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Book of Abstracts

11th EAWE PhD Seminar on Wind Energy in Europe

23 - 25 September 2015
University of Stuttgart, Germany

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Table of Content

Session: Control and Load Reduction

Appendix

Site maps and directions

Tuesday, September 22, 2015

TIME	EVENT
1:00 pm - 6:00 pm	EAWE Board Meeting - EAWE Board Meeting
7:30 pm - 9:00 pm	Ice Breaker - Cafe Faust, Geschwister-Scholl-Str. 24c

Wednesday, September 23, 2015

TIME	EVENT
8:00 am - 9:00 am	Registration - Register for the Conference & Poster Installation
9:00 am - 9:15 am	Welcome (V47.03) - Various
9:15 am - 10:15 am	The key role of uncertainty in forecasting and future electricity markets (V47.03) - Pierre Pinson
10:15 am - 10:30 am	Poster Presentation 1 (V47.03) - 1 min presentations of posters
10:15 - 10:20	› CFD Simulation of a floating horizontal axis model wind turbine - *Levin Klein, University of Stuttgart, Institute of Aerodynamics and Gas Dynamics*
10:15 - 10:20	› Genetic Algorithm with Gradient Based Optimization for HAWT blade design - *YouJin Kim, Institutes of Fluid Mechanics, FAU Busan Campus*
10:15 - 10:20	› Lift Force Control of a Stand-Alone Airfoil - *Aline Aguiar da Franca, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Institut für Regelungstechnik*
10:15 - 10:20	› NUMERICAL ANALYSIS OF A SWEEP-TWIST WIND TURBINE BLADE - *Mehmet Numan Kaya, Karamanoglu Mehmetbey University*
10:15 - 10:20	› Steady and unsteady CFD power curve simulations of generic 10 MW turbines - *Eva Jost, University of Stuttgart, Institute of Aerodynamics and Gas Dynamics*
10:20 - 10:25	› Aerofoil Design Optimisation for Wind or Tidal Turbines - *Chandra Pun, University of Strathclyde*
10:20 - 10:25	› Free-form design of low-induction rotors - *Luca Sartori, Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano*
10:20 - 10:25	› Modal testing of a reinforced wind turbine blade - *Hongya Lu, Department of Mechanical Engineering,Tsinghua University*
10:20 - 10:25	› QBlade: an open source toolbox for unsteady lifting line simulations of HAWT and VAWT turbines - *David Marten, TU Berlin*
10:25 - 10:30	› Aerodynamic Study of Curved Blades Using Lifting Line Code - *Zi Wang, G. J.W. van Bussel, Terry Hegberg*
10:25 - 10:30	› Comparison of different rotating modelling techniques for 3D wind turbine rotor simulation - *Ye Zhang, Delft University of Technology*
10:25 - 10:30	› Ice Accretion Prediction on the Wind Turbine Blades under Atmospheric Icing Conditions - *Ozcan Yirtici, METU Center for Wind Energy*
10:30 am - 11:00 am	Poster Session & Coffee Break (Foyer basement)
11:00 am - 11:30 am	Lidar-assisted control concepts for wind turbines (V47.03) - Experienced PhD: Dr.-Ing. David Schlipf

TIME	EVENT
11:00 am - 11:30 am	Towards optimized support structures via efficient analysis and computer-aided algorithms (V47.05) - Experienced PhD: Sebastian Schafhirt
11:30 am - 12:30 pm	Session: Rotor Design and Testing (V47.03) - Alessandro Croce
11:30 - 11:50	› Integrated high fidelity design optimization of wind turbines - *Pietro Bortolotti, Technical University Munich*
11:50 - 12:10	› Aerodynamic scaling of a generic wind turbine blade for wind tunnel investigations - *Frederik Berger, ForWind – University of Oldenburg*
12:10 - 12:30	› 2D-PIV Investigation of the Effects of Tip Injection on the Tip Flow Characteristics of a Model HAWT - *Ezgi Anik, Middle East Technical University - ANAS ABDULRAHIM, Middle East Technical University - Oguz Uzol, Middle East Technical University*
11:30 am - 12:30 pm	Session: Remote Sensing (V47.05) - Jakob Mann
11:30 - 11:50	› Radial wind speed uncertainty of nacelle-mounted profiling lidars - *Antoine Borraccino, DTU Wind Energy*
11:50 - 12:10	› Evolution of wind towards wind turbine - *Ashim Giyanani, Wind Energy Research Group, Delft University of Technology*
12:10 - 12:30	› Analysis of Two-dimensional Inflow Measurements by Lidar-Based Wind Scanners - *Alexander Meyer Forsting, Danmarks Tekniske Universitet*
12:30 pm - 2:00 pm	Lunch (Commundo)
2:00 pm - 3:00 pm	Wind Energy and Society: Is the Past Prologue? (V47.03) - Bonnie Ram (DTU)
3:00 pm - 3:15 pm	Poster Presentation 2 (V47.03) - 1 min presentations of posters
15:00 - 15:05	› A Southern German joint research project towards a better understanding of complex terrain sites - *Christoph Schulz, Institute of Aerodynamics and Gas Dynamics, University of Stuttgart*
15:00 - 15:05	› Experimental Study of Effects of Tip Injection on the Performance of Two Interacting Wind Turbines - *Yashar Ostovan, Metu Center for Wind Energy, Department of Aerospace Enginnering, Middle East Technical University*
15:00 - 15:05	› Improving wind climate estimation using one-way coupled meso- to microscale models - *Bjarke Tobias Olsen, Department of Wind Energy*
15:00 - 15:05	› Numerical investigations of an airfoil in the wake of a slotted cylinder - *Annette Fischer, University of Stuttgart, Institute of Aerodynamics and Gas Dynamics*
15:00 - 15:05	› Steady and Transient 3D Analysis of a Model Wind Turbine - *Narges Tabatabaei, Luleå University of Technology*
15:05 - 15:10	› Numerical investigation and validation of wind energy relevant flows using a stochastic based eddy resolving turbulence model - *Ghazaleh Ahmadi, ForWind, Institute of Physics, University of Oldenburg*
15:05 - 15:10	› RECONSTRUCTION OF MICRO SCALE ATMOSPHERIC FLOWFIELDS BASED ON PROPER ORTHOGONAL DECOMPOSITION - *tansu sevine, Middle East Technical University, METU Center for Wind Energy*
15:05 - 15:10	› The influence of shear flow on the performance and wake characteristics of a model turbine - *Guro Maal, Norwegian University of Science and Technology - Jan Bartl, Norwegian University of Science and Technology*
15:05 - 15:10	› Wake development behind a turbine for different flow inlet turbulence - *clio ceccotti, Norwegian University of Science and Technology - Andrea Spiga, Norwegian University of Science and Technology*
15:05 - 15:10	› Wind-farm performance prediction and optimization with a unique weather predictor - *YouJin Kim, Institutes of Fluid Mechanics, FAU Busan Campus*

TIME	EVENT
15:10 - 15:15	› Combined power output of an array two turbines in-line - *Piotr Wiklak, Technical University of Lodz - Szymon Luczynski, Technical University of Lodz*
15:10 - 15:15	› Empirical analysis of wake effects in an operating wind farm - *Nymfa Noppe, Offshore Wind Infrastructure-lab / Vrije Universiteit Brussel*
15:10 - 15:15	› LES for industrial wind farm aerodynamics - *Dhruv Mehta, Delft University of Technology, Energy research Centre of the Netherlands*
15:10 - 15:15	› LES modelling of wind turbine wakes at full and reduced scales - *Jiangang Wang, Technical University of Munich*
15:10 - 15:15	› Uncertainty of Power Production Predictions of Stationary Wind Farm Models - *Juan Pablo Murcia, PhD Student, Wind Energy Department, Technical University of Denmark*
3:15 pm - 3:45 pm	Poster Session & Coffee Break (Foyer basement)
3:45 pm - 5:05 pm	Session: Rotor Dynamics and Aerodynamics (V47.03) - Oguz Uzol
15:45 - 16:05	› Aeroelastic Stability Analysis of Large Composite Wind Turbine Blades - *Touraj Farsadi, Middle East Technical University, METU Wind Centre*
16:05 - 16:25	› Wind turbine with iced blades: Stability analysis of coupled blade's in-plane and tower motions - *Sudhakar Gantasala, Luleå University of Technology*
16:25 - 16:45	› An examination of rotational effects on large wind turbine blades - *Galih Bangga, Institute of Aerodynamics and Gas Dynamics, University of Stuttgart*
16:45 - 17:05	› An integral boundary layer method for modelling the effects of vortex generators - *Daniel Baldacchino, Delft University of Technology*
3:45 pm - 5:05 pm	Session: New Concepts (V47.05) - Carlo L. Bottasso
15:45 - 16:05	› A New Concept for Tower Structures of Wind Turbines - *Ilja Fischer, Vienna University of Technology - TU Wien*
16:05 - 16:25	› Gust Load Alleviation through Enhanced Fluid-Structure Interaction - *Ulrike Cordes, Darmstadt University of Technology*
16:25 - 16:45	› A multi-band virtual sensing approach for fatigue assessment of monopile wind turbines - *Alexandros Iliopoulos, Vrije Universiteit Brussel*
16:45 - 17:05	› PIV study of wall bounded Fractal-grid-generated Turbulence - *Hooman Amiri Hazaveh, Middle East Technical University (Aerospace Engineering Department)*
7:00 pm - 8:00 pm	Reception at City Hall - Rathaus, Marktplatz 1

Thursday, September 24, 2015

TIME	EVENT
8:30 am - 9:00 am	Registration - Register for the Conference
9:00 am - 9:15 am	Info (V47.03) - Various
9:15 am - 10:15 am	Game-changing innovations in wind energy (V47.03) - Henrik Stiesdal
10:15 am - 10:30 am	Poster Presentation 3 (V47.03) - 1 min presentations of posters

TIME	EVENT
10:15 - 10:20	› Adaption of Wind Turbine Model For Incorporation into Wind Farm Simulation - *Paul Hammond, University of Strathclyde*
10:15 - 10:20	› Advanced Lidar-Assisted Control Concepts for Large Wind Turbines - *Holger Fürst, Stuttgart Wind Energy (SWE)*
10:15 - 10:20	› State Feedback Disturbance Rejection for Pitch Regulated Variable Speed Wind Turbine - *Rohaida Hussain, University of Strathclyde*
10:15 - 10:20	› Stochastic Analysis of Aerodynamic Forces acting on Airfoils in turbulent Inflow - *Gerrit Kampers, ForWind, Center for wind energy research, University of Oldenburg*
10:15 - 10:20	› Support Structure Load Mitigation of Offshore Wind Turbines by Different Control Concepts - *Binita Shrestha, ForWind-Center for wind energy research*
10:20 - 10:25	› Derivation of a Lumped Parameter Model of a Vertical Axis Wind Turbine - *James Steer, University of Strathclyde*
10:20 - 10:25	› Model Based Approach to Examine the Interactions of Electrical and Mechanical Wind Turbine Subsystems – Part 1 - *Arne Bartschat, Fraunhofer Institut for Wind Energy and Energy Systems Technology*
10:20 - 10:25	› Model Based Approach to Examine the Interactions of Electrical and Mechanical Wind Turbine Subsystems – Part 2 - *Marcel Moriße, Leibniz Universität Hannover*
10:20 - 10:25	› Model Fidelity Evaluation in the Multidisciplinary Optimisation of Offshore Wind Farms - *Sanchez Perez-Moreno Sebastian, Delft University of Technology*
10:20 - 10:25	› Towards the Robust Design Optimization of Wind Turbines - *Jaikumar Loganathan, GE Global Research, Technical University Munich*
10:25 - 10:30	› A broad sensitivity analysis of uncertainties for offshore wind turbine support structures - *Lars Einar S. Stieng, Norwegian University of Science and Technology*
10:25 - 10:30	› Slamming Load Considerations for Offshore Wind Structures - *Ying Tu, Norwegian University of Science and Technology*
10:25 - 10:30	› Synchronous Machine Assisted by Permanent Magnets for Direct-Drive Wind Turbine - *Maxime Ployard, Ecole Centrale de Lille*
10:25 - 10:30	› Unsteady and Turbulent Rotor Loads - *Sebastian Ehrich, ForWind, Institute of Physics, University of Oldenburg*
10:25 - 10:30	› Wind Generation Modelling in Reliability Studies: Challenges and Opportunities - *Edgar Nuño, Wind Energy Division - Risø National Laboratory for Sustainable Energy*
10:30 am - 11:00 am	Poster Session & Coffee Break (Foyer basement)
11:00 am - 11:30 am	Synthetic turbulence inflow method for atmospheric turbulence and its application in complex terrain (V47.03) - Experienced PhD: Christoph Schulz, Yusik Kim
11:00 am - 11:30 am	Turbulence in wind turbine wakes under different atmospheric conditions from static and scanning Doppler LiDARs (V47.05) - Experienced PhD: Valerie-Marie Kumer
11:30 am - 12:30 pm	Session: Wind Farm Control (V47.03) - Gijs van Kuik
11:30 - 11:50	› Detection of Partial Wake Impingement for Wind Farm Control by Analysis of Rotor Loads - *Johannes Schreiber, Technical University Munich*
11:50 - 12:10	› Lidar – a measurement tool for wind farm control - *Steffen Raach, Stuttgart Wind Energy, University of Stuttgart*
12:10 - 12:30	› Dynamic Wind Farm Controller - *Tanvir Ahmad, School of Engineering and Computing Sciences, Durham University, UK*
11:30 am - 12:30 pm	Session: Load Measurements and Testing (V47.05) - Christof Devriendt

TIME	EVENT
11:30 - 11:50	› How different turbulent inflow conditions affect wind turbines – an experimental approach - *Jannik Schottler, ForWind, Center for wind energy research, University of Oldenburg*
11:50 - 12:10	› Statistical Extrapolation Methods for the Estimation of Offshore Wind Turbine Extreme Loads - *Sarah Lott, Stuttgart Wind Energy @ Institute of Aircraft Design*
12:10 - 12:30	› Towards monitoring the consumed fatigue life of fleets of offshore wind turbines - *Wout Weijtjens, Offshore Wind Infrastructure-lab / Vrije Universiteit Brussel*
12:30 pm - 2:00 pm	Lunch (Commundo)
2:00 pm - 3:00 pm	The importance of wind turbine aerodynamics Illustrated with results from international cooperation projects (V47.03) - Gerard Scheper
3:00 pm - 3:15 pm	Poster Presentation 4 (V47.03) - 1 min presentations of posters
15:00 - 15:05	› A wind-wave coupling system for coastal storm simulations - *Jianting Du, Department of Wind Energy*
15:00 - 15:05	› Application of meteorological databases for wind resources estimation in dispersed wind energy - *Anna Chudy, Lodz University of Technology*
15:00 - 15:05	› Evaluation of methods to calculate wind speed profiles: A case study on Frøya, Norway - *Sören Fechner, Norges teknisk-naturvitenskapelige universitet*
15:00 - 15:05	› Investigation Of The Flow Over An Escarpment With Regard To Wind-Energy Research Using Small Remotely Piloted Aircraft. - *Alexander Rautenberg, Eberhard Karls Universität Tübingen*
15:00 - 15:05	› Operational Fatigue Calculation from Wind Characteristics for Wind Turbine Tower and Blades - *Edward Hart, University of Strathclyde*
15:05 - 15:10	› Condition Monitoring and Fault Diagnosis of Wind Turbines Using Generator Output Signals - *Raed Ibrahim, Loughborough University - Simon Watson, Loughborough University*
15:05 - 15:10	› Derivative action charge control for a heaving buoy, PolyWEC device - *Ben McGilton, University of Strathclyde*
15:05 - 15:10	› Embedded system for wirless communication - *Yacine Bouanba, MERSEN*
15:05 - 15:10	› Mechanical-level Hardware in the Loop Simulation for a Wind Turbine Nacelle Test Bench - *Christian Leisten, Center for Wind Power Drives, RWTH Aachen University, Institute of Automatic Control, RWTH Aachen University*
15:05 - 15:10	› WEC Array Modelling Benchmarking Study - *Giorgio Zorzi, University of Strathclyde*
15:10 - 15:15	› Survey of Wind Turbine Inspection - *Tim Rubert, University of Strathclyde*
15:10 - 15:15	› Vibration Analysis of Multi-Stage Epicyclic Gearboxes - *Owain Roberts, Wind and Marine Energy Systems, Centre for Doctoral Training, University of Strathclyde*
3:15 pm - 3:45 pm	Poster Session & Coffee Break (Foyer basement)
3:45 pm - 5:05 pm	Session: Modelling of Wind, Turbine and Foundation (V47.03) - Michael Muskulus
15:45 - 16:05	› Importance sampling of severe wind gusts - *René Bos, Wind Energy Research Group, Delft University of Technology*
16:05 - 16:25	› Probabilistic Gust Characterization - *Asta Hannesdottir, Department of Wind Energy*
16:25 - 16:45	› Periodic Stability Analysis of a Wind Turbine Analytical Model with Individual Pitch Controller - *Riccardo Riva, Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano*
16:45 - 17:05	› Model Calibration for the Soil-Structure-Interaction of an Offshore Wind Turbine with Suction Buckets - *Andreas Ehrmann, Institute of Structural Analysis - Leibniz Universität Hannover*

TIME	EVENT
3:45 pm - 5:05 pm	Session: Grid Integration, Storage and Reliability of Electrical Components (V47.05) - Sandrine Aubrun
15:45 - 16:05	› Optimising Power System Integration based on the Energy Ratio - *Bruno Schyska, University of Oldenburg, ForWind Center for wind energy research*
16:05 - 16:25	› Transmission, Storage and Backup Estimates for a Global Electricity Grid with High Shares of Renewables - *Alexander Kies, ForWind-Center for wind energy research*
16:25 - 16:45	› Experimental Set-up for Applying Wind Turbine Operating Profiles to the Nacelle Power Converter - *Christopher Smith, School of Engineering and Computing Sciences, Durham University*
16:45 - 17:05	› Hybrid Classifier for Drift-like Fault Diagnosis in Wind Turbine Converters - *Houari TOUBAKH, Ecole des mines de Douai*
7:00 pm - 10:00 pm	Conference Dinner - Kursaal Cannstatt, Königsplatz 1

Friday, September 25, 2015

TIME	EVENT
8:30 am - 9:00 am	Registration - Register for the Conference
9:00 am - 9:15 am	Info (V47.03) - Various
9:15 am - 10:15 am	How to manage innovations and technologies to lower wind cost of energy (V47.03) - Mark Jonkhof
10:15 am - 10:45 am	Poster Session & Coffee Break (Foyer basement)
10:45 am - 11:15 am	TBA (V47.03) - eawe Excellent Young Wind Doctor Awardee
10:45 am - 11:15 am	Time-domain load mapping for floating offshore wind turbines (V47.05) - Experienced PhD: Alexis Campos Hortigüela
11:15 am - 12:15 pm	Session: Control and Load Reduction (V47.03) - Po Wen Cheng
11:15 - 11:35	› Load mitigation for wind turbines by a passive flap - *Pierluigi Montinari*
11:35 - 11:55	› Advanced Multivariable Control Design for Modern Multi-MW Wind Turbines - *Ritter Bastian, Technische Universität Darmstadt*
11:55 - 12:15	› Active Control of Wind Turbines Through Varying Blade Tip Sweep - *Achilles Boulamatsis, University of Thessaly*
11:15 am - 12:15 pm	Session: Meteorological Effects and Wind Power Estimation (V47.05) - Thorsten Lutz
11:15 - 11:35	› Variations of the wake height over the Bolund escarpment - *Julia Lange, Technical University of Denmark*
11:35 - 11:55	› Influence of turbulence intensity on wind turbine power curves - *Lars Morten Bardal, Norwegian University of Science and Technology*
11:55 - 12:15	› Wind Power Estimations using OpenFoam Coupled with WRF - *Engin Leblebici, METU Center for Wind Energy, Middle East Technical University*
12:15 pm - 12:30 pm	Farewell (V47.03) - Various

TIME	EVENT
12:30 pm - 2:00 pm	Lunch (Commundo)
2:00 pm - 4:00 pm	Excursion - please find more information by clicking the tab "excursions" on the left. - please find more information by clicking the tab "excursions" on the left.

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Lidar-Assisted Control Concepts for Wind Turbines

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In recent years lidar technology has found its way into wind energy. At the beginning of the research of the present thesis project, ``Lidar-Assisted Control Concepts for Wind Turbines", the main application was the assessment of sites for wind turbine installations. The possibility to optimize the energy production and reduce the structural loads by nacelle or spinner based lidar systems was already considered a promising field of application. This is because of the fact that wind turbines are highly dynamic systems that are excited by stochastic influences from the wind and most of the wind turbine control is designed to deal with variations in this disturbance. However, traditional feedback controllers are only able to react to impacts of wind changes on the turbine dynamics after these impacts have already occurred. Lidar-assisted control algorithms, which can exploit preview information of the wind, are promising to provide improved operation over conventional control algorithms, with the ultimate aim of increasing the energy yield while keeping the structural loads low. The principle can be depicted by an analogue: a person riding, and thus controlling, a bicycle uses the vision and the prediction of the movements to circumvent obstacles instead of reacting to the impact of the obstacle on the wheels. In a similar way, lidar-assisted wind turbine control is expected to improve the control performance significantly over conventional feedback controllers. Due to limitations in the lidar measurement principle, the complexity of the wind, and nonlinear dynamics of the wind turbines, lidar-assisted control of wind turbines is a highly interdisciplinary field of research, including meteorology, signal processing, remote sensing, mechanics and control. With a holistic and integrated approach, the world's first proof-of-concept of lidar-assisted control could be successfully performed within this thesis project. This has been achieved by dividing the overall problem in to separate measurement and control problems. The measurement problem addresses the question: how can signals which are useful for control be extracted from lidar measurements? The control problem addresses the question: how can these signals then be used to improve the performance of wind turbine control. However, these questions are highly correlated with each other. While the data generated by the measurement device must contain useful information to allow for improving the control performance, the control algorithm itself requires continuous adaptation to the quality and information content present in the measurements. Furthermore, the level of detail of the computational models of the wind turbine and the disturbances employed by the control algorithm must also be in accordance with the measurement quality and at the same time they should meet the requirements imposed by the chosen control approach.

Based on these considerations, the first part of this thesis presents the work done in the field of processing raw lidar data. Here, two important issues have been addressed and solved for providing signals for lidar-assisted control from raw lidar data. The first issue addressed is the limitation of line-of-sight wind speeds. The lidar system measures the speed of the aerosols traveling in the direction of the laser beam, thus only a one-dimensional component of the three-dimensional wind vector. Therefore, it is mathematically impossible to measure a three-dimensional wind vector with a single nacelle or spinner based lidar system. To solve this issue, model based estimation techniques have been developed to provide a good estimate of wind characteristics such as the rotor effective wind speed. The second important issue for processing raw lidar data is that the wind characteristics measured by a lidar system will differ from those experienced by the turbine, because of several effects such as wind evolution. In this thesis an analytic model has been developed which calculates the correlation between the lidar estimates and the reaction of the wind turbine. The model can be used to optimize lidar scan configurations and to design an adaptive filter essential for preview control of wind turbines.

The second part presents possible lidar-assisted control concepts. All controllers are designed first for the case of perfect wind speed measurements and then adjusted for realistic measurements. The most promising approach is the collective pitch feedforward controller using the knowledge of the incoming wind speed. The approach provides an additional control update to assist common collective blade pitch control and therefore is convenient for industrial applications. Significant improvement in rotor speed regulation and in load reduction were achieved in realistic simulations and have been confirmed with successful field tests on two research wind turbines. Moreover, a flatness-based feedforward approach has been designed that allows the calculations of the control action based on trajectories of the rotor speed and tower motion. With this approach, the tower loads can be regulated directly by providing an update to the collective pitch and the generator torque. An analysis with simulated lidar measurements reveals that the tower loads can be further reduced compared to the collective pitch feedforward controller. However, the flatness-based controller is more difficult to tune.

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Determination of aerodynamic damping of wind turbines using inverse impulse based substructuring

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Keywords – Aerodynamic damping, impulse response functions, simplified wind turbine analysis, rotor loads

I. INTRODUCTION

Offshore wind turbines are commonly analysed in the time-domain in order to obtain accurate results, since nonlinear effects and controller dynamics have to be taken into account. The analysis of an offshore wind turbine is, therefore, computationally demanding, especially for offshore wind turbines with multi-member lattice support structures. A reduction in simulation time is more than welcome.

One solution is the replacement of the rotor simulation by suitable time-series, applied at tower top. The main obstacle here 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.

Previous studies investigated empirical and theoretical approaches to determine aerodynamic damping [1-3]. It has been shown that these methods perform well below rated wind speed, but underestimate the aerodynamic damping for variable speed turbines operating above rated wind speed.

The study presented here uses a new approach to assess the aerodynamic damping. Time series of displacements at tower top obtained from an integrated simulation of the entire wind turbine are used with inverse impulse based substructuring in order to calculate the rotor loads acting on the wind turbine. These are compared with loads from a stand-alone rotor simulation with a fixed support. The difference between these loads is equal to the aerodynamic damping forces.

The study is performed with the modified UpWind jacket used within the OC4 project and the well-known generic NREL 5-MW reference wind turbine. Simulations are performed without gravity and wave forces for simplicity, but an inclusion is straightforward.

A. *Calculation of loads at tower top*

Time-domain simulations of the entire offshore wind turbine were performed and time-series of displacements in all 6 DOFs at tower top were extracted. These time-series were used with previously calculated impulse response functions in order to estimate the loads acting on tower top using [4]

$$\boldsymbol{f}(t_i) = \left(\boldsymbol{u}(t_i) - \sum_{\tau=0}^{t_{i-1}}[\boldsymbol{f}(\tau)\boldsymbol{h}(t_{i+1}-\tau)]\right)\boldsymbol{h}(t_1)^{-1}\ , \qquad (1)$$

where $\boldsymbol{u}$ are the displacement at tower top, which are a function of time, $\boldsymbol{h}$ is the impulse response function of the system, and $\boldsymbol{f}$ are the forces corresponding to the displacement at time step t_i. This calculation results in time-series for forces and moments. An integrated simulation of the offshore wind turbine under aerodynamic loading will lead to exactly the same results as a time-domain simulation of the offshore wind turbine without rotor, but with these forces and moments acting in all 6 DOFs at tower top.

B. *Calculation of aerodynamic damping*

Simulations with the stand-alone rotor model were performed with the same turbulent wind field as for the integrated simulation. Forces and moments on the bottom of the turbine were extracted. It is straightforward to determine the aerodynamic damping force (F_{AD})

$$F_{AD} = F_I - F_{RL}, \qquad (2)$$

where F_{RL} are the loads from the stand-alone rotor simulation and F_I are the loads obtained with the inverse impulse based substructuring.

II. CONCLUSION

The method presented here allows for calculating the aerodynamic damping of a wind turbine in terms of forces and moments acting at tower top. It is possible to determine the “real” aerodynamic damping, which enables the simulation of an offshore wind turbine where the rotor is replaced by rotor load time series. This speeds up the simulation time significantly and general FEM-software can be used. The outcome of this study regarding the rotor loads can also be used to improve the accuracy of frequency-domain calculation or can be used with other calculation methods (e.g. IBS) in order to speed up the calculation process further.

ACKNOWLEDGEMENTS

Support by the Norwegian Research Centre for Offshore Wind Technology (NOWITECH FME, Research Council of Norway, contract no. 193823) is gratefully acknowledged.

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[3] Salzmann, D.J. C., van der Tempel, J., “Aerodynamic Damping in the Design of Support Structures for Offshore Wind Turbines”, Proc Offshore Wind Energy Conference, Copenhagen, Denmark, 2005
[4] Passon, P., Branner, K., “Load calculation methods for offshore wind turbine foundations”, Ships and Offshore Structures 9:433-449, 2014

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Synthetic turbulence inflow method for atmospheric turbulence and its application in complex terrain

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Keywords – Mann turbulence box, wind resource assessment, homogeneous isotropic turbulence, complex terrain

As the size of wind farms increases, a marginal improvement in a power prediction during the design process can lead to a significant difference in the annual energy production. Thus, high accuracy in wind resource assessment during a wind farm design process is critical, and orography makes it difficult to achieve.

Bechmann et al. [1] performed a blind comparison of the wind in natural complex terrain predicted by different numerical models. The most successful model compared to the measurement showed 10% of the mean speed-up error which is higher than wind farm designers would accept [1]. One main reason for such deviations was because of difficulties in controlling upcoming turbulence.

In the wind energy group at the Institute of Aerodynamics and Gas dynamics (IAG), University of Stuttgart, we have implemented and validated a synthetic turbulence inflow condition to simulate wind fields in complex terrain using a RANS/LES hybrid turbulence model. The synthetic turbulence inflow was validated in homogeneous isotropic turbulence (HIT), and then it was applied on a flow over a realistic terrain in Southern Germany near the town of Stötten within the Southern German joint research project LIDAR COMPLEX.

I. CURRENT PROGRESS

Mann's turbulence model was used to generate 3D turbulence field as in [2], and it was injected into the domain via a momentum source term. For numerical simulations, the block structured compressible solver FLOWer was used. This code was developed by the German Aerospace Center (DLR), and has been applied in several wind turbine simulations .

A. *Homogeneous isotropic turbulence*

Decaying HIT was simulated to validate the current numerical approach. The decay rate of the turbulence kinetic energy follows a theoretical slope with a fine mesh, see Fig. 1.

B. *Terrain Simulations*

After the validation a generic turbine placed in a test area close to Stötten was simulated using atmospheric turbulence and propagating these to the turbine. The results showed an impact of the terrain on the turbulence and consequently on the turbine's performance as well as a terrain induced distortion of the near wake, similar to those described for a yawed inflow by Schulz et al. [3]. An impression of the flow field is given in Fig. 2 showing an iso-surface of the vorticity magnitude in the near wake as well.

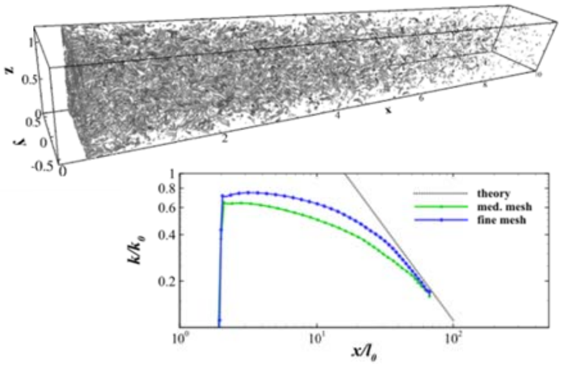

Fig. 1 Iso-surface of vorticity magnitudes (top) and decay of turbulence kinetic energy in the stresmwise direction (bottom).

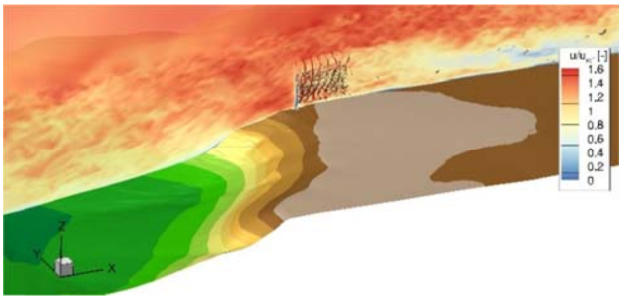

Fig. 2 Relative velocity increase at a steep edge inside Stötten test area. In the near wake of the turbine an iso-surface of the vorticity magnitude is shown.

II. CONCLUSION

The implemented inflow condition is validated for decaying HIT and it is applied for flow over a realistic terrain. First results gave reasonable agreement to theoretical estimations.

ACKNOWLEDGEMENTS

All computational resources were provided by the High Performance Computing Center Stuttgart. The research for LIDAR COMPLEX has been founded by the German Federal Ministry for Economic Affairs and Energy.

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Turbulence in wind turbine wakes under different atmospheric conditions from static and scanning Doppler LiDARs

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Keywords – LiDAR, wind turbine wakes, atmospheric stability

ABSTRACT

Wake characteristics are of great importance for wind park performances and turbine loads. Wind tunnel experiments helped to validate wake model simulations under neutral atmospheric conditions. However, recent studies show strongest wake characteristics and power losses in stable atmospheric conditions [1] [2]. Considering all three occurring atmospheric conditions this study presents a turbulence analysis of wind turbine wake flows measured by static and scanning Doppler LiDARs at the coast of the Netherlands.

We use data collected by three Windcubes v1, a scanning Windcube 100S and sonic anemometers during the Wind Turbine Wake Experiment – Wieringermeer (WINTWEX-W). Turbulence parameters such as Turbulence Intensity (TI) and turbulent kinetic energy (TKE) are retrieved from the collected raw data.

First results show highest turbulence on the flanks of the wake where strong wind shear dominates. On average the spatial turbulence distribution becomes more homogeneous with conical areas of enhanced TI (figure 1). Highest turbulence and strongest wind deficits occur during stable weather conditions.

Despite the ongoing research on the reliability of turbulence retrievals of Doppler LiDAR data, the results are consistent with wind tunnel studies and show promising opportunities for a qualitative study of wake characteristics such as wake width, wake length and wake peak frequencies.

ACKNOWLEDGEMENTS

The authors would like to thank the NORCOWE consortium for making the WINTWEX-W measurement campaign possible. Especially many thanks to the Energy Centre of the Netherland who allowed putting our instruments around their research turbines in the wind turbine test facilities Wieringermeer and maintained the LiDAR data availability.

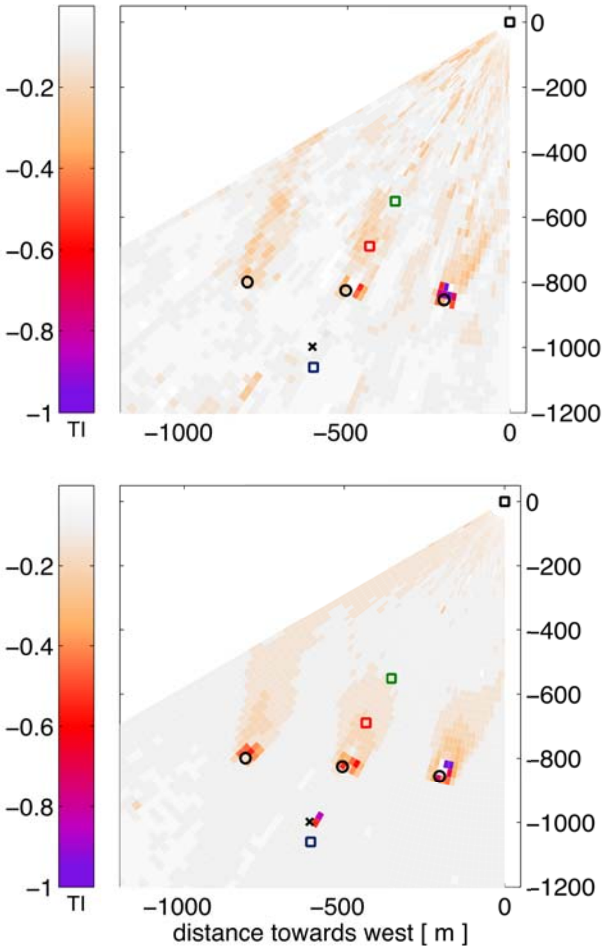

Fig. 1 Turbulence intensity of radial wind speeds during 10 minutes (top) and averaged over one day (bottom) measured by a Windcube 100S.

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TIME-DOMAIN LOAD MAPPING FOR FOWT'S

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Keywords – Floating, Offshore, Concrete, Loads, Mapping, Offshore, Structures

I. INTRODUCTION

Since floating offshore wind energy has become a real option for the energy market, the engineering knowledge acquired along decades in the Oil & Gas is clearly shown in the concepts and prototypes which have been developed in several different countries.

The use of steel as basic construction material is the most common choice for them, despite the investment and the maintenance costs of steel are much larger. This situation has enforced the industry to consider other materials cheaper and durable like reinforced concrete.

Because the limitations of the different existing software for the structural assessment of concrete floating offshore structures, as the difficulty to obtain a time-domain load mapping over the structure or the fact that most of them are designed for steel structures, a computational tool is under development.

II. THE NUMERICAL TOOL

The main objective of the code is to be useful for the predesign of a floating structure under wave and wind loads.

The tool is focused to obtain the internal forces by mapping the 3D pressures around the structure at each time step, being useful for structural pre-design, highly customizable and with the capability to add new modules to consider new effects and improve the precision of the actual modules. At the present stage, the structural assessment is done assuming rigid body and bar elements, which is a good approach to slender structures as SPAR buoys (Figure 1).

Currently the numerical code is capable to predict the non-linear behaviour of the floating structure, computing the hydrodynamic forces by using Morison's equation with linear and non-linear wave kinematics.

The hydrodynamic behaviour accuracy of the numerical tool has been proven during the experimental campaign of a SPAR-type structure [2], where the results were successfully simulated with the code [1].

The implementation of potential flow theory is under development to be possible to deal with larger structures such as TLP or semisub platforms. Also a 3D FEA is under development in order to be able to deal with the structural assessment of those larger structures, which cannot be simulated with linear members as beams.

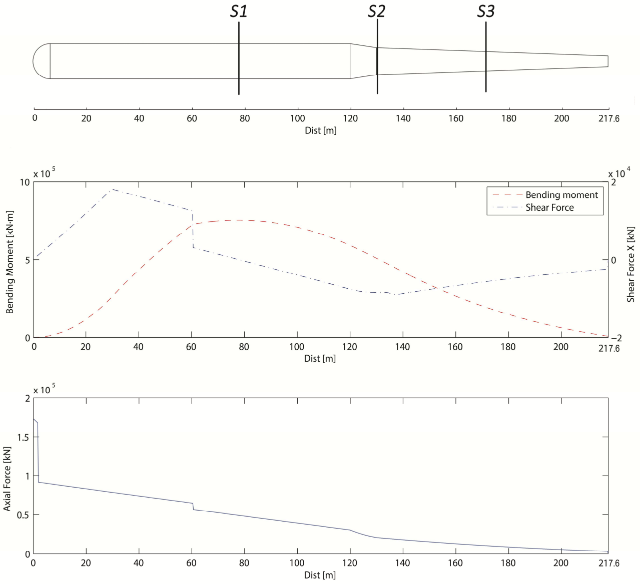

Figure 1: Internal forces envelopes from a time-domain simulation of a SPAR type structure

III. CONCLUSION

A powerful tool is under development for the time-domain dynamic structural analysis, which scope includes the vast majority of the offshore platforms types.

The code merges the structural information from the diffraction problem, usually provided by other software in frequency-domain, with the pressures computed in time-domain, which offers valuable structural information of any member in a time-domain series, including the non-linearity of structure itself in the motions computation.

ACKNOWLEDGEMENTS

We would like to acknowledge to *Generalitat de Catalunya*, the Catalan government, for its financial support during the development of the code.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Session: Control and Load Reduction

A new concept to mitigate loads for wind turbines based on a passive flap

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Keywords – Loads Reduction, Control, Aeroelasticity, Wind turbines

This paper considers the preliminary investigation of a passive flap for the mitigation of loads on wind turbines. In comparison to active flaps, this solution has the advantage of not requiring sensors nor actuators, resulting in a particularly simple implementation, with potential benefits in manufacturing and maintenance costs. This proof of concept is then given by a simulation study conducted with the combination of a sectional model of the flap and a multibody model of the rest of the machine. Results, obtained for a 10MW wind turbine, indicate the ability of the passive flap in attenuating blade vibrations in a significant frequency range, which in turn yield a reduced fatigue damage to the structure.

I. INTRODUCTION

The main idea is to use one or more flaps at suitable locations along the blade span, which move in response to blade vibrations in such a way as to oppose them.

A Simplified model here are used with the main goal of investigating the feasibility of the system and its potential for load alleviation and vibration reduction.

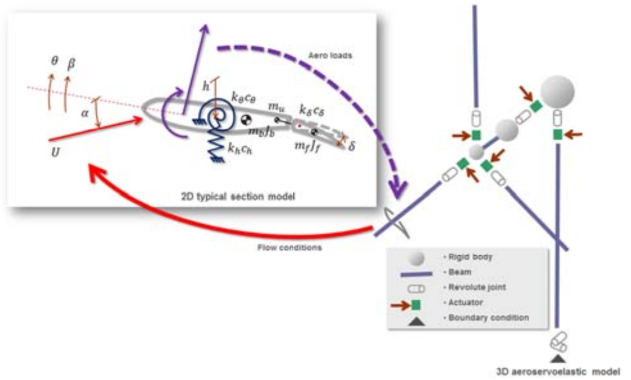

Fig. 1: 2D Blade typical section model coupled with 3D aeroservoelastic model

II. SIMULATION MODELS AND METHODS

Fig. 1 shows The 2D blade section corresponding to the section at 75% of the blade span [1], which is used for conducting numerical simulations. Apart for the plunge and torsional concentrated stiffnesses and damping coefficients (which replicate the structural features of the blade), is relevant to underline the presence of the offset mass m_u so that when the blade accelerates in one direction the flap is automatically deflected in the other, resulting in a change of camber that opposes the blade motion.

