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Hydrodynamic coefficients and pressure loads on heave plates for semi-submersible floating offshore wind turbines: A comparative analysis using large scale models

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Hydrodynamic forces on heave plates for a semi-submersible floating offshore wind turbine are discussed herein. A model of one of the platform columns has been built. This allows for the fitting of either a plain solid plate or the real heave plate prototype design. The latter is equipped with a vertical flap at its edge. The influence of the flap on the hydrodynamic coefficients is investigated through a results comparison with the plain solid one. The model plate diameter is 1 m, thus becoming, to the authors' knowledge, the largest for which results have been published. Results from experiments, in which added mass and damping coefficients have been measured, are presented. This experimental campaign also comprised the direct measurement of dynamic pressures on both heave plates, a fundamental magnitude for the structural design, which, until now, had not been experimentally explored for this type of system. For comparative reasons, numerical simulations were also conducted following common industry standards, both with a wide-spread frequency domain panel method (WADAM) and a RANS CFD commercial code (ANSYS CFX). Finally, results are compared with literature and consistent non-dimensionalizations are sought, with the aim of making these results useful for preliminary design purposes. The authors believe this research could benefit the offshore wind industry by improving the hydrodynamic design of the concept.

1. Introduction

Floating offshore wind turbines (FOWT) are a promising mean for harvesting electric power from a renewable source. Within the three main FOWT concepts [1], the semi-submersible one is receiving significant attention due to several advantages [2]. Namely:

1. these types of platforms can be fully assembled onshore and towed ready-to-use to their final destinations;
2. the available mooring systems are well-known and cost competitive;
3. if properly designed, downtime in operational sea states, due to excessive platform motion, is low.

Most semi-submersible FOWT platforms consist of three cylindrical columns linked together with a set of braces [3]. In order to minimize heave motions and accelerations, and to shift heave resonance periods out of the first-order wave energy range, heave plates are attached to the column base [4]. The hydrodynamic performance of such plates has received some attention in the literature: Tao and Dray [5] performed experiments with solid and porous plates in deep water conditions and Ref. [6] used a porous square plate, performing experiments and numerical analysis with varying depth. Philip et al. [7] and Nallayarasu and Bairathi [8] numerically and experimentally assessed the effects of including a heave plate in a spar type floater. Wadhwa and Thiagarajan [9] and Wadhwa et al. [10] analyzed the dependence of the hydrodynamic response with the motion amplitude for a fixed oscillation frequency, finding a critical value above which response stops increasing. This analysis was done both close to the free surface and close to the seabed. For the latter, their results were numerically confirmed by Refs. [11,12].

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Nomenclature

Magnitude symbol

A_{33}	added mass coefficient
A_w	waterplane area
B_{33}	damping coefficient
D_c	column diameter
D_d	disc diameter
$F_H(t)$	hydrodynamic force time history
$F_H^1(t)$	$F_H(t)$ motion frequency harmonic
$F_I(t)$	body inertia force time history
$F_K(t)$	hydrostatic restoring force time history
$F_{meas}(t)$	measured force time history
g	gravity acceleration
h	platform draft
h_b	distance between disc and basin bottom
$KC = 2\pi A/D_d$	Keulegan–Carpenter number
M	column mass
r_d	disc radius
Re	Reynolds number (eq. (18))
S_d	disc area
T	motion period
t_d	disc thickness
ρ	fluid density
β	frequency parameter (eq. (8))
ΔP	maximum pressure difference for a sensor pair
$\Delta P'$	non-dimensional form of ΔP(eq. (13))
$\Delta P''$	non-dimensional form of ΔP (eq. (14))
$\Delta P'''$	non-dimensional form of ΔP (eq. (15))
$\mathscr{T}$	time-periodic time interval of pressure history for a sensor pair
ω	motion frequency

