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An hybrid approach for the comparison of VAWT and HAWT performances for floating offshore wind turbines

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Abstract. This article describes the experimental comparison of the DTU 10MW HAWT with the WindQuest 10MW VAWT scaled models when both fitted on the Nautilus-10 semi-submersible. For the campaign in Ifremer Wind&Wave tank, different rotor representations are tested from inertia only to hybrid testing with propellers and a Software in the Loop. The hybrid testing uses a tabulated approach for thrust computation and is discussed in this article. The different thrust reproduction methods are compared to OpenFAST simulations calibrated during the Lifes50+ project and used as reference points. When quantifying the scale model's fidelity to Open Fast, cross-correlation was increased up to 14% with the use of the SiL. Thanks to the validation of hydrodynamic simulations based on experimental responses of the floater, it is shown that the VAWT rotor can be upscaled to 13MW for the same platform.

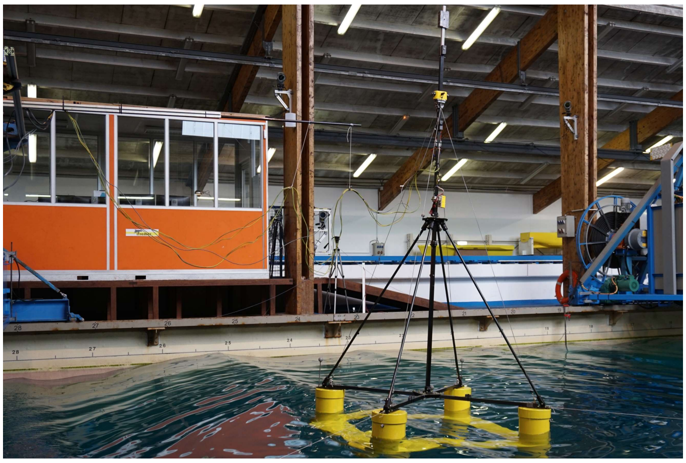

Figure 1: Scale model during the wave tank tests

1. Introduction

An increased interest is observed for Floating Offshore Wind Turbines (FOWT) as they allow for the exploitation of new areas with more energetic and less turbulent winds located in deeper waters. This urge is driven by stronger interests of renewables in the energy mix. As FOWT are still in a development phase, there is a need for a highly reliable prediction of FOWT behavior as they need tailoring for each site.

The WindQuest [1] counter-rotating vertical axis wind turbine (VAWT) was developed by HydroQuest as an alternative solution to Horizontal Axis Wind Turbines (HAWT) for FOWT. Several issues, such as the power output, the torque applied to the floater, or the lateral forces, have been addressed during the design process.

With lower Center of Thrust (CoT) and Center of Gravity (CoG), VAWT [2] experience a regain of interest for floating applications. Indeed they might allow for a stress reduction over the sub-structure, decreasing its size per MW installed, leading to lower Levelized Cost Of Energy (LCOE). However, with faster rotation speeds and lighter structures, VAWTs might trigger the sub-structure's resonance frequencies [3]. Both of these questions are addressed in this paper.

Issues raised by FOWT create the need for numerical and experimental modeling solutions. We are here investigating experimental modeling. Froude scaling used for the floater's hydrodynamics [4] is incompatible with the wind turbine's aerodynamics Reynolds scaling. Several possibilities for modeling the wind turbine can be seen in the literature[5][6]: drag discs with tuned porosity, blowing systems with low Reynolds turbine [7–9], cable actuators [10] or ducted fans and propellers [11–13].

In this article, the WindQuest10MW turbine is compared to the reference DTU10MW [14] HAWT developed for the Lifes50+ project. The Nautilus-10 [15] semi-submersible floater is used with both turbines. The sea-keeping of the two FOWT is studied experimentally at the Ifremer waves & wind tank, Brest, France (Figure 1, Figure 2 and Figure 3).

The wind turbine thrust is modeled thanks to a propeller (Figure 4). This solution, seen previously in the literature, is selected as a flexible solution to solve the Reynolds Froud scaling incompatibility [16]. A Software in the Loop (SiL) using tabulated values is implemented for thrust computation (Figure 5). This solution is employed for both VAWT and HAWT configurations. In this article, the experimental set up developed in Ifremer Wave&Wind tank is described. The different approaches simulating the rotor's action are presented, from the inertia only to the hybrid testing approach using electrical fans and a SiL. The reproduced thrust is compared to OpenFAST simulations. Finally, the behavior of the two rotor configurations VAWT and HAWT are compared and design projections are made.

