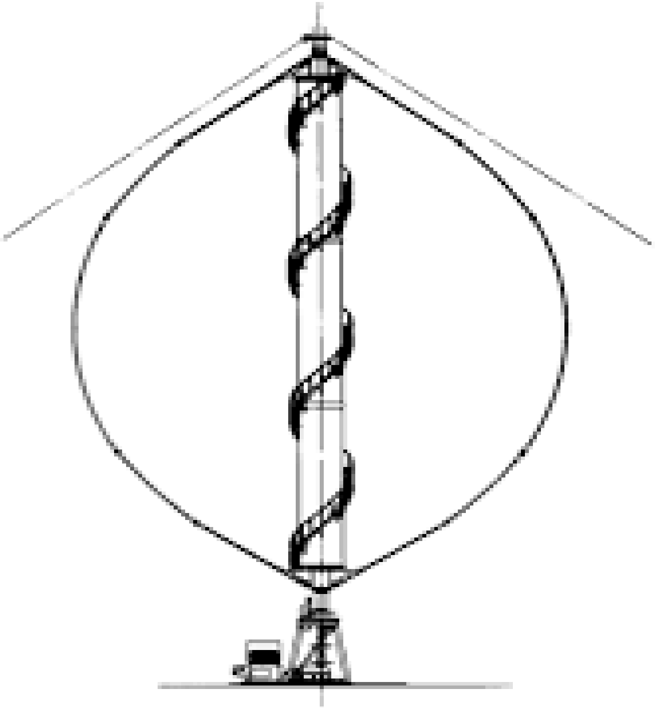
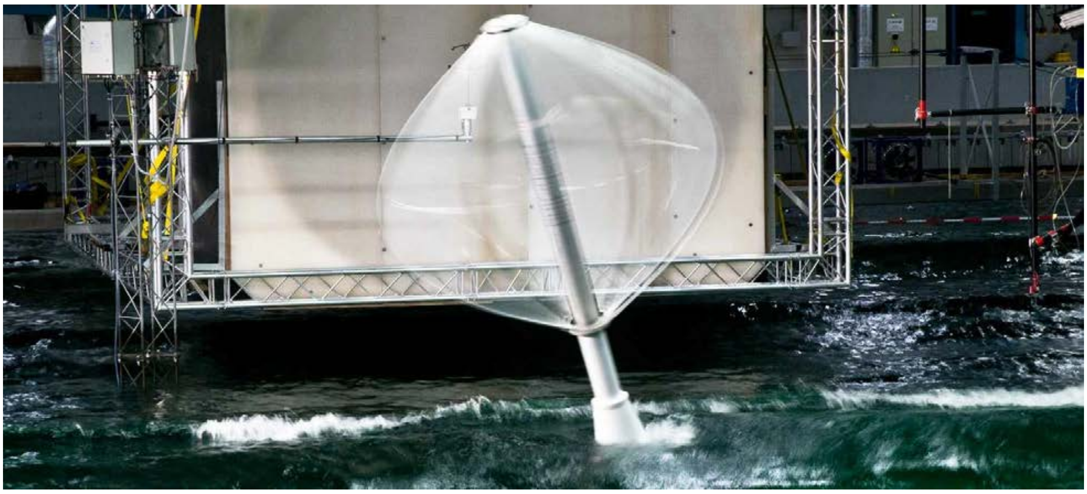
Euromech Colloquium 583
Scientific and Technological Challenges in Offshore Vertical Axis Wind Turbines

7 September – 9 September 2016
Delft, The Netherlands





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After 30 years of successful implementation of Onshore Wind Farms based on Horizontal Axis Wind Turbine (HAWT) technology, the wind energy industry faces new challenges in developing offshore wind farms. Although most of the development of wind energy is expected to be in offshore wind energy, our current level of wind turbine technology, based on the HAWT concept, does not yet economically meet the requirements, driving the cost of offshore wind energy 70%-85% larger than onshore wind energy. For floating offshore wind energy, the challenge is even larger. The Vertical Axis Wind Turbine (VAWT) is a promising solution for floating offshore wind energy due to its scalability, robustness, reliability, simplicity of installation, low center of mass and insensitivity to yaw and pitch.

However, the VAWT is both a scientific and an engineering challenge. Its aerodynamics are defined by a 3D unsteady asymmetric actuator volume, where blade-vortex interaction and dynamic stall are predominant. Currently, we lack validated models at airfoil, blade, rotor and wake scale. The lack of prototypes and test beds at real scale means that the few existing aero-elastic models are yet to be validated. Due to its 3D shape and asymmetric flow field, the design space is still mostly unexplored. This challenge in knowledge is further increased by the application of a VAWT to a floating concept, where floater design and dynamics, including wave loading and mooring are key.

There is now an emerging community of researchers and industrial developers for floating VAWT, new developments in industrial prototypes, several national and EU funded projects on offshore VAWTs, and an increasing number of publications every year. These developments warrant a meeting of experts to present the conclusions of the existing and recently concluded projects, and to identify key challenges and developments in design, models and scientific research. However, this community lacks a forum for exchange of ideas and for the presentation and discussion of the state of the art. This colloquium aims to bring this community together for the first time under an event dedicated to VAWT technology, science and research.

Main topics:
(1) Aerodynamics and aeroacoustics, including wake modeling and analysis.
(2) Structural design and aero-elasticity.
(3) VAWT drivetrains & their major components, advanced loads and control strategies, including both active and passive approaches.
(4) Offshore support structures and foundations including fixed-bottom and floating platforms.
(5) Novel VAWT architectures and configurations.
(6) System-level design studies and optimization.
(7) Cost analysis and making the business case for offshore VAWTs.
(8) Industry activities including technology demonstrators and industry perspective.

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Special thanks to Mrs. Sylvia Willems and Mr. Bruce LeBlanc for organization and administration of the colloquium.

Scientific Program

Wednesday September 7, 2016

Time	Event	Speaker
12.30	Lunch	
13.00	Arrival and Registration	
13.45	Welcome Remarks	Carlos Ferreira
14.00	Keynote: ***The Sandia Legacy VAWT Research Program***	Dale Berg
15.00	Presentation: ***TU Delft*** *Aerodynamic Challenges of Vertical Axis Wind Turbines*	Carlos Ferreira
15.25	Presentation: ***University of Pisa*** *A simplified aerodynamic model for floating VAWTS*	Edoardo Cicirello
15.45	BREAK	
16.00	Key Presentation: ***University of Stavanger*** *A review of State-Of-The-Art in Torque Generation and Control of Floating Vertical-Axis Wind Turbines*	Uwe Schmidt Paulsen
16.45	Presentation: ***RWTH Aachen University*** *An Integrated Simulation Environment for Vertical-Axis Wind Turbines*	F. Thönnißen
17.05	Presentation: ***Michigan State University*** *Low-Order Vibration Modeling of Vertical-Axis Wind Turbine Blades*	Brian Feeny
17.25	Visit to TU Delft Facilities	
19.00	Reception	

Thursday September 8, 2016

Time	Event	Speaker
08.45	Arrival, Coffee	
09.00	Key Presentation: ***Sandia National Laboratories*** *Design and Cost Studies for Large-Scale Floating Offshore Vertical Axis Wind Turbines: A Sandia Perspective*	D. Todd Griffith
09.45	Presentation: ***Politecnico di Milano*** *Experimental Activity and Numerical Modelling on the PoliMi IPC- VAWT Physical Model for Wind Tunnel Tests with Open-Data Purposes*	Ilmas Bayati
10.05	Presentation: ***Vrije Universiteit Brussel*** *Wind Tunnel Testing of a Pair of VAWTS for Offshore Applications*	Tim De Troyer
10.25	Presentation: ***Uppsala University*** *Force measurements on a VAWT Blade in Parked Conditions*	Anders Goude
10.45	Break	
11.15	Presentation: ***Go-ELS Ltd.*** *Blackbird: A Hybrid CAES Storage Anchored Mono- TL VAWT-WEC*	Christopher Golightly
11.35	Presentation: ***RWTH Aachen University*** *Conceptual Design and Multi-Body-Simulation of a Floating VAWT*	Björn Roscher
11.55	Presentation: ***University of Stavanger*** *Off-grid Market Opportunities for Floating VAWT*	Siri Kalvig
12.15	Lunch	
13.45	Presentation: ***Eolfi*** *Spinfloat Composites Design*	Benoit Paillard
14.05	Presentation: ***Aalborg University*** *On the Design, Laboratory Model and Performance of the Controlled Magnetic Journal Bearing for the DeepWind Project*	Ewen Ritchie
14.25	Presentation: ***Aalborg University*** *On the Design and Performance of a Power Electronics Converter for the DeepWind Project*	Ewen Ritchie
14.45	Presentation: ***Aalborg University*** *Specification, Design, and Performance of the Generator for the DeepWind Project*	Krisztina Leban
15.05	Break	
15.35	Presentation: ***Nenuphar*** *Development and Numerical Validation of an Aero-Servo-Elastic Code for Floating Vertical Axis Wind Turbines*	Guillaume Venet
15.55	Presentation: ***University of Leeds****2D Modelling of a 17 meter Sandia VAWT*	Kelly Marsh
16.15	Presentation: ***Principal Power Inc.*** *Large-Eddy Simulation of Counter-Rotating Vertical-Axis Wind Turbines at Low Reynolds Number in 2D*	Samuel Kanner
16.35	Presentation: ***Israel Institute of Technology*** *Adaptive Slot Blowing for VAWT Blade Load Control*	David Greenblatt
16.55	Presentation: ***Eolfi*** *Analysis of Dynamic Pitch Control for Fatigue Life of Vertical Axis Wind Turbines*	Clémence Gellée
17.15	End of Day 2	
19.00	Conference Dinner	

Friday September 9, 2016

Time	Event	Speaker
08.45	Arrival / Coffee	
09.00	Presentation: ***Université Catholique de Louvain*** *Vortex Particle-Mesh Simulations of VAWT Wakes Over Large Scales*	Philippe Chatelain
09.20	Presentation: ***Norwegian University of Science and Technology*** *Dynamic Analysis of Floating Vertical Axis Wind Turbines Under Extreme Conditions*	Zhengshun Cheng
09.40	Presentation: ***Nenuphar*** *Visualization of dynamic stall on large-scale VAWT*	Joanna Kluczewska-Bordier
10.00	Presentation: ***ECN*** *S4VAWT: Floating Vertical Axis Wind Turbine with Pitched Blades*	Feike Savenije
10.20	BREAK	
10.50	Key Presentation: ***Nenuphar*** *A Story Focused on Floating VAWTs*	Frederic Silvert
11.35	Presentation: ***Carleton University*** *Design of a Troposkein Two-Bladed Shifted Vertical Axis Wind Turbine*	Fred Nitzsche
11.55		
12.15	Closing / Lunch	
13.30	VODCA Kickoff Meeting	

Abstracts

The abstracts appear in order of the Scientific Program.

Aerodynamic Challenges of Vertical Axis Wind Turbines

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The Vertical Axis Wind Turbine (VAWT) is highly suitable for offshore due to its scalability, robustness and reliability, and simplicity of installation. One of the challenges of the VAWT is its complex aerodynamics. The energy exchange and loading is due to an unsteady tri-dimensional process, dominated by blade-vortex interaction and complex wake dynamics.

Aerodynamic modelling and design is required for the prediction of loads at the rotor blades and structure, and performance of wind farms. The complexity and lack of knowledge result in physically inaccurate aerodynamic simulation tools and design options, hindering the development of cost efficient VAWTs.

The intermittent research and development of VAWTs means that equivalent models and knowledge developed for Horizontal Axis wind turbines is still not known for VAWTs. These include the effect of: atmospheric turbulence, wind shear, wind directional changes both in time and in space, and wake effects from neighbouring wind turbines. Additionally, the 3D actuator geometry leads to blade vortex interaction and streamlines which cross the actuator surface twice, and an unsteady flow.

The challenges and knowledge and numerical modelling are reinforced by challenges in validation, due to the limited data available from experiments both in controlled conditions and in field tests. The geometry of the VAWT also implies more complex and costly experimental setups and measurements.

This presentation builds upon the work done by Sørensen and Ferreira in [1] for the analysis of the scientific challenges in wind turbine aerodynamics. Following this approach, we explore some key topics: improvement of simplified and low-fidelity models; hybrid, Eulerian and Lagrangian models; experimental simulation and model validation; unsteady flow control; wake development and interaction; VAWT airfoil aerodynamics; the VAWT actuator surface formulation; and interaction with a floating platform.

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A simplified aerodynamic model for floating VAWTs.

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To ensure successful modeling of a floating wind turbine, its aerodynamic behaviour has to be investigated. At the time of writing, the only relevant studies on the topic are about VAWT in skewed flow. There is lack of experimental, numerical or theorical studies about floating turbines.

In the following paper, the aerodynamic performance of a periodically oscillating VAWT is investigated through theorical and computational means. The complex dynamics of a floating turbine was simplified to a sinusoidal pitch motion, assuring simplicity without losing meaningfullness.