The aerodynamic loads on the blade section are computed using classical unsteady strip theory under the hypotheses of inviscid and incompressible flow. The Duhamel's integral of the Wagner indicial step responses leads to a linear time invariant aeroelastic state space model which is used for the numerical simulations.

III. RESULTS AND DISCUSSION

To estimate the effect of the passive flap system, turbulent simulations are conducted considering angle of attack fluctuations and pitch time histories computed by means of closed-loop aeroservoelastic simulations within the entire envelope of the machine. Then DEL's weighted by the Weibull probability function of the typical class A wind turbine [2] are evaluated using the plunge motion. In Fig. 2 the benefic effects of the passive flap can be appreciated.

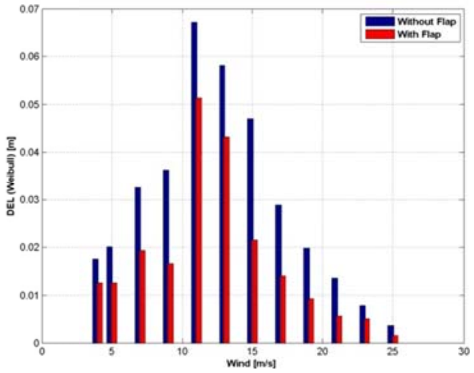

Fig. 2: Weibull-weighted DEL vs. wind speed

IV. CONCLUSION

The results obtained so far seem to indicate that the idea has some interesting potential: 1) although not shown here for space limitations, the solution appears to be compatible with standard active blade pitch, and to be applicable without radical changes in the design of blades; 2) load alleviations are noticeable, and further analysis demonstrated that only modest AEP reductions occur; 3) the behavior is robust and consistent within the entire operating regime, without necessitating of scheduling of system parameters with respect to wind speed or other quantities.

ACKNOWLEDGEMENTS

Support of the FP7 INNWIND.EU project is gratefully acknowledged.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Advanced Multivariable Control Design for Modern Multi-MW Wind Turbines

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Keywords – Wind Turbine Control, Centralized Multivariable Control Design, Load Reduction, Costs of Energy

In the recent decades wind turbine size has increased significantly in order to reach higher nominal power output. At the same time the necessity of lowering the costs of energy (COE) has forced manufacturers to build more flexible wind turbines [3]. This development has promoted several approaches of active vibration control like axial and lateral tower damping [5] to reduce the fatigue loads on expensive components. However, control design as well becomes more complex as multiple control objectives have to be maintained simultaneously and system interactions may increasingly influence the current decentralized design which may not lead to the best controller in future any more. On the other hand advanced and centralized design strategies offer the possibility to develop wind turbine controllers which incorporate all control objectives in a convenient fashion. First simulation results with a centrally designed controller for the full load regime confirm the chosen approach.

I. INTRODUCTION TO RESEARCH PROJECT

Modern utility-scale wind turbines have at least four independent control actuators and several measurement signals which provide information of the current state of operation. These often include today sensors for generator speed, tower top accelerations, load and pressure/flow measurement at the rotor blades. Thus, wind turbines are multiple input multiple output (MIMO) systems [4]. The aim of the ongoing research project is to investigate the potentials of central model-based design techniques including generator torque and individual pitch control. For both, model-based design and control, a suitable process model is needed, tailored to the control objectives and the required model accuracy. Therefore, in [2] an extendable design model is presented which fulfills this requirements. To improve wind turbine operation, power production and load mitigation are the major objectives to be reached which leads in general to a nonlinear multivariable controller.

II. CENTRALIZED CONTROL DESIGN

As preliminary study of the above described research project, a reduced first principle wind turbine model with four relevant degrees of freedom is used to design centrally a multivariable controller for the full load regime (Fig. 1). The idea is to design a linear controller which is compared to a standard nonlinear industrial controller extended by load reducing feedback loops. The performance of both controllers is evaluated for the whole full load regime with several wind seeds showing very good results for the state controller concerning power production and the fatigue load reduction for the tower base/top moments as well as the drive train.

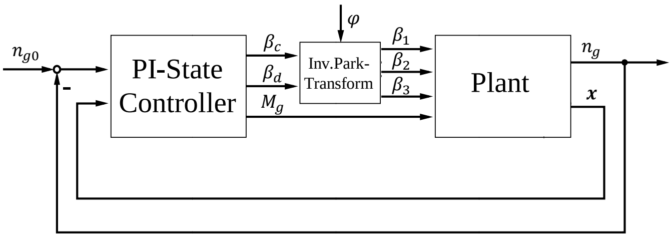

Fig. 1 Sketch of the control circuit with a linear PI-state controller

Obviously, the linear state controller has still two drawbacks namely the full state feedback and full load regime operation only. Nevertheless, the central LQR-approach incorporates already several control objectives and is the first step ahead to an optimal wind turbine controller. Moreover, it can be considered as special case of the model predictive control (MPC) which has become more and more attractive for wind turbines in recent years due to the increase of available computing power [1].

III. CONCLUSION

This contribution briefly summarizes the current state of the PhD project of advanced multivariable control design for wind turbines. The presented central LQR-design approach shows a good performance and is the basis for more advanced nonlinear control strategies like MPC. This type of control offers from today's perspective the most benefits for future wind turbine operation. Though, to the author's knowledge no publications including results from field testing exist to this day.

ACKNOWLEDGEMENTS

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Active Control of Wind Turbines Through Varying Blade Tip Sweep

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Keywords – Active Control, Swept Blades, Unsteady Lifting Line Theory, Blade Element Momentum Theory

OVERVIEW

Over the past few years there is a continuous effort for increasing energy production and reducing dynamic loads of wind turbines. In [1] there is an extensive review of the current status in smart rotor control that goes beyond the borders of conventional control methods like pitch or stall regulation. However, these features have to be carefully designed in order to compensate for their complexity and the fault cases that they may impose.

In this research work an introduction to an innovative control method is presented through tip swept rotor blades that have the ability to pivot simultaneously aft or fore (in-plane movement) about an axis located at the blade tips. The swept tip can be either part of the main blade with an internal mechanism or an added surface (add-on) to the blades, as it is shown in Figure 1. The idea of this control feature is to actively adjust power and blade loads in accordance to the incoming wind inflow variations through small sweep angle changes at the blade tip. Similar research efforts like [2] and [3] have already demonstrated the benefits and drawbacks of passive swept rotor blades for aeroelastic control but have not yet examined the concept of active control.

Fig. 1 Wind Turbine sweeping aft to compensate for a gust

The methods used in the present work in order to examine the effects of tip sweep are: the Vortex method and CFD. At first, a Matlab code based on Unsteady Lifting Line Theory (ULL) is developed in order to study the effect of tip sweep on a fixed wing, both in steady and oscillatory conditions. Then, the results are compared to CFD simulations in ANSYS CFX [4] and the code is modified for a three bladed Wind Turbine, where more parameters are investigated such as Power, Thrust and Blade root Bending Moment. The role of tip sweep in the code is modeled according to the following considerations:

a. Lift coefficient of a swept blade is linked to the lift coefficient of the unswept blade with the Eq. (1).

$$CL(sw) = CL * \cos^2(\Lambda) \qquad (1)$$

b. The resultant velocity of the blade tip sections contains an additional in-plane velocity due to tip movement .

c. The radial position of the blade tip sections is dependent on the sweep angle.

RESULTS

The current results refer to the 5MW NREL wind turbine equipped with tip swept blades (up to 30% of their total span) and the unsteady response is examined through step and harmonic sweep angle variations. The amplitude is of the order of ±10deg and the frequency range from 0,25 - 1 Hz. In this stage though, only the aerodynamic effects are studied as the rotor is considered rigid. In particular, it is seen that variations of this scale impose a Power fluctuation up to 1.8%, a total Thrust fluctuation up to 10.5% and a blade root bending moment up to 14.2%. The phase lag between sweep angle and the above parameters is strongly dependent on frequency and changes rapidly in this small frequency range. In the blade level, it is seen that variations of that type mostly influence the swept part of the blade and especially the hinge area where a kink in the level of the induction velocity is observed.

CONCLUSIONS

The early results indicate that there is a good potential in using active tip sweeping as a control method in unsteady wind turbine environments. The objective is to optimize those fluctuations in real conditions in order to claim net benefit. Therefore, one of the challenges in perspective is the development of a modified Blade Element Momentum (BEM) code that takes into account tip sweep and has the ability to control the turbine performance and loads with a suitable controller.

ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe
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Importance sampling of severe wind gusts

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Keywords – extreme loads, wind gusts, Monte Carlo method, importance sampling

An important problem that arises during the design of wind turbines is estimating extreme loads with sufficient accuracy. This is especially difficult during iterative design phases when computational resources are scarce. Over the years, many methods have been proposed to extrapolate extreme load distributions from relatively short time series with "mean turbulence". In this work, however, we focus on finding the response to extreme gusts based on the ability to generate conditional turbulent wind fields. Load distributions can then be constructed on the basis of a Monte Carlo method with importance sampling.

I. THEORY

The most straightforward way to determine an extreme load distribution is by a crude Monte Carlo simulation. In this case, N ten-minute wind fields are generated from the mean wind speed distribution, $f(\bar{U})$, and fed to an aeroelastic model. When, for each sample, the maximum load is extracted, it results in a series of extreme loads $x_1, \dots, x_N$ to which a distribution can be fitted. Perhaps unsurprisingly, the crude method is not very effective; about $2.6 \cdot 10^6$ ten-minute wind fields are needed to reach the 50-year return level.

In practice, 50-year loads are extrapolated from much smaller sample sizes. This can be very difficult because the shape of the extreme load distribution can contain bends or curves that can easily lead to bias [2]. Therefore, only a fraction of the data is really usable for fitting (say, the 5–10% highest loads) and a lot of computation time is needed to predict extreme loads with sufficient accuracy.

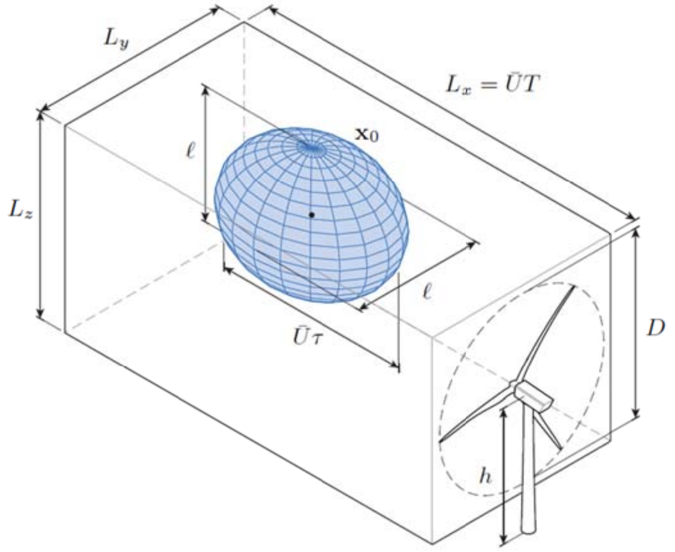

Fig. 1 Sketch of a wind gust in a constrained wind field, showing all the relevant parameters.

A common approach to reduce the uncertainty in Monte Carlo methods is to work with *importance sampling*. In this case, N samples are drawn from a particular distribution, $w(\mathbf{k})$, and are weighted by the *likelihood ratio*, $f(\mathbf{k})/w(\mathbf{k})$:

$$\hat{F}(L) \approx \frac{1}{N}\sum_{i=1}^{N} 1(x_i \leq L)\frac{f(\mathbf{k})}{w(\mathbf{k})}, \tag{1}$$

where $f(\mathbf{k})$ is the probability density function associated with the parameter space $\mathbf{k}$. After choosing a number of relevant parameters, the sampling distribution can be chosen such that the computational budget is efficiently spent on simulating severe events. Ultimately, this leads to much better predictions than what is obtained with a crude Monte Carlo method, where most of the extreme loads are cluttered around a mean.

II. GENERATING WIND GUSTS

Importance sampling becomes interesting when one has control over a large number of relevant parameters. In order to gain more control over the wind field, one can rely on the principle of *constrained stochastic simulation*. This makes it possible to simulate a conditional turbulence field that adheres to a number of constraints. These constraints can be set such that a predefined extreme gust is embedded within the field (see Fig. 1). In this study, we define spheroidal gusts through seven parameters: the mean wind speed, $\bar{U}$, the gust's amplitude, A, the gust's position, $\mathbf{x}_0 = [x_0, y_0, z_0]^\mathrm{T}$, the longitudinal time scale, τ, and the lateral length scale, ℓ.

Based on random field theory, it is possible to find the probability associated with such events [3]. What remains is finding out which combination of parameters lead to the most severe load cases.

III. PRELIMINARY RESULTS

Preliminary results have shown that this approach to extreme load prediction has several advantages. First and foremost, it has the potential to greatly reduce uncertainty since the computational resources can be efficiently spent on the cases most relevant to the 50-year load. Secondly, the tail of the extreme load distribution already has its basic shape with a small sample size, which makes fitting much easier. Moreover, it removes a large part of the bias that crude Monte Carlo methods can suffer from.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Probabilistic Gust Characterization

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Keywords – Gusts, Rotational sampling, Transfer function, Joint distribution

I. BACKGROUND

The IEC international standards for wind turbines **[1]** prescribe a set of design requirements to ensure that wind turbines are properly engineered. These standards take into consideration extreme wind conditions and various operational turbine load regimes, and specify the damage a wind turbine may withstand over its lifetime. The characterization of loads in the IEC standards is limited, and does not adequately represent the variability in the atmospheric flow parameters used as input in load simulations. Deterministic 'gust shapes' are used for several types of load cases, which do not take into account a large number of expected gust scenarios

II. AIM

In this project, a more realistic representation of gusts, based on statistical analysis, will account for the variability observed in real-world gusts. The gust representation will focus on temporal, spatial, and velocity scales that are relevant for modern wind turbines and which possibly affect the loads. Emphasis will be put on gust rise time and velocity jump (amplitude), within the context of extreme as well as normal turbulence.

III. METHODOLOGY

To achieve a statistical representation of gusts, long time series of high-resolution wind speed measurements from cup anemometers will be analyzed. To process such long time series, an automated gust detection algorithm has been developed. The algorithm includes a frequency transfer function that uses the natural frequency of a wind turbine blade from different reference wind turbines. In addition, the effect of rotational sampling of turbulence will be accounted for by means of a model for power spectra of a rotating wind turbine blade **[1]**.

The analyzed data is from Høvsøre, a coastal site in western Jutland. The wind speed is measured at heights representative of 'state of the art' wind turbines.

IV. CONCLUSION

The gust characteristics achieved will be analyzed and shown as joint distributions of two variables, e.g. the gust rise time vs. the velocity jump.

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Periodic Stability Analysis of a Wind Turbine Analytical Model with Individual Pitch Controller

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Keywords – Stability analysis, Floquet, Coleman, IPC

I. STATE OF THE ART AND MOTIVATION

Linearized wind turbine models are characterized by matrices having periodic coefficients. Currently two theories exist to perform their periodic stability analysis: the Coleman approximation and the exact Floquet method. The Coleman transformation yields a linear time invariant model only when applied to isotropic systems [1]. However, when the system is anisotropic, a residual periodicity remains and an average over the period must be performed to obtain constant-in-time coefficients. An increasing residual periodicity is typically associated with increasing levels of anisotropy. Unfortunately, lower or upper bounds for the error made by the Coleman approximation have not been proven yet. The approximation implied by Coleman's approach can be bypassed altogether by using the exact theory of Floquet, which is however still expensive when applied to high-fidelity wind turbine models.

To investigate the potential differences between the two approaches, we consider here the stability analysis of an analytical wind turbine model. The model is simple enough to allow for an exact Floquet analysis, but sufficiently sophisticated to capture the combined effects of several important sources of periodicity and anisotropy.

II. METHODOLOGY

The analytical model approximates the blade and tower flexibility through equivalent hinges, and includes blade element aerodynamics and an Individual Pitch Controller (IPC) [2]. Each blade is equipped with two hinges modelling edgewise and flapwise deflections, while the hub side-side motions are modelled by a linear spring. The aerodynamic model is adapted from [4] with minor modifications. The combined aeroelastic model represents the lowest eight modes of a horizontal axis wind turbine. To obtain a Linear Time Periodic system, the nonlinear equations of motion of the open-loop model are first analytically linearized around a periodic trajectory. Next, IPC is applied separately to the nonlinear and the linear systems. The results of the periodic stability analyses have been interpreted according to [3], and reordered by means of the Modal Assurance Criterion (MAC).

III. APPLICATIONS

The model coefficients were tuned so as to represent a 6MW three bladed wind turbine. Various stability analyses were conducted with the two methods in different operating and wind conditions, in the presence of closed-loop IPC. Some illustrative results are reported in Figure 1 and Table 1.

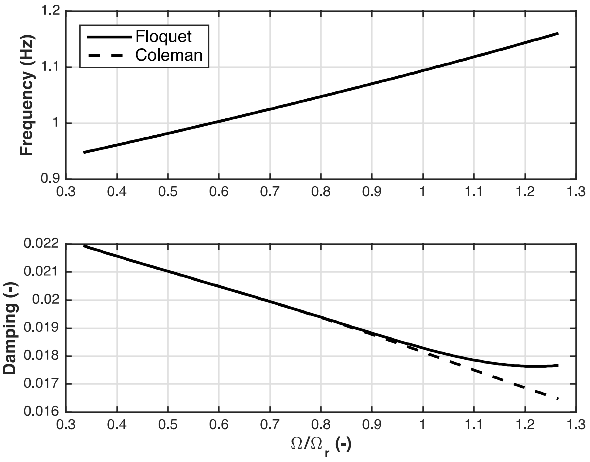

Fig. 1 Edgewise forward whirling mode in axial wind with IPC.

Case	Condition	Rel. Error %	Mode
Axial wind	1.266 Ω/Ω_r	6.769	Edgewise forward whirling
Crosswind	− 4°	1.207	Edgewise forward whirling
Wind shear	$\alpha = 0.6$	6.066	Edgewise forward whirling

Tab. 1 Maximum relative damping errors, in various wind conditions with IPC. A positive error means conservative (i.e. lower) result.

IV. CONCLUSIONS AND FUTURE DEVELOPMENTS

Results indicate that even in highly anisotropic conditions the Coleman approximation yields solutions in terms of frequencies and damping values that are typically very close to the ones of the exact Floquet theory. This apparently surprising result highlights the importance of proving error bounds for this method, bounds which are still unfortunately lacking. The largest relative errors appear in the damping, in particular for the forward whirling modes. The main drawback of the Coleman approximation resides in its inability to capture more than three harmonics per mode. A collateral result is that the use of IPC causes a steepening of the frequencies of the flapwise whirling modes.

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Model Calibration for the Soil-Structure-Interaction of an Offshore Wind Turbine with Suction Buckets

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Keywords – Offshore Wind Turbine, Soil-Structure-Interaction, Model Calibration, Evolution Strategy, Global Criterion Method, Response Surface-based Optimization, Least Squares Polynomial Regression

The soil-structure-interaction (SSI) for the prototype of a jacket substructure with suction bucket foundations for an offshore wind turbine (OWT) is currently monitored within the wind farm Borkum Riffgrund in the German North Sea, see Fig. 1. Continuous measurement data provide results of eigen-frequencies and eigenmodes for different states of construction and operation states.

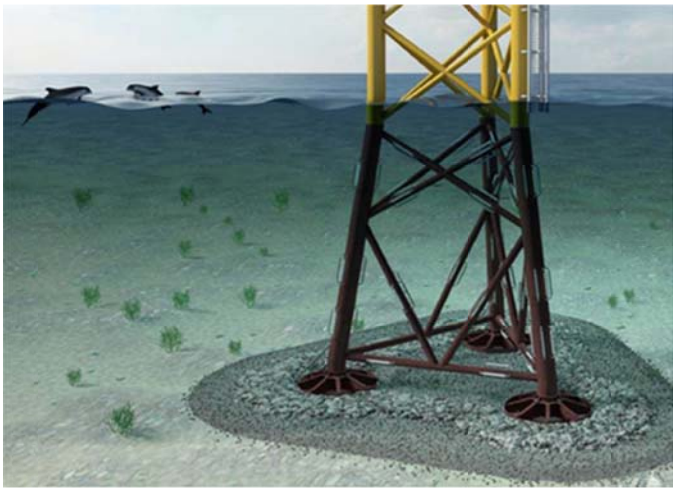

Fig. 1 Suction Bucket Jacket within the offshore wind farm Borkum Riffgrund (illustration from DONG Energy)

In parallel a precise finite element model has been built. The soil-structure-interaction is regarded in terms of a condensed stiffness matrix K_{SSI} (1) at the height of the suction bucket top, representing the whole soil-structure-interaction. Inertia from the SSI is neglected. The objective is to adjust the six independent stiffness coefficients $(k_h, k_v, k_\varphi, k_t, k_{H\varphi}, k_{Mh})$ with an optimization algorithm, so that a certain number of eigenfrequencies and eigenmodes of the FE-model coincide as much as possible with those results from the measurement data.

$$[K_{SSI}] = \begin{bmatrix} k_h & 0 & 0 & 0 & -k_{H\varphi} & 0 \\ 0 & k_h & 0 & k_{H\varphi} & 0 & 0 \\ 0 & 0 & k_v & 0 & 0 & 0 \\ 0 & k_{Mh} & 0 & k_\varphi & 0 & 0 \\ -k_{Mh} & 0 & 0 & 0 & k_\varphi & 0 \\ 0 & 0 & 0 & 0 & 0 & k_t \end{bmatrix} \quad (1)$$

For adjusting the stiffness coefficients the Evolution Strategy $(\mu/\rho \overset{+}{,} \lambda)$-ES is applied, which is a metaheuristic global evolutionary optimization algorithm by RECHENBERG and SCHWEFEL based on selection, recombination and adaptive mutation, as described in [1].

To reduce the multi-objective to a single-objective optimization problem (n eigenfrequencies + n eigenmodes) one of the most common general scalarization methods is used – the Weighted Global Criterion Method [2]. The residuals from the comparison of eigenfrequencies $R_{EF}^{(ref,FEM)}$ and those from the comparison of eigenmodes $R_{MAC}^{(ref,FEM)}$, utilizing the modal assurance criterion (MAC), are cumulated considering weighting parameters (v_i, w_i) and smoothing parameters (p, q), see (2).

$$R_{total} = R_{EF}^{(ref,FEM)} + R_{MAC}^{(ref,FEM)} \rightarrow min \quad (2)$$

$$R_{EF}^{(ref,FEM)} = \left\{ \sum_{i=1}^{n} v_i \left[\frac{EF_i^{FEM} - EF_i^{ref}}{EF_i^{ref}} \right]^p \right\}^{\frac{1}{p}} \quad (2a)$$

$$R_{MAC}^{(ref,FEM)} = \left\{ \sum_{i=1}^{n} w_i \left[1 - MAC\left(\phi_i^{ref}, \phi_i^{FEM}\right) \right]^q \right\}^{\frac{1}{q}} \quad (2b)$$

Finally the model calibration procedure based on a high number of single FE-analyses is compared with a response-surface-based optimization. Here a relatively small number of samples is analysed initially with Latin Hypercube Sampling to span a response model with Least Squares Polynomial Regression [3]. Subsequently the optimization is performed independently from the structural model but on the response surface (“fitness landscape”). Quality in terms of successful model calibration and the according computation time of both strategies are compared at the end.

ACKNOWLEDGEMENTS

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Variations of the wake height over the Bolund escarpment

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Keywords – Bolund, Wake height, Complex flow, WindScanner

For high quality results in numerical and physical modeling, the models need to be verified with reliable real world measurements. Bolund, an isolated flat-topped hill with steep sides in the Roskilde Fjord, Denmark, serves as such a baseline reference for various studies, since a mast based atmospheric experiment was conducted by DTU Wind Energy during winter 2007-2008 [1], [2]. To obtain a more comprehensive understanding of the flow pattern over the Bolund peninsula, especially close to the surface, a complementary field experiment on the Bolund peninsula was conducted. In October 2011 a laser anemometer, in the following called WindScanner [3], [4], was placed on the peninsula 20 m inland from the westward facing escarpment.

I. APPROACH

The WindScanner, aligned on the 270° axis, was operated during westerly wind conditions to scan the area downstream of the Bolund edge. The atmospheric flow was measured in seven, 7-m high vertical profiles with distances between 8 m and 31 m from the scanning lidar (Figure 1)

In addition to the seven vertical profiles a horizontal arc extending ±60° was scanned 90 m away from the instrument. The line-of-sight wind speeds of the eighth profile were used to determine the undisturbed inflow wind speed and wind direction.

Lidar measurements were recorded continuously during an almost 24 hour long measurement period.

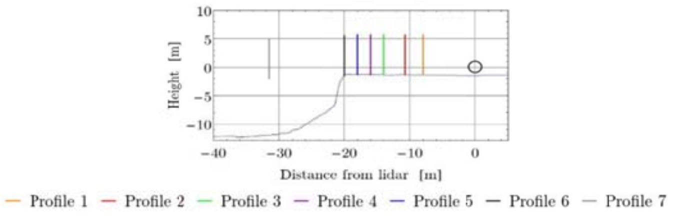

Figure 1: The position and height of the 7 vertical profiles scanned by the lidar relative to the Bolund escarpment. The position of the WindScanner itself is indicated by the circle.

II. METHOD

The characteristic of the escarpment induced wake is investigated by identifying the boundary between the turbulent flow layer and the less turbulent layer above. Due to the high measurement-sampling rate a precise determination of the interface between the two distinctly different layers is possible. We determine the wake height using three different methods. One of the used methods is the calculation of the displacement thickness. The results of the wake-height identifications with this method is exemplary presented in Figure 2

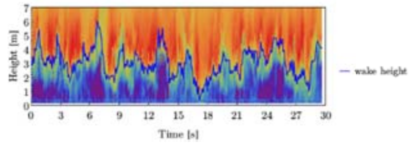

Figure 2: The line-of-sight projected wind-speed scanned at profile 2, during 30 seconds. 300 consecutive vertical profiles are plotted and the determined wake height is shown as the solid blue line.

The calculated wake height for each profile location can be put in relation to the undisturbed wind direction and speed. With increasing distance from the escarpment, the wake heights show stronger dependence on the wind direction as visualized in Figure 3.

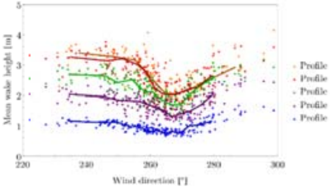

Figure 3: Dependence of the determined wake height and the wind direction. The solid lines depict the average wake height. The profile number increases with the distance from the WindScanner. The wake height is calculated through the definition of the displacement thickness.

III. CONCLUSION

The new remote sensing based wind profile measurements provide a unique data set for validation of unsteady flow modeling over complex terrain for wind energy.

Based on the analysis of the high frequency atmospheric measurements with a rapidly scanning continuous-wave Doppler lidar a relationship between the escarpment induced wake height and the wind direction could be shown.

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Influence of turbulence intensity on wind turbine power curves

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Keywords – Power curve, Lidar, turbulence, AEP

In this study the effect of turbulence on wind turbine performance measurements have been investigated. Experimental data has been collected from a wind turbine test site at the coast of Norway over a 10 month period and the effect of turbulence intensity (TI) on power curves and annual energy production has been studied.

I. INTRODUCTION

Accurate wind turbine power curves are needed for reliable estimations of annual energy production (AEP) of planned wind farms. It is evident that power curves are sensible to site specific conditions such as wind shear, air density, flow inclination and turbulence. The draft of the second edition of the IEC 61400-12-1 standard for performance measurement of wind turbines[1] includes corrections for shear, air density and turbulence in order to reduce the site dependence. The effect of turbulence is partially caused by the 10-minute averaging of wind speed and partially by the direct influence of turbulence on the aerodynamic performance of the turbine blades. Several studies have investigated the influence on power performance and suggested appropriate methods to reduce the influence [2-4]. This study aims to quantify the effect of turbulence intensity on the estimated AEP of a wind turbine and evaluate the turbulence correction method found in the new IEC standard draft.

II. MEASUREMENTS

A. Valsneset test site

Measurements were performed at a wind turbine test site on the coast of Mid-Norway. The site includes a small wind farm consisting of five 2,3MW wind turbines and a 3MW pilot test turbine. The measurement sector was restricted to a 212 degree sector including both offshore and mixed fetch following the guidelines of Annex A in [1].

B. Measurements

A Windcube v2 ground based lidar from Leosphere was used to measure the wind speed at a distance of 3 rotor diameters from the 3MW wind turbine with a rotor diameter of 100,6 meters and a hub height of 92 meters. 10 minute averages of net power output were synchronized with 10 minute wind speed averages from the lidar. Meteorological data was also collected from a 33 meter met-mast at the site.

III. RESULTS

The average turbulence intensity at hub height in the measurement sector, as measured by the lidar [5], was 0,088 during the measurement period. Power curves binned according to 3 similarly populated TI bins presented in Fig.1 shows a clear effect of TI on power, especially of high TI in the rated wind speed region. For this site the difference in estimated AEP compared to the power curve derived from all data is -0,6% for the high turbulence bin and +1,2% for the low turbulence bin.

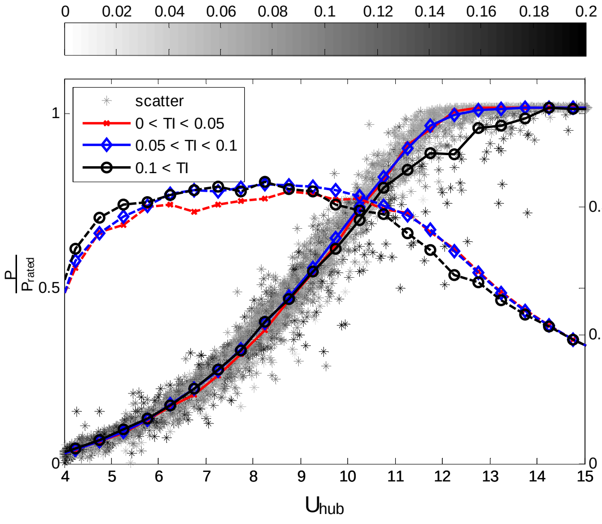

Fig. 1 Normalized power curves and power coefficient curves binned by turbulence intensity. Scatter plot showing the individual data points.

IV. CONCLUSION

Depending on the local conditions the effect of turbulence may have a significant effect on estimated AEP derived from uncorrected power curves. The largest influence on power is found in the region around rated wind speed.

ACKNOWLEDGEMENTS

The authors would like to thank Blaaster for access to wind turbine data and VIVA for access to the test site.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Session: Meteorological Effects and Wind Power Estimation

Wind Power Estimations using OpenFoam Coupled with WRF

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Keywords – Computational Fluid Dynamics, Wind Energy, Power Prediction, OpenFOAM, WRF

I. THE ONE PAGE ABSTRACT

The objective of the this study is the development of a tool to predict daily wind energy production potential accurately for a region of interest.

Most of the commercial wind power prediction tools either use statistical methods or linearized computational fluid dynamics (CFD) models for which the observation data is a must. Also, those using linearized models use fictious flowfields that are created just by using different uniform velocity inlet, pressure outlet boundary conditions as seen in Figure 1. Those flowfields are then correlated with the observation data.

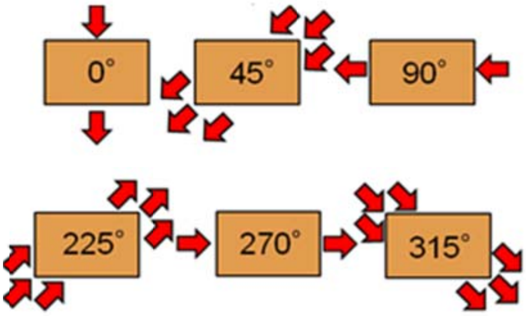

Fig. 1 Linearized model Boundary Conditions

Because of the uniformity of the boundary condtions and absence of time dependency in linearized CFD models, most of the commercial wind power prediction tools cannot answer the question "how much energy can be extracted tomorrow?" which is a valuable information for the energy market.

In this study, mesoscale weather prediction model WRF (Weather Research and Forecast) will be coupled with the opensource CFD solver OpenFOAM via using low resolution WRF data as unsteady and spatially varying boundary condtions in the CFD solver 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 2.

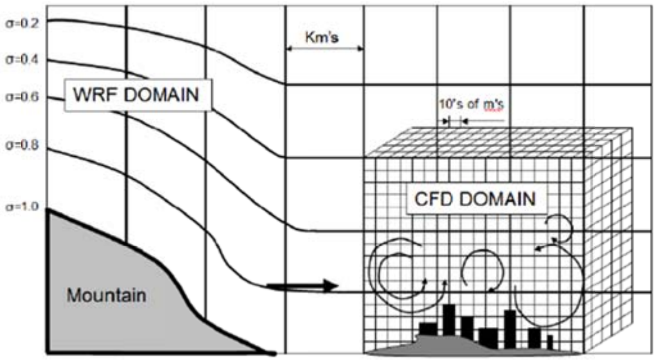

Fig. 2 Coupling WRF with OpenFOAM

Unlike other methodologies, in this study, capability of time resolved energy prediction is attained and also, observation data is not a must. Spatially varying boundary conditions taken from WRF can be defined in the CFD code, not only on one point like commercial tools but on whole of CFD domain boundaries.

In the previous study[1], only steady solutions are obtained using the WRF weather prediction data at a specific time as spatially varying inlet-outlet boundary conditions for OpenFOAM. Research is ongoing about making the above mentioned boundary conditions unsteady.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Stuttgart, Germany
Session: Remote Sensing

Radial wind speed uncertainty of nacelle-mounted profiling lidars

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Keywords – lidar, wind, profile, nacelle, calibration, uncertainty

Developing standard procedures for power curves using lidars requires to assess lidars measurement uncertainty that is provided by a calibration. Using the radial wind speed (RWS) calibration results [1] [2] from two lidars (Fig. 1), the Avent 5-beam Demonstrator and the Zephir Dual Mode (ZDM), we present how to derive RWS uncertainties.

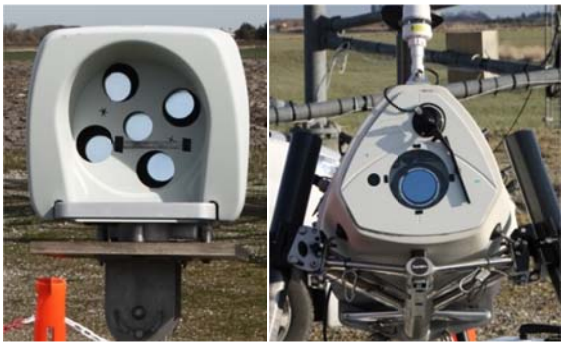

Fig. 1 Left: 5-beam Demonstrator (Avent Lidar Technology), right: ZephIR Dual Mode (ZephIR lidar)

I. INTRODUCTION

A. *Profiling lidars in power performance*

In power performance testing, it has been demonstrated that the effects of wind speed and direction variations over the rotor disk can no longer be neglected for large wind turbines [3]. A new generation of commercial nacelle-based lidars is now available, offering wind profiling capabilities. The use of profiling nacelle lidars to assess power performance could remove the need to erect expensive meteorology masts, especially offshore.

B. *The need for calibration procedures*

The fundamental reason for developing calibration procedures is to assign uncertainties to lidar wind measurements. Commercial applications of lidars, e.g. power performance testing or resource assessment, demand the estimation of measurement uncertainties.

Metrology standards [4] define a calibration as a 3-step process:

- Establishing a relation between the measurand and reference quantity value;
- Derivation of uncertainties on the measurand using both the reference measurement uncertainty and calibration process components;
- Applying the calibration relation to preserve traceability in the measurement chain.

II. RADIAL WIND SPEED UNCERTAINTIES

A. *Calibration principles and reference measurand*

The RWS calibration consists in calibrating all the input quantities of the reconstruction algorithms employed by lidars. Indeed, lidars combine radial wind speed measurements, beam localisation quantities – e.g. inclination and roll angles of the beam – and the geometry of the scanning pattern in order to reconstructed wind parameters such as speed, direction, shear, veer, etc.

Since the RWS corresponds to the wind vector projection onto the Line-of-sight (LOS) direction, the reference measurand is:

$$Ref_{eq\,RWS} = HWS \cdot \cos(\varphi_{physical}) \cdot \cos(\theta - LOS_{dir}) \quad (1),$$

Where HWS is the horizontal wind speed measured by a cup anemometer, $\varphi_{physical}$ is the tilting of the beam, θ is the wind direction measured by a sonic anemometer, LOS_{dir} is the LOS direction.

B. *Methodology for measurement uncertainty assessment*

In the procedure, bin averages of 10-min mean values are used to provide the calibration relation between the RWS and $Ref_{eq\,RWS}$. The assessment of uncertainties is performed using the GUM [5] – a standard methodology based on the law of propagation of uncertainty.

Two separate uncertainty assessment methodologies, i.e. with two measurement equations, are presented and their results inter-compared:

1) $\boldsymbol{\langle RWS\rangle = a \cdot \langle Ref_{eq\,RWS}\rangle}$, where $\langle\ \rangle$ denotes 10-minute averages, a is the gain of the forced regression between bin averages of $\langle RWS\rangle$ and $\langle Ref_{eq\,RWS}\rangle$;
2) $\boldsymbol{\langle RWS\rangle = \langle Ref_{eq\,RWS}\rangle + \Delta_i}$, where Δ_i is the average deviation between $\langle \mathrm{RWS}\rangle$ and $\langle \mathrm{Ref}_{eq\,RWS}\rangle$ in bin number i.

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Evolution of wind towards wind turbine

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Keywords – wind evolution, remote sensing, lidar data, wind field modelling

I. 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 is of high importance for further applications of the data.

Within the framework of Top consortium for Knowledge and Innovation Offshore Wind (TKI-WoZ), ECN initiated the LAWINE (Lidar Applications for Wind farm Efficiency) project in cooperation with XEMC Darwind, AventLidar Technology and TU Delft. Two measurement campaigns were 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.

G. I. Taylor suggested for certain cases, the turbulence might be considered to be frozen as it advects past a sensor [1]. This is particularly applicable in cases where the turbulent eddies evolve at a timescale longer than the time of eddies advection past the sensor. With Lidars, this case is invalid and the evolution of wind from far wind to the wind turbine could be studied. Bossanyi proposed a method recently to unfreeze the turbulence and performed some simulations to reduce the fatigue load reductions [2]. The model from Bossanyi is already incorporated in the recent versions of Bladed and requires further testing and improvements based on atmospheric and site conditions. Simley and Pao concluded that the error induced due to induction zone is negligible and suggested more studies replicating realistic conditions to be necessary [3]. Most of the current models lack in some or the other aspect and the trick lies in developing a model which bridges the gap between measurements and the controls of the wind turbine.

In this paper, the parameters important for unfreezing of turbulence are studied and compared using a nacelle mounted pulsed Lidar at the ECN test site as shown in Fig. 1. Wind field simulations using the different existing models and coherence functions are compared. The blockage effects along with the coherence model representing time and phase delay of the evolution wind field are modelled with the simulated wind fields. The eddy size and the life of eddies are of high importance in these studies and this is also linked to the concept of wavelet analysis [4]. Schlipf et al. found that the eddy size uptil $k = 0.128\ \mathrm{rad/s}$ satisfy the assumption of Taylor's frozen turbulence [5]. The parameters introduced here would be accounted for in the wind evolution model to provide deeper insight into the dynamics of the wind upwind of the turbine using the Lidar measurements.

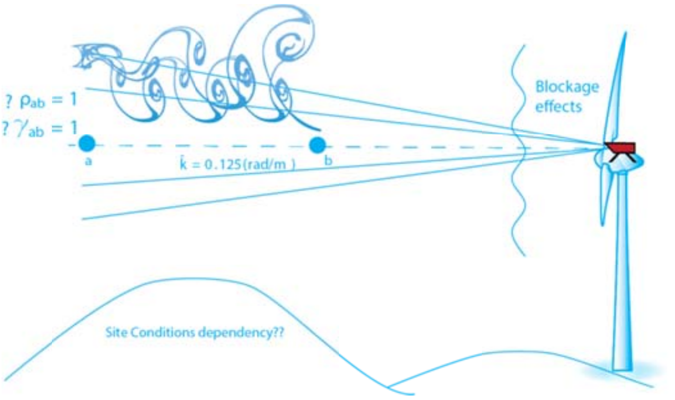

Fig. 1 Parameters important for the wind evolution model, characteristic of Taylor's frozen turbulence wind fields and influence of blockage effects and site dependency

The model thus developed would be tested with valid Lidar measurements and using a transfer function with range weighting included into the wind turbine control simulation. The validation of the model would be done with the help of Computational Fluid dynamics, CFD.

