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Since April 1st ECN and TNO have joined forces.

Contents

Acknowledgement

This project received support from TKI-WoZ.

The following main project team members are acknowledged for their contribution to the project: Carlos Simao Ferreira and Bruce LeBlanc of TUDelft, Koert Lindenburg of WMC, Sebastien Gueydon and William Otto of MARIN, Fons Huijs, Ebert Vlasveld and Mael Gormand of GustoMSC, Benoit Paillard of EOLFI, Marco Caboni, Stoyan Kanev, Gabriele Bedon and Johan Peeringa of ECN.

1 Project overview

1.1 Project data

- Project number: TEWZ115016
- Project name: Semi-Submersible Support Structure for Vertical Axis Wind Turbines (S4VAWT)
- Project consortium: ECN (coordinator), TU Delft, WMC, MARIN, GustoMSC, EOLFI
- Project period: 2015/09/01 - 2018/02/28

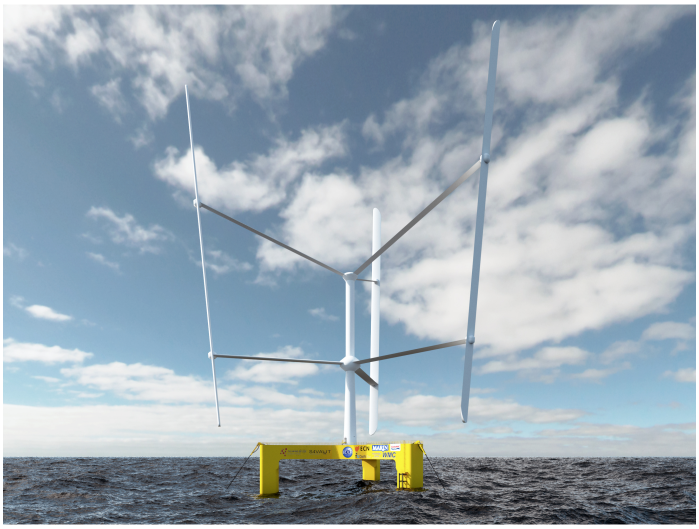

Figure 1.1: Artist impression of the S4VAWT Tri-Floater

1.2 Project consortium

Table 1.1: S4VAWT consortium

logo	name	description	contribution
	ECN	R&D institute	Research on integrated design approach (aerodynamics, control) and numerical simulation of floating vertical axis wind turbines and project management
	TUDelft	University	Research on aerodynamics of floating vertical axis wind turbines and blade design
	WMC	R&D foundation	Development of a documented code for structural dynamic response of vertical axis wind turbines. This is done by implementation of different modules for floating VAWT wind turbines in an integral dynamic simulation program.
	MARIN	R&D institute	Research on numerical simulation and experimental validation of floating vertical axis wind turbines
	GustoMSC	Offshore developer	Design of cost-effective floater and mooring system for floating vertical axis wind turbines
	EOLFI	Wind farm developer	Development of wind farm existing of floating vertical axis wind turbines

1.3 Project summary

This TKI-WoZ R&D project with partners GustoMSC, EOLFI, TU Delft, WMC, MARIN and ECN, investigated the optimization of a floating support structure for a Vertical Axis Wind Turbine (VAWT). Due to their low center of gravity and ability to handle vertical inclination, VAWTs have potential for floating application. Supported by the prediction and mitigation of the design driving load cases, the optimized design developed in this project confirmed this potential.

Besides the above mentioned benefits, upscaling of a VAWT is not driven by gravity forces (as for HAWT) and the VAWT does not require a yaw system. However, there are also challenges to be faced, for which the consortium initiated the project S4VAWT: Semi-Submersible Support Structure for Vertical Axis Wind Turbine. The project focused on the following main activities:

1. aerodynamic and structural modelling of the VAWT to generate the expected loads acting on the floating support
2. design of the rotor and controller for a floating VAWT with blade pitch
3. optimization of the floating support structure for VAWT
4. requirements for a wave basin model test campaign

A semi-submersible Tri-Floater has been designed to support a 6 MW vertical axis wind turbine with active blade pitch control. Due to the low centre of gravity and large allowable floater tilt angle, a relatively small floater can be used to support a VAWT. Coupled simulations including hydrodynamics, mooring system, aerodynamics and control system have been performed to analyse the strongly coupled dynamics of floater and wind turbine. Software tools have been developed or were upgraded to enable these simulations. Based on typical extreme operational and survival design load cases, it is illustrated that the active blade pitch control system can be successfully used to minimize the governing loads on the floater. Whereas for a VAWT with fixed blades, the parked survival conditions are typically design driving for the floating support structure, this is not the case when blade pitch control is applied. It is concluded that, compared to a horizontal axis wind turbine (HAWT) with the same rated power, a 20% lighter floater can be used as support structure for the VAWT with active blade pitch control.

2 Project technical achievements

2.1 Introduction

Offshore wind power in North-West Europe is mainly bottom-mounted offshore wind power. Large areas in the world will have to rely on floating offshore wind power because water depths are significantly larger at locations near load centres with sufficient wind . The growing size of wind turbines leads to the observation that vertical axis wind turbines are becoming more and more attractive as cost-effective competitors to horizontal axis wind turbines. Analyses show that above 15MW vertical axis wind turbines (VAWTs) have significant advantages. For floating wind power, the lower centre of gravity of vertical axis turbines (because the generator is at the bottom) leads to significantly lower mass of the floating support structure. Floating offshore wind is primarily an export product and Dutch companies are aiming for a dominant position in this market.

In 2015, an international consortium initiated the design of a large offshore wind farm using floating vertical axis wind turbines. The ALBATROSS initiative aimed at validating a ground-breaking technology for floating wind turbines specifically designed for far offshore conditions and setting a new industry standard by introducing the concept of a large scale floating VAWT with pitched blades mounted on a semi-submersible floater. The concept combines a vertical axis rotor (Spinfloat) developed by EOLFI in France and a semi-submersible floater (Tri-Floater) developed by GustoMSC in the Netherlands.

