Inflow measurements from blade-mounted flow sensors: Flow analysis, application and aeroelastic response

General information
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Organisations: Department of Wind Energy, Wind turbine loads & control, Aerodynamic design
Authors: Pedersen, M. M. (Intern), Larsen, T. J. (Intern), Aagaard Madsen , H. (Intern), Larsen, G. C. (Intern), Schmidt Paulsen, U. (Intern)
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Condition monitoring of a rotor arrangement in particular a wind turbine
The present invention relates to a method of determining the condition of a device comprising a rotor arrangement. The rotor arrangement comprising a rotational shaft and a number rotor blades each connected at the root to the rotational shaft and extending radially from the rotational shaft. Sensors are arranged to measure for each rotor blade corresponding values of one or more of the following parameters: azimuth angle (Φ) (or a parameter related to the azimuth angle), root bending moment(s) (q), such as the edgewise and/or flapwise root bending moments. The method comprises, while the rotor arrangement rotates, recording corresponding values of azimuth angle and edgewise and flap wise root bending moments for a plurality of rotations of rotor arrangement, transforming by use of e.g. a multi blade coordinate transformation, a Park's transformation or similar transformation the recorded edgewise and flap wise root bending moments (q) into a coordinate system rotating with the rotational shaft, thereby obtaining transformed root bending moments (qf). The method further comprising identifying periodicity in each of the transformed root bending moments, determining the condition of the rotor arrangement to be faulty, in case the one or more periodicities are identified in the transformed root bending moments.

General information
Aeroelastic Analysis of Olsen Wings 14.3m Blade-Bladigue Project

HAWC2 model description and basic analysis of a 15 m rotor radius horizontal axis wind turbine (HAWT) based on 14.3m blade from Olsen Wings and the V27 wind turbine (WT) tower and nacelle properties. The subcomponents of the aeroelastic HAWC2 model have been created in previous projects. The aim of this analysis is to give an overview of the whole model properties and response through simulations. The blade structural and aerodynamic properties in HAWC2 format have been provided by Frederik Zahle and the HAWC2 model of the V27 structure by Morten H. Hansen of DTU Wind Energy Department. The current analysis is part of the Bladigue project (Bladigue, 2020).

Aerodynamic code validation - A mixed collection of examples

General information

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Organisations: Department of Wind Energy, Wind turbine loads & control
Authors: Larsen, T. J. (Intern)
Number of pages: 10
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Volume: 635
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Aeroelastic multidisciplinary design optimization of a swept wind turbine blade

Mitigating loads on a wind turbine rotor can reduce the cost of energy. Sweeping blades produces a structural coupling between flapwise bending and torsion, which can be used for load alleviation purposes. A multidisciplinary design optimization (MDO) problem is formulated including the blade sweep as a design variable. A multifidelity approach is used to confront the crucial effects of structural coupling on the estimation of the loads. During the MDO, ultimate and damage equivalent loads are estimated using steady-state and frequency-domain–based models, respectively. The final designs are verified against time-domain full design load basis aeroelastic simulations to ensure that they comply with the constraints. A 10-MW wind turbine blade is optimized by minimizing a cost function that includes mass and blade root flapwise fatigue loading. The design space is subjected to constraints that represent all the necessary requirements for standard design of wind turbines. Simultaneous aerodynamic and structural optimization is performed with and without sweep as a design variable. When sweep is included in the MDO process, further minimization of the cost function can be obtained. To show this achievement, a set of optimized straight blade designs is compared to a set of optimized swept blade designs. Relative to the respective optimized straight designs, the blade mass of the swept blades is reduced of an extra 2% to 3% and the blade root flapwise fatigue damage equivalent load by a further 8%.

General information
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Organisations: Department of Wind Energy, Wind turbine loads & control, Aerodynamic design, Fluid Mechanics
Authors: Pavese, C. (Intern), Tibaldi, C. (Intern), Zahle, F. (Intern), Kim, T. (Intern)
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Web of Science (2016): Indexed yes
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Scopus rating (2015): SJR 1.196 SNIP 2.086 CiteScore 3.06
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.272 SNIP 3.75 CiteScore 3.42
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.275 SNIP 2.464 CiteScore 2.75
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
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Scopus rating (2012): SJR 1.126 SNIP 2.39 CiteScore 2.36
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
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ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
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Scopus rating (2010): SJR 1.487 SNIP 2.013
Web of Science (2010): Indexed yes
A framework for medium-fidelity wake dynamics in moderately complex terrain

General information
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Organisations: Department of Wind Energy, Wind turbine loads & control, Aerodynamic design, Resource Assessment Modelling
Authors: Larsen, G. C. (Intern), van der Laan, P. (Intern), Ott, S. (Intern)
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Main Research Area: Technical/natural sciences
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Analytical gradients of wind turbine towers fatigue loads

General information
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Organisations: Department of Wind Energy, Wind turbine loads & control, Wind Turbine Structures and Component Design
Authors: Tibaldi, C. (Intern), Hansen, M. H. (Intern), Stolpe, M. (Intern)
Number of pages: 28
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Original language: English
Series: DTU Wind Energy E
Volume: 0138
Main Research Area: Technical/natural sciences
Benchmarking (Code2Code) of the 1Hs 3-Bladed Onshore VAWT
This study is part of the Inflow project. In this report the Nenuphar’s onshore 3-bladed Vertical Axis Wind Turbine (VAWT) prototype (1HS) is modelled in HAWC2 aeroelastic code. In the first part the model properties are summarized. Then the analysis is focused on the rotor performance and various cases are simulated assuming rigid structure. Finally, a code two code comparison is presented based on the HAWC2 results (DTU) and a 2D/3D vortex simulations from IFPEN. From the code to code comparison, a very good agreement is found on aerodynamic performance when dynamic stall effects are not included on the blade. When these effects are added, HAWC2 and vortex simulation results differ. Looking in the overall rotor performance, aerodynamic power predictions also vary between the codes for the blade. The main reasons that have been identified from the analysis are the dynamic stall modelling, the Reynolds effects on the airfoil polars and the blade-wake interaction and the finite aspect ratio effects. Finally, by studying the blade performance within HAWC2 it was made clear that the airfoil polars which are the main input for the simulations, apart from the structural modelling, can lead to different results especially on the rotor power performance.

Characterization of a new open jet wind tunnel to optimize and test vertical axis wind turbines
Based on the increasing interest in urban environmental technologies, the study of small scale vertical axis wind turbines shows motivating challenges. In this paper, we present the characteristics and potentials of a new open jet wind tunnel. It has a nozzle exit area of 1.5 x 1.5 m², and it can be operated with exit velocities from 3 m/s to 17 m/s. The characterization of the flow has been carried out with calibrated pitot tubes, cup anemometers, and hot wire anemometers. Two different configurations of the test area, with and without a ceiling, are considered. Measurements in the range of available exit velocities show that the cross section, where the velocity and turbulence intensities show an acceptable level of uniformity, has an area of 0.8 x 0.8 m² and a streamwise dimension of 2 m from the nozzle exit of the tunnel. In this working section, the maximum turbulence intensity is 4%. The detailed characterization of the flow carried out indicates that the wind tunnel can be used to test small scale models of wind turbines.
Conceptual research of a downwind turbine, based on Suzlon 2.1MW onshore turbine

General information
State: Published
Organisations: Department of Wind Energy, Wind turbine loads & control, Suzlon Blade Science Center, SDU Mads Clausen Institute
Authors: Wanke, G. (Ekstern), Larsen, T. J. (Intern), Hansen, M. (Ekstern), Buhl, T. (Ekstern), Madsen, J. I. (Ekstern), Bergami, L. (Ekstern)
Number of pages: 19
Publication date: 2017

Cross-Cutting Activities 2016 on Wind Turbine Noise, Summary Report
The goal of this report is to summarize activities that took place in year 2016 as part of the Cross-Cutting Activity on Wind Turbine Noise, self-financed by DTU Wind Energy. A short description of the background behind this project (in particular Cross-Cutting Activities conducted in year 2015), the main objectives of the various studies and scientific achievements are reported in the introduction. Then, each Work Packages constituting this project are described in more details in the following sections.

General information
State: Published
Design of a wind turbine swept blade through extensive load analysis

The main focus of this work is to offer an extensive investigation regarding the use of backward swept blades for passive load alleviation on wind turbines. Sweeping blades backward produces a structural coupling between flapwise bending towards the tower and torsion towards feathering. This coupling mitigates loads on the wind turbine structure due to a decrease in the angle of attack. The load alleviation can be achieved by changing the blade geometry according to three parameters: starting point for the change of shape along the blade span, blade tip sweep, and blade forward sweep. A parametric study is carried out on a 10 MW wind turbine with the purpose of outlining the relation between load variations and three geometric parameters used to introduce passive control on wind turbine blades. The objective is to estimate and analyze extreme and fatigue loads, formulating suggestions for the design of a wind turbine that employs backward swept blades. From the investigation, it is concluded that mildly and purely backward swept shapes are the best option because they allow the wind turbine to achieve load alleviations without a large increase of the blade root torsional extreme and lifetime equivalent fatigue moment. The efficacy of the design procedure provided with this work is proved through its application on a 5 MW wind turbine design.
Development of a Mechanical Passive Pitch System for a 500W Horizontal Axis Wind Turbine
The goal of this paper is to design, analyze, manufacture, and test a mechanical passive pitch mechanism for a small horizontal axis wind turbine. Several pitching concepts were investigated in the wind industry and related fields before ultimately deciding on a centrifugal governor design concept in a pitch-to-stall configuration. Inertial and aerodynamic models were developed in order to predict steady-state performance and an optimization routine was created to optimize the pitch mechanism configuration subject to manufacturing constraints. Dynamic modeling in HAWC2 validated the steady-state design code, aeroelastic simulations were performed in turbulent wind conditions to simulate the pitch system dynamics. Physical testing of the full turbine was not completed, however the hub sub-assembly was tested on its own to validate the passive pitch characteristics and showed good agreement with the simulation tools developed.
Elastic deformations of floaters for offshore wind turbines: Dynamic modelling and sectional load calculations

To achieve economically and technically viable floating support structures for large 10MW+ wind turbines, structural flexibility may increase to the extent that becomes relevant to incorporate along with the corresponding physical effects within aero-hydro-servo-elastic simulation tools. Previous work described a method for the inclusion of substructural flexibility of large-volume substructures, including wave-structure interactions through linear radiation-diffraction theory. Through an implementation in the HAWC2 simulation tool, it was shown that one may incorporate the effects of additional modes on substructure and wind turbine response as well as predict the excitation of substructure flexible modes. This work goes one step further and describes a method to calculate internal substructural stresses that includes dynamic effects. In dynamic calculations, the substructure flexibility is considered through a reduced set of modes, selected based on their relevance to the external load frequency range, and represented with a superelement. The implementation of this method in aeroelastic simulation tool HAWC2 and wavestructure analysis program WAMIT is described, highlighting the practical challenges. A case study of the DTU 10MW Reference Wind Turbine installed on the Triple Spar concept is presented to illustrate the method. The results show that the substructure flexible modes, global platform motion and wind turbine loads can influence sectional loads within the substructure.