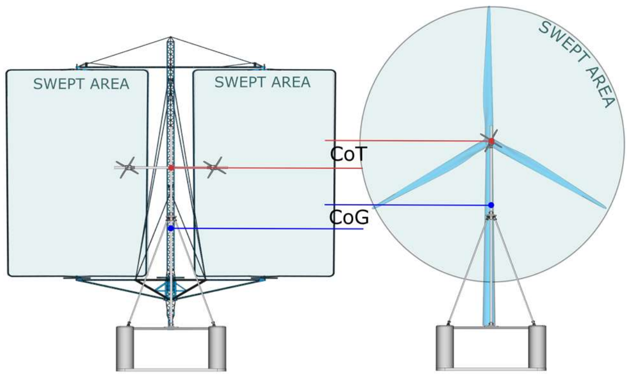

Figure 2: comparison of the WindQuest (left) scale model with the DTU (right). Two propellers were used for the WindQuest configuration to produce differential thrust if needed. The two wind turbines are installed on the same Nautilus 10 floater. Both turbines concepts are overlaid on the background for illustration

2. Experimental Setup

2.1. Scale model

Scaled model tests were carried out at the waves and wind facility IFREMER, Brest, France. The 50m long wave tank is illustrated in Figure 3. On the left, the wavemaker generates unidirectional regular or irregular waves. The scale model is positioned on the 25m marking. At this position, the water is 10m deep. The damping beach on the right reduces swell reflection.

The 1/42th Nautilus semi-submersible model is shown with full ballasts (dimensions in Table 1). Both VAWT and HAWT configurations are tested (see Figure 2). The scale was selected to conform with the wave generator capabilities and allows the use of readily available materials.

The depth of the basin 10m corresponds to a 420 m water depth full scale. The catenary mooring described in the literature is designed for 130 m (depth in the Gulf of Maine). Thus it was decided to use an equivalent mooring with added weight installed in the floater to compensate for the weight of the chains and pre-tensioned springs to reproduce mooring stiffness for small surge displacements.

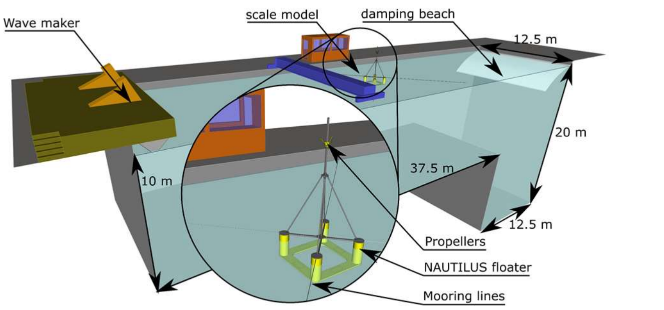

Figure 3: Representation of the Ifremer waves & wind tank with the scale model positioned for tests

Table 1: general properties of the Nautilus floater at model scale

Nautilus floater 1/42 scale		
Mass	105.01	kg
Height	0.62	m
Width	1.55	m
Columns diameter	0.25	m
Heave plate thickness	0.037	m

2.2. *Testing procedures*

Wave tanks testing for FOWT generally includes several types of tests described here: 1) decay tests in still water where each DoF is individually excited to measure its resonance frequency 2) regular waves use monochromatic waves to measure the response of the system to a specific frequency (results of those tests will not be discussed here) 3) irregular waves which reproduce representative sea states. Their wide frequency bandwidth makes them useful for spectral analysis. Sea states used during the campaign were sourced from the Lifes50+ deliverables.

Wind turbine simulations in wave tank discussed in this paper can be gathered into four categories: 1) wind steps are used in still water to measure the stationary attitude of the floater submitted to a range of wind speeds. 2) The inertia only ("no Wind" in figures) without any thrust generation. This configuration is the first one tested. 3) The "no SiL" configuration uses the generation of a constant thrust as a first approximation for the wind turbine interaction with hydrodynamics. 4) The SiL configurations use more realistic thrust computations influenced by the floater's movements.

Such tests are used here to compare the behavior or the WindQuest and the DTU FOWT configurations. In this way, both floating structures are submitted to the same tests.

Special attention is paid to comparing the experimental measurements with tests replays on OpenFAST. Those simulations were calibrated during the Lifes 50+ project at the SINTEF facilities [17]. Slight modifications are made to correct discrepancies between experimental and theoretical values. Measured surface elevation time series are used as an input for HydroDyn, the hydrodynamics module coupled with FAST.

2.3. *The software in the Loop (SiL)*

While the hydrodynamics are scaled in the wave tank, the aerodynamics is simulated thanks to an actuator. It was decided to use a fan, such as in [11,12]. The thrust is computed and applied in real-time. Drag equations [18] are used to compute thrust. The measurements from the motion capture system Qualisys are streamed in real-time to account for platform motions. Thrust setpoints are computed thanks to tabulated aerodynamic parameters extracted from simulations. The DTU's aerodynamics are sourced in [14] and the VAWT parameters were computed using [19] as a guideline. The resulting setpoint is computed in real-time, thus allowing for a feedback loop in between the aerodynamics and the hydrodynamics (illustration in Figure 5).

