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Dynamic effects in the response of offshore wind turbines supported by jackets under wave loading

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ABSTRACT

This paper studies the effect of structural dynamics on the response of an offshore wind turbine (OWT) supported by a jacket and subjected to wave loads. The study includes a series of time-domain dynamic analyses based on loading from regular and irregular wave histories and three example OWT support structures. The OWT support structures are proportioned to collectively span a broad range of the first fundamental period of an OWT supported by a jacket. For each dynamic analysis, a representative static analysis is also considered, and a dynamic amplification factor (DAF) is calculated and discussed as a function of wave height, wave regularity, and structural period. The results demonstrate that dynamic effects may amplify the structural response significantly for loading caused by smaller waves, but the amplification is minimal for loading caused by large waves, which have longer periods and, for the jacket geometry considered here, cause large wave-in-deck forces. For the specific scenarios and models considered in this paper, the structural period is found to have a small influence on the DAF.

1. Introduction

Performance-based design considers the diverse needs and objectives of owners and users of infrastructure by explicitly assessing the performance of structural designs during both expected and extreme loadings, the latter of which are anticipated to damage the structure [1]. Performance-based design relies on the assessment of the vulnerability of structures and on the recurrence of hazards, resulting in estimations of the probability of damage for the structure during its lifetime [2–7]. Such information is essential to understanding and mitigating the risk of hazards, whether natural or otherwise. In the initial development of performance-based design, structural assessments were first based on nonlinear static analyses (i.e., static pushover analyses [8]) which aimed to 'equivalently' represent dynamic loading. Such static approaches have been used widely to, for example, estimate the structural capacity of buildings under earthquakes [9], offshore platforms under wave loads [10] and offshore wind turbine (OWT) support structures under wind and wave loads [11]. While static pushover analysis provides a reasonable and practical way to assess a comprehensive range of structural behavior by scaling a static force distribution that is representative of expected dynamic loading [8], the implications of this static approximation are not well understood for OWT structures and the intent of this study is to provide insight into the practice of approximating dynamic loading with static loading to see if equivalent static approaches can be used to reasonably assess the performance of OWTs supported by jackets.

The preference for static analysis is due, in part, to the computational burden and greater overall complexity of modeling the dynamic response of a structure subject to time-varying loading [12]. The growth of computer processing power, however, has enabled the efficient assessment of structural performance using dynamic, time-domain analysis. In earthquake engineering, which has led the evolution of performance-based design, Vamvatsikos and Cornell started the transition to dynamic analysis with the development of the now widely-used method termed incremental dynamic analysis (IDA) [13]. In wind engineering, the influence of dynamic effects on structural inelastic behavior have been considered by Tabbuso et al. who developed a method based on dynamic inelastic models of building frames subject to stochastic wind with long duration [14] and by Judd and Charney who have studied the inelastic behavior of buildings using an IDA-based approach [15].

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In offshore oil/gas engineering, dynamic methods have been established to estimate the behavior of offshore jacket platforms against environmental wave loading. Golafshani et al. have introduced the idea of Dynamic Incremental Wave Analysis (DIWA), which estimates capacities for oil/gas jacket structures through nonlinear dynamic analysis [16]. In offshore wind engineering, Taflanidis et al. have developed a surrogate model based on elastic dynamic analyses of OWTs supported by tripods to predict structural response under extreme wave and wind loads [7].

Although dynamic analysis is becoming more commonplace, static analysis remains popular because of its simplicity. For offshore structures, the difference between dynamic and static analyses in the response of offshore structures is still a subject of active research. For example, Jensen [17] studied the dynamic amplification factor (DAF) of a jack-up platform subjected to non-Gaussian wave loads and a single degree of freedom structural model. Golafshani et al. [16] studied oil/gas jacket platforms under wave loads and found that, for two different example platforms, the difference between the maximum structural base shear of dynamic and static analyses was either negligible (less than 0.5%) or approximately 14%, with dynamic analysis providing a larger maximum response. Horn et al. [18] investigated the dynamic amplification of drag dominated structures and found that simplified analytical methods were not accurate for considering dynamic amplification in irregular seas. Kim et al. [19] considered both static pushover and dynamic approaches to assess the response of a 5 MW offshore wind turbine supported by a monopile subjected to seismic loading considering nonlinear soil-pile interaction and found pushover analysis compared well with dynamic analysis results.

