Active power dispatch for supporting grid frequency regulation in wind farms considering fatigue load

This paper proposes an active power control method for supporting grid frequency regulation in wind farms (WF) considering improved fatigue load sensitivity of wind turbines (WT). The control method is concluded into two parts: Frequency adjustment control (FAC) and power reference dispatch (PRD). On one hand, the proposed Fuzzy-PID control method can actively maintain the balance between power generation and grid load, by which the grid frequency is regulated when plenty of winds are available. The fast power response can be provided and frequency error can be reduced by the proposed method. On the other hand, the sensitivity of the WT fatigue loads to the power references is improved. The explicit analytical equations of the fatigue load sensitivity are re-derived to improve calculation accuracy. In the process of the optimization dispatch, the re-defined fatigue load sensitivity will be used to minimize fatigue load. Case studies were conducted with a WF under different grid loads and turbulent wind with different intensities. By comparing the frequency response of the WF, rainflow cycle, and Damage Equivalent Load (DEL) of the WT, the efficacy of the proposed method is verified.

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

Large-scale floating vertical axis wind turbines have great potential for offshore applications. This paper will review the 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.
A vortex-based tip/smearing correction for the actuator line

The actuator line (AL) was intended as a lifting line (LL) technique for computational fluid dynamics (CFD) applications. In this paper we prove – theoretically and practically – that smearing the forces of the actuator line in the flow domain forms a viscous core in the bound and shed vorticity of the line. By combining a near-wake representation of the trailed vorticity with a viscous vortex core model, the missing induction from the smeared velocity is recovered. This novel dynamic smearing correction is verified for basic wing test cases and rotor simulations of a multimegawatt turbine. The latter cover the entire operational wind speed range as well as yaw, strong turbulence and pitch step cases. The correction is validated with lifting line simulations with and without viscous core, which are representative of an actuator line without and with smearing correction, respectively. The dynamic smearing correction makes the actuator line effectively act as a lifting line, as it was originally intended.
Changes in design driving load cases: Operating an upwind turbine with a downwind rotor configuration
This work considers the design driving load cases from a full design load basis analysis on an upwind turbine changed into a downwind configuration. The upwind turbine is a commercial class IIIA 2.1-MW turbine, manufactured by Suzlon. The downwind turbine shows an increase in the normalized tower clearance by 6%, compared with the upwind concept. Removing the blade prebend increases the normalized minimum tower clearance by 17% in the downwind configuration compared with the upwind configuration. The extreme loads on the longitudinal tower bottom bending moment are seen to generally increase by 17% because of the overhanging gravity moment of the rotor-nacelle assembly. The extreme blade root bending moments are reduced by 10% flapwise, because of the coning of the rotor in downwind direction. The fatigue loads suffer from the tower shadow, leading to an overall increase of the fatigue loads in the blades with up to 5% in flapwise direction in the downwind configuration. Because of blade deflection and coning direction, the downwind configuration shows a 0.75% lower annual energy production. Removing the prebend increases the annual energy production loss to 1.66%.

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Comparing rotor plane induction determined from full-scale measurements and CFD simulations
This paper investigates the flow field in the rotor plane of a full-scale operating wind turbine using full-scale light detection and ranging (LiDAR) measurements for the first time. Comparison of the measured flow field with results from large eddy simulations (LES) combined with an actuator line approach is also presented for in-depth study of the induction field in the rotor plane. The measurements include data from two synchronized LiDAR systems—one scanning the undisturbed upstream inflow field and one measuring in the rotor plane. The standard deviation of the mean of velocity time series are presented as a measure of reliability. The method for calculating the axial velocity based on the line-of-sight velocity is explained and the uncertainty of such method is presented. The process of calculating the yaw misalignment is described. The time-averaged and phase-averaged axial velocity and induction factors are presented relative to radius and azimuth, and the general behavior is described relative to the flow regimes around the blades, tower and nacelle. Simulations and measurements are compared with special emphasis on the flow structures in the vicinity of the individual rotor blades. A convincing agreement between measurements and simulations is demonstrated. The uncertainties originated from the imprecise positions and angles of the measurement instruments are shown. The uncertainties are limited to the middle parts of the blades between 15 m to 25 m from the root. In addition, longer selected time series show smaller uncertainties. This proves the reliability of the application of the methodology for even longer time series.

