eawe
european academy of wind energy

VUB VRIJE UNIVERSITEIT BRUSSEL

14th EAWE PhD seminar

Brussel, Belgium,
18-20 September 2018

With the support of:

PARK WIND

Contents

1 Committees

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14	Wim Munters	KU Leuven
15	Cédric Peeters	Vrije Universiteit Brussel
16	Steffen Raach	Universität Stuttgart
17	Maik Reder	CIRCE
18	Mark Richmond	University of Strathclyde
19	Pedro Santos	DTU Wind Energy
20	Luca Sartori	Politecnico di Milano
21	Helene Seyr	NTNU Trondheim
22	Quanjiang Yu	Chalmers University of Technology

2 Plenary Sessions

2.1 Academic Keynote

Understanding and controlling turbine wakes

Start: 18/09/2018 09:45 — **Room: D.0.02**
Carlo L. Bottasso — Wind Energy Institute, Technical University of Munich

Wakes couple wind turbines within a power plant, and affect power production and loading of downstream machines. Recent efforts from several research groups worldwide are shedding new light on wakes and their behavior. This new insight is crucial not only for a more accurate modeling of wakes, but also for controlling their path and recovery with the final goal of mitigating their effects. In this talk we will review some recent work in this area, with a focus on the interplay between numerical simulations and experiments in explaining some of the complex characteristics of wind turbine wakes.

2.2 Meet the Industry

Meet the Industry

Start: 19/09/2018 13:00 — **Room: D.0.02**

Encouraged by requests at the past PhD seminar in Cranfield we are happy to announce the new format "Meet the Industry". This session will be kicked off by an introduction by WindEurope discussing the state of the industry. Afterwards, the room is given to companies of the wind energy sector such as manufacturers, operators and developers to introduce their businesses and share their view on the coming years and how they evaluate the role of research to reach their goals. We are excited for discussions within the following coffee break!
Don't miss this unique momentum to meet and network with industry representatives, so pack up those business cards!
This session was made possible with the support of WindEurope.

Start	Presenter
13:00	WindEurope
13:25	ZF
13:40	Jan de Nul
13:55	Parkwind
14:10	Inno Energy
14:25	OCAS
14:40	Siemens Gamesa
14:55	Networking break

2.3 Industrial Keynote

Offshore wind – growing ever bigger

Start: 19/09/2018 16:30 — **Room: D.0.02**
Cedric Vanden Haute — Lead structural engineer, Parkwind

Offshore wind energy is rapidly developing as a reliable source of renewable energy for large parts of Europe. In this talk the ever growing scale of offshore wind and the resulting new challenges faced from the developer's side will be hihglighted.

2.4 Closing session

Closing and feedback session

Start: 20/09/2018 11:30 — **Room: D.0.02**

3 Senior Ph.D. Workshops

3.1 Tuesday 18 September

3.1.1 Working with SCADA data

Start: 18/09/2018 14:15 — **Room: D.0.02**
Elena Gonzalez and Sofia Koukoura — UCLM/University of Strathclyde

Ok, you know how the wind blows... but, how do wind turbines really work on site and how do they fail? In this workshop you will learn about the challenges related to operation and maintenance of wind turbines and the current efforts towards reducing their related costs, including predictive maintenance strategies. Aspects of condition monitoring solutions will be covered, along with practical examples from real wind turbine case study failures. Machine learning, diagnostics, SCADA, vibrations... if you want to learn more about these buzzwords join our session!

3.1.2 Marine Ecology

Start: 18/09/2018 14:15 — **Room: E.0.05**
Paul Causon — Cranfield University

Offshore wind turbine foundations are rapidly colonised by marine organisms, which form complex and highly dynamic communities. This process of biological colonisation, often referred to as biofouling or marine growth, can roughen the foundation and increase cross-sectional surface areas, affecting loading on fixed turbines. However, it is not yet understood how biofouling would affect floating turbines and their mooring systems. In addition, although it is often thought to be environmentally benign, or even beneficial, much like planting a forest in a field, an offshore wind farm will change the ecosystem. By forming a network of artificial reefs, wind turbines might have profound effects on processes and functions associated with the local marine ecosystem. Although there may be benefits to the environment, there may also be unforeseen trade-offs. But can we expect the same effect with floating structures installed further offshore and in deeper waters? In this workshop we will address the challenges that wind farms present for marine ecosystems; as well as the challenges marine ecosystems present to the structures themselves. We will compare fixed and floating turbines and discuss uncertainties facing new technologies as we push further offshore.

3.1.3 Airborne wind energy

Start: 18/09/2018 14:15 — **Room: E.0.06**
Thomas Haas — KULeuven

Airborne Wind Energy is an emerging technology in the field of renewable energy. The key idea is to harvest high altitude wind energy by means of tethered airborne systems, such as aircrafts or kites. The technology makes it possible to operate at heights exceeding those of conventional wind turbines, thus tapping into untouched wind resources. In this seminar, the underlying working principles along with the historical development of the technology will be introduced. Further, several concepts, in particular the on-board turbine-based power generation and the ground-based pumping-cycle power generation, and their practical implementations will be presented. Finally, the challenges faced by the Airborne Wind Energy community and the proposed solutions will be discussed.

3.2 Wednesday 19 September

3.2.1 Turbine Modelling

Start: 19/09/2018 9:30 — **Room: D.0.02**
Clemens Hübler and Benedikt Hofmeister — Leibniz Universität Hannover

Wind turbines are complex structures that are designed using simulation models. However, wind turbine components like blades or foundations can hardly be modelled independently of each other, but should be analysed using a coupled aero-servo-dynamic model in time-domain that takes turbine, tower, substructure, foundation, etc. into account. That is why this workshop deals with coupled wind turbine modelling. It covers an introduction in the state-of-the-art modelling. Afterwards, some limitations – concerning accuracy, deterministic parameters, and simulation data – are discussed in details.

- State-of-the-art turbine modelling: FAST, Bladed, or HAWC2.
- Limitations of state-of-the-art models and more accurate alternatives
- Turbine reliability: Deterministic vs. probabilistic modelling
- Can numerical modelling tell us everything?

3.2.2 Working with LiDAR data

Start: 19/09/2018 9:30 — **Room: E.0.05**
Elliot Simon — DTU

The wind LiDAR workshop is targeted towards individuals who would like to improve their understanding of LiDAR technology as well as get a chance to work with real measurement data. As such, it will feature both an informational and hands-on component.

The schedule includes:

- General introduction to LiDAR for wind energy
- Overview of available systems (commercial and research)
- Summary of different measurement techniques
- Tutorial/exercise using real measurement data

Example code (using Python v3) will be provided in the form of a Jupyter notebook. You can either simply follow along, or join on your own computer to modify and extend the analysis. For the latter, it would be helpful to come with the latest build of Anaconda already installed (Python 3.6): https://www.anaconda.com/download/

3.2.3 Vertical Axis Wind Turbines

Start: 19/09/2018 9:30 — **Room: E.0.06**
Bruce Leblanc and Vincent Leroy — TU Delft/EC Nantes

The development of floating wind turbines has given rise to concepts based on a vertical axis rotor. These rotors are less prominent in current bottom-fixed application but show interesting features for floating applications. For example, Vertical Axis Wind Turbines (VAWTs) can have lower centers of gravity and thrust which improves their stability at sea. The overall Cost of Energy may thus be lower than for Horizontal Axis Wind Turbines (HAWTs). However, their aerodynamics and dynamic behavior at sea can be very complex to model.

4 Oral Presentations

4.1 Tuesday 18 September

4.1.1 Rotor and Aerodynamics 1

Start: 18/09/2018 11:00 — **Room: D.0.02** — **Chair:** Bruce Leblanc

11:00 (23) Challenges and Opportunities in Wind Farm Modelling Using the Lattice Boltzmann Method: A Review
Henrik Asmuth — Uppsala Universitet

In recent years, large eddy simulations (LES) based on the lattice Boltzmann method (LBM) have become a viable alternative to implementations using classical Navier-Stokes formulations. The main advantages of LBM-LES are the simplicity of the numerical scheme and the suitability for extreme parallelization, both leading to significantly increased computational performance. Yet, as opposed to other fields such as automotive aerodynamics or biomedical flows, applications of the LBM to atmospheric boundary layer flows, and specifically wind farm simulations, are still rare. In this discussion paper we shall outline the opportunities and possible challenges for LBM-LES in the field of wind farm modelling. A review will be given on essentials for this application in a lattice Boltzmann framework such as sub-grid scale models, near-wall treatment, the coupling to temperature fields and the use of wind turbine actuator models. Also, the suitability of typical wind farm cases for LBM implementations on GPGPUs (General Purpose Graphics Processing Units) is discussed including two exemplary estimations of computational performance compared to cases found in the literature.

11:15 (33) High-Fidelity Analysis of Wind Turbines in Complex Terrain with Focus on Solver Coupling and Structural Modeling
Philipp Bucher — TU Munich, Chair of Structural Analysis

Operating wind turbines in complex terrain introduces additional difficulties in the simulation process mostly due to the turbulent flow conditions. High-Fidelity simulation are needed to capture all the effects resulting from the operation of the turbine in such environments. This means a CFD-analysis is required to accurately model the wind, coupled with a CSD-analysis to compute a detailed structural response of the turbine.

The finite-element method is used for the CSD-analysis, the turbine is modeled with shell elements. Such models can accurately describe bending-torsion interactions and changes in the cross-section of the blades. Furthermore it is possible to model the composite-material of the blades, which could be used for fatigue analysis.

To simulate the interaction of the wind with the turbine, the CFD solver (modeling the wind) is coupled with the CSD solver (modeling the turbine) in a partitioned Fluid-Structure Interaction simulation. This brings additional technical difficulties, one of them being the data exchange between the two solvers. Special mapping techniques are necessary to deal with the usually non-matching meshes on the interface of the solvers. Due to the high computational effort, high-fidelity simulations are usually run on large computer systems such as clusters or supercomputers. This also requires special treatment of the mapping because the domains and therefore also the interface are distributed over the compute-nodes of these computers.

For constant inflow conditions the interaction between the wind and the turbine is usually rather stable, which means that it is sufficient to exchange the data between the solvers once per time-step. Due to the unsteady inflow conditions in complex terrain this is not longer suitable, the data has to be exchange several times per time-step, until convergence is achieved.

11:30 (40) Design of wind turbines for low wind
Helena Canet Tarrés — TU Munich, Wind Energy Institute

Important efforts are being made to increase the penetration of wind energy far beyond the actual levels. However, in some parts of Europe, such as Germany or northern countries, an excess of wind generation at negative prices and insufficient generation at high prices can be spotted. This work investigates the design of wind turbines to solely operate at these low wind speeds. To this scope, real wind speed data and spot market price of different German regions is collected to establish a relationship that can be considered in the cost of energy merit function that governs the optimization.

11:45 (24) Electronic TellTale (E-penon) sensor to detect flow separation on wind-turbineś blades
Antoine Soulier — Centrale Nantes, LHEEA Mer Agitée

Wind turbineś inflow conditions are highly unsteady and inhomogeneous due to, for instance, atmospheric turbulence, wind shear, blade rotation in front of the mast, and rotor misalignment. These perturbations contribute to increase fatigue loads which limit the wind turbine´s life-time and decrease the energy extraction. These perturbations lead in particular to aerodynamic flow separations on the blade. However, most of wind sensors are located on the nacelle while it should be more appropriated to monitor the dynamics of flow separation on the blade itself. Nowadays, there is no such sensors, used on productive wind turbine blades. A sensor designed by Mar Agitée to detect the flow on the blades is used in this study. The electronic TellTale is an electronic device mounted on the aerodynamic surface with an embedded strain gauge on which a silicone tail is attached. The aim of the study was to understand the behavior of the sensor regarding to the detached flow. Wind tunnel tests were performed in an aerodynamic wind tunnel in LHEEA, Centrale Nantes with a modified NACA-654-421 profil and a scale-model of the electronic TellTale sensor. TRPIV was used to study the flow around the profile, its wake and the interactions with the e-TellTale.

4.1.2 O&M and Condition Monitoring 1

Start: 18/09/2018 11:00 — **Room: E.0.05** — **Chair:** Cédric Peeters

11:00 (38) Identification of unexpected patterns and relationships in wind turbine SCADA data using dynamic structural equation modeling
Baher Azzam — RWTH Aachen

The high cost of downtime for wind turbines drives the on-going efforts of researching the factors resulting in failure of turbine components. Knowledge of these factors is important to eliminate the failures causes and prevent their occurrence. SCADA data generated by wind turbines throughout their operation gives an insight into the states of the most critical drivetrain components and the experienced external conditions as they develop over time. The large quantity of multidimensional SCADA data generated by turbines offers opportunities to find novel, unexpected relationships between the different states of the drivetrain components. This research aims to analyse SCADA data collected from a 6 MW turbine at the North Sea during a year of operation to identify novel relationships between the states of its components. K-means clustering was performed on the data at hand and proved useful in identifying periods of nonoperation in an unsupervised manner. Eliminating such periods was a necessary first step of data analysis since feeding them into the machine learning models could lead to inaccurate relationships between variables. For example, a number of data points with high values for wind speed and very low/zero power output values can distract from the fact that wind speed and power output are positively related. Several machine learning techniques such as self-organizing maps and random forests were then used to identify relationships, which could be compared to the results from SEM. Using t-distributed Stochastic Neighbour Embedding (t-SNE) to cluster the resulting data points, 33 clusters were identified and examined leading to identification of an inverse relationship between power output and input temperature of gearbox lubricant. The extended abstract and presentation will present first results of the comparing methods, showing the methodsṕotential, the identified relationships between the variables from the SCADA data e.g. the already identified inverse relationship between power output and gearbox input oil temperature. It will also discuss the methodology for reaching said relationships and the challenges faced when processing and analysing the SCADA data and the respective solutions.