A Dutch consortium, consisting of GustoMSC, EOLFI, TU Delft, WMC, MARIN and ECN, decided to support this effort and initiated the TKI-WoZ project S4VAWT.

2.2 Objectives

The Dutch consortium has taken the initiative to develop the semi-submersible floater for the vertical axis wind turbine and is supported by the French company EOLFI. The specific objective of the S4VAWT project is to design a competitive semi-submersible support structure for a large vertical axis wind turbine and to develop the required design tools.

The concept design of the floater and its mooring system, the definition of optimum size and shape, and the estimation of the weight and costs will allow to take full advantage of the lower need for stability required by a vertical axis rotor versus conventional horizontal axis rotors. As a result, this semi-submersible floater with vertical axis wind turbine will be a competitive concept for floating offshore wind power.

In order to reach a safe, reliable and cost-effective floating substructure and mooring system, the performance of the design in combined wind and waves will be verified by state-of-the-art numerical simulations. This activity will include:

- Application of an integrated design approach towards VAWTs, using coupled existing hydrodynamics/mooring design tool to perform coupled time domain simulations of a floating VAWT, enabling verification of the complete dynamic system;
- Identification of the most relevant load cases and the loads that will have to be supported by the complete structure comprising the floating support structure, mooring system and wind turbine;

2.3 Approach and results

This section describes the technical progress in the different work packages. In a nutshell, the approach has been as follows. First an aerodynamic model for the vertical axis rotor has been developed and implemented in the ECN AeroModule using a method sufficiently fast for design calculations. In parallel, the existing program Phatas in the FOCUS6 wind turbine design package of WMC has been modified to allow for vertically orientated blades. The wind turbine code had been coupled to the hydrodynamic software packages Ansys AQWA and aNySIM before and this coupling has now been updated to deal with VAWT. The developed coupled tools have been used to optimize and verify the GustoMSC Tri-Floater and its mooring system for supporting a VAWT. During several design iterations, the floater dimensions have been optimized in order to achieve the most cost-effective design. A dedicated family of airfoils has been designed by Delft University of Technology, combining high aerodynamic and structural performance. ECN control system technology for floating wind turbines has been further developed for use on floating VAWT. Initial design loops have been performed using uncoupled and simplified analyses, followed by final integrated design loops with fully coupled simulations. Preparing already for future work, MARIN has defined requirements and a proposed setup for wave basin model testing of the floating VAWT.

This shows that a strong link exists between the different work packages, each builing on results from others. Figure 2.1 shows the general outline and connection of the different WPs.

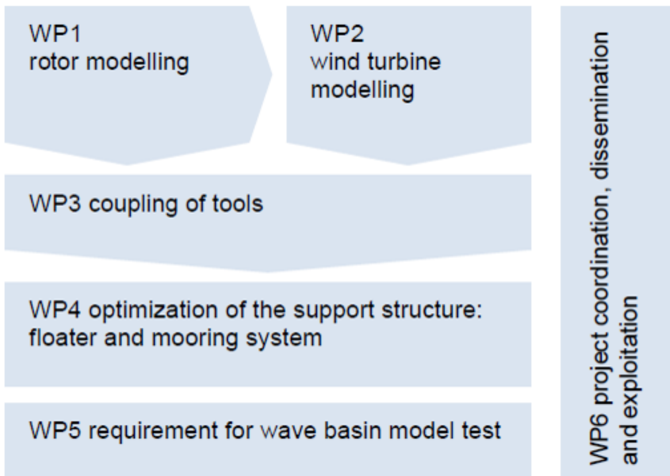

Figure 2.1: General outline of the project and connection between the work packages

2.3.1 *WP1 rotor modelling*

The first workpackage contains the following tasks that support development of a VAWT rotor suitable for floating application:

- Aerodynamic modelling (see T1.1)
- Improved airfoil design (see T1.2)
- Control design for VAWT (see T1.3)

2.3.1.1 *T1.1 Aerodynamic modelling*

ECN Aero-Module is a software package containing state-of-the-art aerodynamic models originally developed for horizontal axis wind turbines (HAWTs). Two aerodynamic methods are currently available for the Aero-Module's users. A method based on the classical blade element momentum (BEM) theory, and a method based on the free vortex wake model coupled to the lifting line model, named Aerodynamic Wind turbine Simulation Module (AWSM). Being based on more physically realistic models, AWSM is more flexible and accurate than BEM, allowing one to achieve improved aerodynamic simulations of wind turbine rotors. Clearly the more accurate simulations achieved by AWSM come at the cost of longer simulation times.
The work reported in [1] has aimed at extending the original capability of Aero-Module by simulating vertical axis wind turbines (VAWTs). A novel coordinate system for VAWTs has been developed and implemented. The implementation has been verified against the simulations performed by means of two other simulation codes for VAWTs. In this project, only the AWSM model has been made available for VAWT simulations, nonetheless the current Aero-Module's architecture will allow ECN researchers to easily couple a BEM code for VAWTs as well.
The results of the verification test reported below have shown a good agreement between the simulations performed by means of the newly developed Aero-Module for VAWTs and those obtained by the reference simulation codes (see figure 2.2). It is also shown that the large inherent CPU time associated with AWSM calculations can be considerably reduced, with minor accuracy penalties, by appropriately setting up the code inputs. This makes Aero-Module a valuable analysis and design tool for both HAWT and VAWT, by which advanced aerodynamic simulations of unconventional blade shape are possible, allowing engineers to explore larger design space at affordable computational expense.

In addition to the work on the AeroModule, the prescribed wake model PW2DiVa has been developed at TUDelft based on their panel method (U2DiVa). Comparison against free wake results shows good agreement, except for heavily loaded rotors. This model could be used as an alternative if calculation speed is most important.

During the project, an opportunity emerged to add an experimental campaign for validation of the aerodynamic modelling to the scope of work. A model scale test setup has been created for a measurement campaign in the Open Jet Facility of the TUD. Figure 2.3 show the wind tunnel setup. In [2], LeBlanc and Ferreira show that the measurement setup is capable of capturing the VAWT aerodynamics under variable active pitch operation. The testbed has a modular setup and will be used for future campaigns looking at specific details of the VAWT (such as fairings and wake).

