

Experimental and numerical analysis of a semisubmersible floating wind turbine under waves and wind

Lucas H. S. Carmo^{a,*}, Alexandre N. Simos^a and Pedro C. de Mello^a

^aUniversity of São Paulo, Av. Prof. Mello Moraes, 2231, São Paulo, 05508-030, Brazil

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ABSTRACT

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1. Introduction

Floating offshore wind turbines (FOWTs) have been the subject of numerous studies due to the possibility of exploiting the vast wind resources located in deep waters. As an emerging technology, the growth of the wind energy industry depends on FOWTs achieving more competitive costs, which has pushed for larger rotors and new designs for both floaters and moorings.

Since FOWTs are complex structures, their design requires the evaluation of performance and structural integrity for a myriad of environmental conditions (wind, wave, current, among others) and operating conditions (power production, normal shut down, fault conditions, etc.). Due to their intricate dynamics, this procedure requires modeling software capable of accounting for the couplings between aerodynamics, hydrodynamics, controls, moorings and structural behavior, which are commonly referred as aero-hydro-servo-elastic tools. A substantial effort has been made to validate these software, as exemplified by the OC3 (Jonkman and Musial, 2010), OC4 (Robertson et al., 2014) and OC5 (Robertson et al., 2017) projects, but this is still an ongoing development.

In fact, the experiments required to validate the numerical tools, usually performed in model scale, are far from an easy task, for it is impossible to keep all the dimensionless parameters that describe the different physical aspects of the problem. For instance, while the scaling of the waves requires that the Froude number ($Fr = U^2/(gL)$, with U a characteristic speed, L a characteristic length and g the gravitational acceleration) be conserved, the aerodynamic loads are governed by the Reynolds number ($Re = UL/\nu$, with ν the kinematic viscosity). To work around this incompatibility, some alternatives have been tried to perform tests with both wind and waves, and a thorough review of experimental techniques for doing so can be found in Otter et al. (2022). For instance, some works have used a Froude scaled rotor with the wind generated by fans at higher speeds than the scaled ones, so that the correct rotor thrust was obtained (Martin et al., 2014; Skaare et al., 2007; Mortensen et al., 2018); however, this approach has the downside that either the tip speed ratio (TSR) or the excitation frequencies are not preserved. Others have employed performance scaled rotors (Goupee et al., 2014; de Ridder et al., 2014; Bredmose et al., 2017), in the sense that the rotors were redesigned with geometrically modified airfoils to compensate for the low Reynolds number obtained in a Froude scale experiment.

A different line of thought is adopted by the so-called hybrid tests, in which either the aerodynamic or hydrodynamic forces are computed numerically and applied to the FOWT instead of being a consequence of the physical interaction of the hull/rotor with the waves/wind. The present work deals with the case in which the experiments are performed in a wave basin, so the waves are still generated physically, while the aerodynamic forces are replaced by a numerical

*Corresponding author.

✉ lucas.carmo@usp.br (L.H.S. Carmo)

ORCID(s): 0000-0001-8744-1391 (L.H.S. Carmo); 0000-0002-1879-5468 (A.N. Simos); 0000-0003-2621-9644 (P.C.d. Mello)

model. This approach, called software-in-the-loop (SIL), was first employed by Azcona et al. (2014), who used a single ducted propeller in place of the turbine rotor to emulate the aerodynamic thrust, while the aerodynamic forces acting on the other degrees of freedom were disregarded. In a nutshell, it consists in measuring the motions of the FOWT model, which is floating in the wave basin, and feeding these motions to the software, in which the aerodynamic forces acting on a virtual rotor under the action of a virtual wind are computed numerically – in that case and in the present work, using Blade Element Momentum Theory (BEMT). Finally, the rotational speed of the fan is controlled in order to provide the required thrust. The fact that this procedure happens in real time and taking into account the motions of the structure makes it simple to synchronize wave elevation and wind loads, besides allowing the modeling of aerodynamic damping and turbine control. In subsequent works, the SIL method has been applied with multi-propeller actuators in order to model not only the aerodynamic thrust, but also the forces and moments along the other degrees of freedom (Pires et al., 2020; Otter et al., 2020).