11:15 (50) SCADA based anomaly detection - challenges for automated ANN application
Simon Letzgus — TU Berlin

SCADA data analytics has attracted considerable research interest for monitoring wind turbine condition without additional sensors and equipment. Especially normal behavior modelling based on artificial neural networks (ANNs) has shown promising results, often being able to detect malfunctions months before they developed into costly component faults. Moreover, structural conditions, such as available computing power, data storage cost and the awareness of SCADA data within wind industry have developed in favor of a broad application. However, such models are still not being widely applied in the field. Therefore, the contribution identifies and discusses selected lessons learned from applying ANN based normal behavior models to a large and heterogeneous turbine fleet. Challenges that will be touched upon are feature selection, automated training data validation and robust alarm interpretation. The contribution aims to spark the discussion among SCADA data analysts from academia and industry, on how to improve applicability of the above-described approaches.

11:30 (52) Machine learning method for IPC controller selection from wind features
David Collet — IFP Energies Nouvelles

The wind energy production has been exponentially growing in the last decades, with about 539 GW globally installed in 2017 out of 94 in 2007. In order to achieve the COP21 objectives in terms of CO2 emissions, the growth of the wind energy industry is expected to keep rising. Such a large development implies a consistent cost in terms of raw materials extraction and process which limits the wind power capacity increase rate. Thus, there is a need for reducing turbine CAPEX or/and OPEX, and this could be achieved using an innovative and advanced control strategy that aims to reduce fatigue loads, while maximizing the energy production.
This is precisely this issue that we are addressing through my PhD thesis at IFPEN, in collaboration with Gipsa-Lab and CNRS. Above rated wind speed, the main objectives of variable speed wind turbines control are to regulate rotor speed and generator power. This is currently achieved by maintaining the wind turbine in its operating range and the output power signal as constant as possible.
The recent research on LiDAR measurements and wind field reconstruction, allows to have more accurate knowledge of wind spatio-temporal variations in rotor plane with time preview. This enhanced information on the main exogenous variable of the system gives way to a new generation of controllers. The latter can anticipate the pitch angle to apply on each blade individually, in order to minimize a cost function corresponding to wind turbine fatigue, while regulating the turbine rotor speed and power. To reduce fatigue cost on the wind turbine using control and wind field reconstruction from LiDAR, we are currently validating an innovative solution, using machine learning and estimated wind features to select the best suited controller among a discrete set of pre-designed controllers.

11:45 (111) Automatic Detection of Events Critical for Drivetrain Monitoring Using Machine Learning
Pieter-Jan Daems — Vrije Universiteit Brussel

The installed capacity of offshore wind energy has increased drastically over the last years. At present day, a big challenge remains to reduce the Operation and Maintenance (O&M) costs of offshore wind farms. An up-scaling trend is seen within turbines to tackle this problem, decreasing the number of needed machines per Mega-Watt. This however results in bigger (not quasi-static) loads on turbine components that can significantly influence machine lifetime, presenting new design challenges. These are tackled by optimizing the performance of turbines using simulation models. It needs however to be verified if these simulations are a correct representation of reality. To this end, Operational Modal Analysis (OMA) is a commonly used tool. The use of OMA however requires several pre-processing steps, which are dependent on the operating regime of the turbine. The detection of run-up and coast-down events is therefore critical to be able to automate OMA schemes. During this presentation, a methodology based on pattern recognition and machine learning approaches will be discussed to detect these events. The working principles of the algorithm will be illustrated using SCADA 1-second speed data of offshore wind turbines.

4.1.3 Wind and Turbulence 1

Start: 18/09/2018 11:00 — **Room: E.0.06** — **Chair:** Wim Munters

11:00 (47) Characterization of wind turbine siting parameters in complex terrain using Multi-Lidar measurements

Pedro Santos — DTU Wind Energy

When considering complex terrain, the wind resource characterization has to account for site dependent topographical effects. The present-day solution of commercial Doppler laser remote sensing technology, called Lidars, has to rely on the necessity to average the wind over a large volume, which presume a horizontally homogeneous flow. This work aims to present a full-scale experiment planning and preliminary results of flow characterization in complex terrain using Multi-Lidar measurements towards a new approach for matching *in situ* measurements and numerical modelling to reduce the uncertainties in wind resource assessment. The Alaiz Experiment is located in Navarra (Spain), at a site consisting of a mountain range of 1000m a.s.l. To the North, aligned with the prevailing wind, measurement equipment are located at a valley 500m lower in altitude. The experimental layout aims to provide a high-quality dataset from six met masts as well as five Windscanner systems spread on the valley to scan the area north from the mountain within a 5km radius. The Multi-Lidar scanning patterns can provide 2D and 3D wind reconstruction at several points of interest, e.g. the mountain top. The intersecting scans used for wind speed reconstruction can be rendered into virtual met masts or transect lines that follow the terrain at a certain height, 125m in this work. The continuous real-time monitoring of all five systems allowed to identify and solve hardware failures within 24h, but also spot flow patterns of interest as well as periods with low clouds and fog, which compromise the range of the scans. Results show that the Windscanner system is capable of capturing main flow patterns as speed-ups on ridge tops and valley flow between ridges, with valid data from 100m to 3500m. Therefore, this work successfully presents all the steps for a Multi-Lidar campaign, from a research objective, measurement planning, logistics & deployment to flow pattern results. The next steps will be coupling these results with meso-to-micro scale modeling in a collaborative blind test format, open to contributions from the scientific community.

11:15 (54) Investigation into Boundary Layer Transition on the MEXICO Blade

Brandon Arthur Lobo — University of Applied Sciences Kiel

Boundary layer transition studies have been carried out using the unsteady surface pressure data from the EU project MEXICO and the later New-MEXICO experiment at the DNW wind tunnel, which have been subject of investigation in IEA Wind Task 29 Mexnext. The experiments were conducted on a specially designed 4.5 m diameter wind turbine with and without zig-zag roughness strips applied to the outboard part of the blades. Standstill tests with the MEXICO blades were also conducted at the TU Delft LTT wind tunnel including oil flow and stethoscope tests.

Transition is determined by detecting and observing the growth of Tollmien-Schlichting (TS) packets through a Power Spectral Density plot in the frequency domain. The expected frequency range of these waves is determined using a database developed by Van Ingen. The transition results are compared to those determined by RFOIL, a program for the analysis of aerofoils which uses the eN method for transition detection. Generally a good agreement was observed between measurements and predictions. In addition to that the effectiveness of the roughness strips was studied. The result is a unique database in controlled conditions to be used for validation and improvement of transition modelling of wind turbine blades.

11:30 (62) Coupling the actuator disc flow model to a high order meteorological LES solver in order to study wind farm flows over complex terrains

Pierre-Antoine Joulin — IFP Energies Nouvelles, Météo France

In the coming years, wind farms will extend to complex terrains as oceans and mountains. In order to study their wakes with the aim of optimising energy production and evaluating the potential environmental impact, a numerical coupling was done between actuator disc flow model and a meteorological solver. This solver is Meso-NH, a meso-scale (Meso) atmospheric and non hydrostatic (NH) research model based on the Large Eddy Simulation (LES) framework. It includes high order physics and chemistry models. In this study, the Generalized Actuator Disc (GAD) flow model (without rotation) has been implemented and coupled with Meso-NH to simulate wind farm flows. This well-known model represents the turbine as a motionless porous disc applying a thrust force in the flow. An experimental study [Tian et al., 2013] and a numerical simulation [Shamsoddin & Porté-Agel, 2016] have been performed on five wind turbines sited on a two-dimensional hill in a wind tunnel. To validate our LES-GAD model, simulations have been set up to compare with the results of the available dimensionless data. It includes a scaling study to simulate the flow in a full scale. As a first step, the flat terrain domain was tested to infer the scaled roughness length. Next, the two dimensional

gaussian hill was placed to ensure that the scaled mean wind profile and turbulence intensity profile fitted well with data at various positions. Finally, wind turbines have been included to analyse their wakes. As a result, the implemented LES-GAD model seems to give a correct representation of the atmospheric boundary layer and wind turbine wakes, regarding wind velocity deficit and turbulence intensity generation.

11:45 (105) Modelling the influence of atmospheric stability on the wind resources of a complex terrain site
Chuka Nwabunike — Loughborough University

Assessing the wind flow over complex terrain sites has proven to be more challenging than the trivial flat terrain sites that the wind industry is used to. This terrain complexity often leads to increased uncertainty in the assessment of the wind energy potential of the investigated site. It is therefore important to understand the behaviour of the wind flow in relation to some physical parameters such as atmospheric stability as this could help reduce the uncertainties. In this paper, the influence of atmospheric stability on the wind resources of a complex terrain site will be assessed. Data from four meteorological masts (A1, A2, B1, and Flu) that are within approx. 15 km radius from one another will be used. A1, A2, and B1 are monitoring met masts in an existing wind farm while Flu is a scientific met mast installed for research purposes. Depending on the parameter, Flu measurements were carried out at different heights (ranging from 1.5 m to 10 m) while A1, A2, and B1 measured at only one height (69 m). Monnin-Obukhov-Length (MOL) was calculated from the Flu data and was used to infer stability across the site. The met mast data will then be analysed to investigate the influence of atmospheric stability on the wind resources of this site. This will also be modelled by extracting point data from the site which will be used to form the terrain geometry. The wind flow over this geometry will be simulated for different atmospheric conditions using commercially available computational fluid dynamics (CFD) software. The simulations results will be analysed the same way as the met mast data and both results will be compared to see if they imitate one another in terms of the behaviour of the wind flow.

4.1.4 Rotor and Aerodynamics 2

Start: 18/09/2018 13:30 — **Room: D.0.02** — **Chair:** Pedros Santos

13:30 (22) Fluid Structure Interaction for Wind Turbines in Atmospheric Flow - A Project Outline
Christian Grinderslev — DTU Wind Energy

My extended abstract / presentation will be a description of my goal and the methods to achieve these for my PhD project, as I haven´t obtained any results yet.

With the steady increase in size of modern wind turbines, the design process is highly dependent on the availability of accurate prediction tools. This is especially true in the field of Fluid Structure Interaction (FSI), where aerodynamic forces and wind turbine responses are coupled and highly complex. For some of the currently used designing load cases for modern wind turbines, the current engineering aerodynamics models, based on Blade Element Momentum (BEM) theory, are insufficient and might predict unrealistic stability properties. These unrealistic predictions will only grow in significance, as wind turbine blades become longer and more flexible in the future. This naturally becomes a problem, since underestimations of stability issues could turn out fatal, and overestimations on the other hand will demand unnecessary stiff designs increasing the cost of the turbine. To resolve these accuracy problems, the blade resolved CFD method offers an obvious alternative to the engineering aerodynamics, especially with the exploding computational power available in recent years. Combining these highly accurate aerodynamic load calculations with structural codes for turbines will create highly accurate wind response predictions. Coupling of structural codes for wind turbines with accurate CFD codes is yet not widely used in the wind turbine industry, because of computational cost and need of development of the codes. The purpose of this specific project is to go further in the development of FSI modelling, by implementing Atmospheric Boundary Layer (ABL) flow and hybrid ABL/engineering turbulence models to the existing FSI solver of DTU, HAWC2CFD, which combines the widely used HAWC2 structural code and Ellipsys3D CFD code. As of today, most of the FSI simulations of wind turbines are made with uniform flow and simple RANS turbulence models. By adding the possibility of using high fidelity ABL wind flow, more physically realistic simulations of the fluid structure interaction between wind and turbine are possible.

13:45 (108) Fluid-structure interaction simulations of a large horizontal axis wind turbine in the atmospheric boundary layer
Gilberto Santo — Ghent University

This work summarizes the results of several fluid-structure interaction (FSI) simulations of a large horizontal axis wind turbine immersed in the atmospheric boundary layer (ABL). The considered three-bladed rotor has a diameter of 100m and is entirely made of composite materials. By means of an in-house code, two commercial codes are coupled, one of them for the computational fluid dynamics (CFD) and one for the computational solid mechanics (CSM). A strong coupling is imposed and the force and displacement equilibrium on the fluid structure interface is, thus, always satisfied. On the fluid side, the rotation of the blades and their deformation during the simulated time are handled by an overset technique. The ABL is prescribed at the inlet and correctly preserved through the computational domain by means of modified wall functions. On the structural side, a detailed model reproducing the complex composite layup of each blade is employed. Using the outlined model, several simulations are carried out in order to investigate the effect of the supporting structures (i.e. tower and nacelle) and of rotor misalignments with respect to the incoming wind on the FSI of the analyzed rotor. The ABL always induces oscillating loads and deformations on the blades and its effect is analyzed in detail.

4.1.5 Turbine Modeling 1

Start: 18/09/2018 13:30 — **Room: E.0.05** — **Chair:** Clemens Hübler

13:30 (6) Global Sensitivity Analysis of Offshore Wind Turbine Foundation Fatigue Loads
Joey Velarde — Aalborg University

The design and analysis of offshore wind turbine foundations are traditionally based on deterministic design approaches, where partial safety factors are applied to account for the uncertainties in the design parameters. A probabilistic approach offers a more rigorous way to account for uncertainties, particularly site-specific environmental parameters. In this study, the sensitivity of fatigue loads with respect to primary structural, geotechnical and metocean parameters are investigated for a 5 MW offshore wind turbine installed on a gravity based foundation. Linear regression of Monte Carlo simulations is performed for three design load cases. Results showed that parameter significance rankings vary according to which design load case is considered. In general, uncertainties in the fatigue loads are highly influenced by turbulence intensity and wave load uncertainties, while uncertainties in soil property suggest significant nonlinear or interactive effects. This work provides insights to foundation designers and wind turbine manufacturers on which parameters must be assessed in more detail in order to reduce uncertainties in load prediction.