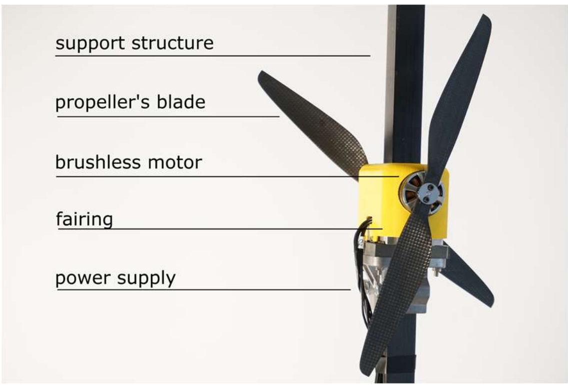

Figure 4: thrust generator used for simulation of the wind turbines during the wave tank tests.

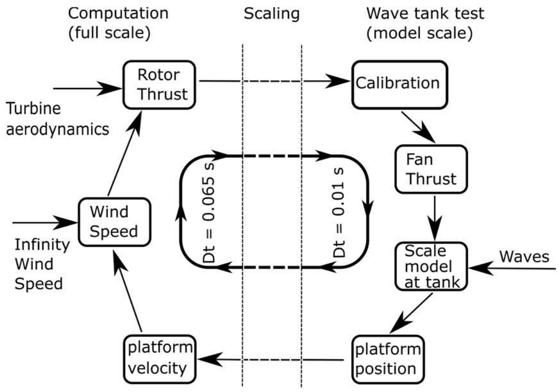

Figure 5: SiL retroaction loop with the scaled part on the right and the computations on the left.

2.4. Thrust computation hypothesizes

The hypotheses described below are used for the wind turbine's variable thrust. Gyroscopic moment and aerodynamic torque are not reproduced. Three simple wind turbine behaviors are considered.

- The first configuration: computes constant thrust using equation (1) and only considers environmental wind speed. For each condition, the mean thrust is computed and used as a setpoint. This hypothesis is chosen as a comparison point for the other representations. ρ stands for the air density, S the swept area, C_T the thrust coefficient and v_∞ the environmental wind speed.

$$T = {}^{1}/_{2}\, \rho S C_T v_\infty^2 \tag{1}$$

- The second configuration: The same model is used but for real-time thrust computing. For each time step, effective wind speed (v_{eff}) in equation (2) is computed as the sum of environmental wind speed (v_∞) and apparent wind speed (v_r). Thrust coefficient is extracted from tabulated values (see 2.2). This hypothesis simulates the thrust of a wind turbine adapting its roational speed for each time step (3) thus maintaining optimal tip speed ratio.

$$\overrightarrow{v_{eff}} = \overrightarrow{V_\infty} + \overrightarrow{V_r} \tag{2}$$

$$T = {}^{1}/_{2}\, \rho S C_T(v_{eff}(t)) v_{eff}^2(t) \tag{3}$$

- The third configuration: The wind turbine is assumed to be rotating at a constant speed defined by the environmental wind speed. It is thus needed to adapt the C_T while taking into consideration v_∞, v_r and the tip speed ratio λ.

$$\lambda = \frac{r\Omega}{V_{eff}(t)} \tag{4}$$

$$T = {}^{1}/_{2}\, \rho S C_T(\lambda(t)) v_{eff}^2 \tag{5}$$

2.5. Propellers calibration

The propellers are tested on a 6 DoF balance for thrust calibration and observation of the system's dynamic response before its use during the wave tank tests. Once the propellers are validated for constant thrust, the system's dynamic response is studied. For this operation, thrust time series are generated using OpenFAST and applied to the propellers as setpoints after scaling down. The thrust PSD is compared to the instruction in order to identify potential flaws in the actuator's response. The resulting measurements are shown in Figure 6. For this particular Design Load Cases (DLC) the FOWT is operating for maximal power production below rated wind speed in the 50 years return waves conditions.

A good representation of the rotor thrust is observed. These tests highlight the propeller's capability to reproduce the scaled wind turbine thrust. When analyzing the time series, a constant delay is observed. After measuring the different sources of delay the Electronic Speed Controllers are shown to the primary source of latency.

3. Results

From the experimental campaign, conclusions are drawn over those three points: 1) the simulation of the FOWT behavior during wave tank tests 2) the Thrust computation using tabulated values for SiL applications 3) the comparison between HAWT and VAWT configurations. Those results are discussed in this section.

