Comparison of coupled aero-hydro-servo-elastic simulations for floating wind turbines with model tests

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Abstract

The initial target of this thesis was the validation of the coupled software tool ANSYS AQWA-PHATAS which can perform coupled time domain aero-hydro-servo-elastic simulations for floating offshore wind turbines. Numerical models of two semi-submersible designs (DeepCwind from OC5 project and Tri-Floater from GustoMSC) were created in this software tool and simulations were compared with the available model tests. The "model the model" approach was followed in the simulations, that is to say the numerical models were created to fully represent the properties of the model tests. From the comparison of simulations and model tests in irregular waves, the damping levels of the structure were estimated by determining the drag coefficients on columns and heave plates from a sensitivity analysis. For wind and waves loading conditions under fixed rotor speed and blade pitch angle, the surge and pitch motions, the accelerations on top of the tower and the mooring line tensions are very well predicted by simulations with respect to model tests. The thrust variation is presenting some differences in the wave frequency (WF) range but this is not influential on the motional behavior of the floater. Simulations with active controller were also performed and compared with model tests. In the above rated conditions, due to the presence of controller, the low frequency (LF) thrust variation is diminished by both model tests and simulations but in higher frequencies the model tests and simulations do not match. The latter, however, does not have significant effect on the motions. Moreover, for these conditions (above rated), uncoupled simulations with a constant force equal to the mean thrust are proposed which can predict accurately the floater's motions and mooring tensions. The second target of this thesis was the investigation of the impact of aerodynamic loads on the floater's motions. It was found that the high mean thrust increases the horizontal stiffness of the system and the coupling between pitch and surge. Moreover the wind variation is mainly affecting the LF surge and pitch motions but it is not influencing the WF motions and the accelerations on top of the tower. It was also proved that the inclination of the floater due to high mean thrust values is not significantly affecting the hydrodynamic characteristics of the system. Finally an estimation of the aerodynamic damping for conditions without controller was derived from decay simulations with wind, and was correlated with a theoretical derivation.

1. Introduction

Nowadays Offshore Wind Turbines (OWT) are typically fixed to the seabed but due to the immense need to go in deeper water depths, more than 50 meters, floating OWTs are becoming more competitive. Floating wind turbines have several advantages with respect to, close to shore, fixed wind turbines such as the stronger and steadier wind potential over deep waters, no visual pollution or disruptive noise and easier installation and construction process since they can be assembled in protected areas and then be towed to the in the desired location by simple tugs. However, despite the advantages of FOWT, there remain significant obstacles to widespread deployment. One of the challenges of FOWTs is that in operational conditions, especially in rated and above rated wind speeds, aerodynamic loads can be quite high and can potentially interact with the hydrodynamic loads. This could reflect a forceful effect on the translational and rotational motions of the wind turbine's floating foundation. The complexity of this interaction can be amplified by the presence of active controller on the wind turbine [1]. Consequently, in order to better understand the motional behavior of the floater, coupled simulations with aerodynamics, turbine structural dynamics, active controller, hydrodynamics and mooring line dynamics are needed. In this work, the coupled software tool ANSYS AQWA-PHATAS was used, which can perform the so-called aero-hydro-servo-elastic simulations. To increase the confidence on the aforementioned simulations, it is crucial to validate this software tool with results from model tests. Model test results were available from 2 campaigns which used two different semi-submersible designs as the support of a wind turbine (DeepCwind from OC5 project [2] and Tri-Floater from GustoMSC [3]). Thus, the first objective of the current thesis was the validation of the software tool. Moreover, the impact of the aerodynamic loads on the floater's motions was investigated in depth in order to acquire a better insight on how and in what extent, the motions of the floater are affected by the aerodynamic loads.

2. Creation of numerical models

As it was mentioned before, two semi-submersible designs were modeled in AQWA-PHATAS, the first is the DeepCwind which is shown in Figure 1 and the second is the Tri-Floater which can be seen in Figure 2.

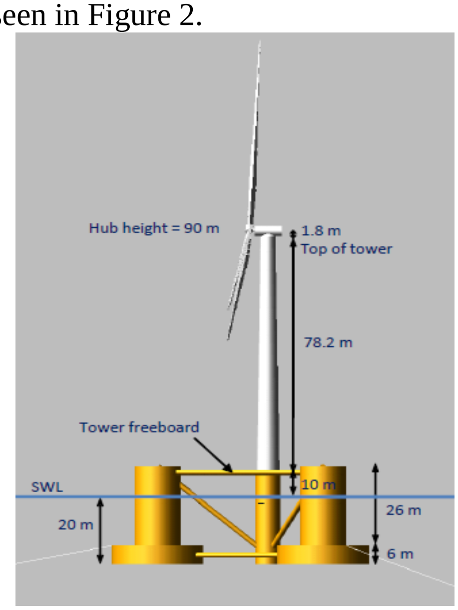

Figure 1: DeepCwind semi-submersible [2]

Since most of the model test results from the DeepCwind semi-submersible have not been released yet, the most emphasis was given on the Tri-Floater, thus the next description and results correspond to the Tri-Floater semi-submersible model.

