10th EAWE PhD Seminar on Wind Energy in Europe
October 28-31, 2014 in Orléans, France

# Book of abstracts

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The **10th EAWE PhD Seminar on Wind Energy in Europe** takes place in Orléans, on the University Campus, from the 28th to 31st of October, 2014.

The local organizers, Boris Conan and Sandrine Aubrun, are very pleased to welcome all of you and they hope that you will spend a very pleasant and fruitful stay in Orléans.

This seminar provides an opportunity for PhD students and their supervisors from all over Europe to exchange information and experience on research in wind energy, to meet new people and create networks. It is organized and partially funded by the European Academy of Wind Energy (EAWE).

The first day of the seminar (28th of October) will be devoted to an introductory day of lectures provided by 'senior' PhD students and/or young Doctors. The goal will be to provide general information to new PhD and to master students on a broad panel of topics related to wind energy. This day will be an occasion for young students to get familiar with the various problematics of wind energy and for the presenters to have a first experience as a lecturer.

The last three days (29-31 of October) will be devoted to the conventional PhD seminar. PhD students will present their activities during 20min slots. Some specific sessions will be also devoted to poster exhibitions. The main topics covered by the seminar are:

- Materials and structures
- Wind, Turbulence
- Aerodynamics
- Control and System Identification
- Electricity conversion
- Reliability and uncertainty modelling
- Design methods
- Hydrodynamics, soil characteristics, floating
- Offshore environmental aspects
- Power generation by wind (wind park as power plant)

# Introductory Lectures on Wind Energy

dedicated to Master and young PhD students

10th **eawe**
PhD Seminar on
Wind Energy
in Europe

October 28, 2014
9:00-18:30
Polytech Orléans
site Vinci
Cabannes lecture hall

**Professional networking event: wine cocktail from 17:30**

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## PROGRAM

**Taking to the Air: Alternatives to horizontal axis turbines**
Jonathan Samson
University of Strathclyde, United Kingdom

**Wind tunnel testing for wind turbine aero-elasticity, floating platform dynamics and wind farm control**
Filippo Campagnolo
Technische Universität München, Germany

**Vertical axis wind turbines: aerodynamic challenges to be tackled**
Laurent Beaudet
Université de Poitiers, France

**Probabilistic Forecasting of Wind Power Generation**
Jethro Dowell
University of Strathclyde, United Kingdom

**Testing airfoils for wind turbines: the 3D challenges**
Marinos Manolesos
National Technical University of Athens, Greece

**Computational modeling of wind turbine in OpenFOAM**
Hamid Rahimi
Universität Oldenburg Institut für Physik & ForWind, Germany

**Introduction to the multi-scaling statistics of the wind**
George Fitton
ENPC, France

**Wind resource assessment in complex terrain, a wind tunnel approach**
Boris Conan
Université d'Orléans, France

# Book of Abstracts Index

# NUMERICAL INVESTIGATION OF AN AIRFOIL WITH MORPHING TRAILING EDGE FOR LOAD REDUCTION

**T. Wolff[1], J.R. Seume**

**[1]ForWind – Center for Wind Energy Research, Leibniz Universitaet Hannover, Institute of Turbomachinery and Fluid Dynamics, wolff@tfd.uni-hannover.de**

## ABSTRACT

The length of wind turbine rotor blades has been increased during the last decades. Higher stresses arise especially at the blade root because of the longer lever arm. One way to reduce unsteady blade-root stresses caused by turbulence, gusts, or wind shear is to actively control the lift in the blade tip region. One promising method involves airfoils with morphing trailing edges to control the lift and consequently the loads acting on the blade [1].

In the present study, the steady and unsteady aerodynamic behavior of a typical thin wind turbine airfoil equipped with a morphing trailing edge (see fig. 1) is investigated. Steady-state, two-dimensional Reynolds-Averaged Navier-Stokes (RANS) simulations have been carried out to determine an optimal trailing edge geometry. The defined geometry is used to investigate the unsteady aerodynamic behavior of the deformable trailing edge by time-resolved simulations with a deformable grid. The phase shift between the trailing edge motion and the lift coefficient is analyzed for different angles of attack and velocities of the trailing edge motion.

The oral presentation will include a short introduction into the topic as well as the flow solver and boundary conditions used for the simulations. Furthermore, the definition of an optimal trailing edge geometry will be discussed. Finally, the investigation of the phase shift between trailing edge motion and change in lift coefficient will be presented, including the procedure as well as the corresponding results.


Figure 1: Airfoil equipped with a morphing trailing edge

## REFERENCES

[1] Torben Wolff, Benedikt Ernst, Joerg R. Seume, "Aerodynamic behavior of an airfoil with morphing trailing edge for wind turbine applications", The Science of Making Torque from Wind 2014, Copenhagen, Denmark (Paper accepted)

# WIND TUNNEL TESTS AND WAKE EFFECTS OF PITCH- AND LOAD CONTROLLED MODEL WIND TURBINES

**J. Schottler[1], J. Peinke[1], M. Hölling[1]**

**[1]ForWind, University of Oldenburg, Institute of Physics, jannik.schottler@uni-oldenburg.de**

## ABSTRACT

It is well know that the working condition of a wind turbine significantly influences its wake, which in turn has a major impact on the performance of turbines operating within the wake [1]. Therefore, a further understanding of those interactions is necessary. This study aims to investigate the effects of a wind turbine's control system on its wake and on the performance of a downstream turbine.
We present wind tunnel experiments with two small model wind turbines (D=58cm) as shown in fig.1, each equipped with a collective pitch control system as well as a control of the rotational speed. The pitch control is realized by an encoder-equipped stepper motor that allows precise tuning and monitoring of the pitch angle. The rotational speed is controlled by a varying electrical load of the generator, which allows a dynamic variation of the tip-speed-ratio (TSR).

Detailed characterizations of the model wind turbines where conducted, whereby a maximum power coefficient of $c_{P,max} \approx 35\%$ was achieved. Wind tunnel tests of the control systems in partial- and full load condition proved a stand-alone performance at varying wind speeds.
As a next step, a second turbine is placed in the wake of a controlled model turbine as previously described. Further, the effects of different control strategies of the upstream turbine on the wake and therefore on the performance of the downstream turbine are examined. Those control strategies include an operation at varying TSR in partial load condition as well as changing the rated power and the maximal rotational speed by adapting the pitch control system. Finally, the influence of the control strategies on the overall performance of the turbine-array is investigated.

**Fig.1: Model wind turbine, rotor diameter D=58cm.**

## REFERENCES

[1] R. J. Barthelmie et. al. , "Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms", Journal of Atmospheric and Oceanic Technology, vol.27 (2011) pp. 1302-1317.

# The right size matters: Investigating the offshore wind turbine market equilibrium

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## ABSTRACT

Although early experiences indicate that the maturity of deployed technology might not be sufficient for operating wind farms in large scale far away from shore, the rapid development of offshore wind energy is in full progress. Driven by the demand of customers and the pressure to keep pace with competitors, offshore wind turbine manufacturers continuously develop larger wind turbines instead of improving the present ones which would ensure reliability in harsh offshore environment. Pursuing the logic of larger turbines generating higher energy yield and therefore achieving higher efficiency, this trend is also supported by governmental subsidies under the expectation to bring down the cost of electricity from offshore wind. The aim of this article is to demonstrate that primarily due to the limited wind resource upscaling offshore wind turbines beyond the size of 10 MW (megawatt) is not reasonable. Applying the planning methodology of an offshore wind project developer to a case study wind farm in the German North Sea and assessing energy yield, lifetime project profitability and levelized cost of electricity substantiate this thesis. This is highly interesting for all stakeholders in the offshore wind industry and questions current subsidy policies supporting projects for developing turbines up to 20 MW.

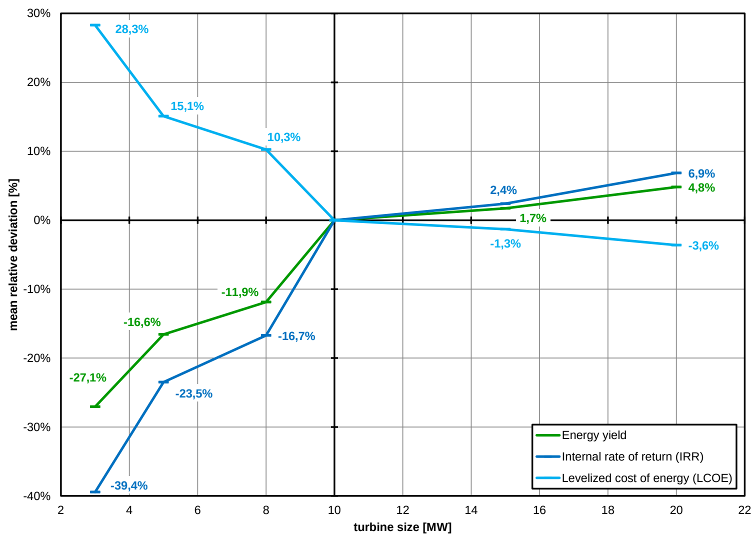


Figure 1: Mean relative deviations of energy yield/IRR/LCOE subject to OWTG size using 10 MW as a benchmark.

## REFERENCES

[1] Nikolaus Ederer, The right size matters: Investigating the offshore wind turbine market equilibrium, Energy, Volume 68, 15 April 2014, Pages 910-921, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2014.02.060.

# Physiological Responses to Wind Turbines in a UK Landscape

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## ABSTRACT

While there is generally strong public support for wind power, there also tends to be strong local opposition to proposed developments [1]. Although some suggest this is simply due to NIMBYism (Not in My Back Yard), other researchers have argued that the situation is considerably more complex [2]. Jones et al. [3] note that there is a lack of understanding of the relationship between people's attitudes to wind turbines and the number of turbines or groups of turbines that they will accept within certain landscapes. If the UK is to meet the 2020 targets, it will need to almost double its current onshore wind energy capacity, which will result in a significant increase in the number of turbines present in the landscape. As wind turbines become an increasingly common part of the UK landscape, the reaction of people to the cumulative effects of these wind turbines becomes increasingly important. This study examines physiological reactions to viewing multiple wind turbines/farms in a UK landscape, as well as assessing participant attitudes and characteristics.

Sixty participants were shown two videos that pan across a landscape in the UK that includes several wind farms. One of the videos panned left to right, the other right to left; the presentation order was counterbalanced. A pre-screening questionnaire was used to divide the group into those who like and those who dislike wind turbines in the landscape (30 in each group). Galvanic skin response and eye gaze were measured while they watch the videos. A two-way mixed ANOVA revealed a significant main effect for 'Turbine Group' with regards to fixation duration, Wilk's $\lambda = .752$, $F(4, 52) = 4.296$, $p < .01$, partial eta squared = .248. There was no significant interaction between turbine group and the like/dislike grouping, Wilk's $\lambda = .984$, $F(4, 52) = .213$, $p = .93$, partial eta squared = .016. These findings suggest that those who like and those who dislike wind turbines do not differ in terms of physiological arousal when viewing turbines. Findings also indicate that different turbines may attract different levels of attention, particularly turbines that are not moving.

## REFERENCES

[1] M. Wolsink, "Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives'," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 6, pp. 1188–1207, Aug. 2007.

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[3] C. R. Jones, B. J. Orr, and J. R. Eiser, "When is enough, enough? Identifying predictors of capacity estimates for onshore wind-power development in a region of the UK," *Energy Policy*, vol. 39, no. 8, pp. 4563–4577, Aug. 2011.

# WIND FARMS AND ACCEPTABILITY IN RURAL AREAS OF THE LOIRE VALLEY

**R.Garcia, F. Ardillier-Carras**

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## ABSTRACT

In a context of energy transition, marked by the recommendations of the Grenelle Environment for reducing GHG emissions, and the 2020 Factor 4, the rise of renewable energy in an landscape dominated by nuclear and Petroleum is a key element of a strategy for energy independence, especially in European countries, low in hydrocarbons.

The environmental benefit of renewable energy sources - water, wind, solar, biomass - clean, is indisputable. It could unite all conscious of ecological interest and sustainable development economic and political actors.

However, the installation of wind farms generates tensions and even use at all levels conflicts among both decision-makers and citizens whose environmental concerns displayed translate into practice by rejecting these facilities. The acceptability of infrastructure is yet in view of the behavior of distrust and opposition to the project, a prerequisite for the development of the main renewable energy sources.

This is a thread revealing cleavages deep political, economic and social order in France it is not the same in all European countries where the question of the acceptability arises differently. The look of the geographer takes here all its meaning, both to treat physical and economic conditions for the production of renewable energy, as for the analysis of the territories or factors for sustainable development in rural areas.

Faced with the dilemma of sustainable development, environmental conservation, reducing energy dependence via the "bouquet" energy, as well as financial benefits in rural areas, supports the production of wind power, the debate and addresses a fundamental component of energy policy in the EU.

# DISTRIBUTED CONTROL OF WIND FARMS USING A FLOW INTERACTION MODEL AND A MULIT-AGENT APPROACH

**M. Vali[1], M. Kühn[1]**

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## ABSTRACT

Large-scale wind farms (WFs) are rapidly growing worldwide due to more deployment of wind energy. EWEA has reported wind energy targets to produce almost half of EU electricity demand by 2050. One pathway to materialize this ambitious goal is the further improvement of the cost-effectiveness of wind energy e.g. with the exploitation of WFs with new advanced control algorithms.

Wind farm control (WFC) is much more challenging than control of a single wind turbine due to aerodynamic interactions among turbines. Theses interactions come from the fact that downwind turbines are in the wake of upwind turbines. In today commercial WFs, individual turbines are regulated independently disregarding their interactions. Thus, new advanced control algorithms for both individual wind turbines and WFs are needed to minimize wake-induced loads and energy losses. The main objective of this PhD project is to develop and test new advanced WFC concepts to reduce wake effects in WFs (Figure 1).

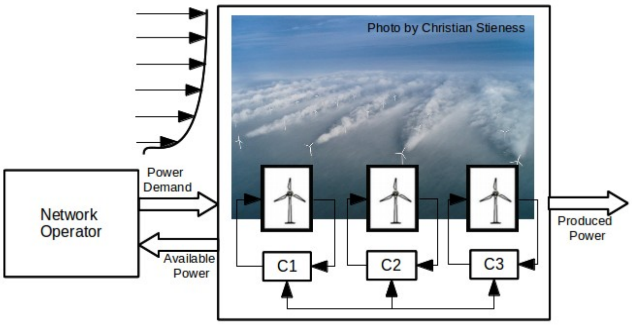


*Figure 1: Schematic demonstration of distributed architecture of wind farm control*

So far, several model-based and model-free approaches have been proposed to WFC [1, 2]. Existing results are mostly based on static models. There is still no development of dynamic control in the classic sense for WFs [2]. The main focus of the present PhD project is to elaborate the exploration in this area. The next two steps aim firstly to use system identification methods for the development of a simple engineering model of wake-induced interactions of three wind turbines located in a row. Thus, it is possible to analyze WF behaviour as a unique interconnected multi-agent system. Secondly, an advanced distributed control system is developed for this modeled row of turbines, which can be extended to a whole WF with several machines. In this concept, turbines share information with their neighbors to optimize WF performance. Although model-free optimization approaches [1, 2] verify the effectiveness of distributed control for WFs, they suffer inevitable drawbacks such as slow convergence and inaccuracy due to lack of the wind turbine interactions model. In comparison with them, this PhD project intends to explore the importance of aerodynamic models for WFC. Finally, the effectiveness of two newly developed approaches for three turbines located in a row is evaluated through some simulations made by open source *SimWindFarm* [3] simulation model.

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[2] T. Knudsen, T. Bak and M. Svenstrup: "Survey of wind farm control – power and fatigue optimization", Wind Energy, Published online 9 May 2014 in Wiley Library.
[3] J.D. Grunnet, M. Soltani, T. Kundsen, M. Kragelund and T. Bak: "Aeolus toolbox for dynamics wind farm model", Proc: European Wind Energy Conference and Exhibition (EWEC) 2010, Warsaw.

# Wind Farm Modelling and Control

**S.Poushpas, B. Leithead[1]**

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**To comply with the grid code requirements wind farm operator must have full control on its output power. this can be done using a central (higher level) control system along with each individual turbine power adjusting control system (PAC)[1][2]. The central control system uses the available data (flags) from each turbine to dispatch the power demand between them based on their power output. The aim is to dispatch the demanded power in such a way to optimize the output power of whole wind farm and reduce the mechanical loads on each individual wind turbine.**
**In this study the aim is to develop a wind farm control algorithm to provide these ancillary services while taking into account the local wind turbine conditions and their availabilities.**
**A suitable wind farm model is developed in this study for wind farm control objectives.**

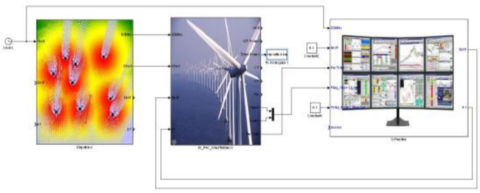
Figure 1, wind farm model

**Wind farm model contains ten 5MW Supergen wind turbine models. Each turbine is equipped with a full envelop controller with an augmented power adjusting controller (PAC). Both controllers for each turbine are written in C code and validated against similar controller in Bladed.**

**A Wind farm control algorithm is developed for absolute and Delta control for grid support.**

[1] "Development and application of the power adjusting controller." [Online]. Available: http://www.supergen-wind.org.uk/docs/presentations/GA2014_Posters/Stock.pdf. [Accessed: 11-Jun-2014].

[2] "The Power Adjusting Controller." [Online]. Available: http://www.supergen-wind.org.uk/docs/presentations/5th_Seminar_Presentations/2012-EdinburghPresentation-A_Stock.pdf. [Accessed: 11-Jun-2014].

# AGGREGATE WIND FARM POWER PERFORMANCE CURVES

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## ABSTRACT

The aim of the present project is to obtain the aggregate wind farm power curve for a wind farm based on data collected using SCADA system. The power curve is plotted for single turbine , group of turbines and wind farm. The power performance for a wind farm is examined as a single power curve that describes the power characteristics of this wind farm . The errors and uncertainties in the power curve are also examined and the effect of turbulent wind is also included .

This project examine the impact the size of the wind farm , density of the turbines ,by making careful sub-selections of turbines in a given area and turbulence influence by binning by chosen turbulence classes. The final and most challenging part of the project is to develop a suitable statistical model that can be used to compute the aggregate power curve given a known individual power curve and other key parameters, including at minimum turbine spacing, total number of turbines.

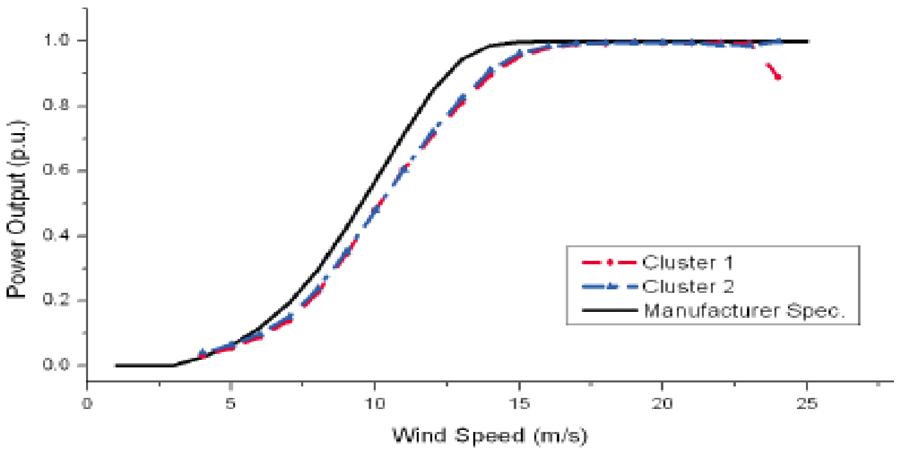


Figure 1: Equivalent aggregate wind farm power model.

## REFERENCES

[1] Hayes, B.P., Ilie, I., Porpodas, A., Djokic, S.Z., “Equivalent Power Curve Model of a Wind Farm Based on Field Measurement Data”, PowerTech, 2011 IEEE Trondheim, pp. 1-7.

# Development of a wind farm tool using an advanced actuator disk model

**M. Moens[1], M. Duponcheel[1], G. Winckelmans[1], P. Chatelain[1]**

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## ABSTRACT

The present project aims at improving the level of fidelity of unsteady wind farm scale simulations through an effort on the representation and the modeling of the rotors. The chosen tool for the simulations is a Fourth Order Finite Difference code, developed at Université catholique de Louvain [1]; this solver implements Large Eddy Simulation (LES) approaches. The wind turbines are modeled as advanced actuator disks : these disks are coupled with the Blade Element Momentum method (BEM method) and also take into account the turbine dynamics and controller.
A special effort is made here to reproduce the specific wake behaviors. Wake decay and expansion are indeed initially governed by vortex instabilities. This is an information that cannot be obtained from the BEM calculations. We thus aim at achieving this by matching the large scales of the actuator disk flow to high fidelity wake simulations produced using a Vortex Particle-Mesh method [2]. It is obtained by adding a controlled excitation at the disk.
We apply this tool to the investigation of atmospheric turbulence effects on the power production and on the wake behavior at a wind farm level. A turbulent velocity field is then used as inflow boundary condition for the simulations, computed beforehand by means of LES.

