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## Drift stability of HyStOH semi-submersible supported by airfoil shaped structures

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**Abstract.** This study presents the results of the German research project HyStOH funded by German Federal Ministry of Economic Affairs and Energy (BMWi). The project consortium of German universities, wind turbine designers, wind farm developers and certification bodies design a novel semi-submersible steel structure with a single point mooring and self-aligning capabilities. The tower, which carries a 6 MW two-bladed downwind turbine, has an airfoil shaped cover, which supports the self-alignment of the full structure towards the main wind direction. The downwind operating wind turbine in combination with the lift force generating tower enables a passive yaw system acting against hydrodynamical impacts from waves and currents. Simulations in time domain applying the fully coupled aero-hydro-servo-elastic code Bladed\_4.8 demonstrate the drift sensitivity and the self-aligning capabilities of the HyStOH design. The hydrodynamic coefficients for the simulations have been adjusted by calculations with an 1:1 model of the panel code panMARE, developed by Technical University of Hamburg-Harburg. The motivation of this analysis is to capture the complex coupled motions of an innovative FOWT by numerical simulation tools [1]. The analysis presents dynamic simulations of the HyStOH design operating in turbulent wind and irregular sea state with special focus on the yaw drift behaviour of the FOWT. The sensitivity study of yaw drift is based on numerous variations of wind-wave-current misalignments during normal operation. The results of the simulations demonstrate the weathervane capabilities of the airfoil shaped structures.

### 1. Introduction

The currently installed floating wind projects indicate the transition from demonstration projects towards first commercial application. The technology readiness level (TRL) for floating offshore wind turbines (FOWTs) is increasing consistently. Worldwide, especially in countries such as France, Japan, Norway and the US, new floating wind projects are being planned. Many of the projects make use of the availability of large multi mega Watt offshore wind turbines.

Different floater concepts of FOWT are currently on the market and until now and there is no distinct design concept which has been established in the industry as the most favourable concept so far. The top four floater concepts realised in the last years have been the semi-submersible, spar buoy, tension leg platform (TLP) and barge types [2].



In the German research project HyStOH funded by the BMWi, the project partners design an innovative variant of the semi-submersible floater concept. The consortium comprises German universities, wind turbine designers, wind farm developers and certification bodies. The novelty of this concept is a self-aligning floater, combined with an aerodynamical shaped tower and a downwind 6 MW rotor-nacelle assembly (RNA). A single point mooring turret below the floater structure carries five catenary mooring lines and provides the yaw degree of freedom similar to Floating Production Storage and Offloading (FPSO) station keeping systems. Thus, the RNA of this concept has no active yaw system and is directly flanged to the tower. Figure 1 illustrates the design concept of the HyStOH research project.



**Figure 1.** The HyStOH SelfAligner designed by the project consortium

Due to the trapezoidal floater design, the single point mooring axis has a distance of about 70 m to the tower axis which provides a large excentricity between aerodynamic forces and station keeping system. In this configuration, the airfoil shaped tower is acting as a weathervane and aero forces generate yaw moments to align the full structure into the main wind direction [3].

This study presents fully coupled aero-hydro-servo-elastic load simulations in time domain with Bladed\_4.8, describing the drift and self-aligning effects during normal operational conditions of the HyStOH concept and its dynamic response to wind-wave-current misalignment.