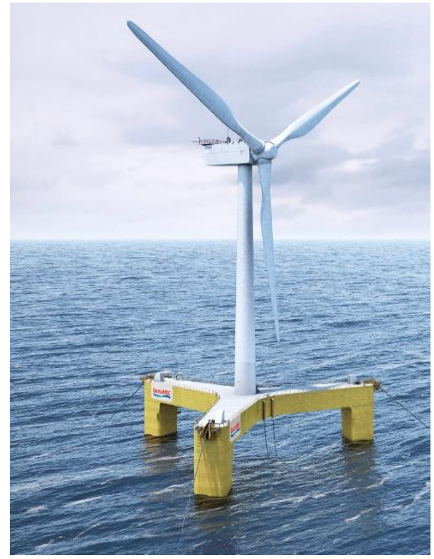

Figure 2: Tri-Floater semi-submersible

Firstly, the mesh was created for the substructure of the floater (see Figure 3), in order to perform the diffraction analysis and derive the hydrodynamic characteristics. Moreover, to account for the quadratic drag forces, Morison elements were used [4] for the columns and the heave plates correspondingly. The mooring lines were modeled with the exact properties that were achieved in the model tests. Thus, composite elastic catenary chains were used and quasi-static mooring analysis was performed.

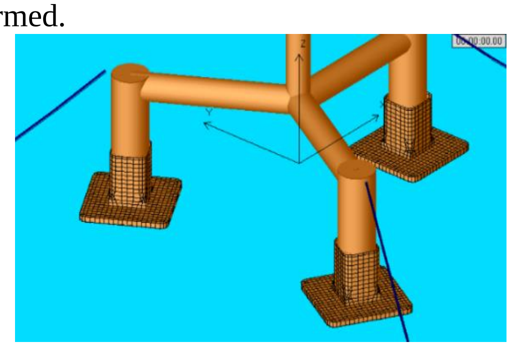

Figure 3: Diffracting elements [5]

Finally, since the target was to follow the "model the model" approach, that is to say to create the same properties in the numerical model as they were achieved in the model tests, the MARIN Stock Wind Turbine (see [2]and [5]) was modelled in PHATAS.

3. Coupling of AQWA – PHATAS

The interface between AQWA and PHATAS can be interpreted as the physical connection between the floater and the wind turbine. In the

AQWA-PHATAS coupling the interface is chosen as the tower base of the wind turbine [7]. At this interface, the floater's motions and velocities are assigned to the wind turbine and reaction forces are transferred from the wind turbine to the floater. In the AQWA-PHATAS coupling the floater motions and wind turbine reaction forces are exchanged within an interface code which is called USERFORCE.DLL. The information which is exchanged between the programs as well as the inputs and outputs can be shown in Figure 4.

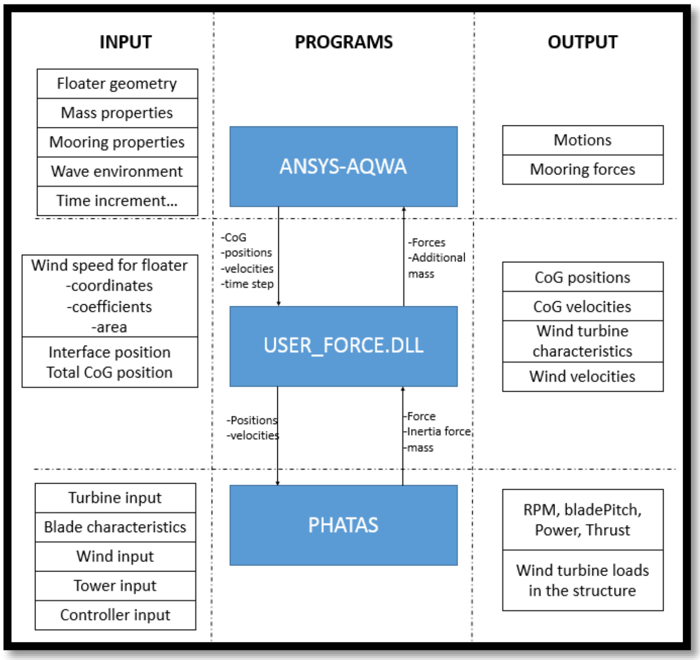

Figure 4: Coupling of AQWA-PHATAS

4. Comparison of simulations with model tests

a. Irregular waves only

Simulations were performed for multiple loading conditions and compared with model tests. The initial objective was to determine the damping levels of the Tri-Floater in the numerical model according to model test results. For this reason decay simulations were performed but since the coupling among the degrees of freedom was very high, the correct damping levels could not be derived from decay tests. As a result, the hydrodynamic quadratic drag coefficients were determined by the comparison of simulations and model tests in irregular waves (H_s=4.5m, T_p=10sec). These coefficients were determined after a sensitivity analysis, trying to match the simulations with model tests. Emphasis was given to match the surge and pitch motions because these two degrees of freedom (DOF) are the most important in this study. It was observed that the surge DOF was significantly affected by the change of the column drag coefficient and the pitch DOF by the change of the heave plate drag coefficient. The corresponding spectra are shown below:

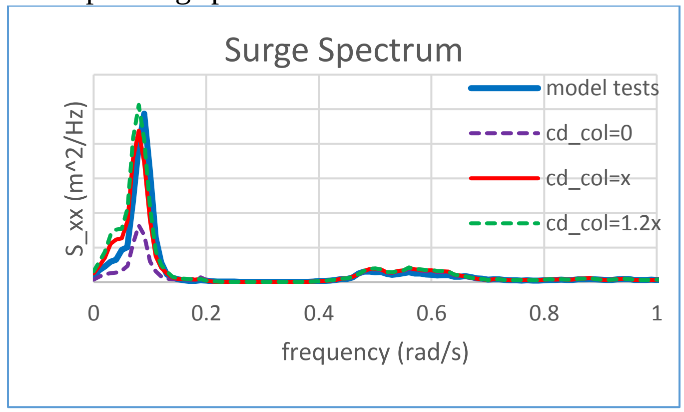

Figure 5: Surge spectrum for waves only

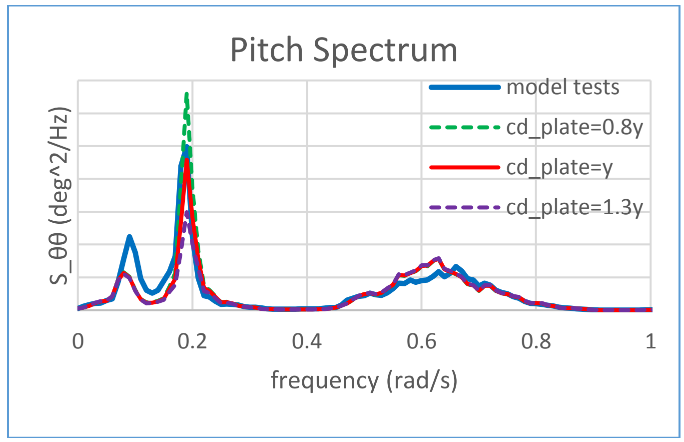

Figure 6: Pitch spectrum for waves only

Based on the above graphs, the final damping levels were determined. Thus applying these drag coefficients, it was important to investigate how accurately the simulations can predict important values for the design of the Tri-Floater, such as the maximum pitch angle, maximum tensions and accelerations on top of the tower. The maximum pitch angle between simulations and model tests has a difference of 5%. The maximum tensions show a difference of around 14% but this difference is mainly caused due to the non-inclusion of mooring line dynamics. Another important factor which is crucial for the design of floating wind turbines is the horizontal acceleration of the nacelle. It was observed that the maximum horizontal accelerations for both model tests and simulations is in the order of magnitude. For the next simulations with wind and waves, those drag coefficients did remain the same.

b. Dynamic wind + irregular waves

Since the hydrodynamic model was accurately validated, the next step was to perform aero-hydrodynamic simulations for the Tri-Floater, with fixed blade pitch and rated RPM. For a valid comparison with model tests it was important to estimate as accurately as possible the wind speed time trace which was achieved in the model tests. For this reason the wind speed was selected from wind speed calibration tests, at the hub's position as it is shown in Figure 7.

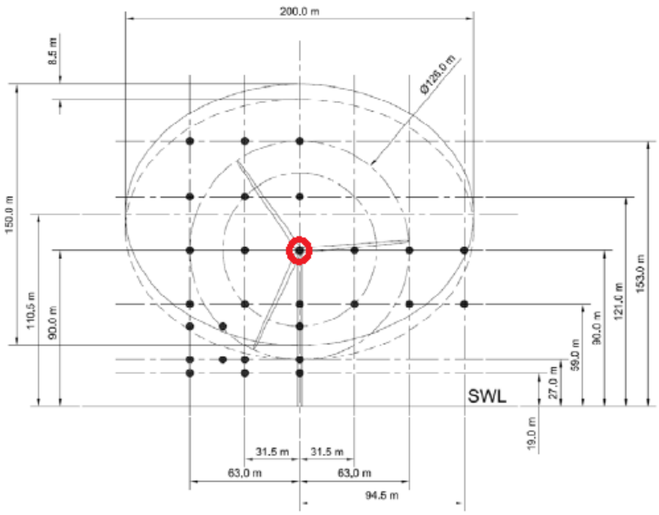

Figure 7: Derivation of wind speed time trace from the hub's height [2]

After selecting this wind speed time trace, the wind speed spectrum was derived and is shown in Figure 8. From this spectrum it is observed that the most wind speed energy is in very low frequencies (with its peak around 0.05rad/s).

From coupled simulations, the thrust was derived and was compared with the thrust from model tests. The mean thrust value differs only by 1%, but the standard deviation was higher in the model tests mainly due to higher excitations in the WF range, the first tower bending mode and the blade passing frequency (3P). The aforementioned differences though, are not producing any influence on the motions of the floater (the WF thrust variations are one order of magnitude smaller than the wave-induced variations, and the peaks in first tower bending mode and 3P frequencies are far-outside the frequency area where the motions of the floater are excited). The low frequency (0-0.3rad/s) thrust variations are very well predicted in simulations with respect to model tests which means that both the wind speed input and the aerodynamic characteristics are accurately modelled. The thrust spectra for model tests and simulations are depicted in Figure 9.