3.1. Software in the Loop: scope of validity

During the Lifes 50+ project, when studying the behavior of the floaters [20], it was identified that pitch and surge motions could be dominated by wind, wave forcing or both. It would thus be coherent to observe an influence of DLCs on the motion fidelity as the thrust's impact over the floater varies.

The SiL brought an overall gain in platform motion fidelity. Those gains are quantified using cross-correlation between experimental and OpenFAST time series. Table 2 illustrates those results where a link between Pitch cross-correlation and wind or wave loading can be observed. Some DLC such as the one plotted in Figure 7 with strong wind forcing and small waves forcing show an apparent improvement. Other configurations with predominant waves forcing as the one presented in Figure 8 show smaller gains. Intermediate results are observed.

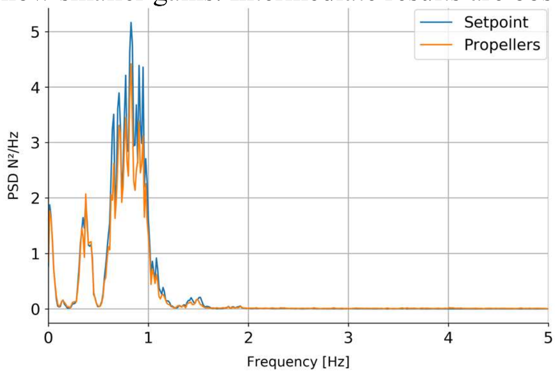

Figure 6: the PSD comparison in between the setpoint and the measured Thrust

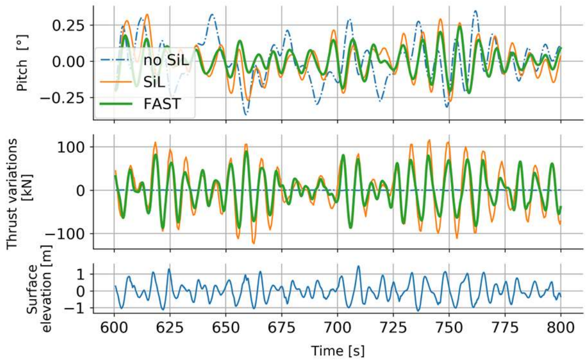

Figure 7: DTU configuration - Thrust variation and pitch variations time series Hs=2.2m Tp=8s WSPD = 10.3m/s

Figure 9 highlights the advantage of a SiL for wind-driven cases: both degraded approaches No wind and No SiL excite the floater's natural frequency when no such energy transfer is observed in OpenFAST. The SiL follows the FAST simulation trend by filtering the natural frequency and maximizing the power in the wave spectrum. Though the SiL configuration shows higher levels of energy around 0.5 – 0.7 Hz bandwidth while the no Wind and no SiL configurations show similar results when compared to OpenFAST.

Table 2: DLC wind and wave configurations with the correlation of Pitch motion compared to FAST calculations. Wind-driven DLCs in blue, intermediate DLCs in green and wave-driven DLCs in red

Waves strength	Wind Strength	Hs (m)	WSPD (m/s)	No Sil Pitch cross-corr.	SiL Pitch cross-corr.	Thrust cross-corr.
+	+	1.26	5	0.6	0.67	0.78
+	++	1.68	7.1	0.63	0.75	0.9
+	+++	2.18	10.3	0.64	0.78	0.9
++	+	7.7	5	0.75	0.81	0.79
+++	++	10.9	7	0.67	0.70	0.81

3.2. Thrust fidelity

Thrust validation is discussed in this subsection. As for the other DOFs, the thrust variations are compared using the thrust cross-correlation with OpenFAST as an indicator. With values mostly contained between 0.8 and 0.9 (Table 2), good agreement is seen between the two computations. Time series presented in Figure 7 and Figure 8 respectively illustrate the computed thrust for wind forcing and wave forcing DLC. Note that we are studying here the thrust variations as it influences the dynamic response of the floater. None the less as an offset ranging from 150 to 200 kN is observed between OpenFAST and pure aerodynamic loading such as described in [14] used for SiL computations as OpenFAST computes the mechanical load due to the rotor's mass and inertia as well as aerodynamics.

The WindQuest design being a twin counter-rotating turbine, the perpendicular forces characteristic from VAWT [19], cancels out. It is thus possible to use the same thrust generators. As a first approximation, the thrust oscillations during a blade's rotation is not reproduced as it is expected to be filtered out by the floater.

A comparison with a more sophisticated solution such as BEM [14] and OpenFAST (for HAWT) would be useful for gains quantification of such solutions. For VAWT, the use of a double multiple stream tube model or vortex methods such as CACTUS [21] could be used for enhanced thrust fidelity.

