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Slow-drift of a floating wind turbine: An assessment of frequency-domain methods based on model tests

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ABSTRACT

The second-order hydrodynamics of a semisubmersible offshore wind turbine is investigated in this paper by analyzing and proposing a set of different options for estimating the slow-drift motions during its design. A case study consisting of a three-floater semisubmersible designed to support a 1.5Mw turbine is considered. An experimental campaign focused on characterizing second-order surge response was carried out and its most salient results are documented in the paper. The campaign was conducted in two different facilities and comprised decay tests, regular, bichromatic and irregular waves. Wind has not been considered in this phase of the research. Numerical modeling with frequency domain solver WAMIT has been carried out. Due to location depth and mooring length restrictions, the natural periods of horizontal excursions are smaller than those of well studied DeepCwind platform. This may change the importance of the different second-order components, something investigated in present research by comparing simplified and full Quadratic Transfer Functions (QTF) computations. Results obtained with experiments and simulations are compared, focusing on the mean and slow-drift motions and forces. It is shown that the Newman approximation underestimates the second-order response in some cases while the white noise model retains the main physics involved, a novel result which may change the paradigm for mooring design of these artifacts in the near future.

1. Introduction

The interest of the electric power generation sector in floating offshore wind turbines (FOWTs) is growing up. This interest is exemplified in the recent successful launch and test of full scale prototypes: Hywind in Norway [1], WindFloat in Portugal [2], Mitsui in Japan [3] and VolturnUS, the 1:8 large scale unit of university of Maine [4,5]. The reason for this interest is that 61% of the US coastal areas, nearly all of Japan's, and various European locations such as off the coast of Norway and Mediterranean, require floating foundation technology due to large water depths.

Among the FOWTs platforms, three concepts have emerged as the most attractive: TLP, spar and semisubmersible. In particular the semisubmersible concept has received attention in the recent literature (see e.g. Refs. [2,6]) due to several claimed advantages [7], namely: these types of platforms can be fully assembled onshore and towed ready-to-use to their final destinations; the available mooring systems are well-known and cost competitive; if properly designed, downtime in operational sea states, due to excessive platform motion, is low.

One common feature of offshore floating platforms is that, in order to avoid resonance in the wave energy range, the design natural periods for some of the motions are quite large (or low in the case of the TLP concept). In addition, although not as large as typically observed for floating units in deep waters, FOWTs with conventional catenary mooring systems still present large natural periods of horizontal excursions. This brings the need to look at wave second-order excitations.

Goupee et al. [8,9] conducted experiments with representative designs of the three prevalent FOWTs concepts within DeepCwind R&D U.S. project. They excited the floaters with irregular seas and found that low frequency surge motions can be quite energetic for the semisubmersible concept. Some of these authors also

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documented different aspects of the experimental setup [10–12] without however paying specific attention to the challenges of directly characterizing the second-order response of the floaters by experimentally evaluating their QTFs.

Roald et al. [13] studied the second-order forces of a spar (OC3-Hywind) platform and a TLP (UMaine), trying to assess their relevance when compared to aerodynamic ones. Coulling et al. [14] focused, however, on the semisubmersible concept using Goupee et al.'s [8] experimental data to validate the implementation of second-order wave forces in FAST time domain solver. They used Newman approximation to compute the QTF [15], thus implying only mean-drift terms, which can be obtained from first-order potential, were accounted for. They largely improved the estimation of the surge response spectrum when compared to considering just first-order forces. However, they needed to modify/tune damping obtained from decay tests in order to accurately reproduce such motion spectrum. In addition, their platform had a quite large surge natural period ($\sim$ 100 seconds), fundamental for the accuracy of Newman's approximation, which may not be representative of the behavior of other floaters, mainly those working in shallower waters (it must be borne in mind that the water depths of as important floating devices testing sites as BIMEP in Spain, the recently approved Mistral in France, and WindFloat location, range between 42 and 90 m). Goupee et al. [8] looked as well at the mooring tensions, whose predictions showed reduced accuracy compared to that of the motions, something that they attributed to a poor representation of the mooring dynamics.