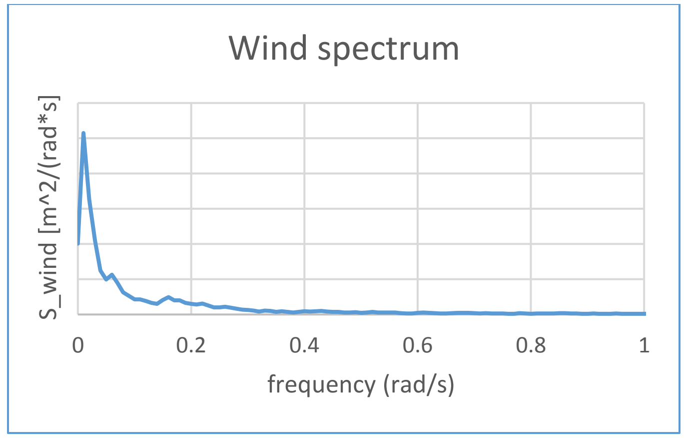

Figure 8: Wind speed spectrum for rated conditions

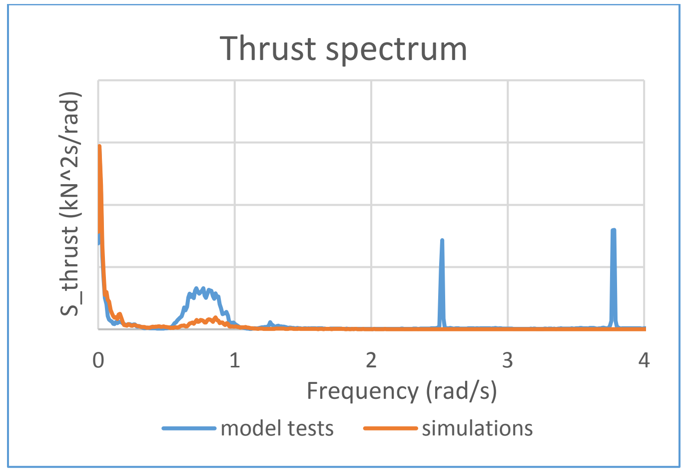

Figure 9: Thrust spectrum for rated conditions

In coupled simulations with fixed blade pitch angle, the motions are also very well predicted in both LF and WF range. The surge and pitch spectra, which are mostly affected by the presence of wind loads, are shown in Figure 10 and Figure 11. From both figures it is observed that the variation of motions is captured quite well from the coupled simulations.

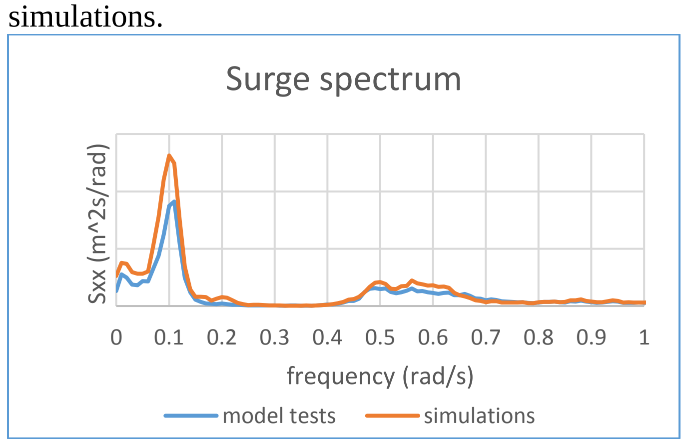

Figure 10: Surge spectrum for wind&waves with fixed blade pitch

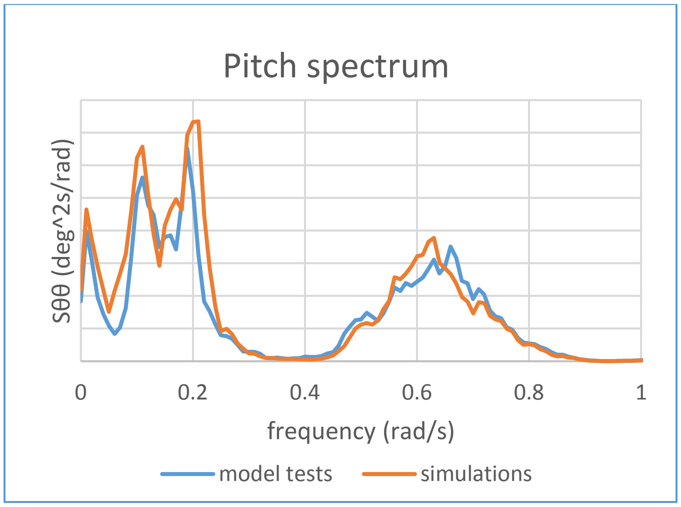

Figure 11: Pitch spectrum for wind&waves with fixed blade pitch

From the pitch spectrum a high pitch-surge coupling is also noticed. This is exciting the pitch motions in the surge natural frequency (0.01rad/s) and is caused due to the presence of the mooring system as it will be explained later. However, for higher wind states, the wind variation is so high in the low frequencies that this pitch-surge coupling is not apparent in the pitch spectrum.

As far as the mean values is concerned, the pitch motions in simulations differ less than 2%. In the surge motion, mean surge offset was higher in the simulations and the reason for this deviation is that before the execution of each model tests all the measuring devices where zeroed which possibly didn't capture an initial surge offset. This can be also justified after comparing the x_offset and tensions of this model test with respect to excursion tests. Thus, the mean surge offset should be higher and closer to the value derived from simulations.

Since the motions from simulations show a good behavior according to model tests, the accelerations are expected to be well predicted as well. The RMS accelerations on top of the tower for simulations and model tests differ only by 6%. What is noticed from the acceleration spectra is that the accelerations are significant in the WF range (where wave-induced loads are prevalent) and not in the LF range where the wind-induced loads are present. Even for higher wind speed variations the LF accelerations are small compared to the wave-induced accelerations.

