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Dynamic response sensitivity of an offshore wind turbine for varying subsoil conditions

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ABSTRACT

In this paper, a comprehensive study is performed on the dynamic response of an offshore wind turbine installed on a monopile. The aim is to evaluate to what extent a change of the soil properties affects the fatigue loads for parked conditions. Based on consistent lumped-parameter models calibrated to semi-analytical impedance functions of a monopile embedded in a linear viscoelastic soil layer, fully coupled aero-hydro-elastic simulations are conducted in the nonlinear multi-body code HAWC2. Correlation of wind speeds and waves is derived on basis of wind–wave scatter diagrams from the North Sea. Changes of the soil stiffness, the soil damping and the presence of sediment transportation at seabed are shown to be critical for the fatigue damage equivalent moment at mudline that may change with more than 30% for parked wind turbine conditions.

1. Introduction

For water depths less than 30 m, the monopile foundation concept is often employed as the foundation for offshore wind turbines due to its proven technology, simple fabrication and installation methods (EWEA, 2013). Compared to other substructures, the monopile is a very slender and flexible structure providing resonance frequencies of the wind turbine close to excitation frequencies related to environmental loads from wind and waves. Consequently, even a small change of the global system stiffness or damping may lead to a high increase in the fatigue damage accumulation.

According to IEC 61400-3 (International Electrotechnical Commission, 2009) and GL (Germanischer Lloyd, 2005), the design of an offshore wind turbine requires the computation and analysis of thousands of load cases (LCs) representing the various loads it will experience during its service life. This includes operational and temporary conditions with system faults and irregular sea states that may be investigated by a time-domain or frequency-domain solution—the last-mentioned for instance by using the recently proposed method by Arany et al. (in press). Contrary to the fore–aft direction, the aerodynamic forces out of the rotor plane are low for normal turbine operations. Hence, operational fatigue LCs containing wind–wave misalignment or standstill conditions for a wind turbine installed on a monopile with eigenfrequencies close to wave excitations necessitate a proper modelling of the dynamic soil–pile interaction, i.e. the soil stiffness and the soil damping should be represented reasonably well in the load simulations. The soil–pile interaction can be investigated by analytical linear, viscoelastic continuum models (Novak and Nogami, 1977; Nogami and Novak, 1977), linear Winkler type medium models (Winkler, 1867; Lombardi et al., 2013; Bisoi and Haldar, 2014), finite-element (FE) models coupled with infinite elements or boundary-element (BE) models (Medina et al., 2013) that all can be used for fully coupled load simulations (Böker, 2009) with the application of an appropriate system reduction technique (de Klerk et al., 2008). Nevertheless, independent of the simulation strategy, a number of soil parameters are required. In general, these properties are highly uncertain and cannot be controlled. As proved by Damgaard et al. (2013), time-varying stiffness and damping properties of the subsoil take place for wind turbines installed on monopiles. In addition, existing literature of full-scale testing of offshore wind turbines indicates strong disagreement of the soil damping contribution, see for instance (Versteijlen et al., 2011; Tarp-Johansen et al., 2009; Shirzadeh et al., 2013). Damgaard et al. (2014b) compared full-scale measurements of the natural frequencies of offshore wind turbines installed on monopiles with computational Winkler models and showed that the soil stiffness was underestimated meaning that the calculated eigenfrequencies were more than 10% lower than the measured values. Here, the initial stiffness of the non-linear p–y curve formulations recommended by API (API, 2000) and DNV (Det Nordske Veritas, 2007) were applied. Finally, offshore in situ

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tests to gain full insight into the material properties on each location are expensive. Therefore, in conclusion, physical and statistical uncertainties related to the soil properties always exist.

In this study, the intention is to evaluate to what extent a change of the soil properties affects the fatigue damage equivalent loads for 20 year design life of a parked 5.0 MW wind turbine installed on a monopile at 30 m water depth. Based on semi-analytical impedance functions for monopile vibrations (Nogami and Novak, 1977, 1976; Novak and Nogami, 1977), consistent lumped-parameter models (LPMs) (Wolf, 1994) for different soil conditions are calibrated and implemented into the aeroelastic nonlinear multi-body code HAWC2 (Larsen and Hansen, 2007; Larsen et al., 2013). The ocean conditions are based on wind–wave scatter diagrams for a wind park located in the North Sea which enables the determination of the joint probability of wind and waves. The sensitivity analysis is restricted to parked and idling conditions according to design load case (DLC) 6.4 and DLC 7.2 (International Electrotechnical Commission, 2009). These conditions are selected since they contribute significantly to the accumulated fatigue damage for large, flexible wind turbines. The combination of low structural eigenfrequencies close to the peak in the wave spectrum and low damping levels causes this tendency.

Following the introduction, Section 2 shortly outlines the concept of the derivation of a consistent LPM as illustrated in Fig. 1. Section 3 describes the wind and wave conditions used for the LC generation. In addition, the section contains a description of the investigated wind turbine structure and the different subsoil conditions used for the sensitivity study. The main results of the fully coupled aeroelastic simulations are discussed in Section 4, whereas general conclusions and remarks are given in Section 5.

