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Aerodynamic damping on a semisubmersible floating foundation for wind turbines

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Abstract

The objective of this work is to study the effect of the rotor thrust on the motions of a semisubmersible floating foundation for Horizontal Axis Wind Turbines (HAWT). The main targets are the drift motions and the additional damping caused by the operating rotor, so-called aerodynamic damping. The semisubmersible used in the Offshore Code Comparison Collaboration Continuation (OC4) project, which operated under International Energy Agency (IEA) Wind Task 30, is chosen for this study. Two numerical models are built in aNyPHATAS, a coupled hydrodynamic and aerodynamic tool for simulations of floating wind turbines. The numerical model of the original design of the semisubmersible (OC4), and a numerical model calibrated against model tests (OC5) are compared with measurements. For practical reasons, the physical model at the scale of the basin needs to be adjusted. One key modification is done on the rotor of the wind turbine so that its performance remains equivalent while Froude scaling is applied. This comparison is done for two load cases: operational waves only, operational waves and steady wind simultaneously with a turbine operating at fixed rotation speed (without control). It serves to check the extent to which a design concept and a physical model built at small scale match.

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1. Introduction

Nowadays, a few offshore floating wind turbines (OFWT) have been installed and wind energy suppliers are thinking of using floating foundations for wind turbines in areas where fixed offshore wind turbines would be too expensive. Model testing enables one to investigate how floating structures behave under controlled environments. Therefore, they are very useful for the development of new concepts, such as OFWT. However, model tests in a combined wave and wind basin need to cope with the challenge of properly reproducing, simultaneously, wave loads on floaters and wind loads on turbines at basin scale. The so-called 'performance-scaling' [1] is currently followed by MARIN to model the rotor of a wind turbine. In this approach, the blades are re-designed for the flow regime experienced in the basin so that the rotor's performance at model scale is equivalent to the design performance of the original full scale rotor. With such a performance matched turbine, the coupled response of OFWT to waves and wind can be investigated in a hydrodynamic laboratory and eventually compared to numerical models for validation. Numerous publications have compared simulations and model tests from the first campaign of the DeepCwind consortium (2011) for the three common types of floating foundations: Tension Leg Platform [2, 3], spar [4], semisubmersible [5, 6]. However, these model tests were done with a geometrically scaled rotor and the wind was adjusted to compensate for the thrust deficit. A second series of tests [8] were carried out with the MARIN stock turbine in 2013, which was 'performance-scaled'. Despite this major improvement, such model tests remain challenging and some of the issues listed by Robertson et al [7] have not been completely solved. Most importantly, it is practically impossible to keep all properties of a full-scale turbine at the basin scale. Moreover, in the design process of a floating foundation for a wind turbine, some characteristics may evolve (choice of the turbine, mass distribution, etc...). Also, it is not trivial to determine the input data for the rotor of the experiment that are necessary to calibrate a numerical model for a validation study [9]. As a consequence, it is not uncommon that the scaled-down prototype of a OFWT in the basin differs from the design prototype. In this case, the calibration of a numerical model and its validation are not strictly speaking done for the original design prototype but for the 'model of a model'. Therefore, it is advisable to check that the response of the calibrated model and the design prototype don't differ too much. In the present study, the submersible of the phase II of the Offshore Code Comparison Collaboration Continued (OC4) project, operated under IEA Wind Task 30 [10] for the National Renewable Energy Laboratory (NREL) is chosen as the full scale design prototype. The offshore 5-MW baseline wind turbine [11] is envisaged to be assembled on top of this floating foundation. Model tests done at MARIN of the same floating wind turbine, the second testing campaign of the DeepCwind semisubmersible [8] (Fig. 1), are used to calibrate a numerical model with aNyPHATAS [12]. The effects of the damping, including the damping caused by the action of the rotor, on the numerical model of aNyPHATAS are scrutinized.

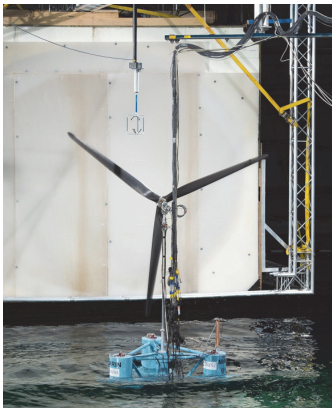

Fig. 1. Semisubmersible floating turbine being tested (OC5)

2. Model of the model

2.1. Motivations

For practical reason the scope of model tests is limited, and the tested OFWT may differ slightly from the specifications of the prototype. For instance, it is very difficult to reproduce a wind turbine at 1/50th-scale with the same mass distribution as a full scale turbine. For example, the mass of the nacelle, equipped with an engine and a blade pitch control mechanism, is likely to exceed the desired scaled-down mass for this component. The tested OFWT is often slightly different than the design OFWT with regards to:

- the rotor aerodynamic characteristics
- the rotor mass distribution
- the mass distribution between all components of the turbine (tower, rotor, nacelle, axis).