Fault diagnosis and condition monitoring of wind turbines

This paper describes a model-free method for the fault diagnosis and condition monitoring of rotor systems in wind turbines. Both fault diagnosis and monitoring can be achieved without using a model for the wind turbine, applied controller, or wind profiles. The method is based on measurements from standard sensors on modern wind turbines, including moment sensors and rotor angle sensors. This approach will allow the method to be applied to existing wind turbines without any modifications. The method is based on the detection of asymmetries in the rotor system caused by changes or faults in the rotor system. A multiblade coordinate transformation is used directly on the measured flap-wise and edge-wise moments followed by signal modulation. Changes or faults in the rotor system will result in unique signatures in the set of modulation signals. These signatures are described through the amplitudes and phase information of the modulation signals. It is possible to detect and isolate which blade is faulty or has been changed based on these signatures. Furthermore, the faulty component can be isolated, ie, the actuator, sensor or blade, and the type of fault can be determined. The method can be used both on- and off-line.
General information
State: Accepted/In press
Organisations: Department of Electrical Engineering, Automation and Control, Department of Applied Mathematics and Computer Science, Dynamical Systems, Department of Wind Energy, Wind turbine loads & control, AF Consult
Authors: Niemann, H. H. (Intern), Poulsen, N. K. (Intern), Mirzaei, M. (Intern), Henriksen, L. C. (Ekstern)
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Scopus rating (2016): CiteScore 2.04 SJR 0.886 SNIP 1.102
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.012 SNIP 1.084 CiteScore 1.69
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.245 SNIP 1.357 CiteScore 1.98
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.945 SNIP 1.256 CiteScore 2.07
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.843 SNIP 1.286 CiteScore 1.84
ISI indexed (2012): ISI indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.889 SNIP 0.988 CiteScore 1.45
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.871 SNIP 1.217
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.39 SNIP 1.578
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.374 SNIP 1.89
Scopus rating (2007): SJR 1.049 SNIP 1.59
Scopus rating (2006): SJR 0.716 SNIP 1.047
Scopus rating (2005): SJR 0.657 SNIP 1.217
Scopus rating (2004): SJR 0.744 SNIP 1.105
Scopus rating (2003): SJR 1.275 SNIP 1.448
Scopus rating (2002): SJR 1.339 SNIP 0.988
Scopus rating (2001): SJR 0.34 SNIP 0.476
Scopus rating (2000): SJR 0.654 SNIP 0.997
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Scopus rating (1999): SJR 0.634 SNIP 0.991
Original language: English
Blade faults, Model-free fault diagnosis, Multiblade coordinate transformation, System monitoring, Signal modulation, Wind turbines
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Publication: Research - peer-review › Journal article – Annual report year: 2017
Fundamental aeroelastic properties of a bend–twist coupled blade section
The effects of bend–twist coupling on the aeroelastic modal properties and stability limits of a two-dimensional blade section in attached flow are investigated. Bend–twist coupling is introduced in the stiffness matrix of the structural blade section model. The structural model is coupled with an unsteady aerodynamic model in a linearised state–space formulation. A numerical study is performed using structural and aerodynamic parameters representative for wind turbine blades. It is shown that damping of the edgewise mode is primarily influenced by the work of the lift which is close to antiphase, making the stability of the mode sensitive to changes in the stiffness matrix. The aerodynamic forces increase the stiffness of the flapwise mode for flap–twist coupling to feather for downwind deflections. The stiffness reduces and damping increases for flap–twist to stall. Edge–twist coupling is prone to an edgetwist flutter instability at much lower inflow speeds than the uncoupled blade section. Flap–twist coupling results in a moderate reduction of the flutter speed for twist to feather and divergence for twist to stall.

General information
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Organisations: Department of Wind Energy, Wind turbine loads & control
Authors: Stäblein, A. R. (Intern), Hansen, M. H. (Intern), Pirrung, G. (Intern)
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Scopus rating (2016): SJR 1.316 SNIP 2.051 CiteScore 2.62
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.277 SNIP 1.895 CiteScore 2.33
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.428 SNIP 2.738 CiteScore 2.69
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.582 SNIP 2.841 CiteScore 2.96
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.154 SNIP 2.356 CiteScore 2.14
ISI indexed (2012): ISI indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.386 SNIP 2.369 CiteScore 2.16
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.534 SNIP 2.711
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.515 SNIP 2.366
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.398 SNIP 2.688
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.385 SNIP 2.142
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.285 SNIP 2.934
A high-fidelity linear time-invariant model of the aero-servo-elastic response of a wind turbine with trailing-edge flaps is presented and used for systematic tuning of an individual flap controller. The model includes the quasi-steady aerodynamic effects of trailing-edge flaps on wind turbine blades and is integrated in the linear aeroelastic code HAWCStab2. The dynamic response predicted by the linear model is validated against non-linear simulations, and the quasi-steady assumption does not cause any significant response bias for flap deflection with frequencies up to 2-3 Hz. The linear aero-servo-elastic model support the design, systematic tuning and model synthesis of smart rotor control systems. As an example application, the gains of an individual flap controller are tuned using the Ziegler-Nichols method for the full-order poles. The flap controller is based on feedback of inverse Coleman transformed and low-pass filtered flapwise blade root moments to the cyclic flap angles through two proportional-integral controllers. The load alleviation potential of the active flap control, anticipated by the frequency response of the linear closed-loop model, is also confirmed by non-linear time simulations. The simulations report reductions of lifetime fatigue damage up to 17% at the blade root and up to 4% at the tower bottom.
Identification of critical design load cases for a jacket supported offshore wind turbine

This paper identifies the most critical design load cases of ultimate load analysis for an offshore wind jacket foundation from IEC 61400-3 to understand the relative severity among different operation situation. A comprehensive design load cases for ultimate load analysis were simulated using the DTU Wind Energy aero-elastic code HAWC2. The superelement modelling was used to speed up the simulation. The modified INNWIND.EU reference jacket and DTU 10MW wind turbine were used as the reference model. A variety of critical design load cases were identified from all the investigated cases considering the bending moments at tower bottom and jacket mudline as the key design parameters for wind turbine and jacket foundation, respectively. It is shown that the hydrodynamic loading in severe sea state is the design drive load for jacket foundation with respect to the ultimate bending moment at the mudline.
Identification of Critical Design Load Cases for a Jacket Supported Offshore Wind Turbine

This paper identifies the most critical design load cases of ultimate load analysis for an offshore wind jacket foundation from IEC 61400-3 to understand the relative severity among different operation situations. A comprehensive design load cases for ultimate load analysis were simulated using the DTU Wind Energy aero-elastic code HAWC2. The superelement modelling was used to speed up the simulation. The modified INNWIND.EU reference jacket and DTU 10MW wind turbine were used as the reference model. A variety of critical design load cases were identified from all the investigated cases considering the bending moments at tower bottom and jacket mudline as the key design parameters for wind turbine and jacket foundation, respectively. It is shown that the hydrodynamic loading in severe sea state is the design drive load for jacket foundation with respect to the ultimate bending moment at the mudline.

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Scopus rating (2015): SNIP 0.525 SJR 0.319 CiteScore 0.19
BFI (2014): BFI-level 1
Scopus rating (2014): SNIP 0.622 SJR 0.407 CiteScore 0.23
BFI (2013): BFI-level 1
Scopus rating (2013): SNIP 0.557 SJR 0.338 CiteScore 0.23
ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 1
Scopus rating (2012): SNIP 0.448 SJR 0.341 CiteScore 0.16
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SNIP 0.561 SJR 0.353 CiteScore 0.19
ISI indexed (2011): ISI indexed no
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Scopus rating (2010): SNIP 0.695 SJR 0.37
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Inflow conditions and wake effects for wind turbines in forested terrain

General information
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Organisations: Department of Wind Energy, Meteorology & Remote Sensing, Resource Assessment Modelling, Wind turbine loads & control, Technical University of Denmark, Uppsala University
Authors: Dellwik, E. (Intern), Papetta, A. (Ekstern), Arnqvist, J. (Ekstern), Nielsen, M. (Intern), Larsen, T. J. (Intern)
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Main Research Area: Technical/natural sciences
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LIDAR Correlation to Extreme Flapwise Moment: Gust Impact Prediction Time and Feedforward Control
A conventional wind turbine controller uses feedback parameters reacting to wind disturbances after they have already impacted the rotor. LIDARs are able to measure the wind speed before it reaches the wind turbine rotor. These anticipated values can be used in control systems designed to reduce turbine loads. This report is focused on gust prediction events, based on nacelle mounted LIDAR measurements, which lead to large blade flapwise moments. The prediction could be...
used as a mitigation system decreasing the loading and extending the turbine lifetime. The data obtained from the UniTTe project (www.unitte.dk) is used in this task. The measurements come from three different acquisition systems: a met mast, an Avent 5 beam LIDAR and a series of sensors installed on a SWT-2.3MW-93. The turbine is owned by Vattenfall and is placed in Nørrekær Enge. The impact of wind gusts on the blade root bending moment will be studied. In this report, first the measurement data is synchronized and second a sub-set of cases are chosen based on the wind turbine status, mean wind direction and cause of the blade root bending moment peak. Then, the LIDAR measurements are compared to the met mast and wind turbine loads. Finally, a discussion of the prediction accuracy of the current LDIAR set-up and some aeroelastic simulations are performed.

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Organisations: Department of Wind Energy, Wind turbine loads & control
Authors: Meseguer Urban, A. (Intern), Hansen, M. H. (Intern)
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Publication information
Publisher: DTU Wind Energy
Original language: English

Loads in wind farms under non-neutral ABL stability conditions: A full-scale validation study of the DWM model.
The purpose of this study is twofold: To validate a generalized version of the DWM approach for load prediction under non-neutral atmospheric stability conditions, and to demonstrate the importance of atmospheric stability for wind turbines operating in wind farm conditions.

General information
State: Published
Organisations: Department of Wind Energy, Wind turbine loads & control, Fluid Mechanics
Authors: Larsen, G. C. (Intern), Larsen, T. J. (Intern), Hansen, K. S. (Intern)
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Loads in wind farms under non-neutral ABL stability conditions: A full-scale validation study of the DWM model.
The purpose of this study is twofold: To validate a generalized version of the DWM approach for load prediction under non-neutral atmospheric stability conditions, and to demonstrate the importance of atmospheric stability for wind turbines operating in wind farm conditions.

General information
State: Published
Organisations: Department of Wind Energy, Wind turbine loads & control, Resource Assessment Modelling, Fluid Mechanics
Authors: Larsen, G. C. (Intern), Larsen, T. J. (Intern), Ott, S. (Intern), Hansen, K. S. (Intern)
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Media of output: Power Point Presentation
Original language: English
Main Research Area: Technical/natural sciences
Electronic versions:
Medium fidelity modelling of loads in wind farms under non-neutral ABL stability conditions – a full-scale validation study: Paper

The aim of the present paper is to demonstrate the capability of medium fidelity modelling of wind turbine component fatigue loading, when the wind turbines are subjected to wake affected non-stationary flow fields under non-neutral atmospheric stability conditions. To accomplish this we combine the classical Dynamic Wake Meandering model with a fundamental conjecture stating: Atmospheric boundary layer stability affects primary wake meandering dynamics driven by large turbulent scales, whereas wake expansion in the meandering frame of reference is hardly affected. Inclusion of stability (i.e. buoyancy) in description of both large- and small scale atmospheric boundary layer turbulence is facilitated by a generalization of the classical Mann spectral tensor, which consistently includes buoyancy effects. With non-stationary wind turbine inflow fields modelled as described above, fatigue loads are obtained using the state-of-the art aeroelastic model HAWC2. The Lillgrund offshore wind farm (WF) constitute an interesting case study for wind farm model validation, because the WT interspacing is small, which in turn means that wake effects are significant. A huge data set, comprising 5 years of blade and tower load recordings, is available for model validation. For a multitude of wake situations this data set displays a considerable scatter, which to a large degree seems to be caused by atmospheric boundary layer stability effects. Notable is also that rotating wind turbine components predominantly experience high fatigue loading for stable stratification with significant shear, whereas high fatigue loading of non-rotating wind turbine components are associated with unstable atmospheric boundary layer stratification.

