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Integrated simulation challenges with the DeepWind floating vertical axis wind turbine concept

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Abstract

This paper presents the experiences and challenges with concurrently carrying out numerical model development, integrated simulations and design of a novel floating vertical axis wind turbine, the DeepWind concept. The floating VAWT modelling capabilities of the aero-hydro-elastic HAWC2 simulation tool are briefly described and the design approach adopted for such a challenging project was to independently design subsystems in parallel, apart from essential design specifications. Instability issues encountered when integrating all subsystems in the unified numerical model, in particular blade edgewise and controller instabilities, are presented and efforts to alleviate such issues are detailed. A multidisciplinary design and optimization approach is proposed to eliminate these issues and accelerate future design cycles.

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1. Introduction

1.1. The DeepWind project and concept

As presented previously [1] the DeepWind consortium consists of twelve partners, with the aim to develop a novel floating vertical axis wind turbine concept for deep waters that could substantially reduce the cost of electricity [1] of floating offshore wind energy. The DeepWind concept, depicted in Figure 1, consists of a Darrieus type rotor installed on a rotating spar platform, that is moored to the seabed through torque arms and catenary mooring lines, as further detailed by Paulsen et al. [2].

During the course of the project, the concept and the numerical tool were developed in parallel, as no pre-existing engineering simulation codes were suitable for such a concept. The objective of this paper is to present experiences and challenges encountered during the numerical modelling and simulation of the DeepWind concept. Such integrated numerical simulations involve the interaction of five distinct engineering fields: aerodynamics, structural dynamics, hydrodynamics, mooring line dynamics and generator-control dynamics.

This article is organised as follows: first a brief description of the developed numerical tool is given, followed by an overview of the design approach utilised in the DeepWind project. With this background, challenges encountered during integrated simulations are detailed, and finally an outlook on future design cycles is presented.

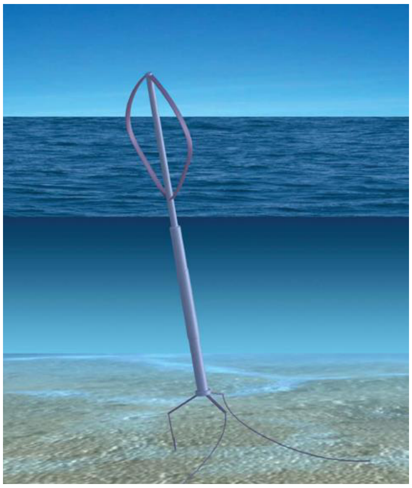


Figure 1: Visualisation of the DeepWind concept

2. Simulation Tool Description

The HAWC2 aero-hydro-servo-elastic design tool was utilized for this work, with a number of modifications applied to the codes so as to be capable to model the aerodynamic and structural characteristics of the DeepWind floating VAWT system.

The interaction of the turbine with the incident wind is modelled using the Actuator Cylinder model, as detailed by Madsen et al. [3], whereby the VAWT is considered as a stack of 2D actuator cylinders [4] rather than one or more tandem actuator disks as done in other approaches for floating VAWTs, e.g. Vita [5], Collu et al. [6], Wang et al. [7]. Both the turbine and floating support structure are modelled with Timoschenko beams, which include gyroscopic effects. Hydrodynamic forces are applied using the Morison equation to both the submerged floating support structure and mooring lines, with the former being modelled using a finite element approach [8]. Magnus forces due to the interaction between the submerged rotating platform and water (including wave and currents) are also implemented in code [9].

3. Design Approach

Due to the large number of partners involved in the DeepWind consortium, the design of subsystems by subgroups, each consisting of a small number of partners, were initially carried out independently in parallel with some interaction between design groups for essential design specifications. However, the different design models as used for the controller, floater, generator and blades did use some simplified models to account for the some of the most relevant interactions with the other subsystems.

