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Dynamic soil-structure interaction in offshore wind turbines on monopiles in layered seabed based on real data

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ABSTRACT

The present paper studies the soil-structure interaction (SSI) effects on the dynamic properties of offshore wind turbines (OWT) founded on monopiles. For that purpose, a three degrees-of-freedom substructuring model based on modal parameters is proposed. The whole superstructure is reduced to a punctual mass by its fundamental modal mass and height, while the pile-soil stiffness is represented by the corresponding impedance functions. The proposed model, together with characteristic relations between the fixed-base fundamental frequency and the modal parameters obtained from data of existent OWTs found in the literature, is used to analyse the influence of the superstructure and foundation dimensions and soil profile on the magnitude of the SSI phenomena. The obtained results confirm the relevance of including the foundation stiffness in the design stage of OWT systems, as variations in the fundamental frequency close to 15% can be produced. The homogeneous assumption, even if $c_{s,30}$ mean values are assumed, yields to misleading results if the actual soil profile presents properties that vary with depth. The superficial layers of the soil profile are found to play a major role in the estimation of the OWT system fundamental frequency and damping when the SSI phenomena are included.

1. Introduction

In the last years, the use of Offshore Wind Turbines (OWT) has experienced a great increment owing to the reduction in cost and the increase in the generators size and power. However, further research is demanded in order to better understand the dynamic behaviour of their supporting structure and so that design and lifespan can be improved.

The principal foundation type for OWTs is the monopile (80.1% of the OWT installed in Europe are founded on monopiles according to EWEA (2016)). Monopile foundations consist of a short hollow pile with large diameter that is driven into the seabed, and are commonly used for water depths of 20–40 m. The simplicity of the construction and assembly is the principal advantage of this foundation type. However, the pile is a very slender structure and, consequently, more flexible than other foundation configurations (e.g. gravity based or jackets). The soil-structure interaction (SSI) effects have to be carefully considered when studying the dynamical behaviour of the OWT, being these effects highly dependent of the foundation typology used.

One of the principal effects of the SSI is the change of dynamic properties, i.e. fundamental frequency and damping, of the foundation-structure system with respect to the fixed-base structure. The variation in the eigenfrequency has to be carefully considered when designing the OWT structure in order to avoid resonance with the excitation frequencies and the corresponding increase in fatigue damage. Besides the wind and wave loads that present a frequency content below 0.1 Hz, the principal frequencies to avoid are the rotor frequency (1P) and the blade-passing frequency (3P or 2P depending on the number of blades). The first corresponds to rotor or aerodynamic unbalance loads, while the latter is produced by the shadowing effect from the wind of the blades passing the tower. The DNV (2002) recommendation is to keep the tower frequency outside the $\pm 10\%$ range of these frequencies. Additionally, depending on the relation between the tower fundamental frequency and the aforementioned frequencies, three classical designs are distinguished (Kühn, 2001; van der Tempel, 2006): soft-soft if the tower frequency is

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below the 1P, soft-stiff if it is between 1P and 3P, and stiff-stiff when the structural eigenfrequency is higher than 3P. The soft-soft design is usually avoided as it corresponds to very flexible structures and shows the eigenfrequency near to the wind and wave loads. On the other hand, the stiff-stiff design is not a common choice owing to the high material requirements in order to reach the desired frequencies. Thus, the soft-stiff design is the one that is usually adopted. This design causes the OWT natural frequency to be within a very narrow range, highlighting the importance of an accurate estimation.

Despite giving a proper literature review is out of the scope of the present paper, the authors want to refer the interested readers to the works of Galvín et al. (2017), Bisoi and Haldar (2015), Damgaard et al. (2014a), or Zaaijer (2006), where numerous recent studies addressing the influence of the SSI effects on the variation of the OWT tower eigenfrequency and damping are presented.

The present work proposes a simplified substructuring model based on modal parameters to analyse the variations in the fundamental frequency and damping of OWT systems due to the SSI effects. The whole superstructure is reduced to a punctual mass through its modal mass and height. On the other hand, the foundation stiffness is addressed through impedance functions obtained numerically by an integral time-harmonic model. This model makes use of Green's functions for the layered half space to represent the soil behaviour and treats the pile, discretized by the FEM as a Timoshenko beam, as a load line acting within the soil. The one degree-of-freedom mass and the impedance functions are then coupled together into the proposed simplified substructuring model, and the modal approach is validated against a more elaborated substructuring FEM model considering the complete superstructure dimensions. Then, the proposed methodology is applied to study the influence of the soil-structure system properties on the magnitude of the SSI effects, paying special attention to the soil profile. The analyses are carried out by assuming characteristic structural properties obtained from data of actual OWT systems and soil profiles based on boreholes of the North Sea.