2.3.1.2 *T1.2 Improved airfoil design*

The floater mass is driven by the rotor mass, aerodynamic loading and its requirements in terms of maximum allowable tilt. A key process to reduce floater mass is to reduce the rotor mass and to reduce the maximum unsteady aerodynamic loading on the rotor. This requires blade design that allows for high aerodynamic performance

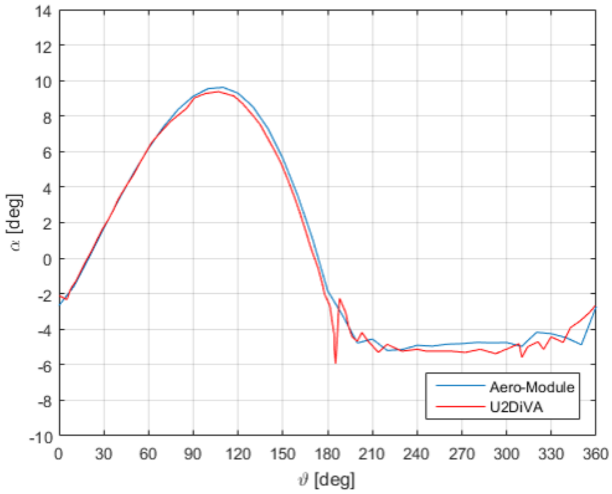

Figure 2.2: Comparison of the angle of attack alpha over a rotation between U2DiVa and AeroModule

Figure 2.3: The scaled model for the wind tunnel measurement campaign

and low mass, taking advantage of the load control allowed by the blade pitch system. In this task, a dedicated family of airfoils has been designed, optimised for power performance, load control and structural performance. As starting point, a large database of existing airfoils have been analysed and compared for power and strucural performance. The best performing airfoils then have been fed to an optimization routine to increase the power output for the specific S4VAWT rotor topology.

The airfoil family for the rotor has been designed based upon the work of Ferreira and Geurts. A multi-objective genetic algorithm has been used to maximize both the aerodynamic and structural properties of the airfoils. An initial airfoil population has been chosen which exhibits a wide range of airfoil qualities such as thickness or camber. Each of these airfoils has then been evaluated based upon two criteria: the aerodynamic performance, in this case the slope of the CL - α curve divided by the average

drag of the airfoil during operation; and the structural performance, here, the area moment of inertia of the airfoil assuming a thin wall structure. The aerodynamic performance has been calculated in both clean and soiled conditions, a weighted average has then been applied to the airfoils that penalizes large differences in performance between clean and soiled conditions. This in effect penalizes airfoils which are highly sensitive to roughness.
The dual-objective optimisation generated a Pareto front of airfoils, trading aerodynamic and structural performance. This Pareto front set of airfoils then went through a series of calculations to determine overall turbine performance and loading. The airfoil shape which proved to provide the most consistent level of performance both aerodynamically and structurally has been incorporated into the VAWT design and has been used to determine rotor loads in the coupled simulations. The resulting airfoil has a 24% relative thickness and a 1% camber toward the exterior of the rotor and is shown in figure 2.4. The performance of this airfoil with active blade pitching is verified using the numerical simulations in WP4.

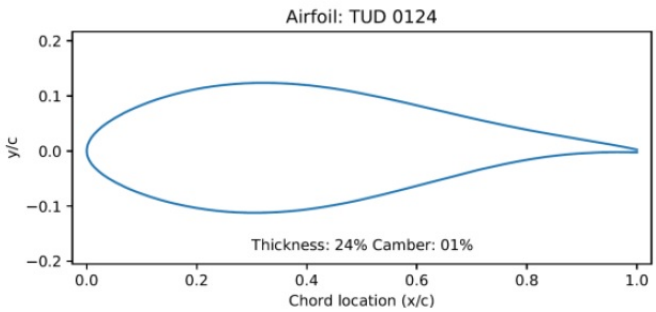

Figure 2.4: Dedicated airfoil created in S4VAWT to balance the aerodynamic performance and loading of the wind turbine blades

2.3.1.3 *T1.3 Control design for VAWT*

The VAWT concept with active blade pitch control is very promising, as it can

1. increase power capture in partial load,
2. allow rotor speed regulation and load reduction in full load and
3. alleviate loads in parked conditions.

However, the floating vertical axis system requires a dedicated controller to exploit all benefits of this feature. In this task, ECN combined its knowledge and experience from previous studies on wind turbine and floating wind turbine control, and used that knowledge to develop a dedicated controller for the VAWT mounted on the Tri-Floater that reduces the floater motions and wind turbine loads at the natural frequency of roll and pitch, while keeping the power output constant at its maximum level.

To make sure the project builds on previous work, a thorough literature survey on control for vertical axis machines has been performed. This review is reported in the internship report by Kumar [3], supplemented by chapter one of [4]. This review shows that much work has been done already on the search for pitch trajectories that optimize power performance in partial load. However, no previous work has been found on the rotor speed regulation using blade pitch angle in full load for VAWT.

The report [4] considers the design of baseline pitch control algorithms for VAWT, including partial load full load and parked operation. The blade pitch angle is used differently for the three region. First, the pitch trajectory in partial load is optimized to maximize the energy production during one revolution of the rotor. Besides using pitch control for improving the aerodynamic performance at below-rated wind conditions, pitch can also be used to control the rotor speed at above-rated wind conditions. To the best of the authors' knowledge, there are as of present no publications focused on the topic of pitch-based rotor speed control. The report contains a detailed approach for designing pitch-based rotor speed control algorithm for VAWT. It is based on a strategy that results in aerodynamic coefficients (C_p and C_t with a form very similar to that of HAWT. This allows the direct application of well studied and widely accepted methods for rotor speed control for HAWT. Finally, active control of the blade pitch angle can be used to alleviate the loads in parked (storm) conditions.