Below, Table 1 gives a summary of the main characteristics of the OC4 design prototype (OC4) next to the characteristics of the model-test prototype (OC5). All data are converted to full scale for the ease of comparison. More data on these prototypes are available in literature ([10] for OC4, [8] and [9] for OC5).

Table 1. Main characteristics of the full scale design prototype (OC4) and the physical model as built (OC5).

Designation	Unit	OC4 (design)	OC5 (as-built)
Draft	m	20.0	20.0
Mass	ton	14,260	13,958
Centre of gravity above keel	m	9.96	11.93
Longitudinal metacentric height	m	7.34	5.29
Roll radius of gyration in air	m	32.07	32.63
Pitch radius of gyration in air	m	32.84	33.38
Yaw radius of gyration in air	m	31.83	31.32

The vertical position of the centre of gravity and the pitch radius of gyration are different between the design prototype (OC4) and the model-test prototype (OC5) as a consequence of a different mass distribution. Also, the longitudinal metacentric height has changed between OC4 and OC5. All these changes mainly affect the roll and pitch motions. Although the OC5 model was not intended to be a perfect representation of the OC4 concept when it was tested by the DeepCwind consortium, the comparison of these two systems is a good illustration of the possible differences between a design prototype and a physical model, and their consequences on the motion responses of these systems. Numerical modelling tools are a convenient way to check that the differences between the tested prototype and the design prototypes are acceptable and therefore simulations of these two systems will be compared in the rest of this paper. Several papers have been written on validation studies from the model tests of the DeepCwind semisubmersible of 2011 (i.e. [5], [6] and [14]). The present study utilises the data of the additional tests of the DeepCwind semisubmersible of 2013, where the MARIN stock turbine was used. This paper reports more exclusively on the interaction of the aerodynamic loads and the hydrodynamic loads and their combined effect on the motion response of this platform. Moreover, this study aims to check if this effect is equivalent on the design prototype (OC4) and the model-test prototype (OC5).

2.2. Numerical tools & calculation process

The simulations are done by applying potential flow theory in several steps (Fig. 2). Firstly, the hydrodynamic properties of the floater are obtained in frequency domain using the in-house tool DIFFRAC. Secondly, the equations of motion of the floater seen as a rigid body are solved in time domain using a database derived from the DIFFRAC computation. aNySIM, developed by MARIN, is used for this purpose. If the effect of an operating wind turbine needs to be accounted for then a third step is necessary. A wind turbine can also be included in the time domain simulation using the Blade Element Momentum (BEM) theory. MARIN and the Energy research Centre of The Netherlands (ECN) have coupled ECN's BEM tool PHATAS [15] to aNySIM to simulate floating wind turbines. This coupled tool is called aNyPHATAS [12].

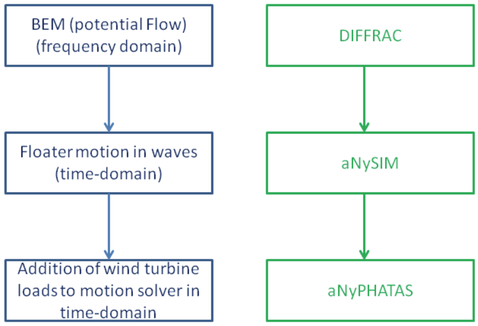

Fig. 2. Numerical tools

Wave loads and motions of offshore structures in waves are calculated by applying potential-flow theory. DIFFRAC is the potential-flow theory used for this study. DIFFRAC solves the potential flow equations at the first- and second-order. The results of DIFFRAC are obtained for:

- a frequency range of [0.05, 3.0] (rad/s) for first- and second-order quantities.

Despite the great potential of the theories used in this numerical approach, these theories have some limits and shortcomings. For instance, the potential flow theory used for the hydrodynamic loading does not considered any water viscosity and assumes a flat water line. Viscous damping, non-linear restoring (mooring system), slow drift motion and associated damping are ignored by this theory. The translation in time domain (aNySIM) enables to add these loads while the equation of motions are solved. However, these loads are often characterized by coefficients that need to be determined. When model test data are available then the numerical model can be calibrated against these test data and these coefficients can be determined. For the floater, a standard calibration includes the determination of:

- the submerged weight and pre-tension to meet the (non-linear) restoring characteristics of the mooring system as modeled (see appendix A.1)
- linear and quadratic damping coefficients from decay tests (see appendix A.2).