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Analysis of Two-dimensional Inflow Measurements by Lidar-Based Wind Scanners

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Keywords – Lidar, Induction, Inflow, Blockage, WindScanner, Data Processing, Modelling

The emergence of reliable and sophisticated lidar technology allows for the first time to fully capture a wind field over a large area in a relatively short time frame. Furthermore with the in-house developed 3-D short range WindScanners (windscanner.eu) it is possible to acquire all three wind speed components [1]. The UniTTe project (unitte.dk) wants to establish lidars for power and load estimations for modern wind turbines. As these novel methods rely on scanning the flow upstream of the turbine, they come under the influence of the turbine induction zone [2], which develops due to the pressure jump induced by the turbine. Modelling and understanding the induction zone is key to establishing lidars as an industry standard for power and load estimations. Successfully modelling the upstream effects of the turbine, though, necessitates validation via measurements. This paper presents the challenges and methods in post-processing two-dimensional wind fields acquired by lidars for model validation purposes.

I. EXPERIMENTAL METHOD

The 3-D short-range WindScanner is based on three synchronised continuous wave Doppler lidars. They estimate the mean line of sight wind speed from the frequency shift in the laser Doppler spectra, resulting from moving airborne particles. The three lidars are synchronised such that their focal points are coinciding. There were two measurement grids that were continuously scanned for 30 minutes. Both grids were fixed and thus only aligned with the turbine for one single wind direction. The horizontal plane was located at hub height and spanned the entire diameter (41 m) of the Risø NTK 500 turbine, as well as 62 m upstream. The vertical plane was perpendicular to the horizontal plane and had the same dimensions. One scan was completed in 15 s for the horizontal and 30 s for the vertical plane. Over three month a total of 32.5 h of data were acquired.

II. POST-PROCESSING

The data processing incorporates many different levels. In this work the focus lies on post-processing of the line of sight velocities. There are many steps involved in the processing of the velocities such that they can be interpreted sensibly and finally be applied in the validation of the model (see Fig. 1).

The first step is to find and remove spikes in the data. To assess the measurement quality of the de-spiked data, the lidar velocities were compared to those acquired by a sonic anemometer that was situated on a short met mast inside the measurement grid. The correlation of these measurements was overall very satisfying, though it emerged that there was a random time shift between the two signals.

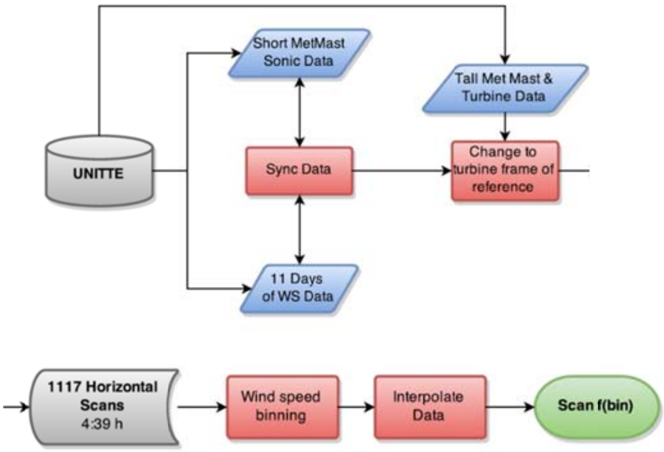

Fig. 1 Overview of the post-processing steps.

Syncing allowed rejecting data for times when the turbine was barely running and enabled transforming it into the turbine frame of reference via the turbine's yaw data.

The wind speed binning is a critical step, as it is hard to determine the exact reference wind speed for an individual data point inside one scan iteration. After these steps a special interpolation method was applied to the lidar measurements that allowed to group scanning points from different yaw conditions.

III. CONCLUSION

Lidars can characterise large wind fields remotely, potentially allowing the validation of numerical models over the entire domain of interest. For a fair comparison multiple robust post-processing methods have to be applied to the lidar measurements.

ACKNOWLEDGEMENTS

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A New Concept for Tower Structures of Wind Turbines

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Keywords – Tower construction, precast elements

The increase of worldwide wind energy delivery output led to the design of wind turbines with big hub heights using tower structures made of concrete or the combined use of concrete and steel (hybrid tower structures). A new approach to constructing towers out of double walls (two thin concrete slabs connected by steel bars) is presented in the current work. In order to show the feasibility of the proposed construction method a prototype was erected. The experiences and results gained from the prototype erection are promising and indicate that the new construction method is likely to establish itself on the market.

I. TOWER CONSTRUCTION METHOD

The proposed building method is based on simple double wall elements. These light-weight double wall elements can easily be transported to the construction site by standart construction vehicles. There a preassembly field is used to position, angle and temporarily fix the single elements by skew bracings, so that the loose elements can be connected to form polygonal ring segments. After each ring segment is assembled it can be placed on top of the preceding segment. In order to create a monolithic structure the separate segments are then filled with in-situ concrete. The continuous filling of the segments with in-situ concrete allows the structure to rise without any joints in the core of the hollow elements. As a final optional step of the tower erection, all segments can be, if needed, post-tensioned vertically against the foundation.

II. PROTOTYPE

A prototype tower was built to test the previous proposed construction method. This prototype consists of six segments with different heights result in a tower with a total height of 16.15 m and an outer diameter of 4.15 m at the bottom, whereby the cross section of the structure is chosen as a regular nonagon, see Fig. 1. A method using semi-precast elements to erect a concrete structure is confronted with various challenges during the erection, which is further discussed in a master thesis [2]. One of these challenges is the connection of the double walls which should resist all erection load cases so that the set up segment geometry is secured. Another one is the segment joint sealing construction enabling the concreting of the tower.

III. COMPARISON OF CONCRETE TOWER STRUCTURES

The relevance of the new building method can be shown by comparing the different erection methods of concrete towers for wind turbines. In-situ concrete towers erected with slip- or climbing formworks show the best load bearing and fatigue resistance but there erection is too time-consuming and therefore expensive because only approx. 4 m high segments per day can be produced. At present the most common concrete tower for wind turbines made of fully bodied precast elements can be erected very fast and is therefore a cheaper variant but the elements have to be kept in place by post-tensioning. Thus, the new construction method using double walls should combine the advantages of the in-situ and the precast towers allowing for producing a tower which can be erected fast but can still be designed without post-tensioning.

Fig. 1 Erected Prototype with an outer diameter of 4.15 m at the bottom and a total high amounting to 16,15 m

IV. CONCLUSION

It can be stated that the present results gained from the prototype erection and the structural analysis show that the proposed construction method is promising and is likely to establish itself on the market.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Austrian Federal Ministry of Science, Research and Economy (bmwfw) for their funding, the company Franz Oberndorfer GmbH & Co KG for the good collaboration and to the austria wirtschaftsservice GmbH for the financial management.

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Gust Load Alleviation through Enhanced Fluid-Structure Interaction

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Gust Load Alleviation, Non-stationary Aerodynamics, Wind tunnel testing

An airfoil with mechanically coupled leading and trailing edge flap is tested in a wind tunnel under non-stationary inflow conditions to examine its potential for gust load alleviation on wind turbines.

I. INTRODUCTION

Wind turbines often operate in highly turbulent conditions where the angle of attack can change significantly. The resulting aerodynamic load fluctuations are transmitted from the blades to the drive train and tower. These unsteady loads increase fatigue, which decreases lifetime and limits the upscaling of turbines. State-of-the-art pitchmechanisms are designed to alleviateload fluctuations in the order of minutes to hours but are too slow to account for high frequency fluctuations due to turbulence. Several new and faster load reduction active mechanisms are currently under investigation, but these systems involve complicated control schemes. At the Technische Universität Darmstadt, a passive load reduction mechanism has been developed by Hufnagel and Lambie [1] and tested under stationary inflow by Lambie [2]. A two-dimensional airfoil equipped with this concept has now been investigated experimentally under unsteady inflow conditions in the active grid wind tunnel at the University of Oldenburg.

II. ABSTRACT FORMATTING

A. *System Description*

The adaptive camber concept features a mechanically coupled leading and trailing edge flap which adapts its camber passively to the inflow conditions (Fig. 1).

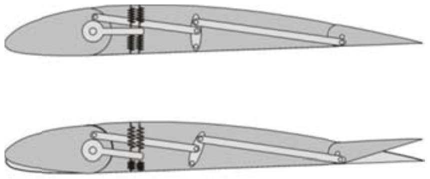

Fig. 1 Schematic view of adaptive camber airfoil principle. High angle of attack induce an up bending moment on the leading edge flap which is transferred to the trailing edge flap. The combined motion of both flaps leads to a decrease of camber.

Decreased aerodynamic pressure and/or angle of attack lead to an increased camber and load increase, whereas increased aerodynamic pressure and/or angle of attack lead to a de-cambering and to a decreased load. High peak loads are alleviated whereas overall load is maximized for small dynamic pressures and angle of attack.

B. *Non-stationary Experiments*

An airfoil equipped with adaptive camber mechanism is submitted to dynamic angle of attack variations $\alpha(t)$. The mean angle of attack α_m was varied by pitching the airfoil around its *c*/4 axis. Sinusoidal oscillations α' were generated using the active grid. Total angle of attack $\alpha(t)$ is a sum of the mean angle of attack α_m and the sinusoidal variations $\alpha'(t)$.

$$\alpha(t) = \alpha_m + \alpha'(t) = \alpha_m + A\sin(2\pi f t) \qquad (1)$$

Fig.2 shows the temporal resolved lift response of the adaptive camber airfoil compared to a rigid reference configuration. It can be seen that dynamic load fluctuations are reduced by the adaptive camber airfoil.

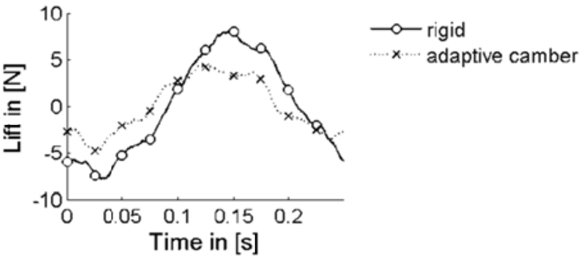

Fig.2 Phase-Averaged time resolved lift response of a rigid and the adaptive camber airfoil undergoing sinusoidal changes of angle of attack

III. CONCLUSION

Dynamic system response of the adaptive camber airfoil shows good potential for gust load alleviation on wind turbines.

ACKNOWLEDGEMENTS

This project has been funded by the German Research Society DFG.

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A multi-band virtual sensing approach for fatigue assessment of monopile wind turbines

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Keywords – Modal Decomposition, Modal Expansion, Virtual Sensing, Response Estimation, Structural Health Monitoring, Offshore Wind Turbines

Fatigue life is often a design driver for the foundations of offshore wind turbines (OWT). Insight about wind farm inspections and end-of-life actions on the OWT can be gained through continuous monitoring of the fatigue life of the structure.

This paper introduces a complete methodology for fatigue assessment of monopile wind turbines based on limited information acquired from a sensor network installed on the structure. The fatigue monitoring strategy uses data from an OWT on monopile foundation operating outside the Belgian coast to validate the proposed multi-band virtual sensing approach.

I. INTRODUCTION

Since fatigue life is a design driver for the foundations, the continuous monitoring for life-time assessment of an offshore wind turbine during its wide range of operational states can serve as a valuable tool for maintenance, end-of-life decisions and feedback into design for optimization of future substructures. For the offshore wind turbine, though, practical limitations prohibit to mount sensors at stress (and fatigue) hotspots. E.g. for a monopile foundation, the most popular design, the stress hot spot is at the mudline below the water level. Installing a measurement system at the mudline is unfavourable in terms of cost and maintenance. This limitation is overcome by reconstructing the full-field response of the structure based on the limited number of accelerometers and a calibrated Finite Element Model of the system. A reduced-order model that exploits the limited information obtained by the acceleration sensor data and adaptively incorporates them to permit adaptation to system changes is utilised for optimal generation of virtual dynamic strains. The model uses a multi band modal decomposition and expansion approach for reconstructing the responses at all degrees of freedom of the finite element model. The paper will demonstrate the possibility to estimate dynamic strains from acceleration measurements based on the aforementioned methodology. These virtual dynamic strains will then be evaluated and validated based on long term actual strain measurements obtained from a monitoring campaign on an offshore wind turbine on a monopile foundation. This new structural health monitoring approach has the ability to interrogate an entire structure and accurately assess fatigue life consumption and remaining useful life at the true fatigue hot spots.

II. RESULTS

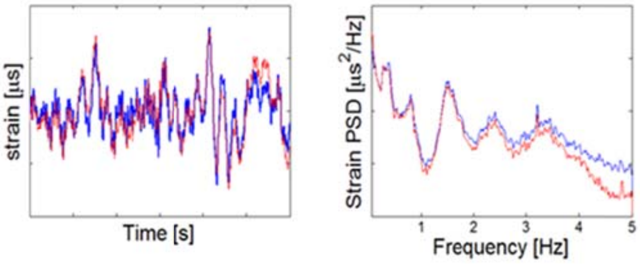

Fig. 1 Multi Band Virtual Sensing (MBVS) approach for strain prediction. Detail time history (left) and estimated PSD (right) of the FA strain at level h=19 m LAT for an indicative 10-min dataset in rotating conditions. The measured strains are shown in blue, the estimated strains from the modal decomposition and expansion algorithm are shown in red.

It is made clear that the superposition of the low-frequent and the high-frequent strain components that results in the so called MBVS response, gives good match between the measured and the predicted signals. This good match is observed both in the time domain as well as in the frequency domain, both in terms of amplitude and in terms of temporal evolution.

III. CONCLUSION

A new structural health monitoring approach that has the ability to interrogate an entire structure and accurately assess fatigue life consumption and remaining useful life at the true fatigue hot spots is introduced.

ACKNOWLEDGEMENTS

This research has been performed in the framework of the Offshore Wind Infrastructure Project (http://www.owi-lab.be) and the O&O Parkwind project. The authors also acknowledge the financial support by the Agency for innovation by Science and Technology (IWT). The authors gratefully thank the people of Parkwind and the colleagues in OWI-lab for their continuous support within this project.

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PIV study of wall bounded Fractal-grid-generated Turbulence

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Keywords – Multi-scale turbulence, Fractal turbulence grid, Particle Image Velocimetry

There are pervasive industrial applications of Multi-scale/Fractal grids which have been introduced recently. These grids are designed to generate multi-scale turbulence by directly exciting a wide range of fluctuation length scales in the flow. There is a great potential for this so called “new class of turbulent flows” in wind energy research context [1]. Fractal grids with square patterns leave a considerable elongated turbulence production region [2]. Since it has been shown that the presence of walls has a minor and negligible effect on the turbulent properties generated by a fractal/regular grid [3], it can be used to establish flows with specific turbulence intensities with wide range of length scales to reproduce the atmospheric boundary layers for wind turbine experiments.

In this study, the flow passing through fractal grid turbulence generator as well as regular turbulence grid is measured using 2-D PIV to study the characteristics of the flow structures generated throughout the decay region and to evaluate the sensitivity of the experimental setup in detecting the level of turbulence intensity and in resolving the small length scales. This study aims to put a step forward in preliminary assessment of the ability of PIV in measurement of turbulence properties and power spectra while resolving small scale eddies which are formed much further downstream of the grids, where the predominant noise makes it difficult to capture the turbulence intensity components [4].

I. GEOMETRY OF GRIDS

The complete descriptions of the fractal and conventional square grids used in this study are shown in Table 1. Blockage ratio is kept identical for both grids while the effective mesh size is similar. Both grids were made from 4 mm thick transparent plexiglass, cut in a CO_2 glass tube type Laser cutting machine with a resolution of 0.5 mm. The Fractal Square Grid (FSG) has a fractal dimension (D_f) of 2.0. The scaled diagrams of constructed grids is shown in Figure 1.

Table. 1 Conventional square grid (CSG) and Fractal square grid (FSG) parameters

	Number of Iterations	*Thickness ratio*	*Iteration Length ratio*	*Iteration Thickness ratio*	*Blockage ratio*	*Minimum thickness of bars*	*Effective mesh size*
	N	t_r	R_L	R_t	σ	$t_{\min}$	M_{eff}
CSG	1	1.0	0.5	1.0	0.25	2.36mm	17.65mm
FSG	4	8.5	0.5	0.49	0.25	1.1mm	17.28mm

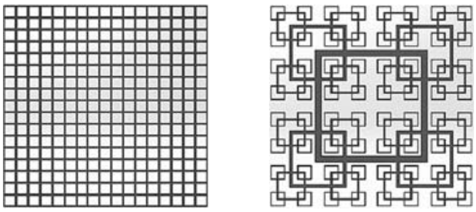

Figure 1 Scaled view of CSG (Left) and FSG (Right) used in the experiments

II. EXPERIMENTAL SETUP

Experiments are conducted in an open circuit suction type wind tunnel with an extended square test section (0.3m x 0.3m x 4.0m). The purpose of this elongated test section is to study the turbulent flow properties (e.g. turbulence intensities, homogeneity and isotropy) much further downstream of the grids. To avoid any boundary layer growth effect on the core turbulent flow the walls are made divergent maintaining the stream-wise pressure gradient close to zero along the test section. The grids are placed immediately after the contraction of the tunnel. The turbulence level when the test section is empty is lower than 0.5% along the centreline of the tunnel. The Reynolds number based on the velocity at the inlet of test section without the grids and the effective mesh size is about 1.12×10^4.

An Nd:YLF high speed laser with a light sheet thickness of about 1 mm illuminates the stream-wise planes passing from the centreline of the test section downstream of the grid, seeded with olive oil droplets. A Phantom V640 12-bit high-speed camera together with TSI Laser pulse synchronizer (Model 610036) with resolution of 25 ns are used to get 2-D images of the illuminated region.

Capability of 2-D PIV to resolve scales smaller than Taylor micro-scales exist in the decay region of multi-scale/fractal generated turbulence will be assessed. In-plane turbulence intensities and 1-D energy spectra will also be presented to confirm the exponential decay observed by Hurst and Vassilicos [2].

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Optimising Power System Integration based on the Energy Ratio

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Keywords – System integration, Transmission, Storage, Global and regional potential of renewable energies

I. INTRODUCTION

In recent years the potential of renewable energies to meet future world energy demands has been assessed by numerous studies (see for instance [1], [2], [3]) – coming to significant different results: While [1] conclude, that “the amount of wind power plus solar power available worldwide […] exceeds projected world power demand by more than an order of magnitude”, [2] and [3] doubt this from both an economical as well as socio-technical-environmental point of view. In fact, they claim, that “overall energy reductions […] will be needed […]” [3]. These difference can amongst others be explained by the different treatment of the energy ratio E_R:

$$E_R = \frac{E_{out}}{E_{in}} \qquad (1)$$

where E_{out} is the energy yield of a power plant – usually computed over a typical lifetime of the plant considered – and E_{in} is the input energy for manufacturing and erecting the power plant including recurring energy needs for maintenance and operation [3]. It has been shown by [3], that the energy ratio is an important measure to quantify renewable energy potentials. Additionally it can be interpreted as a proxy for the sustainability of the energy supply. In this study, we show, that the energy ratio can furthermore be used to find an optimal distribution of renewable power plants for system integration from both a technical as well as socio-economical perspective.

II. METHODOLOGY & DATA

A 100 % renewable German electricity supply system is modelled. The – spatially and temporally – fluctuating generation from photovoltaics (PV) and wind is simulated based on meteorological data from the NWP model COSMO-DE and from Meteosat as well as based on the spatial distribution of wind power plants and PV modules obtained from the German TSO’s. To be able to measure the effect of different degrees of decentralisation, simulations of electricity generation are also conducted based on scenarios for the spatial distribution of installed PV and wind energy capacities. Load data is obtained from Entso-E.

Based on the simulated time series of electricity generation, time series of the electricity mismatch are computed for the 400 administrative areas in Germany. From these time series the administrative area’s storage needs as well as the transmission capacity needs of the whole supply system are computed and compared between the different scenarios considered for the spatial distribution of PV and wind energy capacities.

Similar to Eq. (1) the energy ratio can be assessed for whole energy supply systems, by including losses due to storage and transmission as well as the input energy needs for the same devices and assuming:

$$E_R = E_R(C_F, T, S) \qquad (2)$$

where C_F is the capacity factor, T is the transmission capacity and S is the storage capacity. By maximising Eq. (2) an optimal distribution of installed renewable energy capacities within a supply system can be derived.

III. CONCLUSION

In this study we show, that the energy ratio – when computed for whole energy supply systems – is a worthwhile measure for finding optimal distributions of renewable energy capacities and for quantifying the sustainability of the system from a both regional and global socio-technical-environmental perspective.

IV. ACKNOWLEDGEMENTS

Bruno Schyska thanks Stephan Spaeth, Ontje Luensdorf and Jan Kuehnert for providing the scripts to perform the simulations of electricity generation from wind and PV respectively.

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Transmission, Storage and Backup Estimates for a Global Electricity Grid with High Shares of Renewables

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Keywords – Renewable Energy, Energy System Analysis, Global Power Grid, Storages, Power Transmission, Wind Energy, Photovoltaics, Hydro power, Concentrated Solar Power

A vision of a global renewable electricity grid has been described in [1].

Such a system might consist of renewable power generation around the earth connected to the major load centers by long distance high voltage transmission links.

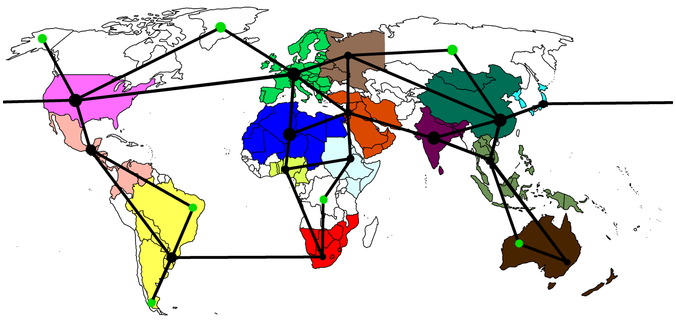
In general, wind and photovoltaics generation facilities have, due to the weather dependency of their power sources, highly fluctuating feed-in profiles. This is true for mostly dispatchable hydro power generation to a lesser degree.

In this work we compute backup, transmission and storage needs for a global power system consisting of major load centers in 2050 (estimated by an economic outlook [2]) connected to renewable generation by high voltage long distance transmission links.

I. BACKGROUND AND METHODOLOGY

Growing shares of renewables make their integration into the power system difficult. This is due to the intermittent nature of renewable power generation. To operate a power system in a stable way, electricity needs to be consumed when it is generated. Several solutions have been proposed in the past to overcome the load-generation mismatch problem like storages and over-installation [3][4] or transmission grid extensions [5].

We model generation from global reanalysis data with a spatial resolution of ca. 70 km for 10 years with hourly temporal resolution for the renewable sources wind, photovoltaics (pv), concentrated solar power (csp) and hydro.



Together with modelled load data we simulate flows in the power grid using a common DC flow approximation for the AC power flow equations.

From this we compute infrastructure estimates for a global fully decarbonized power system.

II. RESULTS AND CONCLUSION

In this work we calculate the backup energy, backup power capacity, transmission capacity and storage reservoir capacity needs for this fully renewable (with generation on average equal to load) global power system and discuss the found infrastructure estimates and the benefits of such a global system.

We show that a global electricity system has the potential to reduce the requirements for backup and storage to a large degree compared to the isolated nodes.

We analyze the interplay of the investigated renewable sources on the global scale and compute the infrastructural needs for transmission lines of such a electricity system (capacity and length).

ACKNOWLEDGEMENTS

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Fig. 1 Conceptional scematic overview of a global electricity grid connecting the global load centers (indicated as unicolored superregions) with additional energy harvesting regions (pictured as green nodes).

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Session: Grid Integration, Storage and Reliability of Electrical Components

Experimental Set-up for Applying Wind Turbine Operating Profiles to the Nacelle Power Converter

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Keywords – Experimental set-up, Nacelle Power Converter, Reliability, Operating Profiles

I. INTRODUCTION

To meet EU renewable energy targets for 2020 and beyond, the Levelised Cost of Energy (LCoE) of offshore wind needs to be reduced to below £100/MWh [1]. Operation and maintenance (O&M) accounts for around 30% of this LCoE [2] and therefore research has focussed on understanding the reliability of components and their impact on the LCoE.

A number of turbine failure datasets have been examined [3] to find the components causing wind turbine failure. Control and electrical subsystems, such as the converter, have been the source of highest failure frequency. Furthermore, the datasets are based on mature onshore wind turbines where the number of power electronic devices is much lower than modern offshore turbines. Offshore turbines also have reduced accessibility, leading to higher downtimes from electrical subsystem failures. Therefore the number of failures due to power electronic devices is set to increase, with their respective downtime per failure also due to increase.

With power converters becoming reliability-critical, researchers have attempted to predict converter lifetime. This has been carried out using cycles-to-failure against insulated gate bipolar transistor (IGBT) junction temperature swing (ΔT_j) data [4]. However, whilst power module failure modes are well understood, manufacturing data is often produced at fixed ΔT_j [5]. This is not representative of how a converter is operated in the turbine [4]. Therefore harmful operating conditions may have their impact on reliability omitted.

To address this, an experimental rig is being designed which will apply the power converter under turbine operating conditions and monitor the impacts of operation on converter health. This paper details the outline of this rig.

II. METHODOLOGY

The rig is outlined as follows. An AC power supply will be controlled to apply wind turbine specific operational profiles on a device under test (DUT). These operational profiles have been determined by a previous work [6]. The DUT is switched to convert the AC input to DC and feeds a DC link. This DC link sinks the power back to the grid.

A Mitsubishi 1200V/35A IGBT converter was chosen for the DUT. Whilst this device is much smaller than the typical 1700V/1000A devices used in turbines, in terms of reliability the chip technology and packaging type are identical.

An AC power supply was used as, to date, turbine generator technology has not been standardised. Therefore, instead of using a generator in this rig, the generator output is emulated using a controllable AC power supply. This allows the rig to be easily modified to investigate the impact of different generator technology operation on converter health without changing the rig's construction.

The DC link has been modelled as ideal. This is as, in a typical wind turbine drive train, the machine-side converter (MSC) typically experiences a more varied operating profile compared to the fixed frequency grid-side converter (GSC). The MSC is consequently of greater interest for reliability analysis. Therefore, only the MSC is used as a DUT and the GSC maintained DC link is replaced with a constant voltage source.

III. CONCLUSION

Power converters are becoming increasingly important for turbine reliability analysis. However, whilst power module failure modes are well understood, manufacturing cycle data is often produced at fixed frequency and magnitude $\Delta T_{j.}$ To address this, an experimental rig is being designed which will apply the power converter under turbine operating conditions.

The experimental rig consists of a IGBT rectifier as the DUT, with an AC power supply emulating the turbine‘s generator and a DC sink to provide an ideal DC link.

Following rig commisioning the operatonal profiles of interest will be applied to the DUT. This will facilitate detailed anaylsis of reliability in a turbine-specific application.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Hybrid Classifier for Drift-like Fault Diagnosis in Wind Turbine Converters

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Keywords – Drift monitoring, Data mining, Drift-like fault detection, Multicellular converters, Wind turbine

I. ABSTRACT

Wind turbine converters are Discretely Controlled Continuous Systems (DCCS) since they switch between several discrete modes in response to discrete control events issued by a discrete controller. Faults in converters may impact significantly the availability and the production performance of wind turbines. These faults can occur as a gradual abnormal change in the values of parameters describing the system continuous dynamics in a discrete mode. In this case, they entail a drift in the system operating conditions until the failure takes over completely. Detecting this drift in early stage allows reducing the power production losses as well as the wind turbine unavailability and maintenance costs. However, this drift can be observed only when the system is in the discrete modes where the continuous dynamics described by the affected parameters are active. Consequently, this paper proposes an approach based on the use of a hybrid dynamic classifier able to monitor a drift in converter normal operating conditions in discrete modes where the continuous dynamics are impacted by a parametric fault. This allows keeping the useful patterns representative of the drift and therefore to detect it at an early stage. The proposed approach was applied to achieve a multiple drift-like fault diagnosis in the capacitors of a three cell converter using three different speeds of drift (high, moderate and slow). The drift indicators have detected successfully the drift, for these three speeds in early stage before its end for the both cases of simple and multiple faults scenario.

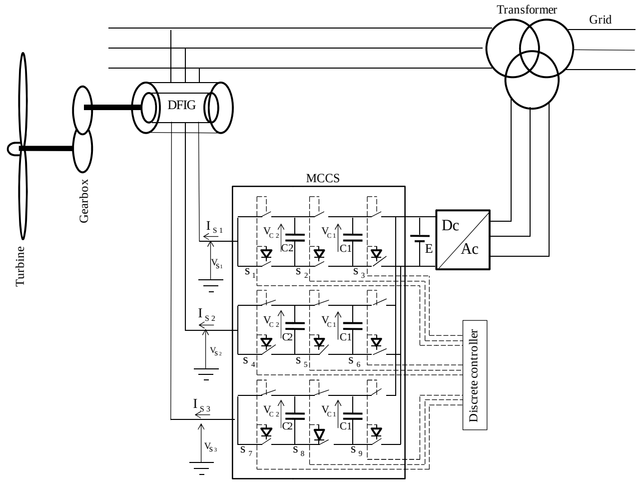

Fig.1 Architecture of the block DFIG-MCCS

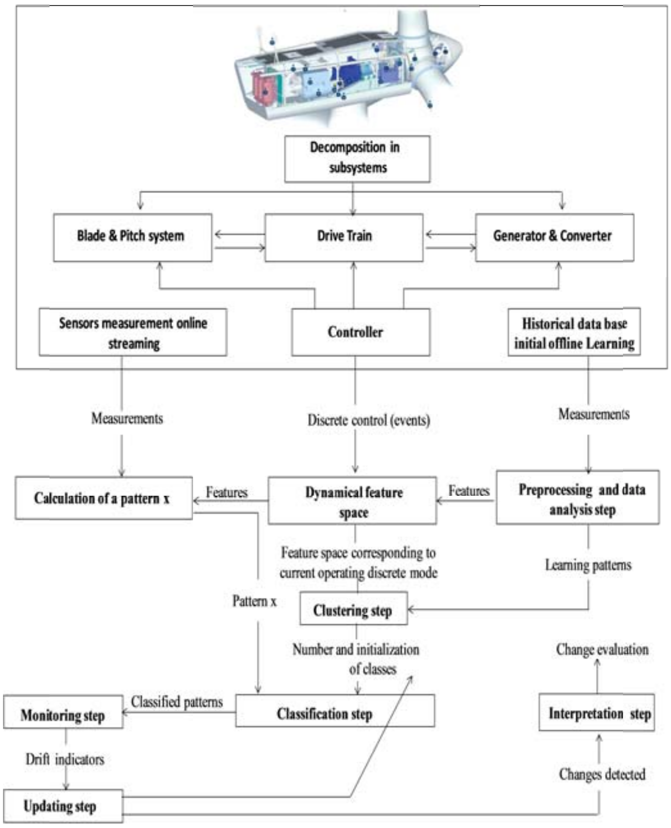

Fig.2 Proposed online self-adaptive scheme steps.

II. CONCLUSION

A hybrid classifier able to detect a drift in the normal operating conditions of the multicellular converter in each discrete mode based on dynamical feature space is realized. It is based on the monitoring of the drift of the characteristics of classes representing the normal operating conditions of converter in each discrete operating mode. Future work will focus on the estimation of the remaining useful life by using the patterns representing the drift (the degradation dynamics).

ACKNOWLEDGEMENTS

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Integrated high fidelity design optimization of wind turbines

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Keywords – Wind turbine, Rotor design, Integrated optimization, Multi-body dynamics, Aeroservoelasticity

The present work describes innovative methodologies for the integrated design of wind turbines, ultimately aiming at a cost of energy (CoE) reduction. The design process presented herein follows an industrial and certification approach and it is based on high fidelity aeroservoelastic models, which allow for a detailed design of the aerodynamic, structural and control aspects of a wind turbine. The design methodologies are applied to a conceptual 10 MW wind turbine representative of the next generation large offshore machines and to a 2 MW wind turbine representative of mid-size onshore machines.

I. INTRODUCTION

The design of wind turbines is a multi-disciplinary activity that requires the integration of optimization algorithms for the aerodynamic, structural, control and systems design. Such procedures make use of high fidelity simulation models, which can accurately predict the wind turbine response and capture the couplings among the different sub-disciplines. The most suitable global merit figure for such a design process is the CoE, which expresses suitable trade-offs among all various possible design choices [1].

II. DESIGN METHODOLOGIES

In recent years, Technische Universität München has been working in strict collaboration with Politecnico di Milano to develop automated tools for the holistic design of wind turbines [2]. The design tool Cp-Max (Code for performance Maximization), which is based on the high fidelity aeroservoelastic multi-body code Cp-Lambda (Code for Performance, Loads, Aeroelasticity by Multi-Body Dynamics Analysis), has been recently improved to optimize rotor diameter, hub height, rotor cone angle, nacelle uptilt angle, blade aerodynamic shape and blade and tower structures. Cp-Max is indeed now capable of optimizing the global configuration of the wind turbine aiming at a reduction of the CoE, which is computed from two sophisticated cost models, the INNWIND CoE model and the SANDIA blade cost model.

Following a recent interest in the literature, the possibility to design rotors with a lower aerodynamic efficiency has also been added, trading aerodynamic optimality for lower loading. Low induction (LI) configurations are obtained by a suitable aerodynamic design of the blade, together with a pitch offset design variable. The goal is to increase the rotor area, and therefore the power capture, without increasing the loads on the fixed structure of the wind turbine.

III. APPLICATIONS

A. *10 MW offshore*

Cp-Max has been used to optimize the design of a conceptual 10 MW machine designed by the INNWIND consortium. The identified global trend is to significantly upscale the initial design moving towards a larger rotor and higher hub height. This causes a significantly higher turbine capital cost, +33.7%, but also a massive increase of the annual energy production, +17.2%. Overall, the optimized design produces 7.0% of savings in terms of CoE.

B. *10 MW offshore low induction rotor*

A LI configuration of the INNWIND 10 MW machine has also been designed, achieving 1.8% savings in terms of CoE thanks to a 5.6% larger diameter. The limit of this solution is that only rotor thrust and the blade root combined moment could be constrained to the baseline values, while storm-driven components exhibited a load increase.

C. *2 MW onshore*

The presented design methodologies are currently being applied to a 2 MW machine. The goal is to explore and finally highlight the potential differences in optimal configurations, design drivers and trade-offs for the two rated power classes.

IV. CONCLUSIONS

This work presents the latest developments produced by our collaborative efforts for integrated high fidelity design methodologies of wind turbines. Applications to a 10 MW wind turbine are presented, highlighting two design options: a global design optimization that leads to CoE savings of 7.0% and a low induction rotor concept to limit loads on the structure. The work is currently being expanded to a 2 MW wind turbine.

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Aerodynamic scaling of a generic wind turbine blade for wind tunnel investigations

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Keywords – Aerodynamic scaling, wind tunnel model turbine, turbulence interaction

An approach for an aerodynamic blade design for a wind tunnel wind turbine model with a diameter of 1.8 m is described. The process is based on the well-known generic NREL 5MW blade design.

I. INTRODUCTION

In recent time numerical simulations of aerodynamics and aero-elastics are important tools for the research on wind turbine systems. Experiments provide valuable insight into flow phenomena and the interaction of the turbulent wind with the wind turbine, as is not entirely possible by simulation. Free field investigations evince the phenomena of interest, but the wind cannot be controlled and many influencing factors are unknown. In the controlled environment of a wind tunnel, conditions are widely known and the influence of a specific variable on the wind turbine system can be studied due to the repeatability of the experiment. Dimensions however are restricted by the wind tunnel and scaled wind turbine models are usually used for such investigations. A main consideration is the scaling approach for the rotor blade in regards to aerodynamics. Not all non-dimensional numbers can be maintained and so the scaling approach depends on the focus of the experiments.

II. METHOD

Here the main field of interest is the interaction of the turbine with the turbulent wind field. The design tip speed ratio is considered to be among the most important factors and is adopted from the NREL 5MW turbine, as described by Jonkman in [1], which is the starting point of the design. The tip speed ratio of the reference blade is maintained to enable a maximum level of comparability of the investigation's results to contemporary multi MW wind turbines, especially regarding the dynamic loads on the turbine blade in the turbulent wind.

The geometrical blade dimensions are scaled by a factor of 1/70 (0.9m/63m). The Reynolds number consequently is decreased by a factor of 1/70 and is of the size 10^5. It will be shown how power and load parameters change due to the scaling approach. The setup of the accordingly scaled model turbine is outlined including planned measured quantities that include tower bending moments, rotor revolutions and torque as well as blade root bending moments and angle of attack estimation at a radial blade station. Further the influence of the non-dimensional Strouhal and Froude number will be discussed.

The strong decrease in Reynolds number leads to largely stalled flow, if the original profiles would be employed for the model blade. Therefore the profiles are exchanged with thin low Reynolds airfoils, which provide a similar slope of glide ratio (C_L/C_D) over angle of attack. In detail two airfoils are used, the first for the inboard region with a relative thickness of 16 % and the second for the mid and outboard region with a relative thickness of 10%. Further the lift of the important second airfoil is rather low, so that the chord length is increased to maintain the scaled lift and thus the Reynolds number is increased.

The scaled blade design is investigated with BEM for the rotor parameters power coefficient and thrust coefficient and compared to the NREL 5MW rotor, as shown in Fig 1. These and further quantities will be discussed

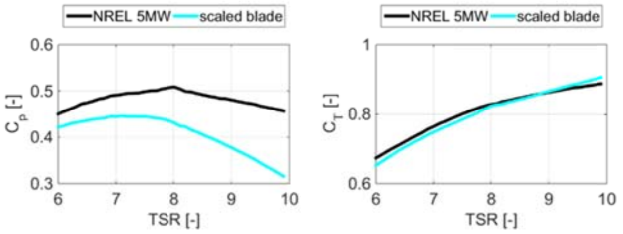

Fig. 1 Power coefficient C_p (left) and thrust coefficient C_T (right) over tip speed ratio (TSR) for the NREL 5MW blade and the scaled blade for wind tunnel investigations

On the basis of RANS CFD investigations of the rotating blade, with the software Star CCM+, a deeper insight is taken on the flow over the scaled blade at different operational states. In Fig. 2 streamlines are shown for operation at rated wind speed, indicating flow detachments at the blade root.

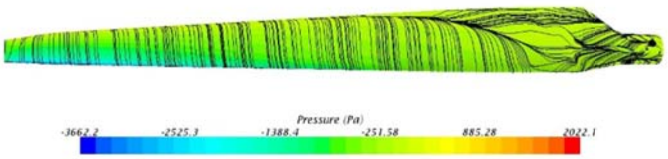

Fig. 2 Pressure distribution and velocity streamlines on suction side of the scaled blade design at rated wind speed

III. CONCLUSION

The wind tunnel investigations aim at a better understanding of the interaction of turbulent wind with a wind turbine system regarding aerodynamics and loads. The scaling approach for a small-scale wind turbine blade for these experiments is presented and investigated by BEM and CFD.

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Session: Rotor Design and Testing

2D-PIV Investigation of the Effects of Tip Injection on the Tip Flow Characteristics of a Model HAWT

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Keywords – HAWT, Tip injection, Active flow control, Tip vortex

I. ABSTRACT

This paper represents an experimental study which aims to investigate the effects of tip injection on the near tip flow characteristics of a Horizontal Axis Wind Turbine. Experiments are performed in front of an open jet wind tunnel facility using 2D Particle Image Velocimetry system. Two different injection rates and baseline measurements are compared in terms of tip flow field characteristics as well as power budget analysis. Results show that as injection rate increases, the characteristics of the tip vortex as well as the wake are changing significantly. In addition, only minimum injection case shows power efficiency.

II. INTRODUCTION

The effects of tip injection on a model wind turbine have been investigated by the authors and showed that it effects the tip flow field and tip vortex characteristics of the model wind turbine [1,2].

III. EXPERIMENTAL SETUP

The experiments are done at the exit of an open-jet wind tunnel which has a 1.7 m jet exit diameter (Fig 1). The model HAWT has a 0.95 m diameter 3-bladed rotor with NREL S826 profile and the blades have variable chord and twist distribution along the span.