Tao and Thiagarajan [13] performed a detailed numerical analysis of the vortex shedding mechanisms, responsible for the main part of induced damping in heave plates. Tao and Thiagarajan [14] analyzed, in a column with a heave plate the relationship between damping, plate thickness and motion amplitude, for a fixed motion frequency. They provided rationale for an accurate extrapolation of the results. Takaki and Lee [15] computed, with a moving grid Navier–Stokes solver, the added mass and damping of an oscillating plate close to the free surface. They found and provided experimental validation, that, under these circumstances, radiation is the main damping factor. Koh and Cho [16] performed a similar analysis using AQWA and a multimodal type (MEEM) potential method. On the other hand, Ref. [4] found that radiation damping is a small fraction ($\sim$ 10%) of the viscous damping when the heave plate depth is large.

It is relevant to mention that, in a seakeeping analysis, having an accurate estimation of viscous damping is crucial when predicting the platform behavior in survival conditions with time domain simulations, often coupled with the aeroelastic code FAST (see e.g. Refs. [17,18]).

It is also important to highlight that, in practice, the heave plates require some structural reinforcements that may alter their hydrodynamic performance. In the present research, a plain solid heave plate an a reinforced version, to be built at full scale, with a vertical flap at its edge, have been considered. While the influence of the plate edge sharpness in the hydrodynamic response has received some attention in the literature [19,20], to the authors' knowledge, flaps influence has not been investigated.

In addition, in order to dimension the plate thickness and the previously mentioned reinforcements, knowing the pressure difference during the heave motion between the bottom and top sides, becomes very important. With this aim, the present experimental campaign has also included the direct measurement of dynamic pressure on the heave plates, which is a fundamental magnitude for the structural design. The cost of the floater is a major component of the initial investment [21] and therefore, cost reductions due to an optimized structural design are crucial in order to attain a competitive alternative. Such an optimized structural design may assist in reducing other high-cost factors such as transport, disposal, etc. Ref. [22]. Since electricity is a commodity, being a competitive technology mostly means being cost competitive for the final user, something very challenging for floating offshore wind turbines considering the many different well-established available electrical power sources. Therefore, having an optimized design with minimum cost, that can be replicated for large farms [23], becomes a crucial design goal.

This paper is organized as follows: the case study characteristics are first described. Experimental procedure and numerical solvers are discussed next. Test matrix and results are then presented and compared with literature. The prototype reinforced configuration results are then discussed. Finally, some conclusions and future work threads are summarized.

2. Case study

2.1. Prototype

The heave plates under study belong to the semi-submersible platform whose second order surge motions were analyzed by Ref. [24]. The structure of the floater consists of three vertical columns linked by trusses. A circular heave plate is added to the bottom of each column, as a mean to increase the natural heave period and, as a consequence, to prevent resonant motions in both operational and survival sea states.

The main dimensions of the platform are given in Table 1 and a schematic view of the floater geometry is presented in Fig. 1. The depth-radius ratio of the heave plate can be considered large (15.5/10 = 1.55). To put this figure in perspective, it must be noted that, for example, Ref. [9] in their specific work regarding free surface influence in hydrodynamic coefficients, considered only depth-radius ratios lower than 0.5. With this depth-radius ratio (1.55), it is expected that viscous damping will be dominant with respect to radiation damping.

Table 1
Main dimensions of the platform (prototype and model scale, 1:20). Distance between legs not included at model scale since only one column model was considered. Full scale heave plate steel thickness not available.

Characteristic	Symbol	Prototype	Model
Platform draft, disc depth	h	15.5 m	0.775 m
Legs centre to centre distance		35 m	
Columns diameter	D_c	7.0 m	0.35 m
Heave plate (disc) diameter	D_d	20 m	1.0 m
Heave plate (disc) radius	r_d	10 m	0.5 m
Heave plate (disc) thickness	t_d		5 mm
Depth-radius ratio	h/r_d	1.53	1.53
Disc aspect ratio	t_d/D_d		0.0049
Leg mass	M	663 t	82.83 kg
Disc distance to the tank bottom	h_b		1.425 m
Disc distance to the bottom-radius ratio	h_b/r_d		2.85