In partial load the apparent wind velocity and the inflow angle at which it acts on the blade are shown to vary significantly over the revolution of the rotor. To maximize the power production, an optimal pitch angle trajectory is designed that optimizes the aerodynamic torque on the rotor at each azimuthal position of the blade. The pitch trajectory is designed to account for wake effects on the production at the downstream part of the rotor by operating at a slightly higher pitch angle upstream. Other than in earlier studies, the optimal pitch trajectory is not restricted to any particular form, such as sinusoidal, and is based on an optimized pitch angle - inflow angle relationship that only depends on the blade aerodynamic properties, but is further independent on the operational variables. The final pitch angle trajectory as function of the azimuth position (see figure 2.5) is constructed using an iterative procedure involving aerodynamic simulations to determine the inflow angle at each azimuthal position.

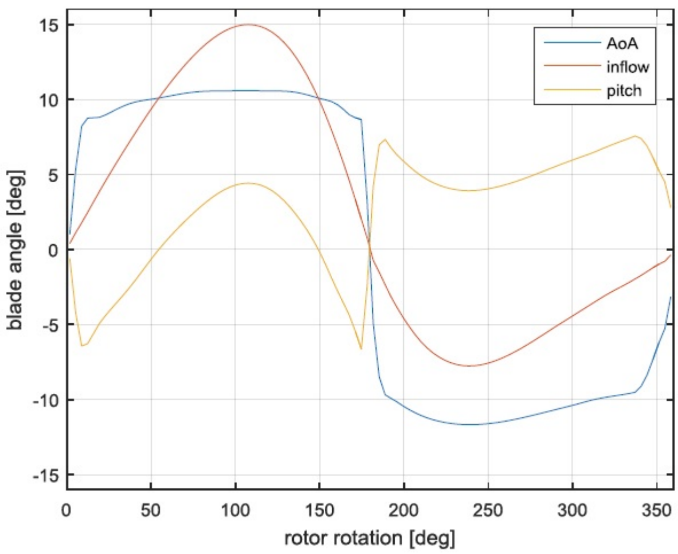

Figure 2.5: Blade pitch angle trajectory for a full rotation that optimized power capture below rated

In full load, a pitch angle offset is added to the baseline partial load pitch trajectory to control the rotor speed at its rated value. The pitch offset is implemented into the optimal pitch-inflow relationship, from which the actual offset-based pitch trajectory is calculated. It is shown that by calculating a predefined operating inflow angle trajectory and using it to construct the pitch trajectory for a given tip speed ratio and pitch angle offset results in aerodynamic coefficients that resemble these for HAWT. This allows the use of widely accepted pitch control algorithms for HAWT in the VAWT case.

Initial investigation of the coupled response in WP4 indicated that wind turbine loads during parked (storm) conditions could be design driving for the floating support. To alleviate these loads, an active blade pitch strategy has been developed that operates during parked storm conditions. This ensures that the blade pitch angle is oriented such that the blade loads are minimal (using a feedback control loop from blade load to blade pitch angle). Results from the coupled simulations in WP4 ([5]) show that it effectively mitigated the design driving loads for those cases.

In addition, the MSc student Vimanyu Kumar (supervised by ECN and TUDelft) further explored an advanced control method for reduction of the cyclic loads experience by the blades of a VAWT. The literature review [3] identifies repetetive control as a promising method for load reduction on a VAWT system. The thesis [6] on repetetive control of VAWT further investigates this method combined with system identification in the lifted domain. The obtained model is large and has been reduced using a carefully selected set of basis functions. As there is a strong relation between cyclic loads and power for a VAWT, the cost function has been determined using tracking control. This allows to minimize loads, while power is maintained at the specified reference. Figure 2.6 shows the blade load reduction that was obtained using this method.

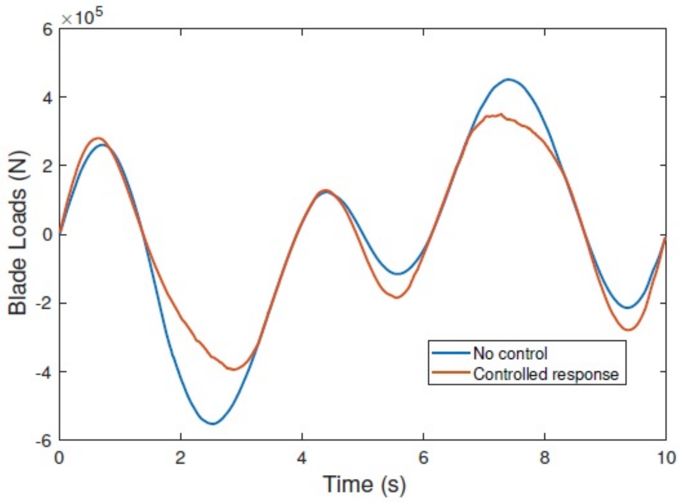

Figure 2.6: Blade load reduction (presented for a single rotation) with repetetive control for VAWT

2.3.2 *WP2 wind turbine modelling*

The Wind Turbine module (WTmodule) was initially developed at ECN in 2011 from the existing program 'Phatas' for Horizontal Axis wind Turbines. For the design of the floating wind turbine in the TKI-WoZ project S4VAWT the program Phatas (and the Wind Turbine module) had to be modified to enable the description of a vertical axis rotor geometry, VAWT. The report [7] describes these modifications and the VAWT specific interactions with regard to wind description and the rotor aerodynamics.

The Wind Turbine module WTmodule is provided as dynamically linked library; wtmodule.dll. A detailed description of wtmodule is given in [8]. By providing a specific intermediate library, wtmodule can be called by the MARIN program aNySIM or by the program Ansys AQWA. For the latter application GustoMSC has developed an intermediate library 'user_force.dll'. The program aNySIM (v10) has been re-structured by MARIN to aNySIM XMF (v12), which is the development platform at MARIN since 2016. The program aNySIM XMF has an interface for the wind turbine module that uses an additional variable for the rotational momentum in the turbine (in fact the rotational momentum of the rotor). For testing WTmodule a calling program XMF-shake was developed with which the user can calculate the turbine response for a time series of imposed base motions. Within S4VAWT a floating vertical axis wind turbine (VAWT) is developed. The design loads are calculated with a combination of dynamic simulation tools for:

- Motion of the floating support, using aNySIM XMF (MARIN) or Ansys AQWA
- Wind turbine dynamic response, using WTmodule (a modular version of Phatas)
- Aerodynamics of the rotor, using ECN-Aeromodule (vortex wake description)
- Cyclic individual pitch control, using a dedicated controller

Figure 2.7 shows the connection of the different building blocks in the complete tool chain. The design of the floating VAWT turbine in the S4VAWT project is performed with the VAWT-specific version of WTmodule, named VATmodAERO.dll.