Fig. 1: Experimental setup; Open-jet wind tunnel and the PIV system

The PIV measurement plane is an 8 cm x 12 cm grid. The PIV system consists of a 30 mJ Litron Nd: YLF laser and a Phantom V640 camera with a maximum resolution of 2560x1600 pixels at a frequency of 1.5 kHz. Measurements are performed at 742 Hz with Δt= 20 µs. Measurements are performed at 5 m/s wind speed, at TSR=5 and for two injection ratios in radial direction given in Eq. (1) at R_{TS}=1.16 and R_{TS}=3.26 and baseline case (no injection).

$$R_{TS} = \frac{U_{jet}}{\Omega R} \quad (1)$$

IV. RESULTS

Flow field measurements show that as it can be seen in Fig. 2. as injection ratio increases the trajectory and the strength of tip vortex change as well as the expansion and velocity characteristics of the wake also changes. Power budget calculation is given in Eq. (2)

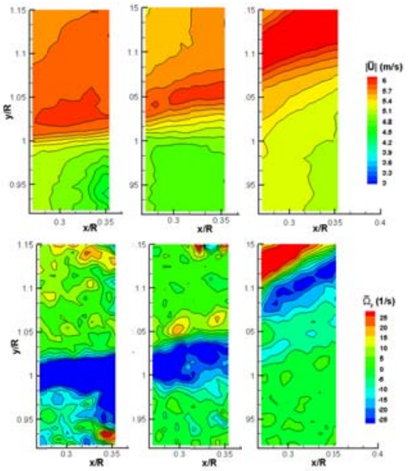

Fig. 2: Top row: Mean velocity contours; Bottom row: Mean vorticity contours from left to right: baseline, R_{TS}=1.16 and R_{TS}=3.26.

$$PB = \frac{(P_{INJ} - P_{BL}) - P_{jet}}{P_{BL}} \quad (2)$$

V. CONCLUSION

Tip flow field characteristics as well as power budget analysis have been performed for a model HAWT.

ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
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Session: Rotor Dynamics and Aerodynamics

Aeroelastic Stability Analysis of Large Composite Wind Turbine Blades

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Keywords – wind turbine aeroelasticity- Thin walled beam- Unsteady aerodynamic

Bending-twisting coupling induced in big composite wind turbine blades is one of the passive control mechanisms which is exploited to alleviate loads incurred due to the flexing of the blades. For the purpose of the study, the composite wind turbine blade is modelled as an elastic cantilevered rotating thin-walled composite box beam with the developed Circumferentially Asymmetric Stiffness (CAS) structural model. For the aeroelastic stability analysis, a proposed aerodynamic approach based on Theodorsen's strip theory (unsteady lift/ moment) and Loewy (returning wake) method are employed in conjunction with a structural model.

I. INTRODUCTION

The size of commercial wind turbines has increased dramatically in the last 25 years from approximately a rated power of 50kW and a rotor diameter of 10–15m up to today's commercially available 5MW machines with a rotor diameter of more than 120 m. This development has forced the design tools to change from simple static calculations assuming a constant wind to dynamic simulation software that from the unsteady aerodynamic loads models the aeroelastic response of the entire wind turbine construction, including tower, drive train, and rotor and control system.

A thin-walled beam (TWB) is a slender structural element whose distinctive geometric dimensions are all of different orders of magnitude such that its thickness is small compared to the cross-sectional dimensions, while its length greatly exceeds the dimensions of its cross-section. Sina et. al. [1] investigated the rotation effects in eigenvalue analysis of single cell-laminated composite TWB with closed cross-section. The effects of rotation, ply angles, taper ratio, slenderness, and hub ratios on natural frequencies and mode shapes of rotating TWB with flap–twist elastic coupling are studied.

Since wind turbines operate for most of their time in an unsteady flow environment, it is important for the analyst to recognize that many of the tools to model unsteady aerodynamic effects on airfoils have already been laid down.

Results for incompressible, unsteady airfoil problems have been formulated in both the frequency domain and the time-domain, primarily by Theodorsen, and loewy [2].

The main idea of the present work is to provide an accurate and reliable tool to determine the aeroelastic instability characteristics over the operating range for isolated rotor blades of wind turbine.

II. ROTATING THIN WALLED BEAM

The composite wind turbine blade is modelled as an elastic cantilevered rotating thin-walled composite box beam with the developed Circumferentially Asymmetric Stiffness (CAS) structural model. In the case of rotating composite TWB, CAS configuration leads to the decoupling between bending-twisting and extension-transverse shear. Circumferentially asymmetric stiffness structural model takes into account a group of non-classical effects such as the transverse shear, the material anisotropy and warping inhibition.

III. UNSTEADY AERODYNAMIC

The unsteady aerodynamics is based on Loewy's theory. Loewy postulated a two dimensional model representing the aerodynamic of an oscillating rotary wing airfoil operating at unsteady incompressible flow in terms of Hankel functions where the effect of the spiral returning wake beneath the rotor is taken into account approximately. In The Loewy function the shed wake wraps along an infinite line and discretely shifts downwards instead of converting downstream. This downwards shift accounts for the rotor inflow.

IV. CONCLUSION

In this study, aeroelastic stability analysis results with respect to the variation of structural parameters such as fibre angle will be presented for varying rotational speed and inflow velocity. Moreover, results of the classical aeroelastic stability analysis approach will be compared with the results of the overspeed analysis that will be performed in the wind turbine multi-body simulation code PHATAS which uses unsteady BEM method as the aerodynamic solver.

ACKNOWLEDGEMENTS

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Wind turbine with iced blades: Stability analysis of coupled blade's in-plane and tower motions

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Keywords – Stability, wind turbine, icing

I. ABSTRACT

Wind turbines have a self-excited instability due to interaction between tower and blade in-plane vibrations (lead-lag) [1]. The rotational speed at which instability occurs depends on the structural properties of the blades and the tower. Wind turbine blade's aerofoil cross sections are twisted and tapered along the length whose mass density decreases from the root to its tip. Icing on the blades changes this distribution influencing stability behaviour of the coupled tower and blades lead-lag motions. This study highlights how the structural changes in the blades due to icing alone can influence stability of the NREL 5 MW model wind turbine. Different ice mass distributions are assumed along the length of the blades to study stability of the coupled tower and blades lead-lag motions. Instability doesn't exist for the case without icing on the blades, whereas a linearly increasing ice mass equal to 30% blade mass in the lower half of all the blades causes instability to occur at 74 rpm. However this instability speed is far away from the rated speed (12.5 rpm) of this turbine. Icing on the blades will initiate instabilities which occur at earlier speeds with increasing ice mass.

II. INTRODUCTION

Rotating bladed systems can be studied using rigid and flexible beam models [2,3]. In case of rigid beam models, flexibility is modelled using torsional springs attached at the blade root and vibration behaviour is studied for equivalent inertias calculated about the blade root [2]. In case of flexible beam models, linear and nonlinear bending theories of rotating beams are used to study their vibration behaviour [3]. In the present work, NREL 5 MW model wind turbine's [4] tower and blades are modelled using linear bending theory of non-rotating and rotating beams. As the rated speed of this turbine is less than the first bending natural frequencies of the tower and blades, mode superposition method considering first two bending modes of a simple cantilever beam are used to approximate their vibrations [3].

Tower experiences collective effect of all the blades. Interaction between rotating and non-rotating structures can be considered in the coupled equations of motion (EOM) using coordinate transformation of the rotating blade vibrations to multi-blade coordinates (MBC). MBC transformation models collective blades vibration in the stationary frame of reference. After the MBC transformation for a three bladed rotor, blade vibration degrees of freedom (DOF) are changed to collective, progressive and regressive modes [1]. Eigen values of the system matrices (transformed to MBC coordinates) calculated at different rotational speeds reveal stability characteristics of the wind turbine structure. Campbell diagram and modal damping of this model wind turbine data are shown in Fig. 1(a) & (b) in which no instability exists in the speed range of 0-100 rpm. Stability behaviour changes with ice mass, for a case with linearly increasing ice mass (in the lower half of the blade length) equal to 30% of blade mass, Campbell diagram and modal damping are shown in Fig. 1(c) & (d). Instability exists between 74-79 rpm range for uniform ice mass on all blades which can be identified from the positive real part of the eigen values in Fig. 1(d). This study only considers change in mass properties of the blade due to icing. Uneven ice mass distribution on the blades and effects of icing on aerodynamic damping can further change the rotational speeds at which instability occurs.

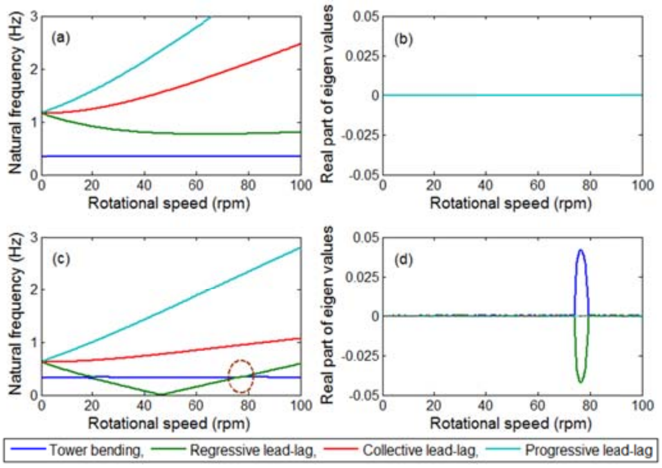

Fig. 1 Campbell diagram and real part of eigen values (a) & (b) No ice, (c) & (d) 30% ice mass,

III. CONCLUSION

Structural changes in the wind turbine blades due to icing initiate instability in the coupled vibrations of the blades and tower. The rotational speed at which instability occur advances with increasing ice mass. More icing in the lower part of the blades aggravates this instability.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Session: Rotor Dynamics and Aerodynamics

An Examination of Rotational Effects on Large Wind Turbine Blades

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Keywords – Rotational Augmentation, Stall Delay, Large Blades, CFD, Wind Turbine Aerodynamics

I. INTRODUCTION

The accurate prediction of wind turbine power and thrust remains challenging due to the flow complexity at the inner part of the blades. The difficulties come from the fact that rotation plays an important role on the boundary layer development under highly separated flow at the post-stall regime. The centrifugal force, which has a strong influence on the separated area [1], transports the flow in the radial direction from the root towards the middle region of the blade and the Coriolis force, due to radial flow component, acts as a favourable pressure gradient afterwards. The detailed mechanism of the flow physics is however far from being well understood and most investigations regarding to the underlying phenomena were focused on small stall-controlled wind turbines. The wind turbine size increases significantly nowadays and rotational effects are expected to be less important for these large wind turbine blades [2]. However, it should be kept in mind that the tip speed ratio of larger turbines is comparable with the smaller one [3], resulting in the congruous value of Rossby number, and this leads to the similar effects of rotation as consequence. Currently, information available on this matter is inadequate and deeper investigations are necessary. Therefore, the present work is addressed specifically to investigate rotational effects at the inboard section of the large wind turbine blades.

II. NUMERICAL CALCULATIONS

The unsteady numerical investigations of the flow over rotating blade have been conducted by utilizing the computational fluid dynamics (CFD) code FLOWer. The (URANS) *SST-kω* turbulence model was employed. Dual time-stepping was utilized to obtain second order accuracy in time. To show that the solutions are independent of the spatial resolution, grid convergence index (GCI) studies have been performed [4]. The 10MW blade from AVATAR project was chosen in the examination. The calculations were performed at the condition: $U_\infty = 10.5$ m/s and $n = 9.0218$ rpm. Uniform inflow condition has been selected to isolate the rotational effects from unsteady phenomena e.g. dynamic stall.

The simulations are validated against CFD results from the other project partners and a very good agreement was achieved in terms of predicted power and thrust. Fig. 1 shows that rotation enhances the lift coefficient (C_l) up to 40% of the blade span. The augmentation is dependent on the type of airfoils. The boundary layer code XFOIL calculations are included for comparison. Fig. 2 illustrates the flow field of the airfoils at 20% radial position for rotating (3D) and non-rotating (2D) cases. The Coriolis force delays the separation with a significant reduction in the wake size, which in turn stabilizes the flow and augments the lift coefficient [2,3].

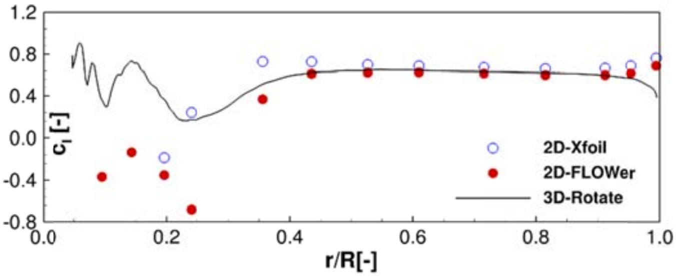

Fig. 1 Averaged 3D and 2D lift coefficients.

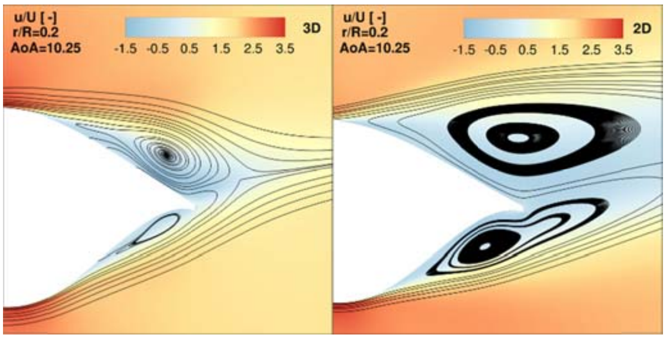

Fig. 2 Averaged flow field for 3D (left) and 2D (right) cases.

III. CONCLUSION

An investigation of rotational effects on large wind turbine blades has been conducted. The rotation plays an important role only at the inner part of the blade and the resulting forces are airfoil dependent. The evaluation of the flow field leads to a better understanding of the origin of rotational augmentation. The detailed flow physics of the underlying phenomena will be discussed more in the present paper.

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An integral boundary layer method for modelling the effects of vortex generators

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Keywords – passive flow control, vortex generator, integral boundary layer, flat plate, RFOIL, PIV

In this work, the measured modulated integral boundary layer (IBL) characteristics of low-profile vortex generators (VGs) are used to validate new developments in a viscous-inviscid interaction code which is modified to incorporate the effect of the passive mixing devices. The motivations are laid out and sample validation data is presented within this abstract.

I. PROBLEM STATEMENT

An imperative part of every wind turbine design process concerns the integrated design of the airfoil/blade sections. Despite the increased use of Computational Fluid Dynamics (CFD) for airfoil performance evaluation, the cost of capturing the influence of blade add-ons remains prohibitively high. A more efficient, robust approach is thus sought using an integral boundary layer approach.

II. BACKGROUND

In recent years, increased experimental research has shed light on the flow physics of vortex generators i.e. the interplay between the stream-wise vortices and the encompassing boundary layer. Modelling work has been mainly limited to the modification of CFD based codes to incorporate the effect of VGs. However, recent findings by Velte et al. [1,2], also seen in Baldacchino et al. [3] show that embedded stream-wise vortices may exhibit useful analytical and self-symmetric properties, as shown in Fig. 1. It remains to be seen though how these new physical insights can be coupled with existing numerical codes or formulated in such a fashion so as to practically improve airfoil design codes and routines.

III. METHODS

An initial approach is to modify the formulation of the turbulent shear stress production at the location of the VG trailing edges in the boundary layer formulation, according to

$$\tau_{vg} = \begin{cases} 0, & \forall\, x < x_{vg} \\ A.\,exp^{-\sigma(x - x_{vg})}, & \forall\, x > x_{vg} \end{cases}, \qquad (1)$$

indirectly capturing the presence of the VG. A second approach seeks new scaling laws for actuated boundary layer profiles. For this, high resolution Particle Image Velocimetry measurements performed in [3] for low profile VGs are used. This data will be partially used to validate the implemented code modifications. Sample results for the controlled axial velocity profiles are shown in Fig. 1 and the 3D nature of the boundary layer development is shown in Fig. 2.

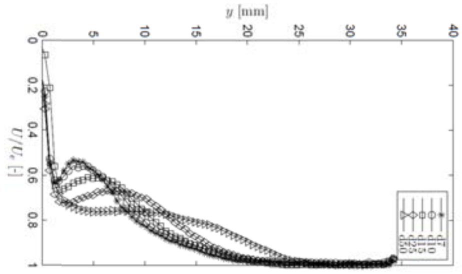

Fig. 1 Typical wake-like axial velocity profiles downstream of the VG, extracted from the span-wise location of the vortex core position

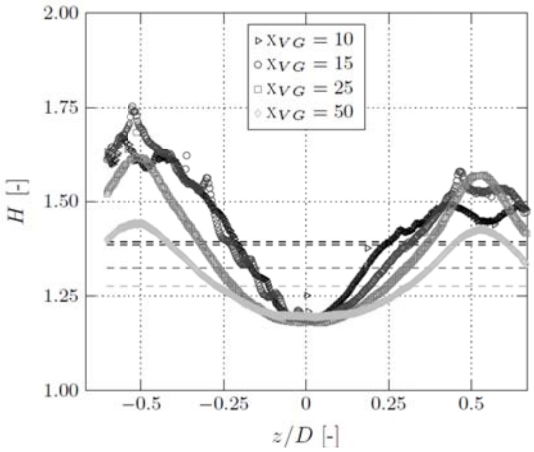

Fig. 2 Span-wise variation of the actuated boundary layer shape factor over a VG-pair span at four different streamwise locations.

IV. CONCLUSIONS AND NEXT STEPS

The final paper and presentation will discuss results comparing the newly implemented modelling scheme in the in-house RFOIL code, compared with current flat plate experimental data. Comparisons will also be made with the DU-range of wind turbine airfoils sporting vortex generators, which have been measured in previous experimental campaigns at the TU Delft low turbulence wind tunnel [4].

ACKNOWLEDGEMENTS

This work is part-financed by the European FP7 AVATAR project.

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How different turbulent inflow conditions affect wind turbines – an experimental approach

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Keywords – Model Wind Turbines, Active Grid, Turbulence

Modern wind turbines operate within the atmospheric boundary layer (ABL). Therewith, they are exposed to complex, turbulent wind conditions, whose characteristics significantly impact their performance. A proper analysis of these flow characteristics reveals that they feature highly intermittent, non-Gaussian statistics, which are currently not accounted for in industry standards [1]. These intermittent statistics have a big impact on the wind energy conversion process, as they lead to heavy fluctuations in mechanical loads, which are considered to increase wind turbine failure rates [2]. Further, it can be shown that for small time scales (1Hz) these intermittent characteristics remain evident in the power output of wind turbines and even of entire wind farms [3]. Thereby, strengthening the importance of understanding the impact of turbulence on wind turbines. Still, information about the flow characteristics that significantly effects wind turbines is not captured by an industry-standard description of turbulence.

As proper modelling of turbulence remains problematic within CFD simulations and suitable data from field measurements is rare, our approach is to scale down the situation in the field to the laboratory for experimental investigations on the impact of turbulence on wind turbines.

We present wind tunnel tests using a model wind turbine exposed to different turbulent inflow conditions, which are created using an active grid for flow manipulation. This setup gives the possibility to precisely tune single parameters of (i) the inflow characteristics and (ii) the turbine parameters in a controlled environment. This allows an isolation of single effects to gain a better understanding of the impact of different turbulent flows on wind turbines.

The model turbine used has a rotor diameter of 0.58m and encloses a torque- and pitch control system. In this study, the considered variables are the power output, torque, and thrust force of the turbine.

The active grid, which is shown in Fig. 1, allows the creation of custom flow conditions in the wind tunnel, ranging from very low turbulence intensities to numerous different turbulent characteristics. Therewith, different wind speed time series that vary in their statistical description can be created and reproduced in the wind tunnel. Upstream of the model wind turbine, a hot wire probe records the apparent wind speed simultaneously with the turbine's parameters.

The main focus of this study is the statistical analysis and comparison of the turbine data during different turbulent inflow conditions. More precisely, we compare scenarios whose differences are not captured by an industry-standard classification of turbulence. Therewith, we show to what extent intermittent flow characteristics impact the wind turbine.

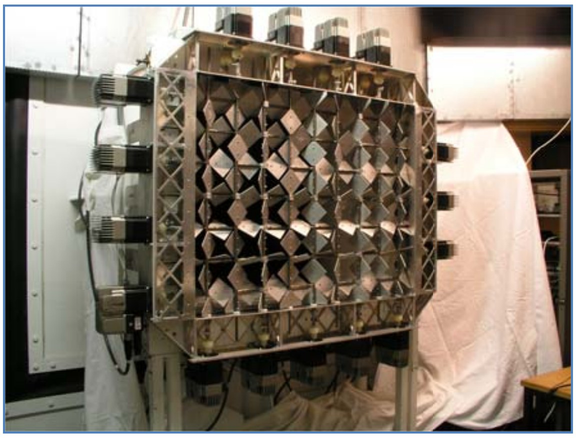

Fig. 1 Photograph of the active grid in the wind tunnel of the University of Oldenburg. Stepper motors control 16 vertical/horizontal axis equipped with square plates for flow manipulation.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Statistical Extrapolation Methods for the Estimation of Offshore Wind Turbine Extreme Loads

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Keywords – Offshore Wind Turbines, Measurement Data, Extreme Loads, Load Extrapolation

Probabilistic methods allow the prediction of long-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 Adwen wind turbine AD5-116 with a tripod foundation located in the offshore wind farm alpha ventus [2] is available. More than three years of high resolution 50Hz 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 loads of an offshore wind turbine and compare them to extrapolated loads obtained from simulations.

Unlike simulated loads, measured loads need to be elaborately processed before performing load extrapolations. This procedure includes among others calibration and visual inspection of the data. Furthermore the measurement data is restricted to specified conditions such as power production or freestream in order to be able to make comparisons with simulations afterwards. The difficulties that arise when using measured instead of simulated loads for extrapolation purposes will be discussed.

Once a reliable data base is established, the maximum values, which will be used for the extrapolation, can be obtained by using different methods such as the global maximum method or the peak over threshold method. The results presented here are based on global maxima.

A study on the selection of the distribution function (e.g. Gumbel, Weibull) as well as the choice of the fitting method (e.g. Method of Moments, Maximum Likelihood Method) will be performed.

An exemplary short-term extrapolation of the fore-aft tower base bending moment is shown in Figure 1. Depending on the choice of the distribution function the expected 50-year maximum load varies significantly.

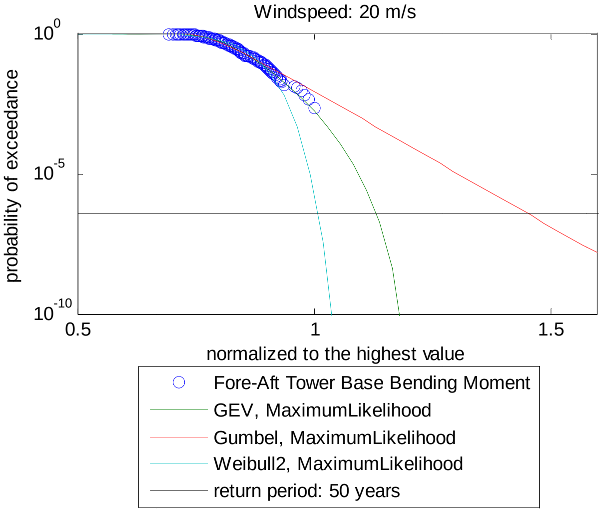

Fig. 1 Example of a short-term extrapolation using different distribution functions.

Based on the results of this PhD project specific recommendations for the extrapolation of extreme loads of offshore wind turbines are to be made.

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Towards monitoring the consumed fatigue life of fleets of offshore wind turbines

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Keywords – Fatigue, Lifetime assessment, Monitoring

The main goal of the current research is to develop a novel methodology that can assess the consumed fatigue life of an entire wind farm and will serve as a support tool for end-of-life decisions and asset management for both onshore and offshore wind farm owners.

The proposed fatigue monitoring approach is to instrument a limited number of turbines, so- called fleet leaders, and extrapolate the measurements to the other turbines in the farm using empirical models based on structural information, meteorological and SCADA data.

I. MAIN BODY

The measurement campaign is performed at the Northwind wind farm, which consists of 72 Vestas V112 3MW wind turbines. The wind farm is located in the North Sea, 37 km off the Belgian coast. The campaign started in 2014 and is currently still ongoing.

For the current campaign two turbines, situated at the outer edges of the farm, were instrumented with accelerometers and (optical) strain gauges to closely monitor their dynamic behavior. Data is transferred continuously to an onshore server and is processed on a daily basis.

The current setup allows determining the resonance frequencies, damping ratios [1] as well as the bending moments at the Transition piece (TP) - Monopile interface and at the tower-TP interface. More importantly the setup also allows monitoring the consumption of fatigue life and the calculation of damage equivalent loads at the aforementioned interface connections. As a result this ongoing campaign has produced a database of over 50.000 instantaneous fatigue rates at different locations for each turbine.

Future developments such as virtual sensing will assess fatigue life at other fatigue-critical locations such as at the mudline [2].

While these results are very relevant for the fatigue assessment of the instrumented turbine, the results need to be extrapolated to the other turbines in the farm. To achieve this goal the monitored fatigue life is first analysed for different operational cases (e.g. parked or rated power) and then modelled case-by-case using the available SCADA and meteorological data at the site. As two turbines are instrumented, the found model is validated by predicting the fatigue life consumption of the other fleet-leader and comparing these predictions to the actual measurements. In the final step the validated model allows to extrapolate the results to the entire wind farm.

II. CONCLUSION

This contribution aims to illustrate the behaviour and progression of fatigue life in an offshore wind farm. A methodology to use the measurements of a limited number of instrumented turbines, so called fleet-leaders, and available SCADA, meteorological data and structural information to model the progression of fatigue life was introduced and evaluated on two instrumented turbines in a Belgian offshore wind farm.

Key parameters that need to be taken into account are the different operational conditions of the individual turbines as well as environmental parameters such as the turbulences in the farm.

The developed methodology will allow to perform a data-driven fatigue assessment of an entire wind farm and serve as a valuable tool for decision support.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Session: Wind Farm Control

Detection of Partial Wake Impingement for Wind Farm Control by Analysis of Rotor Loads

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Keywords – Wind Farm Control, Wind Speed Sensing, Wake Detection

Wind turbines extract energy out of the wind flow and thereby leave behind them a wake characterized by a reduced wind speed and an increased turbulence intensity. In certain conditions within a wind farm environment, turbines may be affected by the wake of upstream machines, an interaction that typically results in reduced power output and increased fatigue loads. Wake mitigation or redirection performed by a wind farm controller may reduce these undesired effects [1]. For any such control logic to be effective, it is crucial to know the flow conditions within the wind farm. A main objective of this PhD project is to develop techniques for utilizing the rotor of each turbine as a wind sensor [2], by measuring wind characteristics as well as detecting potential wake impingements. Together with flow and wake models, those measurements can then be deployed by a closed loop wind farm controller for better energy capture and reduced fatigue loads.

The work presented herein proposes an estimation of the mean wind speed at the position occupied by each blade, based on the blade root bending moments. Those estimates are then used to detect a wake impingement condition on either side of the rotor disk.

I. METHODS

Based on a wind turbine simulation model, an out-of-plane bending coefficient is defined that correlates the non-dimensional blade root out-of-plane bending moment to the mean wind speed at the blade location. Based on this information, a mean wind speed in different sectors of the rotor disc, termed here sector effective wind speed (SEWS), can be estimated. Using as sectors the left and right quadrants, the wind speed estimates on the two sides of the rotor are finally compared to detect a partial wake impingement.

In a simplistic wind farm model, two 3MW turbines are placed with a longitudinal distance of 4D and a variable lateral distance for obtaining different wake conditions. The wake impingent on the downwind turbine is simulated by a high fidelity multibody dynamic model. The wake inflow is modelled by a superposition of Mann's turbulent wind field with the wind speed deficit provided by the Larsen wake model.

II. RESULTS

The wind speed estimates in the two horizontal sectors of the downwind turbine are shown in Fig. 1. Each subplot represents a different wake overlap indicated by the title showing the lateral distance between rotor and wake center. At a lateral distance of ±1.25D the turbine is more or less operating outside the influence of the wake and accordingly the estimated wind speeds have equal magnitude. Between -1D and 0D the wake center is impinging the left sector and the wind speed reduction due to the wake is evident. That deficit is also well captured by the wind speed estimator. Based on those estimates it is possible to detect a partial wake overlap between 0.75D and 0.25D on either side of the rotor disk.

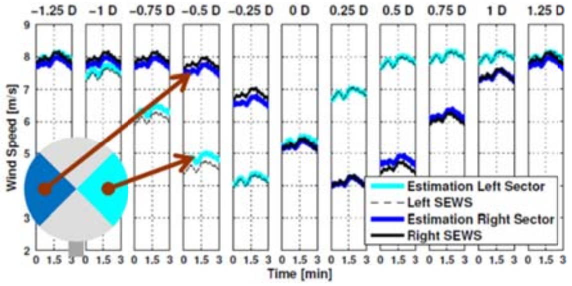

Fig. 1 Estimation of the wind speed in two lateral rotor sectors for different wake impingement conditions.

In addition to simulation studies, the estimation of the SEWS is validated by evaluation of field measurements from the NREL CART3 wind turbine. A nearby met-mast is chosen as wind speed reference. Because it only provides measurements at different heights, the wind speed estimations of the vertical sectors are compared with the met-mast reference. The results show good correlation between met-mast and wind speed estimates, although in this case with reference to a vertical (rather than horizontal) shear.

III. CONCLUSION & OUTLOOK

The presented method of using blade loads for wind speed estimation and wake impingent detection shows promising results in a preliminary simulation study. The method of estimating the mean wind speed in different sectors of the rotor disc is also validated through field measurements. For a more realistic wake inflow assessment, high fidelity LES simulations using NREL's SOWFA code are currently being prepared. It is further planned to validate the impingement detector together with a wind farm controller in a scaled wind farm in a wind tunnel environment, where the ambient wind conditions are more easily determined than in the field.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Session: Wind Farm Control

Lidar – a measurement tool for wind farm control

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Keywords – wind farm control, lidar, wake control

With the growing size of wind turbines and a growing density of installed wind power the interactions between different wind turbines and beyond that between wind farms are getting more and more important. In the past, a lot of investigations have been made to improve a single wind turbine in its aerodynamics, its structural dynamics, and its control towards a smart wind turbine. Nowadays, wind turbine interactions are gaining more and more importance not only because of the reduced power production of wind turbines in a wake but also because of the increased structural loads. Thus, investigation in wind farm dynamics are necessary to understand the main dynamics in coupled system of wind turbines.

I. APPROACH

Thus, in this contribution an insight in wake tracking is given. Wakes are the characterizing interactions between wind turbines and therefore finding adequate methods to describe them in a control fashion helps to reduce the interaction either e.g. by redirecting them or by mitigating their influence.

In this work a method is presented which uses lidar measurements to characterize the wake and its direction. The method uses the internal model principle and a wake description to best fit the model to the measurements within an optimization approach.

Therefore, the measurement system and the waked wind field is modelled dynamically. A kernel function is used for describing the wake propagation and the mixing of the wake. The wake of a 5 MW offshore wind turbine is tracked and the results are presented and evaluated with respect to wind farm control ideas. Figure 1 shows an exemplary reconstruction with the model in the top row and the measurements in the bottom row.

II. CONCLUSION

This approach enables to track the wake centerline and to get further properties of the wake and can be a first step into model based wind farm control where the wake could actively be controlled.

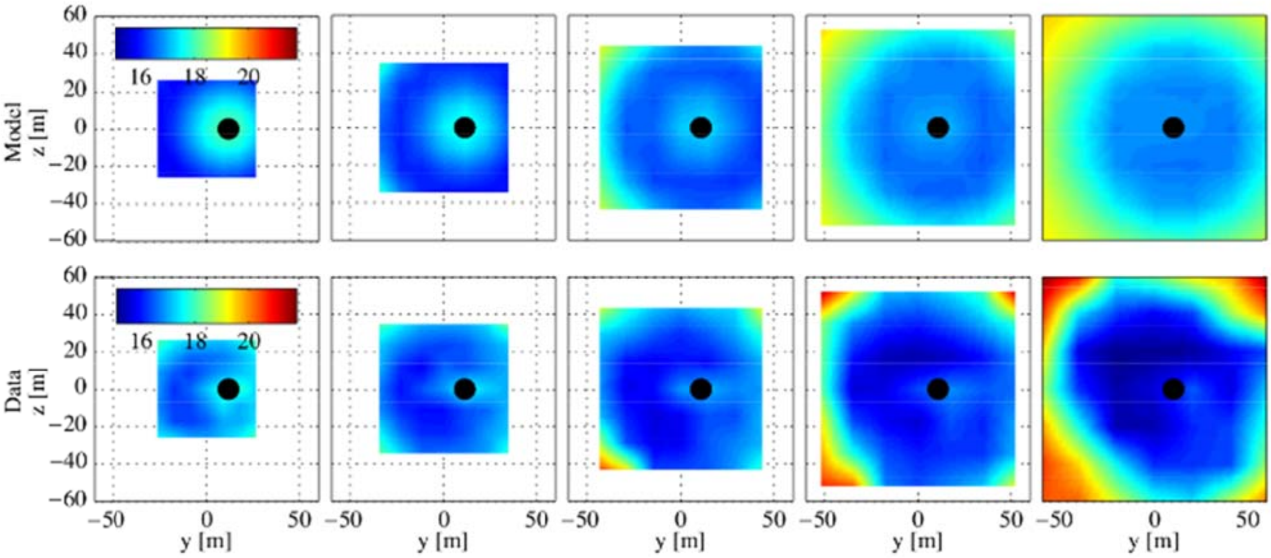

Fig. 1 Model based wake tracking using lidar measurements in five distances within the wake of the wind turbine. The first row shows the identified model, the second row the measurements behind the wind turbine in the wind field.

11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
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Dynamic Wind Farm Controller

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Keywords – Wind Farm Control, Coordinated Control, Particle Swarm Optimisation, Power Maximisation

This work presents a wind farm controller based on Particle Swarm Optimisation (PSO) for maximising power output of the farm. The controller uses a coordinated control approach where output of the upstream turbines is varied for minimising wake effects on the downstream turbines. The speed deficit due to wakes is calculated using the Jensen wake flow model. This model gives wind speed at different locations in the wind farm. PSO is used to generate different sets of coefficient of power for all the turbines and select the one which results in maximum farm output.

I. INTRODUCTION

Wind turbines are installed together in wind farms to take advantages of economy of scale. However, installing turbines together creates aerodynamic interactions among them in the form of wake effects. Due to wakes a wind farm will produce less power than a similar number of isolated turbines.

Conventionally wind turbines in a wind farm extract maximum possible energy from the wind without considering the wake effects on downstream turbines. This will not always result in maximum farm output. Therefore wind farm controllers need to be developed for coordinated control. The farm controller would provide reference points - coefficients of power, to the turbine controllers and the turbine controllers have to follow those reference points.

The aim of this work is to develop a fast farm controller with enough accuracy for maximising the total wind farm output with realistic assumptions. The proposed controller uses the Jensen wake flow model [1] for wind speed deficit calculation and PSO [2] for maximizing the farm output.

II. PROBLEM FORMULATION

The total wind farm power is the sum of individual wind turbines' output. The output of a wind turbine is given by Eq. (1).

$$P_{Turbine} = \frac{1}{2}\rho A u^3 C_P \tag{1}$$

Total wind farm power with N number of turbines is given by Eq. (2), i being the turbine under consideration. Wind speed at turbine i is given by $u(i)$ and the corresponding coefficient of power is $C_P(i)$. The free stream wind speed is assumed to be below rated.

$$P_{Farm} = \sum_{i=1}^{N} P_{Turbine\,(i)} = \sum_{i=1}^{N} \frac{1}{2}\rho A u(i)^3 C_P(i) \tag{2}$$

Now, if all the turbines are operating in free flow conditions with no wakes and at their maximum $C_{P\,(max)}$, the maximum achievable combined output is given by Eq. (3).

$$P_{Farm\_Free\_Flow} = \frac{1}{2}\rho A \sum_{i=1}^{N} {u_0}^3 C_{P(\max)} \tag{3}$$

The optimisation problem is to minimise the difference between Eq. (2) and Eq. (3). Ignoring the constant terms - $\frac{1}{2}\rho A$, the objective function becomes as give in Eq. (4).

$$\sum_{i=1}^{N} {u_0}^3 C_{P(\max)}\,(i) - \sum_{i=1}^{N} u(i)^3 C_P(i) \tag{4}$$

III. RESULTS AND DISCUSSION

An example array of 7 wind turbines is simulated using the proposed controller. All the turbines are assumed to be NREL 5MW turbines. The turbines are assumed to be located in a straight line with a distance of almost 3D between them. The free stream wind speed is assumed to be 15 m/s. Maximum wake interaction is considered assuming that the wind direction is parallel to the turbine array. The proposed controller could produce 2.2% more than the conventional control with these settings.

PSO provides a solution with less than 2 percent of the global optimum value. The particles take 20 iterations on average to find an optimum value as can be seen in Fig. 1.

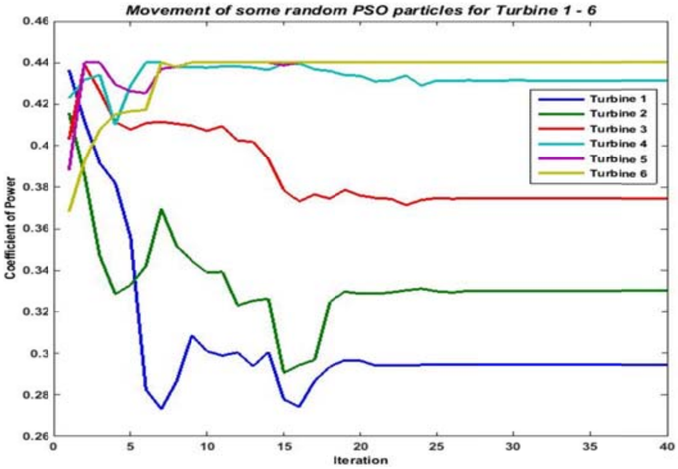

Fig. 1 Movement of PSO particles towards optimum Coefficients of power

The results are validated with data from Brazos wind farm Texas. An increase of up to 3% is achieved when the wind flows in crosswind direction.

IV. CONCLUSION

A PSO based wind farm controller is presented for maximising the wind farm output with coordinated control of the turbines. T. It is found that an increase of up to 3 percent could be achieved with this controller for the assumed example wind farm. Results are validated with data from the Brazos, Texas wind farm.

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Poster 1

Lift Force Control of a Stand-Alone Airfoil

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Keywords – Wind energy, lift force control, MPC, Hammerstein model, variable angle of attack

This paper presents a new concept for the control of the lift force of a single airfoil, using Galerkin method and Model Based Predictive Controller (MPC).

I. INTRODUCTION

The last decades have faced a big increase in the installed capacity of wind turbines, motivated by the need for sustainable energy supply and reduced greenhouse gas emissions [1]. Along with this growth comes the challenge of decreasing the cost of energy by e.g. increasing the efficiency of wind turbines. When thinking about optimizing the efficiency of a wind farm the aerodynamic interactions between single wind turbines have to be considered [2]. This research aims to combine MPC with Galerkin model reduction method to control such aerodynamic interactions. In order to develop and validate the proposed method, a fundamental experiment with two interacting airfoils is chosen.

This paper describes the first step of this research, which consists of using the proposed control strategy to control the lift force of a single airfoil. Such primary investigation is necessary to understand the behaviour of a stand-alone airfoil and how it will influence the downstream airfoil [3].

II. LIFT FORCE CONTROL

The lift force of a rotor blade determines the rotor torque and hence the captured energy of the wind turbine and at the same time causes the mechanical loads. A constant lift force is desirable in order to output constant power and limit fatigue. The lift force is mainly determined by the angle of attack of the wind speed, and can be influenced by rotating the airfoil about the axis along the blade (pitch) [4].

The lift force control loop is shown in Fig. 1. It consists of a MPC that governs the pitch angle using a lift force reference and the current lift force.

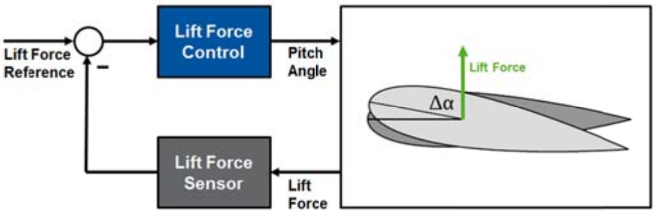

Fig. 1 Control block diagram of the lift force

III. EXPERIMENTAL SET-UP

The experimental study will be performed in a closed-return subsonic wind tunnel. The driving fan generates wind speed up to 30m/s in the test section of the wind tunnel. The flow is considered incompressible.

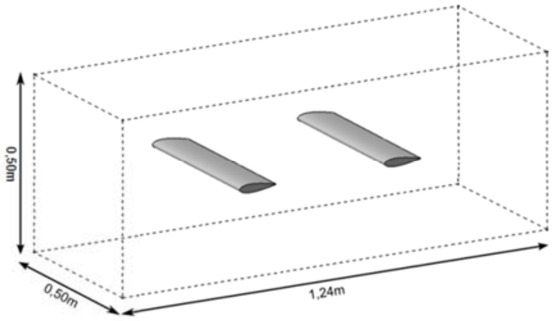

Fig. 2 Sketch of the up and downstream airfoils in the test section

The test section (Fig. 2) consists of two NACA 0012 [5] airfoils in a row. The upstream airfoil will extract a considerable amount of the kinetic energy in the wind and produce a non-uniform flow field for the downstream airfoil. The airfoils are connected with force sensors and motors at the walls of the test section, in order to measure the lift force and to vary their pitch angle.