The difference in the mean tension of the bow mooring line (which is subjected to highest tensions) between simulations and model tests is less than 1%. However, in the model tests, the standard deviation is much higher, mainly in the WF range (this is due to the non-inclusion of the mooring line dynamics as it was said in the irregular-waves case which induces tension variations in the WF range). The dynamic effects of the mooring lines are not affecting the mean tension values but they do affect the maximum ones. For this reason the tension time trace from simulations and model tests was filtered in order to exclude the tension variations in the WF range. The maximum LF tension from simulations is only 2% overestimated with respect to the model tests.

c. *Dynamic wind + irregular waves + active controller*

In modern wind turbines active controller is widely used in order to achieve optimum power and mitigation of loads. Moreover, since the controller can cause significant changes in aerodynamic loads on the rotor, it is important to investigate the effect of the controller on the motions of a floating OWT. For this reason in the campaign of GustoMSC with ECN in MARIN's basin [3], model tests were performed in the rated and above rated wind conditions including control. However, only the tests for above rated conditions was used in the current analysis, because in the rated conditions the controller's performance was not stable. Aero-hydro-servo-elastic simulations were also performed for the above rated conditions and the results were compared with those from model tests.

Firstly wind-only simulations were performed with active controller (above rated conditions, Vwind=20.9m/s). The mean thrust from simulations was overestimated by 19%, and as a result higher mean surge and pitch offset occurred in the simulations. The thrust variation in the very low frequencies (where wind energy occurs) was successfully mitigated in both model tests and simulations by the action of controller in the blade pitch angle. However, in model tests the thrust variation remains high in higher frequencies, whereas in simulations the thrust variation is mitigated in all range of frequencies. From the last we can conclude that the controller in the model tests could not perform as stably as in the simulations.

Moreover, simulations with wind and waves were performed with and without control for the above rated conditions and compared with model tests with control. The thrust response spectra from those cases are shown in Figure 12, where it can be seen that the LF thrust variation is quite high in simulations without controller whereas in both simulations and model tests with controller, the LF thrust variations are cancelled out. In the model tests, however, we still observe (as in the wind only case) WF thrust excitation (in frequencies between 0.4-1rad/s). The latter excitation is induced by the defective behavior of the controller in model tests.

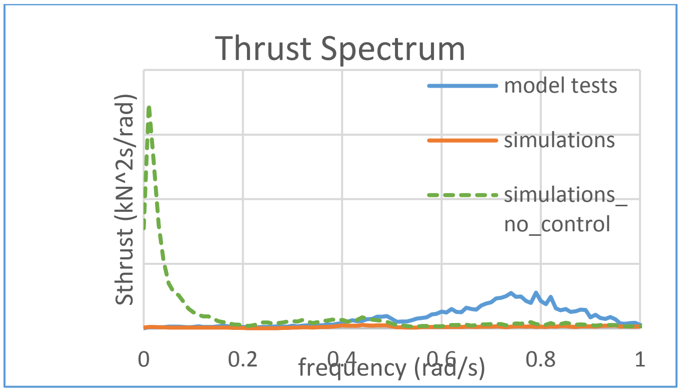

Figure 12:Thrust spectra for above rated conditions with wind&waves

Since the LF thrust variations are mitigated due to the inclusion of controller, the LF motions are also diminished. The surge and pitch motions from simulations with active control are comparable with respect to model tests. Those can be seen in the next figures where the surge and pitch spectra are plotted.

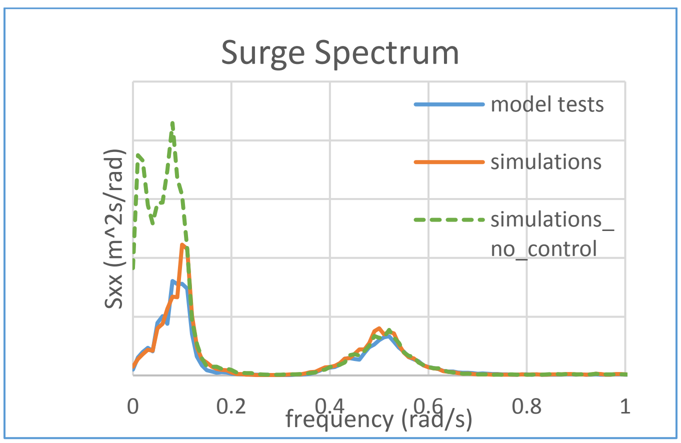

Figure 13: Surge spectra for above rated conditions with wind&waves

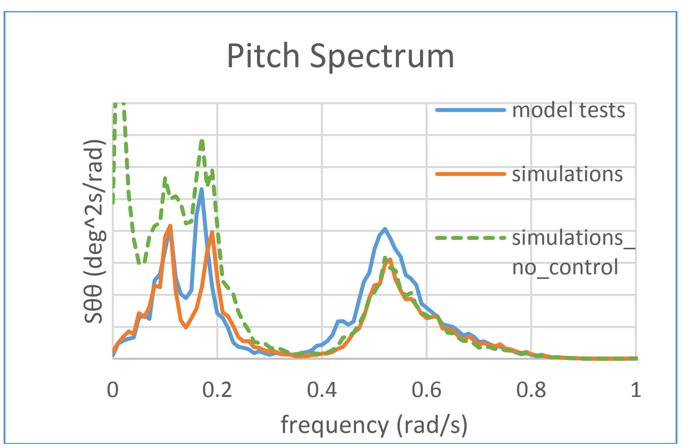

Figure 14: Pitch spectra for above rated conditions with wind&waves

These spectra show that the controller mitigates all the wind-induced LF motions of the floater both in simulations and model tests. However, a difference in the WF range in pitch spectrum in noticed which is mainly due to the wave forces and not due to the WF thrust variation in the model tests because the latter is one order of magnitude less compared to wave-induced forces.