General information
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Applied fluid mechanics, Boundary layer and shear turbulence, Wakes, Power and plant engineering (mechanical engineering), Other structures, Fluid mechanics and aerodynamics (mechanical engineering), Elasticity (mechanical engineering), Buckling and instability (mechanical engineering), Fracture mechanics and hardness (mechanical engineering), boundary layer turbulence, elasticity, fatigue, mechanical stability, offshore installations, wakes, wind turbines, medium fidelity loads modelling, nonneutral ABL stability conditions, wind turbine component fatigue loading, wake affected nonstationary flow fields, nonneutral atmospheric stability conditions, dynamic wake meandering model, atmospheric boundary layer stability, primary wake meandering dynamics, large turbulent scales, wake expansion, atmospheric boundary layer turbulence, classical Mann spectral tensor, buoyancy effects, nonstationary wind turbine inflow fields, fatigue loads, aeroelastic model HAWC2, Lillgrund offshore wind farm, WF, wind farm model validation, wake effects, tower load recordings, atmospheric boundary layer stability effects, rotating wind turbine components, unstable atmospheric boundary layer stratification

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Modal Properties and Stability of Bend-Twist Coupled Wind Turbine Blades
Coupling between bending and twist has a significant influence on the aeroelastic response of wind turbine blades. The coupling can arise from the blade geometry (e.g. sweep, prebending or deflection under load) or from the anisotropic properties of the blade material. Bend-twist coupling can be utilised to reduce the fatigue loads of wind turbine blades. In this study the effect of material based coupling on the aeroelastic modal properties and stability limits of the DTU 10 MW Reference Wind Turbine are investigated. The modal properties are determined by means of eigenvalue analysis around a steady-state equilibrium using the aero-servo-elastic tool HAWCStab2 which has been extended by a beam element that allows for fully coupled cross-sectional properties. Bend-twist coupling is introduced in the cross-sectional stiffness matrix by means of coupling coefficients that introduce twist for flapwise (flap-twist coupling) or edgewise (edge-twist coupling)
bending. Edge-twist coupling can increase or decrease the damping of the edgewise mode relative to the reference blade, depending on the operational condition of the turbine. Edge-twist to feather coupling for edgewise deflections towards the leading edge reduces the inflow speed at which the blade becomes unstable. Flap-twist to feather coupling for flapwise deflections towards the suction side increase the frequency and reduce damping of the flapwise mode. Flap-twist to stall reduces frequency and increases damping. The reduction of blade root flapwise and tower bottom fore-aft moments due to variations in mean wind speed of a flap-twist to feather blade are confirmed by frequency response functions.
OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semisubmersible Wind Turbine
This paper summarizes the findings from Phase II of the Offshore Code Comparison, Collaboration, Continued, with Correlation project. The project is run under the International Energy Agency Wind Research Task 30, and is focused on validating the tools used for modeling offshore wind systems through the comparison of simulated responses of select system designs to physical test data. Validation activities such as these lead to improvement of offshore wind modeling tools, which will enable the development of more innovative and cost-effective offshore wind designs.

General information
This paper is about development and use of a research based stereo vision system for vibration and operational modal analysis on a parked, 1-kW, 3-bladed vertical axis wind turbine (VAWT), tested in a wind tunnel at high wind. Vibrations were explored experimentally by tracking small deflections of the markers on the structure with two cameras, and also numerically, to study structural vibrations in an overall objective to investigate challenges and to prove the capability of using stereo vision. Two high speed cameras provided displacement measurements at no wind speed interference. The displacement time series were obtained using a robust image processing algorithm and analyzed with data-driven stochastic subspace identification (DD-SSI) method. In addition of exploring structural behaviour, the VAWT testing gave us the possibility to study aerodynamic effects at Reynolds number of approximately $2 \times 10^5$. VAWT dynamics were...
simulated using HAWC2. The stereo vision results and HAWC2 simulations agree within 4% except for mode 3 and 4. The high aerodynamic damping of one of the blades, in flatwise motion, would explain the gap between those two modes from simulation and stereo vision. A set of conventional sensors, such as accelerometers and strain gauges, are also measuring rotor vibration during the experiment. The spectral analysis of the output signals of the conventional sensors agrees the stereo vision results within 4% except for mode 4 which is due to the inaccuracy of spectral analysis in picking very closely spaced modes. Finally, the uncertainty of the 3D displacement measurement was evaluated by applying a generalized method based on the law of error propagation, for a linear camera model of the stereo vision system.

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Authors: Najafi, N. (Intern), Schmidt Paulsen, U. (Intern)
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BFI (2010): BFI-level 2
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Using wind speed from a blade-mounted flow sensor for power and load assessment on modern wind turbines

In this paper an alternative method to evaluate power performance and loads on wind turbines using a blade-mounted flow sensor is investigated. The hypothesis is that the wind speed measured at the blades has a high correlation with the power and loads such that a power or load assessment can be performed from a few hours or days of measurements. In the present study a blade-mounted five-hole pitot tube is used as the flow sensor as an alternative to the conventional approach, where the reference wind speed is either measured at a nearby met mast or on the nacelle using lidar technology or cup anemometers. From the flow sensor measurements, an accurate estimate of the wind speed at the rotor plane can be obtained. This wind speed is disturbed by the presence of the wind turbine, and it is therefore different from the free-flow wind speed. However, the recorded wind speed has a high correlation with the actual power production as well as the flap-wise loads as it is measured close to the blade where the aerodynamic forces are acting. Conventional power curves are based on at least 180 h of 10 min mean values, but using the blade-mounted flow sensor both the observation average time and the overall assessment time can potentially be shortened. The basis for this hypothesis is that the sensor is able to provide more observations with higher accuracy, as the sensor follows the rotation of the rotor and because of the high correlation between the flow at the blades and the power production. This is the research question addressed in this paper. The method is first tested using aeroelastic simulations where the dependence of the radial position and effect of multiple blade-mounted flow sensors are also investigated. Next the method is evaluated on the basis of fullscale measurements on a pitch-regulated, variable-speed 3.6 MW wind turbine. It is concluded that the wind speed derived from the blade-mounted flow sensor is highly correlated with the power and flap-wise bending moment and that the method has advantages over the traditional approach where the met-mast wind speed is used as reference, e.g. the capability of measuring the shear, veer and turbulence. The aeroelastic simulations show that the assessment time can be reduced, but this reduction cannot be confirmed from the current measurement database due to sensor problems and practical circumstances. Measuring the wind speed at the rotor plane comes with a price as the wind speed is affected by the induction which may be sensitive to the changes you want to evaluate, e.g. different vortex generator configurations. Furthermore it is concluded that a robust instrument and measurement system is required to obtain accurate and reliable wind speed recordings from pitot-tube measurements.
This paper presents a comparison between measured and simulated tower loads for the Danish offshore wind farm Nysted 2. Previously, only limited full scale experimental data containing tower load measurements have been published, and in many cases the measurements include only a limited range of wind speeds. In general, tower loads in wake conditions are very challenging to predict correctly in simulations. The Nysted project offers an improved insight to this field as six wind turbines located in the Nysted II wind farm have been instrumented to measure tower top and tower bottom moments. All recorded structural data have been organized in a database, which in addition contains relevant wind turbine SCADA data as well as relevant meteorological data - e.g. wind speed and wind direction - from an offshore mast located in the immediate vicinity of the wind farm. The database contains data from a period extending over a time span of more than 3 years. Based on the recorded data basic mechanisms driving the increased loading experienced by wind turbines operating in offshore wind farm conditions have been identified, characterized and modeled. The modeling is based on the Dynamic Wake Meandering (DWM) approach in combination with the state-of-the-art aeroelastic model HAWC2, and has previously as well as in this study shown good agreement with the measurements. The conclusions from the study have several parts. In general the tower bending and yaw loads show a good agreement between measurements and simulations. However, there are situations that are still difficult to match. One is tower loads of single-wake operation near rated ambient wind speed for single wake situations for spacing’s around 7-8D. A specific target of the study was to investigate whether the largest tower fatigue loads are associated with a certain downstream distance. This has been identified in both simulations and measurements, though a rather flat optimum is seen in the measurements.
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**Variable speed control for Vertical Axis Wind Turbine**
A robust variable speed control for vertical axis wind turbine applications is implemented. It is a PI rotor speed controller based on an induction generator model operated at variable frequency. The generator dynamics are approximated by a first order differential equation with a prescribed slip. In order to allow variability in the rotor speed an inverter is assumed which changes the nominal generator speed. Below rated power the optimum tip speed ratio is tracked, while above the power is constrained to rated. The wind speed which is needed in the control it is considered as a known signal and used after a first order low pass filtering with a certain time-constant. The controller has been developed and coded by Torben Larsen and it is compiled as an external DLL file. The simulations are done in the HAWC2 aero-servo-elastic code using a 3-bladed H-type VAWT which has been built within the Inflow project. The investigation of the VAWT performance under different control parameters such as the PI gains has been performed by Christos Galinos. Deterministic and turbulent wind speed steps of 2 m/s from 6 m/s to 24 m/s and back to 12 m/s are applied. The controller gives smooth transient response on rotor speed and the produced power with a small overshoot in the power when the rated wind speed is reached for a wide range of PI gains for both the deterministic and the turbulent wind field. Lastly, it is not affected from the inherent variation in blade loading of VAWTs for each rotor revolution due to a low pass filter in the measured electrical power.

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**Vindmøller. Opskalering, Koncepter**

**General information**
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Wind farm design in complex terrain: the FarmOpt methodology

Designing wind farms in complex terrain is becoming more and more important, especially for countries like China, where a large portion of the territory is featured as complex terrain. Although potential richer wind resources could be expected at complex terrain sites (thanks to the terrain effects), they also expose many challenges for wind farm designers/developers.

In this study, we present the FarmOpt methodology for designing wind farms in complex terrain, which combines the state-of-the-art wind resource assessment methods with engineering wake models adapted for complex terrain and advanced layout optimization algorithms. Various constraints are also modelled and considered in the design optimization problem for maximizing the annual energy production (AEP). A case study is presented to illustrate the effectiveness of the methodology. Further developments of the FarmOpt tool are also briefly introduced.

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Wind turbine influence on surfers wind conditions at Hanstholm

In this report a consequence study regarding the surfers wind conditions east of the Hanstholm harbour area. Four existing turbines with a nominal power of 525kW is planned replaced with three new 4.3MW turbines near the beach are. It is investigated whether these wind turbines could potentially alter the wind conditions on the lee side, which is an important area for wind and kite surfers. The Dynamic Wake Meander Model is used to investigate the wind conditions north east of the planned new turbines at Hanstholm covering a surf area from a location called “Fish Factory” to a location called “Hamburg”. This model, which predicts instationary wind conditions behind one or more wind turbines, has previously been used to predict the changed power and load conditions for wind turbines in wind farm conditions. A very fine agreement to measurements is seen and the model is therefore considered sufficient for this particular study also. Furthermore a more advanced flow solver has been used to give a qualitative understanding of the flow conditions near the existing and new turbines. In general the impact of the new windturbines are very limited and the same order of magnitude as the existing smaller turbines. The reason is that the new turbines mainly disturbs the wind conditions from 30m and upwards.

A coupled near and far wake model for wind turbine aerodynamics

In this paper, an aerodynamic model consisting of a lifting line-based trailed vorticity model and a blade element momentum (BEM) model is described. The focus is on the trailed vorticity model, which is based on the near wake model (NWM) by Beddoes and has been extended to include the effects of downwind convection and to enable a faster and more accurate computation of the induction, especially close to the blade root and tip. The NWM is introduced to model the detailed steady and unsteady induction from the first part of the trailed vorticity behind the individual rotor blades. The model adds a radial coupling between the blade sections and provides a computation of tip loss effects that depends on the actual blade geometry and the respective operating point. Moreover, the coupling of the NWM with a BEM theory-based far wake model is presented. To avoid accounting for the near wake induction twice, the induction from the BEM model is reduced by a coupling factor, which is continuously updated during the computation to ensure a good behavior of the model in varying operating conditions. The coupled near and far wake model is compared with a simple prescribed wake lifting line model, a BEM model and full rotor computational fluid dynamics (CFD) to evaluate the steady-state results in different cases. The model is shown to deliver good results across the whole operation range of the NREL 5-MW reference wind turbine.
Aerial sensor for wind turbines Design, implementation and demonstration of the technology
The EUDP-2012 proposal, "Improved wind turbine efficiency using synchronized sensors" is a project which focuses on improving the efficiency of energy production, primarily for wind turbines, but as a spinoff, also traditional power plants. It builds on the experience and proven technology from three previous wind turbine projects: - A wing mounted inflow sensor for wind turbines. This system has gone through multiple stages of development, and will be greatly enhanced by the synchronization technology from this project.

