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The effects of wind-induced inclination on the dynamics of semi-submersible floating wind turbines in the time domain

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ABSTRACT

This study focusses on the coupling effects arising from the changes in the hydrodynamic behaviour of a semi-submersible floating wind turbine when it undergoes large inclinations under wind loading. By means of a range of time-domain simulations, it is shown that both the hull geometric nonlinearity effect and the alteration of viscous hydrodynamic forces can significantly affect the dynamics of a typical floating wind turbine operating in waves at rated conditions. The consequences of said effects for both aligned and misaligned wind and waves are explored. In general terms inclinations are found to increase motions, where the modes that are more affected depend on the relative direction between incident wind and waves. Understanding the sources of aero-hydrodynamic coupling is key to providing sound design and modelling guidelines for the coming generation of floating wind turbines.

1. Introduction

In recent years floating wind power has been increasingly regarded as an attractive option for the production of low-carbon electricity, thanks to the potential to unlock vast resources which are unexploitable using fixed substructures; these are expected to become gradually unviable for depths beyond 50–60 m [1,2]. Being able to deploy wind turbines in deep water will be crucial to determine the scale of the industry within regions where the maritime continental shelf is steep. In spite of the presence of vast shallow areas especially in the North Sea, an estimate of the technical resource potential in Europe indicates a deep-water share of about 70% [3]. Estimates for France range between 60% [4] and 80% [3]. In Japan, now a prominent country in floating wind developments, 80% of the offshore wind resources are located in deep water according to [5].

Different from most conventional offshore floating structures, floating wind turbines (FWTs) are relatively small bodies which can exhibit stronger nonlinearities in their dynamic behaviour. Moreover, they are designed with the purpose of maximising the aerodynamic interaction related to wind energy extraction, which gives raise to unusually large aerodynamic load to displacement ratios. This constitutes an important source of dynamic coupling, especially as FWT platforms tend to evolve toward more optimised, lightweight solutions. Characterising the mechanical behaviour of a floating wind turbine for design and verification purposes requires the coupling of wind turbine aerodynamics and control with offshore hydromechanics. The understanding of such coupled dynamics under complex met-ocean loading has recently been the driver of a novel generation of coupled offshore dynamic models designed for the requirements of FWT mechanical simulation, such as FAST [6–8], HAWC2 [8,9], FloVAWT [10], Simo-Riflex [8,11], and CALHYPSO of EDF R&D, the software used in the present study.

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1.1. Small offshore structure hydrodynamics

Compact floating platforms can exhibit increased hydrodynamic complexity when subjected to ocean waves compared to their larger counterparts; for example it is more likely to come across regimes where hydrodynamic drag plays an important part in excitation, as it was observed experimentally on the DeepCwind-OC4 platform by Ref. [12], and explained numerically in Ref. [13]. These phenomena typically affect structures featuring sharp-edged motion control devices, tanks, and pontoons, which accentuate flow separation. Surface proximity effects can also manifest on these appendices when their submergence is limited, such as increased vertical wave loading (conjectured in Ref. [14]) and run-up [15]. As shown by the experimental campaign carried out by Ref. [16] on a CALM buoy equipped with a skirt, a semi-empirical numerical model implementing linear potential diffraction/radiation and a Re-independent drag force formulation can satisfactorily (but not comprehensively, as explained in 1.2) represent the hydrodynamic forces acting on this type of structure for the calculation of dynamic response. Similar conclusions have been drawn by Ref. [17] whilst comparing numerical and experimental motion results for a compact water-injection platform concept, the predecessor of the WindFloat platform design. An analogous numerical-experimental comparison carried out for the engineering design of WindFloat itself broadly confirmed the accuracy of this type of numerical model [2]. Next follows a brief close-up on water entrapment device hydrodynamics and the main related modelling challenges.

1.2. Water entrapment plates

The water entrapment principle, often utilised in the hydrodynamic design of FWTs, provides a passive motion control tool through the installation of relatively low-cost appendices. Pioneered by Principle Power with the WindFloat prototype, the heave plate appendix consists in a thin reinforced structure installed coaxially below the platform's columns, as visible in Fig. 1. The dynamic stability provided by the use of heave plates, coupled with the extra static stability insured by a closed-loop active ballasting system, reportedly allowed the WindFloat prototype to adopt conventional aerogenerator technology [18].

The modelling of water entrapment appendices close to the free surface via linear diffraction and radiation plus a drag model should come with a caveat. As pointed out by Ref. [16], the radiation-dependent vertical added mass of these structures is suspected to suffer from the irrotational flow hypothesis (i.e. the model fails to take into account the momentum transfer needed to impel fluid rotation around the edges, causing underestimation of added mass). Another issue consists in the sensitivity of the separation pattern to flow regimes, and in particular to KC [19]. The resulting drag forces – which dominate the hydrodynamic damping for this type of platform – may be affected by such regime changes, thus requiring appropriate adjustments of the drag coefficient. Finally, nonlinearities caused by complex phenomena such as wave decomposition [20] and breaking [21] over the plates may perturb loading in ways that are not captured by the most widespread wave-structure interaction models.

Fig. 1. Detail of a WindFloat prototype column. Photo courtesy of Principle Power.

1.3. Large inclinations

One of the routes to FWT CAPEX reduction is the compression of platform fabrication cost. An immediate consequence of this is the push for the minimisation of platform mass and hence size, that in turn entails the availability of smaller displacements and waterplane areas for the sake of hydrostatic stability. Subsequently, low hydrostatic stability platform solutions are currently being proposed. One option is constituted by TLPs (see for example [22]), whose restoring capacity to oppose the aerodynamic overturning forces is built into the mooring system. An alternative approach is simply the acceptance of large-angle operation caused by limited stability, leading to the introduction of the highly compliant FWT concept [23,24]. This, combined with other technological considerations, has caused a range of tilt-tolerant floating VAWT designs to be spawned (see Ref. [25] for a technical discussion and [26] for an industrial application). Although conventional HAWT rotors are known to be tilt-adverse – especially with respect to their aerodynamic efficiency – angles up to 10° are beginning to be considered acceptable as the operational limit for this type of turbine (see [27, 28]).

Several widespread assumptions of offshore structure dynamic simulation are challenged by the allowance of relatively large angular displacements. First of all, the ubiquitous hydrostatic linearisation may undermine the correct representation of these forces, especially when the geometry around the waterline is complex and/or hull sides are inclined (see for example the WINFLO concept [29]). The classic static representation of the mass matrix in the inertial frame can also cause errors in the computation of inertial reaction forces as angles break the small displacement assumption. Also, the classic linear superposition of small rotations may prove inaccurate, an observation that has led to the development of FWT motion solvers applying sequential Euler angle changes to represent correctly the nonlinear coupling between motions for a rigid-body [30,31] and a multi-body system [32,33]. Finally, the combination of limited draft, significant inclinations, and the presence of hydrodynamically sensitive appendices – typical of semi-submersible FWTs unequipped with active wind load compensation – has been shown to hold significant potential for the appearance of geometric nonlinearities in the diffraction/radiation behaviour of the hull [34]. The present work builds upon these findings, focussing on the effects of large inclinations on FWT dynamic response due to the alteration of both inertial and viscous hydrodynamic forces. Compared to the preceding work carried out on this subject, in this study a time-domain implementation enables an integral representation of drag forces as well as the inclusion of a coupled, yet simplified, aero-gyroscopic module representing the wind turbine rotor and tower forces.

2. Methodology

A program named CALHYPSO (*CALcul HYdrodynamique Pour les*