## ACKNOWLEDGMENT

We gratefully acknowledge the support of GDF Suez for the fellowship of Mrs Maud Moens.

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# RECENT EXTENSIONS OF THE QBADE CODE AND COMPARISON WITH WIND TUNNEL MEASUREMENTS

**D. Marten[1], G. Pechlivanoglou[1, 2], C.N. Nayeri[1], C.O. Paschereit[1]**

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**[2]Smart Blade GmbH, Berlin, Germany**

## ABSTRACT

The Open Source wind turbine design and simulation tool QBlade [1] has been under development at the Institute of Fluid Mechanics and Technical Acoustics of the Berlin Technical University since 2010. The QBlade software and its functionality was already presented at the 9th EAWE PhD seminar. Recently a new version (v0.8) of QBlade was released to the public. Version 0.8 introduces easy to setup, full aeroelastic simulation capabilities of a wind turbine rotor through a coupling to the FAST [2] software suite from NREL (National Renewable Energy Laboratory). To enable this coupling, preprocessors have been implemented in QBlade's graphical user interface, that generate the blade's structural and aerodynamic properties, calculate its mode shapes (fig.1) and frequencies and generate turbulent wind inflow files. In this paper the newly implemented functionality, the applied methodology and the coupling with FAST are presented in detail.

Subsequently, simulation results obtained with QBlade from a 3 m diameter research wind turbine, funded by the German Science Foundation (DFG), that was constructed in 2013 at the TU Berlin, are compared with measured data from wind tunnel test for several different yaw cases.

QBlade is constantly being maintained, validated and advanced with new functionality. Currently an unsteady lifting line – free vortex wake algorithm is being implemented and, through a cooperation with the IMT (Instituto Mauá Tecnologia), a Class II semi empirical trailing edge noise prediction model [3] is being integrated in the software using data generated by XFOIL's panel method and QBlade's BEM method. These new developments and the future plans for QBlade will also be briefly presented.

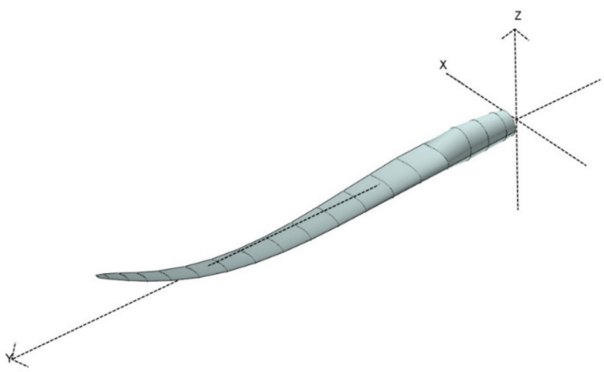


Figure 1: 2nd flapwise mode shape of the NREL 5MW reference blade, QBlade visualization

## REFERENCES

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# Integrated aero-structural optimization of wind turbine rotors

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## ABSTRACT

The design of wind turbine systems is a complex engineering activity that typically aims at delivering the lowest possible cost of energy (COE). The inherent multi-disciplinarity of the design activity and the intricate couplings amongst design variables render the problem extremely challenging [1].
The present work describes an integrated aero-structural optimization of wind turbine rotors that includes the aerodynamic shape optimization, the evaluation of the relevant load conditions and the optimal sizing of the structural configuration, considering the mutual couplings between the various sub-disciplines and simultaneously accounting for the presence of several design constraints.
Previous studies have returned significant issues in tackling the optimization process with a single global optimization approach [1]. In the present study, two different strategies have been investigated. The first approach, hereafter named "sequential", consists of two consecutive steps. First, a family of rotor aerodynamic shapes is created by optimizing the chord distributions of the blades to get the maximum annual energy production (AEP) for different values of solidity and maximum chord, which are introduced as constraints throughout the optimization process. Second, the optimal twist distribution is found maximizing the power coefficient for the given chords. Third, each of these configurations goes through a subsequent structural optimization. Eventually, the global optimum solution is the one producing the lowest COE. Assuming that the family of blades describes a representative field of solution, this procedure allows for a good identification of the global minimum.
The second optimization strategy, hereafter called "nested", is instead implemented having an automatic optimization routine evaluating the aerodynamic parameters through the COE. The cost function of this outer loop includes the blade structural optimization, which internally minimizes blade mass, the evaluation of the AEP and eventually the computation of the COE.
The two different strategies have been tested using as initial guess the baseline reference wind turbine developed during the European project INNWIND [2]. As it is clear in Figure 1, using the sequential optimization a lower COE is identified at higher rotor solidity. The new configuration has a lower aerodynamic efficiency, resulting in a small loss of AEP, but significant weight savings that overcome the aerodynamic disadvantages, resulting in a lower overall COE. The preliminary results obtained from the nested optimization approach are comparable.

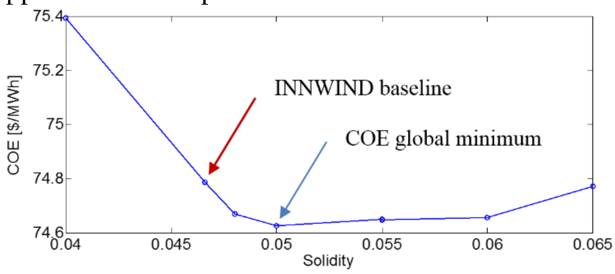


**Figure 1: 2D diagram of the results from the sequential aero-structural optimization**

## REFERENCES

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# Is blade element momentum theory (BEM) enough for smart rotor design

**Wei Yu[1], Carlos Simão Ferreira[1], G.A.M van Kuik[1]**
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## Abstract

Smart rotor emerges as an innovation technique to reduce the impact of dynamic loading on wind turbines. Local movement of distributed aerodynamic devices will enhance non-uniformity and dynamic effects of load, which will challenge applicability of blade element momentum theory (BEM) for smart rotor control design since its assumptions, quasi-steady state and dependent annuli. From a recent report fom Sandia Lab of field test of wind turbine with trailing edge flaps, an unsteady aerodynamic model for the response to turbulent wind and AALC device actuation is needed and a dynamic wake model is necesary [1]. However, most of previous aeroseverelastic study of smart rotor still based on BEM or combined with engineering dynamic inflow models, none of them verify the applicability of BEM for these cases.

In this paper, a free wake model which combined vortex ring with semi-infinite cylindrical vortex tube was developed, and applied to actuator disc with non-uniform and dynamic load. After the model is completed, it was first tested in a steady and a dynamic load case. Three main load cases, non-uniform steady load, uniform dynamic load and non-uniform dynamic load, are investigated. Results from this model were compared with BEM, and with two widely used engineering dynamic inflow models for dynamic load cases. Investigation from non-uniform steady load case shows that effect of local changed load do exist on induced velocity at whole actuator disc plane, though it's not huge when thrust coefficient changed -1/9 locally. For uniform dynamic load case, time delay predicted by free wake vortex ring (FWVR) model is larger than that estimated by Øye dynamic inflow model, and time delay predicted by the latter is larger than that from Pitt-Peters dynamic inflow model for all investigated reduced frequencies. It's concluded from dynamic non-uniform load case that both the two engineering dynamic inflow models predicted well at moderate frequency, but both of them either underestimated time delay at lower frequency or overestimate it at higher frequency, when compared to FWVR. Results from dynamic non-uniform load case further prove incapability of independent annuli assumption of BEM in local changed load case. And phase delay from FWVR only existed in uniform dynamic load case, but not in the non-uniform dynamic load case.

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# Design of a Model Floating Wind Turbine to Measure the Coupled Response to Wind and Wave Action

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## ABSTRACT

This project investigates how to better scale wind turbine rotors inorder to build more representative scale models of offshore floating wind turbine systems. Previous experiments have designed models with the goal of maintaining the Froude number and mass distribution[1].The blade chord Reynolds number drops by several orders of magnitude in such models,this is partiallycorrectd by increasing the windspeed. However doing this increases the drag on the platform significantly and as such the model is limited in its usefulness. The aim of this project is to address the issue of the Reynolds number deficit by radically redesigning the rotor such that the coefficient of thrust of the rotor is representative of a full scale system.

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# Analysis of Inflow parameters using LiDARs

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## ABSTRACT

Remote sensing of the atmospheric variables with the use of LiDAR is a relatively new technology field for wind resource assessment in wind energy. The validation of LiDAR measurements and comparisons with other sensing elements is of high importance for further applications of the data.

Within the framework of LAWINE (Lidar Applications for Wind farm Efficiency) project initiated by ECN, The Netherlands in cooperation with XEMC Darwind, AventLidar Technology and TU Delft under the framework of Top consortium for Knowledge and Innovation Offshore Wind (TKI-WoZ), two measurement campaigns are carried out to evaluate the applications of LiDAR in wind energy. The project lays emphasis on testing and developing the LiDAR technology, wind resource and power performance assessment, optimisation of wind turbine control, load reduction and optimisation of wind farm operation [1].

A measurement campaign with 2 Leosphere vertical scanning WindCube LiDARs and met mast measurements is used for comparing inflow wind variables from LiDAR, sonic and cup anemometers [2]. The comparison considering different factors along with probable causes and solutions are presented here. The aim of the study is to detect the errors in the mat mast installations, improve the uncertainty analysis and allows accurate estimation of inflow properties for wind energy purposes.

Another measurement campaign with a 5 beam forward looking WindIris LiDAR from AventLidar Technology installed on top of a wind turbine is used to analyse the inflow parameters. The inflow parameters using the forward looking LiDAR are compared to the metmast and other vertical scanning LiDARs. The aim of the study is to understand the inflow wind parameters and compare them to the neighbouring sensors and metmast data for evaluating the wind flow.

The results of the analysis would be further used for the modelling the wind towards the wind turbine for efficient control of the wind turbine.

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**Keywords**: remote sensing, lidar data, wind resource assessment, wind data analysis

# 3D stochastic gusts as an alternative to the Mexican hat wavelet

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## ABSTRACT

During the design process of wind turbines, extreme gust loading is usually assessed with deterministic waveforms. Current standards prescribe a fully uniform Mexican hat wavelet combined with a class-specific amplitude. Although this method certainly helps to set clear design limits, the Mexican hat wavelet describes a shape that holds little connection to real life.As such, two important issues arise. First, the assumption of a uniform perturbation velocity across the rotor plane leads to very conservative load predictions. And second, control algorithmsmay be wrongfully tuned for unrealistic events.

In the work of Bierbooms [1], a methodology was developed that allows a designer to generate stochastic gusts embedded in time series. In the present work, an extension of this method—based on three-dimensional gusts (e.g. see figure 1)—is compared with the current design practice. Several points will be addressed, most notably the difference in load levels and the uncertainty that results from a full probabilistic approach [2].

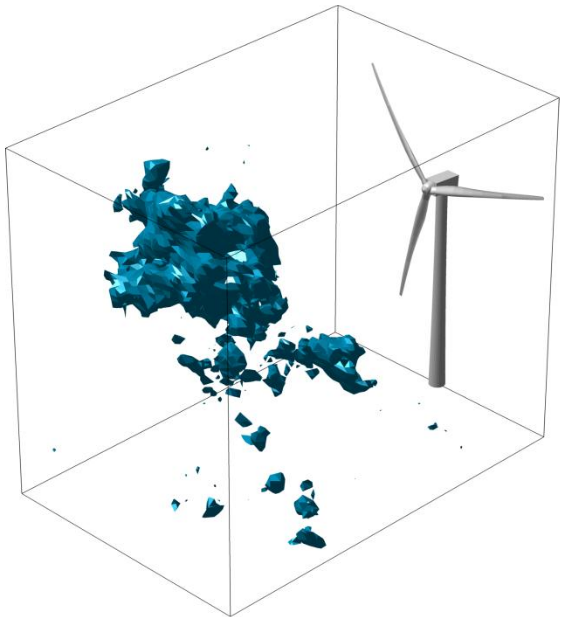

Figure 1: Example of a three-dimensional stochastic gust.

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# Modelling and Evaluation of Wind Speed Time Series for Reliability Analysis of Offshore Wind Farms

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## ABSTRACT

The aim of the project is to provide a suitable model for generating macro-scale wind speed time series for use in reliability analysis of offshore wind farms. In order to determine the suitability of these models, a testing suite has been designed which tests for characteristics of a wind speed time series that are important for reliability evaluation.

In order to meet EU renewable energy penetration targets sustainably for 2020 and beyond, the Levelised Cost of Energy (LCoE) of offshore wind needs to be reduced from the current £170/MWh. Policy makers and operators of offshore wind farms believe that the LCoE needs to be lower that £100/MWh to allow offshore wind to be competitive with conventional generation. In response to this, innovation in the planning and operation of offshore wind farms is required, including the cost-benefit analysis of improving farm availability.

As operation and maintenance accounts for around 30% of the LCoE, a number of researchers have looked into the reliability evaluation of offshore wind farms that consider the stochastic nature of the wind resource. However, the wind speed models have not been analysed to test that their characteristics match those of the real wind resource. This is important, as characteristics such as the energy available and weather windows affect the economics and maintenance strategies of a wind farm.

This paper aims to provide a testing procedure that is suitable for wind speed time series used in reliability analysis. The generated time series was tested for energy available in the wind, the expected power in the wind, the time in a wind speed bin, and the number of transitions between wind speeds when descretised into wind speed bins. These results were then compared to the original wind speed data. The use of spectral analysis in evaluating the accuracy of seasonal characteristics in the wind speed time series has also been introduced.

For this paper, a number of variations of a Markov Process model were used to generate a number of wind speed time series, based on the model found in [1, 2]. Fig. 1 shows the original time series data, and an example generated wind speed time series. The most accurate model had a mean energy available in wind over 1000 wind speed times series within 1% of the original wind time series.

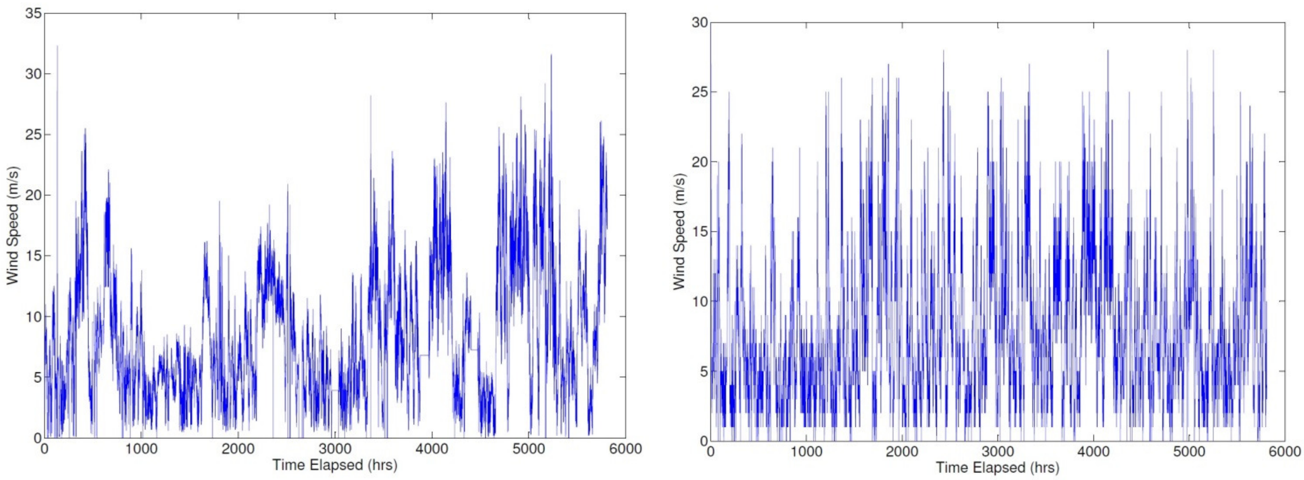


Figure 1: Showing Real time Series (left) and example generated time series (right).

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# Simulation of wind turbines in complex terrain by means of direct CFD

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## ABSTRACT

In the expanding wind energy market onshore wind sites play an important role as many costumers do not want to take the high risks and costs of offshore wind parks. Flat terrain sites are often rare and as a consequence the importance of wind energy in complex terrain steps more into focus. Complex terrain influences the inflow conditions of the turbine significantly and interacts with the atmospheric boundary layer resulting in a change of loads, life time, power output and financial benefit compared to a flat terrain site. One of the key factors in these cases is the atmospheric turbulence which needs to be better understood in order to improve predictions on wind turbine behavior [1].

The aim of the presented work is to simulate a state-of-the-art turbine in a complex terrain site in Southern Germany. Inflow data shall be created from LiDAR measurements, from unmanned aerial vehicles equipped with different measurement instrumentation and a measurement mast [2]. The validation data are collected with these techniques and additionally turbine performance data are recorded. In a first step, a baseline simulation of the turbine in flat terrain is done and compared to the measurements and the several turbine design cases. Later on the complex terrain simulations are performed and compared to the measurements. All simulations are performed using the flow solver FLOWer, which is a block structured code provided by the German Aerospace Center (DLR).

In detail, the presentation will show the numerical approach to the given topic. The whole process chain starting with terrain data processing, complex terrain mesh creation, computational setup "Fig. 1" and the integration of the wind turbine in the complex terrain mesh is described. In addition several meshing issues are discussed as well as the preparation of the measurement data for the simulations. Moreover, an extract of the simulation results is shown and certain effects like the influence of the terrain steepness or turbulence on the turbine performance are presented and estimation models linking terrain features and turbine behavior are developed.

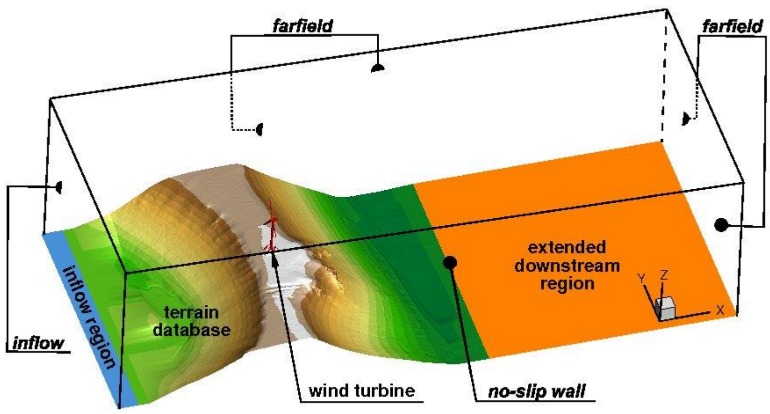


Figure 1: General computational setup

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# Large Eddy Simulation of the meandering of a porous actuator disk wake exposed to atmospheric turbulence using stochastic inflow data

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## ABSTRACT

The velocity deficit in the wake of wind turbines is known to exhibit transient trajectory variations when exposed to certain atmospheric turbulence conditions. This meandering phenomenon has been observed in real flow measurements [1] as well as wind tunnel studies [2] and within the context of CFD simulations [3].

In the present work, the meandering is studied thanks to a Large Eddy Simulation. In order to correctly reproduce the boundary layer turbulence conditions, we choose to use stochastically generated velocity series as input data. The generation method is based on the reverse transform of the Von Karman spectral tensor, so that the resulting turbulence shows realistic spatial coherence and turbulent kinetic energy.

The synthetic velocities are applied on all the boundaries except at the outlet of the box shaped domain. Specifically, the velocity values at the boundaries are calculated according to a Dirichlet-type boundary condition on the inflow face and with a form of hybrid Dirichlet/Neumann boundaries on the tangential faces.

By using such synthetic boundary condition, it is then possible to concentrate solely on the solution of the meandering of the wind turbine wake. The wind turbine is modelled with a discrete pressure jump, according to Froude's actuator disk theory. The observed meandering is compared to wind tunnel data measured in similar flow conditions.

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# INFLUENCE OF THE ATMOSPHERIC BOUNDARY LAYER ON WIND FARM CONTROL

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## ABSTRACT

With the challenge to increase overall power output of wind farms on limited space, wind farm control strategies that aim on influencing wakes become increasingly relevant.
While current turbine control is usually not factoring in the wake interaction within a wind farm, the research on control strategies by utilizing the turbine to modify the flow inside the wind farmis ongoing.The supplementary control strategies either focus on decreasing the wake deficit behind the rotor by a reduction of the induced thrust force or on a cross-stream deflection of the wake by yawing the rotor.The mean properties and the dynamic of wind turbine wakes are however not only subject to the turbine-induced forces but show also a strong dependency on the state of the atmospheric boundary layer [1,2].A precise knowledge of the atmospheric conditions and the wake response is thus essential to predict wind farm power production as well as structural loads on the individual turbines.