13:45 (31) Cross-correlation-based approach to align turbulent inflow between CFD and lifting-line-codes in wind turbine simulations
Florian Wenz — University of Stuttgart, Institute of Aerodynamics and Gas Dynamics

Codes of different fidelity levels are used in industry and research to calculate fatigue loads of wind turbines. If no experimental data is available, high-fidelity computational fluid dynamic (CFD) simulations are used as numerical reference solutions for lifting-line-codes. In cases with turbulent inflow, besides a statistical evaluation, analysing the development of forces over time is a common approach. To allow a time-dependent load comparison between the codes a consistent input of background turbulence in the different codes must be ensured. Since CFD simulations, in contrast to the lifting-line-codes, include the spacial propagation of the turbulence field and, hence, the induction of the rotor on the incoming flow, a time offset between the output time series occurs. We enabled a comparison between the codes by extracting the turbulent velocity field from empty-box CFD calculations at rotor position to capture changes due to propagation but exclude the rotor induction. However, the time shift in inflow due to the blockage effect of the rotor in the CFD simulations with turbine must be compensated in the lifting-line-codes. Therefore, we quantified a temporal offset using a cross-correlation. By applying this offset to the extracted velocity field, which is used as input to the lifting-line-codes, the simulation outputs are temporally aligned to the CFD results and can be compared in time to determine the uncertainty in fatigue load prediction with lifting-line-codes.

14:00 (28) Integration of controllers in wind farm simulations
Chengyu Wang — TU Munich, Institute of Wind Energy

Modern wind turbines are governed by turbine controllers, and future wind farms will be governed by wind farm controllers. The wind farm controllers adopt different strategies to satisfy different goals, like to maximize the wind farm power output or to follow the power requirement. The turbine controllers receive signals from the wind farm controllers and seek the best states of operation that follows the power required by the wind farm controllers. Controllers are also tasked with ensuring safe operation under all wind conditions. Functionalities and robustness of controllers should be tested in the design phase in both numerical simulations and experiments. This extended abstract discusses the significance and approaches of implementing controllers in SOWFA simulations. Different methods of applying controllers in simulations will be compared. The potential of computer-aided development of controllers will be discussed.

4.1.6 Reliability & Uncertainty Modeling

Start: 18/09/2018 13:30 — **Room: E.0.06** — **Chair:** Nicoletta Gioia

13:30 (11) Fatigue reliability analysis of onshore wind turbine foundations
Amol Mankar — Aalborg University

It is important to design wind turbine structures to a specific (target) reliability level, in order to avoid conservative designs and excessive use of materials with aim to minimize the cost of such installations and ultimately the cost of energy. As wind turbines are exposed to cyclic load from wind, this causes fatigue of all components of wind turbine including reinforced concrete foundations of wind turbines. Fatigue design most of the cases governs structural dimensions or percentage reinforcement in foundation of onshore wind turbines. However, estimating level of damage in foundation of wind turbines is difficult and thus prediction of the fatigue life. The current international codes use models for damage accumulation with respect to fatigue of concrete, which are generally conservative and not able to predict the real behaviour accurately and can only predict the remaining useful life with uncertainty. This paper presents a probabilistic framework for reliability assessment with respect to fatigue failure of onshore concrete wind turbine foundation. This includes stochastic modelling of fatigue strength, stochastic modelling of fatigue loads, uncertainties associated with strength and load modelling, and reliability-based calibration of fatigue safety factors (DFF) for design with respect to fatigue failure of concrete. The stochastic modelling will be based on large databases with concrete fatigue test data and on representative stochastic load models applied for establishing recommendations for general material safety factors for wind turbines. Examples of reliability assessment and calibration of partial factors will be presented.

13:45 (58) Robust Design Simulation for a Horizontal Axis Wind Turbine Rotor Design
Hazal Altug — Middle East Technical University, METUWIND

Stochastic nature of wind energy makes robust design methods suitable for wind turbines. Robust Design Simulation (RDS) methodology is proposed to be applied on the design of the rotor of a horizontal axis wind turbine in order to minimize the cost of energy. In this method, first, appropriate design variables and their ranges of validity are chosen. Then, design of experiment (DoE) is implemented to explore a larger design space with lower computational cost. FAST, NRELś simulation tool for the response of wind turbines to coupled dynamics, is executed for each experiment and responses are recorded. The screening process is performed to decide on the subset of parameters that most affect the cost of energy. Later, a new DoE is created using only the selected subset of variables from screening and Response Surface Equations (RSE) are established using response data. Control variables that minimize the effect of noise variables are identified using RSE and the mean of the objective is shifted towards the target. Monte Carlo simulations are executed using the probability distributions for the noise variables are selected based on expected or past behavior. That way, the effect of the uncertain design parameters on the response are obtained as probability distributions. Creation of DoE, sensitivity analysis, calculation of response surface equations and Monte Carlo simulations are done using JMP, a statistical analysis tool developed by SAS. Finally, a robust solution is obtained maximizing the probability to reach the target while satisfying all imposed design constraints.

14:00 (68) Using SCADA in Updating Failure Probability of a Monopile Offshore Wind Turbine Support Structure

Quang Mai — University of Liege

Assessment of existing offshore wind turbine support structures is crucial for a condition-based inspection planning and life extension decision. This paper aims at utilizing SCADA as new information to update failure probability of monopile support structures in fatigue failure mode. The SCADA was collected from a Belgian offshore wind farm. It is assumed that fatigue loading of the monopile support structure comes mainly from wind action. One-year data of measured strain is used together with the concurrently measured 10-minute wind speed to built the limit state function. Fatigue-critical strain history is derived from the data at three measuring locations on the same circumference. The 10-minute mean wind speed is considered as a random variable and used to calculate the fatigue damage. Fatigue damage is calculated using Miner´s rule. The year-to-year variation of the 10-minute mean wind speed, the unrepresentativeness of the measured strain, and the measurement uncertainty are considered together with uncertainties in Miner´s rule and the S-N curve. The Bayesian approach is used to update the 10-minute mean wind speed distribution considering measurement data. Consequently, the failure probability of the support structure can be updated. The results show that after three years of measurement, there is no significant differences in the calculated failure probability between cases where the updated 10-minute mean wind speed distribution and the design distribution are used. The load factor applied to the measured stress (e.g. stress concentration factor, corrosion effects, or interpolation factor for unmeasured locations) significantly affects the predicted failure probabilities. In conclusion, the wind measurement data can be used to predict failure probability of the monopile support structure given that a limited concurrently measured strain data is available. Further research is needed to combine the SCADA with inspection data (crack, corrosion) for optimising the inspection plan or a life extension purpose.

4.1.7 Geotechnics and Structural Integrity

Start: 18/09/2018 15:30 — **Room: D.0.02** — **Chair:** Wout Weijtjens

15:30 (19) Model Predictive Control of Fatigue

Stefan Loew — TU Munich, Wind Energy Institute

Nonlinear Model Predictive Control (NMPC) is an aspiring control method for the implementation of advanced controller behavior. In wind turbine applications, an Economic NMPC is desired which balances produced electric energy and fatigue of specified wind turbine parts. Fatigue is damage of a material caused by long-term or high-cyclic application of stress. Stress levels may be smaller by dimensions than the ultimate stress, where already a single stress peak leads to failure of the considered wind turbine part. The present contribution is focused on the implementation of a novel fatigue metric into Model Predictive Control. Connections to standard fatigue estimation methods are investigated which involve Rainflow-counting, Wöhler-curves and Linear Damage Accumulation. The presented method is applied to tower base fatigue and compared to controller implementations from literature within a high-fidelity aeroelastic simulator. Analyses of dynamic and economic behavior show the benefits of the presented method. Current research on the implementation of advanced fatigue cost models is stated briefly.

15:45 (71) Innovative explicit method to account for cyclic degradation: different applications for OWT foundations

Gianluca Zorzi — TU Berlin

Cyclic loading can lead to progressive degradation of soil in terms of plastic strain accumulation, pore pressure build up, and changes in soil strength, soil stiffness and stress redistribution, which may significantly influence the behavior of foundation structures throughout their lifetime. The prediction of these effects is of vital importance during the design phase, yet there is a lack of a generally accepted method to account for cyclic loading conditions. The present paper introduces the application of an innovative explicit method to predict the accumulated foundation displacement under cyclic loading for different types of offshore wind turbine foundations. The explicit method integrates cyclic contour diagrams derived from cyclic laboratory tests into the finite element software PLAXIS by means of a remote scripting interface. The effect of cyclic degradation is taken into account by reducing the elastic shear modulus of the soil in a cluster-wise division in the finite element mesh. The interface automates the model creation in terms of meshing, cluster division, load parcel application and soil parameter degradation, which is optimal as it minimizes the amount of manual work and the risk related hereto. Application example for different real projects of offshore wind turbine foundations (such as gravity based foundations, monopiles and suction buckets) of the innovative explicit method for a storm design conditions is presented. This paper demonstrates the advantages of the developed method in terms of automatized design while taking into account the 3D behavior of soil surrounding the foundations, simplicity and flexibility for different types of OWT foundations. Future developments are also presented.

16:00 (101) Large scale physical modelling of monopile wind turbine scour protection

Minghao Wu — Ghent University

The monopile foundation type is widely adopted for European offshore wind farms due to the advantage of cheap cost and simple installation. Exposed to ocean waves and currents, scour may occur near the monopile foundation and lead to stability problems and safety issues of the wind turbine, thus a well-designed armor layer protection is needed to prevent the scour development. Therefore, it is necessary to investigate the mechanism of the armor layer behaviors via various research approaches.

The laboratory experiment of the monopile foundation protection layer stability in wave flume or wave basin is an efficient method to gain the knowledge of the hydrodynamic effects on rock armor layer. Several experimental research projects have been carried out to investigate the stability criteria of the armor layer and suggestions have been given regarding to the optimal rock sizes and quantities, such as Boon et al. (2005), De Vos et al. (2011, 2012), Whithouse et al. (2014). As most of these tests are accomplished using small scale models, the scale effects can be significantly large, a new collaborative research project is done recently in HR Wallingford hydraulic research company with the fast flow facility. The objective is to test the large scale monopile foundation stability in combined currents and waves condition. The diameter of the monopile is up to 0.6m and different rock gradings are tested. The initial analysis results show that the scale effects exist in small scale model tests and lead to a conservative estimation of damage. The armor layer damage development is quantified with high resolution underwater laser scanning after 1000 and 3000 waves. The data will be further analyzed to reveal the unknown physical behaviors of the monopile wind turbine foundation and to validate the numerical modelling in the future.

16:15 (113) Subsoil Stress Reconstruction for Fatigue Monitoring of Offshore Wind Turbines Using Accelerometers on the Tower

Maximilian Henkel — Vrije Universiteit Brussel

Monopiles are nowadays the most common offshore wind foundation type with about 80% market share. This underlines recent design developments allowing to build monopiles in water depths well over 20 m. Fatigue is the main design driver for offshore wind turbines on monopiles. In particular the welded connections beneath the sea bed are typically determining the lifetime of the entire structure. The Belgian wind farm Nobelwind contains three monopile foundations which were equipped with optical fiber strain gauges over their entire length prior to turbine erection. This setup allows to measure the stresses directly at the critical locations in the foundation. By recording the stresses on the monopile an assessment of the actual loads and fatigue monitoring are possible. These give valuable information towards fatigue life extension and maintenance optimization. However, sub-soil measurements are too expensive for widespread use and thus more cost-effective methods using solely sensors on the tower are desired. Virtual sensing reconstructs stress time series on the substructure using accelerometers on easily accessible locations. In a first step the acceleration signal is decomposed to its modal coordinates using the structural mode shapes which can be derived from a finite-element model or operational modal analysis (OMA). These modal coordinates can be expanded to reconstruct the fatigue history of any location that is contained in the mode shape vector. Previous work of our group already shows the potential of virtual sensing to reconstruct stresses above sea level. However, with the set-up at Nobelwind a validation of virtual sensing for locations below mudline is possible for the first time. In this contribution we will show the first results from Nobelwind and discuss any limitations of the MDE and suggest possible improvements for virtual sensing in this challenging environment.

16:30 (110) Corrosion Fatigue in Offshore Structures
Jie Zhang — Ghent University

Offshore wind energy industry around globe is expanding rapidly in the recent decade to face challenges on the tremendous demand of eco-friendly electricity. Steel welded substructures for supporting wind turbines are usually subjected to a complex dynamic spectrum of fatigue loads due to wind, wave and current. Fatigue failure can happen when external load that is much lower than material yield strength is applied for a long period of time. At the same time, they are immerged in or exposed to corrosive seawater. The corrosive environment plays an important role during the metal fatigue process, as corrosion accelerates aging rate of material and local high stress concentration at fatigue crack tip reinforce chemical reaction, the interaction of fatigue and environmental degradation significantly reduce life span of the structure and increase cost of installation and maintenance. Therefore, the investigation of combined damage from fatigue and corrosion mechanism is needed for improving understanding of corrosion fatigue phenomenon in offshore structures and advanced numerical tool of simulation and life prediction of corrosion fatigue is required to help engineers design more durable and lightweight structures, so to decrease the cost.

4.1.8 Hydrodynamics, Soil Characteristics and Floating

Start: 18/09/2018 15:30 — **Room: E.0.05** — **Chair:** Vincent Arnal

15:30 (18) Characterising wave-tidal current-turbulence parameters for fatigue design of tidal turbine components
Marilou Jourdain de Thieulloy — University of Strathclyde, Wind and Marine Energy

This paper presents an analysis of wave and tidal current measurements as part of the Flowturb project. The aim of this paper is to characterise the influence of wave on the turbulent parameters for fatigue design of tidal turbine components. The data used for the analyses was from the ReDapt project, which centres around a commercial scale (1MW) tidal turbine developed by Alstom and deployed at EMECs Tidal Test Site located at the Fall of Warness, Orkney, Scotland. The measurement campaign involved a series of modern wave and current sensors, as four beam Diverging Acoustic Doppler Profilers (D-ADPs), three beam plus vertical D-ADPs and over twelve prototype single beam ADPs (SB-ADP).