IV. FUTURE WORK

In a next step the model used by the MPC will be capable of predicting the disturbance injected at the downstream airfoil. Furthermore the experimental set-up will be finished. Then the first experiments with a single airfoil in an empty wind tunnel test section can be performed, followed by experiments with the complete set-up. The controller will also be transferred to real-time hardware.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the supports offered from the RWTH Aachen University and from CAPES Scholarship No. BEX 8999/13-9.

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Poster 2

Steady and unsteady CFD power curve simulations of generic 10 MW turbines

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Keywords – Aerodynamics, CFD simulation, AVATAR reference wind turbine, DTU 10 MW reference wind turbine, power curve

I. MOTIVATION

One of the main focus points of today's wind energy research is the development of large Multi-Mega-Watt turbines of 10 MW to 20 MW size. This trend is driven by the ambition to reduce the overall cost of energy, which can be achieved by increasing the power output per turbine at moderate rise of manufacturing costs. Raising the rotor diameter is one promising way for attaining this goal.

However, the development of these novel turbines is connected to severe technical challenges. As simple up-scaling will lead to heavy-weight rotors, new design philosophies have to be applied. For the generic AVATAR [1] and DTU 10 MW [2] reference wind turbines the rotor weight was reduced by selecting thicker airfoils to increase the moment of inertia and therefore blade stiffness.

II. REFERENCE WIND TURBINES

The DTU 10 MW turbine has a blade length of 89.15m and was designed based on the FFA-W3-xxx airfoil family. At the inner blade region, a rigid Gurney flap was applied to achieve a higher aerodynamic performance [2]. The AVATAR rotor blade is 102.88m long and consists of different DU profiles. In terms of load reduction and wind farm aspects it is designed as low induction blade.

III. COMPUTATIONAL SETUP

The present work researches the aerodynamic behaviour of these turbines by means of CFD. Different operating conditions were investigated in a 120-degree model with periodic boundary conditions. The simulations have been performed using the CFD code FLOWer, which was developed by the German Aerospace Center (DLR) [3]. Steady and unsteady computations based on the Dual-Time-Stepping Scheme were conducted. For turbulence modelling the Menter-SST-model was selected and all simulations are performed fully turbulent without transition.

The simulation mesh consists of four separate grids for background, nacelle, spinner and blade, which are overlapped using the CHIMERA technique. Grid resolution was investigated in a convergence study which led to in total 15.42 millions cells for the AVATAR turbine and respectively 15.34 millions for the DTU 10 MW turbine.

IV. RESULTS

The power curve of the DTU 10 MW turbine is exemplarily presented in this abstract and compared to the results provided by DTU in [2]. In figure 1, a good accordance between the results by FLOWer and EllipSys3D can be seen.

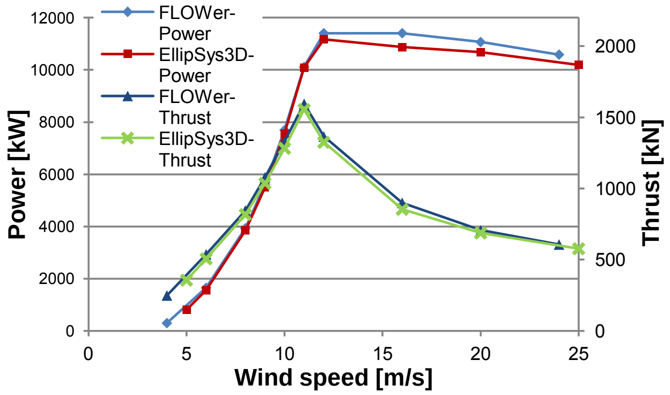

Fig. 1 Comparison of integral power and thrust for the DTU 10MW turbine

Results of the AVATAR turbine will be shown in the final paper. It will include a comparison of radial forces like sectional torque/thrust and the pressure/friction distributions. A comparison between steady and unsteady simulations will be shown.

V. CONCLUSION

Although integral power and thrust agree well, differences occur at the blade root. Large-scaled separation is dominant there resulting in load fluctuations.

ACKNOWLEDGEMENTS

For providing their resources the authors gratefully thank the High Performance Computing Center Stuttgart and the AVATAR project for funding.

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Poster 3

Numerical Analysis of a Sweep-Twist Wind Turbine Blade

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Keywords – Sweep-Twist, blade, CFD

ABSTRACT

Wind energy is being used to generate electricity in many countries all over the world and still the contribution of wind energy to electricity supply increases every day. Researchers work on innovative solutions to increase the efficiency and decrease the cost of wind turbines, especially those of blades. Various blade designs for different operation conditions are presented in the literature and sweep-twist blades are new type of blades introduced recently. This paper describes numerical investigation of the aerodynamics around a sweep-twist wind turbine blade using ANSYS-Fluent. NREL Phase VI wind turbine blade is used as the baseline blade and the sweep-twist blade is designed by adding 5% sweep of the chord length to the tip. The power output and results are compared to the experimental data of original NREL Phase VI blade.

Genetic Algorithm with Gradient Based Optimization for HAWT blade design

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Keywords – Airfoil, Genetic Algorithm, Gradient-based, Optimization, Wind turbine, aerodynamics, Boundary layer

ABSTRACT

The Gradient-based blade design method and airfoil optimization using Genetic Algorithm[1] have been incorporated to increase Horizontal Axis Wind Turbine (HAWT) blade performance.

The blade design method used in this study is called TMASO (Torque Matched Aerodynamic Shape Optimization method) [2]. It generated blade shapes by modifying chord and twist distribution.

TMASO received GA optimized airfoil profile and distributed them in a span-wise direction to calculate the rotor torque. This, in turn, will be compared to the drive torque that has been experimentally measured for minimizing the difference while targeting to maximizing the power coefficient (C_P).

Airfoils were parameterized by B Spline [3] in MATAB. The vertical points of the control points that forming the airfoil shape were set to be variable of GA. The objective function was fixed to have the maximum Gliding Ratio (GR) of the airfoils. After satisfying the best options of GA, the resultant airfoil is inserted into TMASO.

The superiority GA optimized airfoil was validated with comparing its performance with optimized blade using NREL S-series airfoil, S809. Figure1.

C_P values of wind turbine blade using GA optimized airfoil showed higher value than blade with S809. Figure2 Furthermore, transition position in boundary layer and separation of airfoils were also investigated for proving the efficiency of GA optimization.

ACKNOWLEDGEMENTS

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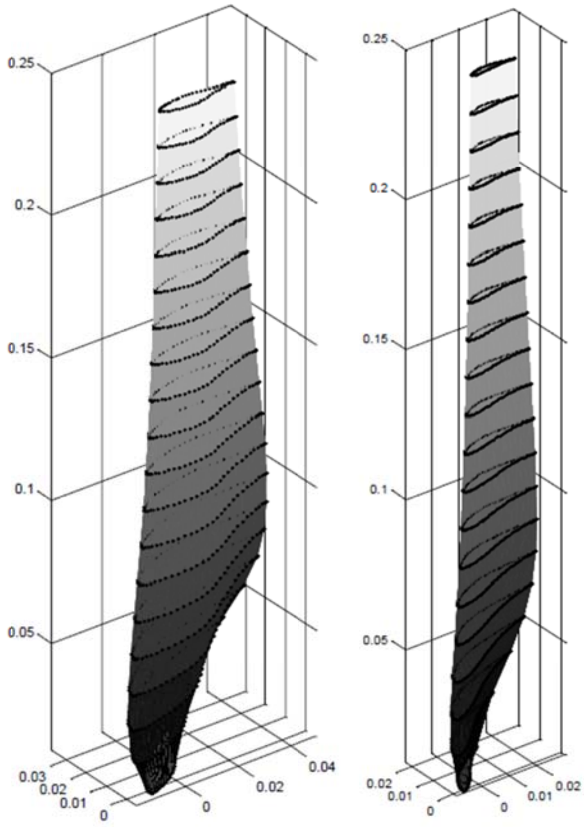

Fig. 1 Optimized wind turbine blade with airfoil S809 (left) GA airfoil (right) by TMASO method

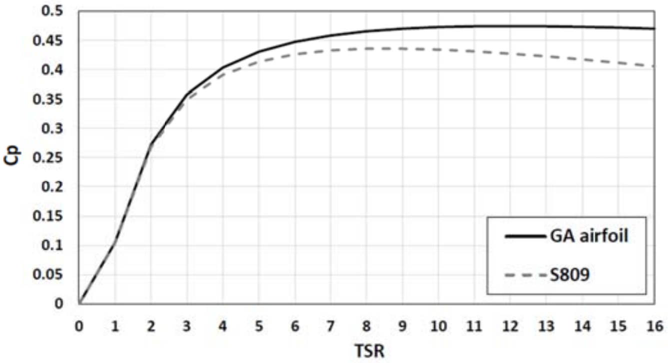

Fig. 2 Cp of optimized wind turbined with TMASO for different airfoils

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Poster 5

CFD simulation of a floating horizontal axis model wind turbine

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Keywords – CFD, model turbine, floating, offshore, wind tunnel, wave tank

Within the European INNWIND.EU project a floating platform for a horizontal axis 10 MW wind turbine is designed. A test campaign in a wave tank has been carried out to investigate the behaviour of the platform under operation conditions. For this purpose a Froude scaled wind turbine installed on the model size platform has been placed in the Ecole Centrale de Nantes (ECN), France, wave tank in the jet of a wind generator (Fig. 1). For validation purposes and to better understand the aerodynamics of floating turbines selected cases will be simulated using a full CFD approach.

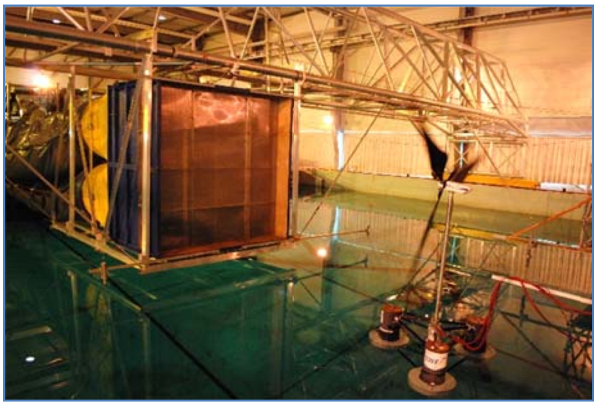

Fig. 1 The INNWIND model wind turbine in action (photo by ECN)

I. INTRODUCTION

Floating wind turbines have the best perspective to assess deep water offshore sites for wind energy production. To test the capability of the developed platform structure in the INNWIND.EU project, wave tank measurements have been performed at ECN. To consider the influence of the turbine correctly, a Froude scaled model rotor with a diameter of 2.8m has been installed on top of the platform. Due to high Reynolds number differences, the turbine was designed only to have a similar thrust as the full scale turbine. A special developed wind generator creates the flow on the wind turbine [1].

During the tests several sensors captured the time resolved position of the turbine as well as time resolved forces and moments. These will be analysed and used to define several load cases for the CFD simulation of the model wind turbine.

II. APPROACH

At IAG CFD simulations are carried out using the DLR developed structured finite volume code FLOWer. Thanks to a dual time stepping approach and the Chimera technique complex simulations of wind turbines can be performed using overlapping grids for all structures. Several points have to be considered to build up the simulation setup of the floating INNWIND model turbine. The blade Reynolds number is very low compared to the full scale rotor. As it is very challenging to consider laminar flow separation correctly, only fully turbulent simulations will be carried out. By using a one-third model of the rotor extensive studies on the behaviour under uniform inflow conditions can be done. The numerical setup has already been built up and uniform inflow simulations are performed, showing good convergence. Being located in the freestream jet of the wind generator the turbine might be influenced by the shear layer at the jets border, as its diameter equals approximately the diameter of the jet. Especially when moving in the waves, this influence seems not to be negligible and probably effects load fluctuations. Simulations with and without turbine will be performed to quantify these effects and to correctly consider them in further simulations.

For the simulation of the turbine with prescribed motion selected cases will be analysed to extract a short representative sequence of the motion. To consider all six degrees of freedom (DOF) the angles are converted to Euler angles so that they can be applied sequentially on the CFD simulation. Nevertheless some simplifications have to be done, as the influence of the waves on the flow can't be considered.

III. CONCLUSION AND RESULTS

The complexity to correctly simulate a floating model wind turbine has been shown. There are many parameters to be considered to reproduce the test environment appropriate. The jet of the wind generator must be simulated carefully, as the blade tips are located in or close to the shear layer at the jets border. The final task will be to simulate the model wind turbine in the environment of the wave tank applying a prescribed 6 DOF motion to gain further insight into the aerodynamics of floating wind turbines.

The paper will outline the approach more detailed and show first results of the numerical studies.

ACKNOWLEDGEMENTS

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Poster 6

Modal testing of a reinforced wind turbine blade

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Keywords – Wind Turbine Blade, Vibration, Stiffness

I. INTRODUCTIONS

The diameter of wind turbine rotors becomes larger to efficiently gain the power from the wind resources in the last decade. 60 meters or even longer blade's flexibility and dynamic behaviour is the imperative issue to be paid attention, as it may develop into instability leading to failure accidents [1, 2]. Two of the main reasons for the instability is the low damping ratio in the edgewise direction and low stiffness of the blade.

To enhance the blade's stiffness and introduce more damping to the blade, a novel design is proposed. The design composes rods mounting between the blades on the basis of original wind turbine rotor. The model of a single blade with rods is firstly investigated to find the effectiveness of the design. Hereby, modal testing method is adopted to obtain the frequency, damping coefficient and mode shape of the blade system, which forms the foundation for the dynamics behaviour of the blades [3].

The damping coefficient and frequency corresponding to relevant mode is compared between the original blade and the blade system with the rod. The tested results demonstrate that the rods mounted on the blade have obvious influences on the stiffness of the blade. In addition, introducing of the damping is possibly achieved in this design, on which aspects the study follows.

II. METHODS AND THEORETICAL BASIS

A. *Tested methods and principles*

Fig. 1 shows the novel design and test setup. Both the single blade from the novel design and the original blade system are tested. The modal parameters – frequency and damping coefficient - are deduced from [4].

$$h_{jk}(\omega) = \frac{x_j}{F_k} = \sum_{r=1}^{N} \frac{\psi_{jr}\psi_{kr}}{m_r(\omega_r^2 - \omega^2 + i\eta_r\omega_r^2)}, \qquad (1)$$

where h_{jk} is one element of matrix H_{jk} representing the frequency response functions (FRF) between two of the arbitrary gauging points; ψ_{jr} denotes the *j*th element of the *r*th eigenvector representing the produced displacement at the *j*th DOF caused by the *r*th mode; ω_r and η_r are the *r*th frequency and damping loss factor; *N* is the overall mode number.

The fitting procedure, as the way of modal parameter extraction, is to find a theoretical model that is most identical to the behavior of the blade. In this case, it is to find the most appropriate ω_r and η_r to describe FRF H_{jk}. Various fitting methods are adopted, such as ERA, PolyIIR and PolyLSCF. By using these approaches, the estimates of frequency, damping coefficient and mode shape of the blade system were obtained.

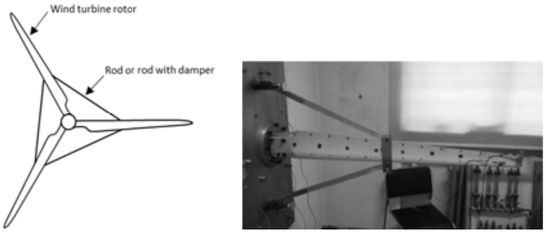

Fig. 1 Design of wind turbine rotor with rods (left) and modal testing setup (right)

B. *Tested results*

.By adding the rods in the rotating plane, the frequency of the first edgewise mode is 46.31 Hz. Compared with the first edgewise frequency of the original blade 34.70 Hz, the stiffness of the blade is increased. The damping coefficient of the tested single blade system is 1.27%. By introducing the rod, damping coefficient of the blade system rises up to 2.12%.

In addition, a rubber damper is mounted together with the rod. This system is tested by modal testing method to illustrate the influences of the rod with damper on the vibration of the blades. Different size of damper brings discrepancies of the damping coefficient of the system, which will be studied further.

III. CONCLUSION

The preliminary modal testing results of the novel blade system design demonstrate the potential function of rods on enhancing the stiffness of the blade. The damping of the system is correlated with appropriate chosen parameters of the dampers.

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QBlade: an open source toolbox for unsteady lifting line simulations of HAWT and VAWT turbines

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Keywords – QBlade, Wind Turbine Aerodynamics, Simulation, Vortex Methods, Lifting Line, VAWT, HAWT

One very important aspect of wind energy, compared to other technologies, is the role of computational efficiency of wind turbine calculation methods. The design load spectrum, which is calculated during a wind turbine certification, covers the full statistics of 20 years of turbine lifetime, broken down into 10 minute time series. For a single wind turbine model this results in approximately 1 to 7 million time steps [1] and the same number of converged aerodynamic calculations. Because computational efficiency is the main driver in the selection of wind turbine simulation tools Blade Element Momentum (BEM) based tools are the most widely spread and are used in every wind turbine certification. However BEM tools are also known for their limitations to model a large range of flow phenomena or turbine states correctly resulting in incorrect load and performance predictions for certain cases.

I. THE LIFTING LINE METHOD IMPLEMENTED IN QBLADE

The higher accuracy of vortex methods compared with BEM codes was already shown in many investigations [2; 3]. The trend that can be observed is that the higher the unsteadiness; non-uniformity of induction or transient effects, the larger the difference between the BEM and vortex methods. This implies the importance of using vortex methods, instead of a BEM code, for simulations in which transient effects are expected to play an important role. To investigate wind turbine rotors operating in turbulent inflow fields or under highly unsteady conditions, the software QBlade [4] was extended with a nonlinear lifting line free vortex wake code. In general the implemented code follows the work of van Garrel [5] with some changes, such as the choice of the blade discretization element, a viscous vortex model and various different time integration schemes. When implementing such a code in a practical and holistic way many small details differ from code to code. Examples for these details are handling of convergence issues, coordinate system selection and implementation of relative blade and rotor movements or initial conditions. The algorithm of van Garrel was furthermore extended to include a large range of functionality, such as the simulation of VAWT. Models for tower shadow and ground effects were implemented; turbulent wind files can be used as wind input. Dynamic turbine simulation, including yaw movement, varying rotational speed or wind input direction and tower base movements with 6 degrees of freedom can be defined via input files. Large efforts were made to achieve a high computational efficiency to enable the simulation of long time series in a reasonable amount of time. Especially the choice of element for the wake discretization plays an important role for the computational efficiency. Instead of modelling the wake with rectangular panel elements, the wake is modelled via vortex line elements which share common vortex nodes. The connectivity between the vortex nodes and the attached vortex lines is tracked with an object oriented attachment/detachment scheme. This allows introducing different strategies to limit the number of free vortex elements in the wake, while still maintaining a high accuracy. Multi-threading is used during the calculation of the free wake convection step to increase the computational performance. The integrated LLT method was thoroughly validated against published data from the MEXICO [6] and NREL Phase VI [7] experiment. The new version of QBlade, including the lifting line for both vertical and horizontal axis wind turbines is made available to the public under the open source GPL license.

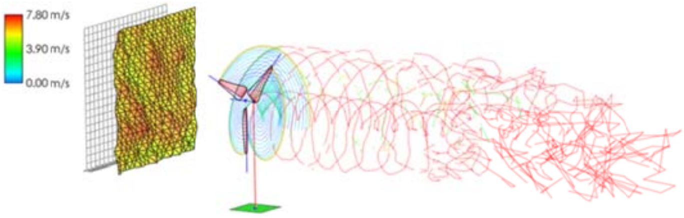

Figure 1: Snapshot during an unsteady lifting line simulation

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Poster 8

Aerofoil Design
Optimisation for Wind or Tidal Turbines.

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Keywords – Aerofoil, multipoint genetic algorithm, Xfoil, StrathAD, Reynolds Number, lift to drag ratio.

ABSTRACT

This paper presents the investigation on suitability of using StrathAD code to develop an optimised aerofoil profiles for the full scale wind turbine blades. The developed profiles are compared against the academic examples found in literatures and should desirably have similar or even better aerodynamic performances. The aerofoil profile optimisation technique used is a search-based multi-point aerofoil design and uses genetic algorithm.

The StrathAd code was developed in [1] and can be used to successfully design the aerofoils of model scale wind turbine rotors with low Reynolds number. The code uses multi-point lift specific aerofoil design approach with search based genetic algorithm, aerofoil shape parameterisation and XFOIL (a 2-dimensional aerodynamic solver) to assess lift coefficients at multiple angle of attacks for the particular Reynold number. This paper assesses the use of the aforementioned approach to design aerofoil profile of full scale wind turbine blades.

The Primary objective of a wind or tidal turbine blade design is to define the aerofoil profiles such that the aerodynamic performance and the structural strength are optimised. While doing so, the profiles are developed in model scale that can replicate the aerodynamic response of corresponding full scale model. Various aerofoil design optimisation techniques and algorithm have been presented in the literatures. Due to the scaling difficulties of wind turbine rotor, the global performance matching solution using thrust coefficient by itself is not sufficient. This can be sorted out by re-designing series of 2-dimensional aerofoils, which have same lift coefficient at different angle of attack at the particular Reynolds number as the full scale one, which is called multi-point design approach. Bearing the large solution space of multi-point aerofoil design and to ensure the robustness and adaptability, search based genetic algorithm is used instead of gradient based aerofoil shape optimisation.

In order to use the SrathAd code for full scale wind turbine blade design, a suitable equal weighing objective function is developed for each operating point, which incorporates the both aerodynamic performance and simplified structural model. This is added to the code and the profiles developed are assessed against academic examples.

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Poster 9

Free-form design of low induction rotors

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Keywords – Blade design, Lightweight rotor, Low induction rotor, Cost of energy

Low Induction Rotors (LIR) have been proposed as a way to increase the energy yield of large wind turbines [1]. Here, a free-form design methodology is employed for the optimization of a 10 MW rotor, in order to evaluate if a LIR configuration could also lead to a reduction in the cost of energy (CoE).

I. INTRODUCTION AND MOTIVATION

The design of a modern wind turbine requires a multi-disciplinary approach, since the ideal solution must at the same time satisfy a variety of physical constraints and keep the cost of energy as low as possible. To satisfy these requirements, a LIR is conceived to trade aerodynamic optimality in favour of reduced loading. This may be exploited by using a larger rotor than in a traditional design, while at the same time reducing the growth of both fatigue and ultimate loads. These features could lead to an increased energy production and/or possibly to a lighter rotor. However, given the aeroelastic implications of a larger rotor, the impact on the cost of energy needs to be thoroughly investigated. The aim of this work is to study if LIR configurations emerge automatically as the result of a cost-of-energy optimization. To this end, we use here an automated free-form methodology, which is able to minimize the CoE by designing simultaneously the shape of the blade (chord, twist), the thickness of the structural members, as well as a set of airfoils specifically adapted to the blade [2].

II. FREE-FORM DESIGN METHODOLOGY

The free-form algorithm manages the blade design by solving an aero-structural optimization problem. At each iterate, the 2D aerodynamic coefficients of the airfoils are computed by a viscous panel method. Then, a classical BEM solver is employed for the computation of the Cp-λ curves of the blade, from which the power curve and eventually the AEP are estimated. The structural description of the blade is based on a 1D beam model coupled to a span-wise distribution of mass and stiffness. The latter are determined at a number of stations by a 2D sectional Finite-Element method, which allows for a detailed representation of the internal layout of the section and of the lamination sequence, including the core material. From this model it is possible to compute the frequencies of the blade, the local state of stress/strain in each structural element, as well as the total blade mass. All these parameters are accounted for in the overall cost-of-energy model [3], which eventually drives the optimization process.

III. APPLICATIONS

The free-form methodology has been applied to a 10MW rotor blade. Results show that a LIR emerges when the sole AEP is maximized. However, this is not the optimum solution in terms of the cost of energy. In fact, the larger radius, and thus the increased blade mass, partially hinders the advantages of a greater energy capture.

In general, it was observed that optimizing the CoE leads to more aerodynamically-efficient solutions, instead of low-induction ones. Furthermore, the best cost reduction is typically achieved when the airfoils are optimized together with the rest of the blade.

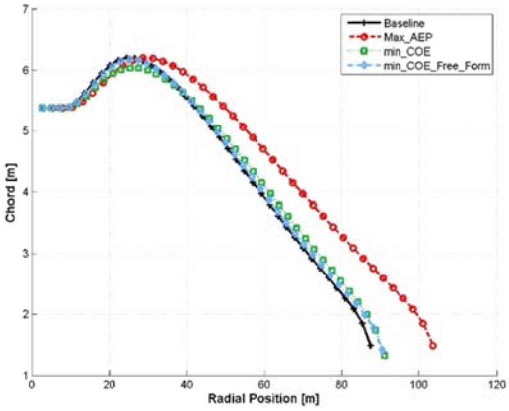

Fig. 1. Blade planform shapes for different optimization strategies.

IV. CONCLUSIONS AND FUTURE WORK

In this work, we investigated LIRs and their ability to reduce the CoE of large wind turbines. This activity will be expanded in the continuation of this research project by repeating the analyses with a more accurate optimization tool, in order to gain a better insight into the physical design drivers. Moreover, some limitations of the current cost model should be overcome. In particular, the ability to account for the cost of the individual materials is of paramount importance, as it allows one to evaluate the impact of different choices of the materials in the cost of energy.

ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe
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Poster 10

Aerodynamic Study of Curved Blades Using Lifting Line Code

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Keywords – Lifting Line Method, Prescribed Wake, Curved Blade.

ABSTRACT

How to increase the energy capture ability without increases in the turbine loads and cost are always the targets of modern wind turbine technology. More energy can be obtained by the way of increasing the wind turbine scale. And the innovative shapes for wind turbine blades has gained a lot of interest since the blade geometry is expected to help to reduce the rotor loads that result in the fatigue problem, therefore the blade cost can be reduced. In addition, the noise reduction is also expected by adopting the innovative blade shape.

A feasible alternative of the innovation of blade geometry is the curved blades, which is also known as swept blades, as shown in Figure 1. A former study[1] has shown that for the aerodynamic calculation of a curved blade, the accuracy of BEM (Blade Element Momentum) theory decreased since the structure airfoil shape used as input of a BEM code is different from the aerodynamic airfoil shape seen by the incoming flow. While more advanced model, panel model, in which any blade geometry can be taken into account, leads to an excessive computing time. Therefore, a lifting line method is chosen in this paper for the numerical investigation of curved blades.

The lifting line code used in this paper is based upon Prandtl's lifting line theory, where the blade is represented by a horseshoe vertex system, consisting of one lifting line with bound vortex on the quarter chord line, and two trailing vortex lines. Weissinger's method is adopted in this code, in which the blade is divided into several elements, and each element is replaced by a horseshoe vertex with a certain bound vortex. This discrete model is applicable for arbitrary blade shape, which makes the code suitable for the simulation of curved blade in this paper. The bound vortex strength is calculated by satisfying the boundary condition, e.g. the velocity components perpendicular to the blade surface of induced velocity $\mathrm{U_i}$, blade rotation velocity $\mathrm{U_r}$, and incoming wind velocity $\mathrm{U_\infty}$ should be zero[2]:

$$(\vec{\boldsymbol{U}}_\infty + \vec{\boldsymbol{U}}_i + \vec{U}_r)\vec{\boldsymbol{n}} = \mathbf{0} \qquad 1$$

With $\vec{n}$ the surface normal, and U_i calculated by the law of Biot-Savart. Once the bound vortex is determined, the lift force can be calculated by the Kutta-Joukowski theorem.

This lifting line code is preliminary developed to investigate the aerodynamic performance of curved blades. The code is compared with experimental measurements for the MEXICO rotor. Though acceptable results are achieved, further improvement is necessary to get more accurate results. A preparatory study of the Sandia STAR blade is carried out by comparing the distribution of normal force Fn and tangential force Ft of this curved blade with the values of a straight blade, and the results show that the curved blade has a good effect on reducing loads. Further studies will focused on the optimization analysis of geometric curvature of the blade, and the effects on power, noise, and sensitivity to the unsteady wind conditions.

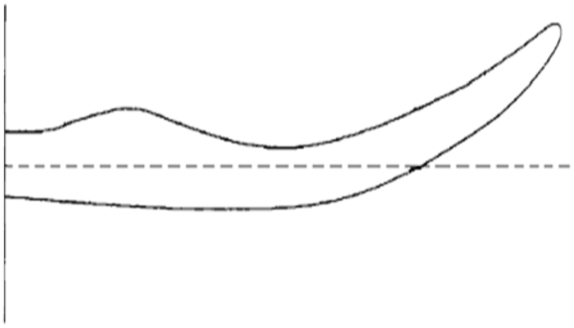

Fig. 1 Curved Blade Geometry

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Poster 11

Ice Accretion Prediction on the Wind Turbine Blades under Atmospheric Icing Conditions

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Keywords – CFD, BEM, Atmospheric Icing, Ice Accretion Prediction

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 predict the shapes of the iced blade section of the turbine blade under atmospheric icing conditions. The Blade Element Momentum method will be employed together with an ice accretion prediction model in order to estimate the energy production of wind turbines both for iced and clean blades. It is observed that amount of accreted ice increases when the relative velocity increases or when local chord length decreases along the span-wise of the turbine blade.

INTRODUCTION

In winters, the wind turbines are exposed to heavy atmospheric icing conditions. Atmospherics icing causes power losses since ice accretion on blades changing the clean blade aerodynamic characteristics and creates instrument or controller errors on wind turbines. The amount of wind power losses depend on the amount of ice accumulation on the blades, blade design and turbine control. In addition, the ice accumulation on blades reduces the torque.

Ice accretion prediction involves complex physics comprising aerodynamics, heat transfer and multiphase flow, which are all time dependent and involve geometric deformation. The numerical method employed in this study predicts the ice accretion on aerodynamic surfaces as a result of water droplets hitting on the surface iteratively. It employs the general methodology for the simulation of ice accretion on airfoils, which is based on the successive calculation of air flow, water droplet trajectories, collection efficiency, heat transfer balance and accreted ice.

Preliminary Results

Ice prediction code was used to predict 2D ice profile shapes on the blade at three different span-wise locations for the Aeolos-H 30kW wind turbine. Operating conditions shown in table 1.

Table 1. Parameters used to define icing profiles

Airfoils	DU93-W-210
Root chord	0.703 m
Tip chord	0.02 m
Turbine diameter ,R	12 m
Liquid water content, ρ_a	0.1 g/m^3
Droplet diameter, d_p	35 μ m
Ambient temperature, T_a	-6.0 °C
Exposure time, t_{exp}	10 hours
Ambient pressure, p_∞	95610 Pa
Humidity	100 %

Predicted ice shapes for span-wise r/R = 0.15, 0.7 and 0.95 can be seen in Figure 1. The shape grows with increasing span due to the increasing sectional velocity and decreasing sectional chord length. Results show that the change caused by ice accretion degraded the aerodynamic performance of the blade, especially near the tip section.

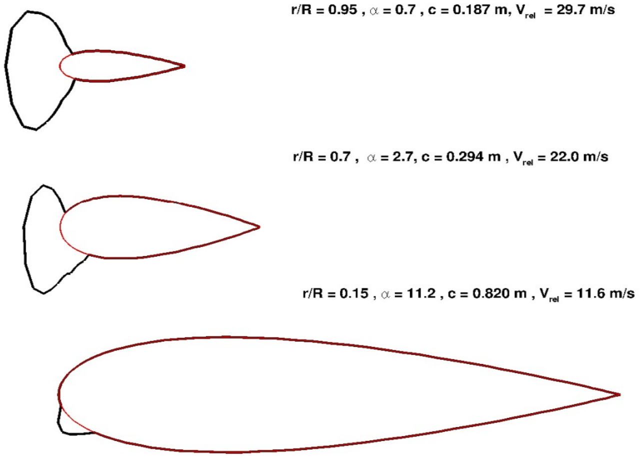

Figure 1. Predicted ice profiles at three span-wise locations for conditions in Table 1.

CONCLUSION

Obtained preliminary results are analyzed and commented. It is seen that predicted ice shape grows with increasing span due to the increasing sectional velocity and decreasing sectional chord length. Results show that the change caused by ice accretion degraded the aerodynamic performance of the blade. In the full paper key results and conclusions will be presented.

11th EAWE PhD Seminar on Wind Energy in Europe
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Stuttgart, Germany
Poster 12

Comparison of different rotating modelling techniques for 3D wind turbine rotor simulation

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Keywords – Wind turbine simulation, OpenFOAM, MEXICO rotor, Multiple Reference Frame (MRF), Sliding Mesh (SM)

I. INTRODUCTION

The increasing computer power over recent years enables computational fluid dynamic (CFD) technique to perform high fidelity full 3D simulation for wind turbine. By numerically performing a three-dimensional simulation on a wind turbine , more flow physics in the vicinity of wind turbine blade can be investigated, such as 3D flow phenomena, laminar to turbulence transition[1], blade/tower interaction. To model the rotating flow induced by the wind turbine rotor in CFD, several methodologies are available. One relatively simple and robust method is Moving Reference Frame (MRF), which is also known as “frozen rotor” simulation. The rotating effect of the rotor is achieved by adding Coriolis and centripetal forces to the momentum equations in MRF zone. The MRF method assumes a weak interaction between the rotating and stationary part. The other method is Sliding Mesh (SM), using a sliding interface technique to solve the unsteady strong interaction between the rotating and stationary part. The unsteadiness and interaction between rotor and stator can be resolved and therefore this method has a better accuracy. In practise, MRF approach is a commonly used approach in 3D wind turbine rotor simulation under axial flow condition with a steady-state solver for saving the computational time if the tower is not modelled in the simulation.

However, it is still not clear and debatable whether MRF approach performs well, especially in the conditions of high rotational speed and high wind speed. Therefore, it is essential and meaningful to determine the relative difference between two approaches for predicting wind turbine rotor aerodynamics. In this paper, both MRF and SM methods are evaluated by predicting the aerodynamics of a small scale horizontal axis wind turbine (HAWT) with different tip speed ratios in terms of computational accuracy and physical reality. The numerical results obtained from both modelling techniques will be validated with the available experimental data, including the overall performance thrust and torque, detailed normal and tangential force distribution along the blade. Apart from that, the computed velocity deficit in the near wake will also be compared.

II. NUMERICAL METHODOLOGY

The computation solves the finite volume-based incompressible Reynolds-averaged Navier-Stokes (RANS) equations. The open source code: OpenFOAM-2.2.1 is employed in the present study. The k-ω SST turbulence model is used to close the equation system. The convection terms are discretised by a second-order accuracy numerical schemes. In order to eliminate the tower influence, only isolated wind turbine rotor is modelled in all simulations.

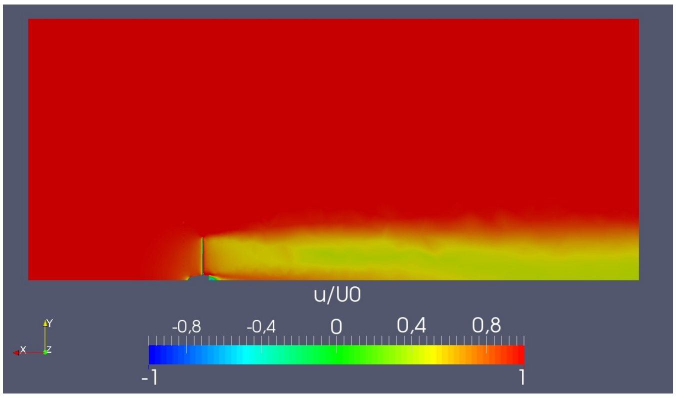

Fig. 1 Axial velocity distribution with MRF approach

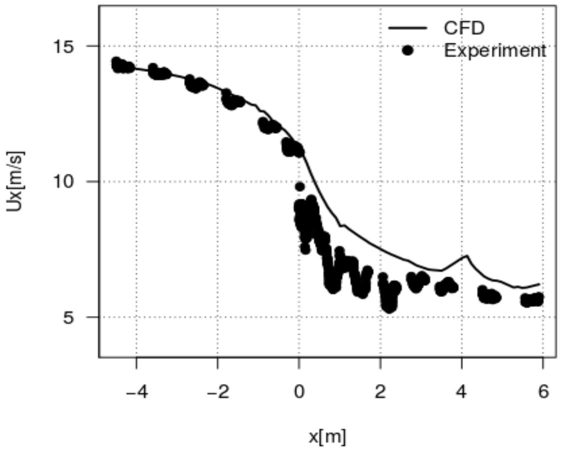

Fig. 2 Axial velocity comparison with experiment with MRF approach

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Poster 13

Numerical investigations of an airfoil in the wake of a slotted cylinder

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Keywords – CFD, wind tunnel, slotted cylinder, airfoil

In order to investigate the effectiveness of load control techniques experimentally and numerically appropriate inflow conditions need to be ensured. A slotted cylinder is one approach to create unsteady inflow conditions for an airfoil located further downstream in a wind tunnel. The wake of such a cylinder and the behaviour of an airfoil are investigated numerically and tested for suitability for further studies.

I. MOTIVATION

Wind turbines experience load fluctuations, caused for example by atmospheric turbulence or tower blockage, leading to fatigue loads which reduce their lifetime and limit the upscaling. Therefore, investigations on load alleviation systems are important. Most of these techniques are tested in wind tunnels before they are integrated in real turbines. However, most wind tunnels are optimized to provide uniform inflow conditions. In the present investigations, the unsteady wake of a bluff body was used to impose AoA fluctuations on an airfoil. The behaviour of the airfoil at different AoA variations and the wake of the bluff body were investigated numerically and will be presented in this paper.

II. NUMERICAL SETUP

The 2D URANS simulations of the slotted cylinder were performed using the block structured code FLOWer, developed by the German Aerospace Center, [1], which solves the compressible Navier-Stokes Equations. The airfoil was integrated using the Chimera technique, [2]. A grid convergence index study after Celik, [3], was used to evaluate the numerical uncertainty of the setup.

III. OPTIMIZATION OF THE WIND TUNNEL SETUP

In previous studies, a slotted cylinder was used to create the unsteady inflow conditions. Experimental investigations of the cylinder placed in the middle of the low speed wind tunnel of TU Darmstadt showed, that for a slit inclination of 0° the wake behaves two dimensional, but the variations exceed the fluctuations seen by a wind turbine blade by far. 2D URANS simulations showed that the AoA variations can be significantly reduced for a closer wall proximity of the cylinder. Therefore, the cylinder was shifted to 1/4 of the wind tunnel. A bar in the middle of the slot, that supresses the flow from one side of the cylinder to the other, was integrated into the numerical setup, leading to further reduction of the fluctuations. More information about this topic can be found in [4].

IV. CONCLUSION / RESULTS

The flow around an airfoil placed in the wake of the slotted cylinder with and without bar was investigated numerically in order to test the suitability of the AoA fluctuations to investigate load alleviation systems in the wind tunnel.

For a cylinder without bar the AoA variations are unrealistic high, leading to separation at the airfoil. Therefore, these inflow conditions should not be used for the investigations of load alleviations systems. However, after including a bar in the middle of the slot, the variations could be reduced significantly, leading to suitable inflow conditions.

ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 14

Experimental Study of Effects of Tip Injection on the Performance of Two Interacting Wind Turbines

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Keywords – wake interaction, tip injection, flow control, wind farm efficiency

I. INTRODUCTION

In wind farms wind turbines operate in the aerodynamic wake of upstream turbines which may lead to significant performance losses as well as increased level of structural and dynamic loads. Consequently, the aerodynamic interaction between wind turbines, have become a field of major interest in the design process of windfarms. It's experimentally shown in a wind tunnel study that the power loss of a downstream turbine can reach up to 46% compared to an unobstructed single turbine operating at its designed condition (Adaramola and Krogstadt [1]).

Vortical structures shed from a wind turbine's blade tips are known to have an important role in the aerodynamic characteristics of that turbine [2]. In order to actively control tip vortices, tip injection was proposed recently as an active flow control method at the blade tips (Anik et al.,[3], Abdulrahim et al. [4]). They showed that pressurized air injection from the tips of a model horizontal axis wind turbine has noticeable effects in the power production [3] as well as the wake characteristics of that turbine [4]. Figure 1 illustrates that tip injection has significant effect on the power coefficient in comparison with the no injection data, especially at TSR values higher than the maximum power coefficient TSR value.