Next to the floater, the numerical model of the wind turbine also needs to be calibrated to represent the turbine of the model tests. In this study, the aero-dynamic loads on the rotor are calibrated (see appendix A.3). The aerodynamic coefficients are chosen so that the thrust characteristics of the rotor are the same in the simulations and in the measurements.

Two numerical models are made using these numerical tools:

- a model of the design prototype (OC4), where the mooring system and the viscous damping are estimated [10]
- a model that is calibrated against the model-test data (OC5) [13]. The main results of the calibration process are given in appendix A.

The same calculation process and post-processing is applied to the results of the OC4-simulations and OC5-simulations. The flowchart of the process is given in Fig. 3.

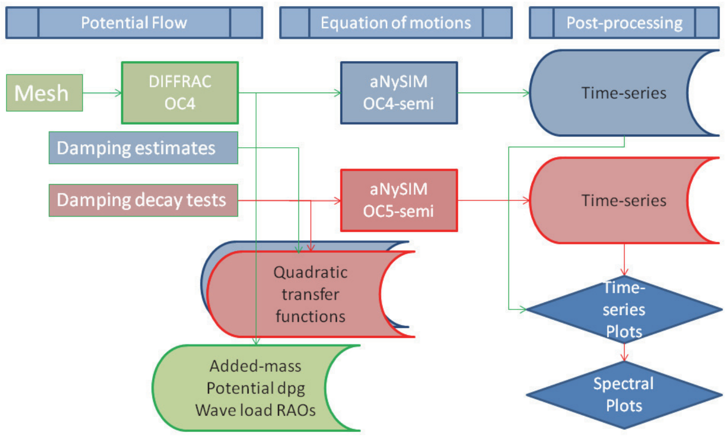

Fig. 3. Calculation process

The pitch natural periods have the biggest difference in proportion between the design prototype (OC4) and the calibrated model (OC5). The tested prototype has a longer pitch period as it has to support a turbine with heavier components at the top.

Table 2. Estimates of natural periods for the full scale design prototype (OC4) and the calibrated model (OC5).

Designation	Unit	OC4 (design)	OC5 (calibrated)
Natural surge period (moored)	s	113.2	106.4
Natural pitch period (moored)	s	25.1	32.1
Natural heave period (moored)	s	17.0	17.2

Among previously mentioned publications reporting on the validation of simulation tools from the DeepCwind model tests, the work of Coulling, et al [6], which is described with a great level of detail, is used to highlight how the present modelling approach differs from previous studies:

- Difference frequency second-order wave loads are accounted for by using a full quadratic transfer function (QTF) in 6 degrees of freedom. Often a Newman approximation was used to determine these loads only in the horizontal plane (surge, sway and yaw) [14], whereas their effects on the other DOFs were shown to be important [16], especially in pitch ([17] and [18]).
- The contribution of the mooring system on the viscous damping is accounted for in the mooring line dynamics. A lumped-mass model is used; this choice is in line with the recommendation of Masciola [19] for FASTv8.
- The tower is considered rigid in the present study, whereas the tower mode shapes and frequencies have been calibrated in other studies ([5], [6]). aNyPHATAS does not support yet the modelling of the tower flexibility, whereas FAST that was used in these studies does. This simplification comes down to implicitly neglect the possible effect of the tower's flexibility on the motions of the semisubmersible, which is thought to be a reasonable assumption as the lowest fundamental bending frequency of the tower (2.2 (rad/s) for the first fore-aft bending mode) is much higher than the motion eigenfrequencies.
- The braces and pontoons are omitted in the present study (as they were in Coulling's work). Based on Benitz's study [20], the contribution of these small elements on the wave excitation is expected to be small for regular small waves (i.e. T =8.8 s and H = 2.75 m) compared to the diffraction loads on larger elements

(4 columns). Nevertheless, their contribution may become more important for the wave that is considered in the present study.

- Two sets of lift and drag coefficients are used for the calibration of aerodynamic loads; the set published by Goupee [9] and another set determined using RFOIL. These sets aims at reproducing the performance of the MARIN stock turbine. Coulling used lift and drag coefficients of the full scale NREL 5-MW turbine with different wind speeds as the turbine was geometrically scaled in the tests of 2011.