A theory is given to predict the aerodynamic torque of an oscillating VAWT, obtaining it from the one of the same fixed axis turbine. A blade-element model was developed to achieve this result, taking into account the effect of oscillation on key parameters affecting the torque, that is angles of attack and relative wind speed. The core idea of the method, is to use blade element theory not as a prediction itself, but as a mean to correct the aerodynamic torque of the fixed axis turbine. The latter may be the result of both experiments, or numerical simulations. The simplest though most effective correction developed is

$$T_o = T_f \left(1 - k \cos(\omega_o t)\right)^2 \quad , \tag{1}$$

where ω_o is the frequency of oscillation in rad/s, and k is the ratio of the maximum oscillation speed for a certain section of the turbine over the freestream wind speed. Three different corrective functions were evaluated, that is one for the effect of the angles of attack, one for the relative wind speed and one considering both at the same time (Eq. (1)). Moreover, the correction may depend on just one representative section, the middle one in this case, or the entire rotor.

Theorical predictions were compared against data from CFD simulations, for two different oscillation frequencies. These were chosen in the typical range of wave energy spectrum, in order to test representative conditions for floating applications. CFD simulations were also performed to obtain the torque of the fixed axis turbine, which was validated against experimental data from the 17m Darrieus-type rotor studied by SANDIA laboratories.

CFD simulations showed aerodynamic forces are deeply affected by oscillation. As intuition suggests, torque increases when the turbine pitches in the opposite direction of the wind, and decreases when it pitches in the same direction. This periodic oscillation causes significative ripple and maximum torque increase. For the higher oscillation frequency, which represents the most extreme condition, maximum torque was about 2 times the one of the fixed turbine. Mean torque was found to be almost unaffected or slightly increased. For the higher oscillation frequency a 4.4% increase was observed.

The theorical model was able to reproduce the behaviour of the oscillating turbine with satisfactory accuracy. To quantify the matching, absolute error was divided by the peak torque of the fixed axis turbine. For the lower oscillation frequency worst accuracy is 13.8%, while mean accuracy is 5.3%. As the frequency grows the hypothesis which the model is based on become less valid, so for the higher oscillation frequency precision decreases, in fact worst accuracy is 29.0% while mean is 9.1%.

The theory proved to attain reasonably accurate results notwithstanding its simplicity, making it a cost-effective tool for quick analysis or optimization. Moreover, the theory could insight the way in which oscillation affects the torque. Considering relative wind speed separately showed that it has little influence, so it can be concluded that torque is affected by oscillation mainly by the change in the angles of attack. Finally, letting the correction depend on the entire rotor or just the middle section yielded almost identical results, proving the simpler model may be used without loss of precision.

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A review of state-of-the-art in torque generation and control of floating vertical-axis wind turbines

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1 Introduction

The increasing demand for renewable energy has resulted in new wind turbine systems, greater installed capacity, new designs and new levels of maturity over the last three decades [1], [2]. Wind turbine systems provide electricity from wind at a competitive cost compared to other existing methods of energy supply.

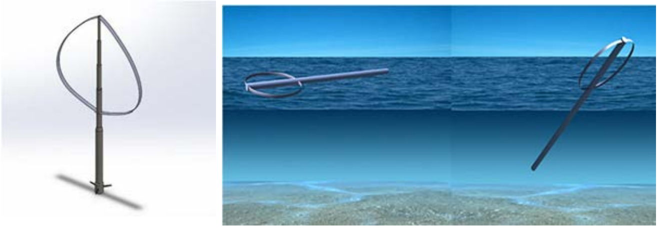

Figure 1 Left: 5MW Deepwind conceptual design. Centre: Deepwind towing scene. Right: Deepwind installation scene

The vertical-axis wind turbine (VAWT) can be beneficial for floating offshore concepts, as floating VAWTs have inherent advantages when compared to floating horizontal-axis wind turbines (HAWTs). Recently, major efforts have been undertaken in both Europe and the United States to explore this technology. The study made on the offshore Deepwind VAWT concept [2], a floating large-scale troposkien-shaped Darrieus turbine, see Figure 1, used the technology for VAWTs developed by Sandia from around 1970-1995 [3]. A report from Sandia reviews the development and configurations of VAWTs, and the lessons learned [4]. The Deepwind VAWT concept is challenging existing offshore wind technology, and has drawn attention due to its new design, well suited for offshore conditions [5]. It builds on the assumption that stall and variable speed control of a troposkien shaped Darrieus rotor will be more competitive than pitch control of an H-shaped Darrieus rotor.

In the USA, Sandia National Laboratories has renewed R&D efforts in VAWTs, investigating innovative VAWT rotor technologies at large-scale, along with efforts to pursue optimal configurations for floating wind turbines, see Figure 2. Several different rotor types have been tested [6]. It is currently unclear if the VAWT can be more economical than existing HAWT for floating offshore applications, and there is no academic agreement on how to derive the most energy from a VAWT on commercial scale with a competitive cost of energy (CoE). The demonstration project INFLOW [7] combines several technologies in a configuration of two counter-rotating, pitch controlled H-rotors (See Figure 2).

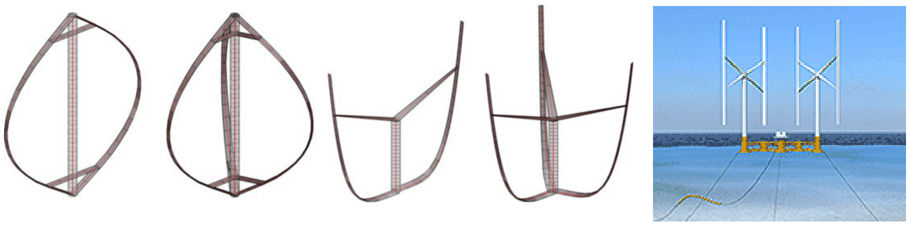

Figure 2 Left: Different innovative rotors considered in Sandia's VAWT research. Right: INFLOW concept: twin rotor on tri-floater

This article will review and summarize the development trends in VAWT design and control for floating offshore applications. The complexity of the control mechanism has an influence on the CoE. Both building cost, which is a part of the capital expenditure, CAPEX, and operation and maintenance cost, called OPEX, will increase as more moving parts is added.

2 Preliminary description of the results

A brief summary of the 5MW DeepWind concept design shows a 108m slender spar floater of currently 180T/MW, carrying the 121 m diameter modified Troposkien- shaped rotor of 143m height. For the 5MW concept, the center of gravity is 60 m above sea water level, and the slenderness provides less displacement than other floater types with similar stability. The rotor operates under variable speed control and stall, with over-speed limitation [2]. The blade geometry is fixed and constant in chord in steps over three major parts of the rotor height, and the structural effect over a span of rpm is limited to axial blade loading, and less bending. Aerodynamic performance investigations on new airfoils for DeepWind showed similar C_P's as horizontal-axis wind turbine (HAWT) rotor blades. CoE is in the range of 50€/MWh, however using concrete instead of steel for the floater, the cost is estimated to 30€/MWh.

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An Integrated Simulation Environment for Vertical-Axis Wind Turbines

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1. Introduction

Increased environmental awareness and the limitation of fossil fuels has led to intensive research in the field of renewable energy. In the sector of wind energy, current systems can be classified into horizontal- (HAWTs) and vertical-axis wind turbines (VAWTs). Modern aerodynamic design codes for both systems should meet three requirements: a) an accurate prediction of rotor loads and power production, b) a high flexibility regarding the turbine definition, and c) low computational effort.

For HAWTs blade element methods (BEM) possess these characteristics in a wide range of operating conditions. Exemplified for axial steady rotor inflow, their predictions show a high level of accuracy compared to experimental data. Additional empirical corrections [1,2] can be used to account for dynamic stall or a yawed inflow. Hence, BEM prediction capability can be extended to a considerably regime of operational conditions.

However, the direct transfer of the BEM to VAWTs should be avoided. The spatial character of a VAWT rotor leads to a strong blade- wake interaction on the leeside rotation. This mechanism cannot be captured using BEM. Consequently, the real blade incident angle on the leeside rotation differs from the one assumed by the BEM. Therefore, the prediction of VAWT rotor aerodynamics requires simulation models, which account for the mechanisms connected to the spatial rotor concept. Although large scale CFD simulations capture this mechanism, their large computational effort prevents their practical deployment.

The aforementioned points motivated the development of the approach presented below, which can be used to accurately capture the aerodynamics of VAWTs for a 2D viscous flow. The current development status, validation, and application to scientific test cases will be discussed in this paper**.**

2. Numerical Method

The structure of the developed numerical approach - named AISE - can be divided into micro- and macro-scale models. In this regard micro-scale models focus on the flow around each blade (blade representation, description of the boundary layer and flow transition), while macro-scale models capture the flow mechanisms on the turbine level (e.g. representation of the wake structure).

The core of the micro-scale models is a 2D vortex panel model, which is used for blade representation. The resulting panel structure is complemented by an additional artificial panel at the blades trailing edge. In case of unsteady flow conditions, this panel is used to shed circulation according to Kelvin's circulation theorem. To calculate the boundary-layer parameters XFOILs viscous boundary model [3] is used due to its well tested nature. Furthermore, flow transition is detected by monitoring the amplitude of the most amplified Tollmien-Schlichting wave. The double-wake concept of Riziotis et al. [4] is applied to capture the occurrence of separation using a second artificial panel at the separation point.

The coupling of the viscous boundary-layer with the surrounding inviscid flow connects the micro- and the macro-scale level. An iterative scheme is used to determine the unknown displacement thickness and match the viscous edge velocity to the inviscid velocity of the farfield. On the macro-scale a Free Vortex Model (FVM) is applied to describe the convection of the shed vorticities. A Fast Multipole Method (FMM) [5] is used to minimize the computational effort of this model with its n-body problem characteristic.

3. Results

A series of test cases is selected to verify AISE’s capability of reproducing the major 2D airfoil flow physics. Each test case verifies the function of a different part of the model and evaluates its accuracy. In addition, this verification strategy is characterized by an increasing complexity of the flow for each further test case. Validated numerical and experimental results from literature are used as reference data.

The first test case considers the numerical prediction of the inviscid static lift polar of a NACA0015 profile. The lift polar predicted by AISE matches the analytical solution with a very good agreement. Hence, the correct implementation of the panel method is verified. The correct representation of the blade-vortex interaction and the formulation of the time dependent potential has been verified using the analytical results of Theodorson [6] for different generic blade pitching motions.

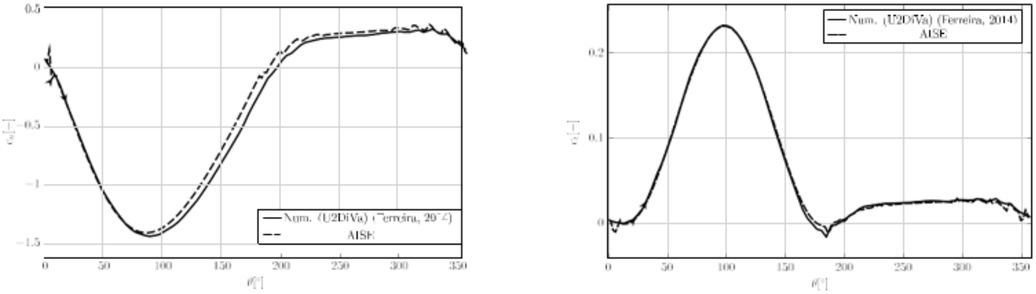
For the viscous flow regime, the prediction of a static lift polar (NACA0015, $Re=1.5 \cdot 109$) matches XFOILs prediction as long as the flow is attached. In the stall and deep stall region AISE’s predictions possess a slightly better agreement with the experimental values than those of XFOIL. Furthermore, a good accuracy is observed when comparing AISE's results in case of pitching airfoil motions in a viscous flow to those of Riziotis et al. [4], Peters [7] or Galbraith et al. [8].

To ensure code integrity in the field of VAWT simulation results from Ferreira et al. [9] for a two-bladed turbine (NACA0015, $\sigma = 0.1$, $\lambda = 4.5$, $Re = \infty$) were used as a reference. Considering the distribution of the tangential force coefficient, the code prediction matches the reference with a convincing agreement (Figure 1), which verifies the code's capability in the field of 2D inviscid VAWT simulations.

Concerning the viscous flow regime, AISE's results for of a three bladed VAWT ($\sigma = 0.3$, $Re = 400000$, $\lambda=[1.9, 2.2, 2.4, 2.6]$) are compared to experimental data. The distribution of the normal and tangential force coefficient for a tip speed ratio of $\lambda = 2.4$ is presented in Figure 2. The difference between the experimental and the predicted power coefficient by AISE for this configuration is about 4%. Comparing AISE with the 2D-URANS simulation results for all five tip speed ratios proves that AISE is able to compete with this numerical method in terms of accuracy. Furthermore, the required computational time of AISE is about two to three magnitudes lower to those of the higher-order numerical method, which makes AISE an effective tool for this kind of simulations.