This study used data collected by a SB-ADP, which was vertically oriented and turbine mounted. The instrument sampling rate of 4Hz (recently increased to 16Hz) allowed more of the frequency range of velocity spectra to be assessed compared to similar equipment at the time of use. Sets of 20 minutes samples at a constant mean velocity have been studied. The analysis of the nonlinear and non-stationary data has been performed using the ´empirical mode decomposition´ method, which allows the decomposition of the dataset in a finite number of elements called ´intrinsic mode functions´. The decomposition is based on direct extraction of the energy associated with various intrinsic time scales , and allows to establish the critical role of wave in tidal current turbulence, especially Turbulence Intensity (TI), Turbulent Kinetic Energy, and Length

scale, at multiples depths. The results of this study will be used to improve theoretical models adopted in the IEC and DNV standards to account for wave-current-turbulence impacts on marine energy devices.

15:45 (37) Wave tank model testing of floating wind turbines : reproducing aerodynamic loads
Vincent Arnal — Centrale Nantes

Despite continuous progress of floating wind turbines numerical modelling, physical testing of floating wind turbines concepts in wave tank experiments is required for the validation of hydro-servo-aero-elastic codes and validation of new designs concepts. However, reproducing at model scale both representative hydrodynamic and aerodynamic loads acting on floating wind turbines is quite challenging because of conflicts between Froude and Reynolds scaling laws. Different experimental methodologies have been developed for the reproduction of aerodynamic and inertial loads acting on the submerged part of a floating wind turbine during wave tank testing. Both 100% physical modelling nd hybrid physical - numerical modelling coupled in real time have recently been developed. After a conclusive review of those methodologies with the main advantages and disadvantages, the presentation will focus on the development of the hybrid physical-numerical methodology. Sensitivity studies regarding importance of the different frequencies of interest and aerodynamic load component on the dynamic of the floating wind turbines will be presented.

16:00 (76) Experimental measurements of the fluid forces on bio-inspired tidal energy harvesters
Marlee Nathalie Basurto Macavilca — University of Strathclyde

Horizontal-axis tidal turbines have been developed more rapidly than other technologies because of their high individual hydrodynamic efficiency, and their similarity to onshore wind turbines. This individual efficiency does not improve when the individual turbine form part of a wind farm, whereas it has been observed and studied that in nature, aquatic animals exploit energy directly from the fluids around them. In other words, they are able to take advantage of each otherś wakes and improve their efficiency in group, for instance, fish shoals. This relative new technology based on mimicking the motion of fishes, called bio-inspired tidal energy harvesters, is based on vortex induced motion and this article focuses of flutter type. It applies for two degrees of freedom (a combination of wing bending and torsion). The other advantages of flapping foil turbines include working at lower foil velocities (reduction of the noise) which is opposite to wind turbines, and operating in shallow water. This study aims to measure the fluid forces on model-scale oscillating-hydrofoil tidal energy harvesters. Thus, it is necessary to develop a controller for two linear actuators that moves an oscillating hydrofoil with the help of a LabView code and a C1100 series Servo Drive from LinMot.

16:15 (99) Design optimization of floating offshore wind turbine blades
Evan Gaertner — UMass Amherst, National Renewable Energy Laboratory

Floating offshore wind turbines (FOWTs) are a promising technology allow access to deeper waters further from shore, avoiding viewshed and competition of use constraints nearshore. However, their nonridged mooring systems introduce six additional translations and rotational degrees of freedom as the system moves in response to wind and waves. This significantly increases the unsteady aerodynamic loading of the rotor. Fore-aft motion of the platform results in an additional velocity component at the rotor and causes complex interaction with the rotor wake. Even low-frequency motion can cause highly unsteady responses for portions of the blades as a result rotor-wind misalignment, resulting in increased variability due to rotational sampling. Peak loads and fatigue damaged are subsequently increased compared to onshore or fixed-bottom offshore wind turbines due to more unsteady loading conditions. Since floating support structures are a novel technology representing a significant leap in complexity, existing wind turbine designs have been employed on the small number of prototypes and demonstrations projects. This neglects the fundamentally different flow conditions at FOWT rotors. While floating support structures are optimized for existing turbine designs, use of turbine rotors outside of their original design space may be leading to suboptimal global systems. Optimization of turbine rotors specifically for use on floating platforms offers the potential to improve performance and reduce loads, with the goal of reducing cost of energy and increasing reliability. A multi-disciplinary, systems engineering optimization approach is necessary due to the complex design challenges brought on by the coupled dynamics of the platform motion, mooring system, and turbine control systems. Such an approach must also account for the effects of highly variable metocean operating conditions throughout the design process. This work presents ongoing progress towards the development of novel systems engineering methodologies for optimizing wind turbine blades for floating offshore applications.

4.1.9 Electricity Conversion

Start: 18/09/2018 15:30 — **Room: E.0.06** — **Chair:** Vincent Leroy

15:30 (46) Comparison Between Different VSC Controllers Connected to a Weak Grid
Matthieu Kervyn — University of Strathclyde

The grid was designed around centralised large synchronous generators that are reasonably close to demand centres. However, the majority of the renewable energy resources are located far away from these demand centres and are often tied to a weak AC network (where the short circuit ratio, or SCR, is low). This results in voltage oscillations, system instability, and difficulty in injecting large amounts of power into the network. Line commutated converters (LCCs) suffer from commutation failure in weak grids which make them unsuitable for most renewable energy converters.

Voltage source converters (VSCs) have therefore become the preferred converter type. Their ability to control active and reactive power independently make them suitable to these remote locations. However, when the grid becomes very weak, some VSC control methodologies, such as vector current control, can also become unstable.

This work explores what factors lead to a very weak grid and attempts to model a weak grid. A Simulink model of a vector current controlled VSC system is built and tested in various low SCR conditions in order to further understand why these problems arise. The performance of the controller is also tested with enhancement features, such as the addition of a feed forward branch, which allows stability to be improved at lower SCR values.

15:45 (48) An Assessment of PLL based controllers for converters in weak AC systems
Leo May — University of Strathclyde

This paper presents a state space model to perform small signal stability analysis of an LC filtered converter operating in a weak grid, defined to be one of high impedance. Stability issues arising from the PLL dynamics are highlighted when using vector current control. It is shown that applying a frame transformation after the current controller is a major contributor to poor stability margins when using vector current control. By omitting this stage, a proportional resonant controller is shown to exhibit improved performance relative to vector current control.

16:00 (56) Cost reduction of subsea cables in offshore windfarms through the use of energy storage
Rebecca Hall — University of Strathclyde

The development of wind turbine technology has resulted in the installation of larger offshore wind farms located at greater distances from shore. As wind farms increase in size it becomes crucial to maximise efficiency throughout the electrical collector in order to keep costs and losses to a minimum. The array layout and electrical collectors must be designed on a site-specific basis to achieve a good balance between electrical losses and utilisation of the subsea cables. One of the advantages of energy storage is its ability to avoid the overloading of transmission or distribution lines by storing energy during high winds, then discharging during low wind speeds. This could be applied to offshore wind farms, where energy storage systems at turbine level could charge during high wind power production and discharge during times of low power production. By doing this, the rating of the cables connecting the wind turbines is reduced since they dont́ need to be dimensioned to the maximum power output of the turbine. This study used an existing windfarm as a case study in order to find the optimum implementation of energy storage for the layout of electrical collector and the local wind resource. Outcomes of the study include the optimum location and size of batteries, the cost of energy storage, the potential reduction in cable rating and cost saving.

16:15 (66) Integrating temporary energy storage for renewable energy devices
Peter Taylor — University of Strathclyde, Wind and Marine Energy Systems

Renewable energy resources are characterised by variable power flows. This is particularly true of wave energy devices in which a full range power oscillation is repeated every few seconds but is also applicable to wind and tidal turbines.

A potential solution to these issues is to integrate energy storage into the DC link of generator and grid side converters. This requires the presence of an energy storage device - for example a supercapacitor or flywheel - that can act in conjunction with the DC link capacitor to provide power smoothing and the capacity for fast network support. This requires the presence of a DC/DC interface which manages the energy storage power flows.

This project utilises a Simulink model of generator and storage interfaces, controllers and modulation to develop high-level algorithms for managing the power flows within. Representative wave states are created in MATLAB for modelling the power from the generator. The grid-side effects of these fluctuations are investigated both with and without the storage device and are used to better understand and control the power flows.

16:30 (91) Wind Turbine Conversion Chain - A Control Contribution - Contribution au Contrôle-Commande d´une Chaîne de Conversion Éolienne

Abdellah Derghal — EleOum El Bouaghi University, ctrical and Automatic Engineering Laboratory

The renewable power sources, particularly wind energy type is one of advanced solutions in the field of energy designed to ensure reliability of system operation or chain energy conversion with better management and control. In this paper, we analyze the modeling and simulation of an energy conversion system based on a double-fed induction machine (DFIM) powered by a renewable source (wind). Simulation results obtained of the system with power control and control MPPT are very encouraged in terms of reference tracking and robustness.

4.2 Wednesday 19 September

4.2.1 Rotor and Aerodynamics 3

Start: 19/09/2018 10:45 — **Room: D.0.02** — **Chair:** Nymfa Noppe

10:45 (59) Assessment of transition modelling for Wind Turbine flows
Konstantinos Diakakis — National Technical University of Athens

The original intermittency-momentum thickness local correlation transition model of F.Menter and R.Lantry and versions of the simplified eN method for transitional simulations on airfoils are evaluated against measured data obtained for different wind turbine airfoil profiles in conditions that range from Re=3 to 40 million, using a modern unstructured and parallelized Reynolds-Averaged Navier-Stokes solver. The choice of inlet conditions for the correlation transition model is discussed. Two-dimensional simulations showed that even though both approaches sometimes agree qualitatively, the eN method is more capable of predicting transition onset and laminar drag bucket behavior than the correlation transition model, especially for higher Reynolds numbers where the correlation transition model always overpredicts drag due to significantly upstream transition prediction.

11:00 (86) Laminar-Turbulent Transition Prediction by High Frequency Microphone Measurements
Özge Sinem Özçakmak — DTU Wind Energy

In the present work, the reliability of various data processing methods for laminar to turbulent transition detection on airfoils is assessed based on experimental data. For this purpose, NACA 63-418 airfoil profile with surface microphones flush mounted on both the suction and pressure sides is used in the wind tunnel experiments. The experiments are conducted at the Reynolds numbers in the range from 1.6 to 6 million at various angle of attack values. In this way, the transition behavior of the airfoil is characterized. An autonomous method to detect transition is generated. The most stable method to detect the transition location is found to be the characteristic frequency approach by spectral moments when the inflow turbulence is low. Pressure standard deviations are observed to exhibit a peak at transition and slightly decreases for the fully turbulent flow being always higher than the laminar flow. The numerical results are in agreement with experimental results on the pressure side where the natural transition occurs. However, bypass transition due to surface irregularity and microphone placement on the suction side is not predictable by the numerical tools. The analysis shows that the typical curve length of the transition process is around 15-20% and it can go up to 30% of the chord. The turbulent inflow, leading edge roughness (LER) and Reynolds number effects on transition is analyzed. It is seen that, increasing Reynolds number leads to an earlier transition position closer to LE at both upper and lower surfaces. The critical height of the LER is to be met in order to have a bypass transition to turbulent flow at the angle of attacks, where the stagnation point is upstream of the LER location. Inflow turbulence is observed to have a larger effect on the transition location than the predicted numerical results.

11:15 (106) Reduced-order modelling of vortex generators: can auto-encoding neural networks do better than POD?
Gael de Oliveira — TU Delft

In a recent paper, we presented an asymptotic model that predicts the effect of vortex generators on boundary layer development. This deterministic model is accurate and simple: it consists of 6 ordinary differential equations (ODEs) and a scalar partial differential equation (PDE). Despite its simplicity, the presence of a PDE means that the model remains too complex for implementation in viscous-inviscid (VI) airfoil solvers like Xfoil or Rfoil. This communication shows how to make that possible.

The ability to predict the effect of vortex-generators in a VI solver is relevant: it would enable the design of wind turbine airfoils optimized for vortex generator actuation. To do so, however, one needs to approximate the PDE with a compact set of ODEs. An effective means for reducing the dimensionality of the PDE consists in running a proper orthogonal decomposition (POD) on finite-difference solutions. The PDE can then be projected onto a truncated series of relevant POD modes. This method works well, and we have found that 3 POD modes suffice to capture 90% of the L2 norm of PDE solutions.

Optimisation of wind turbine airfoils with a single set of truncated POD modes is already possible if the spacing and relative height of vortex generators are set in advance. Sets of truncated POD modes are applicable to arbitrary pressure distributions but need to be regenerated for every new geometry of the vortex-generator array.

We would, however, want to find a more general set of orthogonal modes. One that would be applicable to arbitrary geometries of the vortex generator array. We therefore conclude by demonstrating the use of auto-enconding neural networks to obtain alternative, and generalisable, sets of orthogonal modes.

11:30 (81) Microtabs for Load Alleviation in Horizontal-Axis Wind Turbines

Ali Ghandour — Vrije Universiteit Brussel

Aerodynamic load variations caused by the tower of a horizontal axis wind turbine on the rotor blades, known as tower shadow effect, were reproduced and studied in the wind tunnel using a setup that mimics the interaction between the tower and the blade. Tufts were used to visualize and display the change in the flow pattern between the blade and the tower during the passage of the blade

Experiments were then performed to study the mitigation of the tower shadow effect by using microtabs. The effect of microtab deployment and retraction on the lift coefficient of a NACA0021 blade was studied in a series of wind tunnel experiments at a Reynolds number of 130 000. The experiments show an increase and a decrease in the lift coefficient for a lower and upper surface microtab respectively. The effect of the microtab depends strongly on the angle of attack.

Results from lift force measurements show that a lower surface microtab can mitigate load variations in the case of an upwind blade. However, the variations in the lift force in the case of a downwind blade, where the blade passes through the wake of the tower, are of a different nature. The use of a microtab is not efficient in this case.