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Aeroelastic Optimization of a 10 MW Wind Turbine Blade with Active Trailing Edge Flaps
This article presents the aeroelastic optimization of a 10MW wind turbine ‘smart blade’ equipped with active trailing edge flaps. The multi-disciplinary wind turbine analysis and optimization tool HawtOpt2 is utilized, which is based on the open-source framework Open-MDAO. The tool interfaces to several state-of-the art simulation codes, allowing for a wide variety of problem formulations and combinations of models. A simultaneous aerodynamic and structural optimization of a 10 MW wind turbine rotor is carried out with respect to material layups and outer shape. Active trailing edge flaps are integrated in the design taking into account their achieved fatigue load reduction. The optimized ‘smart blade’ design is compared to an aeroelastically optimized design with no flaps and the baseline design.

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Aeroservoelastic analysis of storm-ride-through control strategies for wind turbines

An investigation of a control strategy to allow wind turbines to operate at high wind speeds by derating the rotor speed and generator torque set-points is presented. The investigation analyzes the wind turbine aeroservoelastic behavior in the above rated operational range by computing the aerodynamic gains and closed-loop eigenvalue solutions using a high-fidelity linear model. A simple strategy to reduce the reference rotor speed based on a pitch angle feedback is presented and analyzed. It is shown that high aerodynamic gains for operation at high wind speeds requires special handling in the scheduling of the controller gains. The computed closed-loop modal frequencies and damping ratios show how most turbine modes become less damped as the rotor speed is derated, and at very high winds the frequency and damping of the first drivetrain torsion mode are significantly reduced. Possible resonance problems can also be seen from the computed frequencies, and these problems may be worsened by the decreased damping during storm-ride-through. Finally it is shown that the dynamics of the pitch feedback to the derated generator speed is significantly affected by the operational wind speed, resulting in a slow response at high wind speeds.

LIDAR-assisted model predictive controller added on a traditional wind turbine controller

LIDAR-assisted collective pitch control shows promising results for load reduction in the full load operating region of horizontal axis wind turbines (WT). Utilizing LIDARs in WT control can be approached in different ways; One method is to design the WT controller from ground up based on the LIDAR measurements. Nevertheless, to make the LIDAR-assisted controller easily implementable on existing wind turbines, one can design a controller that is added to the original and existing WT controller. This add-on solution makes it easier to prove the applicability and performance of the LIDAR-assisted WT control and opens the market of retrofitting existing wind turbines with the new technology. In this paper, we suggest a model predictive controller (MPC) that is added to the basic gain scheduled PI controller of a WT to enhance the performance of the closed loop system using LIDAR measurements. The performance of the MPC controller is compared against two controllers. The controllers are 1) a gain scheduled PI controller and 2) a controller with the same feedback as controller no. 1 and an added feed-forward loop (FF+PI controller). Simulations are used to compare their performances. The simulation scenarios include the extreme operating gust and normal power production using stochastic wind field in the full load region. The results show superior performance compared to the PI controller and a performance marginally better compared to the FF+PI controller. The reason for a better performance against the PI controller is that the MPC controller employs the LIDAR wind speed measurements to predict and compensate future disturbances. The MPC controller is designed based on the closed loop model of the wind turbine including the pitch actuator and therefore an appropriate pitch signal is calculated, while the FF+PI controller employs filter and delay compensation to take the actuator dynamics into account.
Analysis and design of bend-twist coupled wind turbine blades

Bend-twist coupling allows wind turbine blades to self-alleviate sudden inflow changes, as in gusty or turbulent conditions, resulting in reduced ultimate and fatigue loads. If the coupling is introduced by changing the fibre direction of the anisotropic blade material, the assumptions of classical beam theory are not necessarily valid. This chapter reviews the effects of anisotropic material on the structural response of beams and identifies those relevant for wind turbine blade analysis. A framework suitable for the structural analysis of wind turbine blades is proposed and guidance for the design of bend-twist coupled blades is given.

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A novel full scale experimental characterization of wind turbine aero-acoustic noise sources - preliminary results

The paper describes a novel full scale experiment on a 500 kW wind turbine with the main objective to characterize the aero-acoustic noise sources. The idea behind the instrumentation is to study the link and correlation between the surface pressure (SP) fluctuations in the boundary layer of the blade and the noise on the ground in a distance of about one rotor diameter. In total six surface microphones were used to measure the SP at the leading edge (LE) and trailing edge (TE) of the blade. In parallel noise was measured by eight microphones placed on plates on the ground around the turbine in equidistant angles on a circle with a radius of about one rotor diameter. The data were analyzed in segments of 2.2 s which is the time for one rotor revolution. The spectra for the TE microphones on the suction side of the blade show a characteristic roll-off pattern around a frequency of 600-700 Hz. For increasing wind speed the spectral energy increases below this point and the same is seen on the ground microphones spectra. The decrease in the spectral energy above this point is also found for the blade surface microphones but not on the microphones on the ground. An interesting spectrum was observed for the microphone on the pressure side close to the TE. For increasing wind speed the spectra show a very distinct increase in spectral energy up to about 300 Hz after which the spectra collapse. As the boundary layer is laminar it is thought that this spectral energy is due to sound waves from the TE noise on the suction side.

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Organisations: Department of Wind Energy, Aerodynamic design, Wind turbine loads & control
Authors: Aagaard Madsen, H. (Intern), Bertagnolio, F. (Intern), Fischer, A. (Intern), Bak, C. (Intern), Schmidt Paulsen, U. (Intern)
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Benchmarking aerodynamic prediction of unsteady rotor aerodynamics of active flaps on wind turbine blades using ranging fidelity tools

Simulations of a stiff rotor configuration of the DTU 10MW Reference Wind Turbine are performed in order to assess the impact of prescribed flap motion on the aerodynamic loads on a blade sectional and rotor integral level. Results of the engineering models used by DTU (HAWC2), TUDelft (Bladed) and NTUA (hGAST) are compared to the CFD predictions of USTUTT-IAG (FLOWer). Results show fairly good comparison in terms of axial loading, while alignment of tangential and drag-related forces across the numerical codes needs to be improved, together with unsteady corrections associated with rotor wake dynamics. The use of a new wake model in HAWC2 shows considerable accuracy improvements.

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Calculating the sensitivity of wind turbine loads to wind inputs using response surfaces

This paper presents a methodology to calculate wind turbine load sensitivities to turbulence parameters through the use of response surfaces. A response surface is a high-dimensional polynomial surface that can be calibrated to any set of input/output data and then used to generate synthetic data at a low computational cost. Sobol sensitivity indices (SIs) can then be calculated with relative ease using the calibrated response surface. The proposed methodology is demonstrated by calculating the total sensitivity of the maximum blade root bending moment of the WindPACT 5 MW reference model to four turbulence input parameters: a reference mean wind speed, a reference turbulence intensity, the Kaimal length scale, and a novel parameter reflecting the nonstationarity present in the inflow turbulence. The input/output data used to calibrate the response surface were generated for a previous project. The fit of the calibrated response surface is evaluated in terms of error between the model and the training data and in terms of the convergence. The Sobol SIs are calculated using the calibrated response surface, and the convergence is examined. The Sobol SIs reveal that, of the four turbulence parameters examined in this paper, the variance caused by the Kaimal length scale and nonstationarity parameter are negligible. Thus, the findings in this paper represent the first systematic evidence that stochastic wind turbine load response statistics can be modeled purely by mean wind speed and turbulence intensity.

General information

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Scopus rating (2016): CiteScore 0.45 SJR 0.24 SNIP 0.383
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BFI (2015): BFI-level 1
Wind turbine design using calibrated wind models have been proposed to be used in conjunction with load cases which lead to reduced uncertainties in the design of wind turbines with hub heights above 60m. These recommended wind profiles have been made for shear, wind directional change and turbulence. The wind turbulence models used in the loads simulations have been calibrated so that their model parameters reflect the atmospheric stability conditions and the quantile of turbulence intensity considered. Consequently large multi megawatt turbines being designed today can benefit from these more advanced wind inflow models. A revision of the IEC 61400-1 standard is being developed and has incorporated some of the recommendations made from this project. This project demonstrated the impact of wind models by simulating wind turbine loads based on high frequency wind measurements taken between 100m and 200m altitude performed at Høvsøre in Denmark. The project also demonstrated the impact of the new wind models on load cases and the certification envelope of turbines. Further the project provided a detailed assessment of safety factors for IEC 61400-1 load cases using reliability-based procedures incorporating the new models and this has been made as an Annex to the new standard that is due to be issued.

**General information**

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Demonstration of partial pitch 2-bladed wind turbine

This is the final report for the EUDP project performed from January 2012 to December 2015. The main objective for the project was to demonstrate the potential of the partial pitch two-bladed (PP-2B) technology. DTU Wind Energy took a responsibility for three workpackages (WPs) among 6 WPs which were aerodynamic evaluation of partial pitch technology (WP2), aeroelastic analysis of two-bladed turbine (WP3) and On-site testing (WP4). For the WP2, a comprehensive set of 3D CFD simulations including the gap between inner and outer part of the blade and vortex generators (VGs) of both cross-sections on the blade as well as fully resolved rotor simulations, and finally simulations coupling HAWC2 with EllipSys3D, investigating the behaviors of the rotor at standstill, has been performed. For the WP3, the state-of-the art aeroelastic analysis tool, HAWC2, has been updated in order to consider the partial pitch concept and detailed load analyses were performed. Also the comparison studies between numerical results and experimental results were performed. Moreover stability analyses for the PP-2B turbine have been performed with HAWC2 and modal analysis using Hill's method was performed to calculate the mode shapes and modal frequencies. For the WP4, the onsite measurements were successfully carried out at Harboøre Tange, Thyboren, Denmark in the period 28th September 2012 to 14th of January 2016. The structural loads, produced power and turbine controller signals were measured and sampled together with detailed inflow information from the met mast nearby.

DeRisk - Accurate prediction of ULS wave loads. Outlook and first results

Loads from extreme waves can be dimensioning for the substructures of offshore wind turbines. The DeRisk project (2015-2019) aims at an improved load evaluation procedure for extreme waves through application of advanced wave models, laboratory tests of load effects, development of hydrodynamic load models, aero-elastic response calculations and statistical analysis. This first paper from the project outlines the content and philosophy behind DeRisk. Next, the first results from laboratory tests with irregular waves are presented, including results for 2D and 3D focused wave groups. The results of focused wave group tests and a 6-hour (full scale duration) test are reproduced numerically by re-application of the wave paddle signal in a fully nonlinear potential flow wave model. A good match for the free surface elevation and associated exceedance probability curve is obtained. Finally, the utilization of DeRisk's results in practical design is discussed. (C) 2016 Published by Elsevier Ltd.
Design Load Basis for Offshore Wind turbines: DTU Wind Energy Report No. E-0133

DTU Wind Energy is not designing and manufacturing wind turbines and does therefore not need a Design Load Basis (DLB) that is accepted by a certification body. However, to assess the load consequences of innovative features and devices added to existing offshore turbine concepts or new offshore turbine concept developed in our research, it is useful to have a full DLB that follows the current design standard and is representative of a general DLB used by the industry. It will set a standard for the offshore wind turbine design load evaluations performed at DTU Wind Energy, which is aligned
Design of an aeroelastically tailored 10 MW wind turbine rotor

This work presents an integrated multidisciplinary wind turbine optimization framework utilizing state-of-the-art aeroelastic and structural tools, capable of simultaneous design of the outer geometry and internal structure of the blade. The framework is utilized to design a 10 MW rotor constrained not to exceed the design loads of an existing reference wind turbine. The results show that through combined geometric tailoring of the internal structure and aerodynamic shape of the blade it is possible to achieve significant passive load alleviation that allows for a 9% longer blade with an increase in AEP of 8.7%, without increasing blade mass and without significant increases in ultimate and fatigue loads on the hub and tower.