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Estimation and Control of Wind Turbine Tower Vibrations Based on Individual Blade-Pitch Strategies

In this brief, we present a method to estimate the tower fore-aft velocity based upon measurements from blade load sensors. In addition, a tower dampening control strategy is proposed based upon an individual blade pitch control architecture that employs this estimate. The observer design presented in this brief exploits the Coleman transformations that convert a time-varying turbine model into one that is linear and time-invariant, greatly simplifying the observability analysis and subsequent observer design. The proposed individual pitch-based tower controller is decoupled from the rotor speed regulation loop and hence does not interfere with the nominal turbine power regulation. Closed-loop results, obtained from high fidelity turbine simulations, show close agreement between the tower estimates and the actual tower velocity. Furthermore, the individual-pitch-based tower controller achieves a similar performance compared with the collective-pitch-based approach but with negligible impact upon the nominal turbine power output.

Fail-safe truss topology optimization

The classical minimum compliance problem for truss topology optimization is generalized to accommodate for fail-safe requirements. Failure is modeled as either a complete damage of some predefined number of members or by degradation of the member areas. The considered problem is modeled as convex conic optimization problems by enumerating all possible damage scenarios. This results in problems with a generally large number of variables and constraints. A working-set algorithm based on solving a sequence of convex relaxations is proposed. The relaxations are obtained by temporarily removing most of the complicating constraints. Some of the violated constraints are re-introduced, the relaxation is resolved, and the process is repeated. The problems and the associated algorithm are applied to optimal design of two-dimensional truss structures revealing several properties of both the algorithm and the optimal designs. The working-set approach requires only a few relaxations to be solved for the considered examples. The numerical results indicate that the optimal topology can change significantly even if the damage is not severe.
Full-scale 3D remote sensing of wake turbulence - A taster

The aim of the present paper is to investigate the wake turbulence as based on advanced full-scale measurements which, for the first time, makes it possible directly to resolve all three turbulence components in the wake behind an operating wind turbine with high spatial- and temporal resolution. The experimental setup will be described, and analysis of selected runs will be presented with a focus on the expected inhomogeneity of this turbulence field. The analyses are performed in a meandering frame of reference, and in addition to afore mentioned wake turbulence field, the wake deficit field will be resolved and analysed. Atmospheric stability is not considered but is, however, not expected to contribute noticeably to wake turbulence nor to the wake deficit field when expressed in the meandering frame of reference.

More accurate aeroelastic wind-turbine load simulations using detailed inflow information

In this paper, inflow information is extracted from a measurement database and used for aeroelastic simulations to investigate if using more accurate inflow descriptions improves the accuracy of the simulated wind-turbine fatigue loads. The inflow information is extracted from nearby meteorological masts (met masts) and a blade-mounted five-hole pitot tube. The met masts provide measurements of the inflow at fixed positions some distance away from the turbine, whereas the pitot tube measures the inflow while rotating with the rotor. The met mast measures the free-inflow velocity; however the measured turbulence may evolve on its way to the turbine, pass beside the turbine or the mast may be in the wake of the turbine. The inflow measured by the pitot tube, in comparison, is very representative of the wind that acts on the
turbine, as it is measured close to the blades and also includes variations within the rotor plane. Nevertheless, this inflow is affected by the presence of the turbine; therefore, an aerodynamic model is used to estimate the free-inflow velocities that would have occurred at the same time and position without the presence of the turbine. The inflow information used for the simulations includes the mean wind speed field and trend, the turbulence intensity, the wind-speed shear profile, atmospheric stability-dependent turbulence parameters, and the azimuthal variations within the rotor plane. In addition, instantaneously measured wind speeds are used to constrain the turbulence. It is concluded that the period-specific turbulence intensity must be used in the aeroelastic simulations to make the range of the simulated fatigue loads representative for the range of the measured fatigue loads. Furthermore, it is found that the one-to-one correspondence between the measured and simulated fatigue loads is improved considerably by using inflow characteristics extracted from the pitot tube instead of using the met-mast-based sensors as input for the simulations. Finally, the use of pitot-tube-recorded wind speeds to constrain the inflow turbulence is found to significantly decrease the variation of the simulated loads due to different turbulence realizations (seeds), whereby the need for multiple simulations is reduced.