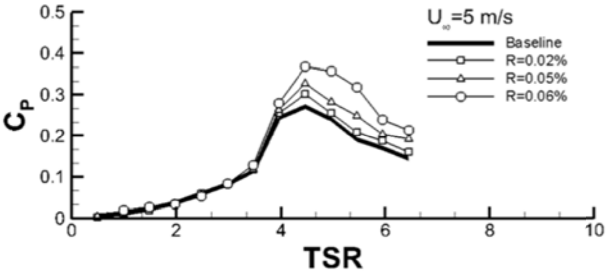

Figure 1 - Effect of air injection from blade tips of a single wind turbine on its power coefficient variations with Tip Speed Ratio (TSR) [3]

The objective of this study is to investigate the effect of pressurized air injection from a model wind turbine's blade tips, on the power characteristics of a similar turbine placed downstream within the wake region. The power and thrust characteristics of the downstream turbine will be measured while tip injection is performed from upstream turbine with different injection momentum ratios.

II. EXPERIMENTAL FACILITY

The experiments are performed in an open jet wind tunnel with an exit diameter of 1.7 m. The wind tunnel has a 1.2 m diameter axial fan as well as a 4.3 meter long circular diffuser with a 3 degree diffusion angle. There are two screens and one honeycomb installed in the straight section just before the exit. The maximum velocity can reach about 12.5 m/s and the turbulence intensity is about 2.5% at the exit of the wind tunnel. Two similar horizontal axis wind turbines with a rotor diameter of 0.95 m will be utilized in experiments. The turbine's nacelle, hub and rotor are designed to have the capability of pressurized air injection from blades tip while the rotor is rotating. The turbines will be positioned in a tandem setup at the exit of open jet tunnel as shown in Figure 2.

Figure 2 - Two model horizontal axis wind turbines positioned at the exit of open jet wind tunnel.

III. CONCLUSION

This study aims to experimentally investigate the effects of tip injection from blades of an upstream model horizontal axis wind turbine on the performance of a similar turbine placed downstream at the exit of an open jet wind tunnel.

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Steady and Transient 3D Analysis of a Model Wind Turbine

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Keywords – **Wind Turbine, CFD, Three-dimensional, Frozen rotor, stage, transient**

In recent years, wind energy has become one of the most economical renewable energy technologies.. Windmills are now introduced in cold areas for which they are not designed. Potential problems such as cracks, separated flow, unbalance, etc. may occur due to icing.

I. PROBLEM DEFINITION

In this paper the numerical simulation of an upwind three blades wind turbine model is presented. Wind tunnel tests have been completed at the Norwegian University of Science and Technology (NTNU) on this turbine. Different measurements have been performed by Krogstad et al, Adamarola et al [1]. They allow to refined numerical models in order to predict the loads acting.

Fig. 1 (left) shows photography of the wind turbine, and the test section of the wind tunnel at NTNU. This model will later be used to simulate icing.

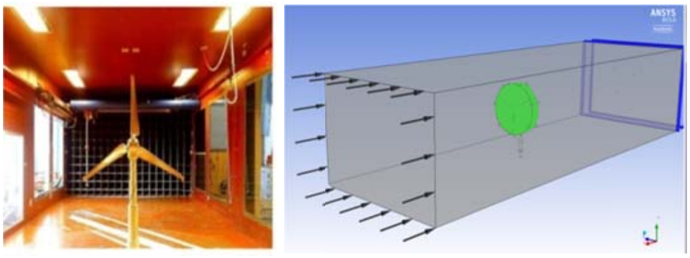

Fig. 1 Model mounted in the wind tunnel (left)
Rotating domain around the blades, inside the stationary domain of wind tunnel (right)

The main goal of the work is a coupled fluid-structure interaction (FSI) to evaluate the effect of icing on the loads acting on the blades. The present simulation methodology aims to accurately simulate the flow on a wind turbine without icing to later include different ice configuration. In the simulation, the effect of the boundary layer resolution is investigated with low Reynolds number Reynolds Average Navier-Stokes models (RANS).

II. METHODS

The geometrical model comport the complete wind turbine model with tower and shaft and has the same scale 1:1. To take into account the effects of wind turbine wakes, the wind tunnel entrance and exit have been considered 4 and 5 diameters (1m) upstream and downstream of the rotor plane, respectively. A multiple frame of reference (MFR) model was activated during the simulation for accommodating the stationary (wind tunnel) and rotating (wind turbine) domains, see Fig. 1 (right). The uniform inlet flow is applied at the tunnel inlet, similarly to the experiments.

Different meshing software have been tested to generate high quality structured hexahedral grid for this geometry. Different configurations of the boundary layer are investigated, i.e., wall function or complete resolution of the boundary layer up to $y^+<1$.

Numerical simulations are performed using Ansys CFX 15.0 solver. Both steady state and transient simulations were conducted. For the steady state analysis, frozen rotor and stage sliding interface have been considered. Transient simulation to take into account the variations of relative positions of two domains is also performed. High resolution advection scheme was selected for the spatial discretization and second order backward Euler scheme for the temporal discretization of RANS equations. Shear stress transport model with automatic wall function was activated to model the turbulent flow. The convergence criteria was set to root-mean-squared value less than 10^{-6}. The numerical results are compared with the experimental data of the test tunnel available, regarding the power coefficients as the representatives of the machine performance in different tip speed ratios

III. CONCLUSION

The performance of the model turbine and wake formed by the rotor is predicted through a numerical study. MFR is considered to simulate the rotating domain around the blade and the stationary flow inside the wind tunnel. The power generation and the thrust force are calculated through the different methods assuming steady and transient simulation. The importance of transient effects is evaluated against the experimental data available.

The aim of this project has been to launch a reliable simulation of a wind turbine, which can accurately predict the loads on the rotor in order to model icing in the next step. 3-D ice shapes over the blade bodies and its effects on the turbine performance is going on.

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Improving wind climate estimation using one-way coupled meso- to microscale models

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Key words: Wind Climate, Resource assessment, Meso-to microscale coupling, WRF, RANS

I. INTRODUCTION

Numerical Weather Prediction (NWP) models, commonly referred to as “Mesoscale” models, are typically run with a horizontal resolution of 1-5 km. This means that they are unable to accurately capture small-scale effects of orography and surface roughness variation, which means that wind climate estimations using mesoscale models only can have large errors in undulating terrain, near coastlines and around forested sites. Stability effects can enhance these errors.

During the first part of this study an analysis of mesoscale models are undertaken. In the European Wind Energy Association (EWEA) Benchmarking Exercise output from more than 20 different mesoscale models is analysed. In figure 1 the bias of the average wind speed at several heights for 20 different mesoscale models are shown at the two sites Høvsøre and Cabauw for the year 2011. While the mesoscale models generally do well for these relatively uncomplicated sites, they still show errors of the average wind speed of 10% in many cases.

To achieve more accurate estimations of the local wind climate in these areas it is necessary to use downscaling techniques that are able to take into account the small scale effects as well. A common technique to achieve this is to couple a mesoscale model with a microscale model. In Badger et al. (2014)[1] the output from a mesoscale model is used to generate wind speed frequency distributions for a number of wind direction sectors and these are then used to create input for the linearized flow model the Wind Atlas Analysis and Application Program (www.WAsP.dk). While the approach in Badger et al. (2014) is based on a statistical-dynamical coupling technique, several attempts of dynamical coupling of meso and microscale models have been made (see Castro et al., 2014[2], Zajaczkowski et al., 2011[3])

During this study several statistical-dynamical and dynamical coupling methods will be compared for wind climate estimation in complex terrain. These will include statistical coupling of mesoscale output data to linearized flow models and RANS microscale models, as well as fully dynamical coupling of WRF and URANS microscale models.

Results of the EWEA mesoscale benchmarking exercise as well as initial results of ongoing meso- to microscale downscaling experiments will be shown.

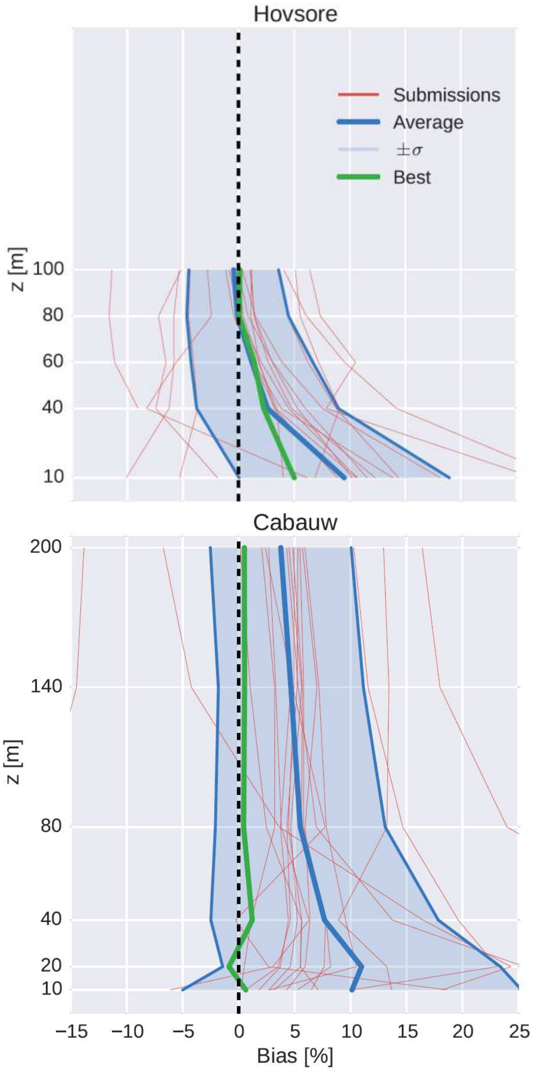

Figure 1. Bias of the average windspeed for 20 different mesoscale (red), the average (blue) and the best model (green) models for several heights at the coastal mast at Høvsøre, Denmark and the onshore mast at Cabauw, The Netherlands

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 17

A Southern German joint research project towards a better understanding of complex terrain sites

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Keywords – complex terrain, site assessment, Lidar, UAV, atmospheric boundary layer, wind tunnel, CFD

I. INTRODUCTION

Looking at the recent developments in the wind energy market it becomes obvious that onshore wind sites gain more importance. These sites influence the local flow conditions at the turbine significantly. Various effects like atmospheric shear, turbulence and inflow angles have direct impact on power and load behaviour of the wind turbine. Site effects like slope steepness, forests or roughness result in a variation of flow characteristics mentioned above. Often, the behaviour of a turbine in such environments is hard to predict. Within the Southern German joint research project LIDAR COMPLEX different techniques are used to overcome this issue and to make predictions more accurate. Therefore, a site in Southern Germany near the town of Stötten is taken into consideration.

II. SCOPE OF THE PROJECT

Within the project, field and wind tunnel measurements as well as numerical simulations based on Computational Fluid Dynamics are used to study the impact of complex terrain. Moreover, also a study about the agreement of the different analyses types will be performed to judge whether e.g. wind tunnel test can give sufficient information about complex terrain effects regarding loads and power of a turbine sited in the investigated terrain.

For the field test two different unmanned aerial vehicles (UAV) are used to perform measurements in the complex terrain as well as in the inflow and near wake of a turbine sited in flat terrain. One of the UAVs is provided by the UNIV. OF TÜBINGEN, the other by the UNIV. OF STUTTGART (Fig. 1). In addition to this, a Lidar System of the UNIV. OF STUTTGART is used to characterize the flow field. A shortcoming of the measurement methods is the limited measurement time. Additionally, a 100m high met mast with anemometers, wind vane and meteorological sensors at the site is providing long term information about the flow conditions.

In the wind tunnel tests a section of the terrain is modelled and placed in the building aerodynamics wind tunnel at the UNIV. OF STUTTGART.

In the final part of the project the data of the measurement campaigns are taken and used to generate inflow conditions for the numerical simulations. The simulations cover a large area of the terrain and are performed with and without turbine. Moreover, the measurement data can be used as well for the validation of the numerical setup. Obviously, the goal is a good agreement between field test, wind tunnel and simulations.

III. CURRENT RESULTS

As the project is still ongoing some work is not finished yet. Nevertheless, the results are quite promising so far. For the comparison of the turbine in flat terrain which can be seen as validation for measurement methods and simulation a good agreement between the data could be achieved. From the field measurements a Hellmann exponent as well as the turbulence intensity and the main flow direction at the site could be determined. Based on this data the area represented in wind tunnel and simulation was chosen, the wind tunnel calibrated to fit the measured atmospheric boundary layer and turbulent inflow data for the simulation were created. At the current point of time the data from the field measurement campaign performed by Lidar and UAVs are investigated in more detail. First numerical simulations of the terrain showed reasonable results like flow acceleration at a steep edge and the change of flow angles according to the terrain slope.

IV. CONCLUSION

So far the project showed good results regarding the agreement between the different measurement methods and gave the ability to access a wide measurement data base for generating inflow data for numerical simulations and for their validation. This is a main outcome of the project as for complex terrain sites the amount of data is very limited. In the future a great knowledge gain from the current data analyses is expected.

ACKNOWLEDGEMENTS

This research has been founded by the German Federal Ministry for Economic Affairs and Energy.

Fig. 1 Field measurements; Helicopter provided by UNIV. OF STUTTGART and aircraft by UNIV. OF TÜBINGEN.

11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 18

RECONSTRUCTION OF MICRO SCALE ATMOSPHERIC FLOWFIELDS BASED ON PROPER ORTHOGONAL DECOMPOSITION

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Keywords – Proper Orthogonal Decomposition (POD), Computational Fluid Dynamics (CFD), Wind Energy

ABSTRACT

The main purpose of this study is to reconstruct micro scale atmospheric flow fields by using a limited number of flow field data and Proper Orthogonal Decomposition (POD).

The proper orthogonal decomposition (POD) is a multivariate statistical method that aims at obtaining a compact representation of the data. The POD method, in general, serves two purposes; order reduction by projecting high-dimensional data into a lower-dimensional space and feature extraction by revealing relevant, but unexpected, structure hidden in the data [1]. In this study, POD is used to extract dominant modes of the micro scale flow field data and to reconstruct unknown flow fields by using those dominant modes.

The POD implementation requires various flow field solutions on the 3D modelling of a terrain using a CFD tool. 3D solution domains may be modelled by structured grids which has 36 nodes in x-direction, 60 in y-direction and 15 in z-direction.

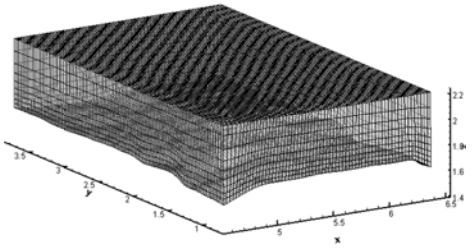


Figure 1 Modelling of Complex Terrain with Structured Grids

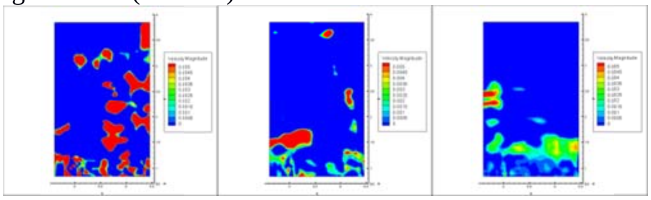
As a preliminary study, a steady flow field data over a complex domain is used for reconstruction of the planar flow field at a given altitude. The POD modes are obtained from 15 cuts taken in the z-direction of the solution. The flow variables at each cut forms the columns of the data matrix:

$$[X] = \left[\overrightarrow{Cut_1}, \overrightarrow{Cut_2}, \dots, \overrightarrow{Cut_n}\right]_{2160x90}$$

Then POD modes are nothing but the eigenvectors of correlation matrix, $[X * X^T]_{2160x2160}$ where X^T is the transpose of matrix X. The eigenvalues of the correlation matrix in descending order sets the significance of the POD modes.

Once the eigenvectors corresponding to the eigenvalues are obtained, they are used for the reconstruction of the data sets. The accuracy of the approximation depends on how many modes are used for the reconstruction. As the number of POD modes employed, which are also knows as the rank of the approximation, increases, and the accuracy of the approximation increases.

The results of the preliminary study are shown in the Figure 2. It can be seen that the reconstructed flow field by POD is in good agreement with the original CFD solution. The following results are approximated by 30 dominant POD modes over 2730 modes. In addition, for the reconstruction last 3 cuts, in other words 3 highest cuts, are used. Because of data are started to taken from top of the domain to the bottom of the domain, below approximations are more accurate at high altitude (2150 m.) than 1750 m.



a) z=1750 m b) z=2050 m c) z=2150 m

Figure 2 Velocity differences between POD and CFD solution at different heights with rank=200

In the full manuscript, 3D atmospheric flow fields over complex domains at various wind directions will be used to form the correlation matrix. The 3D flow fields will then be reconstructed using the POD modes and the wind data a single point in the flow field. The accuracy of the reconstructed flow field will also be assessed as a function of the number of data sets and the POD modes employed.

ACKNOWLEDGEMENTS

This project is partially supported by METU Centre of Wind Energy (RUZGEM) and this support is greatly acknowledged.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 19

Numerical investigation and validation of wind energy relevant flows using a stochastic based eddy resolving turbulence model

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Keywords – Atmospheric boundary layer, Turbulence, Large eddy simulation, Hybrid RANS-LES coupling

Turbulent flow in the atmospheric boundary layer (ABL) is one of the key topics in the scientific and wind energy applications. Due to the complexity of environment, e.g. roughness, geometric changing and thermal conditions, the atmospheric turbulence shows specific characteristics in the statistical representation as well as the flow structures. These phenomena have great influence on the wind turbine performance, which refers to the loading capacity of the turbine construction, the interaction between flow structures and wind blade etc.

Mechanical Turbulence in ABL

Turbulence in the ABL is namely dominated by the surface shear stress and heat flux. The variation in wind with height (wind shear) yields instabilities in the flow that produce mechanical turbulence [1]. In this study the eddy structures of the mechanical turbulence will be studied in the presence and absence of the heat transfer.

I. EDDY RESOLVING TURBULENCE MODELING

The motivation behind LES has been the recognition that the large scales of turbulence often dominate mixing, heat transfer and other quantities of engineering interest, while the small scales are only of interest because of how they affect the large scales. The principal operation in eddy resolving turbulence modeling is to apply a low-pass filtering to the Navier–Stokes equations to model small scales of the solution [2].

Hybrid RANS-LES

Where Reynolds-averaged Navier-Stokes (RANS) methods suffer from the lack of ability to simulate instantaneous turbulence structures and some specific flow patterns e.g. rotational flow or flow over a curved surface, and sufficient fine resolved LES are computationally very expensive in the high Reynolds flow regions close to the wall, which have to be considered in many cases like ABL, hybrid RANS-LES method is a promising alternative.

The general procedure of hybrid RANS-LES coupling is to suppress the Reynolds stress, which is modeled in the RANS regime, by applying a certain filtering criterion. Among all the filtering strategies, detached eddy simulation (DES) determines the modeled turbulent portion depending on the flow characteristics and numerical scales. Heinz[3] developed the unified RANS-LES model which couples the probability density function (PDF) of turbulent velocities [4] into the DES regime which switches between the modeled and the numerical time scales. This is a starting point resolving the eddy structure in the atmospheric boundary layer flow obtaining in this work.

II. APPLICATIONS

By applying the eddy resolving method, the buoyant effect and the interaction between wind turbine and stratified boundary layer can be more realistic discussed and understood.

Furthermore the surface effect of the vegetation like forests, which is an important issue in the onshore wind analysis, can be studied as an application of eddy resolving method. Where forests can be handled as porous media which depending on the drag and leaf intensity brakes the air flowing through it [5].

III. ACKNOWLEDGEMENTS

I like to acknowledge the financial, academic and technical support of the Fraunhofer Institute (IWES).

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The influence of shear flow on the performance and wake characteristics of a model turbine

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Keywords – Model experiment, atmospheric boundary layer, shear flow, wake, turbulence, wind farm efficiency

With a typical hub height between 60m and 100m, offshore wind farms are directly immersed into the atmospheric boundary layer. For the purpose of optimizing the overall efficiency and reduce unsteady loading of the wind turbines, it is important to accurately predict the interactions between the atmospheric boundary layer and the wind turbines operated in it. Following up on a series of model scale wind tunnel experiments investigating wind turbine wake interactions [1], [2], a new experimental study focussing on the influence of shear flow on wind farm efficiency has been realized in the wind tunnel laboratory at NTNU's EPT department.

I. TEST CASE DESCRIPTION

A custom-made, shear-generating grid is set up at the inlet of wind tunnel test section imitating offshore wind conditions with a power law exponent of α=0.11 and turbulence intensity of 10.0%. The performance of a model wind turbine with a rotor diameter D_{Rot} = 0.94 m exposed to this shear flow is investigated. The power output and thrust force are compared to a test case with uniform inflow.

Furthermore, the mean and turbulent wake flow behind the model turbine is mapped at three downstream positions (3D, 5D, 9D) using hot-wire anemometry. The influence of shear flow on the wake shape is analysed by comparing the flow field to a reference case with uniform inflow.

Fig. 1: Model wind turbines exposed to a grid generated shear flow

Finally, a second model wind turbine is installed at the exact same downstream positions in order to assess thrust forces and power output of the second turbine. Thus, the combined wind farm efficiency for different combinations of tip speed ratios of the two-turbine-setup can be mapped.

II. EXPERIMENTAL RESULTS

The single turbine exposed to shear flow showed similar operating characteristics to uniform inflow. Normalizing the reference inflow velocity following the standards of rotor equivalent wind speed [3], a similar maximum power coefficient C_P can be found at a tip speed ratio of λ_{T1}=6.0.

The study reveals significant re-energizing of the wake flow with increasing downstream distance. The near-wake at 3D and 5D downstream is clearly dominated by turbulent structures caused by the tip vortices as shown in Fig.2.

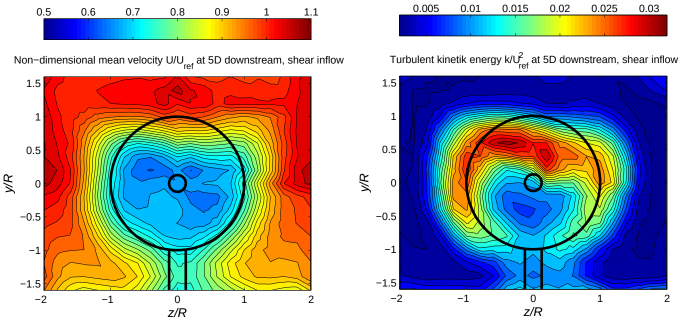

Fig. 2: Non-dimensionalized mean velocity U_{mean}/U_{ref} and turbulent kinetic energy k/U_{ref}^2 in the wake 5D downstream of turbine 1

A comparison of the near-wake flow behind a turbine exposed to shear flow to the same turbine exposed to uniform flow shows slight differences in the vertical wake expansion.

In a two-turbine setup the optimal tip speed ratio of the downstream turbine is trending towards higher rotational speeds with increasing turbine separation distance.

III. CONCLUSIONS

It could be observed that variations from the design tip speed ratio of both turbines influence the total power coefficient only insignificantly. This implies that the total power production of this model test case is not very susceptible to deviations from the optimum rotational speed.

A comparison to the performance characteristics of a turbine setup in uniform inflow reveals that the inlet turbulence has a considerable effect on the performance of a downstream turbine, whereas the effect of wind shear on the downstream turbine performance is rather insignificant.

ACKNOWLEDGEMENTS

Firstly, the authors would like to thank the support of NOWITECH. Secondly, a cooperation between NTNU and TU Berlin, which made this study possible, is acknowledged.

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Wake development behind a turbine for different flow inlet turbulence.

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Keywords – Wind turbine, wind tunnel, wind energy, turbulence, wake development.

In the present work a turbine wake study is carried out in order to describe the wake development at different downstream stations and to improve the understanding into the wake physics. The importance of the wake analysis rises as, in a wind farm, wakes interact each other and directly affect downstream turbine performances. In this context a awareness of the aerodynamic properties of a single turbine wake become essential.

The study is performed varying the turbulence intensity level from the wind tunnel case (low) to a similar-atmospheric one (high).

I. MEASUREMENTS DESCRIPTION

The experimental analysis is carried out at the Norwegian University of Science and Technology (NTNU) aerodynamic laboratories. The wind tunnel has a cross section of (2.7 x 1.8) [m^2] and it is 11.14 [m] long [1]. A model wind turbine (D≈0.9 [m]) is used for the investigation and its characteristics are described in [1].

Wakes are measured at the hub height of the turbine using a hot wire anemometer. Relative flow velocity (U_{rel}, Eq. 1) and turbulence intensity (TI %, Eq. 2) are analysed in several configurations: at different distances behind the turbine (3D, 5D and 9D), both in a low background turbulence level (TI=0.5%) and in a high background turbulence level (TI = 10% over the rotor plane) with the turbine running at TSR=6. The high background turbulence level is created in the tunnel by means of a regular meshed grid installed at the test section inlet.

$$U_{rel}[-] = \frac{\bar{U}}{U_{undisturbed}} \qquad (1)$$

$$TI\ [\%] = \frac{u'}{\bar{U}} * 100 \qquad (2)$$

II. RESULTS

The wake development is shown in Fig. 1 for a low background turbulence level (TI=0.5%). Moving downstream from the rotor plane, the velocity deficit recovers as momentum is fed into the wake through the shear layer. Meanwhile, the momentum feeding produces the radial expansion of the wake. Its limits are well defined by a constant velocity profile, but at 3D the transition region between the wake and the free stream is abrupt, while for 9D it is more gradual according to the physical phenomena.

The turbulence intensity analysis reveals tip vortex presence and allows to focus on the near-far wake transition.

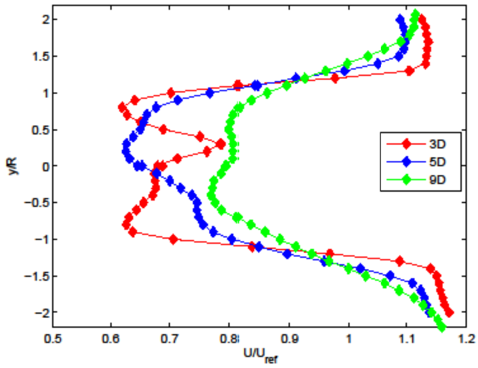

Fig. 1 Horizontal velocity profiles at 3D, 5D, 9D distance. Low background turbulence level. Turbine TSR=6.

The same analysis are performed with a turbulent inflow (TI=10%). Results of the wake development show more similarities with a real case (atmospheric inflow) concerning both the wake velocity and the turbulence intensity. Velocity deficit shows an earlier Gaussian shape and more homogeneous turbulence intensity level at the same downstream distances.

As a consequence, the near-far wake transition region is better matching the reality [2].

III. CONCLUSION

Wake measurements reveal that the velocity deficit recovery and the radial expansion of the wake are dependent on the flow turbulence. The higher the turbulence, the faster the velocity recovery and the bigger the expansion. As a consequence, high turbulence flows allow an earlier transition from near to far wake.

The turbulence intensity background level is revealed to be a key-feature in the wake development analysis.

ACKNOWLEDGEMENTS

The authors would like to thank NOWITECH for cooperation.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 22

Wind-farm performance prediction and optimization with a unique weather predictor

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Keywords: Wind turbine, Wind-farm, Wake analysis, Performance prediction, Optimization.

ABSTRACT

Wind turbines in a wind-farm operate under stochastic environments regardless of the weather conditions. The interactions of atmospheric flow with wind turbines and the mutual influence of wind turbines themselves affect the overall performance of the wind-farm. This effect will be more significant as the scale and number of wind turbine increase. The wind flow passing through the up-stream turbine will acquire additional disturbances that can affect the down-stream turbine.

Adaptive virtual optimization of wind-farms operation is proposed to be done by weather predictor using weather forecasting Figure1, [1]. The atmospheric characteristic of wind flow over the wind-farms is suggested to be represented by using historical daily data and stochastic models, Figure2. Weather generator results maximum, average values of wind speed. The wind flow characteristics from weather generator and turbulence intensity can be combined to express wind flow more delicately.

Predicting the total power extracted by wind turbines in different positions and operating conditions in a wind-farm delivers reliable results than a single wind turbine. Thus, intensive optimizations of wind turbines placed in a wind-farm are required.

The developed model that is based on wake analysis predicts the average wind speed and turbulence intensity is intended to be validated with data measured from Gasiri wind-farm in Jeju, Korea [2].

ACKNOWLEDGEMENTS

This study was supported by Busan-Brain 21 (BB21) project from BMC, South Korea.

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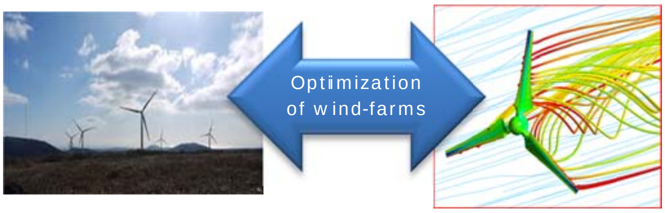
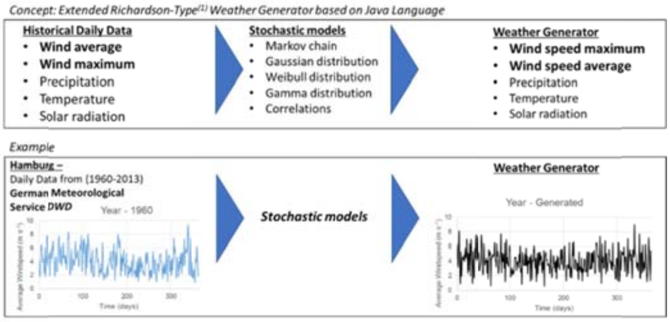


Optimization of wind-farms



Concept: Extended Richardson-Type[1] Weather Generator based on Java Language

Historical Daily Data
- **Wind average**
- **Wind maximum**
- Precipitation
- Temperature
- Solar radiation

Stochastic models
- Markov chain
- Gaussian distribution
- Weibull distribution
- Gamma distribution
- Correlations

Weather Generator
- **Wind speed maximum**
- **Wind speed average**
- Precipitation
- Temperature
- Solar radiation

Example

Hamburg –
Daily Data from (1960-2013)
German Meteorological Service ***DWD***

Stochastic models

Weather Generator

Fig. 1: Weather predictor concept and example [1]

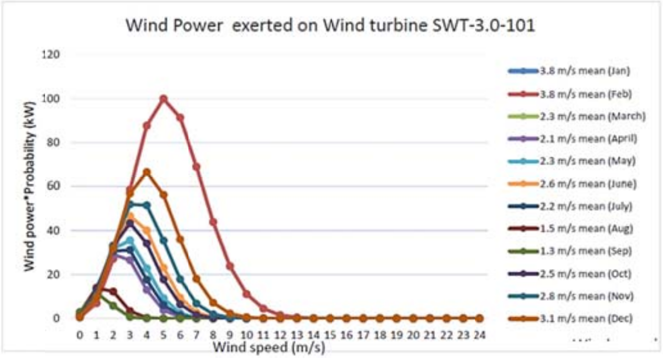


Fig. 2: Examples of wind power exerted on Siemens Wind turbine in Gasiri Wind-Farm using Rayleigh density function [2] [3].

11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 23

Uncertainty of Power Production Predictions of Stationary Wind Farm Models

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Keywords – Wind farm flow models, model validation

The present article is based on the approaches of Roy and Oberkampf [1] and proposes a framework for validation of stationary wake models. The validation data selected for this study consists on the SCADA data of the Danish wind farm Horns Rev 1 (DONG/Vattenfall). Horns Rev 1 is selected because it is one of the wind farm flow benchmark cases defined by Hansen et al. [2]. The present work has the objective of introducing a methodology to determine the model inadequacy of stationary wind farm flow models under uncertain undisturbed flow conditions. The framework presented in this article is applied to two classical engineering wake models: N. O. Jensen's and G. C. Larsen's models.

I. APPROACH

The present framework for UQ can be summarized as (1) To perform a detailed input uncertainty elicitation using the spatially averaged undisturbed wind direction and wind speed as input variables. The spatial variation of both wind speed and wind direction are considered using the nacelle position and power production of the free stream operating turbines. The temporal variation inside the Reynolds averaging period (trends) on both wind speed and wind direction are take into account. The distribution of ambient turbulence intensity is also considered.

(2) To Propagate uncertainty through the wind power plant model to estimate each individual turbine power production variations and compare them with the experimental power production distribution. Additionally the distribution of power production will be studied as a function of undisturbed wind direction and wind speed for both the models and the experimental data. Monte Carlo simulations are used to predict the power production of each wind turbine in an independent manner.

(3) To perform model validation of the engineering wake model as presented in Kennedy and O' Hagan [3]. This means that the distribution of the wake model error will be studied as a function of the input variables.

II. RESULTS

The distribution of power (experimental and modeled) along the wind direction are presented in figure 1 for some example turbines in the same row. From this results the model error can be computed as a function of wind direction. The same process needs to be repeated for different wind speed ranges, and for each of the wind direction quadrants in order to have the stationary wake model error as a function of both wind direction and wind speed.

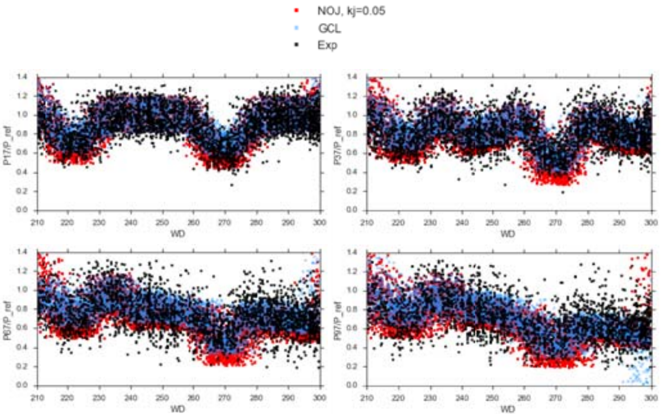

Fig. 1 Distribution of power along the row 7 (T17, T37, T67, T97) in Horns Rev 1 as a function of spatial averaged wind direction.

CONCLUSIONS

It can be concluded that simple stationary wake models can capture the power production variation of individual turbines even in complicated wind power plant layouts. In order to properly model the non-stationary phenomena it is required to consider the spatial and temporal variation of the undisturbed local wind direction and wind speed. On the other hand, wind speed/direction temporal and spatial variations can be used to capture the variation in power production. From these results the distribution of model prediction error (model inadequacy) as a function of both wind speed and wind direction can be studied.

ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe

23-25 September 2015

Stuttgart, Germany

Poster 24

Empirical analysis of wake effects in an operating wind farm

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Keywords – Wake effects, empirical, wind farm

Wake effects do not only affect the power production of wind turbines, but have also an important influence on, among others, the fatigue life consumption of wind turbines [1]. Therefore it is important to gain insight into the wake flows through a wind farm, not only by simulations but also by developing empirical models based on data of an operational windfarm. This contribution will summarise a first analysis regarding wake effects observed at the Northwind offshore windfarm outside the Belgian Coast.

A first step towards better understanding of the wake effects within a wind farm is taken by analysing a subset of the turbine SCADA for the full farm. This analysis will show how parameters like averaged windspeed, power production and turbulence intensity vary within a wind farm, dependent of the wind direction. We will also show the variation in power production for a row of turbines standing in the wake of each other, for several ranges of windspeed.

Further analysis of wake effects will lead to a better understanding of the behavior of several parameters, e.g. power production. Eventually, this analysis will allow to develop an empirical model for the wake effects within a windfarm and compare different lay-outs of windfarms to each other.

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23-25 September 2015
Stuttgart, Germany
Poster 25

LES modelling of wind turbine wakes at full and reduced scales

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Keywords – CFD, Wakes, Wind farm control, Wind tunnel testing

This PhD project focuses on the high fidelity computational fluid dynamics (CFD) simulation of wind turbine wakes, using Large Eddy Simulation (LES). The goal is to support research in wind farm control, and especially on wake redirection techniques [1]. A parallel research project developed at the TUM Wind Energy Institute is developing a scaled wind farm model, which is tested in the large boundary layer wind tunnel of the Politecnico di Milano. Data gathered in those experiments will be used for the validation of the LES simulations. Therefore, the present PhD activity does not only target simulations of wind turbine wakes at full scale, but also the modelling of the reduced scale wind tunnel experimental setup.

In this paper we report the first activities developed so far within this project. Work has initially focused on wake redirection using individual pitch control (IPC), while redirection by yaw misalignment will be targeted next. An open loop IPC algorithm has been implemented and various inflow boundary conditions were tested to simulate the dynamic wake behaviour. The investigation has been aimed at the establishment of a link between wake deflection and loading of the machine. The availability of such a link would allow for the development of a closed loop IPC scheme which, based on loading measured by means of on-board sensors (for example, installed in the blades), would redirect the wake in a desired manner.

I. METHODOLOGIES

In this investigation, simulations of the 5 MW NREL wind turbine were performed with the LES-lifting-line wind farm tool SOWFA [1], coupled with the aeroelastic model FAST [3]. Two inflow conditions were considered: a uniform non-turbulent wind, as well as a turbulent wind computed based on precursor simulations of the atmospheric boundary layer.

An open loop cyclic pitch controller was used, whose expression is

$$\beta_i = \beta_0 + \beta_c \cos(\psi_i + \varphi), \qquad (1)$$

Where β_i is the pitch setting of blade i, β_0 the collective pitch, β_c the cyclic amplitude, ψ_i the azimuthal blade position, and finally φ a phase angle. For given pitch amplitude, the investigation focused on correlating the IPC phase angle φ with wind turbine loading and wake deflection.

II. RESULTS

The results in terms of wake displacement and rotor loading are highly dependent on the inflow and operating conditions of the wind turbine. The uniform inflow, although not representative of realistic operating conditions, was used for an initial correlation of wake displacement and rotor loading, as shown in Fig. 1 Wakes at 7D downstream distances and rotor loads for two IPC phase angles. In particular, it was observed that, as expected based on the simple principle of action and reaction, wake deflection is in the direction of the in-plane rotor force resultant, with a phase delay due to unsteady aerodynamic effects.

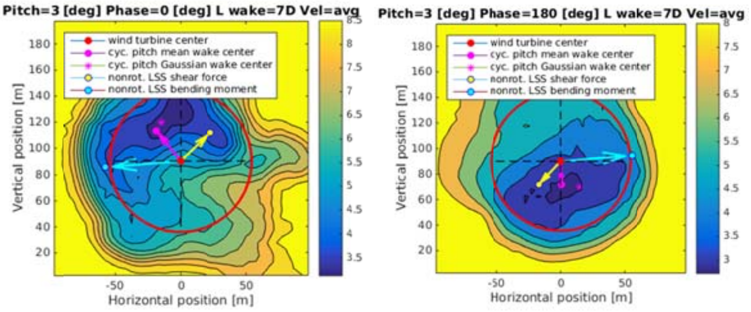

Fig. 1 Wakes at 7D downstream distances and rotor loads for two IPC phase angles

The use of turbulent inflow conditions increases the level of complexity of the problem and the assessment of wake redirection. A sheared wind profile, possibly meandering wake motions and a complex wind speed deficit in the near wake region, are all effects that make it difficult to evaluate with precision the wake centre location, and therefore to quantify exact wake displacement values. For these reasons, the effects of wake redirection are being evaluated in an integral sense, computing the average wind speed on the rotor disk area of the downstream impinged wind turbine. This quantity is less sensitive to imprecisions in the measurement of the wake position, and furthermore it is directly related to the available power to the downstream machine.

III. CONCLUSION AND OUTLOOK

This work described the first steps of a project aimed at the CFD simulation of wind turbine wakes for wind farm control applications. In a continuation of this work, the same simulations will be extended to address similar experiments that are being conducted using scaled wind turbine models in a large boundary layer wind tunnel.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 26

Combined power output of an array two turbines in-line

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Keywords: Experimental fluid dynamics, HAWT, wind tunnel, power output

Interactions between wind turbines have primary importance on the decrease of the total power generated in wind farms. In order to design a wind park, sophisticated simulation software is required. Such models, however, need experimental validation or at least some reference test cases, for example [1,2,3]. Present work is therefore an attempt to build a base of reference data for upgrading or evaluating turbine interaction modeling tools typically used for wind farm design.

I. WIND TUNNEL EXPERIMENTS

In this study two models of Horizontal Axis Wind Turbines (HAWTs) with a rotor diameter (D) around 0.9 m were used.

Measurements were performed in the wind tunnel at the Norwegian University of Science and Technology (NTNU) in Trondheim (11 m long, 5 m^2 cross-section).

The main aim of this project was to find conditions at which the highest combined power coefficient of the two operated in-line turbines (Cp_{max}) were generated. The key parameter for this research; the Tip-Speed Ratio (TSR) was modified separately for the upstream and downstream turbine. Additionally, the separation distance (3D, 5D, 9D) (Fig. 1) between the turbines and incoming flow (two different turbulence intensity (Fig. 2)) was varied to reach an optimum.