## 2. Method

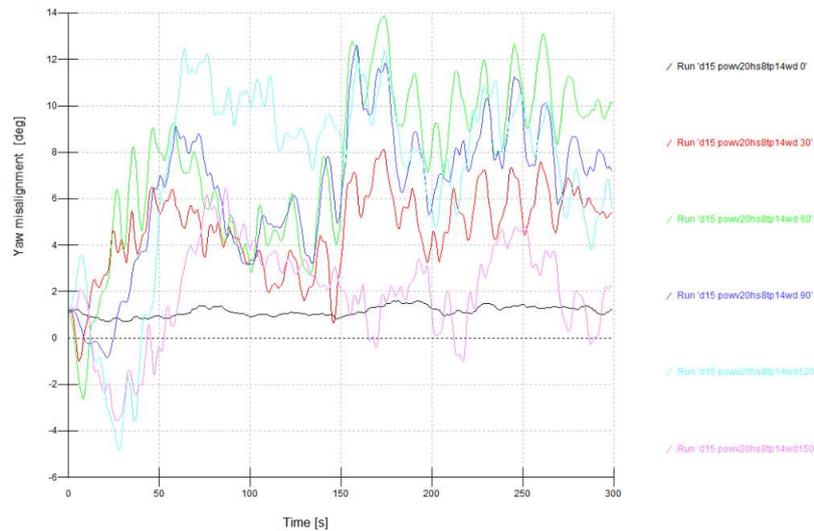
In a first step, the HyStOH site conditions are defined under consideration of wind-wave misalignment effects. Unidirectional approach of waves and currents is considered as most critical for the drift behaviour [4]. Therefore, a constant current of  $u = 0.5$  m/s with a linear shear is approaching in all simulations from the same direction as the waves. The HyStOH FOWT is modelled with the fully coupled hydro-aero-servo-elastic simulation code Bladed\_4.8. For adjusting the hydrodynamic system matrices reference is made to the first-order panel method of panMARE, see section 2.2. The basic environmental conditions applied in the simulations are given in Table 1.

**Table 1.** Environmental parameters of HyStoH Design Basis. Turbulent wind is based on von Karman spectrum with turbulence intensity according to class B [5]. Wave spectrum is based on JONSWAP spectrum.

No.	Wind speed at hub height (10 min. mean) $v_{Hub}$ (m/s)	Significant wave height $H_s$ (m)	Wave peak period $T_P$ (s)	Near surface current $u$ (m/s)
1	1.3	0.70	6.20	0.5
2	2.6	0.80	6.30	0.5
3	3.9	0.96	6.47	0.5
4	5.2	1.20	6.72	0.5
5	6.5	1.51	7.03	0.5
6	7.9	1.88	7.41	0.5
7	9.2	2.33	7.86	0.5
8	10.5	2.85	8.38	0.5
9	11.8	3.44	8.96	0.5
10	13.1	4.10	9.60	0.5
11	14.4	4.83	10.30	0.5
12	15.7	5.63	11.06	0.5
13	17.0	6.50	11.86	0.5
14	18.3	7.44	12.72	0.5
15	19.6	8.45	13.62	0.5

In all simulations the initial position of the floater is aligned along the global x-axis so that rotor axis and the wind direction are co-linear. Thus, the rotor is approached by the wind with a yaw misalignment angle of zero and is producing optimal power output. In 9 steps the wave (and current) direction relative to the wind direction is then increased by steps of 30 degree in a range of  $\pm 120$  degree.

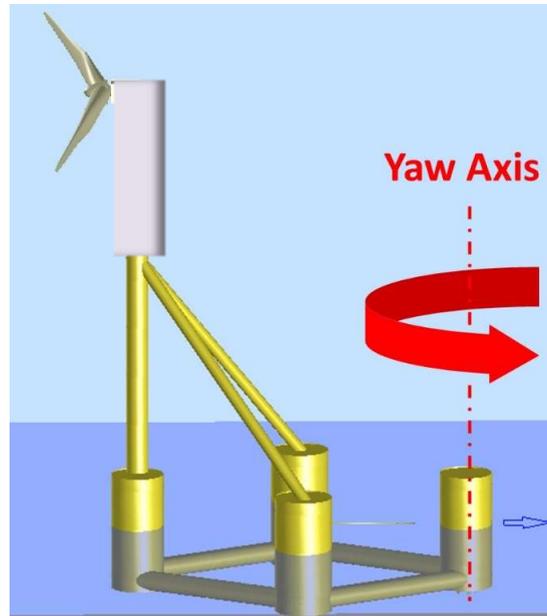
Because of the single point mooring degree of freedom (free yaw DoF) and the motions of the floater in irregular sea state, little yaw motions and hence wind-rotor misalignments occur even under unidirectional wind-wave impact (wave direction zero degree). If the angle between wind direction and waves is stepwise increased/decreased the hydrodynamic wave forces tend to push the entire FOWT out of the wind direction. The HyStoH floater with its 8,000 tons (including ballast tanks) can reach a yaw drift velocity of about 0.2 degree/s as shown in Figure 2 (first 300 s simulation example).