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On the design and performance of a power electronics converter for the DeepWind project
DeepWind is a vertical axis wind turbine (VAWT) concept, with the turbine rotor mounted on a floating spar buoy with the generator at the bottom up to 300 m below the sea. To control the starting, variable speed and overspeed limitation operation of the VAWT, the only method available is to control the torque and speed of the generator. A four quadrant, three level, neutral point clamped inverter configuration is proposed and the design of this discussed. Various operational features are tested on a small scale laboratory version. Sample test results are given. The challenges of the DeepWind marine application are presented and discussed and some solutions are proposed.

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(AIP Conference Proceedings).
On the design, laboratory model and performance of the controlled magnetic journal bearing for the DeepWind project

DeepWind has attracted scientific attention. This is due to its design simplicity, which will reduce costs for installation, operation and maintenance of a deep sea offshore wind generator system. Using this design offers advantages of alternative ways to manufacture the turbine rotor parts, introduce new materials, a novel way to implement a direct drive, Permanent Magnet Generator (PMG) and bearing technology, and a design that offers a reduced cost of energy.

DeepWind uses a generator and bearings module, supported by controlled magnetic bearings technology. However, many technologies implemented in DeepWind are well known from other applications (e.g. Wind Energy, Sub-sea installations, Offshore installations). This paper presents the controlled magnetic bearings proposed for DeepWind.

Optimal open loop wind farm control

This paper presents a general purpose platform for optimal open loop control of wind power plants as seen from a power production perspective. The general idea is to change the controller design criteria from greedy individual wind turbines to a controller design facilitating cooperative and interdependent elements of a wind power plant, with the overall aim to improve the wind power plant power production conditioned on ambient mean wind speed and mean wind direction. The flow within the wind power plant, including all essential interactions between the wind turbines, is modelled using a very fast linearized CFD RANS solver. The wind turbines are modelled as actuator discs, and two design variables per wind turbine - collective pitch, α, and tip speed ratio, λ - are initially defined for the optimization problem. However, a priory we expect one design variable to suffice - i.e. the unique set of (α, λ) representing the lowest thrust coefficient, CT , for a given power coefficient Cp . The conjectured collapse of the design space is justified in this paper. Optimized control schemes for the Lillgrund offshore wind farm are derived conditioned on ambient mean wind direction and wind speed. Aggregated over a year, using the site sector Weibull distributions, an increase in the annual energy production of 1% is demonstrated.
Optimised de-rated wind turbine response and loading through extended controller gain-scheduling

An increasing number of wind turbines are expected to be able to participate in the ancillary services that would normally be provided by conventional power plants, as the penetration of the wind energy in the electricity grid is increasing. Specifically, the turbines are needed to be able to control their active power based on the operator command. Constraining the possible output power, i.e. decreasing the power to less than the maximum or rated power, is therefore important for the wind turbine control system. When a turbine is operating under a de-rating strategy, the operating points of the turbine, i.e. the steady-state blade pitch and the tip speed ratio, change compared to the normal case and this needs to be considered within the controller design. Thus, this paper is to study the influence of the de-rating on the turbine controller gain-scheduling and its effect to power output and fatigue damage of the key turbine components. The results show that the wind turbine response is refined through tuning under the different down-regulation operation points, that translate into less fatigue damage of the key turbine components. For a typical multi-megawatt turbine, it is found that the main component lifetime damage can be reduced substantially. In numerical terms, there are up to 6.5% for the tower BM in fore-aft direction and 2.7% for the blade root flapwise direction, which can lead in a prolonged operational lifetime of the wind turbine.