11:45 (114) Identifying strategic opportunities for blade load alleviation using constrained optimization

Jon Lewis — UMass Amherst, National Renewable Energy Laboratory

Rotor load alleviation technologies are at the forefront of blade research as a means for enabling lighter, and larger horizontal axis wind turbines. The fundamental barrier to scale is the disproportionate growth in mass relative to a turbineś power capacity. As such, aerodynamic load reduction research attempts to beat the so called śquare-cubedĺaw, facilitating scaled up designs which perform better when considering overall windfarm CAPEX and OPEX. While the principle goal of load alleviation is to enhance or exploit the aerostructural response of the blade, the methods which have been proposed to accomplish this vary widely and act in disparate manners on the load portfolio of the blade. Adding load reduction capabilities to conventional blade hardware almost certainly adds cost and mass, therefore the technologies which have an outsized effect have the best potential to fulfill their goal.A method is introduced which can be used to identify the design driving loads and can be used to trend the importance of these loads when variables such as rotor scale and rotor architecture are changed. The basis of this method is to optimize a reference blade design around some design point in the presence of a set of load and deflection constraints. This analysis is used to find the gradient of the objective function with respect to the constraint parameters, known as the Lagrangian multiplier. The relative importance of the constraint functions is found by comparing the magnitude of the Lagrangian multiplier of simultaneous constraints at the minimum value of the objective function. In general, the most promising load reduction technologies will be those that act predominantly on the load constraints with the highest marginal cost. The relative importance of design driving loads is not necessarily the same for all turbine arrangements, hence multiple parallel analysis can be performed to evaluate how the demands on the system vary with scale ? 5 MW to 20 MW reference designs ? and with major architectural differences, such as upwind vs. downwind rotors.

4.2.2 New Concepts 1

Start: 19/09/2018 10:45 — **Room: E.0.05** — **Chair:** Bruce Leblanc

10:45 (34) A novel method for synthetic wind data

Daniele D´Ambrosio — Vrije Universiteit Brussel

The availability of synthetic wind data that are consistent with both a probability density function and a spectral density function can save valuable time in a number of applications.

This work proposes a simple and straightforward iterative methodology to generate synthetic wind speed time series simulating a stationary random process for which the user can specify both the power spectral density function and the probability density function. The method relies on the random-phase multisine signal, a well-known class of signals within the system-identification community, to generate the initial sequence of an arbitrarily large number of discrete samples conforming with the desired, target power spectral density. Next, a rank-reordering step of the samples possessing the desired target probability density function is implemented iteratively so as to match the autocorrelation and hence the PSD of the initial sequence.

Preliminary tests carried out on Gaussian and non-Gaussian sequences with coloured spectral contents show that the method is capable of matching both the target power spectral density and the target probability distribution function for sufficiently large signals ($N > 10^5$).

An application is presented on the generation of mean, horizontal wind speed time series which are Weibull distributed and possess the experimental spectral content deduced by Van der Hoven (Van der Hoven, 1957), yielding highly accurate results in terms of reproducibility of power spectral content. In addition, a comparison with two similar methods selected from the literature is presented, showing that our approach is capable of outperforming them in terms of accuracy of the reproduced spectral density function.

11:00 (103) Wind inflow modeling for Airborne Wind Energy Systems

Markus Sommerfeld — University of Victoria, Institute for Integrated Energy Systems

Abstract 14th EAWE PhD seminar Airborne Wind Energy Systems (AWESs) are an emerging alternative to conventional wind turbines that harvest wind energy via tethered aircraft at altitudes unreachable to current wind energy technologies. Long-term, high resolution wind data is necessary to optimize the flight path and power production, design and size the aircraft, and ultimately estimate levelized cost of energy. Measurements at these altitudes are expensive, time-consuming and their data availability is constraint by measuring technique. In my research I combine LiDAR measurements, mesoscale simulations (WRF) and high resolution LES (PALM) to produce a high altitude inflow model covering a wide range of the wind spectrum. Initial and boundary conditions of the mesoscale model are nudged by LiDAR to increase precision. Results of this simulation drive the LES which inform on high frequency turbulent fluctuations and cross/autocorrelations. Wind velocity profiles and turbulence intensity significantly vary with time of day. Therefore, AWES will benefit from dynamically adapting their flight pattern and operational height to the prevailing wind situations to reduce systemic losses such as tether drag, tether weight and misalignment with the wind direction. Furthermore, atmospheric stability significantly affects wind conditions which cause a wide range of wind speeds and can result in a multimodal probability distribution at higher altitudes, which cannot be represented by a simple Weibull distribution fit. A better representation of the wind statistics improves load and power estimation.

11:15 (109) Optimal Operation and the Power Curve of a Flexible-Kite, Pumping Airborne Wind Energy System

Mark Schelbergen — TU Delft

Three performance models with different complexity are used in numerical optimizations to construct power curves of a flexible-kite, pumping airborne wind energy system. The mean cycle power is optimized over the operation variables for a range of wind speeds. The optimal power curves following from the different models are compared. The model with the highest complexity allows optimizing over a set of operation settings that characterizes the overall shape of the pumping cycle trajectory. The optimal trajectory shape is highly dependent on the wind speed and shear.

11:30 **(45) Electrical systems for Multi-Rotor System-based wind turbines**
Paul Pirrie — University of Strathclyde, Wind and Marine Energy Systems

Multi-rotor system (MRS) wind turbines have been suggested in literature as a solution to achieving wind turbine systems with capacities greater than 10 MW. Potential benefits of MRS wind turbines include cost and material savings, standardisation of parts, increased control possibilities and improved logistics for assembly and maintenance. Almost all previous work has focused on mechanical and aerodynamic feasibility, with almost no attention being paid to the electrical systems. In this research various different topologies of the interconnecting electrical systems for MRS wind turbines are analysed to asses which are the most economically and practically viable options. Cost and losses have been approximated for both AC and DC topologies. Different configurations include star topologies where each turbine is connected directly to a substation situated at the base of the MRS tower and cluster topologies where multiple turbines are connected to a single transformer or converter before the power is collected at the substation. A simple model of a three turbine MRS system is used to assess potential harmonic issues in one of the AC and one of the DC topologies. Results presented include the results of simulations, estimations of losses and estimations of costs of the different topologies.

11:45 **(69) Performance Enhancement of Incompressible Solvers in OpenFOAM for Faster Steady and Unsteady Simulations Around Wind Turbines: Implementation of the Lower-Upper Symmetric Gauss-Seidel Approximation for Segregated and Coupled Solvers with Explicit and Implicit Time Marching Schemes.**
Nelly El Achkar — University of Oldenburg, ForWind

The simulation of unsteady three-dimensional viscous flow around wind turbines is one of the most computationally demanding tasks in modern CFD. The lack of efficient algorithms for non-stationary problems either limits the accuracy to which cases may be solved or creates demands for more computational resources than the user is able to provide. Therefore, new acceleration techniques constitute a necessity. The lower-upper symmetric Gauss-Seidel method approximates the coefficient matrix A by a factorised matrix A´, which enables the solution of the linear system of equations by two sweeps at each iteration, one forward and one backward. This method utilises scalar diagonal inversion and has a minimal memory overhead. In this thesis, we intend to apply this technique to the solution of linear systems of equations of incompressible, pressure-velocity-coupled and -segregated solvers in OpenFOAM for both steady and transient problems around wind turbines. In steady-state, coupling is achieved by substituting the velocity field interpolated at the faces in the continuity equation, which results in a block matrix for the linear system of equations. This the pUCoupledFoam case in OpenFOAM. In unsteady-state, we aim to achieve coupling via dual-time stepping, an artificial-compressibility-like scheme, where the solution of the modified equations, that is steady in pseudo-time, is identical to the instantaneous unsteady solution of the governing equations. Furthermore, this technique allows the extension of explicit time marching schemes into incompressible flow regimes. The implementations will take place according to a stepwise strategy. Each new implementation is validated against the already existing algorithms and linear solvers in OpenFOAM, in terms of discretisation and approximation errors as well as CPU time. Preliminary testing of LU-SGS applied to pUCoupledFoam showed a very good acceleration potential. However, some stability issues still need to be addressed around airfoil meshes.

4.2.3 O&M and Condition Monitoring 2

Start: 19/09/2018 10:45 — **Room: E.0.06** — **Chair:** Sofia Koukoura

10:45 **(25) Diagnosis of in-service wind turbine DFIGs through current signature analysis**
Estefania Artigao — University of Castilla - La Mancha

More modern and larger wind turbine generators are under continuous development. These exhibit more faults when compared to smaller ones, which becomes critical offshore. Under this framework, Operation

and Maintenance (O&M) is key to improve reliability and availability of wind turbines, where O&M costs represent between 25-35% of the total expenditure of a wind farm project. The objective of the present work is to optimise O&M activities through Condition Monitoring, by reducing maintenance costs and increasing reliability and availability of wind turbines. The induction generator of a wind turbine is a major contributor to failure rates and downtime, where doubly-fed induction generators (DFIGs) are the dominant technology employed in variable speed wind turbines. In the present work, Condition Monitoring based on electrical measurements (particularly current signature analysis) is applied to in-service doubly-fed induction generators of various European wind famrs. Current signature analysis is based on the principle that each fault has its own effect on the current spectra. Fault frequency components have been known for long time and their formulae identified in the scientific literature. Operating WT DFIGs have been analysed through stator current signature analysis via Fast Fourier Transform (FFT). The stator and rotor currents, as well as the FTT of the stator currents are analysed. All potential fault frequencies have been calculated and those present in the spectrum identified. The outcome of the present study shows that current signature analysis can be implemented on condition monitoring systems for wind turbines equipped with DFIGs. In this way, incipient faults can be identified before the generator becomes non-operational, following the trend to move away from corrective maintenance towards predictive actions.

11:00 (61) Model Predictive Control-based reduction of the tower bottom bending moment

Thorben Kallen — RWTH Aachen, Institute of Automatic Control

Due to expansion of wind energy, wind farms have already been built in the most favorable areas, such that new wind turbines have to be installed in (suboptimal) less windy or more turbulent areas. At the same time, they must compete with other energy producing technologies in terms of energy yield, production capacity and efficiency. To cope with these new requirements, wind turbines are steadily growing in size. Along with that, their structure becomes lighter and thus more flexible, resulting in an increasing load sensitivity. To reduce these loads, wind turbines are equipped with new sensors combined with new control strategies. This work presents a model predictive controller (MPC), which directly controls the structural loads of a wind turbine. Classical controller concepts have already featured load-reducing controls, which are realized as additional feedback paths. These additional control loops influence one another as well as the baseline control, so that load reduction can have undesired effects on other control aims [1]. The MPC handles these aims in one combined formulation of a tunable optimization problem. For that, the MPC predicts the dynamic behavior of the wind turbine using a dynamic reduced order model and optimizes the controller output accordingly, considering plant-specific constraints. For accurate predictions, the MPC needs the actual dynamic states and loads, which are estimated by an extended Kalman filter using a nonlinear dynamic model of the wind turbine. As the tower bending moments are estimated directly, the presented MPC uses these estimated loads as control variables instead of using indirect load measures, such as tower top acceleration, as control variables [2]. The MPC is tested in simulation with an extreme operation gust, which commonly results in loads critical for the design of the wind turbine. With use of this MPC, it was possible to reduce the deviation of rotational speed and power output around the reference, and to significantly reduced the tower bending moment fluctuation with fewer load alteration compared to a classical controller, which will extend the lifetime of the wind turbine. Moreover, the control formulation allows the explicit consideration of wind prediction algorithms, which is part of future research. Furthermore, the MPC will be extend by individual pitch control, to reduce the loads of the blades.

References:

[1] J Darrow, K Johnson, and A Wright, ´Design of a tower and drive train damping controller for the three-bladed controls advanced research turbine operating in design-driving load cases´, Wind Energy, vol. 14, pp. 571-601, 2011

[2] Jassmann, U., Zierath, J., Able, D., ´Model Predictive wind turbine control for load alleviation and power leveling in Extreme Operation conditions´, IEEE Conference on Control Applications, pp. 1368-1373, 2016

11:15 (70) Potential OPEX and Availability changes from the introduction of larger offshore wind turbines

James Stirling — University of Strathclyde

The second allocation round in the contracts for difference auction has seen strike prices of offshore wind farms fall to £57.50/MWh. With profit margins already tightly squeezed in the offshore wind industry, such low strike prices raise the question of "how will these projects reap financial gain?". The current trend has been to increase turbine size and thus, decrease the high capital costs associated with offshore turbine foundations. However, O&M costs typically represent 25-30% of total lifetime costs of energy for offshore wind farms. Reductions in the O&M costs of a windfarm will, therefore, considerably decrease the total CoE. This paper seeks to analyse the affects on O&M costs and availability of offshore wind farms as turbines scale to 12MW. Failure rate data of wind turbine components were analysed and extracted from the literature and various extrapolation techniques were applied to estimate up to 12MW. These values, along with the costs of repair and mean time to repair were then used as inputs to the DINWOODIE Model developed at Strathclyde University. The O&M costs, availability and O&M costs as a percentage of the CoE are presented and vessel strategies are also explored for one of the failure rate scenarios.

11:30 (84) Development of methods for risk assessment of wind turbine support structures

Sima Rastayesh — Aalborg University

This paper reports on recent contributions by the Marie Skłodowska-Curie Innovative Training Network titled INFRASTAR (Innovation and Networking for Fatigue and Reliability Analysis of Structures - Training for Assessment of Risk) to the field of Reliability approaches for decision-making in wind turbine and bridges (http://infrastar.eu/). The subject of risk analysis and risk assessment has become an eminent subject to increase in research, development, and application in recent years, and is considered and applied at different levels of industry. Nowadays, by the fast development of new technologies many and new risks should be taken in to account. Risk is introduced as a measure of the expected potential loss occurring due to natural or human activities. Wind turbines are subjected to climatic conditions and other environmental impacts, which decrease their life cycle performance and imply increased risk of failure of their components. For instance, in order to ensure acceptable risk levels of wind turbines throughout the whole lifetime, different operation and maintenance strategies are used in offshore wind industry contributing to 20-30% of the cost of energy. Wind turbines are infrastructures for which failure could lead to severe damages, and thereby a high risk. To prevent wind turbine failures, and to account for the consequences, a rational and comprehensive method for assessing the risk exposure to the structures is required. Thus, in order to obtain a reduction in the risk level, it is important to be able to make rational decisions reducing the risk. The objective of this paper is to introduce methods for risk assessment for wind turbines.