Consequently, for above rated conditions, the WF thrust variation is not significantly affecting the motions of the structure and the LF thrust variation is not apparent due to the action of the controller. Thus, it could be feasible to predict the motions of the floater by only applying an external constant force equal to the mean thrust value. The latter simplified uncoupled simulations could be performed in early design stages since they are simpler and faster. Therefore, time domain simulations were performed without wind and control but with a constant force equal to the mean thrust, which was applied on the center of the hub. The results from these simulations with respect to simulations with control are very accurate and can be shown in the following table:

Table 1: Comparison from uncoupled simulations with constant force with respect to aero-hydro-servo-elastic simulations

	surge	Pitch	Tension1	Xtop_acc
mean	0.4%	-2.8%	0.1%	-2.8%
std	0.4%	-1.5%	0.0%	-1.1%
max	0.9%	0.7%	1.0%	2.8%

From the above table all statistical results match quite well. The mean and maximum values from uncoupled simulations with a constant force can very accurately match the mean and maximum values from the coupled simulations with control.

Taking all the above into account, we end up that for above rated conditions of floating wind turbines, the aero-hydro-servo-elastic simulations are not necessary since simulations with waves and a constant force can very accurately predict the motions and accelerations of the floater and the mooring tensions as well. However, this outcome should not be generalized for the rated or below rated conditions because the slope of the thrust with respect to wind speed is higher (this can be seen in Figure 15, where it is shown that the curve is steep close to the rated, conditions, in 11.4m/s, whereas it is more flat in for wind speeds higher than 20m/s).

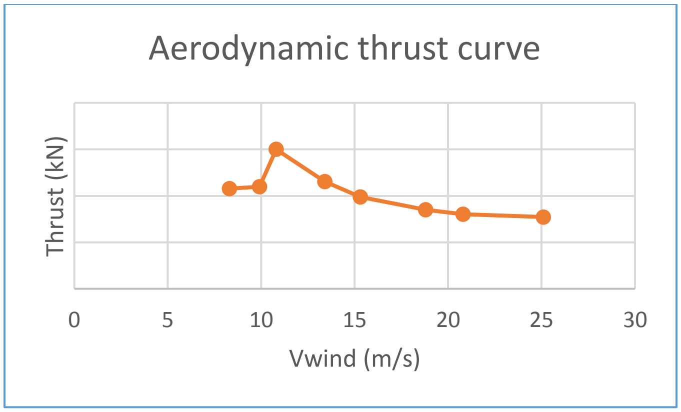

Figure 15: Aerodynamic Thrust - Vwind

The higher the slope of this curve (dT/dV) the higher the variations of thrust for every change in wind speed and as a result more instability or damping of the system (depending on the sign of the slope).

5. Impact of thrust on motions

In addition to the validation of the software tool AQWA-PHATAS with respect to the model tests, the impact of the aerodynamic loads on the floater's motions was investigated. For this reason the thrust was splitted in two components: the mean and the turbulent part as it is shown in the next equation:

$$Thrust = T_{mean} + T_{turb} \qquad \text{(Eq 1)}$$

Thus, the effect of both components on the system was investigated.

The mean part of the thrust is creating a mean surge offset. This mean offset is increasing the stiffness of the system in the horizontal DOF. This can also be seen from Figure 16 where it is shown how much the surge stiffness is augmenting with respect to the surge offset. Since the stiffness is higher, the surge natural frequency is increasing as well. Another effect of this increased stiffness is that the surge motions are reduced. Plotting the simulations with waves only and simulations with waves and a constant force (equal to the mean thrust), it is observed that the surge motions are diminished in the simulations where the mean thrust is applied (see Figure 17).

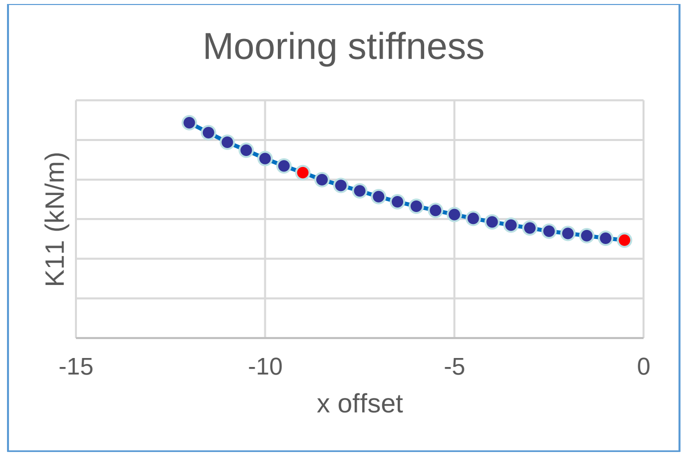

Figure 16: surge mooring stiffness in x-offset

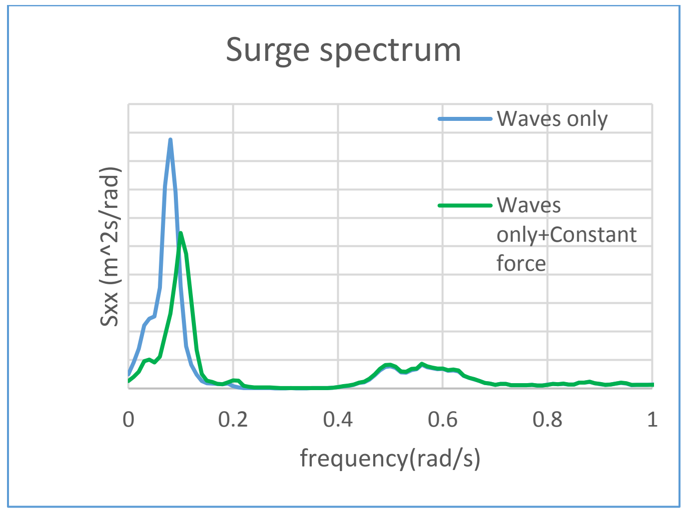

Figure 17: Surge spectra – influence of the axial mooring stiffness on surge motion