Permanent accumulated rotation of an offshore monopile wind turbine in sand during a storm

Offshore wind turbines exposed to storm situations are subjected to static and dynamic loads from the same direction over a considerable period of time. Such cyclic loading can potentially result in soil degradation, leading to an undesired permanent rotation of the wind turbine. This paper presents a workflow to predict the permanent accumulated rotation of an offshore monopile wind turbine in sand during an extreme storm event incorporating the use of fully nonlinear irregular waves versus linear waves in current practice. The fully nonlinear irregular waves are realized from a potential flow solver OceanWave3D previously validated at up to near-breaking wave conditions. Given the wave kinematics, the aero-hydroelastic code HAWC2 is used to calculate horizontal loading and bending moment acting on the embedded pile head. The irregular load series is then decomposed into a set of constant-amplitude load parcels using rainflow counting. Eventually,
the permanent accumulated rotation is predicated using the method proposed by LeBlanc et al. (2010b) with Miner's rule-based superposition. In this paper, a case study of the DTU 10MW wind turbine supported by a monopile at 33 m water depth in sand is presented, where the pile is primarily laterally loaded. The simulation results suggest the importance of taking accumulated rotation into design. The permanent accumulated rotation is primarily decided by soil capacity, loading characteristics and pre-loading history. Furthermore, the results show that wave nonlinearity has only limited influence on the permanent accumulated rotation.

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Porous Structural Design for Additive Manufacturing and Improved Damage Tolerance

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Porous Structural Design for Additive Manufacturing and Improved Damage Tolerance
Porous structural design has attracted tremendous interest because of the advances in additive manufacturing and the superior characteristics of porous structures. This study presents a filter approach for porous structural design in the framework of single-scale density-based topology optimization. It in principle follows the idea to control porosity by limiting the local volume fraction of material. These local limits are usually incorporated into the optimization problem as a number of individual constraints or one condensed constraint. In contrast to the conventional constraint approach, a filter approach is proposed here to explicitly integrate these local limits into the material interpolation and have them automatically satisfied during the optimization iterations. A variety of numerical examples have been studied to validate the effectiveness of the filter approach.

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Power curve and wake analyses of the Vestas multi-rotor demonstrator

Numerical simulations of the Vestas multi-rotor demonstrator (4R-V29) are compared with field measurements of power performance and remote sensing measurements of the wake deficit from a short-range WindScanner lidar system. The simulations predict a gain of 0 %–2 % in power due to the rotor interaction at below rated wind speeds. The power curve measurements also show that the rotor interaction increases the power performance below the rated wind speed by 1.8 %, which can result in a 1.5 % increase in the annual energy production. The wake measurements and numerical simulations show four distinct wake deficits in the near wake, which merge into a single-wake structure further downstream. Numerical simulations also show that the wake recovery distance of a simplified 4R-V29 wind turbine is 1.03–1.44 Deq shorter than for an equivalent single-rotor wind turbine with a rotor diameter Deq. In addition, the numerical simulations show that the added wake turbulence of the simplified 4R-V29 wind turbine is lower in the far wake compared with the equivalent single-rotor wind turbine. The faster wake recovery and lower far-wake turbulence of such a multi-rotor wind turbine has the potential to reduce the wind turbine spacing within a wind farm while providing the same production output.

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Qualitative yaw stability analysis of free-yawing downwind turbines

This article shows qualitatively the yaw stability of a free yawing downwind turbine and the ability of the turbine to align passively with the wind direction, using a two degree of freedom model. An existing model of a Suzlon S111 upwind 2.1MW turbine is converted into a downwind configuration with a 5° tilt and a 3.5° downwind cone angle. The analysis shows that the static tilt angle causes a wind speed dependent yaw misalignment of up to −19° due to the projection of the torque onto the yaw bearing and the skewed aerodynamic forces caused by wind speed projection. With increased cone angles, the yaw stiffness can be increased for better yaw alignment and the stabilization of the free yaw motion. The shaft length influences the yaw alignment only for high wind speeds and cannot significantly contribute to the damping of the
free yaw mode within the investigated range. Asymmetric flapwise blade flexibility is seen to significantly decrease the damping of the free yaw mode, leading to instability at wind speeds higher than 19 m s⁻¹. It is shown that this additional degree of freedom is needed to predict the qualitative yaw behaviour of a free yawing downwind wind turbine.

