of the quasi-static response
- application of a 1-degree of freedom Dynamic Amplification Factor (DAF) to derive the dynamic response

Recently, the concept of simplified derivation of power spectral densities (PSD) of the fore-aft mudline moment and separate handling of 1P and 3P harmonic loading has been introduced.[8] This concept is firstly improved by e.g. re-modeling of the 3P loads, modeling of tower drag and extension of moment PSD at every elevation. To implement the concept in a framework for simplified FLS analysis, several processing blocks have been added, such as finite element model for the structure, Dirlik's method for the stress range histograms and Miner's summation of damages.

To ensure the suitability of the proposed methodology (PM) for its intended use, it is benchmarked with the time-domain (TD) software Bladed. The support structure installed in the Dutch wind farm Egmond aan Zee (OWEZ) is used for the validation and the results show an impressive matching: the error for damage is below 5% while for damage equivalent load (DEL) it is below 1%. A more rigorous look at the outcome of the validation is provided by Fig. 2. A slight over-prediction of wind-induced loads is observed in wind governing states (state 8-11), whereas the damage caused by severe sea states (state 15-22) is under-estimated. This is not only seen in the lifetime DEL (Fig. 2a), but also in the moment PSD for the response to wind and wave, below $0.1Hz$ and at around $0.2Hz$ respectively (Fig. 2b). Such a systematic error shows the need for the correction factors as introduced in Fig. 1, while these would seem unnecessary in a first sight from the close match of the results for the damage. As a last remark, Fig. 2c illustrates that critical states have histograms that are shifted to higher stress ranges.

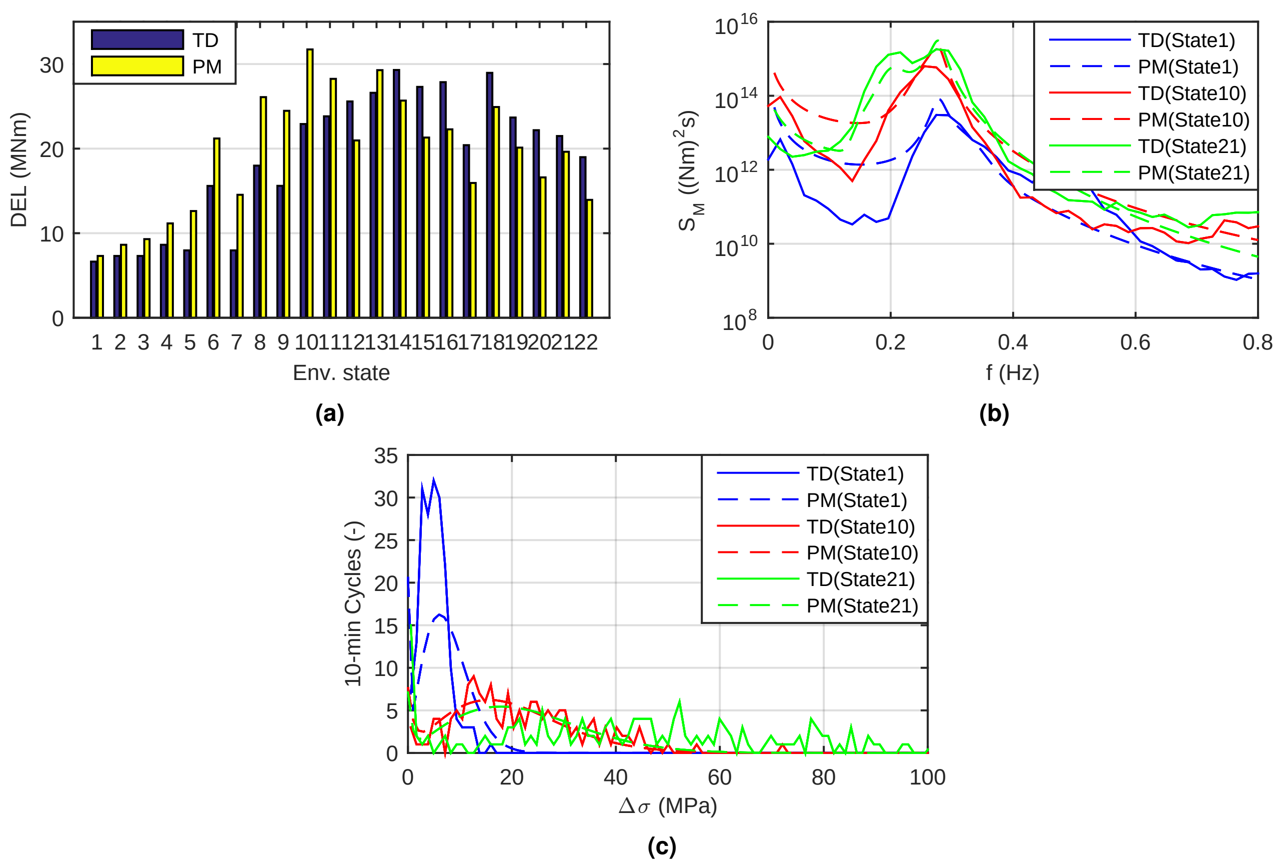

Figure 2. Validation of the proposed methodology (PM) with time-domain (TD) Bladed: **(a)** lifetime-weighted mudline DEL for the environmental states at OWEZ, **(b)** PSD of mudline fore-aft moment and **(c)** stress range histograms for state 1 ($U = 4m/s, H_s = 0.5m, T_p = 3s$), 10 ($U = 12m/s, H_s = 1.5m, T_p = 4s$) and 21 ($U = 24m/s, H_s = 3.5m, T_p = 5s$) and with the 1^{st} eigen-frequency of the structure at $0.28Hz$