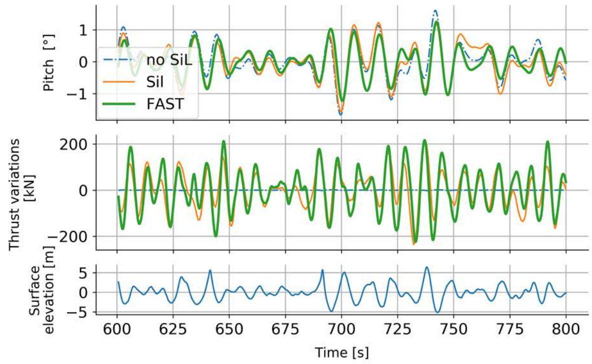

Figure 8: DTU configuration - Thrust variation and pitch variations time series Hs=7.7m Tp=12.4s WSPD = 7.1m/s

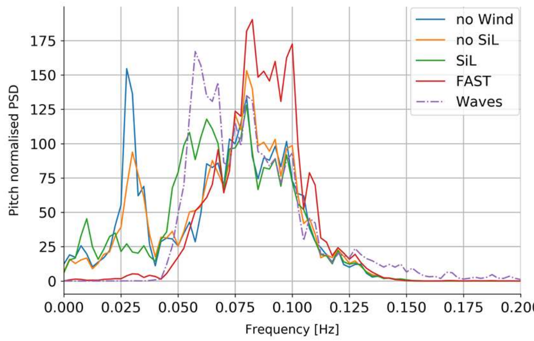

Figure 9: PSD of three experimental measurements no thrust generation (no Wind), constant thrust (no SiL) and SiL. Comparison with FAST. The normalized swell PSD is overlaid.

3.3. *Comparison of WindQuest and DTU FOWT*

3.3.1. Decay test. Surge, Heave, Pitch and Yaw resonance frequencies are measured through decay tests. Table 3 regroups the experimental proper modes periods. Values in parenthesis indicate the experiment's discrepancies with results from the diffraction/radiation software based on potential theory HydroStar [22].

HydroStar is most accurate for the measurement of Pitch periods with 3% and 4% of error. The other DoFs show errors ranging from 7% to 11%. All the results give reasonable confidence in HydroStar simulations and allow us to extrapolate the results from its computation.

Table 3: measured resonance periods for both FOWT and divergence with Hydro Star simulations

	DTU 10MW		WindQuest 10MW	
Surge (s)	114.1	(-10%)	117.0	(-7%)
Heave (s)	19.7	(-10%)	19.6	(-11%)
Pitch (s)	31.0	(3%)	23.3	(4%)
Yaw (s)	95.9	(-9%)	94.4	(-11%)

The WindQuest turbine being 34% lighter and 15% smaller it's inertia is significantly smaller. This gap between the two wind turbines proves to have a significant impact over the Pitch period. The WindQuest configuration thus has a 25% lower pitch period, bringing it closer to the waves excitation bandwidth. The three other DoFs are only slightly impacted when swapping the turbines.

3.3.2. Static step winds. VAWT presents lower CoG and CoT, thus resulting in a lower pitching moment. Several wind speeds below rated are tested and applied to both FOWT in still waters. This experiment is used to quantify the pitching torque applied by the wind turbine on the floater. The measured pitch angles are presented in Figure 10. The use of steps allows for scale model stabilization, which results in measurement uncertainties below 0.1°. The simplified moorings and ballasts lead to a static pitch higher than nominal for the DTU configuration at 11.4 m/s. None the less this experiment highlights a 53% lower torque imposed by the WindQuest to the Nautilus semi-submersible.

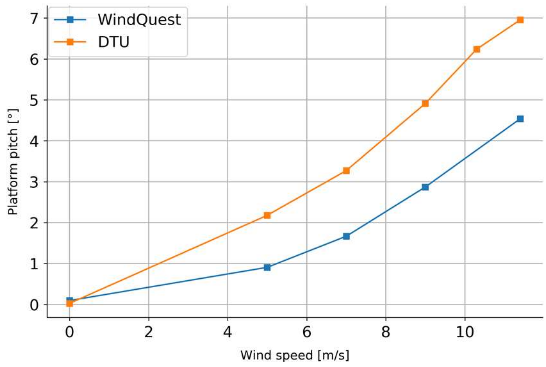

Figure 10: experimentally measured static pitch of the Nautilus platform with DTU 10MW and WindQuest 10MW wind turbines under wind steps

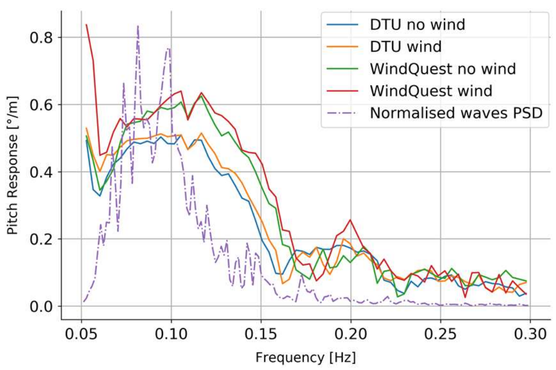

Figure 11: comparison of Pitch RAO for DTU and WindQuest configurations with and without wind. Normalized wave spectrum overlaid. Hs = 7.7m Tp=12.4s WSPD = 7.1m/s