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Scopus rating (2014): SJR 0.253 SNIP 0.344 CiteScore 0.32
Diagnosis of wind turbine rotor system

This paper describes a model free method for monitoring and fault diagnosis of the elements in a rotor system for a wind turbine. The diagnosis as well as the monitoring is done without using any model of the wind turbine and the applied controller or a description of the wind profile. The method is based on available standard sensors on wind turbines. The method can be used both on-line as well as off-line. Faults or changes in the rotor system will result in asymmetries, which can be monitored and diagnosed. This can be done by using the multi-blade coordinate transformation. Changes in the rotor system that can be diagnosed and monitored are: actuator faults, sensor faults and internal blade changes as e.g. change in mass of a blade.
Dynamic behavior of parked wind turbine at extreme wind speed

In wind turbine design process, a series of load analysis is generally performed to determine ultimate and fatigue loads under various design load cases (DLCs) which is specified in IEC 61400. These design load scenario covers not only normal operating condition but also startup, shutdown, parked and other scenario which is assumed to occur during the expected lifetime of wind turbine. This research focus on vibration problem under 50-year storm conditions while rotor is parked and blades are feathered. In this parked scenario, effect of a wind direction change of up to ± 180 degrees for both cases of standstill and idling is analyzed by time domain simulations using two different coupled aero-hydro-servo-elastic codes. Trend in modern wind turbines is development of bigger, lighter and more flexible rotors where vibration issues may cause aero-elastic instabilities which have a serious impact on the ultimate loads. The DTU 10MW Reference Wind Turbine (RWT) is chosen as wind turbine model in this research.

Dynamics of the interaction between the rotor and the induction zone

Traditionally met masts are used for power and load verifications. They are normally placed 2-4 rotor diameters ahead of the turbine. However in complex terrain this can lead to complex analysis of the effect of the terrain on the flow field. A nacelle mounted lidar can provide a better tool for wind field measurements in all terrains. Provided that the measurement is close enough to the rotor disc, the uncertainty in the flow field measurement can be reduced significantly. Therefore any complex terrain calibration and changes in the wind direction can be avoided. However, close distance lidar measurements are affected by the presence of the wind turbine, due to its induction zone. In this work, the dynamic coupling between changes in the wind turbine operating point and the velocities inside the induction zone is studied. Reynolds-Averaged Navier-Stokes (RANS) simulations are used to investigate this interaction. Thereafter, system identification is used to fit first order dynamic models to the simulation results. The parameters of the model are given for the turbine induction zone. These results possibly reduce the uncertainty in lidar measurements, arising from wind turbine blockage.
Effect of Turbulence on Power for Bend-Twist Coupled Blades

Bend-twist coupling of wind turbine blades reduces the structural loads of the turbine but it also results in a decrease of the annual energy production. The main part of the power loss can be mitigated by pretwisting the blade, but some power loss remains and previous studies indicate that it might be related to the dynamic response of bend-twist coupled blades in turbulent flow. This paper contains estimations of the power curve from nonlinear time simulations, a linear frequency domain based method and a normal distribution weighted average method. It is shown that the frequency domain based estimation is highly dependant on the validity of the linearized model, thus estimations are poor for operational points close to rated wind speed. The weighted average method gives good results if an appropriate standard deviation is known a priori. The nonlinear time simulations show that changes in power due to turbulence are similar for coupled and uncoupled blades. Power gains at low wind speeds are related to the curvature of the steady state power curve. Losses around rated wind speed are caused by the effects of controller switching between partial and full power operation.

General information
Experimental and numerical study of a 10MW TLP wind turbine in waves and wind

This paper presents tests on a 1:60 version of the DTU 10MW wind turbine mounted on a tension leg platform and their numerical reproduction. Both the experimental setup and the numerical model are Froude-scaled, and the dynamic response of the floating wind turbine to wind and waves is compared in terms of motion in the six degrees of freedom, nacelle acceleration and mooring line tension. The numerical model is implemented in the aero-elastic code Flex5, featuring the unsteady BEM method and the Morison equation for the modelling of aerodynamics and hydrodynamics, respectively. It was calibrated with the tests by matching key system features, namely the steady thrust curve and the decay tests in water. The calibrated model is used to reproduce the wind-wave climates in the laboratory, including regular and irregular waves, with and without wind. The model predictions are compared to the measured data, and a good agreement is found for surge and heave, while some discrepancies are observed for pitch, nacelle acceleration and line tension. The addition of wind generally improves the agreement with test results. The aerodynamic damping is identified in both tests and simulations. Finally, the sources of the discrepancies are discussed and some improvements in the numerical model are suggested in order to obtain a better agreement with the experiments.

General information

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Experimental and Numerical Study of Rotor Dynamics of a Two- and Three-Bladed Wind Turbine

In this paper the dynamics of a two-bladed turbine is investigated numerically as well as experimentally with respect to how the turbine frequencies change with the rotor speed. It is shown how the turbine frequencies of a two-bladed rotor change with the azimuthal position at standstill and how the frequencies change due to rotor rotation. The frequency of the asymmetric rotor modes changes with multiple \( P \) contributions, not only with \( \pm 1P \), as has previously been seen for three-bladed wind turbine rotors. A three-bladed turbine is also analyzed in a similar way, and the results are compared. This turbine is investigated both in a perfect isotropic condition, where all blades have identical properties, and in an imbalanced edition, where one blade had increased mass.

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Floating substructure flexibility of large-volume 10MW offshore wind turbine platforms in dynamic calculations

Designing floating substructures for the next generation of 10MW and larger wind turbines has introduced new challenges in capturing relevant physical effects in dynamic simulation tools. In achieving technically and economically optimal floating substructures, structural flexibility may increase to the extent that it becomes relevant to include in addition to the standard rigid body substructure modes which are typically described through linear radiation-diffraction theory. This paper describes a method for the inclusion of substructural flexibility in aero-hydro-servo-elastic dynamic simulations for large-volume substructures, including wave-structure interactions, to form the basis of deriving sectional loads and stresses within the substructure. The method is applied to a case study to illustrate the implementation and relevance. It is found that the flexible mode is significantly excited in an extreme event, indicating an increase in predicted substructure internal loads.
Impact of a wind turbine on turbulence: Un-freezing turbulence by means of a simple vortex particle approach

A vortex particle representation of turbulent fields is devised in order to address the following questions: Does a wind turbine affect the statistics of the incoming turbulence? Should this imply a change in the way turbulence boxes are used in wind turbine aero-elastic simulations? Is it acceptable to neglect the influence of the wake and the wind turbine on the turbulent inflow? Is there evidence to justify the extra cost of a method capable of including these effects correctly? To this end, a unified vorticity representation of the flow is used: the wind turbine model is represented by a bound vorticity lifting line while the turbine wake vorticity and the turbulence vorticity are projected onto vortex particles. In the present work the rotor blades are stiff leaving aero-elastic interactions for future work. Inflow turbulence is generated with the model of Mann and converted to vortex particles that are inserted at the inlet of the computational domain. First the quality of the reconstructed turbulent flow field is evaluated and then the wind turbine is added in the simulations. The lack of a driving-force to sustain turbulence is found to give a progressive decay of turbulence away from the insertion point. The presence of the wind turbine and its wake is found to have insignificant effect on upstream turbulence. Finally, the mean velocity profiles in the wake are found to be in good agreement with both lidar measurements and CFD simulations. (C) 2016 Elsevier Ltd. All rights reserved.
In search for a canonical design ABL stability class for wind farm turbines

Production as well as loading of wake exposed wind turbines is known to depend significantly on stability of the Atmospheric Boundary Layer (ABL), which adds a new dimension to design of wind farm turbines. Adding this new aspect in wind turbine design makes the number of design cycle computations to blow up with a factor equal to the number of representative stability bin classes. The research question to be answered in this paper is: Can an ABL stability probability distribution in a meaningful way be collapsed into a representative design stability class as based on a (predefined) confidence level.

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In this paper, wake interaction resulting from two stall regulated turbines aligned with the incoming wind is studied experimentally and numerically. The experimental work is based on a full-scale remote sensing campaign involving three nacelle mounted scanning lidars. A thorough analysis and interpretation of the measurements is performed to overcome either the lack of or the poor calibration of relevant turbine operational sensors, as well as other uncertainties inherent in resolving wakes from full-scale experiments. The numerical work is based on the in-house EllipSys3D computational fluid dynamics flow solver, using large eddy simulation and fully turbulent inflow. The rotors are modelled using the actuator disc technique. A mutual validation of the computational fluid dynamics model with the measurements is conducted for a selected dataset, where wake interaction occurs. This validation is based on a comparison between wake deficit, wake generated turbulence, turbine power production and thrust force. An excellent agreement between measurement and simulation is seen in both the fixed and the meandering frame of reference. Copyright © 2015 John Wiley & Sons, Ltd.
Lidar configurations for wind turbine control

Lidar sensors have proved to be very beneficial in the wind energy industry. They can be used for yaw correction, feed-forward pitch control and load verification. However, the current lidars are expensive. One way to reduce the price is to use lidars with few measurement points. Finding the best configuration of an inexpensive lidar in terms of number of measurement points, the measurement distance and the opening angle is the subject of this study. In order to solve the
problem, a lidar model is developed and used to measure wind speed in a turbulence box. The effective wind speed measured by the lidar is compared against the effective wind speed on a wind turbine rotor both theoretically and through simulations. The study provides some results to choose the best configuration of the lidar with few measurement points.
This paper describes the development of a wind turbine (WT) component lifetime fatigue load variation map within an offshore wind farm. A case study on the offshore wind farm Horns Rev I is conducted with this purpose, by quantifying wake effects using the Dynamic Wake Meandering (DWM) method, which has previously been validated based on CFD, Lidar and full scale load measurements. Fully coupled aeroelastic load simulations using turbulent wind conditions are conducted for all wind directions and mean wind speeds between cut-in and cut-out using site specific turbulence level measurements. Based on the mean wind speed and direction distribution, the representative 20-year lifetime fatigue loads are calculated. It is found that the heaviest loaded WT is not the same when looking at blade root, tower top or tower base components. The blade loads are mainly dominated by the wake situations above rated wind speed and the highest loaded blades are in the easternmost row as the dominating wind direction is from West. Regarding the tower components, the highest loaded WTs are also located towards the eastern central location. The turbines with highest power production are, not surprisingly, the ones facing a free sector towards west and south. The power production results of few turbines are compared with SCADA data. The results of this paper are expected to have significance for operation and maintenance planning, where the schedules for inspection and service activities can be adjusted to the requirements arising from the varying fatigue levels. Furthermore, the results can be used in the context of remaining fatigue lifetime assessment and planning of decommissioning.

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Modal dynamics of structures with bladed isotropic rotors and its complexity for 2-bladed rotors

The modal dynamics of structures with bladed isotropic rotors is analyzed using Hill’s method. First, analytical derivation of the periodic system matrix shows that isotropic rotors with more than two blades can be represented by an exact Fourier series with 3/rev as the highest order. For 2-bladed rotors, the inverse mass matrix has an infinite Fourier series with harmonic components of decreasing norm, thus the system matrix can be approximated by a truncated Fourier series of predictable accuracy. Second, a novel method for automatically identifying the principal solutions of Hill’s eigenvalue problem is introduced. The corresponding periodic eigenvectors can be used to compute symmetric and anti-symmetric components of the 2-bladed rotor motion, and the additional forward and backward whirling components for rotors with more than two blades. Finally, the generic methods are used on a simple wind turbine model consisting of three degrees of freedom for each blade and seven degrees of freedom for the nacelle and drivetrain. The modal dynamics of a 3-bladed 10MW turbine from previous studies is recaptured. Removing one blade, the larger and higher harmonic terms in the system matrix lead to resonant modal couplings for the 2-bladed turbine that do not exist for the 3-bladed turbine, and that excitation of a single mode of a 2-bladed turbine leads to responses at several frequencies in both the ground-fixed and rotating blade frames of reference which complicates the interpretation of simulated or measured turbine responses.