This approach was adopted due to time constraints, and the complexity and novelty of the concept; the majority of components had not been designed before, or was done on a much smaller scale, and a reference point from which the design could develop was required.

4. Integrated Simulation Challenges

As mentioned previously, the floating VAWT capabilities of the HAWC2 integrated simulation tool were developed simultaneously to the concept design process. This provided for a challenging design environment as new observations on changes in turbine performance and dynamics could have had multiple sources, potentially from the inclusion of new capabilities, improved input data and design changes.

4.1. Blade instabilities

One challenge encountered during the evaluation of structural characteristics was to numerically determine the blade structural damping. Whilst values have been well established for horizontal axis wind turbine (HAWT) blades for the structural logarithmic damping decrement to be between one and five percent, it is not necessarily the same for VAWTs. This is so as HAWT blades are only fixed at the root whilst the VAWT blades are pinned at both ends. Due to the absence of detailed investigations into this aspect, the structural damping values were assumed to be within one and five percent as a first approach to modelling the VAWT blade structure within HAWC2.

One characteristic of VAWTs are that blades experience a large load cycle at the cyclic frequency, and in the case of the Deepwind concept, at the *2p* frequency (two bladed rotor). Another major impact is that the rotor is stall controlled which gives a low or even negative damping of edge blade wise vibrations. This presents a challenging environment in which the blade structure needs to operate. In particular the proposed blade structure [1] suffers from low edgewise stiffness that is not sufficient to sustain stable operation in certain operating conditions, specifically when stall occurs in wind speeds greater than 10m/s. This is illustrated in Figure 2, which depicts the time series of the blade edgewise displacement during a wind ramp with fixed rotational speed.

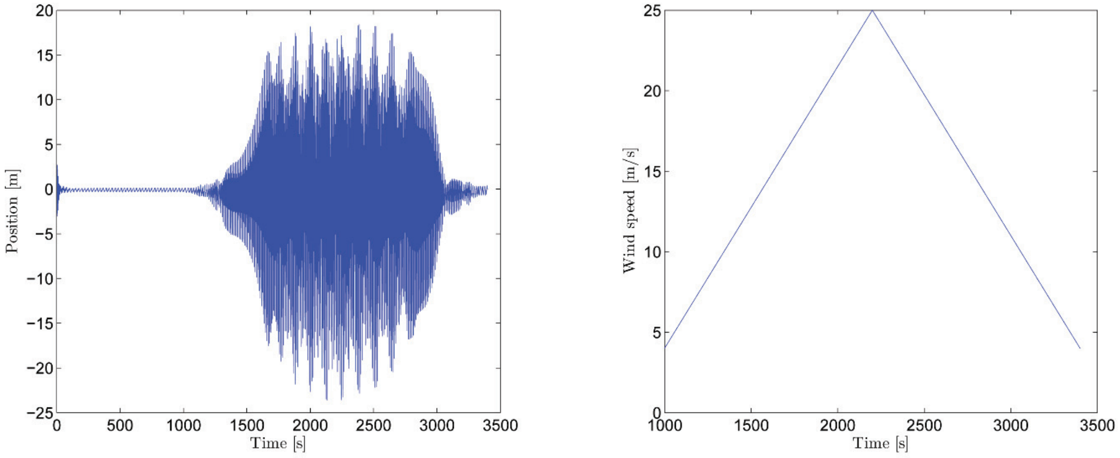
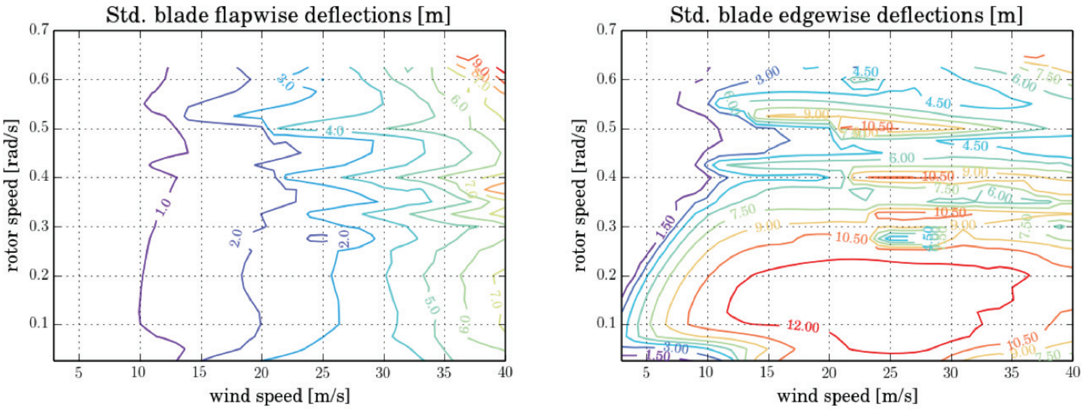