3.3.3. Irregular waves. WindQuest configurations show higher pitch response to wave solicitations. This response is illustrated in Figure 11, where the WindQuest Pitch RAO is sensitively higher than the DTU's. When considering the platform's Surge and Heave RAO (Figure 12 and Figure 13), the experimental measurements show little to no impact of the wind turbine over the platform's response to the swell. The variation in pitch response is due to the lower mass and inertia of the VAWT compared to the design values used for the Nautilus sizing. The other DoFs are mostly influenced by floater geometry and moorings. It is thus coherent not to see significant variations.

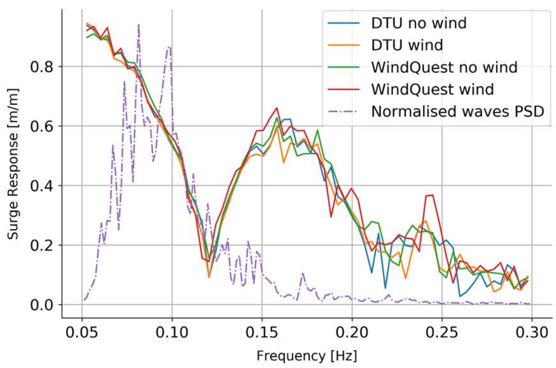

Figure 12: Surge RAO for with DTU and WindQuest configurations with and without wind. Normalized wave spectrum overlaid. Hs = 7.7m Tp=12.4s WSPD = 7.1m/s

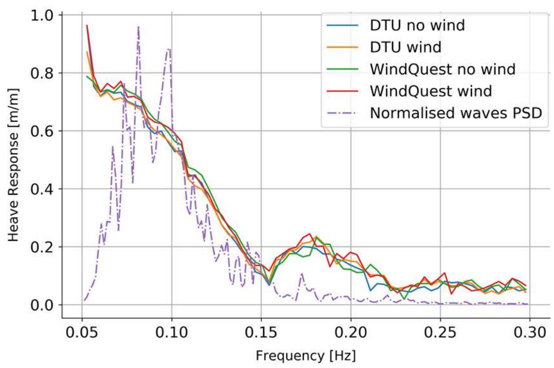

Figure 13: Heave RAO for with DTU and WindQuest configurations with and without wind. Normalized wave spectrum overlaid. Hs = 7.7m Tp=12.4s WSPD = 7.1m/s

4. Upscale to 13MW

Results in section 3 suggest that the WindQuest turbine should match the weight and CoG of the DTU tweaked for the Nautilus to regain behavior closer to design values. This statement agrees with previous works such as [3], who showed that lighter VAWT could have side effects.

4.1. Sketching a concept of WindQuest 13MW

To answer this statement and make use of the lower mass and CoG of the VAWT, a bigger, more power-full WindQuest turbine design is created. It was designed to restore the static pitch torque applied by the DTU 10MW of the Nautilus, as shown in the equation (6).

$$M_{DTU\ 10MW} = M_{WQ\ XMW} \tag{6}$$

It is estimated that a 13MW (illustration in Figure 14) would result in a similar pitching moment on the floater. A simplified beam model is used to sketch such a turbine. By assuming geometrical properties of the turbine, materials properties and airfoils' aerodynamic performances, the centrifuge and aerodynamic constraints in the blades are computed. This process allows for scaling blade skin thickness and tower properties, thus evaluating the weight and inertia of the turbine.

4.2. RAO study with HydroStar

The mass and inertia properties computed for a WindQuest 13MW turbine are then used as input for the HydroStar simulation that was calibrated before (see 3.3.1.). This solution allows for the computation of the Nautilus-10's RAO with each of the three configurations: WindQuest 10 MW, WindQuest 13MW and DTU 10MW. Figure 15 illustrates the results obtained through this process.

One can note that the WindQuest design shows higher optimal TSR and operates 1 to 3 RPM higher than usual VAWT designs, such as those presented in [23,24]. This design choice takes into consideration technical and economic considerations [1]. But this higher TSR results in the WindQuest 10MW configuration response partially overlapping the wave spectrum and the 1P bandwidth. However, the WindQuest 13MW configuration shows a peak frequency shifted to the left of the spectrum, thus making it less prone to be excited by waves and 1P frequencies.