Alternatively, some works have employed cables pulled by winches instead of fans to emulate the aerodynamic loads (Sauder et al., 2016; Bachynski et al., 2016; Thys et al., 2018), while the option of performing the experiment in a wind tunnel whilst the hydrodynamics of the FOWT is computed numerically is discussed by Bayati et al. (2018) and Belloli et al. (2020). However, the SIL method proposed by Azcona et al. (2014) has the advantage of being the simplest option in terms of required equipment for a wave basin such as the one from the Numerical Offshore Tank of the University of São Paulo (TPN-USP).

Besides improving the capabilities of TPN-USP to be able to perform experimental tests of FOWTs under the concomitant action of wind and waves, this work aims at validating the numerical models that were used during the design of a FOWT concept (illustrated in Figure 1) developed in the context of a joint research project with Petrobras (Mas-Soler et al., 2022). Due to these two different objectives, this paper is divided into two parts:

- i. In the first part, which is provided in Section 4, the experiments are used to verify aspects of the hydrodynamics of the floater (which is the part that is physically modeled in the tests) that the numerical analyses should take into account. More specifically, a numerical model as close as possible to the conditions of the experiment is built with OpenFAST Jonkman and Buhl (2005) and WAMIT WAMIT (2004), and this model is used to demonstrate the importance of drag forces on the pontoons and of second-order wave forces in both the horizontal and vertical degrees of freedom (dofs). The impact of considering the mean hull inclination induced by the wind for computing the radiation/diffraction coefficients in WAMIT is also assessed, and it is shown that this effect is negligible;
- ii. In the second part, given in Section 5, the objective is to investigate the relevance of two physical aspects that were not included in the aerodynamic modeling adopted in the tests. The first of them is that the SIL implementation employed a fan assembly that was only able to apply the aerodynamic thrust, thus loads in the other dofs were not present in the model; the other aspect is that blade elasticity was not considered in this first version of the software, a point that is planned to be addressed in future versions. In order to verify the impact of these simplifications, the numerical models that are validated in the first part of the paper are compared with additional OpenFAST models that consider both blade elasticity and the aerodynamic forces on the six dofs.

Before presenting the two topics above, Section 2 describes the prototype and experimental setup, including the SIL method and its limitations, while Section 3 describes the numerical models considered in this work.

2. Description of the prototype and the experimental setup

Falar que foi feito no TPN e dar as principais dimensoes do tanque.

2.1. Main properties of the FOWT

- Características da FOWT, RNA, ancoragem

2.2. Software-in-the-loop approach for aerodynamic loads

Tem que incluir o controle. Adicionar alguns resultados de teste de bancada

2.3. Limitations of the experiment

2.4. Environmental conditions

- Condições de onda e vento

3. Numerical models

The wave forces are considered in OpenFAST by a combination of radiation/diffraction forces, taken into account using Cummins' approach (Cummins, 1962; Ogilvie, 1964) with frequency-domain coefficients computed with WAMIT (version 7.0.1), and the quadratic drag from Morison's equation. Concerning the former, one of the main questions about the numerical modeling of the experiments was whether the mean hull inclination caused by the wind should be considered when solving the radiation/diffraction problem. Indeed, one of the main hypothesis of the Boundary Element Method behind WAMIT is that the body oscillates around a mean position, but it is not clear at first how important the few degrees of inclination induced by the wind are.

For that reason, a different set of radiation/diffraction coefficients (i.e. first- and second-order wave forces, added mass and potential damping) was computed for each wind condition, using low order meshes with different inclinations that were determined by experimentally measuring the inclination of the model under the action of constant wind in calm waters. Since this is a somewhat cumbersome procedure, it is important to assess whether it is worth the cost, so all the OpenFAST simulations were performed twice: once with radiation/diffraction coefficients obtained using the inclined mesh, and once with coefficients from an even keel mesh. One of the inclined meshes (ESPECIFICAR) and the even keel mesh are illustrated in Figures XX, while the differences between the results obtained with them are discussed in Section 4.4.

4. Reproducing the experiments with numerical models

Explicar aqui como é organizada a seção e a metodologia usada p/ mostrar o resultado. O foco é em apresentar três aspectos físicos que tiveram maior atenção na modelagem do problema, e não tanto nos resultados da comparação entre o experimento e o ensaio.