The aim of the PhD project is to better understand the influence of the atmospheric boundary layer on wind turbine wakes. The presentation will concentrate on Large-Eddy-Simulations of wind turbines in atmospheric boundary layers of different stratification. The topic will be the sensivity of the wake trajectory, deficit and dynamic on the strength of the stratification.Further research will also comprisenacelle-based LiDAR measurements of upstream and wake flow of turbines within a wind farm. The focus will be on the implications of the atmospheric stratification on wind farm control concepts tested in the LES model and the wind farm. Within the scope of the project the simplified wake representation in current wind farm wake models will be updated and modified to be able to represent the structure of the wake.

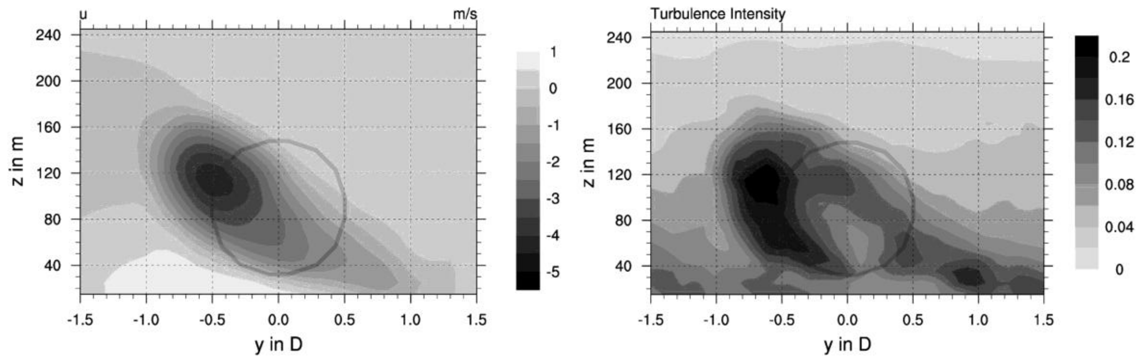


Figure 1: Mean wake deficit and turbulence intensity five rotor diameter behind a yawed wind turbine (20°) in a stable stratified boundary layer. Black circle denotes rotor position.

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# CFD ANALYSIS OF A 2-BLADED MULTI-MEGAWATT TURBINE

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## ABSTRACT

In this work the aerodynamic behavior of a innovative 2-bladed multi-megawatt horizontal axis wind turbine is investigated. The aim is to get a detailed insight into the transient aerodynamic loads on the turbine blades under various operating conditions. The compressible Navier-Stokes solver FLOWer, developed by the DLR, is used to run these unsteady simulations. The results of the high fidelity CFD simulations will be used to evaluate the accuracy of the aerodynamic load prediction of simpler models like BEM. In a further step of the project a degree of freedom will be inserted to reduce the transient loads on the turbine. Therefore geometry and grid adaptions have to be made and in a first step a prescribed motion will be feed in.

The presentation will give an overview of the numerical setup including the meshing process and the assembly of the overlapping block structured grids using the chimera technique [1]. To efficiently build up the simulation setup the process chain for wind turbine simulation developed at IAG was used [2]. The simulations are carried out with increasing complexibilty. To reduce the computational costs and ensure the accuracy of the numerical results, studies on a half model of the turbine have been performed varying e.g. grid resolution on the blade or turbulence model. In the presentation several results of this studies will be discussed "Fig 1". The methodology and the approach from half model simulations with rotational periodic boundaries to full model simulations including tower and nacelle will also be presented.

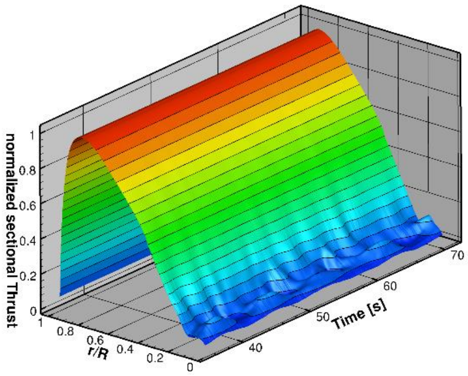


Figure 1: Half model results: normalized thrust distrubution on the rotorblade

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# LARGE-EDDY SIMULATIONS OF S826 AIRFOIL WITH DISCONTINUOUS GALERKIN METHODOLOGY

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## ABSTRACT

Prediction of accurate low Reynolds number (Re<$10^5$) airfoil characteristics is complicated due to the physics of transitional flow regimes, possible laminar separation bubbles and hysteresis phenomena. The presence of laminar boundary layers, much more prone to separation, and the transition to turbulence make these flows very sensitive to freestream turbulence and geometry. For higher incidence flows, the two-dimensional assumption also fails as spanwise flow structures develop e.g. stall cells, requiring full three-dimensional modeling of the flow. Experimentally, high uncertainty on the wind tunnel measurements are observed. Therefore, reliable experimental data for these cases are difficult to obtain and the use of Computational Fluid Dynamics (CFD) is a very attractive perspective.

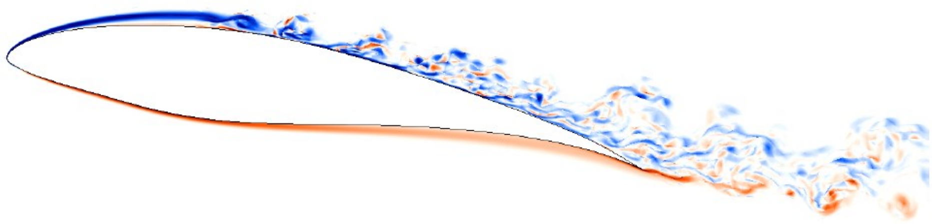

Figure 1: Separation region visualized by z-wise vorticity in the periodic plane for S826 airfoil at Re = 40k, AoA = 10° and Mach = 0.15 with ArgoDG

The main difficulty of CFD simulations obviously is the modeling of flow turbulence. Due to the presence of laminar to turbulent transition and the 3D boundary layer development at higher AOA, Reynolds Averaged Navier-Stokes (RANS) is not suited for the prediction of low Reynolds number flows. Instead, scale-resolving approaches such as Large-Eddy Simulation (LES), which compute part of the turbulent structures directly, should be used. The challenge of LES remains its limit in Reynolds number, although with the present computing capacity, Re=100.000 can be modelled fully.

The aim of the present work is to improve the understanding of low Reynolds flow physics by performing LES of the NREL S826, which is specifically designed for the wind turbines (see fig.1). The results from two LES methodologies, a Finite Volume Method (EllipSys3D) and a discontinuous Galerkin Method (ArgoDG [1]) are compared to a recent experiment performed in the Technical University of Denmark [2]. The results show good correlations between the CFD and the experiment.

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# Aerodynamic Performance Losses due to Ice Buildup in Wind Turbines

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## ABSTRACT

Ice accretion on the blades change the initial shape and this cause alteration in the aerodynamic characteristic of the blades. The objective is to determine the performance losses on the wind turbine due to formation of rime or glaze ice. The shapes of the iced airfoils are obtained from experimental data [1,2] and solution domain is generated by using Gambit mesh generator. In order to predict the aerodynamic performance losses due to ice buildup in wind turbines, flow solution over clean and iced airfoils are obtained by using Navier-Stokes solver. The Navier-Stokes equations are discretized by second order accurately cell centered finite volume method and solved explicitly by using Runge-Kutta dual time integration technique. Fluxes are computed with upwind methods. The numerical simulations are performed in parallel environment using domain decomposition and PVM library routines for interprocess communications. Corresponding non-dimensional free stream conditions; for rime ice case, Mach number of 0.20, Reynolds number of 2.45E+6 and incidince angle of 4 degrees and for glaze ice case, Mach number of 0.23, Reynolds number of 2.3E+6 and incidince angle of 4 degrees are studied. Predicted aerodynamic coefficients can be seen in Table 1and 2.

Table1: Predicted Cl and Cd values for rime ice.

| | Clean airfoil | Iced airfoil |
|---|---|---|
| Cl | 0.0456 | 0.0421 |
| Cd | 0.0228 | 0.0510 |

Table2: Predicted Cl and Cd values for glaze ice.

| | Clean airfoil | Iced airfoil |
|---|---|---|
| Cl | 0.03905 | 0.03736 |
| Cd | 0.0157 | 0.0784 |

Obtained preliminary results are analyzed and commented. It is seen that amount of the aerodynamics performance losses depend on the kind of ice shape. For glaze ice, predicted performance degradation is observed to be more than rime ice. The next step, will be implementing the Blade Element Momentum method to the present solver for predicting energy production losses of the wind turbine.

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10th PhD Seminar on Wind
Energy in Europe
28-31 October 2014, Orléans, France

# AERODYNAMIC MODELING FOR EQUAL FIDELITY AEROELASTIC ANALYSIS

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## ABSTRACT

Fast analysis of composite blade aeroelastic loading could be achieved by using low fidelity aeroelastic models that use sophisticated beam elements for the blade structural analysis. For the equal fidelity aeroelastic model the aerodynamic model consists of a lifting line along the quarter chord of the blade. Since wind turbines operate in highly unsteady conditions it is of great importance that unsteady aerodynamic models are used for the blade. To be able to represent the blade by a single lifting vortex in the unsteady case as well, Weissinger's method [3] is used together with the adaptations proposed by van Holten [2].

For the steady case it has been shown that the higher-order lifting-line theory up to order $A^{-1}$, the reciprocal of the aspect ratio, is similar to a numerical method according to Weissinger valid for straight, yawed and curved elliptical wings. For the verification of the numerical results, the analytical results from the curved lifting line theory [1] were used. For the wind turbine blade, the fixed wing wake has been replaced by a prescribed, cylindrical wake and circulation distributions along blade span are generated as well as normal and tangential force distributions as a function of the blade spanwise coordinate. The 3D blade circulation distributions and blade loadings have been compared with 2D results and give reasonable results.

The numerical unsteady aerodynamic model used calculates unsteady blade loads by generating an aerodynamic mesh in spanwise and chordwise direction of the blade. The wake is assumed to be cylindrical and has a mesh based on the step in azimuth divided by the angular rate of the rotor blade. The idea is to minimize the number of chordwise elements in order to approximate the lifting line case to reduce calculation time. The unsteady results are compared to Wagner's function and Sears' function to verify whether a single bound vortex is sufficient for unsteady blade operation.

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# Towards vibration analysis tools for smart rotor blades

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## ABSTRACT

Wind energy turbines are increasing in size, and there is a need to alleviate the loads acting on the rotor blade. In order to investigate the possibilities to reduce the loads acting on the blade, the concept of "smart blades" using active trailing edge flaps and morphing trailing edges currently receives a lot of attention (e.g. [1]).

In the present study, the vibration behavior of an 80 m rotor blade of a 7.5MW reference wind turbine is investigated. An appropriate modelling capability for structural analysis (vibration and strength analysis) is required. For structural analysis, rotor blades are nowadays typically modeled with a Finite Element discretization using shell elements. Such a model is the basis for vibration analysis (modal analysis, transient analysis, aeroelastic analysis) and stress analysis.

To facilitate the structural modeling and analysis activities related to smart blade developments, an input generator for the General Purpose Finite Element Program ABAQUS has been developed. Blade geometrical and stiffness properties such as blade dimensions, location, shape, and stiffness properties of spars, and laminate lay-up of the skin can be generated with this FE Input Generator tool based on Matlab. The input for the FE Input Generator is parameterized in the sense that various important geometry and stiffness parameters can be specified by the user.

Sensitivity studies with respect to the important structural parameters are carried out in order to obtain an appropriate reference rotor blade. This configuration constitutes a reference for the further development of smart blade configurations. Detailed sensitivity studies on the influence of relevant structural parameters on the blade vibration behavior will be presented for this reference blade. Further, first results of studies on the influence of including a flap or a morphing trailing edge on the blade vibration behavior will be presented.

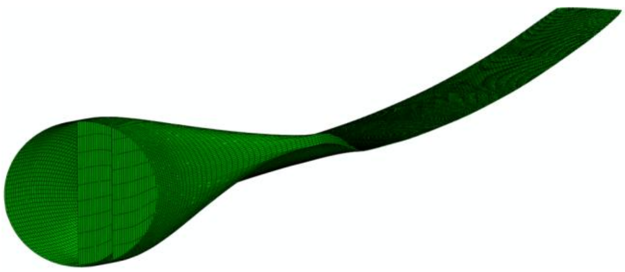

Figure 1: Reference rotor blade modelled using Abaqus, generated with Input Generator Tool.

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# Thickness effect on the static and fatigue properties of composite laminates

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## ABSTRACT

In wind turbines blades, thick laminates can be found in different parts, such as the root or the cap sections. For 40 meter long blades, thicknesses between 30 to 50 mm are typical. Root and cap thicknesses between 100-150 mm can be considered as common for 60 to 70 meter long blades.

The aim of the project is to study the thickness effect in composite laminates with respect to the static and fatigue properties and to determine the main parameters which drive the differences between thin and thick laminates. A thick laminate is considered to have a thickness larger than 5mm. The approach followed in the present work is to identify the main factors involved in the thickness effect, and to evaluate each factor's contribution to the thickness effect independently. The factors considered in the present work are:

- **Self-heating effect during dynamic loading.** This is related to the material energy loss factor. During dynamic loading a certain percentage of mechanical energy is dissipated into heat, leading to a rise of the material temperature. When the temperature approaches the maximum service temperature of the material, a reduction in fatigue life can be observed [1].
- **The manufacturing process influence.** Through-thickness lamina properties have been studied extracting sub-laminates from 60mm thick laminates processed with two different curing cycles.
- **The scaling effect and coupon geometry influence.** Scaled compression tests were performed on laminates up to 20 mm thick. The coupon design was based on finite element analysis and fracture mechanics [2] and the influence of the manufacturing process and self-heating was minimized [3]. Static tests on laminates with different thicknesses showed no significant change in the static ultimate stresses. Fatigue tests showed a decrease in the fatigue life for increasing thickness.

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# Damage tolerant design: failure and crack propagation in composites.

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The historical design philosophy for composite materials is based on conservative analysis methods, with large safety factors, underestimating the material properties, and considering only the linear behavior of the material. As knowledge about material behavior increased it became possible to safely adopt more advanced design philosophies. In a Damage Tolerant design, regular inspection and models describing crack propagation permit the structure to operate despite the presence of damage and more fully exploits the capability of the material, leading to a more competitive structure.

The aim of the present project is to develop the damage tolerance approach in wind turbine blade sub-structures, focusing on the crack growth mechanisms and detection methods. The trailing edge of the blade can develop damage in the composite material and adhesive interface. The delamination is accompanied by the formation of a crack bridging zone, where intact fibers connect the crack faces behind the tip thus increasing the energy required for crack propagation (Damage tolerance mechanism) [1]. A finite element model of the crack growth mechanisms in a double cantilever beam (DCB), representative of the trailing edge, was developed where different fracture modes were addressed. Experimental tests were conducted in order to fully characterize this structure and support the model. Then a crack monitoring technique was implemented using Fiber Bragg Grating (FBG) sensors in order to track the crack tip and its' propagation. This sensor approach was incorporated with the finite element model in order to predict the sensor output and extrapolate to a real trailing edge case. Experiments were conducted on DCB specimen crack growth with FBG monitoring under several fracture modes.

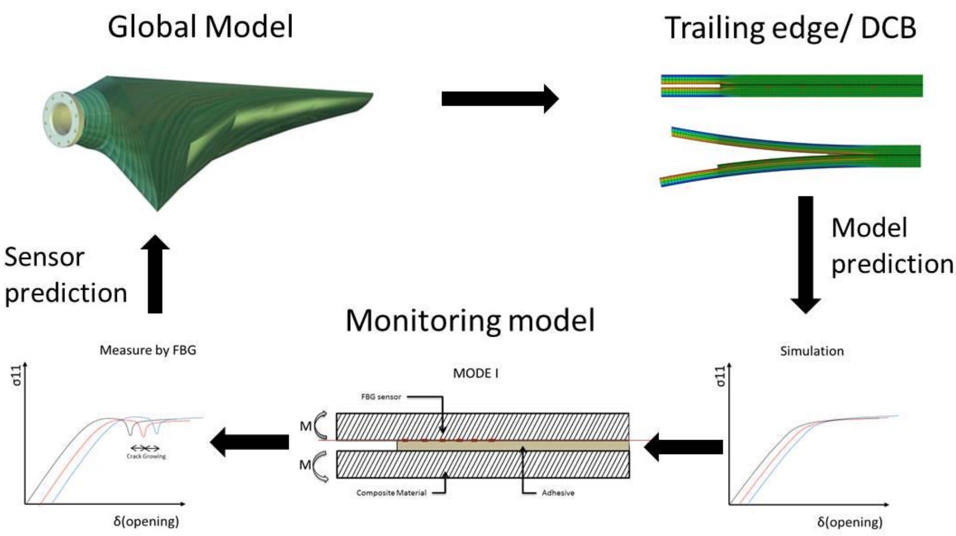


Figure 1: Modeling scheme of crack growing mechanisms and detection methods.

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# CONVEX OPTIMIZATION OF SPACE FRAME SUPPORT STRUCTURES FOR OFFSHORE WIND TURBINES

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## ABSTRACT

The aim of the present project is to reduce the cost of support structures for offshore wind turbines by minimizing their total steel mass. Basic considerations for an iterative optimization approach were presented by Zwick, Muskulus and Moe [1], and these have been improved with a convex problem formulation and faster convergence (fig.1). The errors of several simplified fatigue load assessments have been documented, and a method for site-specific optimization has been developed that is an order of magnitude faster than state of the art methods, while retaining a high level of accuracy. This has been accomplished by using load histories from the initial design to compute correction factors for each member, which enables a single load case of 10 minutes to represent 11 load cases of 60 minutes. A jacket has been optimized with this approach, and a benchmark with the full-height lattice tower concept is presented (fig.2).

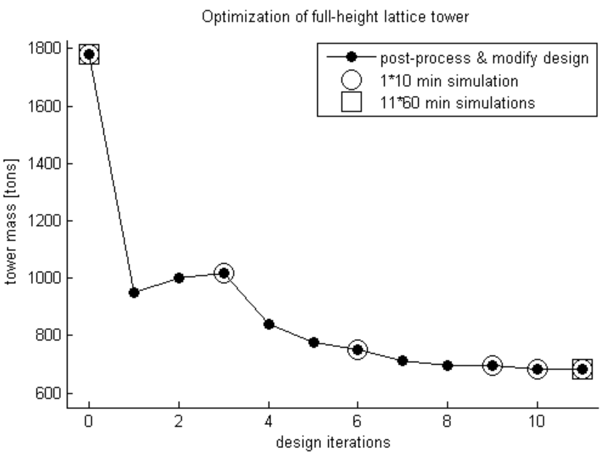


Figure1: The improved optimization approach converges in 10 iterations. Convex problem formulation results in a global minimum.

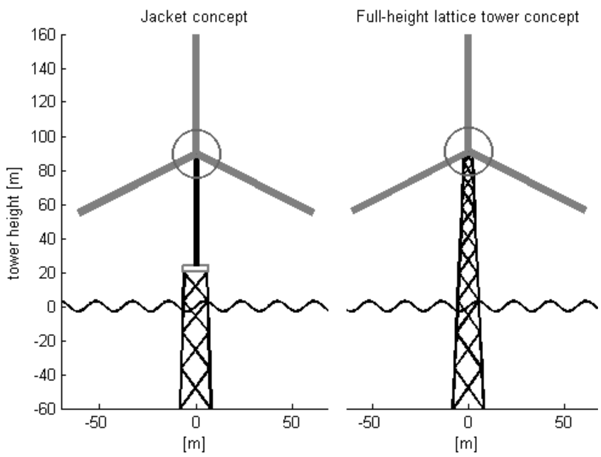


Figure 2: Two support structure concepts that can be optimized with the presented method.

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# WIND POWER PLANT IMPACT ON TRANSMISSION GRID CONGESTION IN POLAND

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## ABSTRACT

Wind energy has comprised a major position of investments in the Renewable Energy Source (RES) power generation sector, accounting for 80$ billion globally or 37% of total investment in power generation in 2013 [1]. These investments are driven by the need to fulfil, in Europe, European Union (EU) targets for RES share in a country's energy profile. The geographically diverse locations of wind power plants and the variability of wind-generated electricity have an impact on the operation and reliability of the transmission grid. It is necessary to have detailed knowledge of those impacts as the rate of development of the infrastructure of transmission grid lags that of the development of wind power plants. Poland, which is the largest Eastern Europe economy in the EU, presents a useful test case as needs to substantially increase its wind sector in order to meet the EU 2020 energy targets [2]. The objective of this work is to assess the impact of wind power plants on congestion in Poland's transmission grid system.