11:45 (67) Finding a connection between load exposure and reliability of wind turbines in a wind farm

Laura Schroeder — DTU Wind Energy

Wind turbine design is typically based on the assumption of the gradual degradation of material properties (fatigue) which is considered directly proportional to the loads acting on the wind turbine. However, the relation between the load exposure of turbines in a wind farm and their reliability has not been sufficiently well defined and demonstrated. Characterising this relation will enable more precise prediction of t́he load budget-́ i.e., the effect of load-induced degradation and faults on the operating costs of wind farms. For this purpose a fatigue lifetime load map within a wind farm will be created using a surrogate model approach. This surrogate model is used to map the wind field and wind farm geometry specific parameters to the fatigue loads. The surrogate model is calibrated using a high-fidelity database of aeroelastic load simulations. The aeroelastic simulations are carried out using the Dynamic Wake Meandering model in order to amount to the wake effects inside the wind farm [1]. Using this high-fidelity data base a Polynomial Chaos Expansion (PCE) [2] is calibrated. The model is then updated using normal behaviour SCADA measurements. The motivation of using such a hybrid approach of combining aeroelastic simulations with SCADA measurements is that it is expected to take into to account additional external conditions that cannot be captured by the aeroelastic simulations. In that way it is expected to give a more realistic representation of the loads in a wind farm. Finally, the load map will be compared against fault reports in order to describe a relation between loads and reliability of wind turbines in a wind farm.

References:

[1] C. Larsen, H. A. Madsen, K. Thomsen, and T. J. Larsen. Wake meandering: a pragmatic approach. Wind energy, 11(4):377-395, 2008.

[2] Xiu D, and Karniadakis, G E 2002 The Wiener-Askey polynomial chaos for stochastic differential equations SIAM Journal of Science Computing 24 619-44

4.2.4 O&M and Condition Monitoring 3

Start: 19/09/2018 15:45 — **Room: D.0.02** — **Chair:** Estefania Artigao

15:45 (16) Retrofit control concepts for lifetime extension

Vasilis Pettas — University of Stuttgart, Stuttgart Wind Energy

As more wind turbines come close to the end of design life time the end of life strategies need to be evaluated. Extending the life time seems to be a financially attractive option for the operators and research is focusing on such strategies. Present work focuses on evaluating retrofit control concepts, like individual pitch control, down regulation, and Lidar assisted control, for life time extension purposes. The life time of wind turbines is limited mainly by the fatigue loading of different components. The fatigue reserves are determined by the design margins as well as the mismatch of the certification loads with the loads induced from the actual operating conditions. Adopting load mitigation control strategies after some period of operation can increase these fatigue reserves and reduce the fatigue consumption rate. The financial and technical feasibility as well as the legislative framework of such an approach have to be evaluated. The present work focuses on the technical feasibility, identifying the benefits and tradeoffs of different control strategies.

16:00 (64) Development of new strategies for optimized structural monitoring of wind farms

João Pacheco — Universidade do Porto

This work aims the development, implementation, validation and optimization of new methodologies to continuously assess the structural elements of wind turbines: tower, blades and foundation. The research includes the monitoring of 3 wind turbines of an onshore wind farm, comprehending accelerometers, strain gages and clinometers, distributed in the blades, tower and foundation. The data processing is based on the continuous evaluation of the parameters that drive the structure dynamic behaviour (vibration frequencies and damping) estimated from the structure response to ambient excitation and advanced statistical modelling, having in mind two main goals: detection of stiffness reductions motivated by the appearance of damage and evaluation of the remaining fatigue life of the main structural components. The first step consisted on the evaluation of the results that can be obtained with different strategies of instrumentation of an utility-scale wind turbine, considering variations on the number of sensors, on their distribution in the wind turbine tower and on their noise level. With the goal of reducing the investment in monitoring equipment, layouts based on a reduced number of low cost sensors are tested. This work was performed using a one year database collected in an onshore 2MW wind turbine, by a quite extensive monitoring system, using low noise accelerometers. The alternative monitoring scenarios are recreated selecting alternative sets of sensors and adding artificial noise to the original acceleration time series. In a second step, now under development, the data collected in several wind turbines of the same onshore wind farm will be used to develop strategies to extrapolate results obtained for one turbine to others of the same farm using SCADA data and minimal instrumentations, focusing of the evaluation of the consumed fatigue life.

16:15 (65) Development of a new discretized vibration model to investigate vibration monitoring of a composite cantilever beam based on a change in local damping

Sharif Khoshmanesh — TU Delft

The possibility to detect damage in composite materials by measuring changes in damping properties has recently gained attention. In this paper, the application of such a methodology to a wind turbine structure is investigated . The adhesive joint in a spar cap-shear web which is a frequent source of failure in a wind turbine blade is considered for a future experimental study. Before such an experimental study, the development of a damage model to show the effectiveness of monitoring changes in damping is important. A wind turbine blade is in principle a cantilever beam, so the development of a model to assess the response and potential to localise damage in a simple cantilevered beam is both instructive and relatively simple to set up. Here a general discretised vibration model of a cantilevered beam including damping is developed. The main purpose for the development of such a model is, firstly, to investigate the use of a change in modal damping as an indication for damage and secondly, to find the effect of damage on the frequency response function (FRF) of the system. The vibrational behaviour of a composite cantilever beam with three different damage

accumulation levels: low, moderate and high, has been investigated. Damage in the beam is simulated by a reduction in stiffness and increase in damping coefficient at the root section of beam which is approximately equal to 8% of the total length of the beam. The results shows that with damage accumulation equivalent to a 6% ,12% and 18% reduction in stiffness and an 18%, 21% and 30% increase in damping, a change in modal damping of 6.95%, 9.2% and 16.24%, respectively was observed in simulation. A change in the FRF is dominant around the resonance frequency and this change is also more obvious in higher vibrational modes than lower modes. In addition, changes in the FRF near the simulated ́damaged ́parts of the structure are more significant when compared with points further from the damage.

4.2.5 Wind and Turbulence 2

Start: 19/09/2018 15:45 — **Room: E.0.05** — **Chair:** Maximilian Henkel

15:45 (39) Characterization of anomalous wind events in observations and in the ERA5 reanalysis over the North Sea.

Peter Kalverla — Wageningen University

Many wind energy applications rely on idealized wind characterizations, such as the wind-profile power-law or the logarithmic wind profile. This facilitates, among others, spatial comparison for wind resource assessment, and temporal extrapolation for load assessment. While these idealized descriptions adequately capture the average wind conditions, their application to instantaneous wind fields introduces uncertainties because of oversimplification. To reduce these uncertainties, our objective is to identify and characterize such ́anomalous wind events ́. An analysis of observational data up to a height of 315 m over the North Sea revealed that low-level jets (violating the assumption of monotonically increasing wind speed with height) occur frequently, up to 12% of the time in July. Based on the same dataset, we developed methodologies to assess e.g. the frequency and strength of wind ramps (violating the assumption of stationarity) and wind veer (violating the assumption of a uniform wind direction with height). However, the observational analysis was still limited to the observational facility, and did not provide complete insight into the physical mechanisms that govern these events. Here we extend the observational study for the complete North Sea domain based on ERA5 reanalysis. Preliminary results suggest that ERA5 adequately captures the diurnal and seasonal cycles of low-level jets, although the exact correspondence between model data and observations requires further investigation. Most importantly, we find that the reanalysis data provide much insight into the spatial structure and physical mechanisms governing these anomalous wind events. The low-level jets are concentrated along the coast and are mainly the result of baroclinic forcing, though they migrate over the North Sea as well. We will present analogous analysis for other anomalous wind events as well.

16:00 (88) On the selection of tracking variables at the interface between wind-farm and turbine controllers in a hierarchic wind-farm control approach

Ishaan Sood — KU Leuven

Modern day wind farms suffer from energy extraction losses due to detrimental effects of wakes originating from upstream turbines rows on downstream rows. To overcome this, previous research has developed control strategies which either misalign turbine wakes through yaw induction or reduce wake strength by (dynamically) deviating from the optimal turbine axial induction set points. Other control aims of interest are to provide active regulation of the power output of wind farms to participate in frequency regulation of the grid, and optimizing wind farm performance to protect turbine components. In this work, we consider a hierarchical approach in which the wind-farm controller sends meaningful state signals to turbines, for a controller to track using classical generator torque and blade-pitch control. Therefore, turbine control remains isolated from the control at wind-farm level. An unresolved question then remains is the selection of state-variables that are passed between the wind-farm and turbine controller. They should be meaningful at the wind-farm level (e.g. disk-based thrust coefficient, power set point, turbine rotational speed, etc.) so that (optimal) control formulations are tractable, but should be easy to track by turbine controllers. The current work aims to conduct a comparative study between tracking efficiencies of different selections of wind turbine state parameters by a simple turbine controller using generator torque and blade-pitch control. To this end, control of the NREL 5MW turbine is simulated using SP-Wind, an in-house Large Eddy Simulation (LES) code developed at KU Leuven. Wind turbines are modelled using an Aero-elastic Actuator Sector Model (AASM) to evaluate aeroelastic loads and determine effects of tracking selected state parameters on turbine structure and power output. Results obtained from this research will be used to determine the ideal control signal to be sent from the wind farm controller to turbine controllers for control of wind farm performance.

16:15 (100) Simultaneous observation of wind shears and misalignments from rotor loads: first wind tunnel validation
Marta Bertelè — TU Munich, Wind Energy Institute

Accurate information about the wind inflow is fundamental to maximize the harvested power and to decrease the loads on the machine. In (Cacciola et al. 2016; Bertelè et al. 2017), a linear model was proposed to estimate yaw and upflow angle along with vertical and horizontal shear starting from the loads measured on the turbine blades. In this paper, wind tunnel tests were performed to validate such model in its simplified formulation. The rotationally-symmetric behavior of the rotor is used to relate the effects caused on the machine by yaw to the ones caused by upflow (the same holding for the shears) allowing for an easier identification procedure, lower computational costs and, most importantly, field tests application. After exhaustive validation in a simulated environment, tests were performed in the wind tunnel of the Politecnico of Milan to validate the methodology experimentally for the first time. The results show that a very limited amount of tests suffices to identify a rotationally-symmetric observer, which is capable of very accurately estimating both wind directions and shears under different turbulence intensity levels.

References: Bertelè, Marta; Bottasso, Carlo L.; Cacciola, Stefano; Daher Adegas, Fabiano; Delport, Sara (2017): Wind inflow observation from load harmonics. In Wind Energ. Sci. Discuss., pp. 1-40. DOI: 10.5194/wes-2017-23.

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4.2.6 Turbine Modeling 2

Start: 19/09/2018 15:45 — **Room: E.0.06** — **Chair:** Christof Devriendt

15:45 (4) Towards numerical simulation of offshore wind turbines using anisotropic mesh adaptation
Louis Douteau — Centrale Nantes

Offshore wind is an emerging field where current fixed-bottom technology is limited when water depths exceeds 50 m. Consequently new solutions are currently being explored, with, in particular, the development of floating wind turbines. Moving offshore enable to capture stronger and more constant winds, but may lead to higher CAPEX and OPEX. Numerical simulation can be used to optimize the design of the structures, from the mooring lines to the blades. The numerical tools involved enable a fine prediction of the behavior the structures have under a large span of conditions, e.g. the loads applied on the structures when extreme events occur. These results can lead to an adjustment of the security coefficients of the wind turbines, which can reduce the CAPEX costs. This work focuses on a methodology enabling the simulation of one or several floating wind turbines using full-CFD, with an accurate representation of their respective geometries. The software library used is ICI-Tech, developed at the High Performing Computing Institute of Centrale Nantes. A monolithic approach is used, with a single mesh in the simulation, where all the interfaces are defined using modified level-set functions. The Navier-Stokes equations are solved using stabilized finite elements and the Variational MultiScale formulation. In order to largely reduce the computational costs, an anisotropic and automatic mesh adaptation is done, which enables to capture physical phenomena having different orders of magnitude. The code is currently being validated for wind turbine usage, and results obtained during this process are presented.

16:00 (44) Experimental analysis of the wake behavior during yaw variation imposed through wind farm control strategies

Stefano Macri — Université d´Orléans, Laboratoire PRISME

The configuration of wind farms always shows a compromise between a minimal distance among wind turbines to increase the number of generators for a given area and a maximal distance among wind turbines to reduce the loss of production due to the wake interactions. A wind turbine extracts kinetic energy from the facing wind reducing the available energy for those in its wake. Moreover, the wake regions are sources of velocity gradient and turbulence production that lead to an increase of the loads on the wind turbine structures. One possible solution to these constraints is farm control by the implementation of strategies of misalignment or power curtailment. The present work focuses on the dynamic analysis of a modelled wind turbine wake during yaw manoeuvres. Indeed, in the context of wind farm control, misalignment of wind turbines is envisaged as a solution to reduce wind turbine wake interactions, by skewing the wake trajectory. To optimize the control strategies, the aerodynamic response of the wake to this type of yaw manoeuvres, as well as the global load response of the rotor disc of the downstream wind turbine, must be quantified. As a first approach, the identification of the overall system is performed through wind tunnel experiments, using a rotor model based on the actuator disc concept. A misalignment scenario of the upstream wind turbine model is imposed and the wind turbine wake deflection and load response are dynamically captured and measured by the use of Particle Imaging Velocimetry and a 6 degrees of freedom aerodynamic balance, respectively.