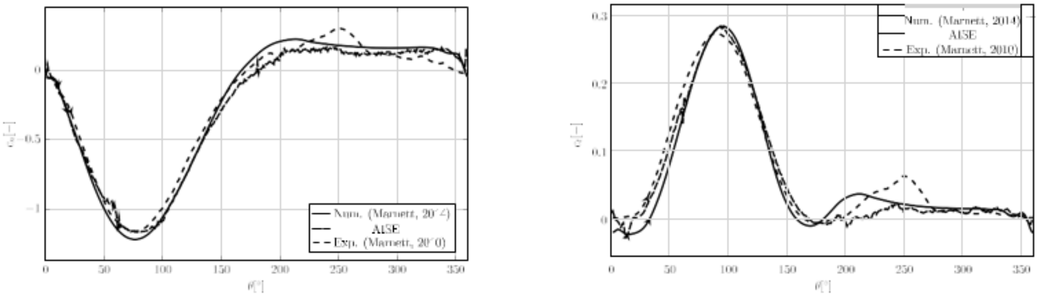
4. Outlook

The presented approach gives an impression on the capabilities and the prediction accuracy of a 2D viscid panel approach for the aerodynamic simulation of VAWTs. However, more sophisticated 3D models will be needed to evaluate the full potential of VAWTs and gain a better understanding of their flow mechanisms.



a) *b)*

Figure 1: VAWT Case: λ=4.5, σ=0.1, Re=∞ - Distribution of a) normal- and b) tangential-force coefficients computed with AISE [10] and compared to U2DiVa [9]



a) *b)*

Figure 2: VAWT Case: λ=2.4, σ=0.3, Re=400000 - Distribution of a) normal- and b) tangential-force coefficients computed with AISE [10] and compared to 2D-URANS results and experimental data [11]

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Low-Order Vibration Modeling of Vertical-Axis Wind Turbine Blades

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1 Introduction

The goal is to develop a low-order blade-vibration model for vertical-axis wind turbines (VAWTs). While studies have shown that VAWTs may be prone to vibration issues, there has not been much vibration modeling done until recently [e.g. Owens et al., 2013; Owens et al., 2014]. A low-order model will be amenable to analyses such that vibration and resonance phenomena may be revealed with analytical predictions on the roles of parameters. Such information will be helpful as the turbines are designed for more extreme operational conditions and environments, such as larger and offshore turbines or with the floating support structure [Owens et al., 2014]. In this work we aim to derive a vibration model for a Giromill wind turbine blade as a uniform straight elastic Euler-Bernoulli beam. A low-order aeroelastic model will be implemented.

2. Formulation

The turbine is assumed to be in steady operation under steady wind conditions, and the interaction between rotor and blade motion is neglected. Thus, the rotor is assumed to be under rotation at a constant rate. The wind velocity is assumed constant, equal to the velocity field far upstream. The wake effects of the blade on the wind, and the influence of the wake on the blade in the downstream position, are neglected. This is a simplifying assumption which will enable our first-generation vibration model, and we hope to relax this assumption in follow-up work. Under these assumptions, energy expressions for an Euler-Bernoulli beam under transverse bend and twist deflections are obtained and then approximated in terms of *n* assumed modal coordinates. Lagrange's equations are applied to obtain *n* equations of motion, and generalized force terms due aeroelastic forces and moments on blades are included. A low-order aeroelastic model such as a quasi-steady or Theodorson model [Dowell et al, 1989] will be used. Lift and drag forces and moments are formulated for an airfoil with changing angle of attack, where stall effects are neglected. The lift and drag formulas are simplified to cubic order. The resulting system has parametric and direct excitation due to the varying magnitude and attack angle of the flow relative to blade. These terms are very complicated and are generated with computer algebra and numerical integration to obtain differential equations with modal-coordinate coefficients as functions of specified parameters.

3. Case Study

The equations are then used to make a vibration simulation and numerical analysis for a blade. We investigate the Giromill, a common type of Darrieus turbine which has straight blades parallel to the axis of rotation and is therefore simpler to model than the “egg beater” configurations. The featured parameters are based on the Sandia 17-m curved-blade Darrieus turbine [Worstell, 1978]. The cross section of the blade is considered to be NACA0012, although an investigation has been done by Sandia National Laboratories to find an optimized airfoil with better structural stiffness [Ragni et al., 2014]. The length of the blade is 17 m and the distance of the blade from the rotor axis, R, is 6 m. The system is linearized for small deflections. Linearized equations of motion are derived for the specific blade described above. The modal frequencies for bending and twisting and their variation with the length of the blade and also the rotor rotation speed, Ω, are investigated. The system with aeroelastic loads is both directly and parametrically excited. The time histories of these excitation functions are examined. Conditions for parametric resonances and instabilities are sought. Simulations of forced responses are conducted. If time permits, perturbation analysis will be performed to indicate the roles of parameters on the vibration behavior.

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Experimental Activity and Numerical Modelling on the PoliMi IPC - VAWT Physical Model For Wind Tunnel Tests With Open-Data Purposes

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1 Abstract

This paper reports the design and the offline structural and performance characterization of the reference h-darrieus vertical axis wind turbine (VAWT), with individual pitch control (IPC), developed for open-data purposes at Politecnico di Milano (PoliMi). More specifically, under PoliMi project "VODCA" (VAWT Open Data for Code Assessment [1]) the features and wind tunnel data of this machine will become available to the community for numerical code validation [2]. The wind tunnel tests will be performed in the high-speed test section of Politecnico di Milano wind tunnel, in open-jet configuration [3]. Furthermore, the supporting CFD/actuator line code developed at PoliMi is herein present and the results about possible IPC control strategies implemented are discussed.

2 Design and Offline Characterization

The full paper reports the design approach adopted for the critical details (motor-reducer-blade units, hardware/software architecture), as well as the structural verification (modal analysis) and the IPC capabilities (effective control bandwith tests) of the built machine, Figure.1. Results are discussed and the design of experiment for wind tunnel tests, based on the machine capabilities, are provided also considering possible control laws implementation available in literature [4].

3 Numerical Modelling

Along with experimentation, an actuator line CFD model (OpenFoam®) of the machine has been developed. The PoliMi AL codes is based on the sectional approach for the lifting line aerodynamic force calculation and, more precisely, blade lines are divided into multiple segments, deriving from the intersection with the mesh. The force along the lifting line comes from 2-dimensional airfoil section aerodynamics according to blade element theory. Standard CFD approach resolves the flow velocities for the entire computational domain, the pisoFoam solver based on the PISO algorithm is used for this work implementing LES turbulent flow modelling with Smagorisnsky sub-grid scale model. Details about the code are provided in the full paper and the related results about IPC runs are analysed. In Figure 2 shows qualitative result about the wake development behind the rotor.

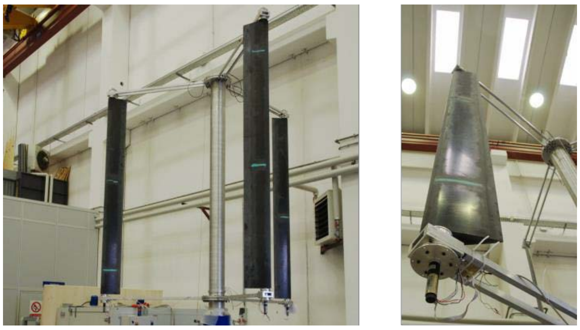

Figure 1 PoliMi IPC H-Darrieus VAWT

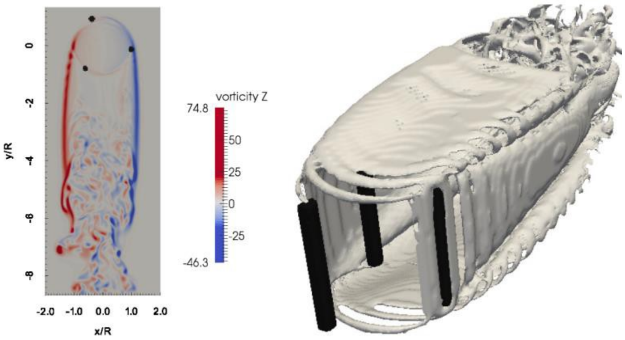

Figure 2 Qualitative wake representation from PoliMi CFD/AL code output

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Wind tunnel testing of a pair of VAWTs for offshore applications

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1 Introduction

For a long time, vertical-axis wind turbines (VAWTs) have been considered to generally have a lower performance than horizontal-axis wind turbines [1].

Recently, Dabiri and coworkers showed that the power of closely-spaced, counter-rotating VAWTs can be increased significantly [2, 3, 4] above their performance in isolation. The cause is a beneficial mutual interaction between the turbines. This interaction was first shown by [5] and has been confirmed since then numerically [6, 7] and experimentally through field tests [3]. This opens the perspective that paired VAWTs may become a competitive technology, with efficiencies comparable to horizontal-axis wind turbines.

VAWT technology can be particularly suitable for floating offshore applications. Nenuphar (www.Nenuphar-wind.com) is designing a large-scale (> 5 MW) floating offshore wind turbine (FOWT) with a pair of counter-rotating VAWTs on a single floating structure, leveraging counter-rotating VAWT technology advantages when used on a floater (improved performance, thrust and wake reduction). Cost of energy is crucial when developing deepwater wind energy and counter-rotating technology has the potential of drastically improving energy production while simultaneously reducing CAPEX costs.

To aid the overall design process and to determine the power increase achievable through turbine pairing, we have performed wind tunnel tests on VAWT scale models. In the present paper, we report on the results of these tests, with the following objectives:

- to experimentally measure the torque and mechanical power of a pair of VAWTs at different inter-turbine distances, and
- to validate numerical models through wind tunnel testing.

2. Approach and methods

We built scale-model VAWTs with a height of 0.8 m, a diameter of 0.5 m and a blade chord of 0.05 m. The rotors are designed to attain rotational speeds of 2000 rpm. The rotors are designed for maximum aerodynamic efficiency, with inclined struts and without external clamping. In this regard, the design is similar to the design we presented in [8]. The rotors were built in-house, using carbon-reinforced composite material for the blades and the struts. We use a brushed-DCmotor as generator, and have a used a dedicated torque sensor (DR-3000 from Lorenz Messtechnik) to measure the torque as a function of the azimuthal angle with a high sampling frequency, allowing detailed comparison with numerical models (see Sect. 2.3).

Preliminary wind tunnel testing of a single VAWT has been performed in our own facilities, with a test section that is two meters wide and one meter tall. A photograph of the set-up is shown in the figure on the right. The set-up with two counter-rotating VAWTs placed side-by-side, at varying distances and with both upwind and downwind rotation in the inter-turbine region, will be tested in the open test section facilities of Delft University of Technology, and the Von Karman Institute for Fluid Dynamics, in June 2016.

Nenuphar will perform comparisons between the experimental data results and its in-house simulation tools (Pharwen), based on vortex models which have been developed by Adwen Offshore, with subcontracting to Delft University, the CORIA inside the Madrillet Technopole, and Nenuphar. The model allows to simulate any wind turbine through a vortex panel method as described in [9]. This code has the advantage to compute the near wake of a VAWT with a good precision, and a relatively low amount of CPU time, which allows to capture the performance enhancement due to counter-rotating effect.

A detailed description of the measurements and the validation will be presented in the full version of this paper.

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Force measurements on a VAWT blade in parked conditions

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1 Introduction

One of the main issues for the survivability of vertical axis turbines is the loads in extreme wind conditions, where the turbine is parked. These loads will depend on the wind speed and the position of the blades in relation to the wind direction. This work contains an experimental study of the forces on a parked turbine, which can be used to estimate the storm loads.

Figure 1. The turbine prototype.

2 Method

The forces are measured on a 3 bladed 12 kW vertical axis turbine with diameter of 6 m and blade height of 5 m located at an open site. The blades have 0.25 m chord at the centre, and are linearly tapered 1 m from the blade tip, giving a tip chord of 0.15 m, see figure 1. On one of the blades, four single axis load cells are attached between the hub and the support arms, which will measure the forces on the blade and support arms combined. The measurements are obtained from 1 s mean values from the forces at each load cell. Data is then processed using the method of bins to calculate the average force at each wind speed. Wind velocities are measured using an acoustic anemometer located at hub height.

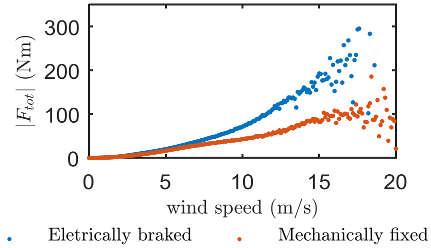

Figure 2. Average total force with respect to wind speed.

I the first measurement case, a small resistive load is connected to the generator, allowing the turbine to rotate at a very low tip speed ratio at high wind speeds. In the second case, the turbine is mechanically locked in place with leading edge of the blade with the measurement equipment facing the dominating wind direction.

3 Results

Data for both cases are presented in figure 2, where all data for each case is included in the plot. Here, the measured forces are on average lower for the turbine with fixed position. To analyse the origin of this, the data has been separated based on flow directions in figure 3. Here, one can expect that slowly rotating turbine, should have approximately equal forces for all wind directions, which seems to be in reasonable agreement with experiments. For the fixed blade, one can expect variations depending in the incoming flow direction, as lift and drag forces on the blade varies with the angle of attack. This is most significant for 240° to 270°, which is the dominating wind direction. In this case, the forces on the fixed is significantly lower than for the other cases, while for most other directions, the two cases are approximately equal. One would also expect lower forces in the case where the trailing edge is facing the wind. However, since this is not a common wind direction, there is not sufficient data to analyse this direction.

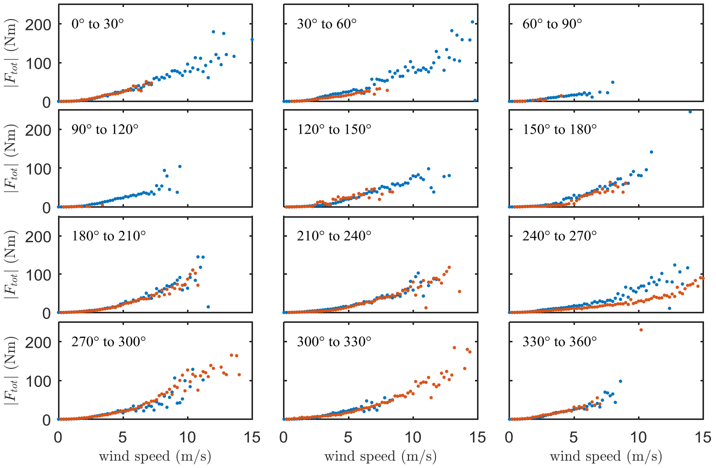

Figure 3. The average total force on the blade sorted by wind direction. In each direction the data has been bucket sorted by the wind speed.