3. Comparison of the responses in waves

The results of simulations and model tests are compared to check the validity of the calibrated numerical model (OC5). The simulation results of the design model (OC4) are also shown on the same plots. The wave history of a tested operational wave is chosen for this comparison. The operational wave is made of a narrow banded spectrum:

- JONSWAP
- significant wave height of 7.1 m
- peak period of 12.1 s.

The Power Spectral Density (PSD) of the 3 main motions for head wave are plotted (Fig. 4):

- surge
- heave
- pitch.

In the wave spectrum range ([0.3, 1.0] (rad/s)), the comparison of the simulation results and the measurements is reasonably good. The OC4 design prototype and the OC5 model have a similar behavior in this range. The differences are more pronounced at the resonance frequency for every motion; surge being the worst. The resonance peaks in surge and pitch are excited by the second-order contribution of the wave loads, whereas the heave resonance peak is a response to the linear wave excitation. The difference in the surge drift response between the calibrated model (OC5) and the measurements was already reported ([18]). It is attributed to a lack of accuracy of the potential flow model for the prediction of the drift loads on small structures together with the difficulty of modeling the viscous damping of a structure made of bluff cylinders like this semisubmersible. Indeed, at resonance the response is very sensitive to any discrepancy in the excitation or imprecision on the level of damping. The design model (OC4) and calibrated model (OC5) give surge drift motions at similar frequencies, although the amplitudes of the surge resonance peaks are not the same. The discrepancies between these two models in total mass, mooring stiffness and damping are causing this difference in magnitude. The heave responses of the two models are comparable, except for the higher resonance magnitude for the calibrated model, which can be explained by the slightly smaller mass of OC5. On the contrary, the pitch resonance peak is not the same for these 2 models. As noted before, the natural period in pitch has changed between the OC4 and the OC5 model. The amplitude of the pitch resonance peak, which depends on the second-order wave loads and the total damping (both function of the frequency), is much smaller for the design prototype (OC4) than for the calibrated model (OC5).

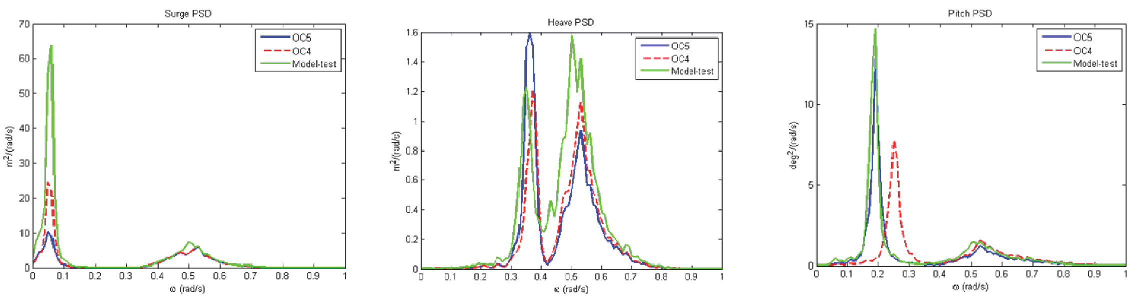

Fig. 4. Surge, heave and pitch PSD in operational wave

4. Comparison of the response in waves and wind

The same operational wave as previously is considered, but this time in combination with a steady wind of 13 m/s. The rotor speed is fixed to 12.1 rpm and the blade pitch angle is fixed to 1 deg for all blades.