The surge offset is also creating a higher coupling pitch-surge mooring stiffness term (K_{51}). This increase is depicted in the pitch spectrum with a peak at the surge natural frequency as can be seen below:

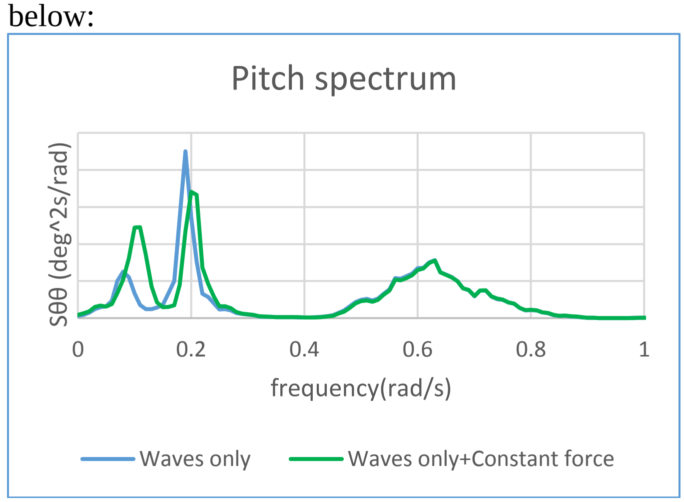

Figure 18: Pitch spectra – influence of coupling stiffness term on pitch motion

In order to determine the influence of the turbulent thrust component, coupled aero-hydrodynamic simulations where performed for different levels of wind variations. From this analysis it was concluded that since the wind energy is mostly in low frequencies (NPD wind spectrum), the thrust energy is also detected in the LF range. As a result, this thrust excitation is significantly affecting the surge and pitch motions in the very low frequencies(0-0.05rad/s) and the frequencies close to their natural frequencies. However, there is no effect of wind loads in the WF range of surge and pitch. Moreover, the maximum pitch angle is increasing with increasing wind speed variation. The mooring tensions are behaving similarly with the surge motions (the tensions are affected only in the low frequencies). Finally the horizontal accelerations at top of the tower, show increased variations in low frequencies for higher wind speed variations.

Due to the high mean thrust values, floating wind turbines are operating under a mean pitch offset. This inclination could potentially change the hydrodynamic characteristics of the structure because of its different shape under the water surface (see also [8]). For this reason the diffraction analysis was performed for an inclined substructure of the Tri-Floater by 5 degrees.

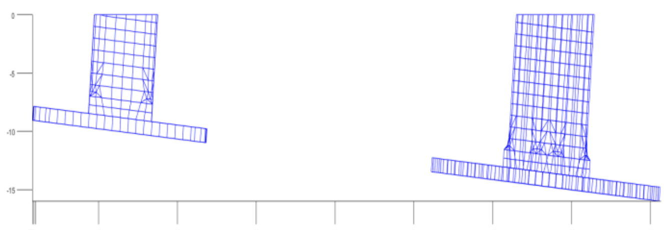

Figure 19: inclined substructure of Tri-Floater

The outcome from this analysis is that despite some differences in the radiation and diffraction forces, the motions of the structure remain almost unaffected with respect to the analysis in the upright position.

Another fact which has not been discussed yet but it can have an influence on the motions of the structure is the aerodynamic damping. The aerodynamic damping is actually produced by the change in relative wind speed which exerted on the rotating blades due to the motions of the rotor. In the current thesis pitch decay simulations with different constant wind speed were applied in order to quantify the aerodynamic damping for constant rotor speed and fixed blade pitch. For the determination of the linear and quadratic damping of the system the p-q analysis was followed which is discussed in [2]. Moreover, in this analysis only the pitch DOF was activated because the surge and pitch coupling was so high that no perspicuous results could be derived if the floater was free in all 6DOFs. From this analysis it was concluded that the aerodynamic damping is linearly dependent on the structure's velocity. The aerodynamic damping is also increasing as the wind speed (and as a result the thrust) increases.

A theoretical explanation of the linear aerodynamic damping can be given by the fact that the thrust is acting in the structure as a drag force. Moreover, since the wind speed is much higher than the rotor's horizontal velocity (Vwind>>$\dot{x}$), the drag force which represents the thrust, can take the following form:

$$\begin{aligned} T &= C\,(V_{wind} - \dot{x})^2 \\ &\approx C{V_{wind}}^2 - 2CV_{wind}\dot{x} \\ &= \overline{T} - b_{1aero}\dot{x} \end{aligned} \qquad (Eq\ 2)$$

This damping coefficient (b_{1aero}) is independent of the floater's motion and is defined by the mean thrust force and wind velocity:

$$b_{1aero} = \frac{2\overline{T}}{V_{wind}} \qquad (Eq\ 3)$$

In order to compare the above theoretically derived aerodynamic damping with the results from the pitch decay simulations, this has to be transformed from the horizontal translational DOF to the pitch rotational one (by analyzing the thrust-induced moments). As a result, the theoretical pitch aerodynamic damping can be calculated by:

$$b_{5aero} = \frac{2\overline{T}R^2}{V_{wind}} \qquad (Eq\ 4)$$

where R is the arm between the rotor's hub and the CoG of the floater.