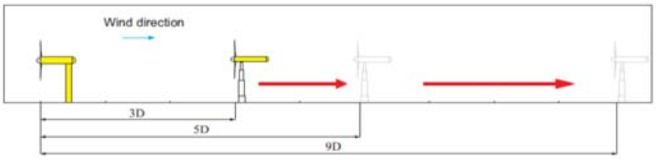

Fig. 1. Arrangement of wind tunnel experiments

Fig. 2. Turbine models exposed to low (left) turbulence inflow and high (right) turbulence inflow

II. CONCLUSIONS

The study confirms that it is possible to find an optimal setup, varying for each considered case (Fig. 3). Herein, Cp_{total} is the value of combined upstream and downstream power coefficient whereas Cp_{max} is the value reserved for the case with highest achieved power coefficient for both turbines.

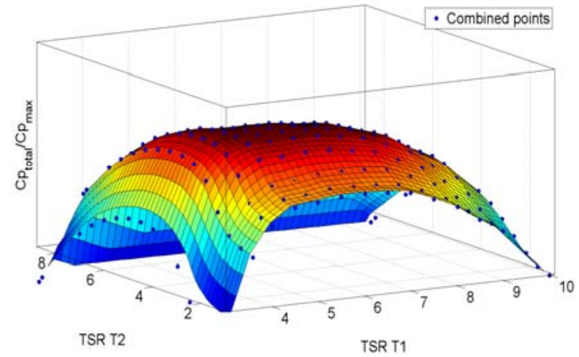

Fig. 3. Matrix of total power coefficients for two operating wind turbines arranged in-line

Depending on the type of inlet turbulence and separation distance between turbines, an increase in total power production was evaluated between 5% to 30%. However, a wide range of tip speed ratio combinations resulted in a close to optimal power output.

The best combined power coefficient for both turbines was found at biggest separation distance with highly turbulent (approx.10%) inlet stream.

III. ACKNOWLEDGEMENT

This study has been realized at Norwegian University of Science and Technology as a part of a partnership between Lodz University of Technology and Norwegian University of Science and Technology.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 27

LES for industrial wind farm aerodynamics

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Keywords – LES, Energy-Conserving, Smagorinsky, ABL

This abstract describes a new Large Eddy Simulation (LES) framework called the Energy-Conserving Navier-Stokes (ECNS)-LES solver, which is being developed by the Energy research Centre of the Netherlands (ECN). It combines the most practical aspects of LES proposed by academia over the last decade to enable the industry to study wind farm aerodynamics (WFA) more comprehensively than done so far with simple engineering models (EM).

I. INTRODUCTION

WFA is the study of how wind turbine wakes interact with the atmospheric boundary layer (ABL), downstream turbines and possibly with each other, as they develop over the length of a wind farm. The velocity field provides insight into the power that is available, how much the turbines extract and to what extent do their wakes recover. Nowadays, WFA could also help predict the effect of wind farms on local weather.

Simple EMs based on basic principles of physics and tuned using experimental observations, are speed and accurate for averaged-statistics but their simplicity precludes any analysis of phenomena like wake-meandering, effects of gusts etc., and also the prediction of local flow variables with high accuracy. Given the importance of wind power in the future, it is wise to switch to numerical models that encompass first-principle physics to a greater extent than Ems, like LES. Although academic LES codes have broadened our insight into WFA, industrial counterparts are not common due to computational requirements and the highly detailed modelling involved. In short, LES is the other end of the spectrum of which, EMs are the simplest models.

However, certain modifications to the practice of LES can adapt if for industrial WFA. Although one cannot expect an LES code to be as quick as an EM, it can certainly help propose modifications and reduced-order models to complement EMs.and make it easier for the reader to get more insight into the topic.

II. APPROACH

A. *Numerical schemes*

Academic codes mostly use pseudo-spectral schemes (PS) because of their accuracy but also incur limitations with regards to non-homogeneous boundaries, for example a hill or location grid refinement, such as in the wake of a turbine. However, PS methods have zero numerical dissipation, which is known to cause premature recovery of wakes and spurious decay of turbulence in simulations.

The ECNS uses a special finite volume method (FVM) that is free from numerical dissipation and permits local grid refinement, called the energy-conserving method (EC). In addition, it uses EC time integration to prevent numerical dissipation through time integration from affecting the solution.

This combination renders the ECNS much accurate for LES, even with large time steps and coarse grids. Thus, one could resolve with acceptable accuracy, the large turbulent scales on a wind farm that dominate the flow.

B. *LES model*

Various LES models, simple through complex, have been used for WFA. However, the ECNS relies on the simple Smagorinsky model (SM), tuned appropriately to simulate wind farms.

This helps us gather the most relevant averaged statistics without excessive computational effort.

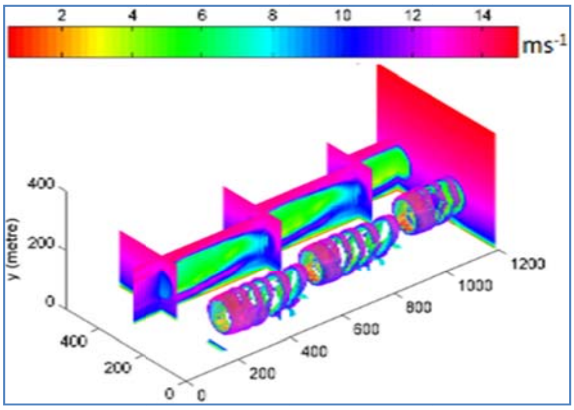

Fig. 1 Isosurfaces of Q-Criterion coloured by stream-wise velocity magnitude on a model wind farm with six turbines using the ECNS.

III. STRATEGY

We will use a precursor simulation to develop a neutral ABL over a flat terrain, and use the same to simulate a wind farm. The aim is to prove that using an EC scheme is essential for LES given its numerical properties that render it a fine alternative to the academically popular PS schemes.

ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 28

Advanced Lidar-Assisted Control Concepts for Large Wind Turbines

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Keywords – Lidar Technology, Advanced Control Design, Systems Engineering, Levelized Cost of Energy

Nowadays it is still a challenging task to increase the electrical energy production of wind turbines while reducing the Cost of Energy (COE) at the same time. To design and manufacture even larger wind turbines is the common goal. Therefore, the development of highly innovative design concepts of beyond-state-of-the-art 10–20 MW wind turbines is pushed forward in several international research projects, e.g. INNWIND.EU [1].

I. INTRODUCTION

Over the last years, lidar technology has shown its great potential in the wind energy sector. While it was only used for site assessment in the beginning, lidar-assisted control concepts have been proven to be very advantageous especially in terms of load reduction [2]. By measuring preview wind information in front of the rotor it is possible to overcome the limits of classical feedback controllers – compensating the variation in the approaching wind field only when its impact already has had an effect on the turbine dynamics.

II. METHODOLOGY

A. Improvement and Expansion of Concepts

Several lidar-assisted control concepts have already been successfully implemented and tested on mid-scale research wind turbines [3]. Transferring the gained insights from research projects and field testing campaigns to large multi-megawatt wind turbines is intended, whereas first steps have already been taken [4].

Furthermore, these existing concepts are still showing great promise for improvement in terms of

- understanding wind physics,
- lidar sensor technology,
- lidar data processing,
- advanced control strategies,
- software engineering,
- and field testing.

Deeper wind field investigation leads to better understanding of the wind characteristics which essentially have an effect on the turbine. Providing a suitable lidar sensor, lidar raw data has to be transformed into usable wind preview signals for the according controller design method. This includes issues like optimizing scan trajectories, timing, filtering, estimation techniques and real time applications. The results of this lidar data processing have a major influence on the controller development. On the one hand it is possible to improve performance by re-tuning the conventional feedback controller. On the other hand application of advanced control strategies, e.g. multivariable control [5], could be taken into account.

B. Systems Engineering Approach

As shown above, lidar-assisted control is a multi- and interdisciplinary task. Many different areas of engineering science have to be brought into accordance. To meet these challenges, methodologies of systems engineering, [6], will be applied. These concepts and tools focus on how large and complex engineering systems could be designed and managed in an effective way. Therefore, all important aspects have to be considered and integrated, whereas the optimization of the whole system is particularly important.

C. Reduction of Levelized Cost of Energy (LCOE)

The overall goal of combining step A and B is to examine how potential load reductions due to lidar-assisted control can be quantified and converted into a reduction of LCOE.

III. CONCLUSION

This PhD project should contribute to the question how lidar-assisted control concepts for large wind turbines can be brought to an even more advanced level – not only by improving the individual concepts but by a holistic approach, which considers the whole system and its environment. Furthermore, the increase of the Technology Readiness Level (TRL) of lidar-assisted control is a main focus.

ACKNOWLEDGEMENTS

The research leading to some of these results is funded from the European Community's Seventh Framework Programme under grant agreement No. 308974 (INNWIND.EU).

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 29

State Feedback Disturbance Rejection for Pitch Regulated Variable Speed Wind Turbine

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Keywords – Wind Turbine, State Feedback Control, Variable Speed Wind Turbine, Above Rated Wind Speed.

ABSTRACT

Variable speed wind turbines are common these days because they capture more wind power than constant speed. It can be operated at its maximum power efficiency for a wide range of wind speed. Therefore turbulence in wind produces fluctuation in the output power, fatigue of components that potentially reduces the life time of the wind turbines. For above wind speed scenario, the control objective is to regulate rotor speed at its rated value to get rated power and mitigate the effect of wind variation using pitch control for variable speed wind turbine. The wind speed has a highly nonlinear characteristic. Various linear and nonlinear techniques can be used to meet the control objective at the above rated wind conditions, such as PID control and Linear Quadratic Gaussian (LQG) control.

A state feedback controller will be developed by taking into account the wind speed as a separate disturbance which is known as separability. Separability is the aerodynamic properties that treat the wind speed as a separate disturbance [2]. The objectives of this project are to:

i. Establish the linearized wind turbine model in state-space form
ii. Estimate plant state disturbance
iii. Design full state feedback controller for disturbance accommodation by pole placement or optimal control design.

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Stochastic Analysis of Aerodynamic Forces acting on Airfoils in turbulent Inflow

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Keywords – Stochastic Analysis, Active Grid, Profile Measurements, Turbulence, Smart Blades, Wind Tunnel

Wind turbines work within the atmospheric boundary layer, which is dominated by turbulence. Such turbulent flows feature non-Gaussian statistics, which are currently not accounted for by industry standards [1]. These intermittent statistics lead to heavy fluctuations in aerodynamic forces and mechanical loads [2], which are considered to increase wind turbine failure rates [3]. Active and passive flow control elements represent a promising approach for the reduction of fluctuating loads. We present an experimental study, which allows for a quantitative analysis of the dynamical behaviour of flow control equipped airfoil profiles in reproducible turbulent inflow conditions.

I. EXPERIMENTAL SETUP

All measurements are performed in the closed test section of the Oldenburg wind tunnel. The turbulent inflow is produced with an active grid. Aerodynamic quantities of interest are measured with a multi component force balance. The investigated profile has a Clark-y baseline shape and is equipped with a self-adaptive camber mechanism, developed at the Technical University of Darmstadt [4]. This concept enables the profile to passively change its camber depending on the pressure acting on the leading edge flap, which is promising for the reduction of turbulence induced fluctuations of the lift. Fig. 1 shows the profile mounted in the closed test section downstream of the active grid.

Fig. 1 Self-adaptive camber profile mounted in the closed test section of the wind tunnel downstream of the active grid.

II. STOCHASTIC ANALYSIS METHOD

We use a stochastic Langevin approach to analyze time series of the measured forces by capturing the dynamics of the measured forces in a stochastic process. This approach decomposes dynamical force fluctuations into a deterministic response and a stochastic (noisy) part. It has been successfully applied to a variety of dynamical problems, such as in-situ damage detection [5]. In this way, the dynamics in a measured Force $\mathrm{F(t)}$ can be described by the Langevin equation

$$\frac{\mathrm{d}}{\mathrm{dt}}\big(\mathrm{F(t)}\big) = \mathrm{D}^{(1)}\big(\mathrm{F(t)}\big) + \sqrt{\mathrm{D}^{(2)}\big(\mathrm{F(t)}\big)}\;\Gamma(\mathrm{t})\,, \qquad (1)$$

where $\Gamma(t)$ denotes Gaussian δ-correlated white noise. The drift and diffusion coefficients $\mathrm{D}^{(n)}$ describe the deterministic relaxation $\mathrm{D}^{(1)}$ of the system to its steady state and the stochastic part $\mathrm{D}^{(2)}$. These coefficients can be obtained directly from measurement data [6]. This method allows for a quantitative analysis of the dynamical behavior of flow control mechanisms in turbulent inflow, independent of stochastic dynamics.

ACKNOWLEDGEMENTS

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Support Structure Load Mitigation of Offshore Wind Turbines by Different Control Concepts

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Keywords – Load mitigation, adaptive control, offshore wind turbine

At present one of the factors that hinder the further exploitation of offshore wind energy is the associated high levelised cost of energy. The typical cost of support structure excluding the costs of transportation and installation is around 20% of the total cost [1]. This factor will be more crucial when considering higher capacity wind turbines and deeper water sites. The objective for this PhD project is to develop a methodology to reduce the offshore support structure loads by tailoring the employment of different load mitigation concepts.

I. INTRODUCTION

There are several control concepts available to mitigate specific load events on a support structure. However, the control concepts can have different collateral effects by increasing the loads in the other components of the wind turbines. For example, Individual Pitch Controller (IPC) is effective on tower side-to-side load reduction in the rated power range. But IPC increases the fore-aft moment and the pitch activity which may lead to unscheduled maintenance which is critical and cost intensive [2].

II. METHODOLOGY

The approach in this PhD is to develop an adaptive controller that selects the most effective controller concepts depending on the load events, operating conditions and the requirement of the controller type using decision from a multi-objective function. The novelty here is to establish a trade-off between the desired load reduction and the collateral effects introduced by the selected controller.

Considering the situation with and without the detailed turbine model information, two approaches will be analysed: Model driven and data driven approach. The flowchart for the model driven approach can be seen in Fig 1. The measurement data from the Alpha Ventus offshore wind farm and FINO1 research platform as the part of the RAVE – OWEA Loads project [3] will be used for the sea state and load estimation. The control concepts will be evaluated for the given condition and the most effective control concept will be selected using a multi-objective optimization which takes into consideration the load reduced as well as the collateral effects due to the selected controller and also the design load envelope. The controller will be activated for a certain amount of time and the sea state and load conditions are constantly monitored in order to decide if the implemented controller concept is still the most effective one.

After discussing the objectives and proposed methodology of the PhD project, the contribution will present a first case study using model driven approach.

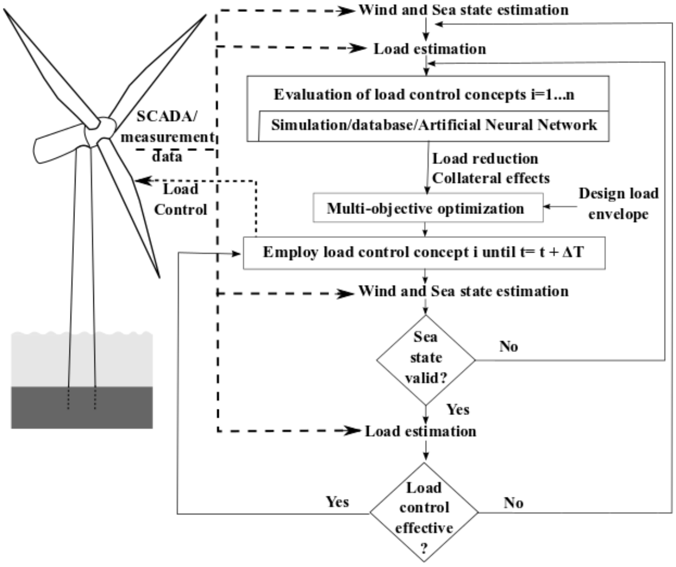

Fig. 1: Flowchart of the model driven approach

III. CONCLUSION

The main objective of the PhD work is to develop and implement a methodology for a controller adaptive to different situations to mitigate critical aerodynamic and hydrodynamic support structure loads of an offshore wind turbine, by evaluating an effective objective function for the controller. The work will be followed by the validation of the effectiveness and generalization and transfer of the proposed method.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 32

Adaption of Wind Turbine Model for Incorporation into Wind Farm Simulation

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Keywords – Control, Wind Farm, Simulation

I. ABSTRACT

Wind farm control is rising rapidly up the agenda for wind turbine manufacturers and operators for a number of reasons. Firstly, power generation from the farm is not maximised by achieving the greatest power extraction from every turbine. The wind interaction with the upwind turbines can slow down the wind to the detriment of the turbines behind them [1]. Controlling the power extraction of the turbines at farm level (as opposed to turbine level) can result in greater power extraction across the farm. The loads on individual turbines are also affected by the turbulence in the wakes developed from upwind turbines [2]. Adjusting power capture can also help alleviate these loads and increase turbine lifetimes. Overall the benefits that wind farm control can provide include more flexible operation of wind farms to meet both grid-requirements and better management of offshore resources to reduce the cost of energy. As the penetration of large scale offshore wind grows the demands on the general services provided through wind farm control will rise and it will become increasingly important.

The design of wind farm controllers requires the development of suitable wind farm models that incorporate models of perhaps 100+ turbines and yet run reasonably fast. The turbine models will need to be in sufficient detail to provide information on loads and the full envelope turbine controller, since its operation directly impacts on these loads. The wind farm model will need to represent both the evolution of the wind field and the wake interactions. Various approaches to the design of such models have been undertaken as described in [3] and currently a detailed simulation is being developed within the DTC at the university.

Key aspects of it are the use of multiple platforms, split integration time steps between the turbines and the farm and the use of C-code rather than Simulink whenever possible.

This project involves converting the wind turbine model used within this simulation into C-code. The turbine's operating principles, loads and controller will have to be discretized and a local compiler designed to decrease run times when used as part of the wind farm simulation.

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Model Based Approach to Examine the Interactions of Electrical and Mechanical Wind Turbine Subsystems – Part 1

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Keywords –Wind Turbine, Drive Train Dynamics, Interaction between Subsystems

I. ABSTRACT

Various studies have proven that the power converters in variable-speed wind turbines are a common source of failure (e.g.[1],[2]). However, the causes and mechanisms underlying these failures are mostly unknown. Among the potential causes are the highly dynamic interactions of mechanical and electrical turbine subsystems, which might not be covered in sufficient detail by the models underlying today's design procedures.

To identify the main drivers of power converter failures and to achieve a better understanding of the actually occurring loads, a detailed model of the mechanical and electrical parts of a modern wind turbine drivetrain has been developed as a part of the power electronics innovation cluster [3].

II. DYNAMIC WIND TURBINE MODEL

A. *Electrical subsystem model*

The focus of this paper is the modelling of the mechanical and aerodynamic subsystems of the wind turbine. A detailed description of the electrical subsystem can be found in Part 2 of this paper. However, some information is given in this paper to allow a better understanding of the combined model. The electrical subsystem consists of a permanent magnet synchronous generator (PMSG) which is connected to the grid by an IGBT-based back-to-back full-scale power converter. The electrical subsystem contains various control structures to meet the grid connection requirements and to be able to handle grid faults.

B. *Aerodynamic and mechanical-subsystems model*

The detailed aerodynamic and mechanical-subsystems models are capable of simulating the different time varying loads at various points of operation. As the coupling of the mechanical drivetrain and the electrical subsystem is described by the air gap torque in the generator, mainly torsional effects are considered in the model. The aerodynamic calculations are based on the blade element momentum theory (BEM) for each of the three elastic blades (3DOF) of the rotor. The tower is modelled as single mass oscillator to describe the relevant fore-aft mode of the tower oscillation. The tower is also taken into account for the tower-shadow model and its characteristic 3P excitation of the drivetrain. The main part of the torsional drivetrain dynamics is the gear which consists of a planetary as well as a spur gear stage. The gear is coupled with the hub and the rotor of the generator to describe the model of the mechanical drivetrain (7DOF).

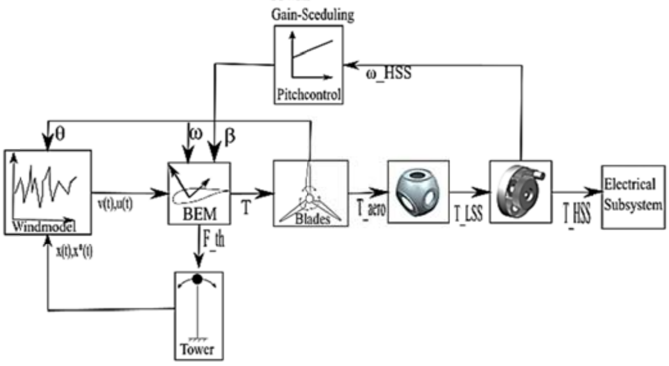

Fig. 1 Structure of the aerodynamic and mechanical model

C. *Control Structure*

The power and speed control of a modern wind turbine can be divided into two control structures. The rotor-speed and the power above rated wind speed are basically controlled by the pitch-controller which consists of a PI-controller with gain scheduling. The gain scheduling considers the specific aerodynamic sensitivity of the rotor at different points of operation. For variable speed at low wind speeds, a maximum power point tracking (MPPT) control structure is implemented in the electrical subsystem.

III. CONCLUSION

The described aerodynamic and dynamic mechanical subsystem is capable of describing the most important dynamic effects and loads of a modern wind turbine drivetrain. Varying the parameters of the drivetrain components in the model can show the impact on the interaction between the electrical and mechanical subsystems.

IV. OUTLOOK

Events acting on the electrical subsystem such as grid disturbances can have harmful influences on different drivetrain parts like the gear. Further investigations will be carried out to identify the impacts of different electrical designs and failure modes on the mechanical drivetrain.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 34

Towards the Robust Design Optimization of Wind Turbines

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Keywords – Robust design optimization, Uncertainty propagation, stochastic variation, Non-intrusive polynomial chaos expansion

The present work proposes a framework for robust design optimization of wind turbines by means of uncertainty quantifications methods to propagate the input uncertainties through a complex model. A Non-Intrusive Polynomial Chaos Expansion [NIPCE] based method is used to propagate uncertainties and estimate the stochastic parameters of the output variables of interest. Preliminary results of a design optimization of blade chord and twist are presented, where a robust design approach is developed accounting for random variations in the lift and drag aerodynamic coefficients C_L and C_D.

I. INTRODUCTION

Wind turbines are usually designed using deterministic optimization methods that involve the integration of complex models of aerodynamics, structures, controls and systems. These multi-disciplinary deterministic approaches do not account for the uncertainties arising from the stochastic nature of input variables and the unknown model assumptions. In order to understand the robustness of the final design and to establish confidence levels on the accuracy of the results, the uncertainty associated with the model input parameters and the resultant output variables should be quantified. This involves efficient and accurate propagation of input uncertainties [UP] through various models, either by changing the model formulation, known as intrusive method, or by using a non-intrusive method, where the model is handled as a black-box.

In intrusive UP the underlying mathematic model is modified to account for stochastic variations in the inputs. Applications of this method are however restricted to simple models and are generally prohibitively complex for multi-disciplinary high fidelity models [1]. The focus of this research is instead to understand the major sources of uncertainty associated with wind turbine design and identify an efficient non-intrusive method to propagate these through a complex optimization model. This uncertainty propagation method is used to develop a robust optimization framework.

II. DESIGN METHODOLOGIES

The intended robust optimization framework is developed by integrating the wind turbine design tool Cp-Max (Code for performance Maximization) [2], which is based on the high fidelity aeroservoelastic multi-body code Cp-Lambda (Code for Performance, Loads, Aeroelasticity by Multi-Body Dynamics Analysis), with the NIPCE tool. Among the many available NIUP methods, PCE is selected owing to its widespread application in robust aerodynamic optimization. In PCE, a stochastic process is represented through a spectral expansion using orthogonal polynomials as

$$Y = \sum_{j=0}^{\infty} y_j \; H_j\,(\boldsymbol{\xi})$$

where ξ is a vector of standard normal random variables, H_j is the Hermite polynomial of order j and y_j is the corresponding deterministic coefficient which is calculated from a limited number of model simulations.

III. APPLICATIONS

The first application of the developed NIPCE is the robust aerodynamic design of a blade installed on an industrial reference 2.2 MW onshore wind turbine. The study consists of introducing random variations in the C_L and C_D by assuming a Gaussian perturbation profile and propagating them through the model by means of the orthogonal Hermite polynomials. The chord and twist distributions of the baseline design are then optimized with the objective function of maximizing the mean of the annual energy production, AEP. Preliminary results show that an AEP improvement of 0.5% can be achieved using robust optimization under uncertain aerodynamic variations. The method is also compared to a MonteCarlo method proving good performance.

IV. CONCLUSIONS

In this work a framework for robust optimization involving uncertainty propagation is presented. Results from an initial study where chord and twist are optimized accounting for uncertain aero properties are discussed.

ACKNOWLEDGEMENTS

The authors acknowledge Prof Koutsourelakis from TUM for the fruitful discussions on uncertainty propagation.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 35

Model Based Approach to Examine the Interactions of Electrical and Mechanical Wind Turbine Subsystems – Part 2

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Keywords – wind turbine, electrical model, control structure, fault ride-through

Failures and downtimes of modern wind turbines are nowadays often caused by damages in the converter system. Due to insufficient monitoring data during and before these failures, the malfunctioning of converters in wind turbines is a topic that is not understood sufficiently yet.

To receive a better understanding of the converter failures caused by actually occurring loads, a detailed model of the mechanical and electrical parts as well as the control of a 5MW wind turbine with a permanent magnet synchronous generator (PMSG) and its converter system has been developed.

I. MODELLING OF THE WIND TURBINE

A. *The mechanical model*

The focal point of this paper is on the modelling of the electrical components while a closer look at the aerodynamic and mechanical parts is given by Arne Bartschat in another paper (Part 1) presented in this seminar.

For the sake of completeness, it should be mentioned that the rotor torque, which is generated by a height-dependent wind speed, is calculated with the blade element momentum theory, and the drive train with a planetary gear is modelled as a seven-mass system.

B. *The electrical model*

The PMSG itself is modelled as a surface-mounted machine in the rotor reference frame like in [1] and is connected to the grid by a back-to-back construction of two three-level converters.

To fulfil the grid connection requirements, the grid-side converter is followed by a choke filter and two resonant filters designed to reduce the current harmonics of the 1st and 2nd order of the switching frequency.

Due to the high power of the system, the turbine is connected to a medium voltage transformer, so that the current through each of the two parallel converters is suitable for modern IGBT technology.

Every semiconductor of the three-level converters is expanded by a thermal model based on real datasheet values.

C. *The control structure*

To be able to ride through various grid faults, which can be a stress factor for the whole system, the model also consists of a complete control structure for the grid-side and the machine-side converters.

As it can be seen in Fig.1, the control of the generator is based on PI controllers in the common cascaded structure.

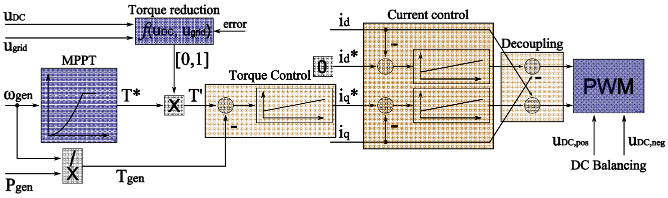

Fig.1 Generator-side converter control structure of the wind turbine model

The overlaid maximum power point tracking (MPPT) control generates the set-point for the q-current of the generator while the d-current is set to zero, assuring the maximum torque per ampere. If a grid fault occurs, which is detected by an additional monitoring structure, and the turbine power cannot be fully fed into the grid, the generator-side converter slowly reduces the torque in the air gap. The reduction rate of the torque depends on the number of affected phases, the actual level of the grid voltage and the deviation of the dc-link voltage to its set-point.

Similar to the generator control, the grid-side converter is controlling the currents in the grid voltage reference frame. In this case, the overlaid dc-voltage control defines the set-point for the current in the q-axis while the reactive power control sets the value for the current in the d-axis.

II. CONCLUSION

With this control structure outlined in brief, the whole system is able to ride through every grid fault defined in [2] according to the grid operator’s requirements.

A first estimation of the losses in the semiconductors compared with those of a simpler model leads to the assumption that a simplification of the mechanical model is acceptable in the case of a big inertia like the one considered here.

III. OUTLOOK

A closer look at the loads of the semiconductors as well as a detailed overview of the model and its parameters will be presented in the full paper. Furthermore, possible interactions of the model with a detailed grid model will be discussed.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 36

Model Fidelity Evaluation in the Multidisciplinary Optimisation of Offshore Wind Farms

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Keywords – Offshore Wind Farms, MDAO, Model fidelity, Optimisation

The design of offshore wind farms (OWF) is steadily becoming more recognised as a multidisciplinary task. Systems engineering is gaining terrain in the wind energy community, to provide the means to analyse, optimise and design large scale power plants. This presentation includes a problem statement in the field of systems engineering for wind energy and the planned methodology to reach a solution.

I. PROBLEM

So far, there has been no clear way for users of a Multidisciplinary Design, Optimisation and Analysis (MDAO) framework to know what model fidelity and optimisation algorithms have to be included in an offshore wind system assessment[1]. This is particularly true when they are using models outside their own discipline. High fidelity models are computationally expensive, and thus have to be smartly used to avoid prohibitively long run times. In this work, a higher fidelity will imply a higher degree of capability to match experimental data although at a higher computational cost.

The problem to be solved is the lack of understanding of the effects that different fidelities of a certain model have on the overall performance of a multidisciplinary optimisation. Different users (e.g. researchers who develop their own models or quantify uncertainties, R&D teams that want to optimise new components from the system point of view, OWF developers interested in global financial parameters or design teams) have different interests when running a MDAO framework, and therefore the optimisers and fidelity of each model will have to change accordingly. The final goal of this project is to develop an algorithm able to find the best combination of model fidelities and optimisers according to the use case of a MDAO framework for offshore wind energy.

II. PLANNED METHODOLOGY

A. *Research Cycles*

The methodology applied to achieve the overarching goal of this project will be to break it down into smaller units of complete research cycles[2], all of which include the following phases: aggregation, assumptions, theorising, justification, validation and consolidation. These cycles will address four specific sub-objectives:

- Definition of a set of standard OWFs to benchmark models and optimiser.
- Definition of the set of use cases of a MDAO framework applied to offshore wind energy, together with their particular interest or goal, global objective function and performance demands.
- Definition of the governing criteria for comparison and selection of models and optimisers.
- A multi-criteria decision analysis tool including a weight determination method that yields the best combination of model fidelities and optimisers.

B. *Software*

To make the connection between models and optimisers, the project will make use of the FUSED-Wind shell, built upon the OpenMDAO framework.

OpenMDAO is being developed as a tool for systems engineering and includes a vast library of optimisers and design of experiment drivers [3].

FUSED-Wind currently contains a standard set of connections of input and output variables of components of a wind farm, including cost and financial models, aero-hydro-servo-elastic models, wake models and structural/foundation models [4].

A plug-in with an algorithm that automates the selection of models and optimisers will be contributed to the existing library of FUSED-Wind.

III. CONCLUSION

Splitting the overall goal into four sub-objectives will provide an efficient methodology, since the outcome of each cycle will be robust and scientifically proven, and their use in subsequent cycles will be fully justified.

This project will contribute to more efficiently use a MDAO framework applied to offshore wind energy.

IV. ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 37

Derivation of a Lumped Parameter Model of a Vertical Axis Wind Turbine

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ABSTRACT

Lumped parameter models of wind turbines are used for analysing their dynamic properties and designing their controllers. For horizontal axis wind turbines (HAWTS) these are well-established and include representations of the aerodynamics, the structure, tower and rotor, and the drive-train. These models need to faithfully represent the dominant dynamic modes, both their frequencies and phase, in terms of basic physical parameters such as inertias. These models provide much insight into the dynamic behaviour of the wind turbines and the relationships between the various modes. As yet there are no equivalent models for vertical axis wind turbines (VAWTS).

Analysis of the rotor dynamics will be carried out and a lumped parameter model developed for the structure of the VAWT. This lumped parameter model will be analogous to similar models that currently exist for HAWTS. A lumped parameter model will then be developed for the drive-train of the VAWT. The two lumped parameter models will be used in the construction of a Simulink model for the VAWT. Initially, a simple, two bladed V rotor with straight blades will be considered with only the first modes in and out of the cone. The project may be extended to H rotors or 3 bladed V rotors.

11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 38

Wind Generation Modelling in Reliability Studies: Challenges and Opportunities

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Keywords – Wind Power Generation, Power System Reliability, Statistical Modelling, RES integration.

Installed Renewable Energy Sources (RES) capacity has experienced a significant growth over the last decades, mostly driven by environmental policy targets and financial incentives. Wind power holds a clear lead among these technologies, currently accounting for 39% of the domestic electricity demand in Denmark [1]. Due to its intermittent nature, this sudden increase in wind power penetration has been translated into a higher uncertainty in the power system calling for new reliability criteria as opposed to the conventional (deterministic) N-1 approach. To this end, the GARPUR [2] project designs, develops, assesses and evaluates such new reliability criteria to be progressively implemented over the next decades, while maximising social welfare. This poster presentation introduces a general overview of the main challenges and opportunities encountered when representing wind generation in reliability studies at a pan-European level.

I. FLEXIBILITY

Power system reliability refers to the ability of a given system to cover the electric demand in each node at all times. It represents a cornerstone of power system design and planning including three broad time horizons: *real time operation*, *asset management* and *system planning*. The proposed methodologies must be flexible enough in order to account for the separate time windows, allowing different representations such as time series or probability distribution functions.

II. VARIABILITY AND UNCERTAINTY

Variability and uncertainty represent the two fundamental characteristics of weather-driven energy sources. The former is generally associated to physical characteristics of the atmosphere i.e. the wind resource and hence cannot be reduced by means of further study. Nevertheless, it must be captured in order to generate plausible future scenarios of wind generation. These scenarios do not necessarily represent a truthful image of reality due to the partial ignorance or lack of perfect information of the phenomena under study. Thus, the uncertainty associated to the model predictions also need to be quantified in order to support decision making, especially at operational planning.

III. MULTIPLE STRATEGIES

Aggregated wind power generation represents the most crucial variable from the TSO perspective. Nevertheless, the lack of available data considering the wide geographical area to be modelled justifies the need for alternative solutions. In this regard, weather reanalysis techniques can provide historical series of meteorological variables with the desired level of resolution which can be subsequently transformed into power using aggregated power curves. Plus, it offers the possibility to account for future expansions of the wind generation flee.

IV. FEASIBLE APPROXIMATIONS

The high dimensionality of the problem at hand requires the identification of feasible approximations in order to ensure convergence and tractability. This will involve testing the effect of different characterizations of the temporal and spatial dependency structure between wind power plants at different aggregation levels i.e. region/country-wise. Furthermore, it will be necessary to assess the effects of weather on the rest of the system components and their possible relation with wind power generation such as component failure rates and outages, which may leave open the possibility to make use of new techniques tools such as *big data* and *machine learning*.

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Synchronous Machine Assisted by Permanent Magnets for Direct-Drive Wind Turbine

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Keywords –Synchronous Generator, Direct Drive Wind Turbine, Experimental analysis, Efficiency, Optimization

This paper proposes an analysis of a salient pole synchronous generator assisted by Permanent Magnets (PM) for a direct-drive wind turbine. Firstly, the principle of assisted PM machine is explained and a model is build. Secondly, by an optimization problem, the control strategy is inferred from the experimental acquisitions.

I. PRINCIPLE OF SALIENT POLE GENERATOR ASSISTED BY PM AND PROTOTYPE CHARACTERISTICS

For salient pole generator, magnetic saturation is a key issue. To reduce the machine size, the rotor poles are designed with an acceptable level of saturation [1]. To overcome the limit due to saturation effects, the synchronous generator assisted by PM is investigated [1], [2]. The structure is based on a classical salient pole machine with PM inserted between the adjacent rotor pole shoes. The flux generated by PM cross the rotor pole in opposite way to the main flux (Fig.1). Therefore rotor pole saturation is decreased and DC current is reduced which improve the generator efficiency. In addition, a part of PM fluxes cross the airgap and increase the electromotive force [1], [2].

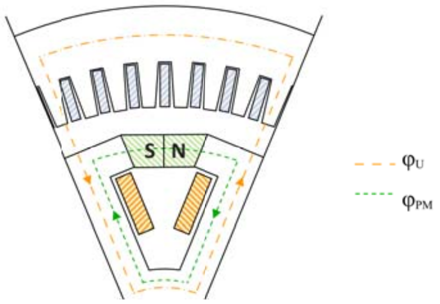

Fig. 1 Principle of Synchronous Generator assisted by PM

The studied machine is a 48 poles direct drive wound rotor synchronous generator assisted by PM. A 900kW prototype was made. Experimental measurements are performed over a period of time with the machine. The measures are used to validate a semi-analytical model and to find the control strategy applied during the test.

II. EQUIVALENT MODEL AND EXPERIMENTAL VALIDATIONS

The model is a first harmonic model based on a synchronous Direct-Quadrature (D-Q) reference frame [3]. This equivalent circuit model employs a D-Q reluctances network. Thanks to these models, the influence of assisted PM on magnetic saturation is well considered.

Fig.2.a and b illustrate respectively the experimental acquisition of shaft speed and active power.

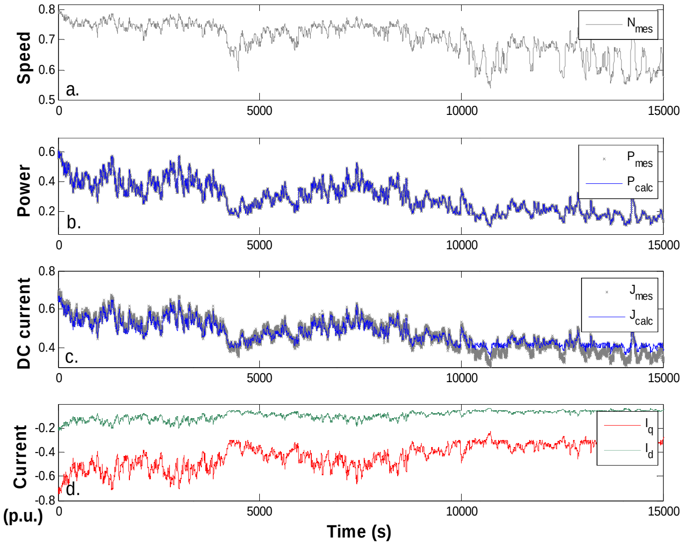

Fig. 2. Experimental measurements and control laws

Using data from measurements, an optimisation problem is formulated. The aim is to find the only solution ($I_d, I_q \text{ and } I_{exc}$) which satisfied the operating point ($V_s, I_s \text{ and } \cos(\varphi)$). Fig.2.c shows the calculated excitation current. In addition the optimisations allow finding the control strategy in the D-Q axis for a unity power factor (Fig.2.c & b) implemented in the control of the prototype. The optimizations are performed for each time step.

III. CONCLUSION

A synchronous machine assisted by PM is investigated for a direct drive wind turbine. The specificity of this generator is briefly discussed. A comparison between experimental and calculation results was done to validate the model. The control laws and the performance of this machine are obtained from an experimental wind cycle. In the final paper, the model will be detailed. Finally, the validated model will be used in an optimisation problem to determine the optimal control strategy to improve the provided energy by the generator.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 40

Slamming Load Considerations for Offshore Wind Structures

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Keywords – Slamming Load, Offshore Wind, Support Structure, Standards, Experiment

I. BACKGROUND

The offshore support structures used in the wind industry are sometimes exposed to plunging breaking waves, which can cause slamming loads featuring a high impact force during a short time [1]. When waves are likely to break on the site of the structure or in its vicinity, wave loads from breaking waves shall be considered in the design of the structure [2]. In various standards and guidelines [2-4], the slamming loads from the plunging breaking waves are taken into account. However, due to the complexity of the wave kinematics, an accurate estimation of the slamming loads is hard to achieve, and how to include these loads in the design practice is also challenging.

This study intends to give an overview of the current methods used for slamming load consideration for offshore wind applications. It also discusses the knowledge gaps of the methods and the potential for improvement based on on-going experimental research.

II. APPROACH

The slamming load consideration parts of various standards and guidelines are reviewed and compared. The comparison focuses not only on the recommended calculation methods of the slamming loads, but also on the methods to include these loads in the structural design.

The assumptions and the parameters used in these methods are summarized, and the knowledge gaps are discussed. Based on experimental data from the WaveSlam project [5], in which a 1:8 scale truss model was tested in the Large Wave Flume in Hannover, possibilities for improvement of the methods are suggested.

III. RESULTS AND DISCUSSION

Slamming loads are mentioned and considered in all the standards and guidelines. A method to estimate the load is also recommended in some of the standards and guidelines. However, in none of them, the (plunging) breaking wave is included as a dedicated load case, although the slamming load obtained with it can play an important role in the fatigue assessment of the structure.