From the directional analysis, it is shown that the reason why the locked turbine has lower forces on average is because most data is collected from the dominating wind direction, which is the direction where it gives lower forces.

4 Conclusion

This paper presents measurements on the blade forces on a straight bladed turbine at stand still. These results can be used to estimate the loads at extreme wind conditions, which is useful for the structural design of vertical axis turbines.

The study also shows that there is a significant directional dependence on the forces, and if the turbine position is fixed, a blade with the leading edge facing the dominating wind direction will experience lower forces than average. This could be useful for two bladed turbines, where if the turbine always is parked in the correct position with respect to the dominating wind direction, the forces would be lower than if it is parked in a random position.

Blackbird: A Hybrid CAES Storage Anchored Mono-TL VAWT-WEC

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1. European Offshore Wind Development

The majority of European offshore wind [OW] turbines installed to date essentially consist of scaled up conventional onshore three bladed horizontal axis [HAWT] turbines, founded almost exclusively on large diameter (4 to 8 m) steel monopiles (WD <35m) or piled tripods/jackets (WD ~ 30 to 55m), with some concrete gravity base structures [GBS].

In northern Europe, average CAPEX costs rose steadily between 2005 and 2010 (Ref. 1). This must at least halve for the industry to become subsidy independent. Current steel fixed and surface floating designs will struggle to achieve this. Major "gamechangers“ will be necessary, utilising simplified construction/installation operations and reduced use of costly installation vessels. Structures and foundations will likely be fabricated onshore and floated out to minimise weather downtime.

The nascent floating OW and marine hydrokinetics (wave and tidal) industries must develop and encourage capabilities avoiding conventional piling. This will likely lead to cost reductions, financial independence, fewer government subsidies, and competitiveness against baseline fossil fuels.

2. Seabed Topography and Geology

Several British, German and French wind project sites exhibit bedrock conditions at shallow depths, with soil cover of only <5-10 m. Large, heavy steel monopiles or “pin” piles are being driven and/or drilled and grouted. This is very costly, requiring specialist equipment spreads and weather dependent vessels. Several UK projects have been cancelled primarily due to shallow bedrock and in the US, high costs have cast doubts upon the future commercial feasibility of projects.

Turbine sizes increasing to over 8 MW suggest piled foundations will only be cost effective for WD<50m if seabed shallow geology allows non-drilled ungrouted piling. Adoption of non-piled foundations has been slow due to risk aversion and conservatism in a subsidy driven industry. Beyond 50 m WD, bedrock anchored floating units are increasingly seen as highly likely, perhaps eventually supporting vertical axis turbines[VAWT].

For fixed and floating structures, installation of single or multiple suction caissons is possible if soil overburden cover is deeper than the caisson diameter. Concrete GBS may be adopted if seabed conditions are hard and/or there are stringent settlement requirements. Groups of skirted seabed anchored foundation templates[SAFT] including suction caissons and pressure grouted tendon rock anchors are known techniques in onshore civil engineering, although such subsea anchoring technology does not yet exist for offshore use.

It is becoming clear that the floating wind, Wave Energy Convertor [WEC] and tidal industries will eventually require commercially viable, fast, robust subsea engineered ROV controlled seabed anchoring solutions for tension rock anchor and pile installation, using pre-installed floated out templates, operated via small vessels using designated launch and recovery systems [LARS].

3. Hybrid CAES Storage Anchored Mono-Tension Leg VAWT-WEC

Fixed OW structures of the North and Baltic Seas have been constructed on geomorphologically simple continental shelf seabeds with substantial soil cover, which has allowed piling. Such conditions are not representative of those which will be developed elsewhere in the world, consisting of steeply sloping rocky seabeds leading rapidly into deep water.

The floating wind industry is still in its infancy, with just a few scaled-down prototypes deployed globally. Most will not become commercialised at array scale or will be too expensive. Broadly, costs must be halved to survive without subsidies.

Offshore floating structures, specifically floating VAWTs could and should represent the future, to the west of Scotland and SW England, along the Atlantic Arc down to Morocco, off the seaboards of the USA (East and West), the coasts of Japan, Korea, India, China, Brazil, Norway and elsewhere. Many of these sites will require the development of new mooring and anchoring technologies, generally available in the Oil & Gas industry, but requiring specific tailoring to the different dynamic requirements of OW turbines, both HAWT and VAWT.

OW must become fully competitive with conventional energy Fossil fuel benchmarks. Heavy steel HAWT semi-submersible units may not be sufficiently robust and are expensive, even accounting for array size economies of scale. Much of the work has focused on the turbines and floating structure, but too little has been developed or considered regarding anchoring with either slack catenary, taut polyester or tension leg [TLP] solutions.

For sites in WD>50m, where wind resources are highest (Ref. 2), in defined environmentally non-threatening marine zones (Ref. 3) a floating technology concept is proposed. This consists of a double contra rotating VAWT similar to the DEEPWIND (Ref. 4) configuration. This is aimed at support from a fully submerged fibre reinforced concrete [FRC] floating buoyant structure secured via a single tension line with in line damping unit. The upper part of the floating structure includes a WEC motion damper. The tension line is attached via a plug-in FPSO connector to a flattened dome FRC subsea pumped CAES storage unit (Ref. 5). Weight is reduced during the empty condition by the use of high capacity single or multiple tension grouted rock anchors, pre-installed via a subsea template.

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Conceptual Design and Multi-Body-Simulation of a Floating VAWT

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Wind energy as one of the most important sources of renewable energy is a key technology to reach the climate targets 2020. Powerful and less turbulent offshore wind speeds offer a possibility to increase the energy supplement. One major problematic is that the levelized cost of energy overruns those of onshore produced wind energy. Especially high operation and maintenance as well as the investment costs can be reduced by to certain design changes. The investment cost of foundations amplifies with increasing water depths. Floating platforms provide a cost effective alternative to monopole foundations. A VAWT has its blade mounted along the tower and commonly the generator is located in the lower region resulting in a low point of gravity. This results in a smaller, cost effective floater with respect to a floating HAWT.

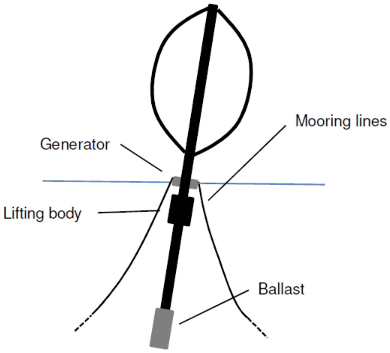

Figure 1: Sketch of the floating -VAWT

To a given 5 MW 2-bladed Φ-Darrieus rotor[1], different floater and turbine design options have been evaluated. Similar to DeepWind[2], a ballast stabilized mono spar design has been chosen for further investigations. In this design, the whole tower rotates with direct contact to the water. A direct drive generator is considered to be located close to sea level. The mooring lines are attached to the generator housing. A sketch of the concept is displayed in Figure 1.

The sub-sea segment of the tower is crucial for the floating stability. It consist of a floating body near the upper end and a ballast body at the bottom end. The floating stability can be adjusted through the variation of several geometrical parameters of the sub-sea section:

- floating body geometry
- tower length
- ballast mass.

This adjustment considers a maximum tilt angle of the turbine and an optimization of material costs and has been realized in an automated design process. In the preliminary design phase dynamical behaviour was neglected.

The design process is initiated with a definition of geometry parameter. In a first sub-process the floating ability is ensured. For this purpose the necessary lifting force is equalized with the sites weight. An extension of the lifting body in the downward direction provides the necessary missing lifting volume. Because of an extension of the lifting body influences the sites weight, this sub-process is realized iterative. A second sub-process calculates the hydrodynamic loads which are dependant of the sub-sea tower geometry. By applying all considered loads to a mathematical model the maximum expected tilt angle can be determined by an angular momentum at the anchor attachment to the site. If the expected maximum tilt angle of the site at hand is smaller than the allowed tilt angle, the sites parameters are saved for a cost comparison. Subsequent a new set of parameters is chosen and the design process is restarted.

Subsequently the determined conceptual design is included in a co-simulation of multi body simulation (MBS) and MATLAB. This environment will be used to investigate dynamical behaviour and floating stability of the VAWT. The aerodynamics of the turbine are modelled by look-up-tables for a NACA0015 profile with solidity of 0.1 and various TSR. Further loads are tower flow resistance, Magnus effect, generator torque, friction losses, turbine weight and buoyancy. In the current state of art eigenfrequencies and eigenmodes are investigated per component. However, in the described simulation environment also coupled eigenmodes and eigenfrequencies are covered. Such an approach is especially relevant for the dynamics of long blades as well as tall, thin walled tower. Both components are highly flexible and the applied loads could lead to critical motions that have not been considered in the conceptual design phase. By knowing these motions it will be possible to improve the design, for example by varying the material distribution and reducing the overall weight. Thus leading a cost competitive alternative in wind energy.

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Off-grid marked opportunities for floating VAWT

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1 Introduction

Off-grid energy solutions are becoming more relevant for industries that formerly relied on fossil fuels energy. This is due to the growing concern for the environment, new economical incentives to reduce carbon footprint and new technology development that make off-grid energy solutions more effective and less costly. In Norway energy prices are low and nearly 100% of the electricity is produced is from clean hydropower. However, some industries cannot connect to the grid because of their remote locations. Fish farms and lighthouses along Norway's extensive coastline represent activities that still uses diesel aggregates for electricity generation. Offshore vertical axis wind turbine (VAWT) concepts are currently being tested out for both activities. We have identified opportunities and challenges with VAWT's use for the fish farm industry and we are starting on a test project for the Norwegian Coastal Administration, at a site with a cold and harsh marine climate.

2 Fish farms in remote coastal areas

Aquaculture is a large industry in Norway. Norway's long coastline with its sheltered fjords, combined with cold fresh seawater, offers excellent conditions for fish farming and Norway is the leading producers of Atlantic salmon [1]. In 2013, 230 of the 991 locations of salmon and rainbow trout farms were using diesel generators [2]. Most of these fish farms are located in open seawaters with good wind conditions. Offshore fish farming, or open ocean aquaculture, is an emerging approach in order to limit the problem with fecal waste. This development towards open seawaters will lead to an increased number of fish farms without grid connection. There is also reason to believe that the environmental rules and regulation regarding the aquaculture licences to operate will become stricter in the future. Therefor there will be an increased demand for off-grid energy solutions for the growing fish farm industry.

3 Gwind

Gwind is an energy company in Stavanger that specialises in off-grid energy solutions and the company has a specific focus on off-grid energy solutions for marine applications. The Gwind off-grid solutions include solar, wind and batteries and a mixture of these technologies – often in combination with diesel aggregates. Gwind has developed and tested a floating VAWT prototype of 1 kW. Now we are looking into the possibility of up-scaling the VAWT specifically targeting the aquaculture industry in Norway. Gwind market research shows that there is a potential for cost efficient co_2 emission reduction for fish farms and at the same time securing the power demand, for the the daily feeding procedure, if a combination of wind energy and batteries are used.

4 Results, challenges and possibilities

In 2014 Gwind's floating prototype with the UGE 1 kw turbine [3] was tested outside Stavanger (Figure 1). The turbine and the mooring managed to survive extreme wind conditions of at least 30 m/s. Gwind's fish farm marked investigations shows that the average power use for a representative fish farm of approximately 6000 tons of biomass is 200 000 kWh per year. A VAWT of 50 kW in combination with batteries could replace 23% of the diesel use. For a 10 kW VAWT the diesel reduction is 5 %. The floating substructure of the VAWT represent a too large cost compare to the turbine cost. VAWT are believed to be more insensitive to harsh weather conditions such as heavy snow, freezing rain, salt and humidity [4]. This makes a VAWT probably more suitable for Gwind's off-grid business cases along the Norwegian coast. Motivated by this we are currently undertaking another test project together with the Norwegian Coastal Administration. They would like to lower the use of diesel related to operation of lighthouses. During the autumn of 2016 we will install a 3 kw VAWT turbine at the Skrova island located in a very harsh climate at 68ºN (Figure 2). This will not be a floating concept, but it will be an installation in marine environment that will give us valuable experience with VAWT in remote areas and challenging climate.

For a floating VAWT concept the leveraged cost of energy is too high and we see this at the biggest challenge in order to create a sound business case for an off-grid solution to the fish farm marked. Nevertheless, we continue to explore the fish farm marked and experiment with different wind turbine designs and we welcome all initiatives to get the cost down.

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Figure 1. Gwind floating VAWT pilot project in Stavamger. Photo: Simen Malmin

Figure 2. Skrova Lighthouse in the north of Norway will be test site for Gwind VAWT project together with the Norwegian Coastal Administration. Photo: Eva Andersen

On the Design, Laboratory Model and Performance of the Controlled Magnetic Journal Bearing for the DeepWind project

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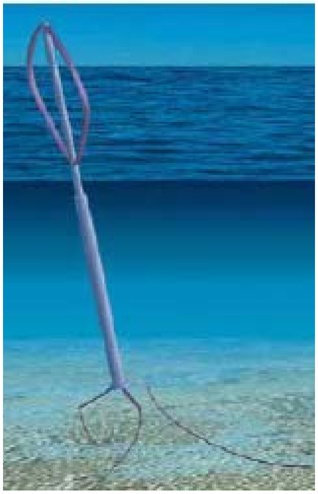

Fig. 1 Illustration of DeepWind concept,[1].