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Normalized performance and load data for the deepwind demonstrator in controlled conditions

Performance and load normalized coefficients, deriving from an experimental campaign of measurements conducted at the large scale wind tunnel of the Politecnico di Milano (Italy), are presented with the aim of providing useful benchmark data for the validation of numerical codes. Rough data, derived from real scale measurements on a three-bladed Troposkien vertical-axis wind turbine, are manipulated in a convenient form to be easily compared with the typical outputs provided by simulation codes. The here proposed data complement and support the measurements already presented in “Wind Tunnel Testing of the DeepWind Demonstrator in Design and Tilted Operating Conditions” (Battisti et al., 2016) [1].

Open access wind tunnel measurements of a downwind free yawing wind turbine

A series of free yawing wind tunnel experiments was held in the Open Jet Facility (OJF) of the TU Delft. The ≈ 300 W turbine has three blades in a downwind configuration and is optionally free to yaw. Different 1.6m diameter rotor configurations are tested such as blade flexibility and sweep. This paper gives a brief overview of the measurement setup and challenges, and continues with presenting some key results. This wind tunnel campaign has shown that a three bladed downwind wind turbine can operate in a stable fashion under a minimal yaw error. Finally, a description of how to obtain this open access dataset, including the post-processing scripts and procedures, is made available via a publicly accessible website.

Open access wind tunnel measurements of a downwind free yawing wind turbine

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PI controller design of a wind turbine: evaluation of the pole-placement method and tuning using constrained optimization

PI/PID controllers are the most common wind turbine controllers. Normally a first tuning is obtained using methods such as pole-placement or Ziegler-Nichols and then extensive aeroelastic simulations are used to obtain the best tuning in terms of regulation of the outputs and reduction of the loads. In the traditional tuning approaches, the properties of different open loop and closed loop transfer functions of the system are not normally considered. In this paper, an assessment of the pole-placement tuning method is presented based on robustness measures. Then a constrained optimization setup is suggested to automatically tune the wind turbine controller subject to robustness constraints. The properties of the system such as the maximum sensitivity and complementary sensitivity functions (Ms and Mt), along with some of the responses of the system, are used to investigate the controller performance and formulate the optimization problem. The cost function is the integral absolute error (IAE) of the rotational speed from a disturbance modeled as a step in wind speed. Linearized model of the DTU 10-MW reference wind turbine is obtained using HAWCStab2. Thereafter, the model is reduced with model order reduction. The trade-off curves are given to assess the tunings of the poles-placement method and a constrained optimization problem is solved to find the best tuning.
Reduced design load basis for ultimate blade loads estimation in multidisciplinary design optimization frameworks

The aim is to provide a fast and reliable approach to estimate ultimate blade loads for a multidisciplinary design optimization (MDO) framework. For blade design purposes, the standards require a large amount of computationally expensive simulations, which cannot be efficiently run each cost function evaluation of an MDO process. This work describes a method that allows integrating the calculation of the blade load envelopes inside an MDO loop. Ultimate blade load envelopes are calculated for a baseline design and a design obtained after an iteration of an MDO. These envelopes are computed for a full standard design load basis (DLB) and a deterministic reduced DLB. Ultimate loads extracted from the two DLBs with the two blade designs each are compared and analyzed. Although the reduced DLB supplies ultimate loads of different magnitude, the shape of the estimated envelopes are similar to the one computed using the full DLB. This observation is used to propose a scheme that is computationally cheap, and that can be integrated inside an MDO framework, providing a sufficiently reliable estimation of the blade ultimate loading. The latter aspect is of key importance when design variables implementing passive control methodologies are included in the formulation of the optimization problem. An MDO of a 10 MW wind turbine blade is presented as an applied case study to show the efficacy of the reduced DLB concept.

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Reduction of fatigue loads on jacket substructure through blade design optimization for multimegawatt wind turbines at 50 m water depths

This paper addresses the reduction of the fore-aft damage equivalent moment at the tower base for multi-megawatt offshore wind turbines mounted on jacket type substructures at 50 m water depths. The study investigates blade design optimization of a reference 10 MW wind turbine under standard wind conditions of onshore sites. The blade geometry and structure is optimized to yield a design that minimizes tower base fatigue loads without significant loss of power production compared to that of the reference setup. The resulting blade design is then mounted on a turbine supported by a jacket and placed under specific offshore site conditions. The new design achieves alleviate fatigue damage equivalent loads also in the jacket members, showing the possibility to prolong its design lifetime or to save material in comparison to the reference jacket. Finally, the results suggest additional benefit on the efficient design of other components such as the constituents of the nacelle.

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Steady State Comparisons HAWC2 v12.2 vs HAWCStab2 v2.12


Timoshenko beam element with anisotropic cross-sectional properties

Beam models are used for the aeroelastic time and frequency domain analysis of wind turbines due to their computational efficiency. Many current aeroelastic tools for the analysis of wind turbines rely on Timoshenko beam elements with classical cross-sectional properties (EA, EI, etc.). Those cross-sectional properties do not reflect the various couplings arising from the anisotropic behaviour of the blade material. A twonoded, three-dimensional Timoshenko beam element was therefore extended to allow for anisotropic cross-sectional properties. For an uncoupled beam, the resulting shape functions are identical to the original formulation. The new element was implemented into a co-rotational formulation and validated against natural frequencies and several static load cases of previous works.
Trailing vorticity modeling for aeroelastic wind turbine simulations in standstill

Current fast aeroelastic wind turbine codes suitable for certification lack an induction model for standstill conditions. A trailing vorticity model previously used as addition to a blade element momentum theory based aerodynamic model in normal operation has been extended to allow computing the induced velocities in standstill. The model is validated against analytical results for an elliptical wing in constant inflow and against stand still measurements from the NREL/NASA Phase VI unsteady experiment. The extended model obtains good results in case of the elliptical wing, but underpredicts the steady loading for the Phase VI blade in attached flow. The prediction of the dynamic force coefficient loops from the Phase VI experiment is improved by the trailing vorticity modeling in both attached flow and stall in most cases. The exception is the tangential force coefficient in stall, where the codes and measurements deviate and no clear improvement is visible.
Using Pretwist to Reduce Power Loss of Bend-Twist Coupled Blades

Bend-twist coupling of wind turbine blades is known as a means to reduce the structural loads of the turbine. While the load reduction is desirable, bend-twist coupling also leads to a decrease in the annual energy production of the turbine. The reduction is mainly related to a no longer optimal twist distribution along the blade due to the coupling induced twist. Some of the power loss can be compensated by pretwisting the blade. This paper presents a pretwisting procedure for large blade deflections and investigates the effect of pretwisting on blade geometry, annual energy production, and fatigue load for the DTU 10 MW Reference Wind Turbine. The analysis was carried out by calculating the nonlinear steady state rotor deflection in an uniform inflow over the operational range of the turbine. The steady state power curve together with a Rayleigh wind speed distribution has been used to estimate the annual energy production. The turbine model was then linearised around the steady state and the power spectral density of the blade response, which was computed from transfer functions and the wind speed variations in the frequency domain, was used to estimate the fatigue loads by a spectral method.

General information
State: Published
Organisations: Department of Wind Energy, Wind turbine loads & control
Authors: Stäblein, A. (Intern), Tibaldi, C. (Intern), Hansen, M. H. (Intern)
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Using_Pretwist_to_Reduce_Power_Loss_manus.pdf
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Validation of buoyancy driven spectral tensor model using HATS data

We present a homogeneous spectral tensor model for wind velocity and temperature fluctuations, driven by mean vertical shear and mean temperature gradient. Results from the model, including one-dimensional velocity and temperature spectra and the associated co-spectra, are shown in this paper. The model also reproduces two-point statistics, such as coherence and phases, via cross-spectra between two points separated in space. Model results are compared with observations from the Horizontal Array Turbulence Study (HATS) field program (Horst et al. 2004). The spectral velocity tensor in the model is described via five parameters: the dissipation rate ($\varepsilon$), length scale of energy-containing eddies ($L$), a turbulence anisotropy parameter ($\Gamma$), gradient Richardson number ($Ri$) representing the atmospheric stability and the rate of destruction of temperature variance ($\eta\theta$).

General information
State: Published
Organisations: Department of Wind Energy, Meteorology & Remote Sensing, Resource Assessment Modelling, Wind turbine loads & control, University of Agder
Authors: Chougule, A. (Ekstern), Mann, J. (Intern), Kelly, M. C. (Intern), Larsen, G. C. (Intern)
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Scopus rating (2016): CiteScore 0.45 SJR 0.24 SNIP 0.383
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Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.253 SNIP 0.344 CiteScore 0.32
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.231 SNIP 0.272 CiteScore 0.25
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.28 SNIP 0.354 CiteScore 0.33
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.292 SNIP 0.352 CiteScore 0.43
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.288 SNIP 0.344
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.253 SNIP 0.321
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.265 SNIP 0.294
Validation of Superelement Modelling of Complex Offshore Support Structures

Modern large MW wind turbines today are installed at larger water depth than applicable for traditional monopile substructure. It appears that foundation types such as jacket and tripod are gaining more popularity for these locations. For certification purposes, a full set of design load calculations consisting of up to thousands design load cases needs to be evaluated. However, even the simplest aero-elastic model of such structures has many more DOFs than monopile, resulting in excessive computation burden. In order to deal with this problem, the superelement method has been introduced for modelling such structures. One superelement method has been proven very promising in the previous project of Wave Loads [1] and a fundamental question in such DOFs reduction methods is which modes that are essential and which modes can be neglected. For the jacket structure, the introduction of a gravity-buoyancy mode (GB mode) demonstrates that this mode is needed for accurate load simulation. A case study is performed in this report to validate the proposed method based on a reference wind turbine on a jacket foundation.

Vertical Axis Wind Turbine Design Load Cases Investigation and Comparison with Horizontal Axis Wind Turbine

The paper studies the applicability of the IEC 61400-1 ed.3, 2005 International Standard of wind turbine minimum design requirements in the case of an onshore Darrieus VAWT and compares the results of basic Design Load Cases (DLCs) with those of a 3-bladed HAWT. The study is based on aeroelastic computations using the HAWC2 aero-servo-elastic code. A 2-bladed 5 MW VAWT rotor is used based on a modified version of the DeepWind rotor. For the HAWT simulations, the NREL 3-bladed 5 MW reference wind turbine model is utilized. Various DLCs are examined including normal power production, emergency shut down and parked situations, from cut-in to cut-out and extreme wind conditions. The ultimate and 1 Hz equivalent fatigue loads of the blade root and turbine base bottom are extracted and compared in order to give an insight of the load levels between the two concepts. According to the analysis the IEC 61400-1 ed.3 can be used to a large extent with proper interpretation of the DLCs and choice of parameters such as the hub-height. In addition, the design drivers for the VAWT appear to differ from the ones of the HAWT. Normal operation results in the highest tower bottom and blade root loads for the VAWT, where parked under storm situation (DLC 6.2) and extreme operating gust (DLC 2.3) are more severe for the HAWT. Turbine base bottom and blade root edgewise fatigue loads are much higher for the VAWT compared to the HAWT. The interpretation and simulation of DLC 6.2 for the VAWT lead to blade instabilities, while extreme wind shear and extreme wind direction change are not critical in terms of loading of the VAWT structure. Finally, the extreme operating gust wind condition simulations revealed that the emerging loads depend on the combination of the rotor orientation and the time stamp that the frontal passage of gust goes through the rotor plane.
Wake dynamics in offshore wind farms

Wind turbines within offshore wind farms spend considerable time operating in the wake of neighboring wind turbines. An important contribution to the loads on a wake-affected wind turbine is the slow movement of the wake from the upstream wind turbine across the rotor of the wake-affected wind turbine. A new approach to this so called wake meandering is proposed. Beside the advantage of higher physical realism, the new approach also offers practical advantages compared to the current state-of-the-art method.