By increasing the size of the WindQuest wind turbine from 10MW to 13MW, the floater could regain better stability. Moreover, the excitation from the 1P and 2P frequencies generated by the rotor would have less impact over the sub-structure. This observation illustrates the strong influence of the VAWT design on the floater's response, thus correlating with the concussions from [24].

4.3. Impact over LCOE

The WindQuest turbine was introduced as a solution for decreasing the Levelized Cost of Energy. Studies such as [25] state that turbines, substructure and mooring manufacturing costs play a significant role in the computation of the LCOE. The low TRL of the WindQuest turbine makes it challenging to estimate the impact of the wind turbine over the LCOE. However, it is still possible to roughly estimate the impact that a smaller sub-structure fitted with a 10MW turbine. The resulting LCOE can then be estimated.

With a measured 53% lower pitch torque, the floater's righting moment can be equally lower. Following Froude scaling this dimension is related to the floater size by the power four. The resulting semi-submersible would then be 85% of its original size. If the cost is proportional to the structure's volume, then the resulting floater would be 72% its initial price. If the results presented in [25] for the Golf de Fos are linearly extrapolated, then fitting a WindQuest turbine would result in a 7% decrease of the LCOE via lower sub-structure costs.

VAWT machines can be packed closer in a wind farm configuration, thanks to the lower wake effects [1]. As the cost of the inter-array cables represents a non-negligible part of the LCEO, a second expense item could be cut down.

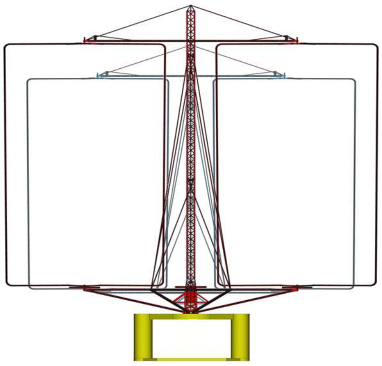

Figure 14: Illustration of the WindQuest 13MW turbine setup on the Nautilus-10 semi-submersible. WindQuest 10MW is overlaid for scaling.

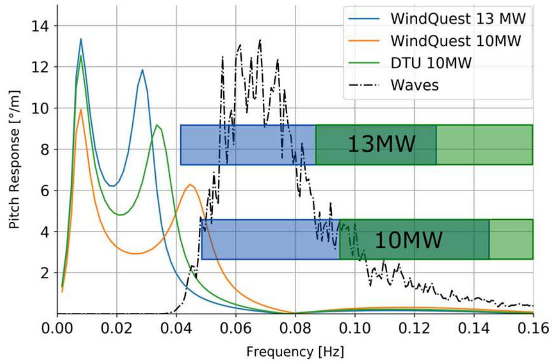

Figure 15: HydroStar computed Pitch RAO of the Nautilus-10 with the three turbines installed. PSD of extreme sea state (JONSAWAP Hs=10.9m Tp=16) is overlaid. 1P bandwidth in blue 2P in green.

5. Conclusions

This paper describes the comparison of WindQuest 10MW and DTU 10MW floating offshore wind turbines on the Nautilus-10 semi-submersible during an experimental campaign at the Ifremer wind & wave tank, Brest, France. Hybrid testing based on electrical propellers coupled to a Software in the Loop was used in order to reproduce the thrust generated by the wind turbines.

Several approaches for rotor simulation are compared from inertia only, constant thrust and tabulated SiL approach based on apparent wind speed. The SiL approach shows good fitting OpenFAST simulation with cross-correlation ranging from 0.8 to 0.9. Platform motions cross-correlation gains ranging from 0.03 up to 0.14 are observed when upgrading from the constant thrust to the tabulated approach. Gains from the SiL approaches depend on the nature of wave and wind forcing. DLCs with prevailing wind forcing show a more substantial SiL impact over the platform motions. Future work will implement models such as OpenFAST for HAWT. The authors plan on reproducing the thrust oscillation characteristic from VAWTS and integrate double multiple streams or vortex methods.

The experimental comparison of WindQuest turbine with DTU (both positioned on the Nautilus-10 floater) shows expected results. The 53% lower capsizing torque for the VAWT leads to the projection of a 30% more powerful turbine on the same floater, consequently enhancing the LCOE. The 13MW VAWT concept restores the design natural frequencies of the Nautilus10 floater. Such a system is less prone to be excited by waves or 1P and 2P frequencies generated by the rotor.

The project being at a low TRL, it is hard to evaluate precisely the impact of such a turbine over the LCOE. However, the impact of a smaller semi-submersible on the LOEO can be estimated. The resulting CAPEX could allow for a 7% lower LCOE.

An experimental campaign at the ISAE-ENSMA Poitiers' wind tunnel will be conducted to measure the impact of platform motions on aerodynamic performances of the WindQuest turbine. These Results will eventually be integrated into the SiL for future wave tank. VAWT's thrust oscillations will be investigated.