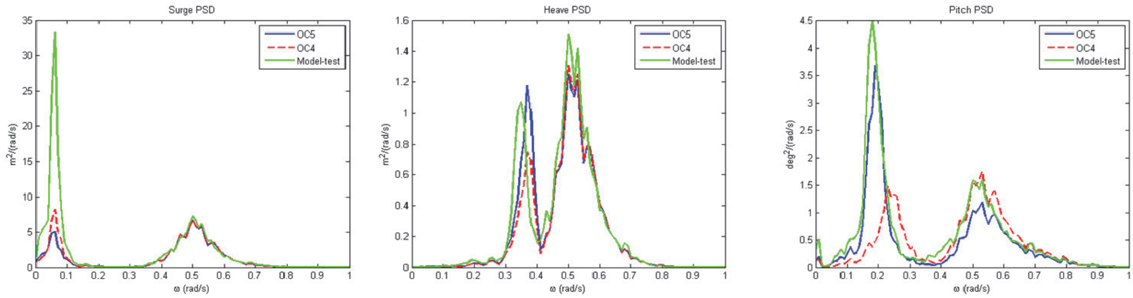

Fig. 5. PSD of surge, heave and pitch in waves and wind

The motions of the semisubmersible in the wave spectrum range are again similar between the simulations and the model tests. It can also be noted that the wave motion responses in this range are still pretty close to what they were without wind. In the other hand, the effect of the wind is stronger on the resonance peaks, where it damps the amplitudes. This effect is very strong in pitch and surge. The calibrated model (OC5) catches this aerodynamic damping caused by the rotor noticeably well in pitch (Fig. 5). This shows that the coefficients determined by Goupee provide a very good representation of the MARIN stock turbine for these conditions. In the model tests, the loads at the tower foot were measured. Thus, it is possible to check how the moment at the tower foot in pitch and the pitch motion correlate. The Cross Spectrum Density (CSD) of the pitch moment with the pitch motion (Fig. 6) clearly shows two peaks below 1 (rad/s):

- a peak at the pitch eigenfrequency (resonance peak)
- a peak at the wave spectrum (wave response peak).

Both peaks are very well predicted by the calibrated model. The resonance peak is bigger than the wave response peak for the OC5 model. The comparison of a simulation with only for the first order wave loads and a simulation with first- and second-order wave loads shows that the interaction with the wind is the strongest for the resonance peak and can be restituted only when the wave second-order loads in pitch are accounted for. This proves that the aerodynamic damping acts mainly on the resonance peak in pitch, which is exited by second-order wave loads. The same phenomenon is visible for the design model, but the wave response peak and the resonance peak have comparable amplitudes in this case. This can be interpreted as a more moderate impact of the resonance response to the second-order wave moment in pitch for the design prototype than for the model tested in the basin. However, the physics that makes the wind turbine loads interact with the wave motions is the same for the OC4 concept and the OC5 model.

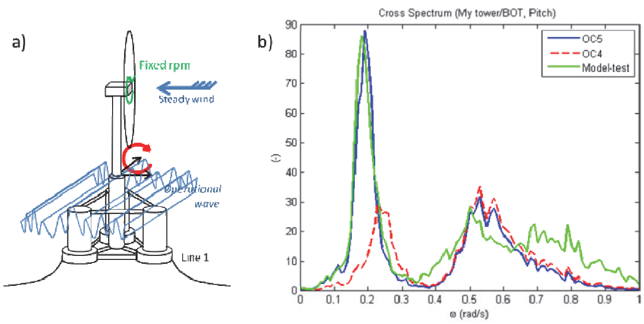

Fig. 6. a) Drawing of the tower moment around y-axis b) CSD between the tower moment around y-axis and pitch motion

4. Influence of rotor force coefficients on the response in waves and wind

The same combined wave and wind conditions as previously are considered with the same rotor settings but other lift and drag coefficients are used to model the aerodynamic loads on the scaled down rotor blades. This time the coefficients come from a RFOIL calculation with a tripped flow.

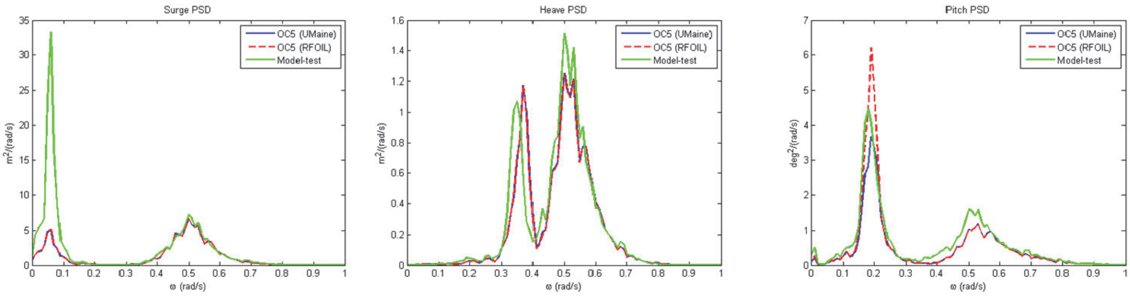

Fig. 7. PSD of surge, heave and pitch for 2 sets of rotor force coefficients ({CL, CD}) and comparison with model test

Using different sets of force coefficients in the calibrated model OC5 does not change the surge and heave motions but does have an impact on the amplitude of the resonance peak in pitch (Fig. 7). This confirms that pitch is the most sensitive degree of freedom to the aerodynamic damping. This can also be interpreted as a warning on the sensitivity of the pitch to any discrepancy in the estimation of the rotor loads and indirectly to the correct determination of lift and drag coefficients for the turbine.