The theoretical and the derived from the decay simulations aerodynamic damping are very close as can be seen in Figure 20.

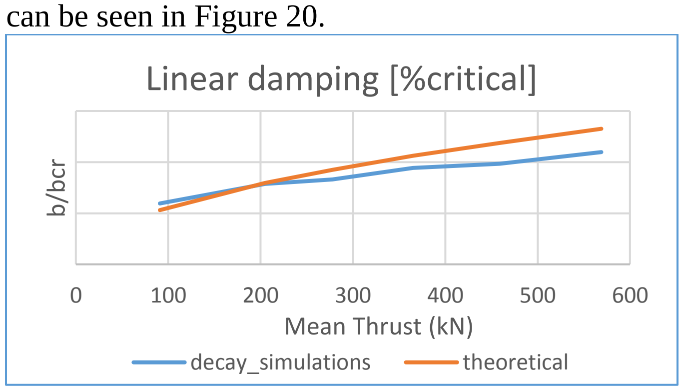

Figure 20: Theoretical damping - damping from decay simulations

Taking all the above into consideration, we end up with the conclusion that the aerodynamic damping in the below rated conditions (so for fixed blade pitch) has a form of linear damping which is increasing as the mean thrust increases. The (Eq 4 can also be used in preliminary studies to estimate the aerodynamic damping for below rated conditions and generally when the active blade pitch controller is not applied.

6. Conclusions

The coupled aero-hydrodynamic time domain simulations was successfully validated with respect to model tests (for fixed rotor speed and blade pitch angle). The motions of the floater and the accelerations on top of the tower were accurately predicted by simulations. The mean mooring tensions are well predicted using the quasi-static mooring analysis but show small differences occur in the maximum tensions mainly due to the non-inclusion of mooring line dynamics.

The validation of the coupled simulations with controller was partly successful for the above rated wind conditions. The LF surge and pitch motions were decreased both in simulations and model tests due to the presence of the controller. A simplified procedure was proposed which allows to replace the aero-hydro-servo-elastic simulations with simulations which include only waves and a constant force equal to the mean thrust (for the above rated conditions only). This simplification provided accurate results in motions accelerations and mooring tensions and can be used for earlier design stages due its higher speed and simplicity.

The high mean thrust (especially close to rated conditions) creates high horizontal mean offset of the floating OWT. This mean offset creates higher horizontal stiffness which leads to lower horizontal motions as well. This offset also increases the coupled pitch-surge mooring term and as a result the pitch variations are augmenting. The wind gust can significantly affect the LF motions of floating OWTs but its influence in WF motions is negligible. Moreover, it was shown that an inclination of the floating wind turbine is not significantly affecting the floater's hydrodynamic characteristics.

After pitch decay simulations, the aerodynamic damping was proved to be linearly dependent on the structure's velocity (for below rated conditions where controller is not applied). This result was also compared with a theoretical derivation of the linear aerodynamic damping. Finally, this theoretical derivation can be applied for the estimation of aerodynamic damping in operating conditions where the blade pitch controller is not activated.

7. Recommendations

On future simulations

Since the numerical model of the DeepCwind of the OC5 project has been created, the simulations could be performed to validate the software AQWA-PHATAS for a different semi-submersible design.

From the current analysis, the simplification of the coupled aero-hydro-servo-elastic simulations for the above rated conditions by using uncoupled simulations with a constant force was valid in the area close to 20m/s of wind speed. Since the slope of the thrust curve varies for different wind speeds, it is recommended to investigate, performing further simulations for different wind speeds, the exact range of wind speed where this simplification is still valid.

On future model tests

As there is some uncertainty in the wind field of model tests it is recommended to use calibration tests with more measurements, in several positions in the swept area of the rotor in order to well predict the 3D turbulent wind in the basin. This would give more qualitative input wind data in the simulations which eventually would give more confidence on the effect of the wind variation in the motions of the floater.

Since model tests with wind, waves and controller are very complex, it is recommended to for future model tests to start with tests as simple as possible and then increase the complexity by adding extra components in the model tests. Regarding FOWTs, it is important to first make waves-only tests for all the sea states and wind only tests for various wind conditions with and without the presence of control. That would give more insight of how much each loading condition contribute to changes in motions, tensions, etc. Having performed those experiments, the combined wind and wave model tests can be done with more confidence and understanding.

The controller in the model tests was based on torque measurements, so the set-point was very sensitive. An alternative would be to design a model test control system which is based on thrust measurements. However, this control wouldn't represent the actual operational control in full scale wind turbines, so further investigation is needed in order to accomplish a stable control system for model tests.

Symbols – Abbreviations

OWT	=	Offshore Wind Turbines
LF	=	Low frequency (0 - 0.3rad/s)
WF	=	Wave frequency (0.3 – 1 rad/s)
DOF	=	Degree Of Freedom
Tmean	=	Mean thrust component
Tturb	=	Turbulent thrust component
$\dot{x}$	=	Velocity of the structure on top of the tower
C	=	Constant value which is determined by the aerodynamic characteristics of the rotor
Vwind	=	Wind speed
b1aero	=	Translational aerodynamic damping
b5aero	=	Pitch aerodynamic damping
R	=	The arm from the hub to the rotation point of the floater.

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