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References

[1] Achard J L, Maurice G, Balarac G and Barre S 2018 Floating Vertical Axis Wind Turbine - OWLWIND Project *Proc. 8th Int. Conf. Energy Environ. Energy Saved Today is Asset Futur. CIEM 2017* 216–20
[2] Sandia National Laboratories 2012 Offshore use of vertical-axis wind turbines gets closer look
[3] Borg M and Collu M 2015 A comparison between the dynamics of horizontal and vertical axis offshore floating wind turbines *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **373**

[4] Heller V 2012 Model-Prototype Similarity *4th Coastlab Teach. Sch. Wave Tidal Energy* 17–20
[5] MÜLLER K, Sangener F, Bredmose H, Azcona J, Manjock A and Pereira R 2014 Improved tank test procedures for scaled floating offshore wind turbines
[6] Stewart G and Muskulus M 2016 A Review and Comparison of Floating Offshore Wind Turbine Model Experiments *Energy Procedia* **94** 227–31
[7] Statement P R 2017 INNWIND . EU D4 . 2 . 4 : Results of wave tank tests Description of Floating Wind Model Tests at ECN and DHI Document information **308974** 1–114
[8] Robertson A N, Jonkman J M, Goupee A J, Coulling A J, Prowell I, Browning J, Masciola M D and Molta P 2013 Summary of conclusions and recommendations drawn from the deepcwind scaled floating offshore wind system test campaign *Proc. Int. Conf. Offshore Mech. Arct. Eng. - OMAE* **8**
[9] Gueydon S 2016 Aerodynamic Damping on a Semisubmersible Floating Foundation for Wind Turbines *Energy Procedia* **94** 367–78
[10] Chabaud V, Eliassen L, Thys M and Sauder T 2018 Multiple-degree-of-freedom actuation of rotor loads in model testing of floating wind turbines using cable-driven parallel robots *J. Phys. Conf. Ser.* **1104**
[11] Azcona J, Bouchotrouch F, González M, Garciandía J, Munduate X, Kelberlau F and Nygaard T A 2014 Aerodynamic thrust modelling in wave tank tests of offshore floating wind turbines using a ducted fan *J. Phys. Conf. Ser.* **524**
[12] Oguz E, Clelland D, Day A H, Incecik A, López J A, Sánchez G and Almeria G G 2018 Experimental and numerical analysis of a TLP floating offshore wind turbine *Ocean Eng.* **147** 591–605
[13] Desmond C J, Hinrichs J C and Murphy J 2019 Uncertainty in the Physical Testing of Floating Wind Energy Platforms' Accuracy versus Precision *Energies* **12** 1–14
[14] Bak C, Zahle F, Bitsche R, Yde A, Henriksen L C, Natarajan A and Hansen M H 2013 Description of the DTU 10 MW Reference Wind Turbine 1–138
[15] W. Yu, K. Müller and F L 2018 D4.2 Public Definition of the Two LIFES50+ 10MW Floater Concepts 1–105
[16] Thys M, Fontanella A, Taruffi F, Manjock A and Belloli M 2019 D7.9 Guidance and Recommended Methods for Hy- brid/HIL-based FOWT Experimental Testing 1–35
[17] Lemmer F, Müller K, Pegalajar-Jurado A, Borg M and Bredmose H 2016 *D4.6 Model validation against experiments and map of model accuracy across load cases*
[18] Kukunk E 2008 Aerodynamics of wind turbines *London Sterl.*
[19] Battisti L, Brighenti A, Benini E and Castelli M R 2016 Analysis of Different Blade Architectures on small VAWT Performance *J. Phys. Conf. Ser.* **753**
[20] Pegalajar-Jurado A, Madsen F J, Borg M and Bredmose H 2018 D4.5 State-of-the-art models for the two LIFES50+ 10MW floater concepts 1–42
[21] Murray J C and Barone M 2018 CACTUS User' s Manual 1–24
[22] Chen X 2004 Hydrodynamics in offshore and naval applications - part I *6th Int. Conf. Hydrodyn.* 1–28
[23] Owens B C and Griffith D T 2014 Aeroelastic stability investigations for large-scale vertical axis wind turbines *J. Phys. Conf. Ser.* **524**
[24] Griffith D T, Paquette J, Barone M, Goupee A J, Fowler M J, Bull D and Owens B 2016 A study of rotor and platform design trade-offs for large-scale floating vertical axis wind turbines *J. Phys. Conf. Ser.* **753**
[25] Lerch M, De-Prada-Gil M, Molins C and Benveniste G 2018 Sensitivity analysis on the levelized cost of energy for floating offshore wind farms *Sustain. Energy Technol. Assessments* **30** 77–90