This work is accomplished using EnerPol, ETHZ's integrated energy assessment tool [3]. Forecasts of the wind-generated electricity were derived from mesoscale simulations of the weather over Poland using Weather Research and Forecast model [4]. A geographically indexed database of generators and transmission grid was developed from publically available sources [5]. Optimal power flow simulations, including also cross-border exchanges [6] are then simulated at hourly intervals to determine the impact in the transmission grid.

A simulation for 2013 "fig. 1" correctly identifies the eight sections of Poland's transmission grid that require upgrade by 2020 in order that Poland meets its EU targets. In the full version of this paper, details of the hourly power flows, including primary flow directions, variances in power flow will be detailed. Furthermore the impact of the variable wind generated electricity on cycling and curtailment of coal power plants that presently account for 90% of Poland's power generation [5] will be discussed.

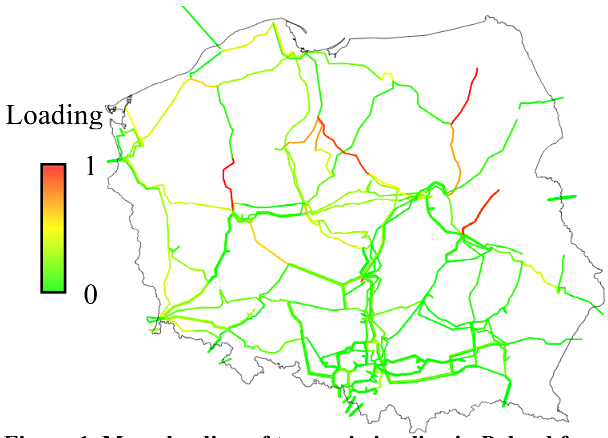


**Figure 1. Mean loading of transmission line in Poland for 2013 based in hourly optimal power flow simulations. The line sections that require upgrading are correctly identified.**

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# Improving availability of offshore wind farm with the use of redundancies

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## ABSTRACT

Up to now, the operation and maintenance costsof an offshore wind farm account about 30% of the energy generation costs[1]. A considerable percentage of those costs is caused by unexpected failures, and their resulted downtimes. The downtimes are increased bythe harsh offshore environment, the (in)accessibility of the wind parks, and the distance to harbor facilities.

The operators are willing to have the turbines working as much as possible. If a component or a system is broken, it would be beneficial to find a mean to let the asset work, even the output power might not be as high as if nothing was broken. To achieve this, existing redundancies can be used: there are three kinds of redundancies: component, network, and functionalredundancies [2].

If one component breaks, a redundant component located next to it can be used. For example, the rotational speed is measured several times over the entire drive-train, and if one sensor is broken, the others can provide the information. This kind of redundancy is component redundancy.

Network redundancy is for instance: if an anemometer of a wind turbine is broken, the neighboring anemometers can provide estimation of the missing information [3].

Last, if the pitch system is broken, yawing the nacelle might control the loading on the blades. This kind of redundancy is known as functional redundancy: a function is performed by a system that was not primarily designed for this task.

Many more redundancies can be found in a wind turbine and in a wind park. The goal of the present paper is to show how redundancies can be used let the wind turbines work while waiting for maintenance, and to reduce the operation and maintenance costs. It is determined which failures can be concerned, if additional equipments or control is needed, and what reduction in the operation and maintenance costs can be expected. Attention is also put on the risk of additional failures caused by this uncommon working condition. This paper shows that the value of the asset can be increased thanks to redundancies.

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10th PhD Seminar on Wind Energy in Europe
28-31October 2014, Orléans, France

# COMBINING MODEL-BASED AND DATA-DRIVEN OPTIMIZATION OF WIND FARMOPERATION IN A LEARNING DATABASE

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## ABSTRACT

Previous studies[1] demonstratedthe potential of improving the wind farm control strategy by considering the aerodynamic interaction of the turbines and their additional losses in energy yield and increased structural loads. Different approaches to reduce these wind farm effects are the focus of recent studies[2], [3].

Mitigating the wake effects at least partly requiresto leave the ideal point of operation of the individual turbineswith respect of power and loadsin order to enhance the energy conversion process of the wind farm as a whole. Both contradicting objectives poses a multi-objective global optimization problem. The solution of such an optimization problem, which is called a Pareto optimium, is generally hard to compute and not explicit. Advanced algorithms as well as further restrictions or conventions are necessary to find one sufficient solution in a feasible time.

The present investigation in the scope of a PhD project is implementing a combination of model-based [3] and data-driven[4] optimization techniques into a learning database in order to manage the challenges of the continuously changing wind farm flow conditions. The first step is the development of a real time application that analyses the variation of the wind speed and direction by measurement e.g. with wind turbine nacelle anemometry. The wind conditions, the farm layout and a dynamic wake modelare used to estimate the current wind farm flow and to store the result in a database. Simultaneously a graph of the turbine interactions is generated. For every wind flow situation in the database a model-based optimization is calculating the best initial operating set-points for the turbines. During the operation of the wind farm these initial set-points are used as starting-points ofthe data-driven optimization to improve the database values for the specific wind flow situation. The purpose of this twofold approach is to combine the advantages of the two techniques. The feedback of the data-driven algorithm will partly compensate the inherent inaccuracies of a wake model, while the model-based method is expected to improve the rate of convergence of the data-driven method.

The paper intends to investigate different optimization algorithms for both the model-based and data-driven approach and to give some general remarks about their pros and cons. The further prospect of the PhD research is to develop the above-mentioned methods for wind farm control application and to validate them with simulations and free field wind measurments.

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# Effects of Tip-Injection on the Flow Downstream of a Model Wind Turbine Rotor Blade Tip

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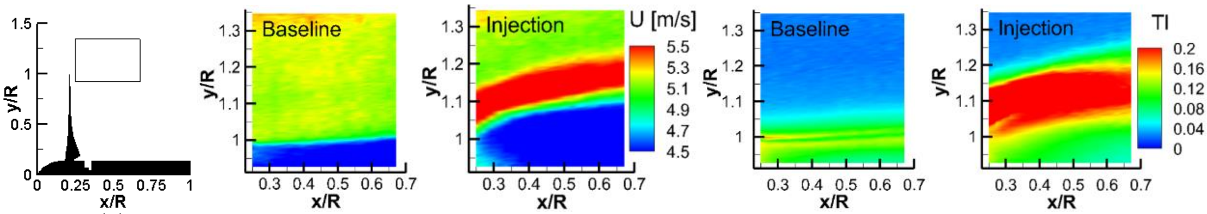
## ABSTRACT

The present paper describes an experimental investigation of the effects of tip-injection on the near wake of a model wind turbine rotor just downstream of the rotor blade tips. Tip injection is considered as an active flow control technique that aims at controlling the leakage characteristics at the blade tips as well as the size, vorticity and turbulence characteristics of the tip vortex. Tip injection has been previously investigated by our research group on fixed wings and turbomachinery blades. Therefore, this paper is dedicated to investigate the flow field in the near wake of the rotor by measuring the instantaneous axial velocity using a single sensor hot-wire driven by a Constant-Temperature Anemometry (CTA) system. The experiments are carried out by placing a specially designed wind turbine rotor at the exit of an open-jet wind tunnel facility. The model wind turbine consists of a 3-bladed rotor of 0.95 m diameter. The rotor blades are non-linearly twisted and tapered with NREL S826 airfoil profile all along the span. The nacelle, hub and the blades are specifically designed to allow pressurized air to pass through and get injected from the blade tips while the rotor is rotating. Mean axial velocity magnitude and turbulence intensity data are collected on the measurement plane shown in Fig. 1a. The measurement plane is a 20 cm x 20 cm grid with step sizes of Δx=0.2 cm Δy=1 cm. The CTA system is controlled by an NI DAQ system through a Labview program. Data have been collected at a sampling rate of 5kHz for 4 secs at each grid point. Direction of flow is from left to right. The position y/R=1 marks the blade tip. Results show that the tip injection has significant effects on the tip vortex wake. Previous studies has been carried out on the same test facility, where the effect of tip injection on the power and thrust curves was studied. Results show that injection has increased the power and thrust coefficients at TSR of maximum $C_P$ [1]. Accordingly, the vortex wake measurements were conducted at the same TSR for 5 m/s wind speed. As shown in the mean velocity magnitude and turbulence intensity plots the trajectory of the tip vortex and the near wake flow characteristics have been significantly influenced by injection. It appears that the injection causes increased diffusion and mixing downstream of the rotor. Furthermore, the injection seems to increase the width of the wake region. The final paper will present the near wake data for the baseline (no-injection) as well as the injection cases for different TSR and wind speeds. Furthermore, Particle Image Velocity (PIV) measurements will be conducted in order to obtain more information related to the vortex characteristics such as instantenous velocity fields, vorticity, as well as turbulence intensity and Reynolds stresses.




(a) (b) (c) (d) (e)

Figure 1: (a) Geometry & measurement plane; (b-e) Velocity magnitude and Turbulence Intensity plots @ $U_\infty$=5 m/s, TSR=5: (b,d) Baseline case (c,e) Injection case

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10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

# CFD studies of a 10 MW wind turbine equipped with active trailing edge flaps

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## ABSTRACT

Many of today's projects in wind turbine research focus on the development of larger rotors to achieve a higher power output. One example is the European INNWIND.EU project, which focuses on a 10 MW reference turbine designed by DTU Wind Energy [1]. Due to the larger size of these novel turbines, simple up-scaling is very challenging as nearly all characteristic parameters like turbine mass or rotor thrust increase disproportionately with the rotor diameter. Therefore, it is necessary to apply new concepts in the aerodynamic, structural and controller design of these turbines.
One of the main aerodynamic challenges is to reduce the dynamic loading caused by the tower shadow, the atmospheric boundary layer or the inflow turbulence. Active trailing edge flaps constitute a very promising approach for these matters as it has been shown by several scientists (e.g. Barlas [2]). The aim of the presented work is to further analyse the effects and potential of active trailing edge flaps in a three-dimensional CFD environment with a fully meshed turbine. The simulations are conducted in the compressible Navier-Stokes solver FLOWer, developed by the German Aerospace Center (DLR), which offers the Chimera technique for overlapping grids [3].
The presentation will include two- and three-dimensional aspects of flap modeling in CFD. Two different possibilities to enable a moving flap will be shown, one based on mesh deformation, "Fig. 1", and the other based on the Chimera technique. The models are validated against measurement data in a 2D case. Furtheron, three-dimensional results will be shown on the DTU 10 MW turbine and the planned application of control algorithms will be presented.

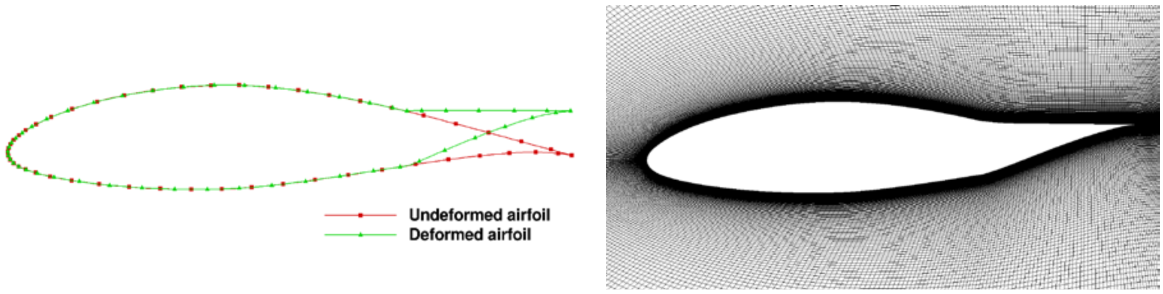


Figure 1: Flap modeling based on mesh deformation

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# FLAPS FOR WIND TURBINE APPLICATION: NOISE SOURCE LOCALIZATION ON A TEST AIRFOIL

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## ABSTRACT

Unsteady wind conditions and the atmospheric shear layer cause high dynamic loads on wind turbine rotors during operation. These high loads can lead to a long-term failure of the blades and to a non-reparable breakdown of the entire wind turbine. Rotors applied with trailing edge flaps have a high potential to reduce these critical loads [1]. However, experimental investigations of airfoils with flaps for aviation applications show a significant higher global sound emission [2]. Specifically, the turbulent, unsteady flow around the side edge of the flap causes additional sound sources, emitting noise in ranges which are audible for humans. Consequently, these additional sound sources can also emerge when using flaps for wind turbine rotors.

In the joint project Smart Blades, the acoustic properties of an airfoil with trailing edge flap for wind turbine applications are investigated. Therefore, an experimental set-up is designed. A test airfoil with a trailing edge flap is placed in an open jet of a wind tunnel. A microphone array is installed above the airfoil, outside the flow. The microphone signals are processed by using beamforming algorithms to generate a noise map of the test airfoil to localize the main sound sources caused by the turbulent, unsteady flow around the airfoil. However, the quality of the noise map is very sensitve to the microphone array settings, the used beamforming algorithms and the background noise level.

The oral presentation deals with the development of the acoustic test set-up. Starting with the presentation of the basic set-up, the activities and applied methods to develop a suitable acoustic set-up are presented. In addition, initial results of the sound source localization at the airfoil are shown.

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# CLARIFIFYING THE PERFORMANCE OF CORDINATED CONTROL FOR LARGE WIND TURBINE LOADS

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## ABSTRACT

The objective is to review coordinated control of tower loads on a large scale wind turbine and clarify the attainable performance. One of the control objectives for large scale wind turbines is to reduce tower lifetime equivalent fatigue loads. The basic approach is to additively modify the pitch demand in response to a measurement of tower speed. An alternative and more effective approach is to employ coordinated control, whereby, both pitch demand and torque demand are modified in response to power and rotor speed. Some uncertainty has recently arisen regarding the most effective tuning for coordinated control when applied to 5MW+ wind turbines. Although coordinated control still performs very well the extent of the improvement over the basic approach needs to be clarified.

# Controlling Large Wind Turbines – The Effect of Wind Turbine Size on Controller Design

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## ABSTRACT

Wind turbines have been steadily increasing in size since they first came to prominence as a power source. This increase in size increases the power capture of each machine but also introduces additional challenges for the designers of the control systems.

Modern controllers are required to maximise the power capture of the wind turbine whilst simultaneously reducing the loads on the machine. Numerous techniques have been developed to achieve this, including drive train filters, tower filters, coordinated control, and individual blade control to name but a few.

An advanced tool boxhas been developed to aid the design of controllers for wind turbines,this project will make use ofthisin order to design controllers for larger machines.The controller should ensure good performance across the range of operational wind speeds, making use of state of the art control techniques.

Using relevant software,a controller will be designed with a model of a 3MW machine. Once this is completed, controllers for larger machines,up to 7MW, can then be designed.Comparisons can be drawn between the design of the two controllers and their relative effectiveness.

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# Investigate derivation of a wind turbine dynamics from measured data

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## ABSTRACT

Wind turbine operators now have large fleets of machines that are out of warranty, including hundreds of the same model. In some cases the wind turbine performance is very poor due to control problems but, unfortunately, the manufacturers no longer provide the support required to rectify these problems. Consequently, there is a growing market for specialist control companies to provide control solutions. Unfortunately, no information is available concerning the original controller design, its code or the dynamic properties of the wind turbine. The best option is to by-pass the existing controller by a new PLC which will implement a new controller design. In order to do so the dynamics of the wind turbine has to be identified. Since lumped parameter models of turbines are used for analysing their dynamic properties and designing their controllers, this project has required mainly the identification of the lumped parameters from measured data. Finally, the utility of this methodolgy has been assesed.

# FEEDBACK CONTROL OF BLADES TRAILING EDGE FLAP FOR BLADE ROOT LOAD MITIGATION

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## ABSTRACT

Within the ongoing evolution of increasing rotor diameter and hub height of wind turbines the importance of load reduction are getting more in the focus of research. Therefore,various new control concepts are under development at present.However, the current control strategies have some limitations regarding the load reduction and rotor speed control due to the limited pitch actuators dynamics and lack of information about the approaching inhomogeneous wind field in advance. To resolve the above-mentioned problems different approaches can be taken. A Light Detection And Ranging (LiDAR) system can be used to obtain more information concerning the inflow. Therefore, a more advanced controller, like feed-forward control, can be developed. Furthermore, while the individual pitch control (IPC) [4] has the potential to reduce the blade root bending moments, it can also wear and tear the pitch system and has a relatively slow reaction due to the considerable mass of large blades. Hence, the lightweight movable trailing edge flaps are considered one option to provide good prospects for fatigue and extreme loads reduction of very large blades [2][3].

The dynamic loads on the rotor blades and tower are mainly caused by turbulence, wind shear and skewed or wake-induced inflow.Their impact can be reduced by controlling the blades pitch or the movable trailing edge flaps angles individually. The first phase of the present PhD project deals with feedback control. Hence, two control concepts are realized where the feedback of the blade root bending moments is used as the control input. In the first concept the blades pitch angels are usedonly to regulate the generator speed. Whilethe control of the movable trailing edge flaps anglesfocuses on the reduction of loads varying with the rotational frequency (1P) and its high harmonics (nP). In the second concept the blade pitch angles are controlled individually to mitigate the 1P load components,whereasthe trailing edge flaps are employed to alleviate the higher harmonics. As a result two feedback control concepts and simulation results will bepresented in respect tothe load mitigation of a 7.5 MW reference wind turbine model.

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10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

# Determining the Wind Speed Distribution within a Wind Farm considering Site Wind Characteristics and Wake Effects

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## ABSTRACT

The aim of this project is to produce a realistic presentation of the wind resource for a wind farm which is suitable for reliability evaluation and the testing of coordinated wind farm control algorthims. This wind model aims to capture both the long term trends of the wind resource at a site, and the distribution of wind speeds within the farm caused by wake effects.

The stochastic nature of the wind and the wakes from upstream wind turbines provide unique fuel characteristics for wind farms. For reliability analysis of offshore wind farms, the need to capture these characteristics is paramount as the wind resource affects the power available to each wind turbine at any given time. By including wind resource characteristics and wake affects in the farm simulation, the affect of failed assets and farm layout on Levelised Cost of Energy (LCoE) can be more accurately quantified.

The model in this paper can be used for evaluation and testing of a coordinated control algorithm with a realistic wind resource. The variation in the wind resource can allow the evaluation of how a control algorithm will perform in real time and how it will affect the farm production and turbine loads over time, potentially increasing reliability and decreasing LCoE.

To produce wind speed time series that represent the stochastic wind resource, a Markov process model is used with transition rates calculated from a raw wind speed time series [1] . This model has been evaluated for a number of key wind speed characteristics and the generated wind speed time series were used as an input for a wake flow model. The wake flow model calculates speed and power in the wind at different turbines inside the wind farm [2]. Multiple and partial wakes are considered in this model to give a better prediction of power in the wind.

Fig. 1 shows the effect of wakes in a two 6MW turbine array for 24 hours of wind speed data. The turbines are 5 turbine diameters apart, with a turbine diameter equal to 60m. According to the model, the downstream turbine has 26% less energy available in the wind when the upstream turbine uses the greedy approach, maximizing its own power, without considering its impact on the second wind turbine. This is in line with results in [3], which show that wake losses can be 20 – 45 % depending upon different variables and conditions such as wind speed and distance between the turbines.different variables and conditions.

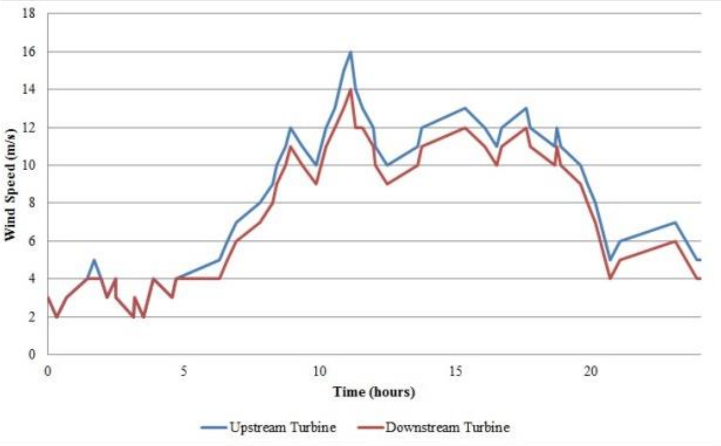


Figure 1: 24 Hours wind speed time series with wake effects.

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# A minimal setup for wind farm control – control oriented modeling of wind turbine interactions

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## ABSTRACT

The aim of the present project is to transfer preview control methods for wind turbine control to the wind farm level. In the control field of wind turbines, several approaches where considered and also new measurement techniques like lidar were introduced for control purposes, see e.g. [1]. So this PhD project goes a step further and focusses on model based wind farm control.
On wind farm level, maximal power production and reducing structural loads are the focus of developing control strategies. Therefore, the interaction between turbines have to be modeled and considered in controller design. Current wind farm models need heavy calculations (see [2]) and are difficult to use in model based wind farm control. Thus, in this project, reduced controller-oriented models for wind farm control will be developed. Further, the ideas of lidar-assisted wind turbine control will be applied on wind farms and adjusted to the wind farm requirements. For the obtained models, centralized and decentralized control strategies should be considered focusing on the one hand on maximum power production and on the other hand on reducing structural loads of the wind turbines.