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**Specification, design and performance of the generator for vertical axis wind turbines of the deep wind project**
The generator of the DeepWind Vertical Axis Wind Turbine (VAWT) concept is reviewed, discussing special challenges, detailing the function specification, briefly presenting the design tool, some results, the proposed construction and aspects of the generator performance.

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**Structural optimization based design of jacket type sub-structures for 10MW offshore wind turbines**
The design of offshore support structures for wind turbines of 10 MW capacity presents a challenge due to potential resonance problems from the low rotor speeds during operation. The present work delineates the optimization based design of jacket type sub-structures at 50 m water depths for a 10 MW turbine by exploring the frequency constraint space of the sub-structure and confirming feasibility of a cost effective design away from rotor excitation. The conceptual design is made using a two-level optimization framework. The outer design problem, i.e. overall jacket dimensioning, is solved by a derivative free optimization method. The inner problem which consists of member sizing is solved using a robust and
efficient Sequential Quadratic Programming method. The objective of the optimization is innovatively chosen as to minimize the fundamental natural frequency of the structure, while subject to frequency constraints, tower top displacement constraints and member ultimate stress constraints. The resulting design is modified during the process of verifying that all ultimate and fatigue limit states are met using fully coupled aero-hydro-elastic simulations. The final design is a low mass four-legged jacket that fully complies with offshore structural standard requirements for all design limit states, while not being affected by rotor excitation, thus being best suited for long operating life.

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**Temporal coherence importance sampling for wind turbine extreme loads estimation**
Estimating long return period extreme wind turbine loads is made especially difficult by the large response variability for “the same” environmental conditions. To alleviate this, we have “opened up the black box” of the turbulent wind generation stage of the simulations. Exploiting the notion of “temporal coherence” allows us to manipulate the turbulent inflow to target extreme wind conditions, while at the same time quantifying “how probable these are”. The resulting importance sampling load estimates achieve a significantly lower exceedance probability (i.e., they represent much longer return periods) than estimates using the same number of samples (i.e., the same computational resources) but only a standard Monte Carlo estimate. This paper presents the underlying methodology and some preliminary results. We find that for some loads the method works remarkably well, but for other loads challenges remain.

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**The effect of wake position and yaw misalignment on power loss in wind turbines**
For a single wind turbine, the efficiency of extracting energy from the wind depends on the ability to align the wind turbine with the dominating wind direction. Considering average power production, yaw misalignment is relevant when the wind turbine operates with maximum power coefficient. On the other hand, the power production is less sensitive to yaw misalignment in high wind speeds, where the available energy in the wind field is higher than the maximum wind turbine
capacity. In a wind farm, the interaction between nearby wind turbines alters the flow, and the power production is reduced. The present study investigates how yaw misalignment affects the power production in these wake situations compared to yaw misalignment effects for a wind turbine in the free-stream. Two generic cases are presented in this paper, offshore and forest, where the atmospheric conditions alter the morphology of the wake and, therefore, the power output of a yawed wind turbine operating in wake conditions. The results show that, for a conventional downstream spacing further than 3 rotor diameters, yaw misalignment results in larger power loss in wake situations than in free-stream. In wake situations, the presented results also show that the spatial distribution of the deficit influences the relative power loss when the wind turbine is operating in yawed conditions.

