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Assessment of natural frequency of installed offshore wind turbines using nonlinear finite element model considering soil-monopile interaction

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ABSTRACT

A nonlinear finite element model is developed to examine the lateral behaviors of monopiles, which support offshore wind turbines (OWTs) chosen from five different offshore wind farms in Europe. The simulation is using this model to accurately estimate the natural frequency of these slender structures, as a function of the interaction of the foundations with the subsoil. After a brief introduction to the wind power energy as a reliable alternative in comparison to fossil fuel, the paper focuses on concept of natural frequency as a primary indicator in designing the foundations of OWTs. Then the range of natural frequencies is provided for a safe design purpose. Next, an analytical expression of an OWT natural frequency is presented as a function of soil-monopile interaction through monopile head springs characterized by lateral stiffness K_L, rotational stiffness K_R and cross-coupling stiffness K_{LR}, of which the differences are discussed. The nonlinear pseudo three-dimensional finite element vertical slices model has been used to analyze the lateral behaviors of monopiles supporting the OWTs of different wind farm sites considered. Through the monopiles head movements (displacements and rotations), the values of K_L, K_R and K_{LR} were obtained and substituted in the analytical expression of natural frequency for comparison. The comparison results between computed and measured natural frequencies showed an excellent agreement for most cases. This confirms the convenience of the finite element model used for the accurate estimation of the monopile head stiffness.

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1. Introduction

Wind, solar power and geothermal heat are representative of clean and renewable energy which have the potential to become alternatives to current supplement of fossil fuel sources of energy in the future. While these alternative energy sources have their advantages and drawbacks, wind energy is widely accepted as the cheapest and most economically available one based on current technology. Today, wind energy has proven to be a valuable feature for large-scale future investment in the energy industries worldwide, and many countries install their proper wind turbine generators (WTGs), mainly on land. As offshore wind turbines (OWTs) have gained their popularity, many WTG manufacturers believe that offshore wind energy will play an increasingly important role in the future development. This is supported by the fact that all principal wind turbine manufacturers currently are spending huge amount of money and effort on developing larger offshore WTGs for deeper waters where wind speed is generally higher and steadier, resulting in an increase in energy output.

Although there are many OWTs support options which may range from gravity foundations (for shallow depths of 0–15 m) to floating foundations (for very deep waters of 60–200 m) (Achmus et al., 2009; Lombardi et al., 2013; Damgaard et al., 2015; Abed et al., 2016), most OWTs are supported on monopile foundations, as they are simple structures which are easy and convenient to construct. The accumulated experience from limited monitored data from OWTs over the last 15 years showed that the available design procedures (mostly contained in the API (API and ISO, 2011) and DNV (DNV-OS-J101, 2004) regulation codes suffer limitations.

The existing methods were established/calibrated by testing small-diameter piles used for supporting offshore platforms in gas and oil industry, often with design criteria and loading conditions

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which are different from those encountered in an OWT. The inappropriateness of these methods comes from the fact that:

(1) The continuum (soil) is replaced by a series of uncoupled springs. However, reliable results necessitate a rigorous method which can properly account for the true deformation mechanism of soil-monopile interaction.
(2) As they rotate freely, monopiles supporting OWT energy converters undergo severe degradation in the upper soil layer resulting from cyclic loading, whereas offshore jacket piles are significantly restrained against rotation at their heads.
(3) Monopiles are relatively shorter and rigid piles with a length to diameter ratio (L_p/D_p) in the range of 2–6 and a diameter (D_p) of up to 8 m envisaged for the next generation of turbines, whereas offshore piled foundations in the offshore oil and gas industry have a length to diameter ratio (L_p/D_p) of over 30 and relevant recommendations have been set on the basis of full-scale loading tests on long, slender and flexible piles with a diameter of 0.61 m (Reese et al., 1974).
(4) The API model is calibrated in response to a small number of cycles for offshore fixed platform applications. However, an OWT over its lifetime of 20–25 years may undergo 10^7–10^8 cycles of loading.

Due to these complex issues, appropriate determination of the dynamic characteristics of these extremely complex structures through their monopiles head stiffnesses is continuing to challenge designers, as the foundation of an OWT behavior is still not well understood, and also not introduced in the current design guidelines.

Concerning accurate prediction of the monopile head stiffnesses, numerical analysis using the finite element method (FEM) constitutes an excellent alternative to capture the real behavior of this type of foundations and hence to accurately estimate the dynamic characteristics of an OWT.