4.1. The need for drag forces on the pontoons

Fazer figuras ilustrativas p/ mostrar o pontoon e a nomenclatura, junto com uma tabela com os diâmetros e coeficientes de arrasto adotados nas colunas/pontoons p/ cada um.

Mostrar os decaimentos com três curvas: experimental, C_D pro caso de um pontoon circular (o errado, tipo heave only p/ surge e surge only p/ heave) e C_D pro pontoon retangular. Daí, mostrar que consegue pegar bem o heave e o surge simultaneamente quando tá retangular, o que não é possível no caso circular.

Resultados a gerar: - Gráfico do Decaimento de heave com (lado a lado com o de surge): — Experimental — OpenFAST - Rect. pontoon — OpenFAST - Circ. pontoon S - Gráfico do Decaimento de surge com (lado a lado com o de heave): — Experimental — OpenFAST - Rect. pontoon — OpenFAST - Circ. pontoon H

- Heave p/ APR01-IDLE-IRR-II – Série temporal e espectro na esquerda – RAO na direita — Experimental — OpenFAST - Rect. pontoon — OpenFAST - Circ. pontoon S — WAMIT no RAO

- Mesma coisa p/ surge

4.2. The importance of second-order forces on both horizontal and vertical motions

Mostrar o offset e o pitch

4.3. Main results

Explicar o procedimento adotado para processar a grande quantidade de ondas, que é baseado nas estatísticas. Mostrar tabela com períodos naturais e níveis de amortecimentos + tabela de resumo das estatísticas p/ ondas irregulares.

Ilustrar c/ gráficos de séries temporais e espectros de casos selecionados (tem que ter a aerodinâmica p/ mostrar que o rotor tá funcionando) + gráfico do máximo e média

4.4. The impact of mean hull inclination when computing radiation/diffraction coefficients

As mentioned in Section 3, one of the objectives of this work is to assess the impact of considering the mean hull inclination caused by the wind when solving the radiation/diffraction problem. Figure X, which summarizes in a boxplot the differences in the maxima obtained for each of the quantities analyzed in the previous sections for all the irregular waves, shows that this is not the case: in fact, the differences are (falar também que a diferença é ainda mais irrelevante quando se pensa na tabela de extremos)

Mostrar um gráfico comparando as estatísticas calculadas c/ inclinação e sem.

As a more in-depth example, **Figure X** presents the time series and PSD's of roll and pitch motion obtained for the FOWT under the combined action of the IRR12 sea ($H_S = 4.44$ m, $T_p = 11.34$ s and incidence of -10°) and the turbulent wind condition (mean wind speed 10.59 s and $TI = 12\%$) with an incidence of 47° , which is schematized in the same figure. This case was chosen for being the one that presented the largest difference in the horizontal acceleration at the nacelle, with the model considering an inclined mesh (denoted by IC) predicting a maximum horizontal acceleration of 0.85 m/s^2 and the one with an even keel mesh (denoted by EK) providing 0.74 m/s^2 , which is actually closer to the experimental value of 0.64 m/s^2 .

****Mostrar gráfico de série temporal do que deu a maior diferença e explicar usando RAO e o .3****

In fact, this could be anticipated by looking directly at the radiation/diffraction coefficients that are imported by OpenFAST. These are illustrated by **Figure X** (first-order diffraction forces), **Figure X** (mean drift force) and **Figure X** (added mass and potential damping). For conciseness, only the mesh with the largest inclination (**dizer qual é aqui, i.e. p/ qual vento, e qual é a inclinação**) and only one wave incidence (45°) is plotted, and the results for sway and roll are omitted because they are qualitatively the same as surge and pitch.

****Mostrar gráficos das forças****

It is worth pointing out that only the impact on the radiation/diffraction coefficients was assessed, and it is possible that hull inclination may be important to effects related to real flow phenomena, such as drag forces.

5. The impact of rotor simplifications adopted in the model tests

- Comparar resultados das simulações nas condições reais e identificar diferenças pro modelo que é mais próximo do ensaio.

- Usar simulações intermediárias p/ explicar essas diferenças

6. Conclusions

CRedit authorship contribution statement

Lucas H. S. Carmo: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft. **Alexandre N. Simos:** Conceptualization, Formal analysis, Writing – review, Supervision. **Pedro C. de Mello:** Experiments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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