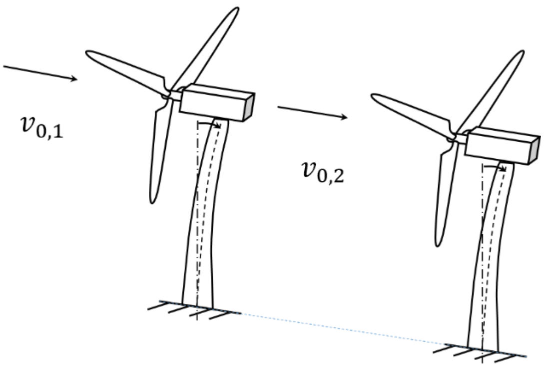


Fig. 1: Considered simple scenario - two wind turbines in a line.

At this early stage of the PhD project, a simple scenario of two wind turbines aligned in a line is considered, as shown in Fig. 1. The analysis of the relationship between the rotor effective wind speed of the turbine in free stream condition and the turbine downwind in the wake is in focus of this poster. Different wake models are analysed for applicability in reduced modeling of wind turbine interactions for model-based control purposes, see [2].

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10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

# Wake Flow Model for Wind Farm Control

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## ABSTRACT

A hybrid methodology for the real-time analysis and modelling of wind turbine wake effect including wind speed and turbulence is presented in this paper.
Large wind farms can take advantage of economies of scale by installing wind turbines in dense arrays. This reduces installation and interconnection costs as well as operation and maintenance costs. However, these turbines generate wake effects and thus suffer from array losses. These losses can be in the range from 20 – 45 %, severity of which depends upon different conditions [1]. A wind farm has to produce the maximum possible energy with limited number of turbines and minimum spacing between them.
Traditionally wind farms operate with a greedy approach, in which each turbine increases its own power using Maximum Power Point Tracking (MPPT), ignoring the wake effects produced. This may not always be the best strategy. Upstream turbines will use significant and substantial quantities of the kinetic energy in wind, reducing wind speed for downstream wind turbines with increased turbulence. Lower wind speeds means less energy production and higher turbulence means increased fatigue loads.
A coordinated control can be used to increase the efficiency and reliability of the wind farm. If the upstream turbine is de-rated so that the decrease in produced power is less than the increase in shadowed turbines powers, then there will be an overall increase in farm output whilst decreasing mechanical loads. This will increase wind farm life and will reduce cost of energy, which will be helpful in making wind energy competitive with conventional energy sources.
Figure 1, presents a preliminary comparative analysis of a simple array of two 6MW wind turbines, quantifying the benefits of a coordinated control strategy. In the first case, the array is operated with the traditional greedy approach. Though upstream turbine is almost producing 6MW - its maximum - the farm output is 10.1MW. However, in the second case – when the upstream turbine is de-rated by (-12.16%) to produce 5.27MW - the farm output is 10.39MW. This represents a net increase of 2.87% in total farm output. In a larger farm the result would be even better. An optimizer can be used for selection of the best possible reference points for each turbine. This optimizer, if used, requires a fast processing wake flow model which gives both speed deficit and turbulence intensity at a downstream turbine with sufficient accuracy.

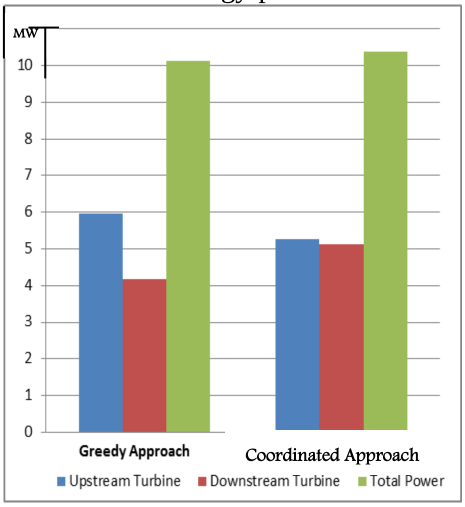


Figure 1: Coordinated Control vs Greedy Control

CFD based wake models could produce accurate results but are computationally expensive. Despite some development, these models are still time consuming and are not the first choice for farm controller / optimizer, especially for real time control.
In this work, a computationally effective wake model based upon the Jensen model [2] is presented which is combined the model developed in [3] to provide a holistic wake effect model including turbulence intensity. This model enables real-time computation of both multiple and partial wakes, enabling the use of wind farm level controllers to optimize yield and minimize fatigue. The integration of real-time wake modelling into a coordinated wind farm controller will significantly increase farm yield whilst significantly reducing upstream turbine fatigue.

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10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

# Long-wave instabilities in a helical vortex

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## ABSTRACT

Various instabilities can exist in a helical vortex system, involving perturbations at different wavelengths: long-wave displacement modes or short-wave vortex core deformations. The former can be described by a filament approach involving the Biot-Savart law for self-induced motion and interpreted as a local pairing of neighbouring helix loops.

Motivated by recent experimental results concerning this phenomenon, we here revisit and extend the theoretical analyses of long-wave instabilities in an infinite single helical vortex of Rankine type made by Widnall[1] and Gupta & Loewy[2]. Both analyses predict instability of the helical vortex. We illustrate the structure of the unstable modes (e.g. in figure 1a), and compare it to the predictions as function of the geometrical parameters (radius *R*, pitch, core radius) and the circulation of the initial helix with more realistic vortex velocity profiles (Gaussian vorticity, axial flow). Finally, this theory is compared to experimental measurements made in the wake of a small-scale single-bladed rotor placed in a water channel. The measured growth rates agree very well with the theoretical predictions (figure 1).

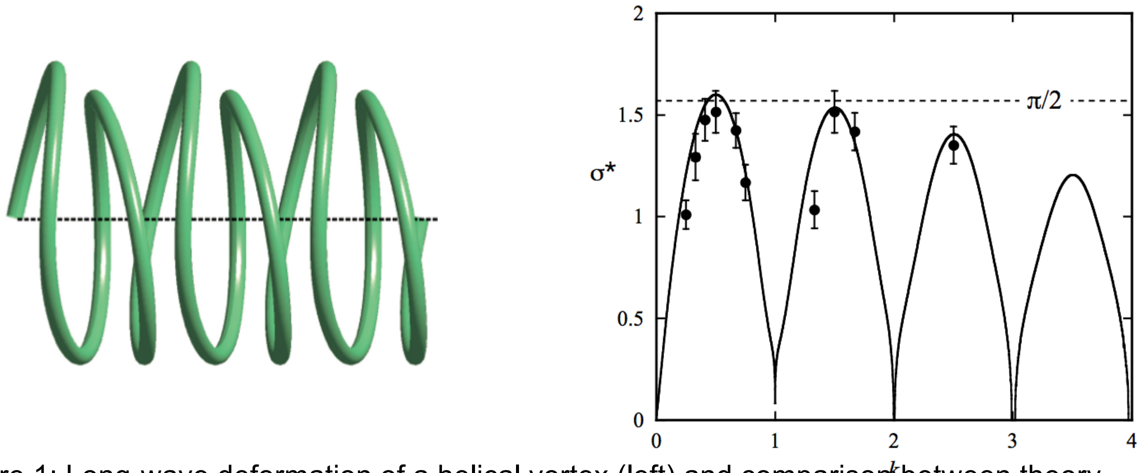


Figure 1: Long-wave deformation of a helical vortex (left) and comparison between theory and experiments (right).

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# The Low Induction Rotor

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## ABSTRACT

The aim is to explore design fundamentals of a low induction rotor considering the interaction of rotor diameter, power and loads.

An optimum axial induction factor of a=1/3 is indicated by actuator disk theory to achieve theoretical maximum rotor power coefficient, $C_p$. Resent research suggests a larger diameter rotor operating at significantly lower axial induction than 1/3 can extract more power without increasing the loads [1]. Using ideal actuator disc expressions for coefficient of performance and coefficient of thrust, gives expressions for the blade out-of-plane bending moment, and power . Allowing radius to vary but constraining the bending moment to be fixed, the following equation can readily be derived; $\frac{dP}{da} = \frac{(1-5a)}{3a(1-a)}P$ . This shows that when the rotor radius is considered as a free variable and designs are developed to meet a fixed blade load level, the optimum induction is not 1/3 but 1/5!

The fig.1 below shows for a=1/5, at fixed bending moment, rotor radius is 12% greater, power is 8% greater and thrust is 10% less than for a standard design (a=1/3). Designing for a = 1/5 changes rotor solidity or requires new aerofoil selection and consideration of extreme loading on a larger rotor will be relevant. Also standard rotors can be operated at lower induction by a pitch change but retain the possibility of picking up the same extreme loading. Thus the larger rotor must be incapable of generating higher lifting loads than the standard rotor.

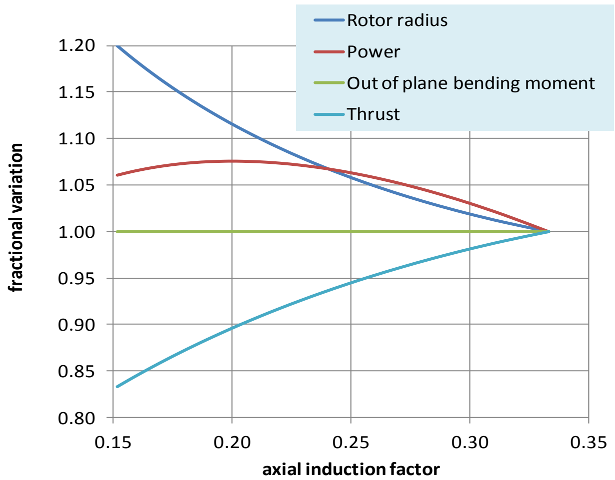


Figure 1: Variation of design parameters with axial induction factor

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# Effects of morphological indices on the wind turbine noise distribution in residential areas

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## ABSTRACT

With onshore wind farms increasingly installed all over the world, a growing number of residents living in suburban areas are affected by the noise from wind turbines. Previous study has demonstrated that in a relatively highly populated suburban area, the wind turbine noise exposure at a dwelling is largely affected by the morphology of the adjacent dwellings [1]. The aim of this paper is therefore to explore the performances of specific morphological indices on the wind turbine noise exposure in suburban residential areas. The paper first reviews the morphology of typical residential suburbs in the UK, and consequently chose four kinds of typical suburbs. Through noise mapping of the sampled sites (shown in Fig. 1) and quantitative analyses, the effect of building morphology on the noise level at building façade is examined. The results show that morphological parameters have considerable effects (up to 7.4dBA) on the minimum noise level that a dwelling exposed to. Although the effects of morphological indices on noise exposures vary at different frequencies, the building length, orientation, its spacing to adjacent buildings, and the building shape are found to be effective on decreasing the 50Hz noise exposures for up to 6dB.

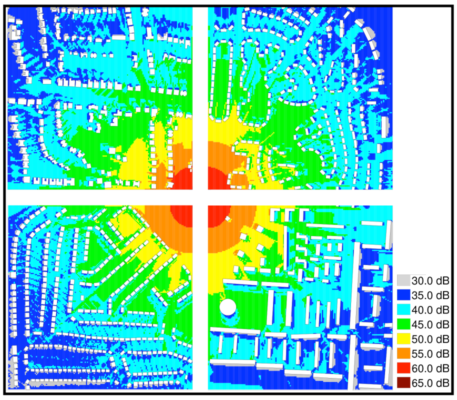


Figure 1. Distribution of wind turbine noise on studied suburban layouts

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# AERODYNAMIC DAMPING OF WIND TURBINES UNDER CONSTANT AND TURBULENT WIND

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## ABSTRACT

The simulation of an entire offshore wind turbine under aerodynamic and hydrodynamic loading is still a complex and time consuming task. A reduction in simulation time is more than welcome. One solution is the replacement of the rotor by force or displacement time series, applied at the tower top [1-3]. An additional advantage is the possibility to use general FEM-software to simulate the wind turbine, or the possibility to use frequency-domain methods. The main obstacle in using these approaches is the interaction between support structure and the rotor. The vibrations of the support structure are damped when the rotor is moving. This aerodynamic damping has impact on the fatigue loads of the structure, since it significantly reduces the motions of the support structure. Simulations with a fixed and a harmonically excited rotor under both constant and turbulent wind were therefore performed to investigate this damping in more detail. A linear correlation between velocity and damping force was found in most cases, even under turbulent wind conditions (fig.1). However, the relationship between damping force and turbine velocity depends strongly on the wind speed and becomes more complex for wind speeds above rated where also controller dynamics have to be taken into account. This study shows how the above mentioned factors influence the aerodynamic damping acting on the top of the tower, and how to calibrate and implement an equivalent linear damping for use with alternative analysis approaches.

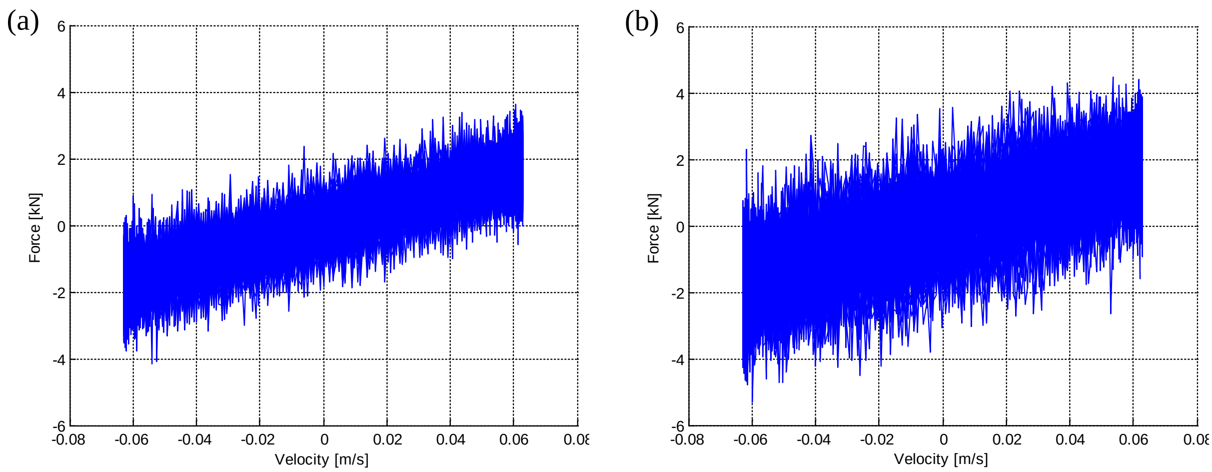


Figure 1: Damping force as a function of the tower top velocity for (a) constant and (b) turbulent wind

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# Towards FSI on wind turbine blades using OpenFOAM

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## ABSTRACT

Rotor blades of wind turbines are nowadays designed increasingly large and flexible. Passive load-reduction methods like bend-twist coupling use structural deformations to reduce the aerodynamics loads acting on the blades. The structural flexibility represents a problem for the field of Computational Fluid Dynamics (CFD), which is used for accurate load calculations and detailed investigations of wind turbine aerodynamics. As the blade geometries within the CFD simulations are considered stiff, the effect of blade deformations caused by aerodynamic loads cannot be captured by the "classic" CFD approach. The coupling of both flow and structural solvers, also denoted as Fluid-Structure Interaction (FSI), can overcome this issue and enables the detailed investigation of flexible wind turbine blades.

In the first part of this PhD project, a finite element framework was implemented into the open source CFD code OpenFOAM [1]. Different linear beam element formulations were implemented and the new structural solver was coupled to stationary and transient OpenFOAM flow solvers. To include the capability of simulating flexible blades, which undergo large deformations, the structural solver is currently extended by the implementation of non-linear beam elements using the Geometrically Exact Beam Theory (GEBT) based on the formulation of Simo [2]. In combination with cross section analysis methods like the Variational Asymptotic Beam Section analysis (VABS) [3], the developed solver will be used to perform accurate load calculations for flexible wind turbine blades. As a simple example, fig. 1 shows stream lines around a simple beam structure deformed by a flow. The response of the structure to the aerodynamic loads was calculated by the implemented structural solver.

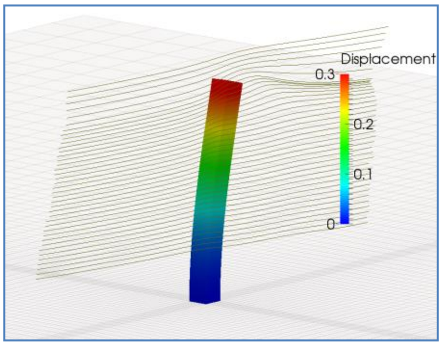


Figure 1:Stream lines around a deformed beam

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# COMPARISON OF FOUR DIFFERENT AIRFOIL PROFILES' EFFECTS ON THE TURBINE EFFICIENCY IN A SOLAR CHIMNEY POWER PLANT PROTOTYPE BY USING CFD METHOD

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## ABSTRACT

The aim of the present project is to obtain an efficient turbine blade profile for the related Solar chimney prototype. Solar chimney power plant is a thermal system which has a quite different working principle than conventional thermal systems produces electric energy from the solar energy shown in Figure1. It has three basic physical working principles which are the greenhouse effect, chimney drag and conversion to kinetic energy. The system has three main components which are collector, turbine and chimney. The air under circular glass collector is heated up with solar radiation coming on top of the collector surface. The heated air under inclined collector roof moves towards the centre of the collector. Air with rising speed moves towards chimney stated at the center of the collector. Air motion turns the turbine with generator and electric energy is obtained. In this study, CFD solution of the whole system of a Solar Chimney Prototype is evaluated. Four different airfoil profiles are compared with each other in turbine models and the most efficient one is determined.

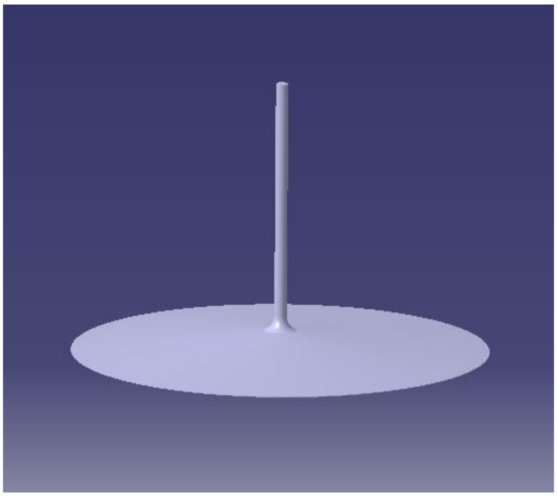

Figure 1: Solar Chimney Power Plant CAD Model

# A REVIEW OF ANALYSIS METHODS USED IN WIND TURBINE AEROELASTICTY

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## ABSTRACT

Wind turbine aeroelasticity has for a long time been treated with rather simple methods, if at all. Classical flutter analysis, a standard part of normal aeronautical design, for instance is not even directly mentioned by standards like the IEC61400, but is considered an "extra case" applied where appropriate[1]. As rotors become larger, some profound effects occur. For example, edgewise blade frequencies drop at the same time as 1P(per revolution)gravity loads become stronger. An investigation from the DTU wind energy group showed that on their 10MW reference rotor edgewise modes could become negatively damped long before the classical flutter modes[2].The previous work of Holierhoek is used as a baseline for identifying relevant wind turbine instabilities [3], [4].

This paper discusses a selection of aeroelastic instabilities found in wind turbines and how they are analysed. Part of the analysis discusses the tools commonly used in wind turbine analysis and how suitable they are to model certain aeroelastic phenomena. For example, comparisons are made between Blade Element Momentum and lifting line theories (capitals),Euler beam dynamics and large deformation dynamics as well as comparisons between sectional analysis methods like FEM and laminate theories[5]. This paper serves to act as a review of the current simulation tools availiable and how capable they are at analysising the instabilities predicted in new large wind turbines. From this review a set of recomendations are draw in order to drive future research.

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# Vortex generator induced flow: an Integral Boundary Layer perspective

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## ABSTRACT

In this work, we analyse various aspects of vortex generator (VGs) induced flow, in terms of integral boundary layer (IBL) parameters. VGs were placed in the turbulent boundary layer of a dedicated boundary layer wind tunnel, enabling measurements in relatively thick boundary layers. The latter is particularly important, in order to effectively translate these experimental findings into closure relations for viscous-inviscid codes such as RFOIL[1]. Such codes are the industrial workhorses for wind turbine airfoil design and optimization cycles. The outcome of the present study is therefore expected to have a sizeable impact on the development of new airfoils incorporating flow control devices, such as passive vortex generators.