2. Computational model of soil and pile response

A combined aero-hydro-dynamic approach has been used to evaluate the dynamic response of the offshore wind turbine structure founded on a monopile. The overall purpose is to establish a model that in a direct manner takes the dissipation effects of the soil–pile interaction into account. Therefore, a consistent LPM consisting of a parallel coupling of so-called discrete-element models is fitted to semi-analytical frequency-domain solutions of dynamic impedance functions of the soil–pile system. This in turn creates a substructure model that facilitates a simple implementation into the aeroelastic code HAWC2.

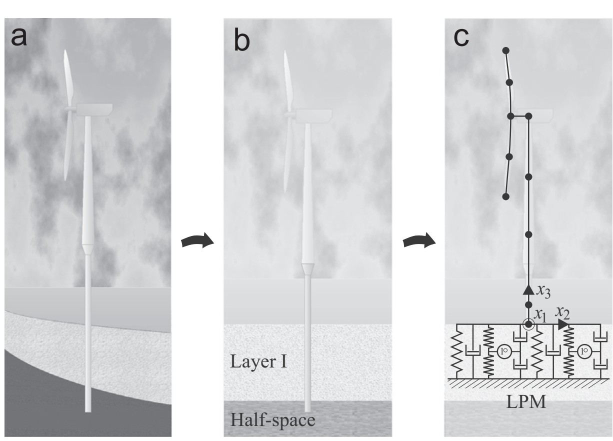

Fig. 1. Overview of the formulation of a consistent LPM: (a) a wind turbine installed on a monopile, (b) a rigorous frequency-domain model of a pile embedded in a linear viscoelastic soil layer and (c) a consistent LPM calibrated to the results of the rigorous model coupled with an aero-hydro-elastic model.

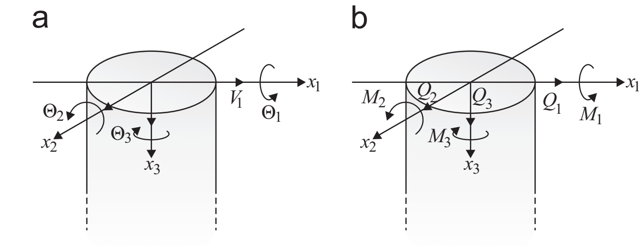

Fig. 2. DOFs for a monopile with a rigid pile cap: (a) displacements and rotations and (b) forces and moments.

According to Fig. 2, a monopile with a rigid pile cap has three translational and three rotational degrees of freedom (DOFs). In the frequency domain, these are related to the complex amplitudes of the corresponding forces and moments

$$\mathbf{r}(\omega) = \mathbf{S}(\omega)\mathbf{u}(\omega)$$
$$\Rightarrow \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} S_{11} & 0 & 0 & 0 & S_{15} & 0 \\ 0 & S_{22} & 0 & S_{24} & 0 & 0 \\ 0 & 0 & S_{33} & 0 & 0 & 0 \\ 0 & S_{42} & 0 & S_{44} & 0 & 0 \\ S_{51} & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \Theta_1 \\ \Theta_2 \\ \Theta_3 \end{bmatrix}, \quad (1)$$

where $\mathbf{S} = \mathbf{S}(\omega)$ is the dynamic impedance matrix defined by the angular frequency ω. Note that $S_{11} = S_{22}$, $S_{24} = S_{42}$, $S_{44} = S_{55}$ and $S_{15} = S_{51} = -S_{24}$ follow from the fact that the geometrical moment of inertia $\mathcal{I}_0$ of a double symmetric foundation is invariant to a rotation of the foundation around the x_3-axis.

2.1. Dynamic impedance functions of a monopile

In the early pioneering studies by Nogami and Novak (1976, 1977) and Novak and Nogami (1977), rigorous semi-analytical solutions were derived and presented of the interaction between a linear, viscoelastic soil layer overlying a rigid bedrock with hysteretic material damping and a linearly elastic pile vibrating horizontally and vertically. The theoretical framework is based on a two-step approach which is composed of (a) the estimation of the soil resistance established in a modal basis after integration of the dynamic soil stresses along the perimeter of a circular pile and (b) the dynamic vibration of an elastic continuous beam subjected to the dynamic pressure given by the previous step. It is noteworthy that the harmonic wave propagation equation of the soil layer for horizontal pile vibrations is formulated considering the vertical displacements as negligible. This approximation is considered rational when the monopile deforms in bending without substantial shear deformations. Thereafter, the complex valued numbers of the dynamic impedances at the pile cap can be determined as the reaction forces obtained after the application of the corresponding boundary conditions, i.e. unit forced displacements or rotations applied one component at a time. An approximate solution is obtained in the frequency domain after the summation of the contribution of a number of mode shapes. Here, it should be noted that for the physical frequencies relevant to wind turbine vibrations, the dynamic impedance functions have been compared with a three-dimensional coupled BE/FE model (Andersen and Jones, 2001). As expected, a reasonable fit was obtained. In addition, a comparison between the static torsional pile stiffness and the dynamic impedance function for torsional vibrations according to a coupled BE/FE model shows almost identical values in the physical frequency range $f \in [0; 8]$ Hz. Therefore, instead of fitting a consistent LPM to the non-varying dynamic impedance function, the static torsional pile stiffness has