16:15 (93) Variable Speed Variable Pitch Control for a Wind Turbine Scale Model

Alessandro Fontanella and Federico Taruffi — Politecnico di Milano

Within last years, floating wind turbines (FOWTs) were recognized as the key technology to push wind energy further offshore and exploit the high-potential of deep-waters coastal areas. However, the development and optimization of FOWTs implies new engineering challenges. In this contest, model testing is of fundamental importance either to validate the output of numerical codes, used to simulate the wind turbine dynamics, as well as to gather data to further optimize the different FOWT components design. Performing scale model experiments on FOWTs is however a complex task since wind and waves loads, gravitational and buoyancy forces, mooring lines and flexible dynamics must be reproduced simultaneously. The hybrid/hardware-in-the-loop (HIL) methodology was recently proposed to overcome the above-mentioned issues, relying on a physical scale model to reproduce only one part of the complete system. The present work deals with the process followed by the authors to implement a variable-speed variable-pitch controller on a wind turbine scale model for wind tunnel hybrid/HIL tests. The PoliMi 1/75 model of the DTU 10 MW reference wind turbine is presented, focussing on the mechatronic system used to control the machine and test control logics. The main differences between the physical model and the reference wind turbine are investigated, clarifying how the controller response is influenced by non-ideally scaled aerodynamics and structural properties. In reason of these differences, the DTU 10 MW controller, is modified, so to be able to reproduce the dynamics of the full-scale system during wind tunnel tests. Experimental tests at the PoliMi wind tunnel were finally performed to assess the behaviour of the controlled wind turbine.

4.3 Thursday 20 September

4.3.1 Rotor and Aerodynamics 4

Start: 20/09/2018 9:30 — **Room: D.0.02** — **Chair:** Wim Munters

09:30 (43) Delayed Detached-eddy Simulation around NREL S826 Blade Section for Transition Prediction
Özgür Yalçin — Middle East Technical University

This proposed study aims at simulating slightly separated flow over the NREL S826 wind turbine blade section profile with delayed detached-eddy simulation (DDES) strategy. The Reynolds number is relatively low and the angles of attack are around the stall region so that flow is not massively detached. This kind of flow where laminar-turbulent transition and laminar separation take place is difficult to simulate by DDES. To handle the problem and increase the capability of DDES, three developments that appeared in literature only recently are combined. The first of these developments is a modification to Spalart-Allmaras (S-A) one equation, which allows setting initial eddy viscosity value as zero for apparent transition behavior and is selected as a turbulence model. Secondly, the shear-layer-adapted subgrid length scale instead of the classical one, maximum edge length of cells, is used in the resolved mode of DDES. By this enhancement, emergence of turbulent content could be accelerated inside boundary layers in case of instability. The third one is about adaptation of Bas-Cakmakcioglu (B-C) algebraic transition model to the modified S-A turbulence equation. The B-C model multiplies simply an intermittency function depending on local turbulent information with the production term of the S-A model, and thereby provides a boundary layer transition prediction. The ongoing simulations are being performed by an inhouse solver, METUDES, developed for aeroacoustic purposes. The solver features low dissipation, low dispersion with fourth-order accuracy which could also be beneficial in preserving instabilities during transition process. In the extended abstract, the aerodynamic results will be compared with those of available data from a DDES study that uses standard subgrid length scale, and from a RANS study that employs Langtry-Menter transition prediction model.

09:45 (73) Numerical Simulation of Ice Accretion on Coated Wind Turbine Blades
Khaled Yassin — University of Oldenburg, ForWind

In many parts of the world, wind farms are located in cold regions and high altitude areas to benefit from high wind speeds. During operation in such areas, wind turbines are exposed to harsh operating conditions that can cause ice accretion on turbinesṕarts especially blades that results in a drop in rotor aerodynamic performance and many other problems. This PhD thesis aims to develop a numerical simulation tool that is able to simulate ice accretion on wind turbine blades. This developed tool will enable the development of new ice growth reducing coatings by simulating the impact of coatingsṕroperties on the ice accretion process. This work is a part of OptAnIce project that aims to develop a new coating-based anti-icing system that optimizes the operation of wind turbines in cold areas by delaying the use of anti-icing heating systems. The first step of this PhD project is to develop a CFD simulation setup that is able to simulate the air flow around iced blade airfoils. To validate this CFD setup, wind tunnel measurements of iced airfoil profiles at different Reynolds numbers will be used. After that, a new OpenFOAM code will be developed to simulate water droplets trajectories and surface impingement, water runback and icing process in order to simulate the ice growth process on the surface. Finally, the obtained ice profiles will be verified against accreted ice profile in icing wind tunnel at specific icing conditions.

10:00 (79) Analytical and experimental investigation of icing phenomena on wind turbine blades
Adriana Enache — Von Karman Institute for Fluid Dynamics

In cold climate regions, the wind energy production is annually decreased up to 25% by operating the wind turbines in icing conditions. For a wide range of low temperatures, the super-cooled water droplets present in atmosphere freeze when they impact the turbine blades. The rime or glaze ice accretion regimes degrade the aerodynamic blade properties and increase the energy losses. Moreover, in some cases the production is stopped because the turbine icing generates unbalanced forces acting on the rotor and important safety hazards due to ice shedding. Ice mitigation systems designed for aeronautic applications by Sonaca could be used to limit these negative effects, although they imply high additional costs and decrease the wind turbine capacity. This project aims to create an easy-to-use experimentally validated analytical tool to adapt the widely used electro-thermal de-icing systems to wind energy applications. The most encountered icing phenomena are studied to characterize the technique´s main limitations, which form due to the phase change produced at the blade-ice interface by the applied heat transfer. Under the wind´s action, dynamic forces are generated and two phenomena are possible: the ice slides and refreezes backward on the blade profile - run-back ice phenomena, or it detaches from the substrate - producing ice shedding. The analytical model is divided into a thermal part, which addresses the phase change, and a dynamic part that predicts the ice sliding or detachment. So far, a one-dimensional temperature-transforming phase change model was developed. The results will be presented and validated against the analytical solution and literature reference cases. Further, the model development and validation will be done performing several experimental campaigns in the VKI-Icing wind tunnel facility. A real blade and a simplified configuration will be used to study both phenomena. Finally, the performances of the adapted technique will be tested on a real blade configuration.

4.3.2 New Concepts 2

Start: 20/09/2018 9:30 — **Room: E.0.05** — **Chair:** Helena Canet

09:30 (26) Feasibility study of a hybrid renewable energy system combining small-scale wind and solar on a rooftop in the Brussels Region
Quentin Deltenre — Vrije Universiteit Brussel

Rooftops in cities are not generally used for energy production. However, as rooftops represent the last little bit of free space in cities, they are now being considered for sustainable retrofitting. Rooftop photovoltaic panels (PV) have already proven their efficiency and are already promoted by public instances. In recent years, also rooftop-mounted small wind turbines (SWT) have been considered and are now being installed on several buildings. Research on hybrid renewable energy systems (HRES) has also developed significantly thanks to the complementary characteristics between solar and wind energy sources. Nevertheless, the HRES are most often studied for ground applications where space is not a limitation. In this work, we study the feasibility and profitability of a hybrid rooftop-mounted PV/SWT system for the tallest buildings of the Brussels Capital Region (BCR). In fact, these rooftops present the best wind and solar conditions. This presented work can be divided in three parts: First, annual energy production of the combination of the two energy production systems is predicted for the 30 tallest buildings of Brussels. We will proceed with a ńaïveínstallation based on rules of thumb. By means of techno-economic indicators, we will evaluate the hybrid systems on these rooftops. The shadow cast by the turbines on the PV panels is considered. Then, one rooftop in the BCR for which we know the wind and solar conditions as well as its spatial layout, is used as a case study. Based on the load demand of the building, it is possible to determine the percentage of consumed energy-produced. Finally, we review other advantages as a result of the hybrid system. The eventual goal is to determine whether hybrid PV/WT systems on rooftops are feasible and profitable. Several rules of thumb will be proposed to analyse the suitability of any other rooftops.

09:45 (36) Design, manufacturing and experimental validation of a pair of vertical-axis wind turbines for wind tunnel tests
Antoine Vergaerde — Vrije Universiteit Brussel

The potential for Vertical-Axis Wind Turbines (VAWTs) has been reconsidered in recent years, with novel possibilities for their implementation. One idea is to place smaller VAWTs amongst large horizontal-axis wind turbines. Another idea involves the use of VAWTs as a pair for offshore applications. Such configurations are inspected numerically or experimentally (usually through wind tunnel or open field tests). However, contrary to the numerical approach, only few experimental results are available in the literature. Facing the difficulties to reproduce real-life conditions with scale models remains challenging as this implies high wind speeds and/or high rotational speeds. This contribution will report on the design, manufacturing and experimental validation of scale models of VAWT rotors for wind tunnel tests.

Downscaling a rotor usually leads to increased rotational speeds. To limit the structural loads, a hollow design was imposed to keep the weight low. The intended application for the scale models of the rotors required them to perform aerodynamically equal. The manufacturing technique should thus allow for high reproducibility. The preferred technique was aerodynamically validated based on wind tunnel tests of NACA0018 blades. Once the design was fixed and the manufacturing technique was selected, the rotors were produced with carbon fibre using a mould with countermould technique to ensure a good fibre-to-resin ratio and allow high quality edges.

The produced rotors were initially submitted to a dimensional verification which was executed by CNC inspection with a dial indicator. The structural properties of the rotors were inspected with static deflection tests and ultimate loading tests. The vibrational behaviour of the whole setup was captured through frequency analysis.

Finally, the rotors weigh 0.88 kg each with a frontal surface of 0.4 m2 while capable of withstanding rotational speeds of 2000 rpm. Their mechanical torques indicated a strong similar performance.

10:00 (63) Assessment of load and cost reduction capabilities of a 10MW-scale wind turbine through ply angle orientation

Giannis Serafeim — National Technical University of Athens

In the present work, the potential to alleviate wind turbine loads through build in material bend-twist coupling passive control method is assessed. It is materialized by introducing an offset angle on the plies of the uni-directional material over the spar caps of the blade. In addition, cost reduction is investigated by reducing the blade mass, while maintaining the same stress levels (compared to the baseline configuration) at the blade cross-sections along the span. The analysis is performed through aeroelastic simulations for the 10MW DTU Reference Wind Turbine (RWT) in conjunction with a cross sectional analysis tool. A subset of representative fatigue and ultimate design load cases of the IEC is simulated and load and mass reduction levels are assessed with respect to the baseline RWT configuration with no aeroelastic control of loads.

4.3.3 Turbine Modeling 3

Start: 20/09/2018 9:30 — **Room: E.0.06** — **Chair:** Mark Richmond

09:30 (17) Quantification of influencing factors onto the annual energy product with respect to the wind farm layout

Bjoern Roscher — RWTH Aachen, Center For Wind Power Drives

The increasing need for electricity from renewable sources indicates the further pro-liferation of wind farms. However, onshore areas for wind farms are limited. Leading to the fact that space has to be used as beneficial as possible. To achieve this the wind farm layout is a crucial aspect in project development. To find the best possible layout, the most influencing factors in wind farm modelling need to be determined as a first step. In this paper three aspects are investigated in detail at the example of WIFO, the analytic wind farm layout optimization software developed at Center for Wind Power Drives. Firstly, the roughness length at the wind farm site is considered. The roughness length is directly influencing the wind speed. The wind speed is related to the annual energy product (AEP). Accordingly, exact knowledge of the roughness length on a site is essential for exact AEP estimation. Secondly, the wake effect within the wind farm is examined. Wind turbines extract energy from the wind resulting in a downstream wake from the wind turbine, where wind speed is reduced and turbulence is increased. Both factors reduce the AEP of a turbine. Depending on the dominant wind direction the relevant wake effects change within a wind farm. Thirdly, the roughness length of the surrounding areas influences the AEP of a wind farm. With changing inflow directions, this aspect is of high importance. The wind speed characteristics reaching the park are highly influenced by the roughness of areas where the wind is coming from. The influence of these three factors on the AEP of a wind farm is investigated and quantified using an onshore wind farm in northern Germany as an example. The in-fluence will vary depending on the inflow direction of the wind. The discretization of wind direction can range from mere cardinal points (N, E, S, W) to degree steps (0°, 5°, 10°,...). To find the required level of detail regarding the investigated inflow direction will be the major goal.

09:45 (41) PhD project: Verification of Structural Properties for Bend-Twist Coupled Wind Turbine Blades
Mareen Tiedemann — DTU Wind Energy

Wind turbine blades increase in size and complexity. This project aims at the in-depth analysis of structural properties and effects of different structural couplings in full-scale wind turbine blade and their successful experimental identification. Within the project various structural properties will be determined experimentally and numerically. The novelty of this project is to obtain a holistic understanding of coupling effects from the structural point in terms of material anisotropy and geometric shape of the wind turbine blade. Further the aim is to facilitate accurate determination of structural properties, understand their preceding effects on structural performance and target verification, enabling more reliable structural design and certification of highly complex large-scale wind turbine blade structures. Challenge

- Increase in size and flexibility of wind turbine blades causes a rise of uncertainties in structural design
- Structural properties of coupled wind turbine blades need to be verified
- In literature, little measurement data for coupled wind turbine blades is available
- Research has provided some data for small scale specimens (ca. up to 25 m blades) but not for large scale wind turbine blades (50 m +)
- Large scale blades may require development of new test methods

The project runs in cooperation between DTU Wind Energy and Vestas Wind Systems A/S.

10:00 (72) Cost - accuracy analysis of wind turbine simulations with geometrically nonlinear blade models
Ozan Gozcu — DTU Wind Energy

The large wind turbine blades have pre-bent geometry and go through large displacements during their operational lifetime. Wind turbine analysis codes need to model the complex geometry and large displacement response of the blades for accurate load calculations. The floating reference frame (FRF) formulation is an effective method to capture complex blade geometry with finite element discretization and geometric nonlinear effects with multi-body modeling of the structures. Therefore, two well known wind turbine analysis codes (HAWC2 and Bladed) use FRF formulation in which higher accuracy comes with a higher computational cost. Hence, the problem becomes a trade off between accuracy and cost of the blade model. The aim of this study is to investigate accuracy-cost correlations and come with a simple model evaluation method for accurate, cost effective blade models in FRF formulation. The cost is directly the computational cost, whereas the accuracy metrics are selected as blade tip displacements, blade and bearing loads, tower top accelerations, controller activity and power output.