Stereo-particle image velocimetry (sPIV) measurements were carried out on counter-rotating, submerged vane-type VGs, mounted on a flat wall inside the boundary layer wind tunnel. Findings from this experimental study are herein presented, in light of the following aspects:

- influence of different adverse pressure gradients by adjusting a flexible wind tunnel wall,
- influence of cross-flow (mimicking the presence of radial root flow over a wind turbine blade),
- characterisation of KE exchange (induced by the VG), through flow decomposition analysis.

Wall-normal flow fields, at various streamwise locations behind a vortex generator array, were acquired (see e.g. *Fig. 1)*. Initial work has focused on identifying the embedded vortices and their spatial evolution, with respect to the decay of vortex strength, core growth, and vortex convection velocity. These were further characterised in terms of the different applied pressure gradients. The experimental field-of-view also enables the assessment of the boundary layer modulation by the VGs, in the spanwise sense. This sheds light on the flow-periodicity of such flow control configurations, and their amenability to quasi-2D simplications for incorporation in IBL codes.

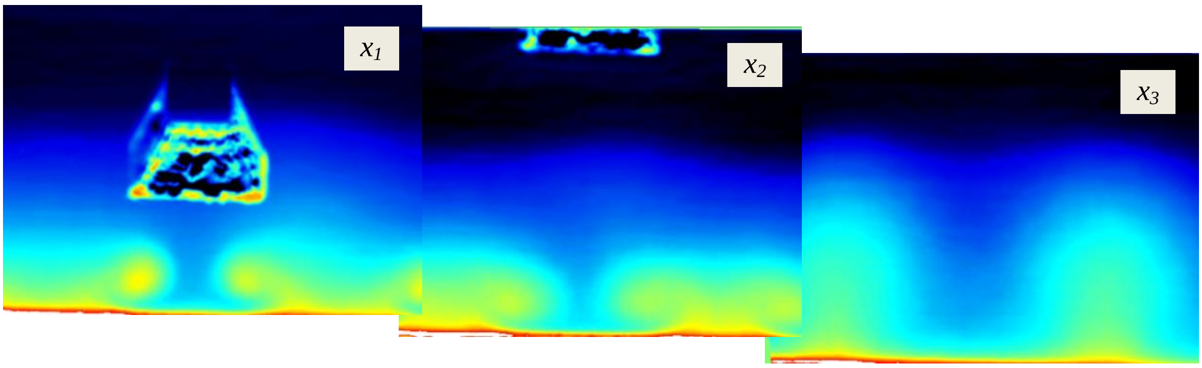


**Figure 1**. Evolution of streamwise (out-of-plane) velocity at three (increasing) locations behind a rectangular VG array ($x_1$<$x_2$<$x_3$) in a zero pressure gradient flow.

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10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

# UNSTEADY AERODYNAMICS OF AIRFOILS FOR SMALL HAWT AT LOW REYNOLDS NUMBERS

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## ABSTRACT

Small wind turbines are often built up in aerodynamic unfavorable areas, e.g. next to obstacles. This results in complex wind conditions with lower wind speeds and high turbulence. The flow conditions are less predictable, i.e. considering a daily basis, they are more variable and intermittent [1]. Furthermore, there are design constraints to small wind turbines, like a simple structure, a compact design and portability [2]. The knowledge of the aerodynamic performance at low wind speeds is crucial to a proper estimation of the energy yield and thus the economic justification of the entire turbine[1]. Other studies have shown that for instance improving the starting performance can increase the annual energy yield by up to 40% [3].

The project this work belongs to concentrates on understanding the unsteady behaviour of airfoils for small wind turbines at low wind speeds. It consists of several parts and experiments. The static performance of well known low Reynolds profiles will be investigated in the first step to validate the measurement setup against literature references. Afterwards we will investigate the dynamic behavior at low wind speeds, like dynamic stall, the influence of turbulence, or the possibilities to control the airfoil performance. The proposed work includes a short overview on the challenges of low Reynolds aerodynamics and presents the measurement setup for the dynamic testing as shown in fig. 1. This implies especially the possibility of synchronous time resolved pressure and balance measurements as well as time resolved or position triggered particle image velocimetry for dynamic airfoil tests up to post stall in an open test section. The subsequent parts of the project are additionally outlined.

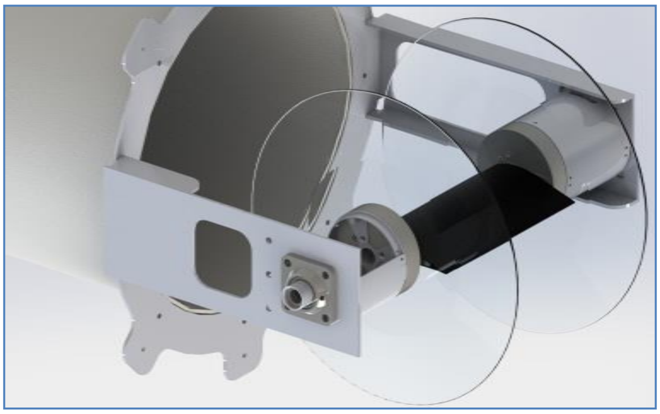

Figure 1: Model of the measurement setup.

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10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

# Hybrid aerodynamic analysis of wind turbines

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## ABSTRACT

In order to reduce the cost of energy for wind power plants, the prediction of aerodynamic loads needs to be improved. Progress has not to be made exclusively towards higher accuracy, but in fact towards a higher efficiency, meaning the ratio of accuracy versus computational effort.

Especially in industry, Blade-Element/Momentum (BEM) methods are a favoured way to estimate the performance of Wind Turbines (WT). Already formulated in the first half of the past century, BEM theory is still a competitive method, although many assumptions and simplifications, like neglecting radial flow, are underlying. On the other hand, these simplification make BEM calculations very economical. The attractiveness of this method must also be credited to the generations of aerodynamicists, who contributed to BEM (and still are contributing, see as an example [1]) with correction models, based on their expertise and experience.
The aerodynamic analysis tool of the future will clearly be based on Computational Fluid Dynamics (CFD), though. With the increase of computational power, the possibilities and advantages of CFD cannot be denied. Like no other calculation method, CFD allows the detailed resolution of flow phenomena. It's major drawback is obviously the immense computational effort, which is often not justifiable. Furthermore, validation and verification of CFD results can be problematic.

The aim of this PhD project is to investigate possibilities, how the two outlined approaches can be coupled, in order to develop a new, more effective hybrid method, combining the advantages of both techniques. In doing so, a deep understanding of the air flow around WT blades is essential, in order to judge, which calculation method is most suitable for a particular flow phenomenon. Additionally, the applicability of the different BEM correction models needs to be considered carefully, if they are to be combined with CFD data, which will be generated with the open-source code OpenFOAM [2].
Against this background, different ways to couple BEM and CFD can be formulated and need to be compared against each other, which will be the first step in the development towards the new method.

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# AERODYNAMIC ANALYSIS OF A SMALL SCALE WIND TURBINE WITH LOOPED BLADES


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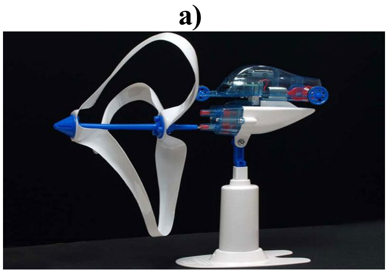
## ABSTRACT


Efficient and unconventional wind turbine design for an urban area is tried to be composed. The design utilizes the venturi effect to create a turbine with lower relative noise due to the absence of blade tip, increased efficiency, and energy generation at lower start speeds for urban location. The venturi effect provides to increase the velocity through the wings and also the efficiency of wind turbines especially. So, venturi effect is used to keep higher the inflow air of the second turbine. The type of wind turbine studied here uses looped blades to achieve the venture effect. Examples of such turbines are the Energyball [1] and the Loopwing [2] shown in figure 1. In order to achive this venturi concept, blades are looped turbine by connecting the ends of two coaxial rotors coned in the opposite directions.

In this study, aerodynamic analysis was performed for looped blades and thus wing profile of an ideal turbine was obtained using blade element momentum theory. Then, coaxial rotor configuration was obtained by placing the same blades on the same shaft downstream and the looped blades were produced by connecting the corresponding blade tips. To reach an optimum performance, pitching angle of rear blades was changed and then $C_p$ value was calculated with using of double-multiple stream tube analysis. It is assumed that blade connections do not generate a torque during the analysis. Preliminary result showed that the pressure coefficient exceeds the Betz limit. However, due to the limitations of blade element momentum theory, a verification is required and this is planned to be done using computational fluid dynamics (CFD). Final paper will include CFD solutions at various flow conditions.


**a)**



**b)**

Figure 1: a) Energyball, b) Loopwing

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# EFFECT OF THE PRESENCE OF DUCT ON THE PERFORMANCE OF SMALL-SCALE WIND TURBINES

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## ABSTRACT

Wind turbines mounted on buildings in urban environments provides the production of energy where it is being used and therefore, not only eliminates the energy transportation problem and but also decreases carbon emissions. Today the most commonly used wind turbine type is the three bladed horizontal axis wind turbine type also known as the Danish concept. However, these turbines are generally designed for open areas while wind turbines employed in urban areas operate in a much rougher environment, at lower wind speeds and higher turbulence levels compared to the turbines in wind farms. Sometimes the rotor is placed in a duct in order to increase the speed of the wind crossing the rotor area, control the wind direction and increase the turbine performance. This study contains a computational investigation on the effect of the presence of a duct on the performance of a small-scale wind turbine. Preliminary analysis and wind turbine blade design will be performed using the open source computer program XROTOR[2]. This software can include the effect of the duct by specifying the ratio of rotor area to the duct exit area and it allows to design and analyze various configurations routinely and quickly. Since the XROTOR software models the duct by area ratio only it is unable to include the duct shape and curvature. Hence, DFDC software[3], which can perform axisymmetric inviscid flow analysis of ducted rotors, will be also used in order to include the duct shape effect. In this study, various high lift airfoils will be used as the duct cross-section and their effect on the power generation will be investigated. One of these duct profiles shown in figure 1, is the Ch10sm high lift airfoil [1]. The figure also shows velocity vectors obtained using in DFDC. Once an optimum profile is selected using DFDC, turbulent flow solutions for this geometry will be performed and presented using computational fluid dynamics with a suitable turbulence model. Final paper will include at different wind speeds and also at non-axisymmetric conditions like yaw error and direction change.

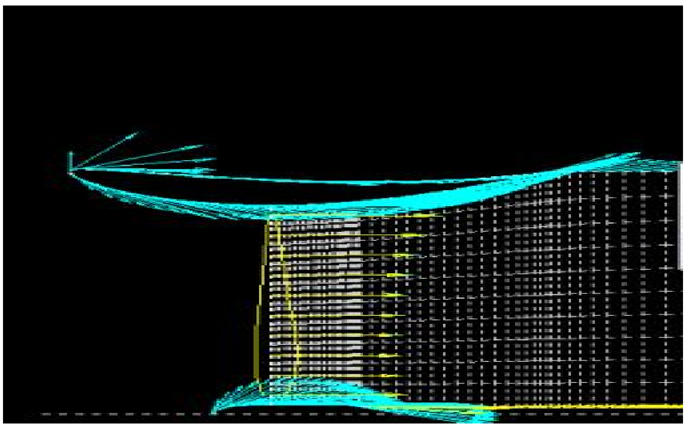

Figure 1: ''Ch10sm'' high lift ducted airfoil analysis on DFDC software

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# Increased Order Modeling of the Aerodynamic Characteristics of Flexible Blades

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## ABSTRACT

Aerodynamic performance has become a critical issue with the increasing size of wind turbine due to the longer and more flexible blades. In addition, different types of blade shapes are designed to increase the performance of windturbines, such as the design of curved blades that make use of bend twist coupling to regulate the load and power of stall controlled machines. Hence the design of such blades is more and more a trade-off between aerodynamic, dynamic and structural optimization. So far Blade Element Momentum theory (BEM) is extensively used in the design of rotor blade, but its validity starts to decrease for large flexible rotor blades.

This paper aims to investigate that how far can BEM be used accurately for the aerodynamic performance of large flexible blades and if vortex panel codes are a better alternative. So a comparative study is performed between three aerodynamic models: BEM, BEM with first order correction and a panel code implementation. Starting from modeling a straight blade and then moves towards increased curvature (see figure 1), the aerodynamic characteristics are calculated and compared between these three aerodynamic models.

First order correction to BEMhas been developed that accounts for the flexibility of the blades or for blades with non-straight initial shape [1]. This paper aims to investigate the accuracy of BEM to determine the aerodynamic characteristics of curved blades and the limit of the first order correction to BEM in improving the aerodynamic characterizing calculated using BEM with first order correction.

In the future, several methods areinvestigated to calculate the aerodynamic characteristics of flexible blades or blade with generic initial shape, with the accuracyclose to panel method and computational timein the same order of magnitude asBEM theory, making it suitable for optimization purposes.An extended lifting line method seems to be a good choice and will be studied in the future work.

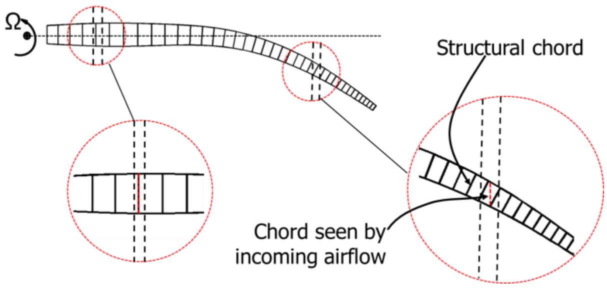


Figure 1: planform shape of curved blade

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# Noise propagation and optimization from wind turbines in wind farm

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## ABSTRACT

Noise and visual impact caused by wind turbines give rise to problems concerning public acceptance of wind energy. When one considers the long range noise propagation from a wind farm, low frequency noise becomes of greater interest since the effect of atmospheric absorption is lower at low frequencies [2]. In Denmark have been introduced stricter regulations for noise generated by wind turbines in the frequency range of 10Hz to 160Hz [3]. Moreover low frequency noise can cause problems out of the human audible capabilities (i.e. low eigen-frequencies of interior organs, excite vibrations of light building structures)[1].

The main aspects that need to be considered for long range noise propagation from a wind farm are:

- ground reflection
- atmospheric refraction: change of the propagation direction of a sound wave due to a sound speed gradient in the atmosphere
- atmospheric turbulence: fluctuations of the temperature and the wind velocity profiles [4]
- irregular terrain: smooth variations of the ground level like hills that can be considered as sound barriers that create a shadow zone behind them [5]

In the first part of the Phd project a numerical code based on the parabolic equation method described in [2] will be developed. The model will consist on a monopole source radiating noise with an axisymmetric pattern. The model should be able to predict, with a relatively short computational time, long range noise propagation from a monopole source at any given frequency. The tasks comprise the development of the parabolic equation (PE) code for a monopole source with refracting atmosphere and irregular terrain, the validation of the newly developed code against [2] and the introduction of a turbulent model for atmospheric turbulence.

The presentation will summarize the results of the first part of the Phd project described above.

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10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

# INVESTIGATION OF NOISE GENERATION OF AIRFOILS IN TURBULENT FLOWS

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## ABSTRACT

Flow-induced noise emission of wind energy converters is still a problem [1]. Simultaneously, the demands on noise prevention are strengthened. Therefore, a better understanding of noise generation on rotor blades is essential.

In the present project, the goal is the investigation of the leading and trailing edge noise of rotor blade profiles in a wind tunnel in turbulent flow. To guarantee the applicability of the results to wind energy converters, which operate in the atmospheric boundary layer, the measurements are carried out in a multiscale turbulent flow generated with a fractal grid. To reduce the background noise of the fractal grid, the grid is mounted in the nozzle of the wind tunnel and the nozzle is covered with an acoustic absorber. In fig. 1, the sound pressure levels with and without an arbitrary airfoil are compared. Clearly, the leading and trailing edge noise are separable from the background noise induced by the grid. Due to these severe changes in the setup, the multiscale flow properties have to be verified. As can be seen in fig. 2, the probability density functions of increments of the flow show multiscale behavior. Therefore, the requirement of an atmospheric-like flow is fulfilled.

As noise is generally induced by high-frequency pressure fluctuations, these fluctuations are measured on the surface of an airfoil. Simultaneously, the noise emission is measured with a directional microphone array. The results of these measurements will be presented. We plan a comparison with simulations run with the same parameters.

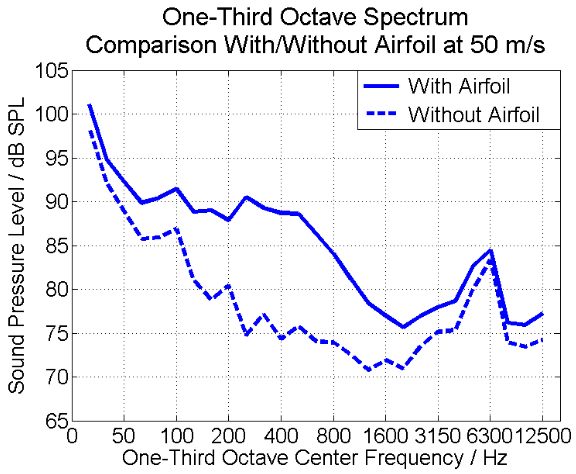


Figure 1: One-third octave spectra of the noise of the fractal grid (dashed) and the grid in combination with an airfoil in the flow at 50 m/s.

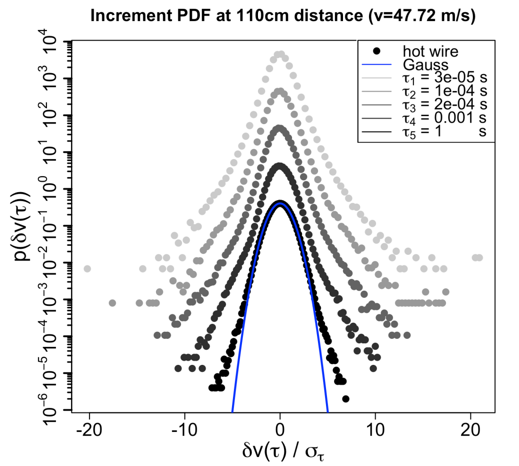


Figure 2: Increment probability density functions at foil position at 47.72 m/s for different scales.

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# Numerical investigations of a passive load alleviation technique for wind turbines

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## ABSTRACT

The diameter of wind turbine rotors grew significantly over the last few years, in order to increase the energy yield. However, a further enlargement of the rotors requires new concepts and technologies in order to avoid the unproportional increase of weight and to decrease the energy generation cost. In particular the reduction of peak and fatigue loads, e.g. as a result of tower blockage, is therefore mandatory for cost-efficient turbines.

The present work deals with the motivation and the objective of load alleviation concepts and the efficiency of one load alleviation concept under various conditions. The concept under investigation was developed at TU Darmstadt [1]. It is a passive system with coupled leading and trailing egde flaps, “Fig.1”, which can change the cambering of an airfoil and therefore influence the aerodynamic loads on the turbine.

The impact of different inflow conditions and structures shall be investigated within the project. As a result of this, the complexity of the model is increased stepwise, starting with a 2D airfoil with load alleviation under steady inflow conditions. Moreover, the project includes airfoil simulations considering the unsteady aerodynamic effects caused by tower blockage as well as 3D simulations of a turbine with coupled leading and trailing edge flaps under various inflow conditions.

All CFD simulations shown in this paper have been carried out with FLOWer, a block structured code develepod by the German Aerospace Center (DLR), which solves the compressible Navier-Stokes-Equations. The results of the simulations will be analysed and compared to wind tunnel results performed by TU Darmstadt [1].

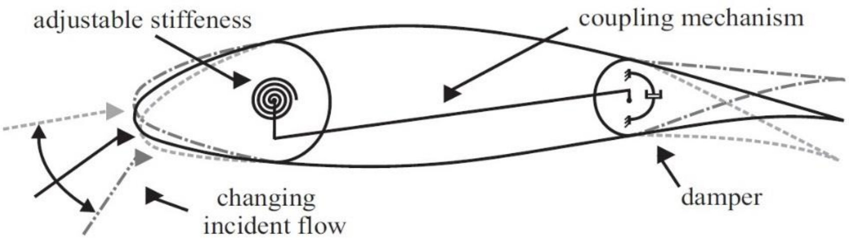


Figure 1: structure of an airfoil with coupled leading and trailing edge flap [1]

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# IMPLEMENTATION OF AN OPTIMIZATION TOOL FOR ROTOR BLADES BASED ON THE ADJOINT METHOD IN OpenFOAM

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## ABSTRACT

Wind turbine blades are constant object of optimization, e.g. to reduce the cost of production, increase life time, adaption for different wind fields and many more. As blades are rather complex geometries, possibly with twisted and prebended parts, optimization becomes complex as solutions are not intuitive. We want to focus on the optimal aerodynamic shapes and behavior of blades in a wind field. As the wind changes quickly both in direction and magnitude of velocity, alternating loads act on the blades during a lifetime of about 20 years. These loads can lead to fatigue and therefor shall be reduced by an optimal bend-twist-behaviour of the blade for different wind load situations.