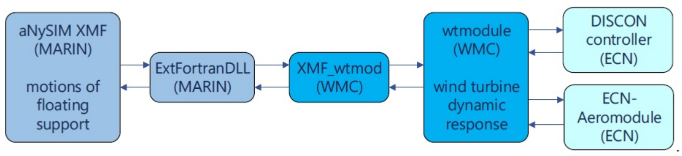

Figure 2.7: Overview of the tool chain used for simulation of floating VAWT with pitching blades

2.3.3 WP3 coupling of tools

The objective of this work package in S4VAWT was to verify and test the coupling between AeroModule, aNySIM XMF and wtmodule for the simulation of a floating Vertical Axis Wind Turbine (VAWT). ECN previously conducted simulations using the coupled tool aNySIMPhatas for horizontal axis wind turbines (e.g. for the IEA task 30 benchmark OC5), which was used as starting point. However, the VAWT properties poses several challenges and MARIN development continues with the new version aNySIM XMF, which caused the need for verification of the new coupled tool.

The verification of the individual tools and their interfaces is reported seperately (for aNySIM XMF in chapter three of [9] and in appendix A of [7] for wtmodule). In [10], results from the aNySIM XMF coupled tool are compared against the results from Ansys Aqwa coupled with WTMmodule and AeroModule.

The aim of the simulation campaign was to test the coupling between the tools. The coupling between aNySIM XMF, Phatas and AeroModule is first tested for a Horizontal Axis Wind Turbine (HAWT) to remove uncertainties deriving from other results of the S4VAWT project, since the development of the VAWT simulation capabilities in AeroModule is part of the project. Reference load cases are designed and selected from OC5, with the aim of considering an incremental complexity to check the coupling capabilities. Similar hydrodynamic models for the floating support are developed for the two software tools, whereas the wind turbine definition was shared.

Load cases are selected to perform accurate testing. Classical staircases with fixed and free floaters are included to have a clear picture in a simplified case of the response of the wind turbine and the floater to steady and dynamic events. Moreover, a number of interesting complex cases are selected for testing, including wind speed stair cases with fixed and free floater, decay tests, regular and irregular waves and stochastic wind.

For most cases, the agreement between numerical and analytical results or results from different numarical methods was very good. Figure 2.8 and 2.9 show a comparison of the results obtained from the different tools for an above rated wind speed case with stochastic wind and irregular waves.

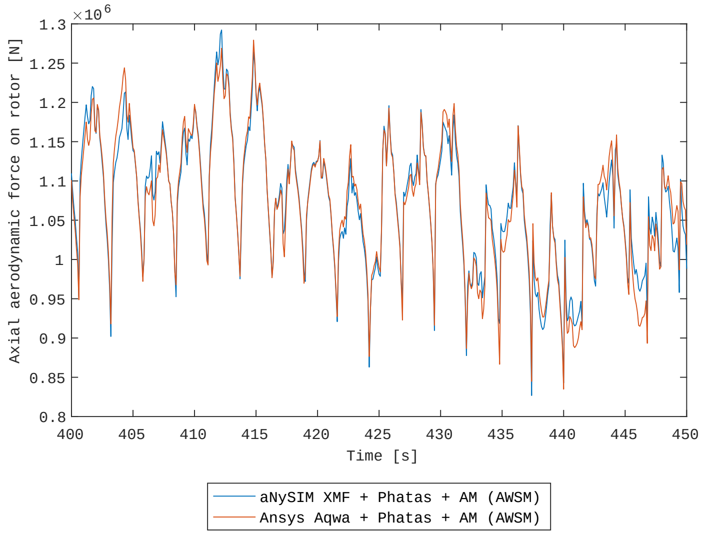

Figure 2.8: Time series of the rotor thrust load for an operational test case with wind and waves

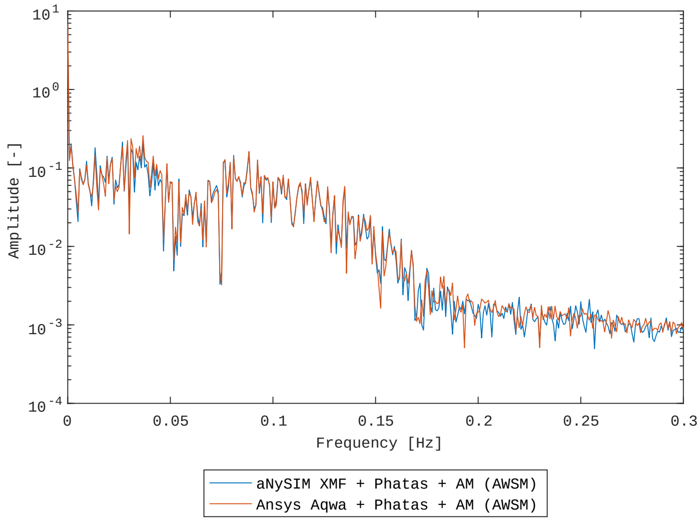

Figure 2.9: Frequency response of the floater pitch motion for an operational test case with wind and waves

2.3.4 *WP4 optimization of the support structure*

The aim of this work package is to optimize the Tri-Floater and its mooring system for lowest cost. It is estimated that the support structure accounts for a significant part of the CAPEX distribution of a floating wind turbine. So in order to reach the lowest cost of energy it has to be properly optimized for the rotor's design. It is a joint effort of the floater designer (GustoMSC) and the rotor designer (ECN, TUDelft), supported by the developers of the design tool (ECN, WMC and MARIN).