Conclusions

In this paper, the effect of wind turbine loads on the motion of a semisubmersible floating horizontal axis wind turbine are studied. This is achieved by comparing the results of simulations and model tests in wind and waves. It was found that the aerodynamic damping acts mainly on the resonance peak of surge and pitch. For this semisubmersible, these resonance peaks are the direct responses to low frequent second-order wave loads. It was also observed in the model tests and the simulations that the aerodynamic damping has the strongest effect on pitch. It can thus be concluded that the wind turbine loads interact firstly with the low frequent pitch response for a rotor spinning at fixed rotation speed in steady wind.

Furthermore, the results of the simulations showed that the motion responses at resonance are sensitive to variations in the amplitudes of excitations and the level of damping. For the considered semisubmersible floating foundation, the heave resonant response in waves is governed by linear wave loads since the heave natural period is within the wave frequency region. Whereas, the resonance responses in surge and pitch are governed by low frequent second-order wave loads. In the current numerical approach the second-order wave loads vary with the frequency and the damping added to represent the viscous contribution. Therefore, the response is more sensitive to modeling choices in surge and pitch than in heave. As a consequence, it was noted that the simulations severely under predict the surge drift motion in comparison with the model tests. Another consequence is linked to the modeling of the rotor's aerodynamic loads. The interaction of these loads with surge and pitch motions are causing the aerodynamic damping. In BEM tools, those loads are the results of lift and drag coefficients. These coefficients need to be determined for the design rotor at full-scale and, also, for the prototype rotor at model-scale. Robust engineering tools are available (i.e. XFOIL [21]) to find these coefficients for a full-scale rotor, while reliable methods to find these coefficients for the low-Reynolds flow experienced during wind and wave combined model tests are still under research [22, 23]. This paper shows that these coefficients have an effect on the level of damping on the pitch resonant peak.

In this study, two variations of the same semisubmersible were looked at through simulations:

- a numerical model of the design prototype: OC4
- a numerical model of the physical model tested in combined wind and waves: OC5.

As a consequence of changes in the mass distribution, the pitch periods had more than 5 s difference between these two systems. However, the simulations done with these two models exhibited the same trends and represented the same physical phenomenon that was observed during the model tests. Indeed, the interaction of the wind turbine loads and the floater's motions works in precisely the same way: the wind turbine loads acts pre-dominantly on the second-order wave response and this is mainly observable in pitch. Next to different pitch eigenfrequencies, other differences were observed in the amplitudes of the pitch responses and in the importance of the second-order low frequent resonant peak with respect to the wave first order response peak. The second-order pitch response was found to be bigger for the calibrated OC5 model than for the design OC4 model.

This exercise proves the value of doing model tests and simulations together, keeping in mind that neither one nor the other is a true depiction of the reality but that both can be used to better understand how a system behaves.

Acknowledgements

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Appendix A. Results of the calibration of the OC5 numerical model

A.1. Calibration of the mooring system

The calibration of the mooring system aims at reproducing the restoring characteristics of the mooring system. Only aligned wind and wave conditions are examined in this numerical study. Therefore, the surge restoring curve is the main objective of this calibration. Figure 8 shows the agreement of the restoring curves in surge between the numerical model and the measurements in the basin.

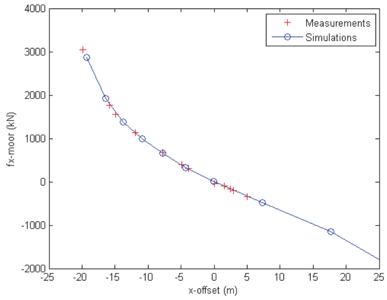

Fig. 8. Mooring system restoring curve in surge

Line dynamics can be simulated. The following drag and inertia coefficients were chosen for the simulations with line dynamics:

- Cin= 3.1
- Cit= 1.7
- Cdn= 2.4
- Cdt= 0.8

A.2. Calibration of the natural periods and decays

The results of simulations and model tests of decays in surge, heave and pitch are compared to check the validity of the calibrated numerical model (Fig. 9).

