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Hydro-Elastic Contributions to Fatigue Damage on a Large Monopile

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Abstract

The present work identifies the qualitative hydro-elastic contributions to fatigue damage on large volume monopiles intended for use in the offshore wind energy industry. Although aerodynamic effects cannot be neglected in a complete dynamic analysis of the structure, the scope of this work is limited to wave loads and soil effects on a turbine in simplified operational conditions. As the rotors are scaled up to improve efficiency and reduce the overall costs in wind farms, the foundation and support structure dimensions are increased. As a result, the fluid-structure interaction becomes important for wave-lengths comparable to the characteristic size of the structure. The importance of including diffraction effects is present in the results. Also, the contributions from ringing type response in a fatigue-limit sea-state is investigated by applying the third order Faltinsen, Newman, Vinje (FNV) formulation. Hydrodynamic loading is applied as particle velocities in a spatial time variant grid for first and second order wave theories in long crested irregular waves. Additionally, the second order diffraction forces are calculated using an internationally recognized panel code for second order sum-frequency diffraction forces.

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1. Introduction

Monopile foundations for offshore wind turbines are presently the most cost-effective solution due to its simple construction. In 2014, 91% of the installed substructure types were monopiles [1]. Even for increasing water depths of more than 30 meters, the monopile foundation has shown to be the preferred choice. Furthermore, over the last 10 years, the average wind turbine capacity has increased significantly. As a result of an evolving industry, extra large monopiles are under development for future offshore wind farms.

With increasing dimensions and higher natural periods due to large rotors and drive-trains, the methods to reproduce environmental loads need to be re-evaluated. Leaving out the wind loads have several consequences strongly

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depending on the turbine, environmental conditions and water depth. The wind is in general expected to contribute to fatigue damage compared to wave-only simulations if the aerodynamic damping is accounted for in both cases. For a mis-aligned or idling case, the wave-induced fatigue damage may be dominating due to the low damping. An analysis of wind/wave contributions can be found in [2], where the wave contribution with interaction effects on a jacket foundation may pose up to 35% of long-term fatigue damage. On a large monopile, wave loads are expected to be even more prominent, but more research is needed on this topic.

In the present paper, several well-known methods for estimating hydrodynamic loads and their effect upon fatigue damage are compared when used in the analysis of a large-diameter monopile (D=9m). The model used is comparable to the DTU 10MW reference wind turbine [3], with regards to mass of nacelle (446tons) and rotor (228tons). For nonlinear time-domain simulations, the space frame analysis program USFOS [4] has been used. Although USFOS supports first order wave loads, all wave kinematics are pre-generated in a MATLAB program, verified in [5], and applied in a spatial grid of velocities and accelerations. The kinematics are converted to loads by USFOS with the Morison equation. Also, second order forces are calculated from the quadratic transfer function (QTF) obtained with the SESAM software HydroD and Wadam [6] and later applied as local forces during simulation. This procedure is similar to what is presented in [7], but on a deep water TLP wind turbine. In this paper, a location at Dogger Bank with 30m depth is considered.

2. Simulation model

For the purely hydro-elastic analysis performed in this study, the monopile with the tower is modeled as a cantilever beam. The rotor and nacelle masses are both lumped onto the top of the tower as only constant aerodynamic forces and damping are accounted for. Still, it is important to get correct mode shapes and periods for the time-domain analysis. Therefore, also the soil is modeled with care to reflect the soil layers from the specific area. Geotechnical considerations are done using API standards for sand and stiff clay, and further implemented as equivalent nonlinear springs on the pile. Fig. 1 shows the main dimensions of the model whose pile is hammered down 42 meters into the soil, and the modal shapes for the two largest eigenvalues.

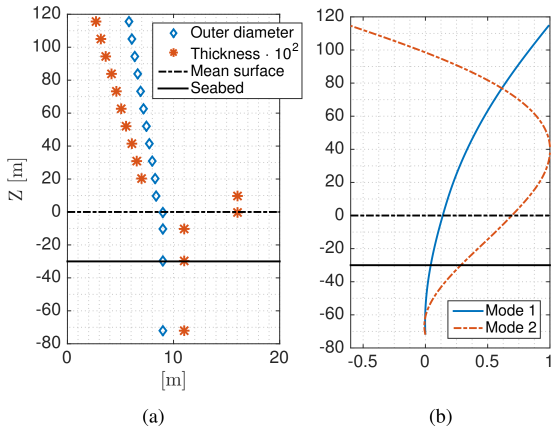

Fig. 1. Main dimensions of monopile with tower in (a) and normalized modeshapes in (b).

The first tower bending mode has an eigenperiod of 4.1 seconds, while the second eigenperiod is 1.0 seconds. Damping is modeled as a Rayleigh structural damping of 1% at the first and second eigenperiod, giving Rayleigh parameters of 0.0256 and 0.0025, respectively. For higher damping ratios, the parameters are increased linearly. In addition, the dissipation of energy due to soil damping is modeled as a hysteresis damping equal to a energy loss of about 4% [8] per each oscillatory cycle in a decay test. An equivalent Rayleigh damping of 3% satisfies this contribution for the present model, including a small compensation for missing aerodynamic damping. Later, variation of damping will be introduced in the analyses to compare responses for lightly damped operational conditions, such as mis-aligned wind and waves.

3. First order wave kinematics

3.1. Finite water depth

The Airy theory wave potential for finite water depth in (1) is used for calculating first order irregular wave kinematics. The dispersion relation is given by (3) and the surface elevation, particle velocity and accelerations can be