- The Tri-Floater's parameters, such as its radius, its height, and the columns' width will be adapted to the stability needs and the aerodynamic loads on the rotor. It is important that the manufacturing costs are optimized.
- Coupled time domain analysis will then be performed to consider the strongly coupled effect of the floater motions, mooring system, and wind turbine control. This study will enable to assess the floater's stability and motion.
- The mooring system of the floating wind turbine has a strong influence on the floater motions. Depending on the floater's design, it can have significant impacts on the floater's dynamic loads. The mooring system will therefore be optimized with the floater.

2.3.4.1 *Basis of design*

The document [11] defines the basis of design by specifying the requirements and conditions. The following list briefly summarizes these:

- The Tri-Floater concept is taken as starting point for the floater support structure design
- The SPINFLOAT concept is taken as starting point for the VAWT
- The design follows the rules, regulations and guidelines specified by Det Norske Veritas (DNV) in [12] 'Design of floating wind turbine structures'
- The design principles mostly follow the DNV recommendations, using Load and Resistance Factor Design (LRFD) methodology for a design life of 20 years.
- The site conditions are taken from a Western Mediterrarean Sea location, with a water depth of 100m and moderate wind and wave climate.
- A limited set of load cases will be considered, including survival (parked in storm), extreme operation, normal operation and mooring system damage.

2.3.4.2 *Optimization of the floating support structure*

The developed coupled tools have been used to optimize and verify the GustoMSC Tri-Floater and its mooring system for supporting a VAWT. During several design iterations, the floater dimensions have been optimized in order to achieve the most cost-effective design. Initial design loops have been performed using uncoupled and simplified analyses, followed by final integrated design loops with fully coupled simulations. To achieve a cost-effective design the integrated design approach is essential, including the dedicated family of airfoils with high aerodynamic and structural performance and the control system technology for floating VAWT.

The report [13] documents the design iterations. The resulting floating support structure is a three-column semi-submersible of the GustoMSC Tri-Floater type which is kept in position by a catenary chain mooring system. Figure 2.10 shows an artist impression of the design.

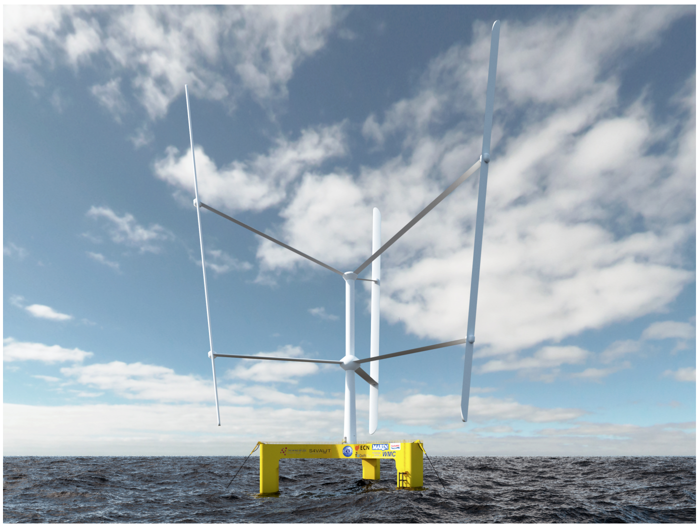

Figure 2.10: Artist impression of the S4VAWT Tri-Floater

The Tri-Floater semi-submersible comprises three columns, which are connected by a deck box structure above the water. The concept was first published in 2003 and further improved and validated by model tests in 2013 for horizontal axis wind turbines. The structure is built out of flat steel panels, optimized for manufacturing using automated welding. The floater is sufficiently stable to assemble the wind turbine in a port, using an onshore crane. Tow-out and hook-up to the mooring system and electrical cables is done with low-cost vessels such as seagoing tugs. The floater dimensions have been minimized during several design loops, to take full advantage of the lower centre of gravity and larger allowable floater tilt angle. A conventional three-line catenary mooring system is used to moor the Tri-Floater to the seabed. Each mooring line comprises of 500 m chain of grade R4 with a diameter of 89 mm. The mooring lines are connected to the floater at main deck level at the outer edges of the columns, in order to minimize the wind overturning moment on the floater and to maximize the vertical distance between anchor and fairlead. The mooring system is secured to the seabed using conventional drag anchors. The main particulars and weights of the final design are presented in tables 2.1 and 2.2 respectively.

The following drawings define the geometry of the optimized floating support structure design in detail:

- general arrangement plan of the S4VAWT Tri-Floater (sheet one) [14]
- general arrangement plan of the S4VAWT Tri-Floater (sheet two) [15]
- mooring arrangement plan of the S4VAWT Tri-Floater [16]

Table 2.1: Floating support main particulars

Dimension	Size [m]
Radius to column centre	33
Overall length	68
Overall width	80
Depth (keel to main deck)	25
Operational draft	10
Transit draft	7

Table 2.2: Floating support weights

Item	Weight [t]
Floater lightship	1700
Wind turbine	550
Subtotal: transit displacement	**2250**
Water ballast	400
Static vertical mooring load	100
Total: operational displacement	**2750**

2.3.5 *WP5 requirements for wave basin model test*

An investigation on how to model a VAWT on a floating platform in a wave basin has been carried out in this workpackage of the project. The approach and the main results of this investigation are summarized in this section. More detail can be found in chpter four of [9].