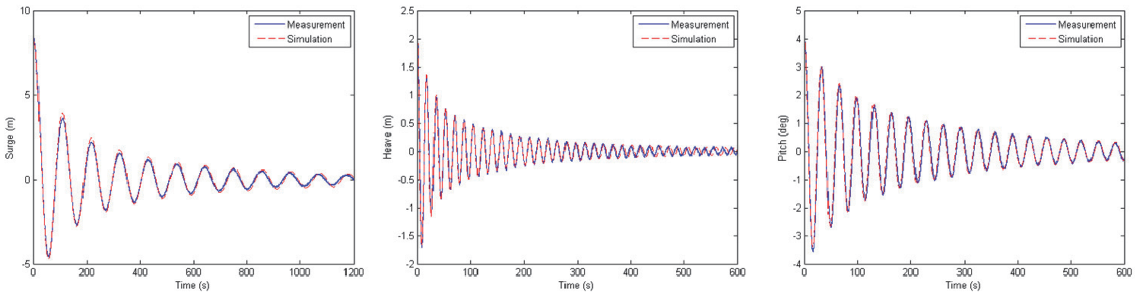

Fig. 9. Comparison of decays in surge, heave and pitch

A.3. Calibration of the rotor loads

Measurements of thrust and power for combinations of wind velocities (steady) and fixed rotation speed of the rotor are compared to simulations (Fig. 10 a). A very good agreement for both thrust and power is found when the optimized coefficients determined by University of Maine ([9]) are used. The same coefficients are then used for the calibrated model (OC5) to simulate a decay in steady wind with a rotor spinning at constant speed. The results of this simulation are compared to measurements and simulations with wind in Fig. 10 b). This figure shows that the constant offset in pitch is well estimated by the numerical model (OC5) but that the damping caused by the wind loads on the rotor is larger than what is observed in the measurements.

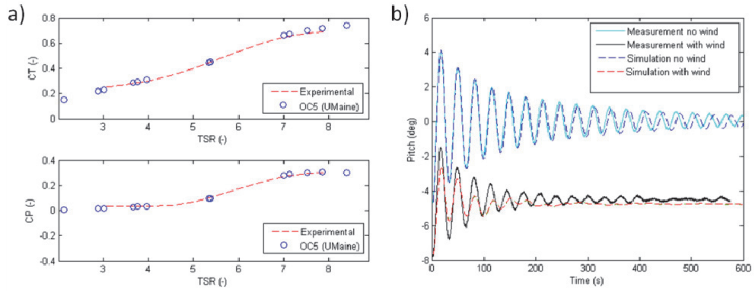

Fig. 10. a) Rotor performance characteristics b) Pitch decay with/without wind

When other coefficients are used in the calibrated model (OC5), i.e. lift and drag coefficients determined by RFOIL in a trimmed flow [24], the simulations in steady wind are similar to those using the values of University of Maine (Fig.11 a). The offset in surge and pitch are equal for both sets of coefficients. It can be seen in Fig. 12 b) that the damping caused by the rotor's loads on the pitch motion is slightly weaker with the new set of coefficients (OC5(RFOIL)) than with the original set of coefficients (OC5(UMaine).

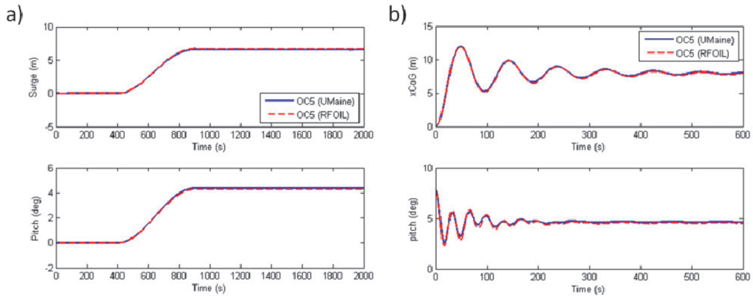

Fig. 11. Surge and pitch motions with 2 sets of rotor force coefficients: a) Steady wind b) Decay in steady wind

References

[1] Ridder, E.J. de, Otto, W., Zondervan, G.J., Vaz, G., Huijs, F., "Development of a scaled down stock wind turbine for model testing floating wind turbines," 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), San Francisco; 2014.

[2] Stewart, G. Lackner M., Robertson, A., Jonkman, A, Goupee, A., "Calibration and validation of FAST floating wind turbine model of the DeepCwind scaled tension-leg platform," 22nd International Offshore and polar Engineering Conference, Rhodes; 2012.

[3] Koo, B., Goupee, A., Lambrakos, K., Lim, H.-J., "Model Test Correlation Study for a Floating Wind Turbine on a Tension Leg Platform," 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Nantes; 2013.

[4] Browning, J. R., Jonkman, J., Robertson, A. Goupee, A., "Calibration and validation of the FAST dynamic simulation tool for a spar-type floating offshore wind turbine," 4th Science of Making Torque from Wind Conference, Oldenburg; 2012.

[5] Koo, B., Goupee, A., Lambrakos, K., Lim, H.-J., "Model Test Correlations with Fully Coupled Hull/Mooring Analysis for a Floating wind Turbine on a Semi-Submersible Platform," 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), San Francisco; 2014.