**Figure 2.** Initial orientation of HyStOH floater for wave directions 0 -120 degree

### 2.1. Aero-elastic simulation code Bladed 4.8

The computer code Bladed (developed by Garrad Hassan) performs analyses in the time domain. Time domain simulations are necessary for non-linear, dynamic and transient processes, which are important for the load analysis of FOWT. Complex hydrodynamic calculations typically consider non-linear mooring systems [6] and the effects of radiation and diffraction forces. Bladed is developed for dynamic load calculations of multibody structures with coupled aerodynamic and hydrodynamic loads. It calculates the structure dynamics with a multibody-dynamic-approach. The components such as blades and tower are modelled from flexible elements whose deformation is determined by modal analyses. This is done by a linear combination of the calculated eigenmodes resulting from a finite element method (FEM) calculation. The aerodynamic forces are calculated with the blade element momentum theory (BEMT) [7]. In addition, Bladed is able to simulate a wake behind the rotor and dynamic stall. Bladed\_4.8 can simulate regular and irregular waves as well as sea currents. Regular waves are used mainly for determination of extreme loads and will be described as Airy-waves or with the stream function. For fatigue loads, a series of irregular waves is created whose amplitude and frequency is defined with a spectral density function as the JONSWAP or Pierson-Moskowitz spectrum. The hydrodynamic forces are calculated with the Morison equation. The mooring system is represented by a force-displacement ratio, linear or non-linear, and are calculated separately by the user and implemented via a stiffness matrix at the fairlead position. A detailed description of this quasi-static approach is given in [8].

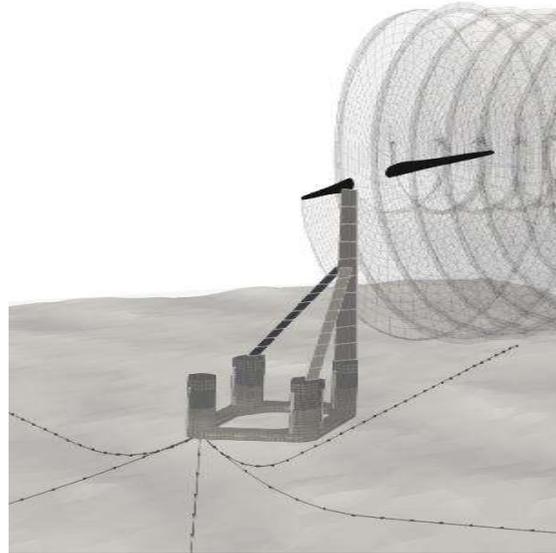


**Figure 3.** Bladed model including extended aerodynamical tower properties

The prediction of onshore and offshore loads from turbulent wind has been validated and proven by numerous projects and measurements over the last decades. Recent extensions of Bladed comprise modelling of elastic properties of large blades, super-elements and the introduction of tidal and floating turbine model capabilities.

### 2.2. Panel code *panMARE*

PanMARE (panel Code for Maritime Applications and REsearch) is a validated code of Technical University of Hamburg-Harburg (TUHH), institute of fluid dynamics and ship theory which has been validated in a number of commercial oil&gas and maritime projects [9]. To simulate the highly unsteady motions of the HyStOH turbine and platform, the code has been extended. Considering the hydrodynamics, panMARE accounts for the geometry of the submerged platform in detail as well as for an inviscid model of the three-dimensional hydrodynamic flow field [10]. In contrast to frequency-domain based methods, unsteady and aperiodic motions do not impair the quality of the obtained hydrodynamic results. The hydrodynamic loads are calculated by instantaneously integrating the static and dynamic pressure on the submerged platform hull. The principal ability of panMARE to directly model radiation and diffraction effects using a discretised water surface is one reason why a potential method has been chosen here [11].