4.3.4 Rotor and Aerodynamics 5

Start: 20/09/2018 10:30 — **Room: D.0.02** — **Chair:** Thomas Haas

10:30 (77) An unsteady actuator annulus relationship for simplified multi-kite systems
Rachel Leuthold — University of Freiburg

For classical horizontal axis wind turbines, there are many available ´engineering models´ that describe the relationship between unsteady induction factors and the nondimensional parameters describing the turbine´s performance, such as power coefficient. There is, as of yet, no such simple unsteady actuator annulus relationship suitable for multiple-kite airborne wind energy systems (MAWES). This work approximates such a relationship from the Biot-Savart integral of a frozen, periodic vortex sheet representing the geometry of a simplified pumping-cycle MAWES. A comparison is made between the behavior of a MAWES as predicted with this new actuator annulus relationship and with the classic Pitt-Peters model.

10:45 (83) Experimental and numerical study on the unsteady aerodynamics of HAWT rotors: new data and results interpretation.

Luca Bernini — Politecnico di Milano

Two main trends are dominating the last years research activity in the wind energy sector: the design of larger, beyond 10 MW rated power, rotors and the development of new floating systems to be used in deep water wind farm. Among all the engineering challenges linked to these two research paths one aspect is the focus of this work: the unsteady aerodynamic response of Horizonal Axis Wind Turbines. In the current industry standard design tools, the wind turbine rotor is aerodynamically designed with the hypothesis of perfect rigidity, aeroelastic effect are taken into consideration only in the design verification phase and usually modeled with dynamic inflow models tuned by a limited series of experimental test results. However, when dealing with very large rotors and floating turbines, big motions of the turbine blade must be considered forcing the necessity of deeper understanding of the unsteady aerodynamic response of turbine rotors. In this work new results from wind tunnel testing on a scaled turbine are presented and compared with numerical models of different complexity, from Blade Element tools up to full rotor CFD models. A series of simplified but representative tests were designed, the aerodynamic of the rotor is studied in term of blade 2d section and entire rotor response. The unsteadiness is considered as an oscillation of the angle of attack on the blade section and as surge motion (i.e. translation displacement in the wind direction) for the whole turbine. Results showed interesting new outcomes partially in contrast with the findings from the literature test campaign. In the full paper the experimental and numerical comparison and analysis of the results will be presented together with an original interpretation of the new results in comparison with literature available findings.

11:00 (96) Vortex ring state prediction for floating offshore wind turbines

Jing Dong — J

The flow state around floating offshore wind turbines (FOWTs) is largely different from that developing around bottom-mounted wind turbines. The vortex ring state (VRS), which occurs when the flow recirculates around the rotor as the turbine moves in its own wake, is potentially a problem that influences the aerodynamic performance of FOWTs. It is still unclear when, and to what extent, does VRS happen to wind turbines. When the VRS occurs to FOWTs, suitable algorithms should be developed to handle it. The aim of this paper is to initially quantitatively predict the VRS associated with FOWTs, which will then be input into the coupled analysis of FOWTs. Two criterions - Wolkovitch´s criterion and Peter´s criterion - are adopted for the VRS prediction, which are both deduced from momentum theory and actuator disk concept. Wolkovitch´s criterion is used to predict the centre of VRS, whilst Peter´s criterion predicts the VRS boundaries on the windmill side and on the propeller side. The results successfully capture VRS in the operating load cases, and important laws of VRS are summarised.

11:15 (97) CFD simulation of floating offshore wind turbines

Marion Cormier — University of Stuttgart - Institute of Aerodynamics and Gas dynamics

The unsteady aerodynamics of a scale model floating offshore wind turbine is numerically investigated. To reproduce the fore-aft translation motion of an offshore floating platform, the base of the horizontal-axis wind turbine is subjected to imposed sinusoidal surge oscillations. The motion parameters are chosen to reproduce realistic flow conditions, as well for a highly unsteady as for a less unsteady case. The unsteadiness is hereby evaluated by means of the characteristic time scale based on the rotor diameter and the inflow velocity, introduced by Snel for dynamic inflow phenomena. The high fidelity CFD set up is presented and validated through comparison of the rotor aerodynamic loads with wind tunnel experiments. The comparison with experimental data shows a really good agreement. Then, the aerodynamic response of both the rotor and the wake development are investigated. The aerodynamic power and loads analysis shows that the power is relatively more marked by the unsteady effects than the thrust. A detailed analysis of the blade loads shows that this is due to an unequally distributed loads response over the blade span for one motion cycle, leading to higher torque fluctuations.

4.3.5 O&M and Condition Monitoring 4

Start: 20/09/2018 10:30 — **Room: E.0.05** — **Chair:** Jan Helsen

10:30 (20) Thermal network modelling of a wind turbine gearbox using matrix inverse method for condition monitoring

Becky Corley — University of Strathclyde

A number of condition monitoring techniques have been applied to diagnose wind turbine gearbox failures. State of the art methodologies predominately use data-driven machine learning techniques to predict failure that rely on large amounts of operational data and failure histories. In this work, a more detailed understanding of the physics inside a gearbox is used, so that when a fault occurs, the failure can be diagnosed, located and a prognosis can be developed to predict and even prevent failure. Thermal modelling based on the principles of heat transfer theory is used to develop this understanding; exploiting temperature measurements to understand a ́healthý gearbox and then use it to detect and locate abnormal gearbox operating conditions.

A wind turbine gearbox is simulated via a lumped parameter model, to calculate the temperature at each node for given heat losses. The heat balance equation is an algebraic statement, under steady state conditions which are formulated out of dimensional information and thermal coefficients. A matrix inverse method is then applied to explore how the heat from losses, propagate through the gearbox. This model is used to simulate gearbox faults to understand how the thermal behaviour changes.

Uncertainty modelling was then undertaken to determine the extent the gearbox model can be simplified, by varying the number of nodes. Additionally, Monte Carlo simulations were carried out on a number of variables to ascertain the significance of assumptions made. Finally, this model was validated using experimental data from a wind turbine gearbox test rig located at the University of Strathclyde, to judge the accuracy and applicability of the simplified model for condition monitoring purposes.

10:45 (53) Comparing rule based and machine learning based vibration condition monitoring for wind turbine gearboxes.

Sofia Koukoura — University of Strathclyde

Vibration condition monitoring is currently based on a traditional rule-based approach in the wind industry. Cost-effective upscaling to a larger fleet using this method becomes a challenge because too much manual analysis is required for some failure modes. Therefore, the objective for this project is to explore the performance of specific machine learning methods applied on vibration data for detecting incipient failures. The proposed methodology utilises gearbox vibration signals in the frequency/order domain in order extract features. These features are used as inputs to a pattern recognition model that can determine the health state of the components. The methodology is validated using vibration data from gearbox failures of operating offshore wind turbines. Failure modes include both gear tooth cracks and bearing race failures. The machine learning and rule-based methods are compared with respect to robustness, missed detections, workload and transparency. The benefits and limitations of methods are discussed.

11:00 (60) Wind Turbine Gearbox Failure Prediction using Deep Learning

Conor McKinnon — University of Strathclyde, Wind and Marine Energy Systems

Wind Turbine gearboxes are susceptible to a large number of faults, many of these can go undetected until they cause some failure in operation. Maintenance scheduling for these components is another problem that can affect the operation of these turbines. This paper looks at the use of a deep learning technique to do predictive condition monitoring for gearboxes to allow for improved maintenance scheduling. This utilises a type of Recurrent Neural Network (RNN) called a Long Short-Term Memory (LSTM) neural network, which has shown to perform well at sequence classification. The LSTM network took labelled vibration time series data from one of the gearbox stages and used this to train itself to be able to classify a previously unseen sequence as healthy or unhealthy. The data being fed into the network was vibration data from healthy gearboxes and data from gearboxes a couple of months before a failure. This unhealthy data was of one specific fault and was used to evaluate how viable this method is. This method utilised no pre-processing of the data or feature extraction and used only the raw data provided. A series of tests were done to find the optimal method for health prediction, this involved changing the various LSTM network hyper-parameters to improve the accuracy. Grouping of data was also tested, with a comparison between only above rated data and all of the data provided. This method did provide some promising results, however more work is needed to improve both the implementation time and accuracy of the network.

11:15 (112) Long Term Modal Parameter Estimation on Wind Turbine Drivetrains
Nicoletta Gioia — Vrije Universiteit Brussel

Wind energy is one of the most promising renewable energy available today. The continuous demand of wind energy production led the interest of the wind industry towards bigger turbines. This upscaling trend has imposed bigger (not quasi-static) loads that are significantly influencing the fatigue life of the wind turbine components and the tonalities generated by the drive train. To tackle noise and vibration problems and validate complex models it is of high interest to continuously track the modal parameters of the machines under operating conditions. This allows a better design of the new prototypes and the reduction of the risk of premature component failures, followed by a possible decrease of the cost of the energy. To do so Operational Modal Analysis represents a powerful tool. One limitation affecting this methodology when applied to rotating machines comes from the presence of harmonics. Their predominance in the spectrum masks the modal content in the signal, making the extraction of the modal parameters impossible. The objective of this research is then to achieve a combination of automatic methodologies for dealing with the harmonics and automatic OMA techniques in order to be able to autonomously process a continuous stream of data.

4.3.6 Wind and Turbulence 3

Start: 20/09/2018 10:30 — **Room: E.0.06** — **Chair:** Elliot Simon

10:30 (85) Development of wake meandering detection algorithms and their application to large eddy simulations of an isolated wind turbine
Nicolas Coudou — UCLouvain, University of Mons, von Karman Institute for Fluid Dynamics

The oscillatory motion of wind turbine wakes, also known as wake meandering, is crucial in wind farms as it increases unsteady loading, in particular yawing moments, on downstream turbines. The study of this phenomenon requires, as a first step, the determination of the position of the wake. Therefore, the aim of this work is to compare several algorithms to track in real-time the centerline of a wind turbine wake. These techniques exploit the velocity/momentum/power deficit inside the wake or are based on the estimation of azimuthal vorticity centroids. They are applied to the data obtained from large eddy simulations of the NREL 5-MW wind turbine subject to a uniform (TI = 0%) and synthetic turbulent inflows (TI = 6%, 10%, 15%). The simulations are performed using a vortex-particle mesh method with the blades modelled using immersed lifting lines. A preliminary analysis of the wake centrelines shows that the amplitude of the wake oscillations increase with the distance from the rotor and with the ambient turbulence level. Furthermore, the wavelength of the oscillations seems to decrease with the turbulence level. Finally, a spectral analysis performed on the streamwise velocity fluctuations in the wake of the wind turbine shows a peak around a Strouhal number St = 0.12, what is in agreement with the literature for wake meandering: $0.1 < St < 0.3$. This study constitutes a first step towards the understanding of meandering mechanisms and its accurate operational modeling.

10:45 (51) Characterization of turbulence spectra using long range pulsed wind lidar
Yiyin Chen — University of Stuttgart, Stuttgart Wind Energy

Because the traditional wind measurement is limited to point measurement (cup and ultrasonic anemometer), study of the spatial structure of turbulence is only made possible by applying Taylor´s frozen hypothesis, which assumes the turbulence eddies remains unchanged while being carried out by the main wind. However, the modern lidar technology, especially the long range lidars, can measure wind at multiple points on a plane and even in a volume in very short time, which make it possible to take a ´snapshot´ of turbulence.
The idea is to use long range lidar data to calculate the wavenumber spectra of turbulence so that the

wavenumber can directly calculated from the spatial displacement of the measurement points and there is no need to use Taylor's frozen hypothesis to convert the temporal frequency into wavenumber. The results will be compared with the turbulence spectra calculated under the Taylor's frozen hypothesis to figure out to what extent the results coincide with each other. Considering that lidar can only measure the line of sight velocity, wind reconstruction must be applied in the analysis.

11:00 (78) Space-time characterization of large-scale atmospheric structures from lidar measurements

Leonardo Alcayaga — DTU Wind Energy

From a wind energy perspective, characterization of turbulent structures with a size comparable to a wind farm is of particular interest when explaining wind turbine wake dynamics and possible spatial variability of the mean wind speed and direction. Based on available 2D data from a dual WindScanner long range LiDAR measurement campaign, carried out at the Østerild test station, Western Denmark, this work aims to analyze variations of such structures under neutral conditions and characterize them in terms of 2-point statistics and spectra. As a first step, a new filtering approach is followed in order to extract valid wind speeds measured far from the LiDAR with low Carrier-to-Noise Ratio (CNR) values. Using several other features measured along with the wind speed, we define a non-parametric, multivariate probability density function and a high dimensional, high probability hyper-region of inliers measurements. This approach allows to reconstruct a larger wind field (range gates spans up to to 7 kilometers for both scanning lidars) and identify large-scale coherent structures.

11:15 (90) LES based 4D-Var data assimilation of a turbulent atmospheric boundary layer using virtual LIDAR sensors

Pieter Bauweraerts — KU Leuven

The turbulent nature of the atmospheric boundary layer leads to wind-turbine power fluctuations, fatigue loading and complex wake interactions in wind farms. Model Predictive Control (MPC) can be used to predict and partially mitigate these effects. This requires a MPC control model capable of capturing the key turbulent flow characteristics. To this end, a large-eddy simulations (LES) based flow model is used, simulated on a relatively coarse grid to reduce computational time. An important block in the MPC toolchain, is the initialization of the simulations based on measurements, which is the focus of the current work. As a case study, we use a fully developed pressure-driven atmospheric boundary layer. To obtain flow information, we employ virtual LIDAR measurements, taken from a LES simulation run on a fine grid, which we use as "virtual reality", and is ideal for development and testing purposes. As a data assimilation technique, we employ a 4D-Var approach on coarse grid LES. In this approach, the 4D-Var, the flow field is optimized such that the measurements of the past period of lenght T are matched as good as possible with the measurements, while satisfying the model equations. Due to the amount of opimization variables, we use a L-BFGS approach combined with an adjoint LES simulation for the gradient calculations.

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