[6] Coulling A., Goupee, A., Robertson, A., Jonkman, J., Dagher, H. J., "Validation of a FAST semi-submersible floating wind turbine numerical model with DeepCwind test data,", Journal of Renewable and Sustainable Energy 5, 2013.

[7] Robertson, A. N.; Jonkman, J. M.; Masciola, M. D.; Molta, P.; Goupee, A. J.; Coulling, A. J.; Prowell, I.; Browning, J. (2013). "Summary of Conclusions and Recommendations Drawn from the DeepCWind Scaled Floating Offshore Wind System Test Campaign," 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Nantes; 2013.

[8] Goupee, A., Fowler, M., Kimball, R., Helder, J., Ridder, E.J., "Additional wind/wave basin testing of the DeepCwind semisubmersible with a performance-matched wind turbine," 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), San Francisco; 2014.

[9] Goupee, A., Fowler, M., Kimball, R., Helder, J., Ridder, E.J., "A Calibrated Blade-Element/Momentum Theory Aerodynamic Model of the MARIN Stock Wind Turbine," 25th International Offshore and polar Engineering Conference, Kona; 2015.

[10] Robertson A., Jonkman J, MasciolaM., Goupee A., Coulling A., Luan C., "Definition of the Semisubmersible Floating System for Phase II of OC4," NREL/TP-5000-60601, National Renewable Energy Laboratory, Golden, CO., Sept., 2014.

[11] Jonkman J.; Butterfield S.; Musial W., Scott G., "Definition of a 5-MW Reference Wind Turbine for offshore System Development," NREL/TP-500-38060, National Renewable Energy Laboraory, Golden, CO., Feb. 2009.

[12] Gueydon, S., Lindenburg, K., Savenije, F. ,"Coupling of Two Tools for the Simulation of Floating Wind Turbines," 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Nantes; 2013.

[13] Helder, J., Pietersma, M., "UMaine – DeepCwind/OC4 semi floating wind turbine," MARIN Report no. 27005-1-OB, Wageningen; 2013.

[14] Coulling A., Goupee A., Robertson A. Jonkman J., "Importance of Second-Order Difference- Frequency Wave-Diffraction Forces in the Validation of a FAST Semisubmersible Floating Wind Turbine Model," 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Nantes; 2013.

[15] Lindenburg, C.; "PHATAS Release "JAN-2012a" USER'S MANUAL, Program for Horizontal Axis Wind Turbine Analysis and Simulation", ECN-I—05-005 Rev.10, ECN, Petten; 2012.

[16] Gueydon, S., Weller, S., 2013. "Study of a Floating Foundation for Wind Turbines," Journal of Offshore Mechanics and Arctic Engineering. 135(3), 031903-1.

[17] Gueydon, S., Duarte, T., Jonkman, J. "Comparison of Second-Order Loads on a Semisubmersible Floating Wind Turbine," 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), San Francisco; 2014.

[18] Gueydon, S.; "Verification of the Second-Order Wave Loads on the OC4-Semisubmersible," Presentation at the 12th Deep Sea Offshore Wind R&D Conference EERA DeepWind'2015, Trondheim, Norway.

[19] Masciola, M., Jonkman, J., Robertson, A., "Extending the Capabilities of the Mooring analysis Program: a Survey of Dynamic Mooring Line Theories for Integration into FAST," 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), San Francisco; 2014.

[20] Benitz, M. A., Schidt, D. P., Lackner, M. A., Stewart, G. M., Jonkman, J., Robertson, A., "Comparison of Hydrodynamic Load Predictions between Rediced Order Engineering Models and Computational Fluid Dynamics for the OC4-DeepCwind Semi-Submersible," 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), San Francisco; 2014.

[21] Drela, M.; "XFOIL An Analysis and Design System for Low Reynolds Number Airfoils," in *Low Reynolds Number Aerodynamics - Springer-Verlag Lecture Notes in Eng.*, Springer-Verlag; 1989.

[22] Gueydon, S., Venet G.; "Influence of the Rotor Characterization on the Motion of a Floating Wind Turbine," 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), St. John's; 2015.

[23] Make, M., Vaz, G., Fernandes, G., Burmester, S., Gueydon, S.; "Analysis of Aerodynamic Performance of Floating wind Turbines using CFD and BEMT methods," 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), St John's; 2015.

[24] Rooij van, R.; "Modification of the Boundary Layer Calculation in RFOIL for Improved Airfoil Stall Prediction", Report IW-96087R, Delft, September 1996.