We want to use stationary computational fluid dynamics (CFD) as a source of information about the flow around such blades and the forces acting on them. As the computational time needed for CFD is already high, the optimization process has to be computational cheap. Based on work for ducted flow optimization by Othmer [1] we prupose the adjoint method as optimization algorithm. It is a gradient based algorithm, and therfor the needed direction of change of the design parameters in order to reach a minimum (or maximum) of the cost function is known. Another advantage is that the adjoint method is independent of the number of design parameters. So it is highly suitable for the combination with CFD, as the fine discretized blade geometries from CFD can be directly used as design parameters for the optimization.

In the past we implemented the adjoint method based on the work of [1] for external flows in OpenFOAM. This is an open-source simulation tool suitable for wind turbine simulation among many other possible applications [2]. The first conducted test case is a drag minimization of a NACA profile, as validation of the optimization is needed. We chose this case, as the result of the optimization is primarily known to be a flat plate oriented parallel to the incoming flow velocity. Good results could be achieved [3]. Before using the optimizer for other purposes, the gradients shall be verified. This can be done by choosing some characteristic design parameters (e.g. at the leading edge) and using finite differencing to compute the gradients at these points. These gradients can then be compared with the gradients computed using the adjoint method.

For the simulations of this project we use the FLOW Cluster of the University of Oldenburg. This work is part of the Smart Blades project supported by the Federal Ministry of Economics and Technology (BMU) under the support code 0325601A/B/C/D on the basis of a decision by the German Bundestag.

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# Large Eddy Simulation of Wind Farms with Energy-Conserving Schemes

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## ABSTRACT

Wind farm aerodynamics (WFA) is the study of wind turbine wakes and their interaction with each other and the Atmospheric Boundary Layer (ABL) [1]. Such knowledge is helpful in assessing the power production of turbines on a wind farm and also the loads they bear while in operation. There are two sources of data: experimental data from wind farms, which is expensive to procure and yet scare, and numerical from simulations. The current research deals with the development of the Energy-Conserving Navier-Stokes, Large Eddy Simulation (ECNS-LES) code for WFA, by ECN and TUD.

The ECNS solves the incompressible *Navier-Stokes* (NS) equations with a finite volume approach on a *Cartesian* grid. Using Energy-Conserving schemes [2], the code ensures that all dissipation is solely through molecular viscosity and artificial dissipation is absent. In addition, it guarantees unconditional stability, even on coarse grids, without artificial dissipation that is used to stabilise numerical schemes.

Artificial dissipation is known to cause the premature recovery of velocity deficit in turbines wakes and the ensuing overprediction of power generation, and even more so on a coarse grid, which are the norm in LES [3]. Although spectral methods are common and preferred for LES, the authors seek to demonstrate how the ECNS-LES with its finite volume approach, could be a fine alternative for accurate wind farm simulations.

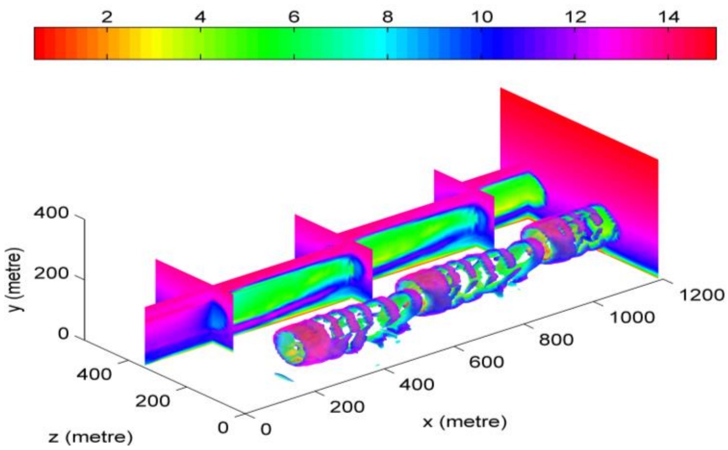


Figure 1: An illustrative simulation of Actuator Disks in an ABL inflow (15 $ms^{-1}$) with the ECNS respresenting the regions of vorticity, which are coloured by streamwise velocity. One notices the asymmetry due to the ground, and the sheet-like voriticity from actuator disks, are well-captured.

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# Dynamic Soaring approach to Airborne Wind Energy

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**Dynamic Soaring is a flying technique which consists in harvesting energy by performing periodic manoeuvres within a vertical wind gradient. Equations of motion are developed for a tethered point-mass-model, flying leeward of a hill. Steady wind profiles are chosen to begin with and various set of control variables are studied. Comparisons with more traditional airborne wind energy are conducted.**

The aim of the present project is to assess the feasibility to fly dynamic soaring trajectories for the purpose of wind-energy-harvesting. It has been established, both theoretically [1] and experimentally [2], that dynamic soaring trajectories enable a flying vehicle to extract energy from the wind by executing periodic trajectory cycles relative to the wind field. The overall energy-harvesting process involves a step-by-step build-up of kinetic energy until losses balance energy gains along the curve.

However, the excess of kinetic energy gained at every path can potentially be converted for on-land available electricity. The converting process would be intrinsically tied to the extraction one, as it would consist in an overall synergy of aeromechanical solutions, like more conventional airborne systems [3]. Advantages of such an approach versus other airborne solutions would need to be highlighted by performing simulations using a methodology derived from dynamic soaring studies.

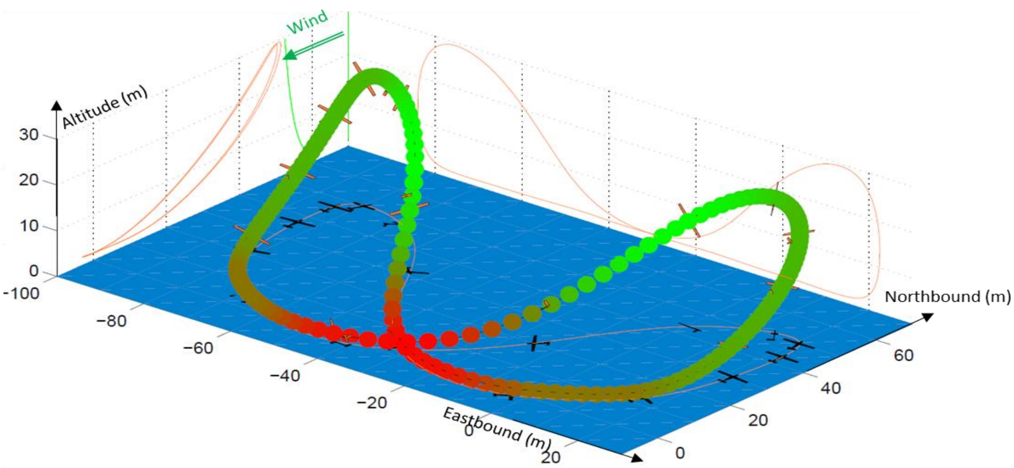


Figure 1: Example of a dynamic soaring energy-neutral closed cycle.

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# EXPERIMENTAL METHODS FOR THE OPTIMAL DESIGN OF SMALL WIND TURBINES

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## ABSTRACT

The design of small wind turbines (SWT) is very often developed through a pragmatical rather than theoretical approach. The small size of these systems allows a fast and cheap prototyping and usually technicians simply try the best solutions without understanding the principle of operation.
In present work a new numerical and experimental approach is proposed in order to quickly characterize, define and test the optimal design parameters for different type of small wind energy converters. This method involves the use of numerical [1] models for the blade design and two different kind of test of the overall wind conversion system:
1. measurements on the electrical generator test rig;
2. wind tunnel test.
Small wind energy turbines usually work with fix blade pitch and a wide range of rotational speed; in this way it could be difficult to define the optimal electrical load curve [2,3]. Measurement on the electrical generator test rig are fundamental in order to define the efficiency of all the components of the energy conversion chain: electrical generator, power conversion systems etc.…
Wind tunnel tests (fig.1) are as well fundamental to finally verify the aerodynamic efficiency of the rotor and to optimize the coupling of mechanical and electrical devices.
In present work results of the characterization of different kind of wind turbines with a rotor diameter up to 2 m and a rated power of 1,5 kW are discussed.
Results demonstrate that this kind of experimental activity can give very useful informations for strongly improve the performances of the system and for a validation of all the design methods.

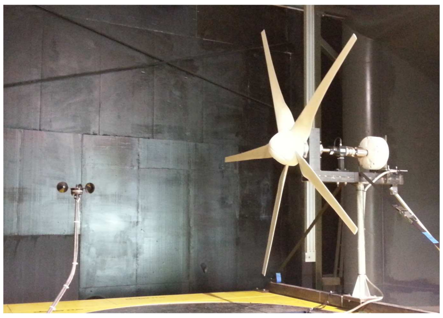

Figure 1: Wind tunnel test for torque and electric power measurements.

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# IMPLEMENTATION OF PASSIVE CONTROL STRATEGIES THROUGH SWEPT BLADES

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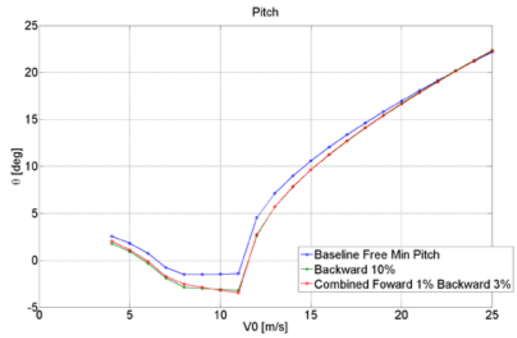
## ABSTRACT

The capabilities to mitigate loads on the structure, while maximizing wind yield and energy output, are central among the requirements for designing a cost-effective wind turbine. Control techniques able to achieve load reduction on wind turbines can be generally categorized in two branches: active and passive control methods. The first consists of technologies able to reduce loads by actively controlling the machine e.g. blade pitch actuators and moving flaps are two examples. The second is based on the idea of designing a structure that, when loaded, deforms so as to induce a load reduction.
The main purpose of this study is to investigate the potential of the implementation of a passive control strategy based on the variation of the geometrical properties of the blades of a wind turbine.
An exhaustive parametric study about the load consequences brought by the use of different configurations of swept blades has already been carried [1], underlining a key feature that has to be further investigated: the power output of a wind turbine that uses swept blades is consistently lower below rated wind speed compared to a wind turbine with straight blades. This negative effect is due to the fact that the swept configuration induced bend-twist coupling, forces the blades to point towards lower angles of attack: aerodynamic loads are reduced through all the wind speeds range, causing a loss of power below rated compared to the straight blades configuration.
In this study, in order to compensate this loss, the swept blades are pitched further towards stall below rated wind speed than the straight blades. New operational points for the controller below rated wind speed are obtained from the linear aero-servo-elastic model HAWCStab2 [2]. Thus, the different wind turbines configurations have similar power curves, giving the possibility of implementing a fair parametric study using the aeroelastic analysis software HAWC2 [3]. Discussion on the approach and comparison of the results with the reference [1] are presented in this paper.



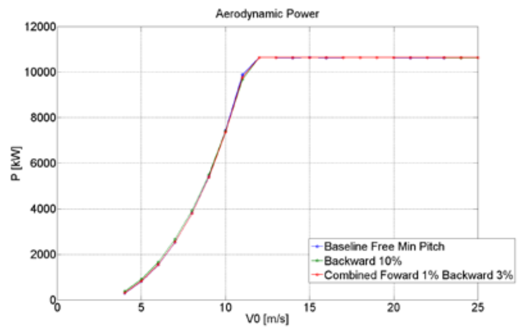




Figure 1 - Pitch Angles and Power Curves for DTU 10 MW WT - Baseline, 10% Swept Backward, Combined Foward 1% Backward 3% (HAWCStab2)

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# Statistical Extrapolation Methods for the Estimation of Offshore Wind Turbine Extreme and Fatigue Loads

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## ABSTRACT

Probabilistic methods allow the prediction oflong-term loading of wind turbines with a limited amount of either simulation or experimental data.The current version of the IEC standard 61400-3 [1] for offshore wind turbines requires statistical extrapolation of loads in order to estimate the 1-year and 50-year extreme loads,  without providing a precise extrapolation procedure. Therefore, the estimated loads depend on the implementation method of the individual designer. This PhD project shall contribute to the validation of common methods for load extrapolation based on the experience gained from the extrapolation of measurement data from an offshore wind turbine.

Within the framework of the project OWEA Loads, strain gauge measurement data of the AREVA 5MW wind turbine with a tripod foundation located in the offshore wind farm alpha ventus is available. More than three years of high resolution data for sensors at the main components of the wind turbine (e.g. blade root bending moments, tower base bending moments) and the tripod have been recorded. This gives the unique opportunity to extrapolate measured extreme and fatigue loads of an offshore wind turbine and compare them to extrapolated loads obtained from simulations.

In order to obtain the data base needed to implement the extrapolation procedures, the measurement data needs to be calibrated and checked. Furthermore, for an appropriate estimation of the wind coditions, only data recorded under free stream conditions will be analysed. Subsequently the short-term and long-term distributionsfor the considered sensors can be determined. A study on the selection of the extreme value probability distribution (e.g. Gumbel, Weibull), the choice of the fitting method (e.g. Method of Moments, Maximum Likelihood Method) and the necessary number of measurement data will be performed. Based on the results of this PhD project general recommendations for the extrapolation of extreme and fatigue loads of offshore wind turbines are supposed to be made.

At this early stage of the PhD project the focus has been set on the study of extreme loads. So far a general overview of the available measurement data has been gained. The next steps will be to eliminate outliers (physically unrealistic values) and to createa data base of maxima for several sensors. To obtain the maxima from the high resolution measurement data different methods will be used: global maxima (one maximum per 10min time series), block maxima (several independent maxima per 10min time series) and the peak over threshold method. The influence of these different approaches on the extrapolated loads will be studied. First results of these investigations will be the subject of the presented poster.

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# Hybrid Automatic Optimization ofHAWTBlade

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## ABSTRACT

In this study, a hybrid of gradient-based shape design and Genetic-Algorithm (GA) optimizations have been incorporated to produce an efficient Horizontal Axis Wind Turbine (HAWT) blade .
The gradient-based was employed to design the rotor blade [1], whereas the GA optimization in combination with the B-spline parameterization were used to obtain the sectional airfoils [2,3].
HAWT blade design that consists of chord and twist angle distributions was optimized aerodynamically to increase the extracted power under consideration of the drive torque.
Blade sectional airfoils were generated and optimized to maximize their Glide Ratio (GR).
In order to generate a smooth airfoil profile, the GA encoding process was conducted to the control points of the B-spline. Upper and lower bounds were limited to keep the airfoil generation restricted within the range of standard of the wind turbines.
The generated airfoils, which evolve from the previous parent airfoils in each GA cycle were automatically evaluated by interfacing with XFOIL, Figure 1.

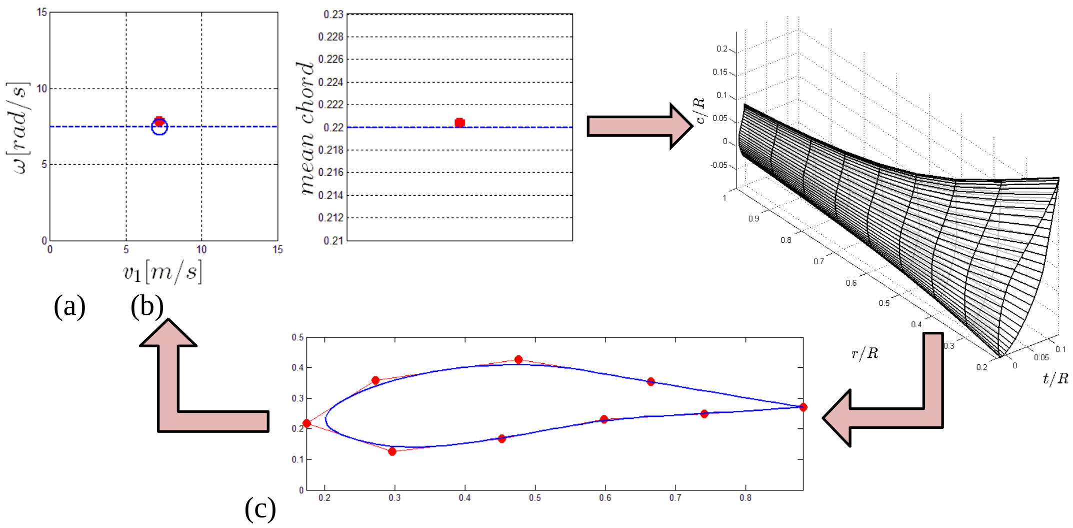


Figure 1: Optimization process (a) Gradeint search (b) Gradeint-Based optimized blade (c) GAoptimization of the sectional airfoil

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# Vertical Axis Wind Turbine Hydraulic Drivetrain Options

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## ABSTRACT

The aim of the project is to consider design options for vertical axis turbines with hydraulic drivetrains. Many companies are looking at the possibility of using vertical axis wind turbines offshore with several drivetrain options being considered[1]. One of which is using hydraulic pumps connected with pipes to a hydraulic motor which is then connected to a generator. Vertax is one such company that has designed an offshore vertical axis turbine[2]. It is used as a case study to analyse the effect of using hydraulics. Specifically an evaluation of the mass and efficiency of the hydraulic system is compared to that of a permanent magnet generator. Consideration is also given to the height at which the motor and generator is placed in the tower. The effect this has on the over turning moment, availability and efficiency is analysed.

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# INVESTIGATING THE EFFECTS OF PITCH CONTROL STRATEGY ON THE POWER ELECTRONICS LIFETIME OF A VERTICAL-AXIS WIND TURBINE.

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## ABSTRACT

A stall-regulated vertical-axis wind turbine (VAWT) will have a shorter power electronics lifetime than a pitch-regulated horizontal-axis turbine of similar rating. This is due to the pulsating aerodynamic torque as the turbine rotates, and also due to the stall regulation leading to significant power fluctuations with wind speed. This causes thermal cycling in the IGBTs in the converter, leading to degradation.

The aim of this project is to extend the existing stall-regulated model of VAWT to incorporate pitch-regulation, and investigate how the pitch regime can be used to limit the torque cycling and extend the converter lifetime.

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# A semi-empirical damping model for floating buoy trifloat with heave plates.

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## ABSTRACT

Hydrodynamics of floating devices is usually estimated with linear diffraction – radiation approach. Based on numerous studies, this method is well validated on usual shapes including barge type floating wind turbines. However for many other concepts (spar, semi-submersible, . . . ) it is necessary to increase the heave period and damping using dedicated devices, such as "heave plates" (similar to horizontal plates), which are badly simulated in these numerical codes. Usually, radiation's coefficients of floating object are determined by linear in diffraction- radiation problem. For many kind of buoy without heave plates, numerical issues and experimental results present a same behaviour. But these predicitons are not satisfactory when heave plates are added to the plateform. Indeed, these heave plates are designed to bring a better stability in sea, in particular by increasing damping effect. Studies showed that radiation coefficients are underestimated compared to harmonic analysis of experimental data [1].
As part of my PhD, forced motion tests are realised in wave tank. The buoy is a trifloat structure which can have heave plates on each cylinder. For few degrees of freedom(ex : heave, surge, pitch , yaw) , the added mass matrix and the damping matrix are obtained with differents amplitudes and period of motions oscillating [1],[2].
Firstly, a harmonic analysis is compared with linear solutions of NEMOH (the diffraction-radiation solver of Ecole Centrale de Nantes). Then,a more complex hypothesis for analyse data is done. The linear damping contribution is compared with numerical solution, and discussions concern other contributions in damping effect like the quadratic contributions. With these results, we hope to implement a new module in NEMOH, which should respect heave plates presence in the damping coefficients calculation.