In literature, recent publications can be found which describe the considerations about modeling the above water loads on a floating horizontal axis wind turbine in a wave basin. To simulate the response of a floating wind turbine correctly it is important that the environmental loads due to wind, waves and current are in line with full scale. For dynamic similarity on model scale, Froude scaling laws are used successfully in the offshore industry for the underwater loads. To be consistent with the underwater loads, the winds loads have to be scaled according to Froude as well.
Previous studies describe that a geometrically-scaled turbine generates a lower thrust and power coefficient with a Froude-scaled wind velocity due to the strong Reynolds scale effects on the flow. A scaling method for the wind turbine blades was developed originally by University of Maine. In this methodology, the objective is to obtain power and thrust coefficients which are similar to the full-scale turbine in Froude-scaled wind. This is obtained by changing the geometry of the blades in order to provide thrust equality between model and full scale, and can therefore be considered as a 'performance scaling'. This method was then used to design and construct a new MARIN Stock Wind Turbine (MSWT) based on the NREL 5MW wind turbine blade, including an active blade pitch control to simulate different blade pitch control systems.
Instead of physically modeling the wind and rotating turbine a different approach can be used, where the above water loads are resolved in software and applied to the model by a set of force controlled winches. This is referred to as hybrid model testing. The underwater part of the system is modeled physically while the above water part, that is assumed to be well described theoretically, is modeled numerically. Both physical and numerical substructures interact, in real-time, through a network of sensors and actuators. Hybrid testing is used in general to study complex systems when (1) the limitations on the physical size or characteristics of testing facilities do not allow a full model of the system to be accommodated, (2) when conflict in scaling between different subsystems hinders the use of conventional model testing, and (3) when the focus of the test is the performance of a single module or component in a complex system. In the latter case, hybrid testing allows simplifying the setup for a more effective execution of the tests, or to reduce uncertainties from the other modules.

There are several specific challenges of the testing of VAWTs in a basin with combined waves and wind identified:

- Active blade pitch control has been applied for the horizontal axis wind turbine on model scale. This system however controls the blade pitch of all three blades simultaneously. The vertical axis wind turbine of consideration has individual blade pitch control. Furthermore, with a vertical axis wind turbine the blade pitch angle is a continuous function of the azimuth angle. Therefore three separate actuators are required mechanically. It has been examined with mechanical engineers whether it is feasible to construct this at model scale. First estimations showed that such a construction is feasible to make, however it will be impossible to obtain the correct, Froude scaled weight distribution of the turbine.
- For the vertical axis wind turbine, the objective is to have a lighter floater than for the horizontal axis wind turbine. Therefore it becomes even more important to have the individual component weights correct. Furthermore, the gyroscopic effect of the rotating turbine is assumed to have an impact on the motion response of the floater. When the model turbine mass is much larger than the

turbine Froude scaled mass, the gyroscopic effect on the floater motions would be exaggerated in the model tests.

- Aerodynamically speaking, the difference with the horizontal axis wind turbine is the larger range of angles of attack in which the airfoils operate. Also, the downwind blade operates in the wake of the upwind blade. Therefore, aerodynamically speaking the 'performance scaling' of the vertical axis wind turbine is even harder than for the horizontal axis wind turbine.

Given the challenges involved in modelling a VAWT with active blade pitch control at scale in the wave basin, it is recommended to represent the VAWT by force controlled winches and a real time numerical simulation model (Figure 2.11), rather than a physical model.

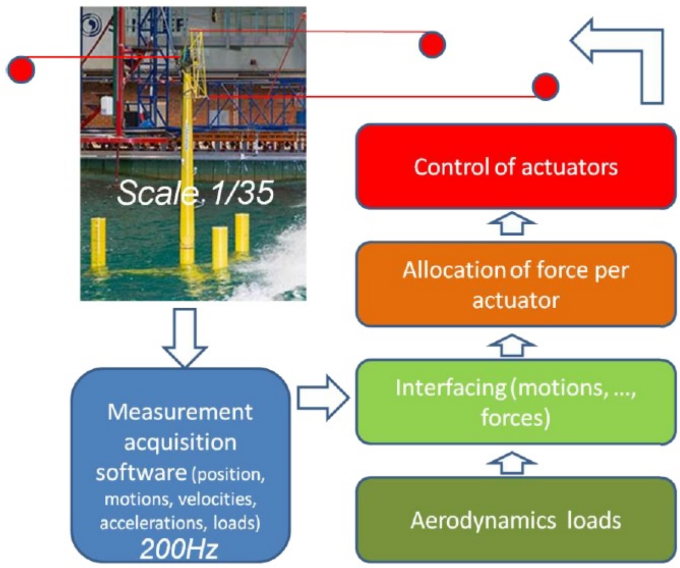

Figure 2.11: Hybrid scaled model test setup

However, hybrid model testing puts several requirements on the software and the hardware that emulates the wind turbine. Report [9] contains a detailed stability and robustness verification of the hybrid solution. A preliminary design of the mechanical testing set-up was made. As winch performance was identified as a bottle neck for the hardware, practical experience has been learned thanks to tests with a single winch pulling on a pendulum. These tests showed that available winches were suited to be used in a force control loop for hybrid testing of a floating wind turbine.

2.4 Conclusions and recommendations

The vertical axis wind turbine (VAWT) has specific features that make it highly suitable for offshore floating applications. Amongst these are the potential for scaling up, the low position of the centre of gravity and the large allowable tilt angle. However, VAWT with fixed blades typically have the disadvantage that the wind loads on the rotor become very large for the higher wind velocities, both during power production and parked survival conditions. This project has shown that these design driving loads can be significantly reduced by introducing active blade pitch control for the VAWT.
A 6 MW VAWT with pitch control and its semi-submersible support structure have been designed for deployment in the French Mediterranean Sea. The airfoil and the control system have been optimized specifically for this floating application. The floater dimensions have been reduced to the minimum required to meet the design requirements, taking full advantage of the lower centre of gravity and larger allowable floater tilt angles. It is concluded that approximately 20% less steel material is needed for the floater, compared to a 6 MW HAWT for the same site, with potential for further optimization.
The final design has been verified by state-of-the-art simulations, using coupled software which has been developed specifically for this purpose. It is concluded that applying active blade pitch control makes the design driving load cases of the floater for a VAWT more comparable to a HAWT, with the rated condition being governing for the tilt angle and tower base moment, rather than the parked survival condition. Floater yaw due to rotor torque has turned out not to be an issue for the Tri-Floater, as its architecture provides sufficient mooring stiffness and hydrodynamic damping in yaw.