Figure 2: left, edgewise position of blade point 4 relative to root; right, wind ramp time series

To attempt to identify the origin of this instability problem, a number of simulations were carried out considering wind speeds from 3 to 40 m/s and rotational speeds from 0.025 to 1.0 rad/s. The tower base was considered fixed, that is, no platform motion was considered during simulations. Figure 3 presents the standard deviation maps for flapwise and edgewise deflections for the given operational conditions. Figure 3 clearly illustrates that this edgewise instability is present for a range of operational conditions, and above rotational speeds of 0.62 rad/s simulations did not converge (lack of contours in Figure 3), potentially indicating a precursor to structural failure. One application of these maps is to assist in the development of generator control strategies, deriving wind speed versus rotor speed curves that cover a wide range of operational conditions whilst navigating around unfavourable operating points. Through the use of aeroelastic tailoring and restricting rotational speeds this would be achieveable.



(a)

(b)

Figure 3: Standard deviation of (a) blade flapwise deflections; (b) blade edgewise deflections

As uncertainty in structural damping might be a possible contributor to these instabilities, high structural damping applied in HAWC2 did not resolve the instability issue. Hence we focused on the cause of instability by modelling the blade structure as stiff. Whilst this assumption removes some of the dynamic blade load content; tower, floater and generator loads would be significantly less affected by the simplification.

One current shortcoming of the aerodynamic VAWT implementation in HAWC2 is that the dynamic stall model (which considers the unsteady aerodynamic effects) does not work reliably for VAWTs. As such, the results presented here have not been simulated with the correct aerodynamic damping characteristics.

4.2. Controller/Drivetrain instabilities

The controller for the DeepWind concept is based on a conventional PI algorithm with a gain scheduler [10]. The challenge in this application of such a controller with a permanent generator is that the stator connected to the torque absorption system and supported by the elastic mooring system provides some degree of movement. This had to be accounted as an additional degree of freedom during the design of the controller [10].

During the course of the project, the controller was designed on the basis of a simplified aerodynamic load model based on a Fourier approximation to emulate aerodynamic shaft loads [10] due to time constraints and concurrent design and tool development.

The final controller, when implemented within the HAWC2 numerical model, performed well at below-rated wind speeds, however at above rated wind speeds some stability issues arose due to interactions between the generator torque and yaw motion of the stator/mooring system. Whilst the simplified model implemented to design the controller behaved as expected, there isn’t agreement with the full model due to more complex interactions within the HAWC2 simulations.

To illustrate this Figure 4 presents the time history of the stator yaw motion and generator torque in a wind speed of 10m/s and no incident waves. In this case it can be seen that the instability is periodic in nature. The same instability characteristic was observed for other conditions including incident waves and turbulent wind. In order to investigate this matter further, the torque arms of the mooring system were extended to 15 and 25 metres to increase the yaw stiffness of the mooring system. The hydrodynamic drag coefficient for the torque arms was also increased from 0.6 to 1.0 for additional damping. In spite of this, the instabilities still occurred with smaller magnitudes, indicating that the source of this issue was not caused by improper yaw mooring stiffness and/or too low (hydrodynamic) damping. It is assumed that the source of the problem is the complex interactions between the soft mooring system and the controller algorithm.

