

Natural frequencies of a monopile supported offshore wind turbine taking into account soil-foundation-structure interaction and incorporating soil spatial variability

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Introduction

Offshore wind is considered as one of the most cost effective means of reducing society's dependence on fossil fuels. Exploitation of offshore wind energy from a severe environment like the sea requires resistant structures with suitable foundations. Multi-megawatt offshore wind turbines with slender tower and large rotor diameters and founded on monopiles are widely used to extract this vast offshore wind energy. For example, the tower height and rotor diameter of the 10 MW DTU horizontal axis reference wind turbine reach 115.63 m and 178.3 m respectively [1].

During their lifetime, OWTs are exposed to intense dynamic loading in a wide frequency range which makes them dynamically sensitive [2, 3 and 4]. Therefore, tuning the natural frequencies of the whole structure including the soil-foundation-structure interaction is of special importance during the design stage [2, 3, 4, 5 and 6]. In fact, the first natural frequency of the overall wind turbine should be carefully adjusted in a very narrow range to be outside the excitation frequencies and thus to avoid dynamic amplification which is known as resonance. The excitation sources for an offshore wind turbine arises from, the wind turbulence, the waves, the rotor spinning at a given rotational velocity termed as $1P$, and the vibrations caused by the blade passing in front of the tower causing a shadowing effect referred to as $N_b P$, where N_b is the number of blades. The $1P$ frequency is not a single frequency but a frequency band having a range associated with the lowest and the highest revolutions per minute of the rotor this is due to the fact that most industrial wind turbines are variable speed machines. In this regard, both the wind and the wave frequencies are typically below the $1P$ frequency, although wave frequencies are much variable and can cover a relatively wide frequency spectrum. Therefore, to ensure that no resonance occurs, three options can be considered in the design phase:

- i. 'Soft-soft design (*i. e.* $f < 1P$ range)' which is a very flexible structure and almost impossible to design for a grounded system
- ii. 'Soft-stiff design (*i. e.* $1P$ range $< f < 3P$ range)', and this is the most common in the current offshore development
- iii. 'Stiff-stiff (*i. e.* $f > 3P$ range)' design and will need a very stiff support structure

Regarding the codes of practice, the DNV code [5] suggests that the first natural frequency should not be within 10% of the 1P and 3P ranges. The safest solution would seem to be placing the natural frequency above the 3P range corresponding to a stiffer design. However, this approach with higher natural frequency require massive support structures and foundations, involving higher costs of materials, transportation and installation. Thus, from an economic point of view, softer structures are desirable, and it is not surprising that almost all of the installed wind turbines are ‘soft-stiff’ designs and this type is expected to be used in the future as well.

It is important to note that, for the design standards for offshore wind turbines, soil structure interaction is taken into account as described in IEC 61400-3, Design Requirements for Offshore Wind Turbines. The general method in the IEC standards relies on the API (American Petroleum Institute) design approach. In the API approach, the soil p-y curves are developed for slender flexible piles, which are widely used for offshore oil and gas platforms. However, the monopiles supporting offshore wind turbines are typically rigid with large diameters (3.5m – 8m) and length (30m – 60m). Therefore, the API approach developed for slender piles may not be applicable for the monopiles.

In this paper, a detailed 3D model of the DTU-10MW wind turbine is developed using the commercially available finite element code ABAQUS/Standard. The tower was discretized explicitly using shell elements. Each blade was modelled as a beam with specific stiffness properties for each section and a hinge connection was employed to simulate the rotation of the blades with respect to the rotor. Concerning the soil it was modelled as a 3D solid continuum and the soil-structure-interaction was simulated using small sliding surface-to-surface master/slave contact pair formulation. Compared to previous simplified models, the present numerical model considers simultaneously the influence of both the geometrical configurations of the superstructure (tower, blade, transition piece and nacelle), as well as the soil-foundation-structure interaction by considering the soil as a 3D solid continuum. Numerical results showing the effect of the monopile geometrical parameters (diameter, thickness, and embedment length) and the soil spatial variability on the wind turbine natural frequencies are presented and discussed.

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