1 Introduction

DeepWind is a VAWT on a spar buoy with journal bearings centring the generator at the bottom, Fig. 1. The bearings connect the turbine system to the mooring system and allow rotation and differences in flotation forces. Forces arise from the action of the wind on the turbine flotation, unbalanced magnetic pull on the generator, the Magnus effect arising from a shaft rotating in moving water, etc. Challenges are to support all radial components of forces reliably on bearings mounted up to 300 [m] below sea level. Plain bearings, rolling bearings and magnetic bearings were considered. A controlled magnetic bearing was selected, to enable shaft position control at standstill and all other speeds, avoid mechanical wear, lubricant and losses. To achieve this, the bearings must be excited at all times. The bearings were modelled under steady state and dynamic conditions, Fig. 2, and the model was verified using a laboratory model, Fig. 3.

The model was used to implement a design tool relating the forces to be supported to the dimensions and materials of the bearing required.

The controlled magnetic bearing could apply force in 3 radial directions as required, a controller and power electronics converter is required for each direction, on each bearing. Current flowing a the winding associated with a direction applies a force of attraction in that direction.

As an example, for the 5 [MW] version, the design forces were estimated to be radial force mean =471 [kN], max=1336 [kN] for the top bearing, when the shaft

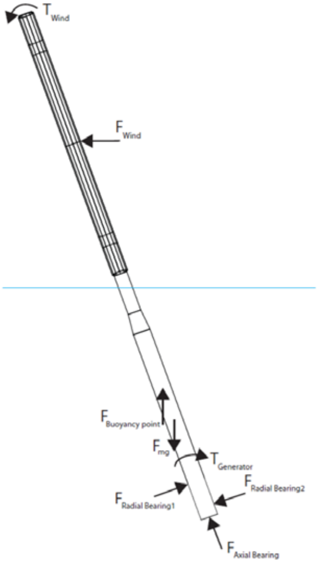

Fig. 2 Simple free body diagram showing forces acting on bearings, [2].

diameter was 5.5 [m], with 5.65 [m] length between the bearings and an air-gap of 0.01 [m]. The bearing required 37.7 [ton] of electrical steel, and 1.7 [ton] of copper. The maximum DC power required to supply the forces was 208 [kw], but the mean power was 26 [kW].

The model used was verified by tests on the laboratory arrangement of Fig. 3, [3]. The two lower stators are journal bearings, and the top stator is an actuator to apply force. The shaft position was sensed for measurements and feedback. Sample results are shown in Fig. 4, showing a step response of position for a move in each of two directions.

Using this model, and an adaptation to model the thrust bearings, all the bearings for the DeepWind project were calculated. There were several iterations, as adjustments were made to reduce the forces and optimise the size of bearing required for each position.

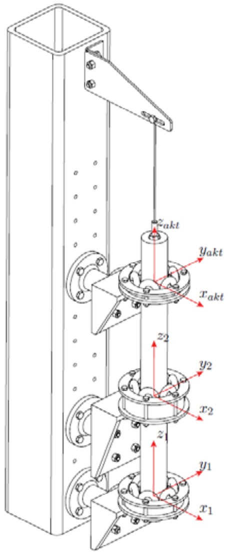

Fig. 3 Sketch of laboratory arrangement, [2].

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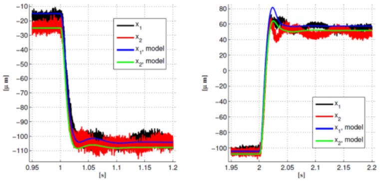

(a) *Step of -80 μm* **(b)** *Step of 160 μm*

Fig. 4 Position step response of shaft for different step inputs. measured and simulated results, [2].

On the Design and Performance of a Power Electronics Converter for the DeepWind project

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1 Introduction

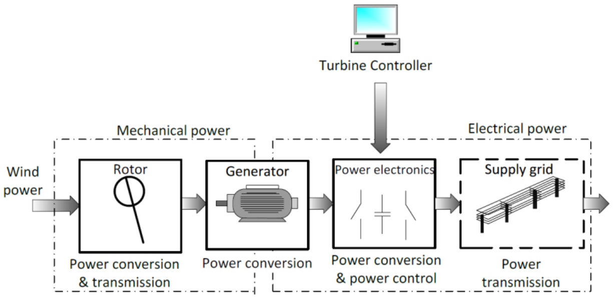

Fig. 2 Diagram of the power flow in the DeepWind system during normal operation. The gereator is acting as a generator.

DeepWind is a VAWT on a spar buoy with the generator at the bottom. Challenges are to design a high reliability four quadrant inverter suitable for a site with a sea depth of up to 300 [m]. DeepWind employs a Darreius wind turbine and ratings of 5 [MW] and 20 [MW] are planned, with a planned demonstrator rated 500 [kW]. The projected shaft speeds for these are 5.4, 1 and 30 [rpm] respectively. This makes the torque, hence the generator diameter, very large. To reduce the diameter, the effects of applying low generator side full load frequencies of 6 and 15 [Hz] have been studied, [1]. At these low frequencies, and the lower frequencies obtaining for speeds less than nominal speed, the large power transistors in the power converter expand and contract during every cycle of the power frequency, which puts added stress on the internal components of the transistor, adversely affecting the reliability of the transistors, [2]. It is planned to generate at a nominal voltage of 13.5 [kVrms] on the 20 [MW] version, to reduce the need for parallel connected output transistors. To reduce the blocking voltage on each output transistor, a neutral point clamped, three level architecture was selected, [3]. Control of the power flow is the only method available to control the Darreius

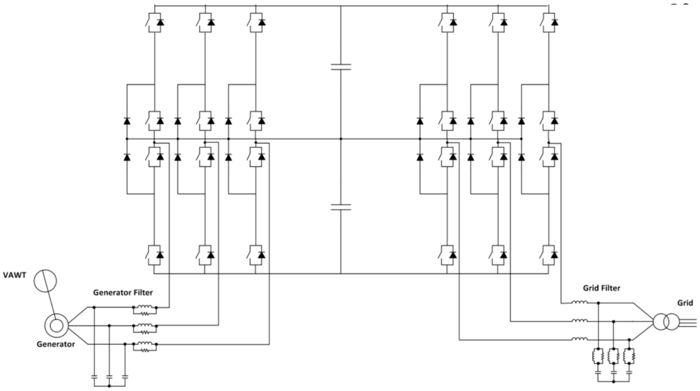

Fig. 1 Diagram of a Four Quadrant, Three Level, Neutral Point Clamped inverter.

turbine, and power flow from the grid to the shaft is required for starting. As the inverters function by high speed modulation, filters are necessary both on the generator side and on the grid side.

A mathematical model for the 3-level NPC converter was implemented and verified by testing in the laboratory, both as a generator side converter and as a grid side converter, in a range of normal and abnormal conditions, [1]. Work has continued after the closure of the DeepWind project, and is reported elsewhere, e.g. [4].

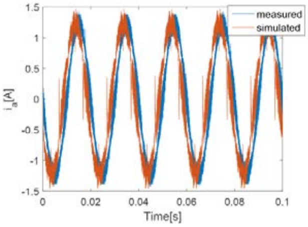

Fig. 3 Measured and simulated phase current in three level inverter.

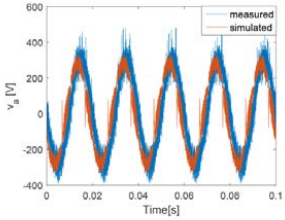

Fig. 4 Phase voltage measured at the load.

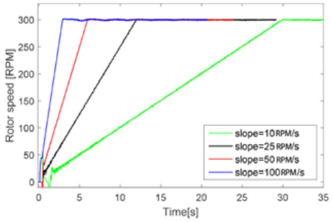

Fig. 5 Measured rotor speed at startup for various ramp slopes. Final speed, 300 rpm and no-load.

Siting of the power electronics system for DeepWind poses special challenges and needs closer study in order to finalise the physical design.

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Specification, Design and Performance of the Generator for the DeepWind project

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1 Introduction

DeepWind is a VAWT on a spar buoy with the generator at the bottom. Challenges are to design a high reliability, easily maintainable generator mounted up to 300 [m] below the sea. The Darreius wind turbine must be started by a motor, braked normally and abnormally, and held stationary by the generator. For the 20 MW version, 3*13.5 [kV] was proposed with lower voltages for the smaller versions. Generated voltage will be less for lower operating speeds. DeepWind work was to design the functional parts of the generator. Remaining challenges are: how to handle the seawater; mechanical design for low cost and maintainability, [1].

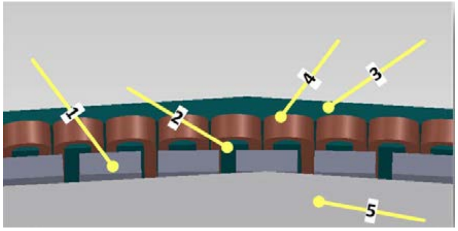
To avoid the use of an oil-filled gearbox, direct drive was selected, requiring high torque at low speed. A 1 [kW] demonstrator version was built and the larger machines were projected.

Attribute	**1 kW**	**500 kW**	**5MW**	**20MW**
Shaft Input Power	1.58 [kW]	550 [kW]	5.00 [MW]	22.5 [MW]
Shaft speed	430 [rpm]	20-27 [rpm]	5.262 [rpm]	5 (1) [rpm]
Rated Input torque	35 [Nm]	239-177 [kNm]	18 [MNm]	43 (215)[MNm]

Torque is inversely proportional to shaft speed for a given power and is a deciding factor for the machine diameter.

3 Generator

In view of the low speed a fractional slot winding was selected. A design tool was implemented and used to design the functional electromagnetic parts of the three larger versions, to minimize generator diameter, the diameter was very large, up to 36 [m] for 20 [MW] at 1 [rpm]. Different topologies of generator, radial flux, transverse flux, single rotor and double rotor were studied, all with permanent magnet excitation. Cooling was assumed to be by sea water, but it remains to determine the configuration of this. The surface- mounted permanent magnet, radial flux machines were found to be the best. The number of rotors added to the complication of the construction but made little difference to the mass of material required. To minimise the number of poles, and thus the diameter, studies were performed at low nominal frequencies, 6 [Hz] and 15 [Hz]. For speeds below 4 [rpm] the 6 [Hz] version required a smaller diameter. Above 4 [rpm], there was no difference. The minimum diameter found for the 2 [MW] version at 4 [rpm] was around 10.2 [m]. This was not optimised, but required 39.3 [ton] of NdFeB magnet, 123 [ton] of magnet steel and 29 [ton] of copper. At 10 [rpm], the required masses of material were considerably reduced, but the wind turbine team found this speed excessive.



1- Permanent Magnet

2- 2-Stator Tooth

3- Stator core

4- Coil

5- Rotor Core

Fig. 1 Generator air-gap view [2]

Fig. 2 The functional parts of the generator form two, thin-walled cylinders with relative rotation, [2]

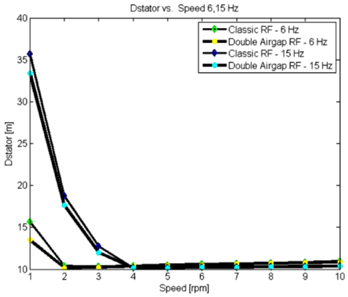


Fig. 3 Stator outside diameter as a function of speed for two full-load frequencies, [2], for a radial flux generator with surface mounted magnets.

For the 6 [MW] machine, the electromagnetic efficiency was found to be 98.5%, assuming a winding temperature of 20 ºC. the generator could develop sufficient torque to provide start, generation and braking under control.

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Development and numerical validation of an aero-servo-elastic code for floating vertical axis wind turbines.

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1 Introduction

The offshore wind industry faces great challenges to escape from low-depth areas where the bottom-fixed technology is confined to. Floating concepts are promising to reach untapped wind resources in deep sea. In order to reach market competitiveness, it is required to design light-weight floater concepts which would most probably cause greater unsteadiness levels in the aerodynamics of the wind turbines. It is therefore crucial to develop reliable design tools, which are able to model this source of unsteadiness.

Vertical-Axis Wind Turbines (VAWTs) are a potentially interesting candidate for this development as they show several advantages for floating offshore conditions and their aerodynamics is inherently highly unsteady. Classic BEM codes fail to model this complex aerodynamics [1] making floating wind turbines and VAWTs orphan of efficient and fast numerical simulation tools to design and optimize them. That is why NENUPHAR has developed, in collaboration with Adwen offshore, the PHARWEN code.

2 Presentation of the offshore aero-servo-elastic code PHARWEN

PHARWEN is an aero-servo-elastic tool for VAWTs. It couples ARDEMA 3DS, a 3D vortex panel calculation module to model the aerodynamics of the wind turbine, with NeSToR, a linear finite element calculation module which uses beam-elements to model its structure, and a wind turbine controller module.

NeSToR (Nenuphar Structural Tool for Rotor) has been developed in-house by Nenuphar and brings all the features to model a rotating structure (Coriolis effect, spin-softening effect…).