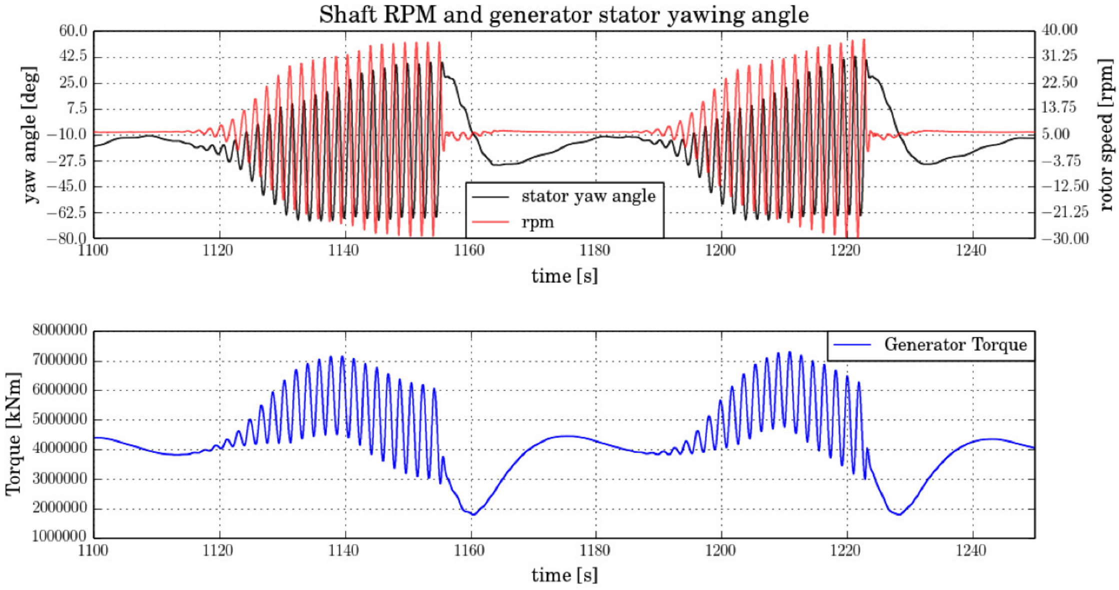


Figure 4: Yaw instabilities and generator torque control interactions for a deterministic wind speed of 10 m/s

5. Future Design Cycles

5.1. Overview

During the DeepWind project, the concept design underwent two system design iterations with major changes of blades and tower weight. However the subsystems underwent significantly more iterations on the basis of the previous system design iteration. In future design cycles it is proposed to adopt more integrated approaches, making use of Multidisciplinary Design, Analysis and Optimization methodologies (MDAO). For example, the OpenMDAO framework, developed by NASA [11,12], has been used before in this context to create an aeroelastic design for the DTU 10MW horizontal axis reference wind turbine [13]. Within the context of the DeepWind design project this would practically mean that the simplified models used for designing the blades, floater/mooring, and control subsystems could be tightly integrated into automated design procedures. Or alternatively, low fidelity (or simplified) models could be replaced with the fully coupled aero-hydro-servo-elastic model in HAWC2. FUSED-wind [14], which is built as extension for OpenMDAO, is another ongoing effort for which different external wind energy related design components are coupled in a single framework to facilitate design approaches that include the variables of many different subcomponents simultaneously. In the following subsections a very brief overview of different models, their integration, and design scenarios are sketched which could be implemented with the help of frameworks such as OpenMDAO and FUSED-wind.