2. Problem statement

2.1. Problem definition

This paper addresses the dynamic characterization of OWT structures founded on monopiles. The system is assumed to be composed by a conical hollow tower, rotor and generator nacelle located at the tower top, and a monopile acting as foundation (see Fig. 1). The tower is connected to the monopile through a transition piece, which is a cylindrical hollow beam presenting some working platforms that give access to the OWT structure for maintenance or repair activities. The monopile is

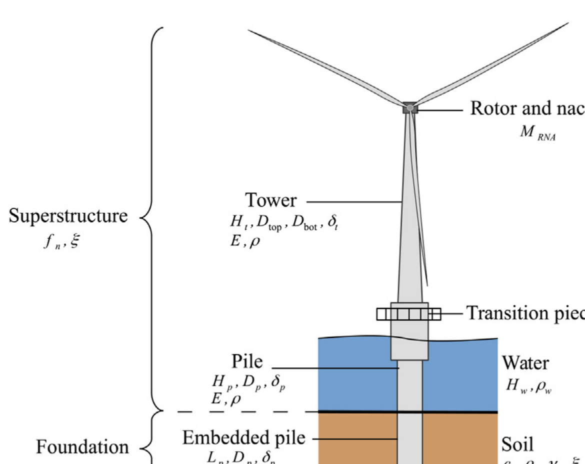

Fig. 1. Representation of a generic OWT and identification of geometrical and material parameters.

assumed to be a cylindrical hollow beam that is driven into the seabed and that is composed by two different parts: the above-soil portion and the embedded portion, both presenting the same cross-section. The tower and pile are assumed to be made of the same material.

The system geometrical and material properties are: tower length H_t, tower top and bottom external diameters D_{top} and D_{bot}, ratio between the tower cross-section inner and outer diameters δ_t (henceforth, thickness ratio), mass of the blades and generator nacelle M_{RNA}, above-soil pile length H_p, pile embedded length L_p, pile external diameter D_p, pile thickness ratio δ_p, Young's modulus E and density ρ. Owing to the small aspect ratios that the embedded pile can present in this type of constructions, the Timoshenko's beam theory is used to model it. Thus, additional geometrical and material properties are required for the embedded pile: Poisson's ratio ν_p, shear coefficient α, and material hysteretic damping ratio ξ_p.

Finally, the problem is completely defined by knowing the water depth H_w and density ρ_w, and the soil profile given by the shear wave velocity c_s, which can change depending on the depth; and soil Poisson's ratio ν_s, soil density ρ_s and soil hysteretic damping ratio ξ_s, which are assumed to keep the same value for the whole profile.

The OWT system can be divided into two different parts: the superstructure (above soil) and foundation (under soil). By considering an infinite rigid base, the superstructure dynamic behaviour can be easily characterized by its fundamental frequency f_n and damping ratio ξ. However, if the foundation flexibility is included in the analysis, the SSI effects produce a reduction in the system fundamental frequency and changes in the damping ratio. The aims of this paper are computing these changes by obtaining the flexible-base fundamental frequency $\widetilde{f_n}$ and equivalent damping ratio $\tilde{\xi}$, and studying how the superstructure, the foundation and the soil profile characteristics affect them.

2.2. Set of existent OWTs taken as starting point

Different OWT systems that can be found in the literature are selected for analysis in this study. Their properties and details are presented in Table 1. OWTs 1–12 were extracted from the work of Lombardi (2010), and correspond to wind turbines from different wind farms already built in the UK. For each farm, a range of hub heights was indicated, so the maximum and minimum values are considered. Only information about diameters and thickness of the Vestas towers was available, so these dimensions are assumed for the Siemens towers too. On the other hand, OWTs 13 and 14 correspond to systems that have been widely studied in different works (e.g. Adhikari and Bhattacharya, 2012; Arany et al., 2015; Bisoi and Haldar, 2014; Lombardi et al., 2013). Thus, more detailed information about them was accessible.

However, for the selected cases, there are very few details available about the dimensions of the transition piece and the length of the pile outside the seabed. For this reason, the transition from pile to tower is assumed to be produced at water level, so the pile length is equal to the water depth ($H_p = H_w$). On the other hand, some structures present a constant wall thickness, while others have a thickness that varies along the height. In order to define all the studied OWT systems in a coherent way, the thickness ratio is kept constant for the whole length. By doing so, thicker walls are presented at the tower base, where the largest diameter is located. The values of δ_t presented in Table 1 are obtained as the mean value of the ones corresponding to the tower top and bottom sections.

For all the structures, the towers and piles are assumed to be made of steel. Thus, a Young's modulus $E = 210$ GPa, a Poisson's ratio $\nu_p = 0.25$ and a density $\rho = 7850$ kg/m^3 are assumed. In addition, for the embedded piles, the hysteretic damping coefficient is set to $\xi_p = 2\%$ and the shear coefficient of a hollow circular cross-section $\alpha = 0.5$ is used. On the other hand, a fixed-base modal damping ratio of the structure $\xi = 1\%$ is assumed. For the water density, $\rho_w = 1000$ kg/m^3 is considered.