ARDEMA 3DS includes an inviscid flow solver [2], developed by ADWEN offshore, coupled to a Beddoes-Leishman dynamic stall model [3-4], developed by Nenuphar, which allows to accurately reproduces the aerodynamic loads, rotor power and rotor wake.

3 Numerical validation of PHARWEN

Two validation steps have been carried out to ensure that PHARWEN correctly models the VAWT aerodynamics, structural dynamics and the coupling between both of them. First, each module has been validated independently on simple cases (cantilever beam, wing,…) against analytical results and on VAWT test cases against high fidelity numerical tools. Secondly, the aeroelastic instability of the Goland's wing [5] has been investigated to test the code behavior under strong coupling effects.

In details, the set of numerical validation cases on a straight wing (assimilated to a cantilever beam) is listed below:

- NeSToR: Analytical results are used to validate the eigenmodes of the beam as well as its deformed shapes and internal loads when a distributed force is applied on the wing, such as its own weight or aerodynamic forces.
- ARDEMA 3DS: The same wing is considered this time as a rigid body and submitted to an incident flow at various angles of attack to check the aerodynamic forces applied on it.
- PHARWEN: the flexible wing is put into an incident flow at variable speeds to find its critical flutter velocity and compare it to analytical results. (Goland's wing [5])

Regarding the code validation on a complete VAWT, the geometry used is a 600 kW NENUPHAR onshore prototype (Figure 1) which is currently the largest H-shaped rotor in the world:

- NeSToR: Aerodynamic loads computed beforehand with ARDEMA 3DS (with no coupling) are applied to both NeSToR and a commercial beam-element model. Then displacements and internal loads resulting from both simulations are compared.
- ARDEMA 3DS: The wind turbine rotor is considered rigid and aerodynamic loads from a commercial CFD solver are compared to the ones computed by ARDEMA 3DS for several tip speed ratios.

As no numerical accurate benchmark exists for the aero-elastic coupling on VAWTs, the validation of PHARWEN is made thanks to experimental comparisons with different NENUPHAR VAWT prototypes. These results are part of another publication [6].

4 Conclusion

This paper presents the development and the numerical validation of an offshore aero-servo-elastic tool for VAWTs. Comparisons with analytical results and commercial software showed satisfactory results. This code will allow modeling realistically the aero-servo-elastic behavior of offshore VAWTs, which is not possible with today's state-of-the-art codes because of the low fidelity of the BEM model that they use. This work is an important step towards the certification and commercialization of floating VAWTs as it allows to compute the wind turbine loads accurately and to optimize the wind turbine by using a fast and reliable engineering tool.

Figure 1: NENUPHAR VAWT prototype

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2D Modelling of a 17 m Sandia VAWT

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1. Introduction

This work begins to explore the applicability for 2D Computational Fluid Dynamics (CFD) models in improving the accuracy of Blade Element Momentum Theory (BEMT) power predictions for Vertical Axis Wind Turbines (VAWTs). This is done using 2D models to replicate the lift augmentation that occurs during dynamic stall. Dynamic stall is a complex flow phenomenon caused by the dynamic nature of the rotating blades of a wind turbine. The orientation and rotation of the blades of a VAWT turbine mean that as the azimuthal angle changes the aerofoil achieves varying angles of incidence with the oncoming flow. This is the equivalent of a stationary aerofoil pitching. When an aerofoil pitches rapidly a large vortex is shed from the leading edge of the aerofoil which is referred to as the dynamic stall vortex. When the vortex is shed large drag and lift variations affect power production (Gharali and Johnson, 2013, Choudhry et al., 2014, Wang et al., 2010).

2. Developing a Methodology

Two models were set up in order to replicate the Dynamic Stall phenomena in a rapidly pitching aerofoil. The first model used varying inlet conditions to represent a varying angle of attack whereas the second model used the sliding mesh function available in FLUENT. The angle of attack was varied according to Equation 1 where $\propto$ is the aerofoil angle of attack and t is the current time step of the flow.

$$\alpha = 10 + 15\sin(18.67t) \tag{1}$$

Two meshes were created using a C shaped domain, one using varying inlet conditions and one using a moving mesh, each with an average y^+ of 1. The standard k-ε model was used with SIMPLE velocity-pressure coupling scheme. The free stream conditions of the flow were given to be: a freestream velocity with a magnitude of 14 m/s, density of 1.225 kg/m^3 and viscosity of 1.27x10^{-4} kg/ms as used in the study conducted by (Wang et al., 2010). The time step used was 1 second. Each time step underwent a maximum 50 iterations with residual convergence criteria set at 1x10^{-3}. The turbulence intensity of the flow was taken to be 0.08% with an assumed length scale of 0.07 m.

The varying inlet model had limited success in being able to mimic the effects of Dynamic Stall. This is because it was not able to replicate the development and shedding of vortices to the extent that the moving mesh simulation can.

3. The Sandia 17m Wind Turbine

The model developed in in the previous section was then modified to replicate the behaviour of the Sandia 17m Darrius Wind turbine operating at a wind speed of 14.5 m/s and 38.7 RPM. The model was altered to include the NACA0015 aerofoil and the blade motion was approximated through the use of a pitching aerofoil whose motion was modelled using:

$$\alpha = -2.02\sin(3.99t + 1.48) \qquad (2)$$

Where $\Delta\propto$ is the angular acceleration and t is time. Both lift and drag characteristics were monitored and the normal force of the turbine calculated and compared against experimental results. The time step used was 0.0215 s and 2000 times steps were undertaken to ensure convergence. The lift and drag characteristics were used to calculate the normal force coefficient and the results compared against experimental data from the blade's equator (Akins, 1989).

3.1 Results

The 2D model over-predicted the maximum and minimum normal force coefficient (Fig.1). Over-prediction when the blade is downwind may be because the model does not replicate the loss of momentum in the air caused by the upwind blade. On the upwind cycle the model appears to be over-predicting the effects of the dynamic stall vortices leading to higher power predictions.

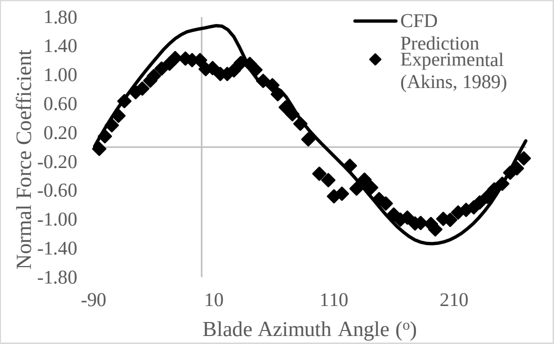

Figure 1: Comparison of CFD predictions against experimental data

3.2 Conclusions and Further Work

In conclusion the initial 2D models were able to predict some of the behaviour characteristics of the turbine but further work needs to be conducted to refine the model and establish if the standard k-ε turbulence model is the most appropriate for power prediction. Integration of BEMT methods will develop more accurate power predictions in the future.

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Large-Eddy Simulation of Counter-Rotating Vertical-Axis Wind Turbines at Low Reynolds Number in 2D

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1 Introduction

By placing two, counter-rotating turbines on a single platform, the torque on the platform can be controlled such that a taut mooring system is no longer necessary to take off power. Furthermore, using a system of clutches the angular momentum of each turbine could used to brake each of the turbines in case of a need of shutdown. For the power to be optimized, though, the wind turbines need to be oriented properly, or else one turbine will be directly in the wake of the other.

1.1 Mathematical Model

Our simulations are based on an artificial compressibility formulation of the Navier-Stokes equations, which can approximate nearly incompressible flows well. The governing equations are derived from the compressible equations by introducing an *artificial equation of state*, which we define by an isentropic assumption defined in terms of an artificial Mach number, M. The resulting compressibility effects can be shown to scale as $O(M^2)$, and with some assumptions the solution approaches the incompressible case as M goes to zero. We impose two types of boundary conditions, free-stream flow (far field) and prescribed velocity (wall).

1.1.1 Model Turbine

The VAWT chosen for this study was the one built and tested by Strickland and reported in Strickland [1]. Since the model VAWT was actually tested in a tow-tank, the average chord Reynolds number for turbine blades is approximately $40x10^3$. The width of the tow tank was 5 m, so the effect of the side walls on the turbine blades is negligible. However, the bottom of the blades were only approximately 35 cm away from the bottom of the tank, so the proximity of this boundary on the blades could have a significant effect on the flow around the blades. A diagram of the turbine and its mirror is shown in Figure 1.

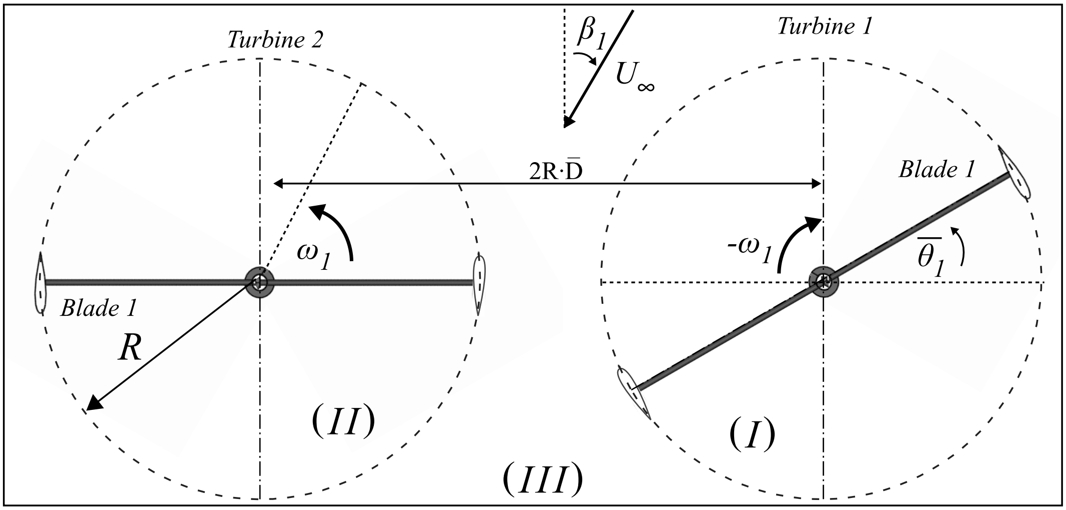

Figure 1. Plan view of counter-rotating VAWTs with definitions of VAWT radius R, azimuthal angular offset θ_0, and normalized distance γ.

1.2 Computational Domain and Moving Mesh Strategy

A structured approach is used to form the boundary layer elements around the airfoils. The rest of the computational mesh is fully unstructured and is generated using the DistMesh mesh generator. We adaptively refine the area behind the trailing edge of airfoils in order to improve the resolution. In addition, as high-order methods require meshes with curved boundaries. We use an elasticity-based approach proposed in [2], which tends to produce well-shaped meshes with globally curved elements.

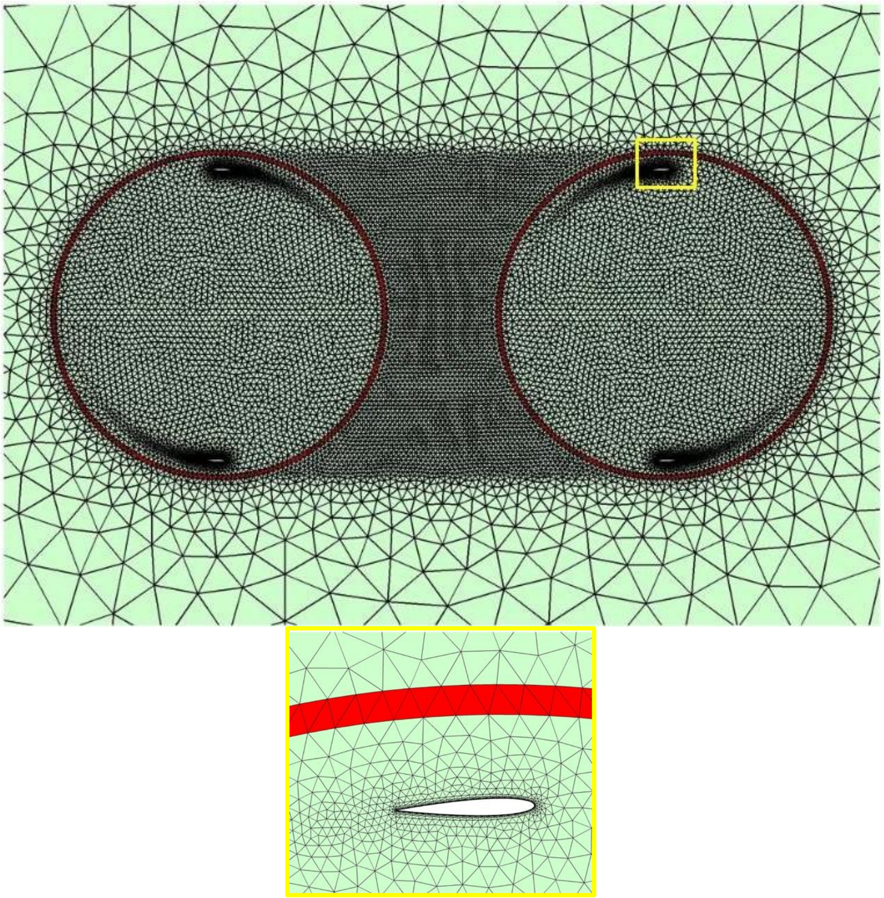

Figure 2. Unstructured Mesh for Double VAWTs. The initial mesh is showed on the top, where all the edge flipping operations happen in the area colored in red. A zoom-in plot is placed on the bottom for the area encircled by the yellow square in order to show structured mesh around the airfoil.