An input to the new meandering approach is the time evolution of the so called spectral velocity tensor. An improved such spectral tensor is therefore developed, which, for neutral atmospheric stratification, predicts spatial correlations comparably to the Mann spectral tensor and temporal coherence significantly better than previously existing models, including the Mann model, which is incapable of predicting any temporal correlations beyond those that follows from the application of Taylor's frozen turbulence hypothesis. As part of the framework a spectral tensor for Lagrangian correlations in space and time is also developed and validated versus measurements of isotropic turbulence. Combined, the models reproduce the cross-over point between Eulerian and Lagrangian temporal covariances. The applications of the Lagrangian spectral tensor, e.g. in the fields of dispersion and mixing, deserve further investigation.

The values of the input parameters of the spectral tensor are shown to be uniquely determined by the friction velocity, the shear and the dissipation of turbulent kinetic energy, all of them physical properties of the flow. If local equilibrium between the turbulent kinetic energy produced by shear and the turbulent kinetic energy dissipated as heat is assumed, then, for neutral atmospheric stratification, the friction velocity and the mixing length determine the spectral tensor. The developed spectral tensor also depends on a dimensionless quantity, which would be beneficial to determine with higher accuracy. An experiment with this objective, studying the ratio between different components of the cross-spectra at known shear, is proposed. Future work could also include investigating if a Rapid Distortion formulation that also includes a term for buoyancy effects is needed in
order to make accurate predictions for non-neutral atmospheric stratification.

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Organisations: Department of Wind Energy, Meteorology & Remote Sensing, Wind turbine loads & control
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Wake flow characteristics at high wind speed
Wake flow characteristic at high wind speeds is the main subject of this paper. Although the wake losses decrease at high wind speeds it has been found in a recent study that for multiple wake inflow the increase in loading due to wake effects are substantial even at wind speeds well above rated power. In the present study we simulate the wake flow for a row of turbines with the wind aligned with the row using a simplified approach. The velocity deficit, being a function of the thrust coefficient, is simulated based on the BEM solution for wake expansion. An axis-symmetric boundary layer equation model (the same as implemented in the DWM model) is subsequently used to develop the deficit down to the next turbine, and then the approach is successively repeated. Simulation results for four different spacing’s in a row with eight turbines show that there are two major flow regimes. In the first flow regime comprising the first turbines in a row the local mean wind speed over the rotor disc is found to decrease linearly from turbine to turbine for the turbines operating at maximum power but also to some extend extend below rated power. The second flow regime is characterized by a constant local equilibrium wind speed. Based on the present results the equilibrium wind speed normalized with the inflow wind speed varies from about 0.4 for a spacing of 3D to slightly above 0.6 for a 9D spacing at an ambient turbulence intensity equal 6%. It is also found that for a turbine in the intersection region between the two flow regimes a strong variation in power and thrust occur, e.g. going from almost zero power to rated power for a wind speed change of 4m/s. Another result is that the inflow profile to the last turbine in the row at a wind speed of 16m/s for a spacing of 3D shows a variation over the profile from around 3m/s to 16m/s, which explains the high loading observed at high wind. Two models for merging wakes are tested, and one works best below rated power and another shows excellent performance around 14m/s. Finally, power measurements from the Lillgrund wind farm in a row with a 4.3D spacing and for wind speeds from 8-14m/s are used to validate the modeling setup.

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Organisations: Department of Wind Energy, Aerodynamic design, Wind turbine loads & control, Fluid Mechanics
Authors: Aagaard Madsen, H. (Intern), Larsen, T. J. (Intern), Larsen, G. C. (Intern), Hansen, K. S. (Intern)
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2016

Wake Influence on Dynamic Load Characteristics of Offshore Floating Wind Turbines
Because the flow conditions of an offshore floating wind turbine and onshore fixed wind turbine differ, it is debatable whether the aerodynamic load predictions of an offshore floating wind turbine using the conventional blade-element momentum theory, which does not consider the dynamic wake effects, are accurate. Although a generalized dynamic wake method has been developed to consider the dynamic wake effect, it is only stable for lightly loaded wind turbines at high wind speeds. In contrast to the blade-element momentum theory and generalized dynamic wake method, the unsteady vortex lattice method can inherently represent the nonuniform flow effects of the trailing wake from the turbine blades. This paper aims to determine the wake influence of offshore floating wind turbines at low-wind-speed conditions by comparing three wake models: the blade-element momentum theory, generalized dynamic wake method, and unsteady
vortex lattice method. The Offshore Code Comparison Collaboration Hywind model is chosen for offshore floating wind-turbine simulation. Results show that the blade-element momentum theory underestimates the rotor torque and speed. Moreover, although responses of the generalized dynamic wake method and unsteady vortex lattice method agree well at moderate wind speeds, the generalized dynamic wake method predicts higher induction factor than that of the blade-element momentum theory and unsteady vortex lattice method at low wind speeds. At low wind speeds, the blade flapwise bending moment, rotor torque, and tower side-to-side bending moment calculated by the blade-element momentum theory are considerably different from those obtained by the unsteady vortex lattice method.

**General information**

State: Published
Organisations: Department of Wind Energy, Wind turbine loads & control, Seoul National University, Korea Aerospace Research Institute
Authors: Jeon, M. (Ekstern), Lee, S. (Ekstern), Kim, T. (Intern), Lee, S. (Ekstern)
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Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.58 SJR 0.884 SNIP 1.672
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.883 SNIP 1.756 CiteScore 1.99
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.875 SNIP 1.754 CiteScore 2.28
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.976 SNIP 1.837 CiteScore 2.25
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.949 SNIP 1.911 CiteScore 1.54
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.108 SNIP 1.725 CiteScore 1.44
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.902 SNIP 1.597
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.96 SNIP 1.519
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.014 SNIP 1.388
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.216 SNIP 1.601
Scopus rating (2006): SJR 1.057 SNIP 1.719
Wind tunnel testing of the DeepWind demonstrator in design and tilted operating conditions

The DeepWind Project aims at investigating the feasibility of a new floating vertical-axis wind turbine (VAWT) concept, whose purpose is to exploit wind resources at deep-water offshore sites. The results of an extensive experimental campaign on the DeepWind reduced scale demonstrator are here presented for different wind speeds and rotor angular velocities, including also skewed flow operation due to a tilted rotor arrangement. To accomplish this, after being instrumented to measure aerodynamic power and thrust (both in streamwise and transversal directions), a troposkien three-bladed rotor was installed on a high precision test bench, whose axis was suitable to be inclined up to 15° with respect to the design (i.e. upright) operating condition. The experiments were performed at the large scale, high speed wind tunnel of the Politecnico di Milano (Italy), using a “free jet” (open channel) configuration. The velocity field in the wake of the rotor was also fully characterized by means of an instrumented traversing system, to investigate the flow distribution downstream of the test section. Special care is taken in the description of the experimental set-up and of the measured data, so that the present results can be used as a benchmark for the validation of simulation models.
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 2.647 SNIP 2.63 CiteScore 5.7
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.54 SNIP 2.593 CiteScore 5.02
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.998 SNIP 2.25 CiteScore 4.25
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.609 SNIP 2.043 CiteScore 4
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.814 SNIP 2.725
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.729 SNIP 2.313
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.106 SNIP 1.444
Scopus rating (2007): SJR 0.913 SNIP 1.481
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.875 SNIP 1.306
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.965 SNIP 1.203
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.711 SNIP 1.115
Scopus rating (2003): SJR 1.093 SNIP 1.496
Scopus rating (2002): SJR 0.952 SNIP 1.287
Scopus rating (2001): SJR 1.091 SNIP 1.078
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 0.82 SNIP 0.992
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.632 SNIP 0.659
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Wind turbine wake measurement in complex terrain
SCADA data from a wind farm and high frequency time series measurements obtained with remote scanning systems have been analysed with focus on identification of wind turbine wake properties in complex terrain. The analysis indicates that within the flow regime characterized by medium to large downstream distances (more than 5 diameters) from the wake generating turbine, the wake changes according to local atmospheric conditions e.g. vertical wind speed. In very complex terrain the wake effects are often “overruled” by distortion effects due to the terrain complexity or topology.

General information
State: Published
Concurrent Aeroservoelastic Design and Optimization of Wind Turbines

This work develops and investigates methods to integrate controllers in the wind turbine design process and to perform wind turbine optimization. These techniques can exploit the synergy between wind turbine components and generate new design solutions. Two frameworks to perform wind turbine optimization design are presented. These tools handle workflows to model a wind turbine and to evaluate loads and performances under specific conditions. Three approaches to evaluate loads are proposed and integrated in the optimization codes. The first method is based on time domain simulations, the second exploits a linear model to evaluate fatigue damage loads in frequency domain, and the third allows avoiding resonant conditions that could lead to excessive fatigue damage. The first technique exploits nonlinear time domain aeroservoelastic simulations, here computed with HAWC2, and the other two approaches are based on a high-order aeroservoelastic linear model implemented in HAWCStab2. The limitations and advantages of each method are illustrated and discussed. Methods to systematically tune wind turbine controllers are improved and presented. This work focuses on basic controllers for wind turbine regulation under normal operation, therefore no controller for load reduction is considered. The approaches presented are based on a pole-placement technique and loads minimization. Two methods allow the tuning of the proportional integral gains of the pitch controller. A third approach, based on time domain simulations, allows the selection of any controller parameter. The methods to evaluate loads and the pole-placement technique are then employed to carry out wind turbine optimization design from an aeroservoelastic prospective. Several analysis of the NREL 5 MW Reference Wind Turbine and the DTU 10 MW Reference Wind Turbine are carried out to illustrate the validity and limitations of these approaches. In some of the test cases, the method reduces the blade mass and increases the annual energy production.

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Authors: Tibaldi, C. (Intern), Bak, C. (Intern), Henriksen, L. C. (Intern)
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Experimental Vision Studies of Flow and Structural Effects on Wind Turbines

In the present thesis, two modern vision technologies are developed and used to study wind turbines:

1- Stereo vision to study vibrations and dynamics of the Vertical Axes Wind Turbine (VAWT) via operational modal analysis (OMA)

2- Background-oriented Schlieren (BOS) method to study the tip vortices that are shed from a Horizontal Axis Wind Turbine (HAWT) blades

The thesis starts with an introduction to the stereo vision and OMA and is followed by two practical implementations of the basics derived in the introduction. In the first experiment, we developed the image processing tools to extract the displacement time series from stereo images taken from a VAWT blade subjected to the random vibrations. For analysing the time series, we devised an averaged approach of the covariance-driven stochastic subspace identification (COV-SSI) method. The method enables us to involve short measurement sets in OMA. Therefore, the first four natural frequencies are identified and agreed fairly with classical modal analysis (EMA) and finite element simulation (FEM). The second experiment is conducted on a VAWT rotor in the wind tunnel in a more controlled and designed condition, and the displacement time series are obtained using a more elaborated image processing algorithm. In OMA part, we developed the data-driven stochastic subspace identification (DDSSI) and frequency domain decomposition (FDD) codes for studying the dynamic behaviour of the turbine. The structural modes of the VAWT obtained with OMA are validated with the simulation and EMA, and then, the differences are explained with the aerodynamic effect and boundary conditions. The other frequencies obtained by OMA are interpreted via vortex shedding phenomena and guy wire effects. In the fifth chapter, the uncertainty of the displacements obtained in the two experiments mentioned above, is evaluated using the law of error propagation and several solutions are presented to decrease the uncertainty in the stereo vision experiments. In the last chapter of the thesis, the BOS method has been used to study the tip vortices behind a Nordtank horizontal axis wind turbine based on the density gradient in the vortex. The BOS method does not need complicated equipment such as special cameras or seeded flow, which makes it a convenient method to study large scale flows. However, the challenging part in the current case is the small refractive index change due to the small Mach number in the flow behind the HAWT. This issue has been addressed in the last chapter by designing a proper experimental setup according to the preliminary estimation of the tip vortex. The changes due to the vortex are modelled, and the tip vortex properties such as vortex size, density distribution and the maximum pressure drop in the vortex core are successfully estimated by comparison between the model and the experimental observations.
Fast Trailing Vorticity Modeling for Wind Turbine Aerodynamics and its Influence on Aeroelastic Stability