Otsmane and Amar Bouzid (2018) formulated a nonlinear pseudo three-dimensional (3D) computation method, combining the FEM and the finite difference method (FDM). They wrote a Fortran computer code called NAMPULAL (nonlinear analysis of monopiles under lateral and axial loadings) to study monopiles under axial, lateral and moment loadings in a medium characterized by the hyperbolic model for representing the stress–strain relationships. In this paper, we attempt to apply NAMPULAL to examining the lateral behavior of monopiles supporting OWTs chosen from five different offshore wind farms in Europe. These offshore wind farms include Lely A2 (UK), Irene Vorrink (Netherlands), Kentish Flats (UK), Walney 1 (UK) and Noth Hoyle (UK).

To accurately estimate the natural frequency of the OWT structure (tower + substructure) which is a function of monopile-subsoil interaction, the monopiles head movements (displacements and rotations) and consequently, the lateral stiffness K_L, the rotational stiffness K_R and the cross-coupling stiffness K_{LR} are obtained and substituted in the analytical expression of natural frequency for comparison. In general, the results of comparison between the computed and measured natural frequencies showed a good agreement.

2. Natural frequency and modal analysis

OWTs are dynamically sensitive structures, in which the dynamic soil-structure interaction is a pivotal aspect of their design process and consequently, they require accurate soil stiffness estimation in order to ensure that the design frequency matches the actual operational frequency when the wind turbines are constructed.

The natural frequency of the hub-tower-foundation system is the key feature on which the response of an OWT to wind and wave loads depends. This is due to the dynamic nature of the loads on the wind turbine structure and the slenderness of the system. Through determination of the natural frequency, designer can assess the strains produced by loading cycles, through which the fatigue failure of the structure can be ascertained. Therefore, an accurate estimation of this parameter is essential to assess the working life of a wind turbine.

Unlike most large-scale civil engineering structures, wind turbines are subjected to millions of periodic excitation cycles during their operating life. The rotor spinning at a given velocity induces mass imbalances (gyroscopic effect), causing a frequency known as 1*P*. In addition to this, the effect of a standard turbine having *n* blades induces a further excitation due to the blades passing the tower. The frequency of this shadowing effect is *nP*, where $n = 3$ in most cases.

The modern installed wind turbines are characterized by a range of different velocities in which their rotors are operating. This results in two ranges of operating frequencies around 1*P* and 3*P*. In order to avoid resonance, the natural frequency of the tower cannot be in any of these two ranges and must be far from 1*P* and 3*P*.

The OWT design can be performed in such a way that the first eigenfrequency lies within three possible ranges: soft–soft, soft–stiff and stiff–stiff as shown in Fig. 1.

(1) Soft–soft range: the natural frequency is less than the lower bound of 1*P*. This implies that the structure is too flexible, and moreover, this is a range where the frequency of waves may lie, therefore leading to resonance.
(2) Stiff–stiff range: this is a range where the tower frequency is higher than the upper bound of blade passing frequency (3*P*). This range is economically unfeasible as it leads to a too rigid (heavy and expensive) structure, making it inappropriate for design.
(3) Soft–stiff range: in this interval, the natural frequency lies between 1*P* and 3*P*. This range is the optimum range for the best possible design.

The system stiffness must be such that the natural frequency of the wind turbine does not lie within the rotor frequency excitation bands, as this may induce resonance which could lower the design life significantly.

In order to satisfy these requirements and to keep the natural frequency of the whole structure in the adequate margin of the soft–stiff range, thus avoiding resonance, a joint effort between foundation designers and turbine manufacturers is performed. Foundation designers need careful site investigations to obtain reliable soil data in order to correctly assess the foundation stiffness.

2.1. Appropriate OWT modeling for dynamic analysis

The natural frequency of a wind turbine is highly dependent on the material properties used in its construction, and is significantly affected by the stiffness of the soil surrounding the monopile. Assessment of foundation stiffness is the key to obtain reliable estimate of system frequency.

In the computation of eigenfrequency f_1, most researchers in the past tried to model this complex system according principally to two concepts (Prendergast et al., 2015; Yi et al., 2015). In the first one, Yi et al. (2015) simply considered the soil as a medium having an infinite stiffness. In this regard, Vught (2000) used a model in

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