We partition the whole mesh into three parts-- two circle meshes around two turbines and one rectangle mesh with two holes for the rest of outside area. In our numerical experiments, two circle meshes are rigidly rotated according to the motion of two wind turbines and the outer mesh remains static. To glue all the parts together, we connect those boundary nodes of each part and form two intermediate layers of triangular elements. Due to the rigid rotations, the elements in the intermediate layers will become stretched and eventually inverted if there is no edge connectivity change. To address this problem, at each time step we can update the mesh connectivity in the intermediate layers by edge flipping operations. We can then flip their shared edge and produce two new triangles sharing the new edge with better element qualities. During each time step, we can perform this operation multiple times until the quality of all the elements in the intermediate layers are above a certain threshold.

5 2.1 Results

The results will be discussed in greater detail during the Colloquium.

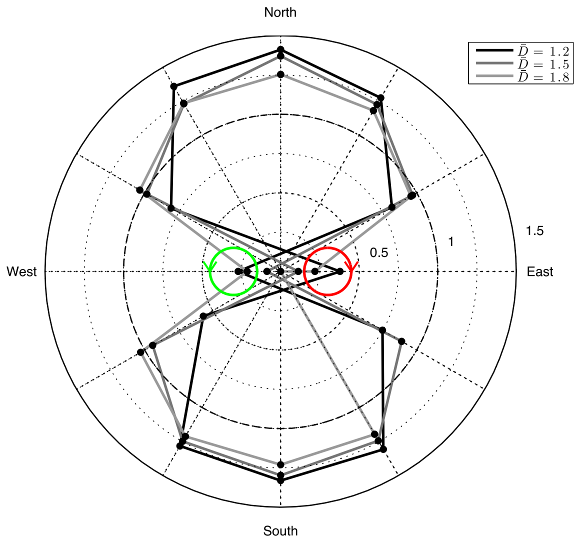

Figure 3. Average power coefficient of counter-rotating wind turbines as a function of wind direction and turbine spacing.

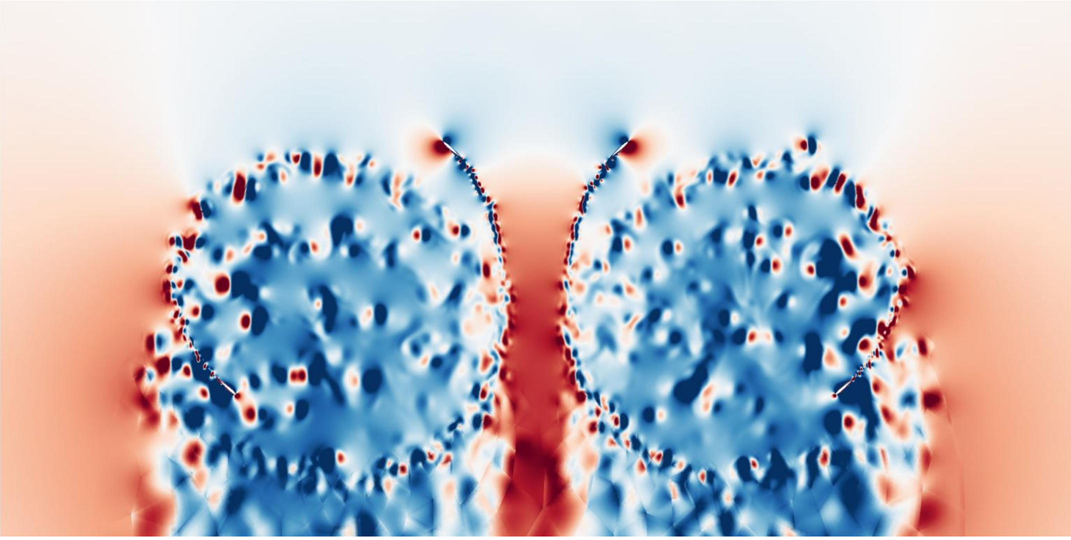

Figure 4. Snapshot of the normalized fluid speed for $\alpha_0=0°, D=1.2, β=0°, λ=5.0.

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Adaptive Slot Blowing for VAWT Blade Load Control

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Vertical axis wind turbines offer an attractive alternative to conventional horizontal axis machines, particularly for floating offshore installations. Insensitivity to wind direction and proximity of the drive-train to the water-level, render them structurally stable and potentially easier to maintain. One disadvantage, however, is their susceptibility to dynamic stall, which is characterized by large unsteady aerodynamic loads that can damage the drive-train leading components. Many of the proposed designs practically cannot include blade pitching for load control and thus a viable alternative is on-blade flow control. We recently studied the technique of leading- edge slot blowing by conducting proof-of-concept wind tunnel tests on a NACA 0018 blade profile. Practically, this required a moderate compressed air source, fed into a plenum within the blade, that supplied a leading-edge blowing slot. Using low momentum slot blowing, we induced separation with reductions in lift coefficient up to 0.5. On the other hand, using high momentum slot blowing we reduced or eliminated separation, with commensurate large increases in lift coefficient, easily exceeding 0.5. The net result was significant control authority over a large pre- and post-stall angle-of-attack range. The concept was further tested in an unsteady wind tunnel with the profile subjected to simultaneous and aggressive dynamic pitching and surging. By employing an adaptive blowing control algorithm, the oscillatory lift loads could be virtually eliminated over a large angle-of-attack range. These results furnished very encouraging physical proof that the technique is viable and warrants further development.

Analysis of Dynamic Pitch Control for Fatigue Life of Vertical Axis Wind Turbines

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Fatigue analysis is an essential part of a wind turbine design and can be a great limitation to its development[1]. All multi-MW nowadays are designed mainly toward better fatigue behaviour.

Our goal is to demonstrate the relevance of the implementation of a dynamic blade pitching device on a vertical axis wind turbine by studying its effects on fatigue life.

We based our study on CACTUS software, developped by SANDIA[2]. CACTUS is an Open Source aerodynamic software dedicated to Vertical Axis Wind Turbine based on vortex theory. It is an appropriate compromise between precision (RANS method, OpenFoam) and computational cost (actutator disk method, FAST) for this kind of study which will require a sensitivity analysis on several parameters.

The first task was to adapt CACTUS's existing source code in order to include dynamic pitching of the blades. The pitch control is defined by a Fourier sum of 2nd order, thus requiring 5 additional inputs to the initial Cactus inputs. The advantage of this approach is to avoid using tabulated data, which can be prone to interpolation issues.

Validation against experimental data was obtained by studying the evolution of the aerodynamic properties of a Darrieus tidal turbine as a function of the pitch angle. First a constant offset[3] and then a first order sinus function[4] were studied. The present approach showed good agreement with references.

MLife and MCrunch[5] softwares were then used. These codes are open-source, and developped by the NREL. They aim at the calculation of fatigue life for wind turbine components. We compared the fatigue life results for a wind turbine submitted to the same environmental conditions with and without pitch control and we later optimized the pitch angle variation law. The dynamic pitch control was found to be beneficial.

Keywords: vertical axis wind turbine, CACTUS, dynamic pitch control, fatigue life, MLife

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Vortex Particle-Mesh simulations of VAWT wakes over large scales

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1 Introduction

The aerodynamics of Vertical Axis Wind Turbines (VAWTs) is inherently unsteady and leads to a wake topology that is far more complex than for their Horizontal Axis counterparts. The robustness of VAWTs to turbulent conditions and different wake decay mechanisms has led to several claims of an advantage of VAWTs over HAWTs in wind farms, and thence the promises of higher power extraction densities.

Because of their unsteady aerodynamics, VAWT simulation and modeling tools have not reached yet the level of development of those for HAWTs, e.g. the Blade Element Momentum method. Over the last few years, the claims mentioned above and experimental results have motivated numerical investigations into VAWT phenomena; the volume of these efforts is quite underwhelming when compared to all the numerical works on HAWTs.

We have carried out large-scale, highly-resolved Large Eddy Simulation of the flows past Vertical Axis Wind Turbines by means of a state-of-the-art Vortex Particle-Mesh (VPM) method combined with immersed lifting lines (Chatelain, 2013). These simulations cover up to 15 diameters downstream of the machine and provide unprecedented insights into the vortical dynamics and the decay mechanisms of VAWT wakes, both with and without ambient turbulence.

2 Methodology

The coarse scale aerodynamics and the wake of the VAWT are simulated using a massively parallel implementation of a Vortex Particle-Mesh flow solver. This method relies on the vorticity formulation of the Navier-Stokes equations for incompressible flows. Advection is handled in a Lagrangian fashion using vorticity-carrying particles and all remaining spatial differential operations such as the solution of the Poisson equation to obtain the velocity, the diffusion and stretching terms, as well as the subgrid-scale modeling are efficiently computed on an underlying grid (Chatelain, 2008), thus in a Eulerian manner (information is interpolated back and forth between the particles and the grid using high order interpolation schemes). The generation of vorticity along the rotor blades is accounted for through an immersed lifting line approach (Chatelain, 2013), very much akin to a Vortex Lattice method, here combined with a Dynamic Stall model.

3 Results

We study a standard H-shaped low solidity VAWT. The simulations are first run in the absence of turbulence in order to isolate the inherent vortex dynamics of its wake; a turbulent inflow is then added by means of a synthetic eddy method.

A representative simulation is presented in Fig. 1 below, through a volume rendering of the vorticity magnitude. This clearly shows the complex structure of the wake: the top and bottom sides of the wake is generated from the tip vortices, whereas the lateral sides consist in the trailing vortex sheets, mostly due to the time-variation of the circulation of the blades. We also identify a recirculation region where, interestingly, turbulent structures tend to accumulate and then be intermittently shed into the far wake at a specific low frequency.

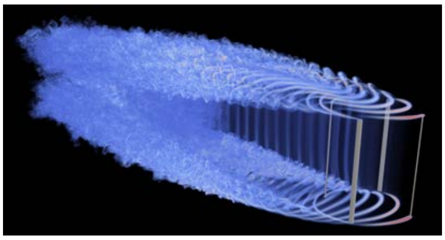

Figure 1: Simulation of a VAWT wake: volume rendering of the vorticity magnitude.

4 Conclusions

The results of the present study will lead to several insights into the vortex dynamics at play in a VAWT wake, both in terms of its mean flow and unsteady features. The impact of these dynamics for the deployment of VAWTs in wind farms is considerable: the generation of sideforces translates in wake deviations and intrinsic wake oscillations are reminiscent of the meandering phenomenon.

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Dynamic analysis of floating vertical axis wind turbines under extreme conditions

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Abstract

Floating vertical axis wind turbine (VAWT) is a very promising solution to harvest offshore wind resources due to its excellent cost-of-energy reduction potential. Currently a number of studies have been carried out to investigate the dynamic behavior of various floating VAWTs under normal operating conditions (Cheng et al., 2015; Cheng et al. 2016c; Wang et al., 2016), while very limited studies have been conducted under extreme conditions (Wang et al. 2014).

For the sake of safety, floating horizontal axis wind turbines (HAWTs) are usually parked with blades parallel to the wind direction in extreme conditions. However, large megawatt floating VAWTs usually operate at a fixed blade pitch angle; their dynamic behavior in extreme conditions is therefore different from that of floating HAWTs and is, if parked, dependent on the blade number and rotor azimuth angle. Moreover, floating VAWTs can also operate at a relatively low rotational speed even in extreme conditions. Whether a floating VAWT should be parked or not in extreme conditions is still unknown yet.

This paper deals with integrated dynamic analysis of floating VAWTs in extreme conditions; their dynamic behavior in parked condition and in condition with a low rotational speed is comprehensively studied and compared using fully coupled time domain simulations.

Three floating VAWTs three floating VAWTs with straight blades, with identical solidity and with a blade number ranging from two to four, are considered. They are mounted on the same semi-submersible platform with identical draft, displacement and mooring system. Properties of the three floating VAWT system, such as specifications of the rotors and structural and hydrodynamic properties of the systems, are described by Cheng et al. (2016c).

Fully coupled time domain simulations are carried out using the code SIMO-RIFLEX-AC which is a state-of-the-art aero-hydro-servo-elastic code developed by Cheng et al. (2016b). The aerodynamic load is computed based on the actuator cylinder (AC) flow model, which is originally developed by Madsen (1982) and further improved by Cheng et al. (2016a). The effect of turbulent wind inflow, dynamic inflow and dynamic stall is taken into account. The AC code has been verified with experimental data (Cheng et al. 2016a) and the code SIMO-RIFLEX-AC has been verified by a series of comparison with the HAWC2 (Larsen and Hansen, 2013) and SIMO-RIFLEX-DMS (Wang et al. 2013) code.

In this study, two scenario are assumed for extreme conditions, i.e. parked condition and condition with a low rotational speed.

- In parked conditions, the effect of rotor azimuth angle and blade number on the dynamic responses of three floating VAWTs is demonstrated. For each floating VAWT, a set of azimuth angle ranging from 0^o to 180^o is used combined with extreme wind and wave conditions.
- In conditions with a low rotational speed, the effect of different rotational speed and deceleration speed on the dynamic behaviour is presented.
- Lastly, a comparison on the dynamic responses in parked condition and rotating condition under extreme conditions is conducted.

As a whole, this paper investigates and demonstrates how floating VAWTs behave in extreme conditions, provides operating suggestions and can benefit their further development.