Gueydon et al. [16] compared computations of second-order forces using WAMIT and DIFRAC codes. While WAMIT is able to compute all second-order force components, DIFRAC is able to compute only those that depend on first-order potential. They conducted time domain simulations using FAST and aNySYM, taking frequency domain forces and added masses from WAMIT and DIFRAC respectively. They used the DeepCwind semisubmersible floater geometry but did not compare with experimental data. Subtle issues regarding the damping modeling are documented, and only minor differences between the two solvers simulations are found. The lead author of such reference had previously considered as well some second-order effects with DIFRAC-aNySYM [17,18] but the formulation was not clearly explained and validation was jointly conducted while considering wind effects, something that makes it difficult to isolate the accuracy of the modeling of second-order wave forces effects.

Jiawen Li et al. [19] proposed a novel hybrid spar-semisubmersible concept for floating offshore wind turbines. In order to analyze it, they implemented a coupled time domain solver using FAST, with first and second-order wave forces (full QTF) obtained in frequency domain with WADAM. In order to validate their approach, they simulated one irregular motion case of the OC4 platform, also studied by Coulling et al. [14]. Jiawen Li et al. [19] results for that case, in terms of surge PSD, were overall similar to those of Coulling et al.'s [14] and they claimed a better representation of the secondary coupled pitch resonance peak. However, the scope of their analysis was quite limited, natural period was high for this case, which makes Newman approximation to be likely in agreement with the full QTF, and discussion on added damping values was not included.

Bayati et al. [20] analyzed, numerically, the second-order hydrodynamics of again the DeepCwind semi floater. They linearized the topside response computed with FAST in order to incorporate its effect into frequency domain computations carried out with WAMIT. They used the full QTF to characterize the second-order response, without explicitly discussing how different compared to the Newman approximation the outcome was. They noted that the predicted second-order effects seemed reminiscent of those found in Ref. [8] irregular motion tests. Bayati et al. [20] also showed that low frequency response due to second-order hydrodynamics dominates over the combined wind and first-order wave effects for large wave heights. This fact provides extra meaning to present analysis, where only the platform hydrodynamics is considered.

Lopez-Pavon et al. [21] (our previous work, with the same semisubmersible floater studied in the present research) conducted tests with the model fixed in bichromatic waves, in order to measure second-order loads directly and assess the accuracy of different numerical approximations to model such effects. The scope of the campaign was somewhat limited, but sufficient results were gathered to document, for example, that Newman's approximation could be not accurate enough for the modeling of that particular floater. This was mainly due to the relatively low resonance periods imposed by the design mooring system, leading to increased errors in this approximation.

Bayati et al. [22] extended their referred 2014 work [20], with water depth of 200 m, to lower water depths down to 30 m. Apart from the second-order hydrodynamics, they also accounted for the setdown effect in the time history of the incoming waves. Due to its low resonance frequency, they found first-order heave motion to be the most affected by reducing the water depth, since corresponding waves were long enough to be significantly affected by the presence of the seabed. They found no significant influence of reduced water depth on second-order surge nor pitch motions when changing it from 200 m to around 60 m. Only when a shallow depth of 30 m was reached, a substantial increase of the mean and oscillating components of surge and pitch motions was observed. In this work, they kept the same surge natural period ($\sim 120s$) regardless of the depth choice. This, however, may be unrealistic since, for catenary moorings, lower depth is usually associated to a lower natural period.

All these analysis ultimately are carried out to assess the impact of second-order hydrodynamics on the mooring design, and the short literature review presented above reveals the absence of a more systematic experimental and numerical analysis planned for investigating, specifically, the slow drift components.

Designing the mooring of a floating offshore wind turbine is a complex matter due to the fact that wind, wave and current loads and coupled structural dynamics have to be accounted for Refs. [23–27]. Accurately assessing second-order slow-drift forces is necessary for an optimized design of the mooring system [21,28]. In addition, it is known that the cost of such mooring system is a major component of the initial investment [29]. Therefore, cost reductions due to an optimized design can be crucial in order to attain a competitive alternative.

Motivated by the considerations above, the focus of this paper is on measurement, estimation and verification of the second-order wave induced forces and motions on a semi-submersible floater operating in lower depth than the one of OC4-DeepCwind and with lower natural periods of excursion. Moreover, the work aims at verifying the main preconditions for defining a proper second-order diffraction model, given that different approximations are available for obtaining the QTFs (and acknowledging that a clever choice can significantly reduce the amount of work required for both building and solving the numerical model).

With these goals in mind, first the paper provides a quick theoretical background on the mathematical description of the slow-drift forces, with a reminder on the main approximations that are available for computing them. Next, the model-scale case-study is presented, with a general overview of the floater and mooring models and details on the experimental setup. This is followed by a description of the numerical model, in which the meshing procedures and convergence are discussed, together with an