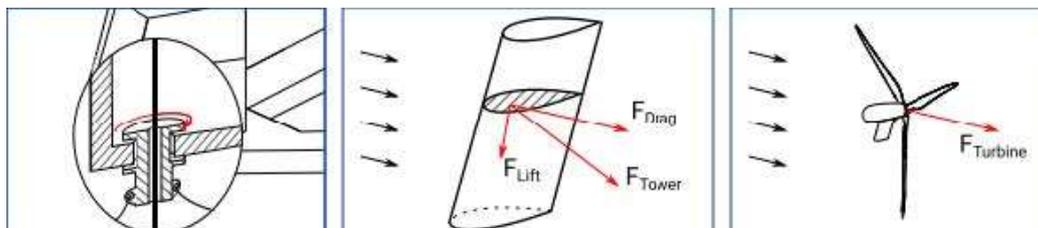


**Figure 4.** Model setup with platform, tower, rotor blades, rotor wake and mooring

Considering the aerodynamics, panMARE is able to account for blade-wake interaction by modelling the structure of the vortex system in the wake of the rotor using a stabilised free wake deformation method. Using the same simulation tool for the aerodynamic and hydrodynamic domains is a unique feature of panMARE and leads to a significant simplification of the coupling process. Both flow fields are solved with the same explicit fourth-order Runge-Kutta time integration scheme simultaneously [12]. Every stage of the integration scheme is performed in both flow solvers, which allows for an update of motions in every intermediate step [13]. Figure 3 is showing the model setup of the HyStOH concept in panMARE.

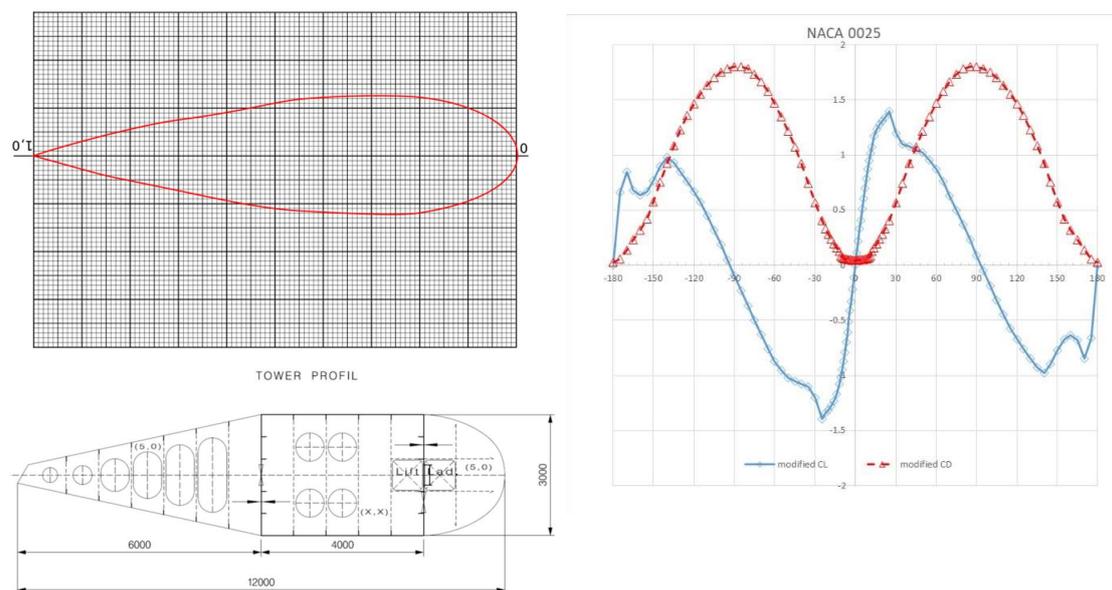
### 2.3. The HyStoH design concept

The special feature of the HyStOH design concept are the aerodynamically shaped tower and support struts. The airfoil shaped elements are horizontally symmetrical and the cord line of is aligned with the rotor axis. Wind direction misalignment with respect to the rotor axis (and thus tower cross section chord line) results in horizontal lift forces which generates a self-aligning yaw moment about the single point mooring / turret buoy. During operation, the self-alignment effect is additionally supported by the downwind rotor. During idling or standstill only the aerodynamic forces are responsible for aligning the FOWT towards the wind direction.