Recommendations for future work:

- Wave basin model tests could be performed to validate the coupled simulation tools and hydrodynamics. Given the challenges involved in modelling a VAWT with active blade pitch control at scale in the wave basin, it is recommended to represent the VAWT by force controlled winches and a real time numerical simulation model, rather than a physical model.
- The rotor has been assumed rigid (no structural flexibility) in this project, which has proven to be a sound assumption for design optimization of the support structure. However, for design optimization of the VAWT, aero-elastic effects should be considered. A modification of the tools would be required to accommodate the rotor topology of a VAWT.
- This project looked at a wind turbine of 6MW as representative for other ungoing floating wind developments. However, upscaling of wind turbines is still ongoing, as it is an effective way of reducing the cost of energy. Upscaling of VAWTs is believed to be relatively easy, as VAWT design is not driven by gravity but by aerodynamic forces (which scale less severe with size). A sensitivity study for future large size VAWTs (10MW+) should be performed to quantify this potential.
- The results of the coupled simulations led to the observation that a shift in the blade pitch angle introduces sideways loading. As this was undesirable from support structure design point of view, the sideways loads were eliminated by aligning the blade pitch with the inflow. However, this sideways component with active blade pitch control can also be turned into an advantage, using the resulting wake deflection to reduce the wake losses when the floating VAWTs are placed in a wind farm setup. Unlike for HAWT, wake deflection for VAWT does not imply power reduction at the deflecting wind turbine leading to a win-win situation. The application for wind farm control of this wake deflection method with VAWT should be further investigated.

3 Project impact

This chapter starts with an overview of the impact of the project. Section 3.2 lists the activities for dissemination of the results and section 3.3 contains an overview of the followup activities.

3.1 Impact

The main impact of the project is advancement of the design of the floating VAWT concept, both on the side of the floating support and on the side of the wind turbine. The project showed that the expected benefits of VAWTs for floating application hold, and presented solutions for the challenges with the floating VAWT concept.

A novel dedicated airfoil and a new blade pitch control strategy work together to increase power capture below rated wind speed and reduces loads above rated wind speed. The lower loads directly benefit the rotor structural design, allowing for a small increase in rotor area and power capture. It also eliminates the generator as one of the main challenges of VAWT design; a much smaller and less expensive generator can be used, due to the reduction of torque fluctuations with the developed generator speed and power regulation using blade pitch control.

Supported by identification and mitigation of the design driving load cases, integral design of the floating support resulted in a significantly lighter and less expensive floater. With the iterations performed during the project, the design has been brought to a level ready for verification with model tests.

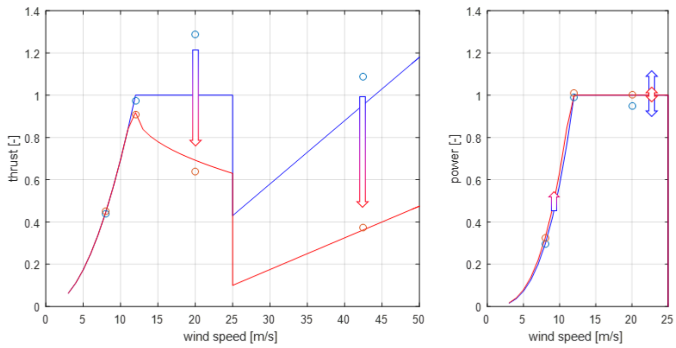

Figure 3.1: Overview of the design drivers for a floating VAWT without (blue) and with (red) blade pitch control

The coupled tool developed in the project can be used to optimize the design of a floating wind turbine, for this and other concepts. A plan for wave basin model tests has been prepared to be ready for design verification at small scale.

Together, these steps bring the floating VAWT concept closer to application.

3.2 Knowledge dissemination

This section provides an overview of the communication activities organized in the project.

3.2.1 External dissemination

The following presentations and publications have been issued:

- pitch at the TKI-WoZ MatchMakingDay (2016)
- presentation at the BlueWeek2016 in Wageningen [17]
- presentation at the WindDays2016 in Rotterdam [18]
- presentation at the EuroMech-583 (2016) in Delft [19]
- presentation at DeepWind2017 in Trondheim [20]
- presentation at the WindEnergyScience2017 conference in Copenhagen [21]
- news item in GustoMSC InSide May 2017 [22]
- presentation at the WindEurope2017 conference in Amsterdam [23]
- presentation at 2018 Wind Energy Symposium AIAA SciTech Forum [2]
- presentation at DeepWind2018 in Trondheim [5]
- presentation at OMAE2018 in Madrid [24]
- presentation at TORQUE2018 [25]

In addition to these presentations and publications, an external project website [26] has been created to introduce the project to interested readers. The website contains a brief summary of the project and the consortium.

3.2.2 Internal communication

To facilitate the interaction within the consortium members, several instruments have been used. Every six months, a physical project progress meeting has been organized, each time by a different partner at their own premises. Objective of these meetings was to discuss the project progress both from coordination and technical side. All project partners have contributed to these meetings with presentations and lively discussion. In between the physical meetings, telcons have been organised by the project coordinator. This ensured communication within the complete consortium at least four times per year.

Dedicated technical telcons have been organised as well to discuss progress of specific tasks within a smaller group. Examples are the aerodynamic modelling in WP1, the software coupling and verification in WP3 and the optimization of the floating support structure in WP4.

An internal (closed to the public) shared website has been created by the coordinator to facilitate the exchange of information between the project partners (such as reports, tools, model input and simulation results).

To speed up the usage of the coupled tool by the partners in the project, the tool developers ECN, WMC and MARIN organised a workshop to demonstrate the tool and provide first use support. This was highly appreciated by the partners that were going to use the tool later in the project.

3.3 Followup activities

The following activities ensure continuation of the work in S4VAWT:

- Both industry partners EOLFI and GustoMSC expressed their interest to continue using the coupled tool for floating VAWT analysis. License agreements for this usage are under discussion.
- EOLFI has initiated a French R&D project to demonstrate the floating VAWT technology on small scale.
- TUDelft and ECN>TNO will continue the work on VAWTs within the HER project TULIPWIND, which aims at development of a medium scale (300kW) VAWT for onshore application. Several of the recommendations for future work will be part of this project, such as aeroelastic analysis, and wake investigations.

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