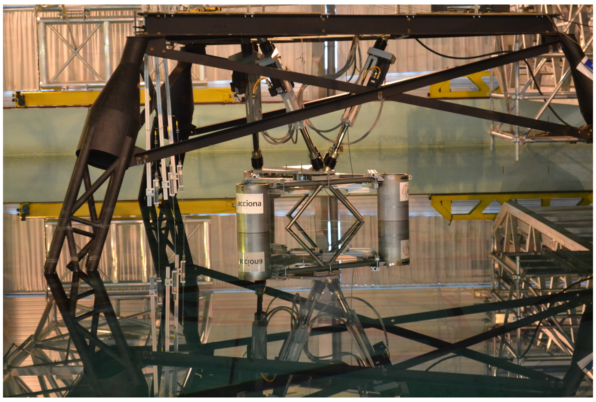

**fig. 1:** Test setup for trifloat model in forced Oscillation.

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# Examining green jobs in Scotland using a hybrid approach

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## ABSTRACT

The Scottish Government has set the ambitious target to reduce $CO_2$ emissions by 42% (compared with 1990) levels by 2020 and to achieve this one of the main objectives is that 100% of the net electricity produced will be from renewable sources. With the introduction of these targets it is expected that there will be a significant increase in the amount of green jobs in the country, especially in the wind sector. Trying to estimate the amount of green jobs which have or will be created as a result of the drive to a low carbon future is difficult and the estimations usually vary greatly depending on the source and approach used. The main problem is that there is no standard approach to defining the sectors which contribute to green jobs in the low carbon/renewable economy. A recent study carried out by Bishop et al (2013) used a new approach to estimating the low carbon economy for the Plymouth area, this new approach was a combination of bottom up and top down mythologies which used Innovas and Standard Industrial Classification (SIC) data. The main advantage of using this bottom up method with the top down SIC code is that allows the calculation over the previous years, and also to follow it over time as new data is published. The purpose of this paper is to apply this new approach to Scotland to determine if it can be used on a national scale and also to find a new estimation for the amount of green jobs created for the drive to a low carbon future.

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# Evaluation of planetary boundary layer schemes and meteorological reanalyses in meso-scale simulations above the North and Baltic Sea

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## ABSTRACT

The development and design of wind energy converters for offshore wind farms require profound knowledge of the wind profile in the lower atmosphere. Especially an accurate and reliable estimation of turbulence, shear and veer are necessary for the prediction of energy production and loads.

Currently existing wind energy turbines in the North Sea have hub heights of around 90 m and upper tip heights around 150 m, which is already higher than the highest measurement masts (e.g. FINO1: 103 m). The next generation of wind turbines will clearly outrange these altitudes, so the interest is to examine the atmosphere's properties above the North Sea up to 300 m. Therefore, besides the Prandtl layer also the Ekman layer has to be taken into account, which implies that changes of the wind direction with height become more relevant. For this investigation we use the Weather Research and Forecasting Model (WRF), a meso-scale numerical weather prediction system [1].

In our study we compare different planetary boundary layer (PBL) schemes (ACM2, MYJ, MYNN, QNSE, YSU) using different meteorological data as boundary conditions (ERA-Interim, MERRA, CFSR). It was found in previous studies that the quality of the boundary conditions strongly differ between meteorological reanalyses [2] and thus influence the performance of PBL schemes. This is due to the fact that the major source of meso-scale simulation errors is introduced by the driving boundary conditions and not by the different schemes of the meso-scale model itself. Hence, small differences in results from different PBL schemes can be arbitrarily distorted by coarse input data.
In addition to the wind profile, also the turbulent kinetic energy (TKE) and the atmosphere's thermal stability are important to estimate power production and loads. Especially the TKE is in the focus of our research since the Master Length Scale of some closure schemes depends on it (i.e. MYJ).
We validate the results using wind measurements around the North Sea. Because the considered heights are much larger than available data from offshore met masts, we use LiDAR observations (light detection and ranging) and higher onshore met masts.

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# ANALYSIS OF THE BENEFITS OF FAULT-TOLERANT CONVERTERS IN OFFSHORE WIND TURBINES

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## ABSTRACT

The converter in a large variable-speed wind turbine has amongst the highest failure rate of any component, but in an onshore setting it has not received much attention as repairs can be carried out quickly and with minimal equipment. In an offshore wind farm, access is by boat or helicopter, which is significantly more expensive and may be restricted by high winds or wave heights. This means that converter failures offshore will cost more to fix, and potentially also lead to a greater downtime, leading to loss of revenue.

Converters can be designed to be modular and to feature fault-tolerance, where the turbine can continue running at reduced power after a fault in one converter module, or fully redundant, in which the turbine can continue at full power. The purpose of this project is to investigate the effects of using such converters on the turbine downtime, maintenance cost and lost revenue.

10th PhD Seminar on Wind Energy in Europe
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# POWER SYSTEM DYNAMIC RESPONSES – COMPARISON BETWEEN SIMPLE SIMULINK MODEL AND MORE COMPLEX TIME-STEP BASED DYNAMIC RESPONSE MODELLING

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## ABSTRACT

With the increase in the percentage of energy produced from wind turbines, come challenges for the power system; especially in terms of grid frequency. Conventional power plant, such as coal fired or gas fired plant, are used to maintain the stability of the system. This is via three broad mechanisms:

1. System inertia
2. Droop Control and primary response
3. Secondary response

Modern wind turbines tend towards being variable speed, pitch regulated machines and as such tend to be asynchronous. This means that they do not supply any inertia to the grid. In order to maintain system frequency stability, various control options have been developed, most notably the Power Adjusting Controller (PAC) previously developed at Strathclyde. This controller would allow wind turbines to supply one, two or all of the previously mentioned mechanisms.

In order to model power systems, various commercial software packages are used such as PowerFactory and PSS/E. One problem with these systems is that they can be processor intensive and slow to compute. In addition, as they are proprietary software, they require licences and not easy to link to other software. This can make modelling the effects of wind turbine control strategies cumbersome and difficult.

A simpler power system stability model has been developed at Strathclyde using Matlab/Simulink. This model is much quicker to run and has the advantage that it can be easily linked with other models designed within the Matlab environment.

This project involved the validation of the simple Matlab/Simulink model through comparison with the commercial software options. This allows for future work to make use of the simpler model, enabling research into the effect on the grid of various wind turbine control strategies to be completed.

# CFD coupled with WRF for Wind Power Prediction

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## ABSTRACT

The objective of the current study is to predict the daily power potential for a region of interest accurately. To do so, 3D unsteady Navier-Stokes solutions coupled with a mesoscale weather prediction model (WRF) are to be utilized using the open source CFD software OPENFOAM. Unstructured grids are used to discretize the complex terrain of interest. High resolution (1.5 arcsec) ASTER GDEM topographical data is used to create terrain following grids in order to capture the viscous effects which dominates the flow characteristics at the surface layer of the atmosphere where majority of the wind turbines reside. WRF solutions can be obtained using the real time weather prediction data ECMWF provides for a region of interest. Spatially and time varying boundary conditions are to be interpolated both in time and space from the WRF solutions and updated for each cell. A schematic for the coupling procedure is given in Figure 1. In previous study [1] , this procedure was done using FLUENT as a Navier-Stokes solver but higher grid resolutions could not be performed due to the fact that Fluent cannot be run in the parallel mode in the presence of a UDF that implements the time dependent boundary conditions from a table of data, and serial computations with the total number of cells exceeding $10^7$ become prohibitively resource demanding. As OPENFOAM is an open source software, it is thought that this problem could be overcomed.

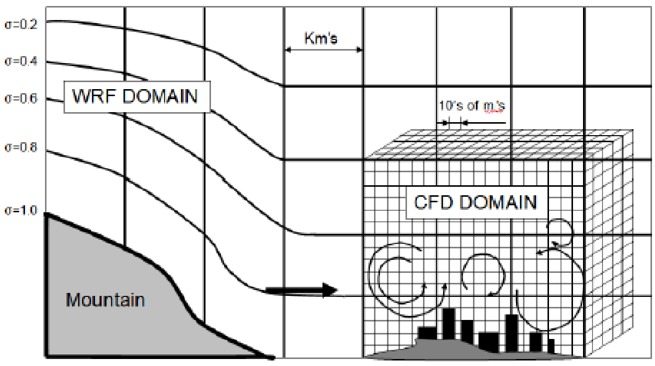


Figure 1: Coupling WRF and OPENFOAM

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# Wind Prediction Enhancement by Supplementing Measurements with Numerical Weather Prediction Now-Casts.

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## ABSTRACT

Forecasting of wind, in particular wind speed, is an important problem [1,2]. In previous work, we have considered the spatio-temporal prediction of wind speed and direction by means of linear complex valued prediction filters [3,4]. There, speed and direction are modelled as magnitude and phase of a complex valued time series. The accuracy of temporal prediction can be enhanced by considering additional spatial measurements; e.g. in [3,4] 13 Met. Office sites across the United Kingdom have been utilised.

This paper explores enhancements of the wind speed and direction prediction model in [2] based on supplementing spatial data. To achieve this, two different data sets have been used: (i) wind speed and direction measurements taken over 50 Met. Office weather stations distributed across the UK, and (ii) outputs from the consortium for small-scale modelling (COSMO) numerical weather model on a grid of points covering the UK and the surrounding sea shown in fig.1. A multivariate complex valued adaptive prediction filter is applied to these data. Using suitable performance metrics and existing approaches in [2] as benchmarks, the study provides an assessment of how well the proposed model can predict the data one to six hours ahead.

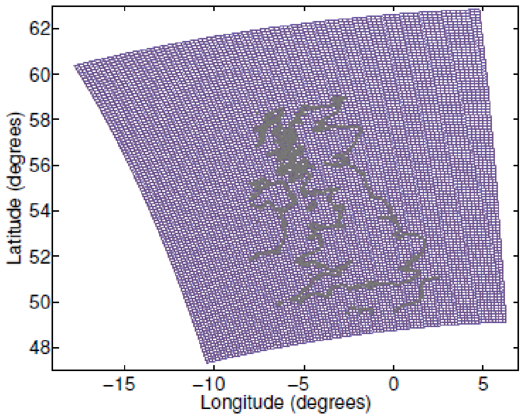


Figure 1: Grid of numerical weather prediction (NWP) outputs from the COSMO model.

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# MARE-WINT: New Materials & Reliability in Offshore Wind Turbines Technology

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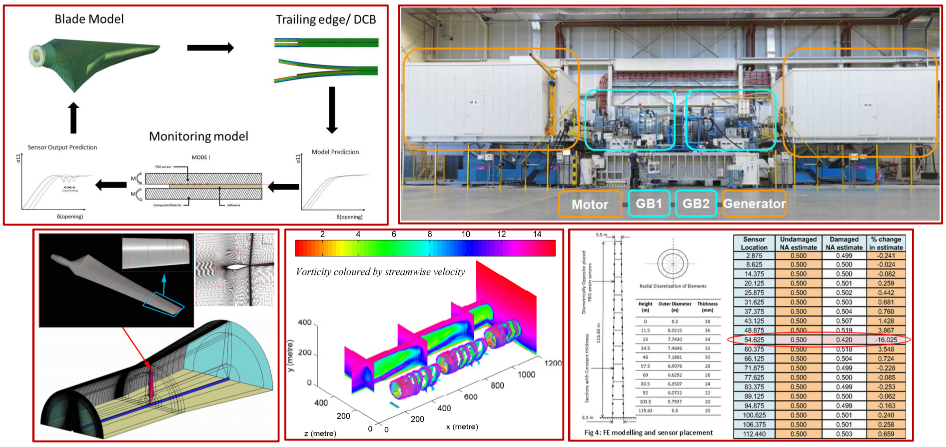
## Improving the Reliability and Optimising O&M Strategies for Offshore Wind Turbines

The aim of the European Commission funded MARE-WINT project is to *'reduce cost of energy, by improving reliability of [offshore] wind turbines (OWTs) and their components, and optimizing operation and maintenance (O&M) strategies'* [1]. The project is divided into six work packages (WPs), and between 14 Early Stage Researchers (ESRs), spread across 17 institutes [2]. WP1, with 2 ESRs, involves work on *innovative rotor blades*; this includes *modelling of manufacturing defects in OWT blades* (Fig. 1), and *CFD investigations of near-blade 3D flow for a complete OWT configuration*. WP2, with 2 ESRs, has a focus on the *drive train and gearbox*; this involves *simulation & experimental validation of drive train loads for offshore specific conditions*, and the *derivation of a strategy for model updating based on experimental data from drive train test facility* (Fig. 2). 2 ESRs are also assigned to WP3, with the primary aim of modelling and analyzing *offshore support structures* – for both, a floating OWT concept, and a bottom fixed substructure OWT. WP4 comprises of 5 ESRs, and addressess OWT *Reliability and Predictive Maintenance*; issues to be addressed include *OWT condition monitoring*, *damage detection in metallic & composite strucutres* (Fig. 3), *reducing wake effect fatigue loads using Large Eddy Simulations (LES)* (Fig. 4), *navigational risk assessment of vessels operating near OWTs*, and an overall *OWT reliability modelling analysis.* 3 ESRs in WP5 are involved with the *fluid-structure interaction* of an OWT; this involves *RANS simulation for hydro-elastic floating substructure prediction,* analysis of a *twist-coupled aero-elastic design for passive loads reduction on a full scale blade,* and investigations into *active flow control to improve aerodynamic performance using blade modelling & high quality grid generation* (Fig. 5).WP6 covers dissemination activities.




Clockwise from top left, **Fig. 1**: *Investigating the presence of damage in blades, understanding damage propagation mechanism & providing solutions for more reliable structure design using new materials, processes, and sensorisation*; **Fig. 2**: *Building further on existing Order Tracking & Operational Modal Analysis techniques, to develop a new method, and validate it by means of numerical models (flexible MBS model) & experimental data (test rig measurement).;* **Fig. 3**: *Damage Detection in Tower structures through the use of Kalman Filter based Neutral Axis tracking. Initial investigations have shown promise in the technique to detect damage, & the metric is sensitive to even small extents of damage and shows robustness to presence of measurement noise.* **Fig 4**: *Using Large Eddy Simulation with Energy-Conserving Schemes to study wind farm wake aerodynamics towards predicting loading & fatigue on offshore wind farms.***Fig. 5**: *Focus on flow control separation on OWT blades in order to ensure aerodynamic performance improvement – carried out through correct blade modelling and high quality grid generation*

## REFERENCES

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# UNSTEADY AND TURBULENT ROTOR LOADS

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## ABSTRACT

Complex and unsteady interactions between highly turbulent atmospheric inflow and the flow over wind energy converting systems (WECS), are of crucial importance with respect to the loads on the rotor blades. The disturbed inflow leads to a strong variation of the effective inflow angle over the entire rotor blade radius. Unsteady aerodynamic effects are the reason for phase shifts between excitation and resulting loads, but those effects have not been well described by models yet.

At the present state, atmospheric wind inflow data for rotor-aerodynamic Computational Fluid Dynamic (CFD) simulations are generated with Large Eddy Simulations (LES) under a high computational cost, e.g. with the program PALM [1]. Another drawback of those wind fields are the missing intermittent statistics (fig.1) which have to be included in all simulations if one wants to consider extreme events of high wind speed fluctuations within a short time intervall which are highly important for load and fatigue calculations. In order to avoid those issues, a probabilistic model, the so called Continuous Time Random Walk (CTRW) model by Kleinhans/Friedrich [2,3], will be implemented in the Opensource Code OpenFOAM [4]. This model shall work for different meteorological conditions and wind behaviours as an inflow model. For industrial usage, an LES subgrid model will be modified in that way, such that the small scale intermittent properties will be transported through different mesh resolutions within the simulation area. LIDAR measurements are used for validation of the stochastic properties of the CTRW model, and load measurements on WECS will be compared to CFD simulated data.

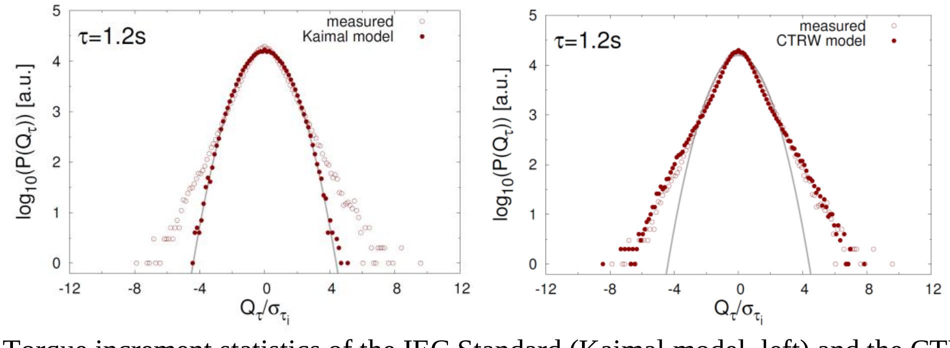


Figure 1: Torque increment statistics of the IEC Standard (Kaimal model, left) and the CTRW model (right) compared to measured data

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# Investigating the interaction between wind turbines and atmospheric flow with a coupling of the aeroelastic code FAST and the LES code PALM

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## ABSTRACT

During the design but especially during the operation of a wind farm it is necessary to consider the mutual aerodynamic influence of turbines. Wake flow conditions could lead to substantial losses in the energy yield as well as an increase in structural loads due to larger inhomogeneity in the wind field and higher turbulence.

Within a current research project a new coupling of the LES flow solver PALM [1] and the aeroelastic wind turbine simulation tool FAST [2] on the basis of actuator line techniques [3] is being developed. This code coupling will allow for a better understanding of the flow development in a wind farm and the wind turbine – flow interaction under various atmospheric conditions as well as the virtual application of different turbine control concepts (Fig. 1).
Based on the simulation results integrated strategies for controlling turbines in a wind farm to increase the overall farm energy output and reduce the structural loads on the individual turbines will be derived.

Current activities within the scope of the PhD project are focussing on a proper validation of the coupling with measurement data of power and turbine loads of an offshore wind farm to provide a sound basis for further investigations. Besides the variation of model parameters (e.g. time steps, grid size, force distributions) to assure its robustness, simulations for different atmospheric condition are conducted to examine the ability of the coupling to reproduce the measurements.

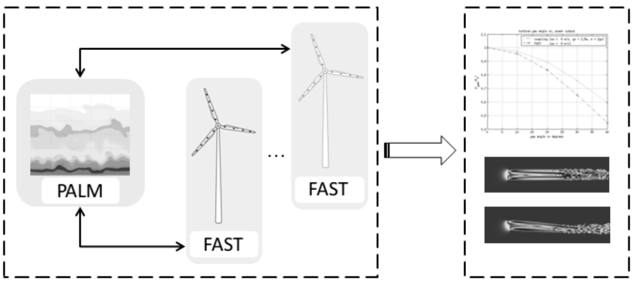


Figure 1: Scheme of coupling interaction

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# Experimental Investigations of the TurbulenceImpacton the performance of the HAWT

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## ABSTRACT

The present study aims at highlighting the influence of the turbulence on the performanceof the HAWT. For the investigation,we have designed a laboratory-scale HAWT that can efficiently perform in the LSTMwind tunnel, [1]. Thus, obtained results are reliable and possible to be reflected and evaluated for different scales of HAWTs.

The turbine has been exposed to turbulence with various energy andlength scale content. The turbulence is generated bytwo static squared mesh grids. Hence, two mainly different turbulence scales are obtained. In addition, the distance between the wind-turbine and the grid is adjusted to have additional sub-turbulence scales for each grid, Figure (1).

The developments of Taylor's micro scale (λg) and integral scale of the turbulence(Lg) in the flow direction at various Reynolds numbers are measured. Furthermore, up and down-stream turbulence intensities (TI) distributions are measured to give insight on the surrounding-wake interaction.

Performance measurementsare conducted with and without turbulence, and winglet is used to isolate the tip vortex effect, Figure (2).

The study shows that the higher the turbulence, themore the power extracted by the turbine. Theturbulence helps in damping tip vortices thus,reduces turbine tip losses. In addition, it contributes in suppressing the boundary layer and preventing the separation that in turn enhances the HAWT performance.

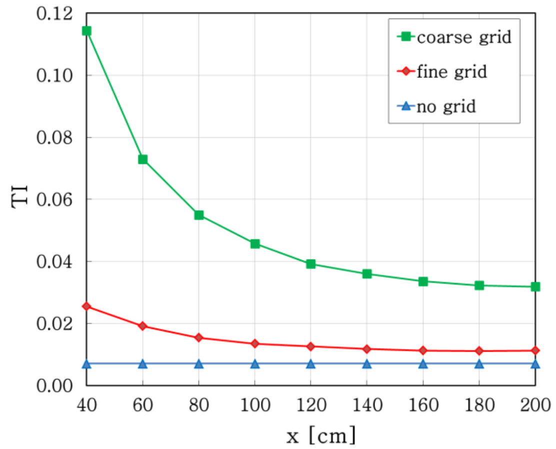


Figure 1: Distribution of the grid-generated turbulence intensity over the test section.

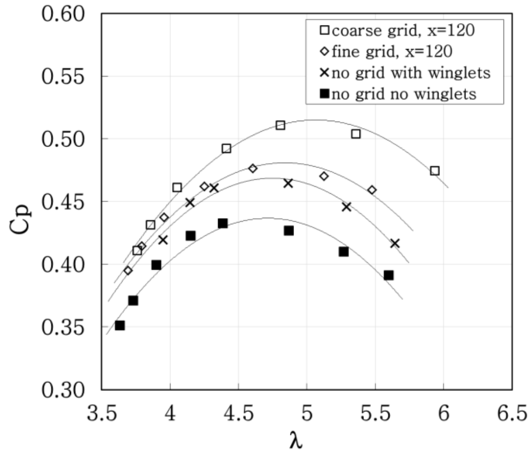


Figure 2: Comparison between the performances

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