**Figure 5.** Single point mooring and self-aligning forces

As described above, the Bladed software calculate the structural loads of beam elements with the FEM approach. The beam elements are generally tubular and have only aerodynamic drag properties defined by an element drag coefficient. In order to generate additional lift forces which depending on the wind speed and angle of attack the Bladed feature “Nacelle cover as airfoil” is applied. The nacelle cover, in the HyStOH concept fixed to the tower, has been virtually extended downwards the tower. This extended nacelle surface area has a representative aerodynamic effective area of about 300 m<sup>2</sup> and is assigned to aerodynamic properties of the symmetric airfoil NACA0025 [14] [15]. It is conservatively assumed that the aerodynamic effective area of the HyStOH concept is located basically in the range between tower top and tower middle (position of the strut connection). Near sea level turbulence and wake effects due to the floater and strut elements are neglected.

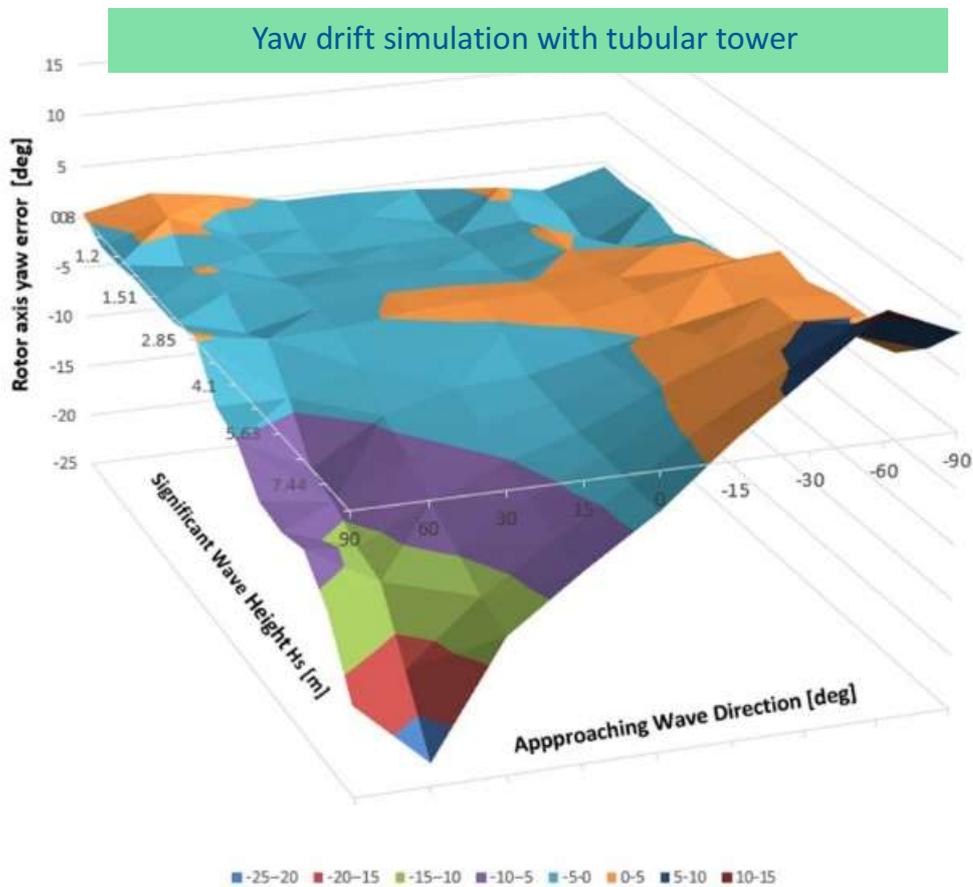


**Figure 6.** Approximation of tower cross section aerodynamical properties

### 3. Results

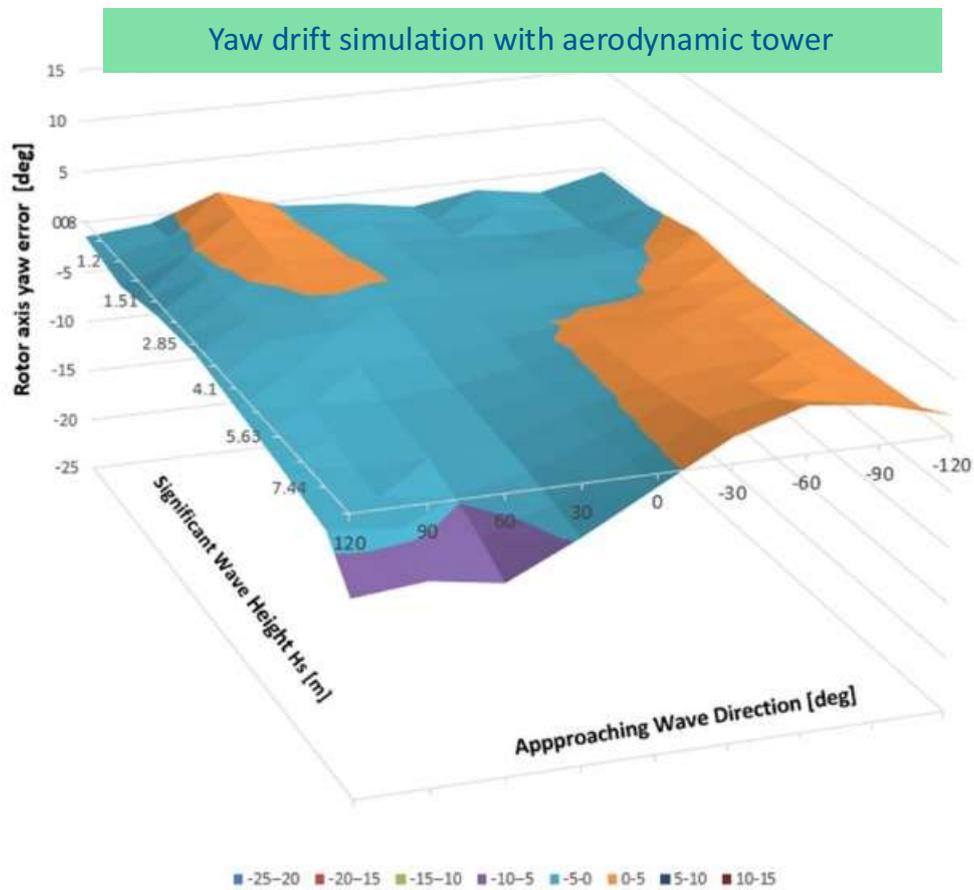
In order to demonstrate the stabilisation of the HyStOH concept against yaw drift, simulations with and without aerodynamic tower support are analysed. It could be shown that the in operational conditions the downwind rotor forces alone, without the aerodynamic support of the profiled tower, provide not sufficient restoring yaw moment. As expected, the yaw drift forces increase with increasing wind speeds and corresponding wave heights.

Typically, in wind turbine operation misalignment angles of 5 to 8 degrees between rotor axis and mean wind direction are accepted with respect to energy yield losses [16]. For rough sea states with significant wave heights  $H_s > 7$  m and wind-wave misalignments  $> 30$  degree the yaw drift and wind-rotor misalignment exceeded 20 degrees. Such high misalignment angles in combination with high wind speed operation will cause a loss in energy yield.