This paper presents the results of a numerical study consisting of a series of time-domain dynamic analyses intended to provide a better understanding of the dynamic effects on the elastic response of OWTs supported by jackets and loaded by waves. Although explicit consideration of the inelastic response of an OWT during the design process is essential to a performance-based design framework, the scope of this study is focused on the elastic response. Consideration of the inelastic response, including dynamic effects, is an important area for further study. Wind loads are not considered in this study, partially to focus the scope of the study and partially because wave loads are expected to drive the dynamic response of the structure considered here during extreme conditions when the rotor will be parked and feathered to minimize thrust [20]. Fig. 1 shows a schematic of an OWT supported by a jacket subjected to irregular waves and identifies key terms in this paper. The magnitude of the dynamic effect is quantified through dynamic amplification curves, which provide a dynamic amplification factor (DAF; i.e., the ratio between the maximum response of a dynamic analysis and an equivalent static analysis) as a function of environmental conditions. These curves are provided separately for multiple modeling conditions, including regular and irregular wave loading and three example structures that have fundamental periods of 2.5 s, 3.2 s, and 4.9 s. The paper is organized as follows: first the analysis procedure and structural models are defined, then results from the numerical study are presented, and finally the results are summarized to better understand the extent of dynamic effects in the assessment of the performance of an OWT supported by a jacket and loaded by waves.

2. Model definition and analysis procedure

This section defines the structural model and analysis procedure used here to assess the extent of dynamic effects for three models of a jacket structure supporting an OWT and subjected to wave loading. The overall configuration of the considered jacket is based on the UpWind reference jacket [21], while the configuration of the OWT is based on the NREL offshore 5-MW baseline turbine [22]. Three different models of the jacket and OWT, each with different fundamental periods, are considered. The intent of studying these three models is to determine how dynamic amplification varies with the fundamental period of the structure and to give insight to practicing engineers applying the results in this paper to structural designs with different dynamic characteristics. As such, these three models are not intended to have a realistic geometry nor to have dynamic characteristics consistent with the NREL offshore 5-MW turbine. The three fundamental periods are selected to consider a range of periods and are realized by scaling the thickness of jacket and tower members in the model, thereby scaling the stiffness and mass of the model. Although wind loading during operational conditions is an important loading for the design of OWTs, Wei et al. [11] studied the ultimate capacity of non-operational OWTs under extreme wind and wave loadings and found that waves were the dominant source of extreme loads for the structural configuration considered here and for the following conditions: the rotor is oriented perpendicular to the wind, the blades are feathered to reduce aerodynamic forces, and the extreme waves contact the deck of the jacket, causing large wave-in-deck forces. Therefore, for this study, only the effect of wave loading is considered. All structural models are analyzed using the commercial finite element program USFOS [23].

2.1. General structural configuration

The tower and turbine in the three models considered here are based on the NREL offshore 5-MW baseline wind turbine [22] supported by a jacket, installed in 50 m water depth. The jacket design is taken from the Upwind project [21] (Fig. 2). The nacelle of the considered turbine has a mass of 240,000 kg and a diameter of 3.5 m. The total mass of the rotor and blades is 107,000 kg. The tower consists of pipe members with diameter and thickness varying along the height. The jacket consists of four legs with four levels of X-braces and cross braces. The four legs are oriented in plan to make a square section with edge length at the mudline of 12 m and at the deck of 8 m. The bottoms of the legs are modeled as being fixed to the mudline. The connections between the braces and legs of the jacket are made with complete joint penetration welds between the contoured ends of the brace member and the continuous chord member (i.e., the leg) without stiffeners or grout. A concrete deck with a mass of 666,000 kg and dimensions of $4.0 \times 9.6 \times 9.6$ m is positioned on top of the jacket and serves as a support platform for the tower of the turbine. The bottom of the concrete deck is 16 m above mean sea level and 66 m above the mudline.

The rotor and blades are modeled as a lumped mass of 107,000 kg horizontally offset from the center of the turbine by 3.5 m. The tower is modeled with eight beam elements due to the non-uniform cross sections along the height. The transition piece is modeled using solid elements, which connect the bottom node of the tower to the top nodes of the four jacket legs, and the mass of the transition piece is distributed uniformly. The jacket is modeled with beam elements with an additional spring element included at the intersection between the central line of chord wall and the intersection between the chord wall and brace (Fig. 3) to account for eccentric loading and flexibility of the joint itself. The axial, bending and torsional stiffness of the additional element are calculated within USFOS [23] based on the joint geometry.

The tower and jacket are modeled as being made from a medium grade structural steel with Young's modulus of 210 GPa and density of 8500 kg/m^3, which includes assumed masses accounting for paint, bolts, welds and all other additional masses that are not otherwise considered [11]. The jacket legs are assumed to be