5.2. Simple models (low fidelity) for the design context

For design purposes, where simulation time should be as short as possible, these multi-physics interactions are usually ignored or greatly simplified. This procedure can work reasonably well under certain strictly controlled conditions. However, the disadvantage is that, given a certain objective and cost function, the optimal solution is not likely not be a global optimum. Additionally, simplifying these models is usually carried out on a per design case basis. This means that the resulting models are simple and fast to compute, which is exactly what is required for a design process.

5.3. Complex models (high fidelity) for load case analysis and design verification

More complex models take all the different physical domains (hydro-, aero-, structural-, electromechanical-, control-dynamics) into account. Usually this means the model is much more computational intensive, and is solved in the time domain. Although complex, these tools can be very general, and are often used in many different contexts. Note this is different compared to the simplified models.

5.4. Hybrid design approach: mixing low and high fidelity models

A straightforward method to design these complex systems is by using a sequential approach: a simple model is used to design one component, which serves as the input for the design of the connected component etc. This procedure was not automated for the DeepWind project, and is challenging since it requires careful agreement on input and output definitions. Because the problem is multi-disciplinary the definition of the interfaces requires a lot of careful planning and discussion since a certain output definition in one field might not be common in another one. All these interactions mean that only a limited number of design cycles are completed, while an optimum solution would require many more. Hence the obvious requirement is for automation of this procedure. However, automation requires that all the different sub-models should be tightly integrated, and the input/output flows should be very well defined and coordinated.

5.5. Hybrid modelling approach: linearise and simplify high fidelity model around operating point

An alternative approach to speed up calculation times for design purposes is to linearise and simplify a high fidelity model around varying operating points. For example: the HAWCStab2 program from DTU Wind Energy uses a linearised model to evaluate the stability of a VAWT at different operating conditions. This requires a tight coupling with the high fidelity model.

5.6. Switching between low and high fidelity models: verification of the simple models

Similar challenges exist when switching between low and high fidelity models: one has to carefully move the simple definition into the complex environment. Usually this means that additional parameters have to be defined and might require secondary models. This procedure is usually not automated, and can introduce translation errors. Within a design procedure one should frequently aim at porting a simple design model to a complex modelling environment to increase the accuracy and reliability of the design and the simple modelling techniques.

5.7. Multi-disciplinary design

Summarizing an integrated design procedure for a complex system such as the DeepWind floating vertical axis wind turbine, one should be able to:

- create simplified models
- connect simple models together
- run connected simple models in an optimization context
- translate a simple model into a complex model
- linearise and simplify a complex model around operating points for stability analysis
- run complex models, optionally in an optimization context
- compare simple and complex models
- perform all these steps in a single environment

6. Conclusions

This paper presented the challenges experienced during the DeepWind project in carrying out integrated numerical simulations of the floating VAWT concept. It is important to stress that for these simulations five distinct engineering fields had to be integrated to closely interact with one another, namely: hydrodynamics (floating support structure); structural dynamics (tower, blades, floating support structure, mooring lines); aerodynamics (rotor); electro-mechanics (generator); and control (generator).

During the DeepWind project, each subsystem was designed independently from and in parallel to one another, apart from essential design specifications. However different design models used for the controller, floater, generator and blades did use some simplified models to account for some of the most relevant interactions with the other subsystems. The initial system iteration produced a stable design with integrated subsystems, although it was not yet an optimal solution.

In the final stages of the project, the different subsystems for the final system iteration were integrated into an integrated numerical model in HAWC2. However stable operation was experienced for only a subset of operational conditions, with blade and controller instabilities emerging a large number of higher-energy metocean conditions, as detailed in Section 4. The operation of the rotor in stall from just below rated wind speed and upwards is thought to be a major cause of the instabilities. Whilst efforts were made to identify and alleviate such issues, they were not completely eliminated. As a result a methodology for future design iterations is presented based on a multidisciplinary approach such that these instability issues are avoided from the outset and design cycle iterations can be accelerated.

Acknowledgements

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