A case study on a conceptually designed farm at Hornsea (UK) is used to demonstrate the efficiency of the scheme of Fig.1. Bladed is used at the reference location to yield the correction factors that are mentioned in the left branch of the scheme. These are determined for different heights in the structure. The simplified FLS assessment is performed at various new locations in the farm and the correction factors are applied to this simplified assessment. For positions at the new location that are below the mudline at the reference location (which has the same depth as location 3) the correction factor at the mudline of the reference location is applied. Finally, Bladed is used as well at the new locations to ultimately reveal any errors obtained with the proposed scheme. Fig. 3 shows the results of the comparison of PM and TD for different heights in the structure. The figure makes clear that the errors of DEL at elevations close to the mudline (i.e. elevation (i), (ii) and (iii)) are fairly acceptable from an engineering point of view at all four positions. On the contrary, the assessments at and above MSL somewhat deviate from TD. The fact that the propagation of the wave loading to the tower and that higher eigen-frequencies are disregarded by PM are the origin of the higher errors in elevations (iv) and (v).

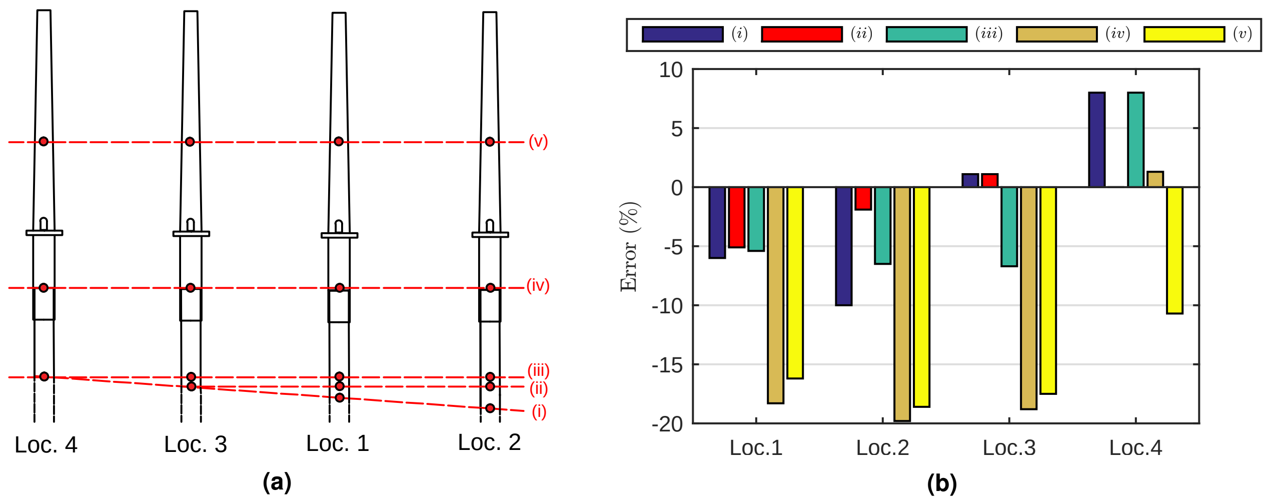

Figure 3. Hornsea case study: (a) different elevations for FLS extrapolation in the case study and (b) DEL errors at every location and elevation

4 Conclusions

The achievement of this study was the development of a framework for FLS estimations in a simple and quick manner so as to address site variations in an OWF, suitable for preliminary optimisation of all support structures in the farm. The concept relies on the analytical approximation of the dynamic response, thus by-passing time consuming numerical processes and advanced software. The reliability is increased with the implementation of correction factors stemming from a reference position and derived by detailed FLS assessment. The balance between reduced complexity (compared to conventional time- and frequency-domain) and high accuracy renders it suitable for investigating numerous locations across an OWF. The proposed method neglects higher natural frequencies and dynamic response of the structure at higher elevations due to loads at lower elevations. The results show that the method is therefore most suitable for locations near the mudline and thus for analysis and optimisation of the foundation pile.

5 Learning Objectives

By presenting this research, the authors want to stress that the benefits of simplification outnumber the implications of reduced accuracy in the early design phase. Less advanced approaches for complex problems is seemingly the solution to the iterative nature of the initial procedures of OWF design. Focusing on the core of the present study, a potential incorporation of the framework to a multi-disciplinary optimisation scheme can:

- provide OWF layout designers with an additional parameter to evaluate, besides wake losses and internal cabling costs: how does positioning of turbines affects fatigue in support structures?
- facilitate financially strategic choices when it comes to support structure design clustering or tailored design: how many different support structure designs should be used within the farm?

- enable the investigation of various proposals by increasing the time-efficiency: how many more design choices can be evaluated compared to the time-consuming detailed procedure?

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