In this work, an aerodynamic model for the use in aeroelastic wind turbine codes is presented. It consists of a simplified lifting line model covering the induction due to the trailing vorticity in the near wake, a 2D shed vorticity model and a far wake model using the well known blade element momentum (BEM) theory. The model is an extension of unsteady BEM models, which provides a radial coupling of the aerodynamic sections through the trailing vorticity. The model is very fast and slows down aeroelastic wind turbine simulations by only few percent, compared to an unsteady BEM model. Compared to earlier implementations, the model has been improved in several ways: Among other things, the need for model-specific user input has been removed, the effect of downwind convection of the trailing vorticity is modeled, the near wake induction is iterated to stabilize the computations and the numerical efficiency is increased. The model is validated against results from full rotor CFD and free wake panel code computations, which show that the model yields improved results in steady and unsteady simulations compared to unsteady BEM modeling. Especially the aerodynamic work due to prescribed in-plane and out-of-plane vibrations agrees much better with high fidelity models. Further, the trailing vorticity effects on the aerodynamic work are found to be of the same order of magnitude as the shed vorticity effects. The trailing vorticity effects are, however, mainly important close to the tip in the investigated cases, which is where the major part of the aerodynamic work is generated. The aerodynamic model is further applied to determine the critical speed of a freely rotating wind turbine rotor with respect to the aeroelastic instability classical flutter. The NREL 5MW reference turbine is used for the computations, but the torsional and flapwise stiffnesses are varied between 70% and 130% of their original value to obtain more general results. In all computed cases, the trailing vorticity increases the critical rotor speeds by four to ten percent. Future work is to compute a full load basis using the new aerodynamic model to evaluate the impact of trailing vorticity modeling on fatigue and extreme loads. The model will further be implemented in the aeroelastic stability tool HAWCStab2.
Relations
Projects:
Fast Trailed Vorticity Modeling for Wind Turbine Aerodynamics and its Influence on Aeroelastic Stability
Publication: Research › Ph.D. thesis – Annual report year: 2016

Results of the benchmark for blade structural models, part A
A benchmark on structural design methods for blades was performed within the InnWind.Eu project under WP2 “Lightweight Rotor” Task 2.2 “Lightweight structural design”. The present document is describes the results of the comparison simulation runs that were performed by the partners involved within Task 2.2 of the InnWind.Eu project. The benchmark is based on the reference wind turbine and the reference blade provided by DTU [1]. "Structural Concept developers/modelers" of WP2 were provided with the necessary input for a comparison numerical simulation run, upon definition of the reference blade [2]. Output is compared in here in terms of weight, stiffness, natural frequencies, deflection (extreme load) and strength & stability (extreme load).

Improving Yaw Alignment Using Spinner Based LIDAR

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Main Research Area: Technical/natural sciences
Servo-elastic dynamics of a hydraulic actuator pitching a blade with large deflections
This paper deals with the servo-elastic dynamics of a hydraulic pitch actuator acting on a largely bend wind turbine blade. The compressibility of the oil and flexibility of the hoses introduce a dynamic mode in the pitch bearing degree of freedom. This mode may obtain negative damping if the proportional gain on the actuator position error is defined too large relative to the viscous forces in the hydraulic system and the total rotational inertia of the pitch bearing degree of freedom. A simple expression for the stability limit of this proportional gain is derived for tuning the gain based on the Ziegler-Nichols method. Computed transfer functions from reference to actual pitch angles indicate that the actuator can be approximated as a low-pass filter with some appropriate limitations on pitching speed and acceleration. The structural blade model includes the geometrical coupling of edgewise bending and torsion for large flapwise deflections. This coupling is shown to introduce edgewise bending response for pitch reference oscillations around the natural frequency of the edgewise bending mode, in which frequency range the transfer function from reference to actual pitch angle cannot be modeled as a simple low-pass filter. The pitch bearing is assumed to be frictionless as a first approximation.

General information
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Organisations: Department of Wind Energy, Wind turbine loads & control, Risø National Laboratory for Sustainable Energy
Authors: Hansen, M. H. (Intern), Kallesøe, B. S. (Intern)
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Scopus rating (2015): SJR 0.24 SNIP 0.373 CiteScore 0.35
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
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BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.231 SNIP 0.272 CiteScore 0.25
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
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Scopus rating (2012): SJR 0.28 SNIP 0.354 CiteScore 0.33
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.292 SNIP 0.352 CiteScore 0.43
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.288 SNIP 0.344
Wind Farm Layout Optimization in Complex Terrain

The overall objective of the project is to develop and provide new reliable tools for designing wind farms located in complex terrain through full scale measurements in wind farms. For wind farms located in flat terrain, the performance of the wind turbines is significantly influenced by the upstream wind turbines and slightly influenced by the ground. For wind farms located in complex terrain the ground effects are relatively more pronounced, as such effects may bend the wakes created by the upstream turbines significantly. The goal of the present Sino-Danish project is to further develop Danish wind farm technology by using measured wind farm data from complex terrain wind farms in China, which is convenient, as Denmark does not have complex terrain that can be used for developing/validating such technology. To improve the wind turbines' performance within wind farms in complex terrain, there are basically three important steps: (1) develop reliable CFD tools for predicting flow in complex terrain with and without wind turbines; (2) develop simplified flow models for predicting wind turbine performance in complex terrain; and (3) design high efficiency wind turbine parks in complex terrain.

Department of Wind Energy
Fluid Mechanics
Resource Assessment Modelling

EMD International A/S
Period: 01/04/2014 → 31/12/2017
Number of participants: 6
Wind Farms
Acronym: FarmOpt
Project ID: EUDP-64013-0405
Project Manager, academic:
Zhu, Wei Jun (Intern)
Hansen, Kurt Schaldemose (Intern)
Bechmann, Andreas (Intern)
Larsen, Gunner Chr. (Intern)
Feng, Ju (Intern)
Project Coordinator:
Shen, Wen Zhong (Intern)

Relations
Activities:
Wind farm design in complex terrain - the FarmOpt methodology

Project
Activities:

**Impact on wind turbine loads from different down regulation control strategies EERA DeepWind 2018**  
Period: 17 Jan 2018 → 19 Jan 2018  
Christos Galinos (Other)  
Department of Wind Energy  
Wind turbine loads & control  
Degree of recognition: International  
Documents:  
DeepWind2018_Poster_Galinos_et_al_A4_v2

**Related external organisation**  
EERA DeepWind'18  
Trondheim Norway, Trondheim , Norway  
Activity: Talks and presentations › Conference presentations

**Inflow conditions and wake effects for wind turbines in forested terrain**  
Period: 27 Jun 2017  
Ebba Dellwik (Invited speaker)  
Alkistis Papetta (Other)  
Johan Arnqvist (Other)  
Morten Nielsen (Other)  
Torben J. Larsen (Other)  
Department of Wind Energy  
Meteorology & Remote Sensing  
Resource Assessment Modelling  
Wind turbine loads & control  
Documents:  
abstract - WESC2017-final

**Related event**  
27/06/2017 → 27/06/2017  
Copenhagen, Denmark  
Activity: Talks and presentations › Conference presentations

**TOPFARM: framework for coupling models to address wind farm optimization challenges**  
Period: 27 Jun 2017  
David Robert Verelst (Speaker)  
Frederik Zahle (Other)  
Pierre-Elouan Réthoré (Other)  
Jennifer Rinker (Other)  
Department of Wind Energy  
Wind turbine loads & control  
Aerodynamic design  
Resource Assessment Modelling

**Related event**  
Wind Energy Science Conference 2017
VAWTs for offshore applications
Period: 14 Dec 2016
Uwe Schmidt Paulsen (Speaker)
Siri Magrethe Kalvig (Panel member)
Department of Wind Energy
Wind turbine loads & control

Description
keynotes on VAWTs for offshore applications; highlights of key issues to be addressed in combining Aqua industry with FVAWTs for Scandinavian and European applications

Degree of recognition: International

Documents:
Wind Turbine Loads and Control (LAC)

Related event
Scandinavian Consortium for a small scale floating VAWT
14/12/2016 → 14/12/2016
Stavanger, Norway
Activity: Talks and presentations › Talks and presentations in private or public companies and organisations

Retrospective aspects of DeepWind (ANFSCD) by Uwe Schmidt Paulsen
Period: 23 Nov 2016
Uwe Schmidt Paulsen (Keynote speaker)
Department of Wind Energy
Wind turbine loads & control

Description
This presentation was performed on the initiative and invitation made by the SUPERGEN Wind General Assembly, focusing primarily on the offshore environment and held at Cranfield University Nov 2016. This free event showcases wind energy research carried out by universities within the EPSRC's SUPERGEN Wind Hub Consortium, focusing primarily on the offshore environment. The Hub encourages researchers, commercial and industrial organisations working in the UK to come along and network with other organisations working in wind energy. The presentation highlights on the development process and design of a conceptual 5 MW floating vertical-axis Wind turbine for offshore operations in Deep Sea. The results presented are outcomes from the European Commission financed FP7 project under the program 'future emerging technologies'

Degree of recognition: International

Documents:
Cranfield_v1

Links:

Related event
SUPERGEN Wind General Assembly 2016-Topic: Novel Turbines: Deepwind
Cranfield, United Kingdom
Activity: Talks and presentations › Talks and presentations in private or public companies and organisations

A review of state-of-the-art in torque generation and control of floating vertical-axis wind turbines
Period: 7 Sep 2016 → 9 Sep 2016
Uwe Schmidt Paulsen (Keynote speaker)
Large-scale floating vertical axis wind turbines have great potential for offshore applications. This presentation will review recent developments for generating torque and controlling vertical-axis wind turbines (VAWTs) specifically for floating applications. The phenomena presented include dynamic stall and pitching of the blades, as well as design of airfoils for VAWT applications.

Held at the Euromech 2016 colloquium hosted by TUDelft 7-9 September in Delft, The Nederlands
Degree of recognition: International
Documents:
A review of state-of-the-art in torque generation and_eratap10

Related external organisation

Euromech
Laboratoire de Mécanique et d’Acoustique Impasse Nikola Tesla CS 40006, 13453, Marseille, France
Activity: Talks and presentations › Conference presentations

Period: 27 Apr 2016 → 28 Apr 2016
Torben J. Larsen (Speaker)
Department of Wind Energy
Wind turbine loads & control

Description
Documents:
HAWC2 Offshore Wind Turbine Simulations

Related event

27/04/2016 → 28/04/2016
Washington, DC 20024, United States
Activity: Talks and presentations › Conference presentations

Period: 27 Apr 2016 → 28 Apr 2016
Torben J. Larsen (Invited speaker)
Department of Wind Energy
Wind turbine loads & control

Description
Goals and Objectives: This workshop will provide an overview of:
•Recent efforts to develop and validate numerical modelling codes for dynamic analysis of OWT,
•Recent research efforts on geotechnical aspects of soil-structure interactions of OWT, and
•The latest wind farm/wind plant design tools.

This workshop will seek to identify ways to ensure that the current state of practice and capabilities of industry’s structural and geotechnical modelling tools and techniques are appropriately considered in the future development of U.S. offshore wind standards and regulations.
Documents:
HAWC2_pdf

Related event

27/04/2016 → 28/04/2016
Washington, DC 20024, United States
Industry meets science, Stavanger, Norway
Period: 6 Apr 2016
Torben J. Larsen (Speaker)
Department of Wind Energy
Wind turbine loads & control

Description
Industry meets science, Stavanger, Norway
Documents:
windturbine_loads
Links:
http://www.norcowe.no/index.cfm?id=428950

Related event
Industry meets science, Stavanger, Norway
06/04/2016 → 06/04/2016
Stavanger, Norway
Activity: Talks and presentations › Conference presentations

Wind Turbine Loading
Period: 6 Apr 2016
Torben J. Larsen (Invited speaker)
Department of Wind Energy
Wind turbine loads & control
Documents:
windturbine_loads

Related event
Industry meets science, Stavanger, Norway
06/04/2016 → 06/04/2016
Stavanger, Norway
Activity: Talks and presentations › Conference presentations