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Design of a Troposkein Two-Bladed Shifted Vertical Axis Wind Turbine

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In this paper a new approach distinct from the Vertical Axis Wind turbine (VAWTs) for both onshore and offshore applications was investigated. This new approach resulted from serious of experimental work to compare the performance of three scaled down models of two-bladed troposkein shape VAWTs. The first model is a conventional troposkein shape VAWT, where the shape created by the two blades resembles an oval. The design of the second and the third models relies on a configuration in which one blade is shifted vertically with respect to the other blade, named herein the Shifted Troposkein Shape-Vertical Axis Wind Turbines (STS-VAWTs) as shown in Fig 1. The distance of the vertical shift is 50% and 100% of the height of the blade for the second and the third models respectively, which is referred to 50% STS-VAWT and 100% STSVAWT. In order to ensure a consistent comparison, all the turbines were fabricated using the same overall height, radius, swept area and NACA 0015 airfoil shape. To achieve a highly efficient troposkein blade shape with much less bending stresses when it rotates about a vertical shaft, the coordinate data along the span of the blade should be obtained by using the Blackwell and Reis equations [1,2]. These equations have been solved numerically as the basis for drawing the original troposkein blade shape. Due to the fact that, original Darrieus troposkein blade shape demands high-quality fabrication combined with expertise, wind turbine manufacturing companies turned to design and build straight/arc troposkein shape configuration. This shape has been providing better aerodynamic performance when its β value in a range between 0.7 to 1.5 as reported by Blackwell and Reis. For this reason, the original shapes were plotted over the straight/arc troposkein shapes of the three turbine models, which were created and then tested in this project as shown in Fig. 2. In this figure, a close fit between troposkein blade shape and straight/arc blade can be observed for both 50% STS-VAWT and conventional models. Even though these two models have different β values, 1 and 1.5 respectively, its curves are very close to each other near the radius and straight section. In contrast, the difference that appears in 100% STS-VAWT model is due to the high value of β which is beyond the β range of troposkein blade shape. The purpose of this investigation was to

achieve two major objectives; the first objective was to reduce the production costs associated with VAWTs, whereas the second objective was to improve the performance of VAWTs. The results of the wind tunnel tests revealed that the 50% STS-VAWT model has superior performance results when compared against the conventional and the 100% models, as shown in the Fig. 3. Although all turbine models had the same swept area, the 50% STS model was lighter than the conventional model because the blade was shorter by 15.4%. Therefore, the mass of the materials used to construct the 50% STS was a 15.94% decrease in the weight of the blade compared with the conventional model, which is a corresponding 15.54% decrease in the material cost to build the 50% STS blade. The result of this improved performance combined with its lower production costs are the 50% STS model' s greatest advantages.

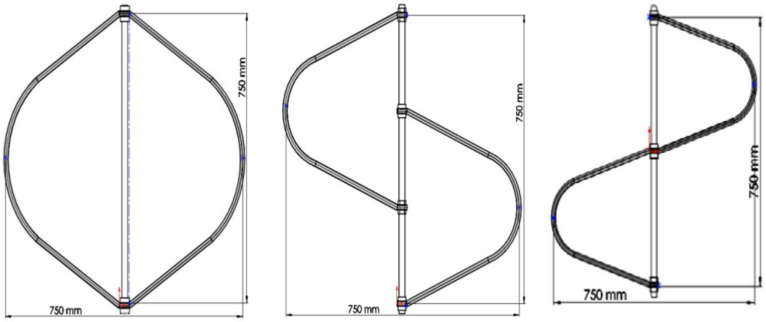

Figure 1. Vertical axis wind turbine models.

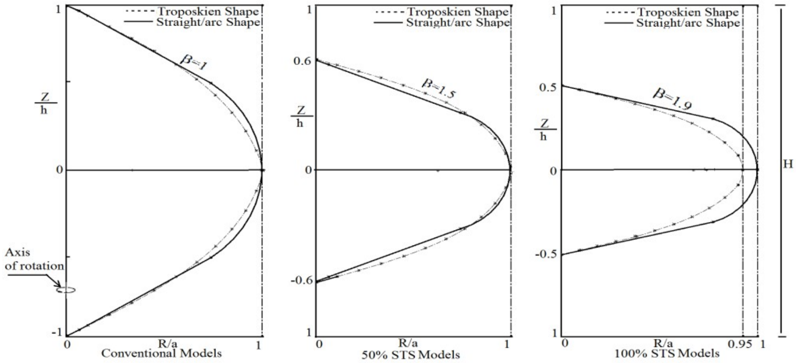

Figure 2. Comparison of troposkein blade shape and straight/arc blade.

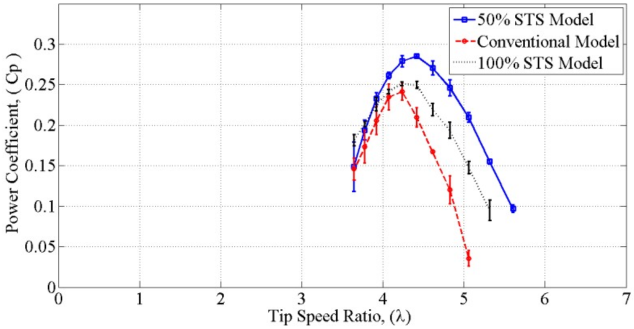

Figure 3. Power coefficient over a range of tip speed ratio at 700 RPM.

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Design of blade profile for offshore vertical axis wind turbines using Double Multiple Stream Tube model with tip loss correction

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Abstract

The present investigation demonstrates a systematic analysis on various airfoils for designing an offshore vertical axis wind turbine. An analysis on NACA 4 series, NACA 5 series and Selig profiles at different tip speed ratios under various chord Reynolds numbers in the range of 60000 to 160000 has been carried out using double multi-stream tube (DMST) model with and without tip loss correction, and lifting line theory (LLT) model. A better and fast prediction capability of DMST with tip loss correction is observed over the other tested methods. The power coefficients of a 3-bladed VAWT with each of the tested airfoils are then calculated using DMST with tip loss correction. Based on the results obtained at different chord Reynolds numbers, Selig profile S1046 is found to be suitable for the desired offshore VAWT.

1. Introduction

In recent years, an increasing interest on vertical axis wind turbines (VAWTs) has been boosted by a strong desire to maximize the renewable and sustainable energy extraction. These wind turbines are potentially useful either as an offshore floating wind turbine or as an onshore standalone system. However, the performance is not optimistic to meet the present global need of energy generation. In this direction, to improve the overall performance of this class of wind turbines, wind tunnel experiments are being conducted at IRPHE laboratory (France) in collaboration with the AEROPITCH project partners EOLFI and CORETI. A three-bladed VAWT with pitch control will be tested at chord Reynolds numbers in the range of 60000 to 160000. The scaling concept of this low range of Reynolds numbers is justified using the Similitude theory of Froude number. The laboratory scaled model (Figure 1) has the dimensions of 0.9 m height, 1.6 m diameter and 0.09 m chord. In order to select the best airfoil for this VAWT, numerous thick and thin airfoils were tested using an aerodynamic tool QBlade v9. In the present analysis, the results obtained with the selected NACA 4 series, NACA 5 series and Selig profiles are discussed.

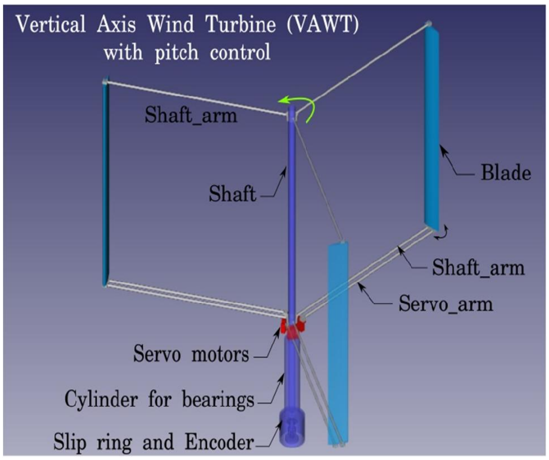

Fig 1. Model of VAWT to be tested in IRPHE Laboratory

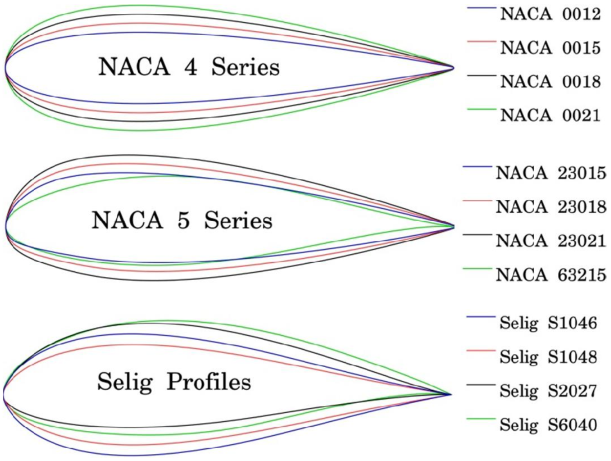

Fig 2. The selected airfoil profiles investigated in this study

2. Methods, Results and Discussion

The lift and drag characteristics of NACA 4 series, NACA 5 series and Selig airfoils under each chord Reynolds number have been obtained with XFOIL aerodynamic tool, and extrapolated for a complete rotational cycle using QBlade v0.9 [1-2]. A validation study of the present methodology using standard double multi-stream tube model (DMST), DMST with tip loss correction and lifting line theory (LLT) has been carried out in comparison to Sandia laboratory experiments [3]. As shown in Figure 3, a better and fast prediction capability of DMST with tip loss correction is observed. Using this model, analysis are carried out at Reynolds numbers of 60000, 80000, 100000, 120000, 140000 and 160000. The dimensions of the three-bladed VAWT are kept same as the experimental model. The results obtained in terms of power coefficients (C_P) at chord Reynolds number of 100000 are shown below. It is observed that the symmetric airfoils of NACA 4-series and Selig profiles have high performance coefficients for three-bladed VAWT as compared to NACA 5-series airfoils, and the C_{Pmax} is obtained with S1046.

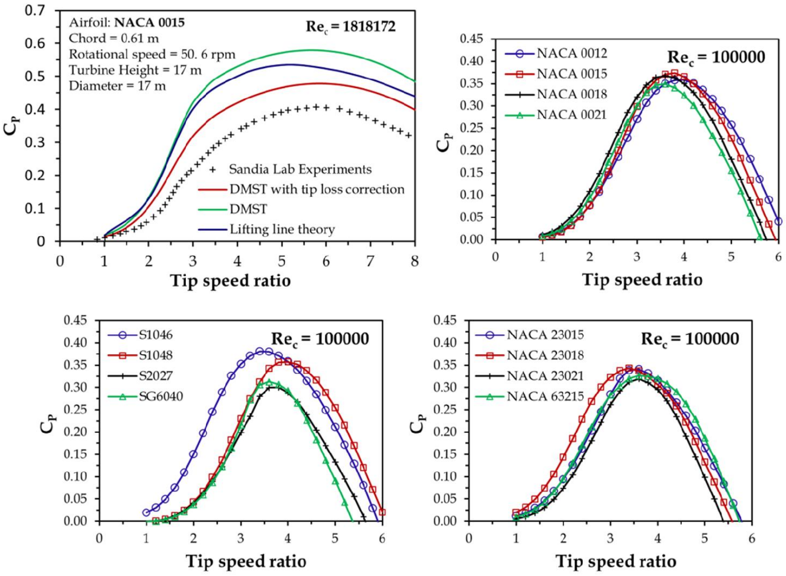

Fig 3. Validation of the model, and the results obtained at $Re_c = 100000$

3. Conclusions

From the comparison of all the tested airfoils at different chord Reynolds numbers, S1046 airfoil has been recommended for the project AEROPITCH. The optimal tip speed ratio (TSR) for S1046 is found to be 3.5 for the entire tested range of chord Reynolds numbers. For verification, the same analysis has also been carried out with unsteady lifting line theory.

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VAWT design using geodesic dome structure for floating platform application

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1 Background

The much lower center of gravity and reduced complexity, due to the absence of a yawing mechanism, are significant advantages of VAWT technology for offshore floating platform application, when compared with HAWT designs. Current VAWT designs characteristically are supported by a central column which affects stability, although not to the extent found in HAWT's. Additionally many current VAWT configurations present challenges with structural integrity. This paper discusses a novel design approach which overcomes these limitations, as well as offering additional benefits.

2 An alternative VAWT configuration

Our team has designed and patented a VAWT using multiple blades, cross cabled in a geodesic dome configuration, which is self-supporting, obviating the need for a central column. In addition this design offers higher solidity for improved performance at low wind velocities, with increased rigidity, much lower mass, and reduced cost. It presents an ideal design for installation on an offshore floating platform such as the VolturnUS that was developed by the Advanced Composites Center at the University of Maine.

2.1 Design characteristics

We will discuss the principal elements in the structural design, and show how the cable configuration contributes to the unit's structural integrity. Results from structural simulation modelling as well as experience drawn from prototype operation will be presented.

2.2 Performance characteristics

The results of simulation modelling of the turbines electrical generating performance under varying wind conditions will be presented, showing the efficiency of the design and particularly the improved specific performance under low to moderate wind conditions.

2.3 Floating platform configuration

We conclude with a discussion of the reduced mass required for a floating platform to accommodate the Lux Wind Turbine. We will demonstrate the advantages of this design for offshore use, together with a cost/benefit analysis..