The slamming coefficient C_s is an important parameter for the load estimation. However, this value varies from study to study. Research is still going on to determine an accurate coefficient.

In order to include the (plunging) breaking wave as a load case, its probability of occurrence should be known. This requires more knowledge of oceanography.

The slamming load estimation methods mentioned in the standards and guidelines are for cylindrical structures. For applications to other structures, the accuracy of the methods is uncertain, due to e.g. non-simultaneous impact on the structure by the breaker [5].

The investigations conducted in the WaveSlam project can lead to a better estimation of the slamming coefficient. Since the experiments were conducted with a truss structure, this approach can also validate the applicability of the slamming load estimation methods for truss structures.

First results show that most approaches described in the relevant standards overestimate the slamming forces, compared to experimental results. This is, e.g., due to the assumption that the wave hits all parts of the structure at the same time, whereas in reality these are hit in a more or less random sequence.

IV. CONCLUSION

Although the importance of slamming loads in the design of structures for offshore wind applications is emphasized by various standards and guidelines, the application in practice still encounters many challenges. With the help of experimental data, the estimation of the slamming loads is expected to be improved.

ACKNOWLEDGEMENTS

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Financial support from NOWITECH FME (Research Council of Norway, contract no. 193823) is gratefully acknowledged.

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SIMULATION OF UNSTEADY AND TURBULENT ROTOR LOADS

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Keywords – Turbulent inflow, Intermittency, LES

In this work a probabilistic inflow model, which reproduces correctly the increment statistics on small time scales and the spatial correlations, shall be implemented into the finite volume CFD Code OpenFOAM [1]. The purpose of this project is the correct description and simulation of short scale fluctuations and extreme events which are interesting for load and fatigue calculations on wind turbines.

I. INTRODUCTION

Of crucial importance with respect to the loads on the rotor blades are complex and unsteady interactions between highly turbulent atmospheric inflow and the flow over wind energy converting systems (WECS). The effective inflow angle over the entire rotor blade radius varies strongly with the disturbed inflow. 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 by precursoring with Large Eddy Simulations (LES) under a high computational cost, e.g. with the program PALM [2]. Besides this time consuming procedure, 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 [3].

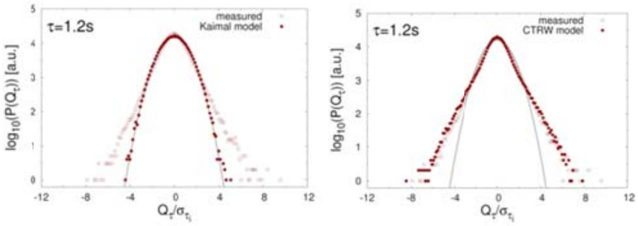

Fig.1 Torque increment statistics of the IEC Standard (Kaimal model, left) and the CTRW model (right) compared to measured data

In order to avoid those issues, a probabilistic model, the so called Continuous Time Random Walk (CTRW) model by Kleinhans/Friedrich [4,5], will be implemented in the Opensource Code OpenFOAM. 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.

II. GOALS AND ISSUES

The goal of this project is the implementation of the CTRW model in OpenFOAM as an inflow model in a 3 dimensional domain and the correct transport behaviour within this domain. Because the velocity components are calculated separately and independent of each other, the velocity field will not be divergence free and the Navier-Stokes equations are not fulfilled at the beginning. One of the main points will therefor be the correction of this model. An ansatz can be the transformation of the generated velocity field to Fourier space, where the spectrum is corrected in that way that the inverse Fourier transform leads to a divergence free field.

Different meteorological conditions and wind behaviours will be tested and a validation is done by means of LIDAR measurements.

In addition to that, load measurements on WECS will be compared to CFD simulated data.

ACKNOWLEDGEMENTS

The authors would like to thank the Bundesministerium für Bildung und Forschung and the federal state government of Lower Saxony, Germany.

The simulations were performed at the HPC Cluster FLOW (Facility for Large-Scale Computations in Wind Energy Research), located at the University of Oldenburg (Germany) and funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, BMU) under grant number 0325220.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 42

A broad sensitivity analysis of uncertainties for offshore wind turbine support structures

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Keywords – Support structure, Uncertainties, Reliability, Sensitivity analysis, Offshore

I. MOTIVATION

In structural analysis and optimization of offshore wind turbine (OWT) support structures, there is a large number of uncertainties in parameters that can have a significant impact on assessment of both fatigue and ultimate limit states. In many cases, these parameters are treated deterministically, leading to a lack of robustness in the assessment. This creates several problems: Firstly, the possibility of errors in the assessment is present. Secondly, the structural design becomes overly site-dependent, which makes mass-production difficult. Thirdly, even where site-dependency is necessary, the varying conditions for each location in a wind park means that non-robust assessments implies designs with too limited applicability.

While quite some work has gone into development of probabilistic methods applied to these systems, structural reliability in particular [1, 2], such analysis is usually limited to a smaller number of non-deterministic parameters [3, 4]. The computational demand of such analyses leads to the necessity of variable reduction, but the choices made in these cases are not made on a solid basis of which parameters have the largest impact. To this end, we propose an investigation into the sensitivity of the probability of failure to a large selection of parameters, many of these not usually studied, in order to have a more solid foundation on which future studies can be based.

II. METHODS AND RESULTS

To facilitate such a study, a simplified model of a monopile support structure for an OWT, based on the OC3 monopile [5], has been constructed. The model features decoupled load simulations for the rotor and wave loads, applied to a simple finite element model of the monopile. This allows fast assessment of the system response to an extensive number of load cases, while still providing fairly accurate results compared with more involved methods. The variables studied include environmental, structural and model parameters, and feature parameters that are often not taken into account in similar studies. Emphasis has been put into selecting realistic (where available) probabilistic models for the various parameters and a discussion of the choices made is included.

Using Monte Carlo sampling of these different distributions, a detailed assessment of the probability of failure with respect to both fatigue and ultimate limit states can be performed. From this, a sensitivity analysis for each parameter is obtained. Given a level of uncertainty for a parameter, it is then possible to give a recommendation for whether the parameter can be taken as deterministic while still maintaining a desirable level of robustness in the analysis.

III. CONCLUSION

The results demonstrate the need for probabilistic methods in general, and a sensitivity based variable selection process in particular, when any accurate design assessment or optimization is to be performed for OWT support structures. Some recommendations for how to implement, and expand on, these results in further work is included.

ACKNOWLEDGEMENTS

This work has been partly supported by NOWITECH FME (Research Council of Norway, contract no. 193823) and by the Danish Council for Strategic Research through the project “Advancing BeYond Shallow waterS (ABYSS) - Optimal design of offshore wind turbine support structures”.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 43

Application of meteorological databases for wind resources estimation in dispersed wind energy

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Keywords: dispersed energy, historical meteorological databases, estimation wind resources

The civic energy sector in last year's is developing more dynamically. Dispersed and integrated sources are gaining importance because of the lack of problems with the transmission, as well stimulation of civic engagement. However, the biggest problem and often the cause of application failures is the suboptimal implementation of such solutions due to miss proper or even lacking resources estimation.

Present work is therefore an attempt to validate the possibility of applying meteorological data bases for estimation of wind resources in citizen driven dispersed energy systems development.

I. COMPARISON OF METEOROLOGICAL AND WIND ENERGY STANDARDS

This study involves the comparison of meteorological and wind energy standards concerning wind measurements and based on high resolution wind measurements will discuss and show the discrepancies with special focus on small scale energy systems applications.

The study aims at:

- determination of the differences between the methods of measurement and analysis of wind data,
- definition of the meteorological requirements for how to measure parameters of wind measuring instruments and their accuracy, the location of equipment, duration of measurement in meteorology and wind energy and to demonstrate the differences between them,
- specification of the data needed to analyse and extrapolate the wind data from meteorological data bases,
- determination of the difference extrapolated values of meteorological data in relation to the experimental data from location turbines.
- identification of limitations that may exist in estimating the energy potential using meteorological data.

II. ANALYSIS

Restrictions and discrepancies in estimating the potential energy primarily relate to:

- insufficient density of meteorological stations,
- the availability of wind measurements on most meteorological stations in only 3 times of the day,
- the need for measurement data extrapolation from a standard height of 10 m a.g.l at hub height.

These discrepancies can cause very big difference between the estimated and real wind speed. Should be remembered that wind power is dependent on the wind speed in the 3 power. Therefore, each discrepancy radically affects the amount of energy gained.

III. CONCLUSIONS

Public historical meteorological databases (National Wether and Meteorology Agencies) can be used as a first, initial layer of input for wind based renewable systems efficiency, they are not ready for direct application.

Due to important discrepancies between the methods of measurement and analysis of wind data for weather forecast and climatology [1] and wind energy applications [2,3] such a concept has to be treated with caution.

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This study has been realized at Lodz University of Technology at the Faculty of Process and Environmental Engineering.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 44

A wind-wave coupling system for coastal storm simulations

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Keywords – wind-wave coupling, storm, coastal, WRF, MIKE 21 SW

A coupled wind-wave modelling system is implemented to simulate the costal wind and waves during storms for offshore wind farm design and maintenance purposes. We use the Weather Research and Forecasting (WRF) Model[1] and the third generation spectral wind-wave model MIKE 21 SW[2] as the atmospheric model and wave model, respectively. The nesting function in WRF enables the model resolution downscale from tens of kilometres to 1 km. And the utilization of unstructured mesh in MIKE 21 SW allows the resolution at the coastal area less than 0.1 km. Fig. 1 shows an example of the meshes and domains that are used in the system. Since the two models are using different meshes, the ESMF regridding software is used to generate the interpolation weights between them. During the coupling, WRF transfers 10 m wind speed to MIKE 21 SW while MIKE 21 SW feeds back sea surface roughness length (z_0) to WRF. At present, the approaches of parameterizing z_0 includes Janssen (1991)[3], Fan et al (2012)[4], Drennan (2005)[5], etc. The coupling system has been applied to model a series of storms of particular conditions using different z_0 schemes. In comparison, the same storms have also been simulated by the Coupled-Ocean-Atmosphere-Wave-Sediment Transport System (COAWST)[6,7]. The results have been validated with point measurements of wind and waves in the North Sea including open ocean, deep water sites such as Ekofisk and Heidrun, and coastal, relatively shallow water sites such as Fino 1 and Horns Rev. When the storms pass by, in the open ocean where the winds and waves are strong and high, the model coupling is important. While in the coastal zone, where the terrain and bathymetry is complex, the high special resolution is more important.

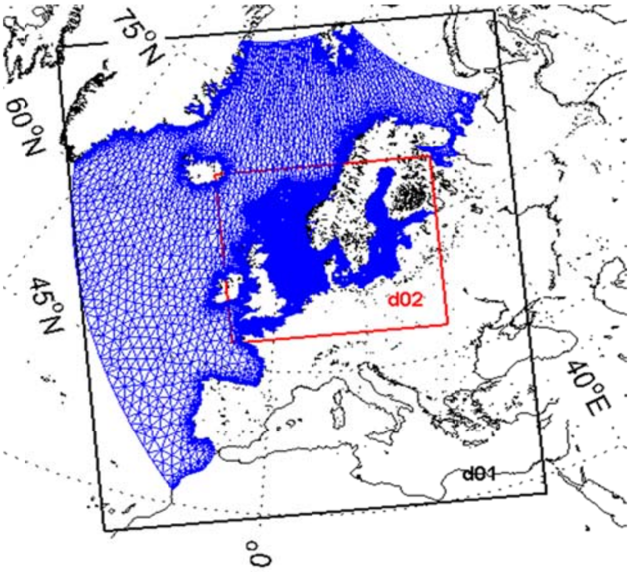

Fig. 1 The meshes and domains that are used in the coupling system

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Evaluation of methods to calculate wind speed profiles: A case study on Frøya, Norway

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Keywords – Vertical Wind Profiles, Atmospheric Stability, Power output prediction

I. INTRODUCTION

Knowing mean wind speeds at hub-heights is necessary for the design process of wind turbines. Due to a lack of measurements at this height, wind measurements are often extrapolated to the necessary height. Current standards such as IEC 61400-3 [1] and DNV-OS-J101 [2] for designing offshore wind turbines are based on onshore experience and show shortcomings in adaptation to maritime environment.

In this study, vertical wind profiles including atmospheric stability such as the Monin-Obukhov similarity theory (MOST) are compared to non-stability corrected wind profiles which are commonly used in wind industry. For this purpose, the atmospheric stability at the Skipheia measurement site is investigated and five different extrapolation methods are tested and compared. The Obukhov-length is calculated with the Richardson Gradient Method. The following extrapolation methods are tested: Power Law, Logarithmic Law, MOST, the wind profile introduced by Peña and a power law exponent by Smedman-Högström and Högström [4]. 10-min average wind speed data, measured by 2D-Ultrasonic anemometer, at 10 m are extrapolated to 70 m and compared to the actual measurement data. This analysis focuses on the deviation of wind profiles due to atmospheric stability and the impact on power output calculations. Therein, the sensitivity of input parameters such as wind shear exponent, roughness length and measurement height are investigated.

II. RESULTS

A. *Comparison of predicted and measured wind speed profiles*

Figure 1 shows the wind speed ratio between the measured and predicted wind speeds (u_m/u_p) against the thermal stratification of the atmosphere. The thermal stratification is expressed by the non-dimensional stability parameter z_1/L_O. Therefore, $z_1/L_O<0$ refers to unstable, $z_1/L_O \approx 0$ to neutral and $z_1/L_O>0$ to stable conditions.

Wind profiles which take the atmospheric stability into account show especially in very unstable and unstable conditions high accuracy. Non-stability corrected wind profiles as the Power Law and the Logarithmic Law overestimate the wind speed at 70 m. Contrarily, the prediction through stability-corrected wind profiles in stable stratification is poorly. Those profiles overestimate the wind speeds. The scattering increases from unstable to stable stratification for all wind profiles.

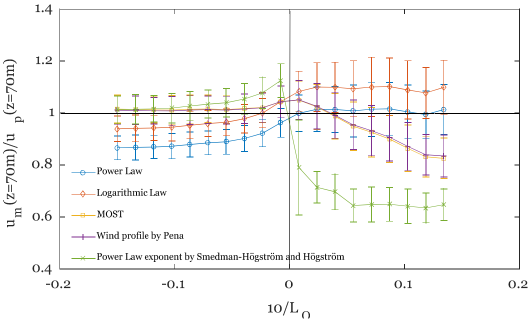

Figure 1: Bin-averaged ratio of measured and predicted wind speeds at 70m versus stability parameter at 10m

The predicted and measured wind speeds at 70 m are used to calculate the power output for a Vestas V100 1.8 MW. The estimation shows that using stability corrected extrapolation methods as MOST and the wind profile by Peña result in the lowest errors. The table below summarizes the results:

Table 1: Power output of predicted and measured wind speeds at 70 m

	Power output [kW]	Error
u(z=70 m)	1314	
Power Law	1245	5.4%
Logarithmic Law	1279	2.8%
MOST	1284	2.4%
Wind Profile by Peña	1285	2.4%
Power Law exponent by SH	1156	12.1%

III. CONCLUSION

It is found that models including atmospheric stability results in reduced deviations to the actual measurements; especially, in unstable and very unstable atmospheric stratification. Considering all stability classes the wind profile introduced by Peña [4] resulted in the highest accuracy. In addition, the lowest error on a power output calculation is found with the introduced wind profile by Peña as well as MOST. Both models achieve an error of 2.4%.

ACKNOWLEDGEMENT

This research was realized through a cooperation between TU Berlin and NTNU. I would like to thank for this possibility.

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 46

Investigation Of The Flow Over An Escarpment With Regard To Wind-Energy Research Using Small Remotely Piloted Aircraft.

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Keywords – complex terrain, flow over escarpment, airborne in-situ measurements, remotely piloted aircraft

I. ABSTRACT

The German government has made sustainable energy a high priority social task in the 21st century, and this requires high-efficiency renewable energy technologies which can compete economically with nuclear and fossil fuel energy resources. Wind energy is of primary importance for renewable electricity generation and large investments are being made in the field. In Southern Germany the best potential sites for wind energy are in complex terrain. However the wind flow in complex terrain is not well understood, and it is not easy to model or predict, which is important for renewable electricity generation.

In a joint effort by several research groups of the WindForS (www.windfors.de) competence cluster, the flow over an escarpment in the Swabian Alb is currently investigated in detail as a potential site for a wind turbine test field. A variety of instruments is installed on site, including a 100 m meteorological tower equipped with sonic anemometers, wind lidars, and a sodar/RASS system. The Environmental Physics working group of the University of Tübingen is collecting airborne in-situ measurements of 3D-wind vector, air temperature and humidity with multiple remotely piloted aircraft (MASC: Multi-purpose Airborne Sensor Carrier [1]).

Fig. 1: MASC in front of wind turbines at the test-site in Schnittlingen

The goal is to study the airflow in different regimes of thermal stability, different wind speeds and wind directions, as well as different seasons with varying land-use and thus surface roughness, in this complex terrain. As a flight strategy on days of intensive measurements, two MASCs are operated simultaneously. One is measuring the vertical profile of the undisturbed airflow upstream the escarpment, while the other MASC is measuring in a fine vertical racetrack grid directly over the cliff and further downstream, in order to detect potential flow accelerations, separation, and reattachment.

Results of these measurements will be used to initiate and validate a CFD model of the area. Preliminary results of several days of measurements will be presented.

II. CONCLUSION

Dependant on the wind direction and mean horizontal wind speed, characteristics of the flow over the escarpment vary. Areas with increased turbulence, lower horizontal wind speed, or the approximate distance to the escarpment, where the influence of the lifted flow is attenuated, can be identified.

ACKNOWLEDGEMENTS

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11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 47

Operational Fatigue Calculation from Wind Characteristics for Wind Turbine Tower and Blades

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Keywords – Fatigue, LiDAR, GH Bladed

ABSTRACT

Wind turbines are huge financial assets exposed to very extreme conditions; as a result of this, utility companies have put lifetime extension high on their agendas. Accurately determining the fatigue damage accumulated by a turbine allows for predictive scheduling of maintenance and repairs, as well as the prediction of remaining life for the turbine and its components. These factors will play a key role in any attempt to extend the operational life of a wind turbine.

This project explores the possibility of using mean wind speed, turbulence intensity and shear profile to predict operational fatigue damage to a wind turbine's tower and blades. LiDAR technology makes it possible for these quantities to be measured during operation, leading to the possibility of a lookup table approach to fatigue damage, from simulated data.

Wind turbine simulations in GH Bladed are conducted for wind files generated from different seeds, but with the same values of mean wind speed, turbulence intensity and shear profile. Fatigue damage analysis is then used to determine whether wind with the above parameters in common results in similar values of fatigue damage.

Sample Abstract for EAWE PhD Seminar 2015

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I. INTRODUCTION

Renewable energies are at the center of discussions and wind energy even more. The main purpose of the thesis is to achieve a technological leap to replace an existing electromechanical system with an embedded system using wireless technology that ensures the same functions while freeing the constraints of the original system (suppression of contact and precious metals, the associated lubrication and annual maintenance representing a significant part of the system’s cost).

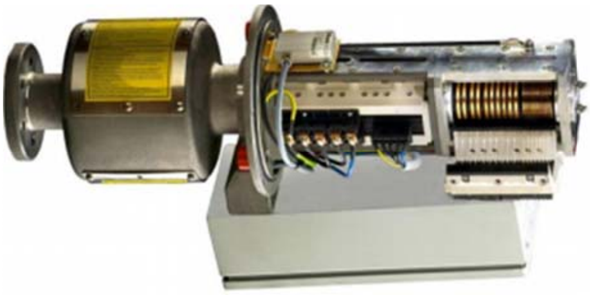

Figure1. Wired Signal Transfer System (MERSEN)

Field buses made communication and interfacing between man and machine simple. The integration of wireless technologies will make the systems more flexible, and will also reduce the cost of implementation (no wiring between fixed and mobile parts). However this integration must respect the working parameters of the existing system.

The project is part of electric transfers in complex mechanical systems. In this thesis we focus on data obtained via a wire communication bus that should be transferred between a stator to a rotor of a wind turbine.

The rotating part is subject to mechanical vibrations and thermal variations in a range from - 40°C to +100°C.

II. OBJECTIVES

The objective is to integrate intelligence within a self-configurable system to allow wireless transmission of data between a fixed and a moving part regardless the number and the type of connected buses to the input of the system. For this purpose it must consider the constraints of communication protocols. For a better integration into an existing wired system, it need to optimize the encapsulation of useful information to reduce the volume of data to be exchanged.

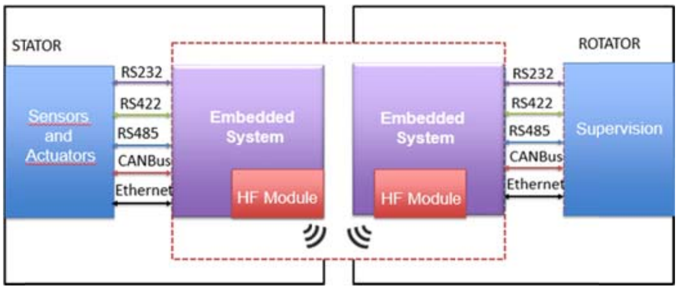

Figure2. Embedded system using wireless technology

The system must be capable of self-diagnose and automatically detecting the presence, number and type of field buses connected to the input. The objectives of such a system are: to reduce the failure risks, by using a product that incorporates its own diagnostic system, and to decrease the operating and installation costs due to the auto configuration system.

III. PROSPECTS

The main Scientific hurdle to unlock is to transfer an ethernet 1GBps channel using wirless communication.

The most important directions to explore will be Optical and RF solutions, we will add also a tool for analysis of tracks in real time and thus creating a self-diagnose tool.

11th EAWE PhD Seminar on Wind Energy in Europe
23-25 September 2015
Stuttgart, Germany
Poster 49

Derivative Action Charge Control for a Heaving Buoy, PolyWEC Device

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Keywords – PolyWEC, Control, Heaving Buoy, Dielectric Modelling

I. ABSTRACT

The aim of this project is to investigate the possibility of using the derivative of the motion of a buoy to determine the charging sequence for a dielectric polymer PTO device in an irregular sea state. The aim is to expand the operation of the PolyWEC device outside of ideal sinusoidal waves and to potentially maximise the energy production available over a varying sea state.

II. OBJECTIVES AND TASKS

- Model the WEC device. The PTO force will be discontinuous and therefore nonlinear. This means that a proper time-domain model of a buoy will be necessary instead of a frequency domain model. Constructing such a model will be time consuming and so David Forehand will supply a Matlab/Simulink time-domain model of a heaving buoy.
- Model the changing capacitance of the dielectric polymer with respect to varying physical parameters for an input sinusoidal force variation.
- Design the control strategy including charge sequence and limits, voltages and material stress limits.
- Combine the control strategy with the PolyWEC model and test operation.
- Test the model for an irregular input.

III. ADDITIONAL INFORMATION

PolyWEC devices operate by the varying capacitance of a dielectric elastomer (DE). When a DE expands, its capacitance, C, increases (as $C = \varepsilon_r \varepsilon_o \frac{A}{d}$) [1]. If the DE is charged when expanded and then kept at the same charge Q when contracted, the voltage, Vout, will increase (as Q = CV). The energy generated is then:

$$E = 0.5\,(C_{out}V_{out}^2 - C_{in}V_{in}^2) \qquad (1)$$

In previous PolyWEC designs the charging and discharging has been controlled through pressure sensors and set time intervals.

Assuming a heaving buoy device which experiences a displacement, z, depending on the wave amplitude, it will experience a 0 point of the displacement w/r/t time twice assuming a sinusoidal force. These points will be related to the wave crests and troughs and thus to the maximum and minimum capacitance of the DE respectively.

It is the objective of this project to design a control strategy where the charging and discharging is determined by $\frac{dz}{dt}$. This would theoretically allow for optimal energy harvesting through a varying amplitude and phase sinusoid and then its application in an irregular or random sea state could be examined.

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11th EAWE PhD Seminar on Wind Energy in Europe
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Poster 50

WEC Array Modelling Benchmarking Study

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Keywords – Wave energy converter array, benchmark study, heaving buoy

I. ABSTRACT

The Wave Energy Converter Array Network (WECAN) is an internationally leading grouping of researchers who are interested in the hydrodynamic modelling of arrays or farms of wave energy converters. This modelling can be analytical, numerical or physical (i.e. in wave tanks). The WECAN group has annual one-day meetings and this year the 8th annual one-day meeting was held in Queen’s University Belfast on Thursday 16th April. As part of this meeting, a comparative benchmarking study was proposed to compare the results of different array modelling tools applied to a specific test case. This test case consisted of two closely-spaced heaving buoy WECs which would interact with each other due the diffracted and radiated waves that they produce.

The WEC to be modelled is an axisymmetric cylinder with a hemispherical end, as was used in the WECwakes [1] and PerAWaT [2] projects. To simplify the analysis the motion of the cylinder is constrained to move in heave and the only external force in the heave direction is due to a coulomb damper, which applies a constant force that opposes the motion of the cylinder. In each sea-state the coulomb damping force should be the same for both WECs and set to maximise the power capture of the isolated WEC.

The simple time domain model used for the benchmark is created exploiting the Cummins’ equation [3] in the form

$$(m+m_a)\cdot\ddot{z}(t)+\int_0^t k_R(t-\tau)\cdot\dot{z}(\tau)\cdot d\tau + k\cdot z(t)=F(t)-F_{PTO}(t) \tag{1}$$

Performances of the WEC array are calculated for different sea-states using a model developed in Matlab and Simulink.

The aim of the project is to perform this benchmarking study using a numerical model of the above equation. From the results of this project, the suitability, accuracy and computational efficiency of the numerical method will be compared against those of other computational methods applied to this problem.

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Poster 51

Condition Monitoring and Fault Diagnosis of Wind Turbines Using Generator Output Signals

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Keywords – Condition monitoring, wind turbines, mechanical failures, signal processing, electrical generator

The work reported here is concerned in developing online non-intrusive condition monitoring (CM) and fault detection methods for wind turbines (WTs). The proposed methods use only the electrical measurements that have already been used by the control and protection systems of WTs; meaning that no additional sensors or data acquisition devices are needed. Generator output signals-based CM and fault detection techniques have great economic benefits and the potential to be adopted by the wind energy industry to detect mechanical failures in the generator, gearbox or indeed other elements of the drive train. However, detecting faults in these latter subassemblies by the analysis of potential fault frequencies is more challenging.

I. INTRODUCTION

Several methods for WT CM have evolved over time but the most prominent techniques are vibration, oil, temperature, torque, acoustic emission, fibre optic, and electrical output. However, each technique requires additional and expensive sensors or specialized tools. Moreover, there is a price to pay to access each WT in order to install the sensors, as well as lost revenue due to the power outages associated with equipment installation and maintenance. Furthermore, it has been demonstrated that sensor failures contribute more than 14% of the total failures in WTs [1]. In such cases, the WTs are turned off and contribute downtime even at simple faults due to the wrong information collected from those sensors which are used for CM. Generator output signals have been proven as a viable CM method for the early detection and tracking of electrical faults in the generators [2].

II. APPROACH

A WT model is built using the MATLAB/Simulink environment. Various fault scenarios that involve changing the fault types such as breaking in gear teeth and short circuits in stator windings are studied, and then the possibility of using current signals which measured from the terminals of the generator is investigated to detect the faults. A signal processing algorithm based on Fast Fourier Transform (FFT) is applied to extract the amplitude of fault frequencies.

III. RESULTS

Figure 1a gives the power spectrum of FFT for a healthy WT. It can be easily observed that no sideband frequency found near the fundamental frequency in the spectrum. Thus, the power spectrum indicates that WT is free from faults. The spectrum of WT under mechanical and electrical fault conditions are shown in Figure 1b and Figure 1c respectively, both scenarios clearly indicate frequency components near fundamental frequency. These frequency components are indication of the presence of faults in WT.

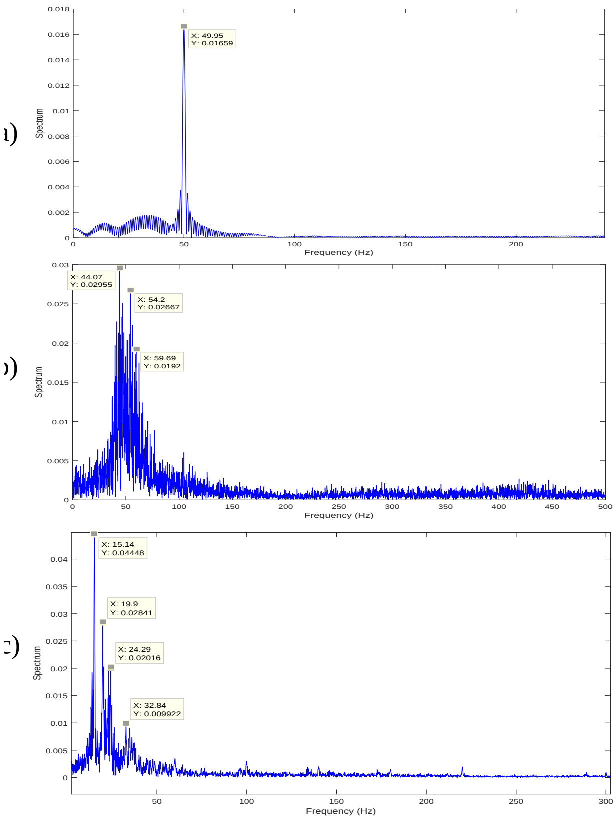

Fig. 1 FFT analysis of stator current for (a) healthy WT (b) mechanical fault (c) electrical fault

IV. CONCLUSION

Simulation results have shown that the stator current signals have characteristic frequencies that give evidence of mechanical and electrical fault. Moreover, FFT is used to extract properly the features related with characteristic defect frequencies. Further work will be validated experimentally on a WT drive train test rig to investigate CM signals in the laboratory.

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Mechanical-level Hardware in the Loop Simulation for a Wind Turbine Nacelle Test Bench

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Keywords – Wind Energy, Mechanical-level Hardware in the Loop Simulation, Inertia-Eigenfrequency Emulation, Nacelle Test Bench, Wind Turbine Control

This paper presents concepts for Mechanical-level Hardware in the Loop (MHiL) simulation applied to the new Wind Turbine Nacelle Test Bench at the Center for Wind Power Drives (CWD) of RWTH Aachen University.

I. INTRODUCTION

The number of wind turbine (WT) installations has grown significantly in the last years motivated by the need for renewable energy sources to establish a sustainable supply in the future, particularly with regard to the world's fast growing demand. One of the most promising research approaches to reduce the cost of wind energy is to minimize the wind loads on the turbines by adjusting control and design. In order to achieve that, the system performance in the field has to be analyzed in detail which is not possible as the wind over the rotor plane cannot be measured precisely. Besides, the measurements are not repeatable. To overcome these difficulties the CWD built a Nacelle Test Bench with MHiL, Power- (PHiL), and Signal-level HiL (SHiL) simulation to investigate the WT drive train behavior [1]. Additionally, this feature provides the opportunity to close the wind turbine control (WTC) loop and thus to take its impact into account.

II. NACELLE TEST BENCH WITH HIL SIMULATION

Fig. 1: Nacelle Test Bench

The above mentioned test bench is depicted in Fig. 1. The rotor shaft (yellow) of the dismounted WT nacelle is connected to the load application system (LAS) consisting of a direct drive (dark gray) and a non-torque load unit (NTL, light gray), while the generator with integrated gear (blue) is connected via the inverter system and the transformer to the electrical grid. The mechanical and electrical loads are calculated by the MHiL and PHiL system, respectively. The missing sensors and actuators are emulated by the SHiL system whereby the original WTC can be tested as illustrated in Fig. 2.

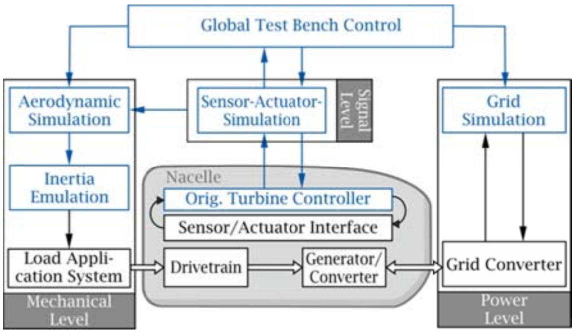

Fig. 2: HiL Concept of the Nacelle Test Bench

III. MHIL WITH INERTIA-EIGENFREQUENCY EMULATION

The MHiL comprises the aerodynamic simulation and the inertia-eigenfrequency emulation. The aerodynamic simulation calculates the wind loads based on the given wind speed as well as the pitch and yaw angles. The inertia emulation decreases the aerodynamic torque by the inertia-related torque of the missing rotor so as to reproduce the original drive train transmission behavior adequately and prevent an unstable WT pitch control loop [2]. Furthermore, such pure inertia emulation is extended towards an inertia-spring-damper system in combination with a state feedback control so that the first and second eigenfrequency of the coupled system are also reproduced [3].

IV. CONCLUSION AND FUTURE WORK

The MHiL approach has been proved correct both in simulation and experimentally on a smaller similar test bench in a recent project. The aim of the current project is to develop it further and adapt it to the new test bench. Finally, a 2.7 MW WT shall be mounted and run in all operation conditions to validate the MHiL concept.

ACKNOWLEDGEMENTS

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Vibration Analysis of Multi-Stage Epicyclic Gearboxes

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Keywords – wind turbine, gearbox, condition monitoring, torque loading, vibration analysis, frequency spectrum, fault detection.

Reducing the cost of energy is a key issue if wind power is to become a major source of electricity and compete with conventional generation. Currently in the UK there is a trend towards bigger machines located in harder to reach offshore locations. As a result condition monitoring of wind turbines is an increasingly important area of research and development to improve availability and reduce operation and maintenance costs. Condition-based maintenance can provide significant savings but commercially available condition monitoring systems are limited by the time consuming and costly data interpretation that is required for meaningful output [1]. Studies of wind turbine reliability show that gearboxes failures are associated with particularly lengthy downtimes due to complex logistical and technical repair procedures [2]. Offshore, these repairs can only be performed in favourable weather conditions. Common gearbox failures include tooth wear and misalignment.

The University of Strathclyde's gearbox condition monitoring test rig consists of two 3-stage epicyclic gearboxes connected back to back, with a mechanical loop to circulate power, and is capable of loop powers up to 200kW. Data capture will be performed using a National Instruments CompactRIO, which has four high-bandwidth accelerometers, as well as several thermocouples for temperature measurement. The main analysis of the captured data will involve observing the frequency spectrum, picking out gear meshing frequencies, which will vary with the gearbox speed, and any possible resonances. The influence of the torque loading and the oil temperature on the vibration signature will also be examined. Small imbalances will be added to the rotating components and the accelerometers will be moved to different positions on the gearboxes.

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Survey of Wind Turbine Inspection

Abstract for
EAWE PhD Seminar 2015

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Keywords – EAWE PhD Seminar 2015, Non Destructive Testing (NDT), Wind Turbine Components

I. ABSTRACT

As wind turbines age they will need a degree of structural inspection, but the extent and focus of this is not clearly understood.

This project will survey the inspection requirements of the wind energy sector, looking at what inspection is currently done and what is likely to be needed in the future. Furthermore, the project will compile a database of turbine failures (onshore and offshore) and attempt to classify them into groups. These groups may include:

1. BLADE LEADING EDGE DEGRADATION
2. BLADE STRUCTURAL FAILURE (LIST CAUSES, SUCH AS WATER INGRESS).
3. MECHANICAL FAILURE OF MOVING PARTS, SUCH AS GEARBOXES
4. CORROSION OF THE TOWER
5. ISSUES WITH THE TOWER WELDS
6. PROBLEMS RELATING TO THE FOUNDATIONS / GROUT.

Secondly rotor blades are analysed in greater detail, i.e. blade failures as well as its financial implications are presented under given scenarios. The estimated costs of these scenarios are further compared to the application of NDTs, in terms of inspection and maintenance intervals over the lifetime of a blade.

II. INDUSTRIAL PARTNERS

This project will be supported by the Research Centre for Non-Destructive Evaluation (RCNDE), a consortium of universities and end users of NDE http://www.rcnde.ac.uk/. RCNDE includes E.ON who have a keen interest in wind turbine inspection.

III. CONCLUSION

To be developed…

ACKNOWLEDGEMENTS

This template was written at the University of Stuttgart. The document is based on the template of the EWTEC 2013 and the guidelines of the IEEE.

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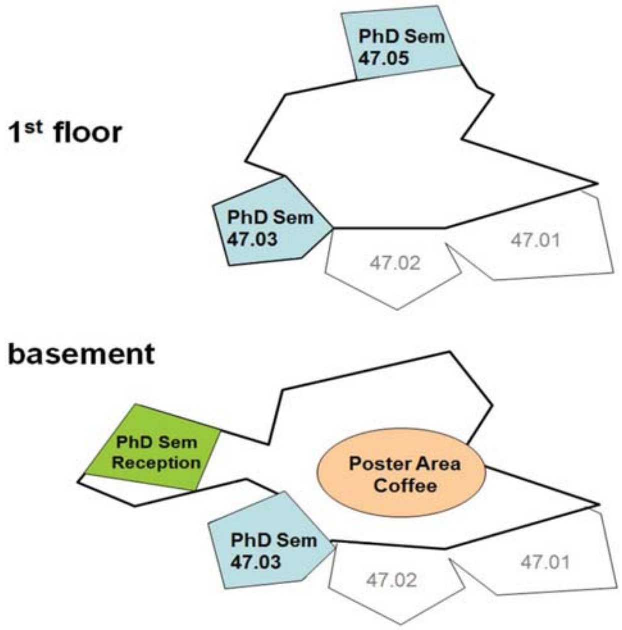

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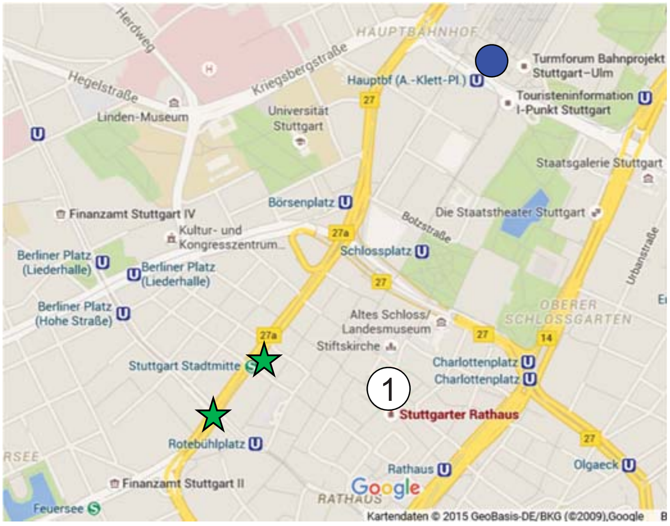

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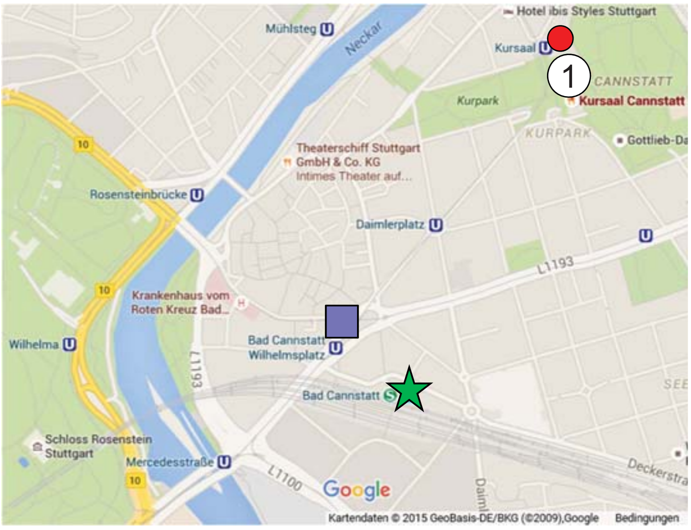

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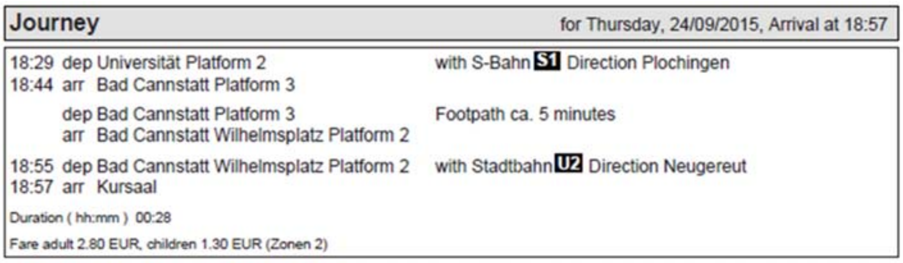

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