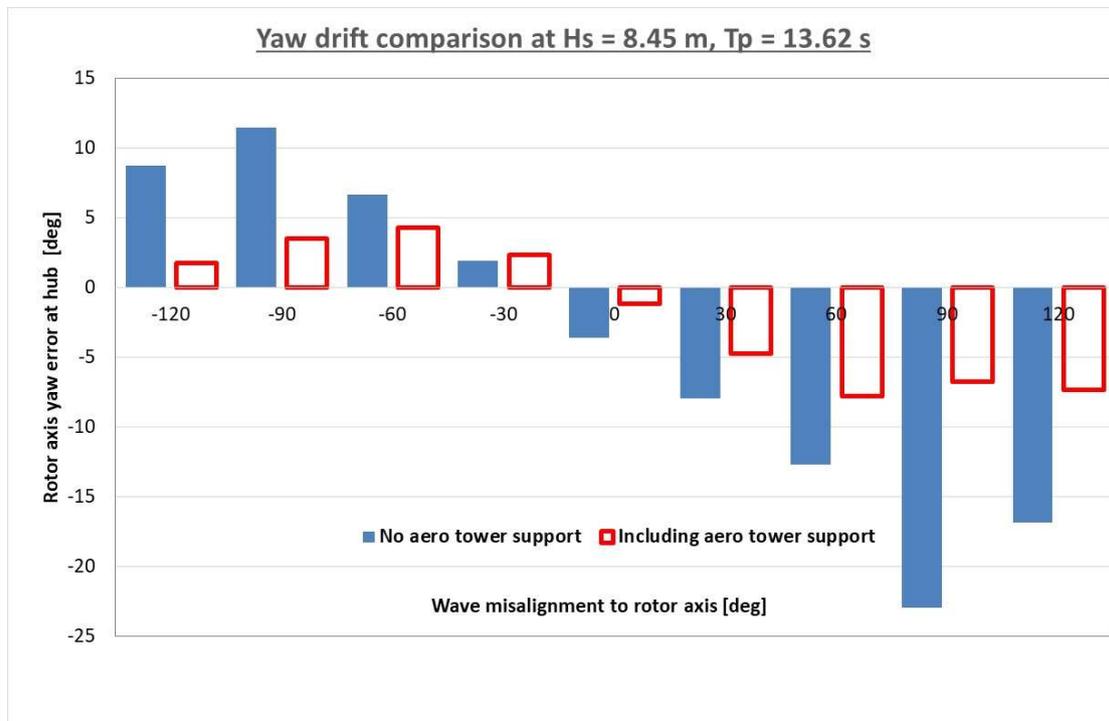
**Figure 7.** Yaw drift depending on wave height and wind-wave misalignment without wind-vane structures

The vertical plot axis “Rotor axis yaw error [deg]” indicates the misalignment angle between wind direction and rotor axis which has been established under the impact of a specific wave formation (600 seconds simulation time for each combination).



**Figure 8.** Yaw drift depending on wave height and wind-wave misalignment including wind-vane structures

For the trapezoidal HyStOH floater design especially wave and current directions from  $\pm 60$  degree with respect to rotor axis result in large yaw drift. The deviation between the drag tower and aerodynamical tower approach is clearly visible for operating wind speed  $v_{Hub} = 20$  m/s, corresponding to a wave height of  $H_s = 8.45$  m.



**Figure 9.** Comparison of yaw drift sensitivity during operation and large waves for various wind-wave misalignment

#### 4. Conclusion

The dynamic transverse and longitudinal stability as well as the yaw behaviour of the HyStOH concept, a self-aligning FOWT, are analysed with time domain simulation tool Bladed and the first-order panel method panMARE. The simulations of the motion behaviour of the FOWT are carried out for various environmental conditions with regard to wind, natural waves and current. The mooring forces are calculated using a dynamic mooring model. The results of the investigation show that a strong coupling between aerodynamics and hydrodynamic loads as well as mooring system induced forces in the simulations is essential for the evaluation of the self-aligning behaviour of the FOWT.

As it is expected, the misalignment increases at lower wind speeds due to low aerodynamic forces. A closer look at the contributions of the different components of FOWT to the aligning moment shows that the main component is delivered by the profiled tower. Especially at higher wind speeds, the tower influence becomes more important and contribute significantly to align the platform.

#### 5. Outlook

The present study considered normal operation load cases between cut-in and cut-out wind speed only (design load case group DLC 1.2 [5]). Furthermore, simplifications in application of wave and current directions have been made which do not correspond ideally to the site conditions of the HyStOH Design Basis. In this study wave and current have been directly linked and current speed was assumed to be constant. Therefore, the individual portion of current forces on the global yaw drift could not be identified. To pursue this study, further design load cases should be analysed, such as idling conditions and storm events. The modelling of sea current could be improved further (e.g. including current profiles and tides) and the portion on the overall yaw drift could be analysed in a separate sensitivity study.

Also, the impact of misaligned operating FOWT on power production and structural fatigue loading is an aspect which is worth to analyse in future studies.

Within the HyStOH project it is planned to perform scaled model tests in a wave basin in 2019. These tests will provide further information of the dynamic behaviour of the concept and of the yaw drift behaviour in particular. A comparison campaign against simulations will further improve the accuracy of the HyStOH simulation model applied herein.

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