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The wake of an actuator line with a vortex-based tip/smearing correction in uniform and turbulent inflow
The force smearing in the actuator line technique ensures its numerical stability, but also breaks its intended similarity to the lifting line by similarly smearing its vorticity in the flow domain. The wake thus induces lower velocities at the blade, linking the blade forces to the force smearing. A recently developed tuning-free, vortex-based correction recovers this missing induction, regaining the lifting-line behaviour of the actuator line. The interplay of this new smearing correction with grid and blade resolution is studied in uniform and turbulent inflow with respect to the blade forces and wake behaviour. With only 10 grid cells along the blade, the thrust is within 2.8% and the power within 5.7% of the high-resolution reference. With 20 grid cells the difference drops to 1.5% and 2.5%, respectively. The influence of the force smearing on the wake velocities dominates over the choice of correction, yet under turbulent inflow the wake characteristics become nearly independent of force smearing 6 rotor radii downstream of the turbine.

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Why curved wind turbine rows are better than straight ones

Wind turbine wake effects in wind farms not only reduce the wind farm power production but also influence the wind farm power dependency on wind direction. In this paper, the wake effects in wind farm layouts consisting of curved and straight wind turbine rows are studied using engineering wake models and a Reynolds-averaged Navier-Stokes model. These models predict a similar annual energy production for both wind farm layouts, but show stronger wake losses in the aligned wind directions for a rectangular wind farm layout, while the wake losses for a curved wind farm layout are more spread out over a larger wind direction sector. An energy system level simulation predicts that the enhanced spreading of wake losses over wind directions results in less hourly variability in energy generation on a Danish energy system level. Thus, our results show that a curved wind farm layout is more favorable compared to a wind farm layout with straight rows.

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Aeroelastic Analysis of B49 Blade-Blatigue Project

This report is part of the EUDP Blatigue project, Fast and efficient fatigue test of large wind turbine blades. In the study the Siemens B49 blade loads are computed using HAWC2 aeroelastic code. The blade is coupled in a generic wind turbine tower and nacelle structure within HAWC2. Furthermore the basic DTU WE controller is used. The aim is to evaluate the blade fatigue and ultimate loads based on the IEC 61400-1 ed.3 standard. The results are further used in the project for the set-up and testing of the real blade at the DTU Risø Large Scale Facility. In the first part the model properties are summarized. Then the IEC load cases are simulated using the HAWC2 code and the analysis is focused on the blade performance. A blade load comparison between HAWC2 and the Siemens results is presented together with a summary of the uncertainties related with the present analysis. Finally, an analysis is performed on a potential way to compute the blade lifetime fatigue damage based on few time series instead of running the full design load basis. The work is funded by the EUDP project BLATIGUE: Fast and efficient fatigue test of large wind turbine blades under project number 64016-0023 which is gratefully acknowledged. Several contributions have been made in the model set-up as well as in the interpretation of the results from Torben J. Larsen, Anders M. Hansen, Kim Branner, Perer Berring and Federico Belloni who are gratefully acknowledged.

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Aeroelastic Analysis of B75 blade - Blatigue Project
This report is part of the EUDP Blatigue project, Fast and efficient fatigue test of large wind turbine blades. In the study the Siemens B75 blade loads are computed using HAWC2 aeroelastic code. The blade is coupled in the DTU 10MW rwt tower and nacelle structure within HAWC2. Furthermore the basic DTU WE controller is used. The aim is to evaluate the blade fatigue and ultimate loads based on the IEC 61400-1 ed.3 standard. The results are further used in the project for the set-up and testing of the real blade at the DTU Risø Large Scale Facility. In the first part the model properties are summarized. Then the IEC load cases are simulated using the HAWC2 code and the analysis is focused on the blade performance. A blade load comparison between HAWC2 and the Siemens results is presented together with a summary of the uncertainties related with the present analysis. The work is funded by the EUDP project BLATIGUE: Fast and efficient fatigue test of large wind turbine blades under project number 64016-0023 which is gratefully acknowledged. Several contributions have been made in the model set-up as well as in the interpretation of the results from Torben J. Larsen, Anders M. Hansen, Kim Branner, Perer Berring and Federico Belloni who are gratefully acknowledged.

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A working-set approach for sizing optimization of frame-structures subjected to time-dependent constraints
In this paper, we propose a working-set approach for sizing optimization of structures subjected to time-dependent loads. The optimization problems we consider have a very large number of constraints while relatively few design variables and degrees of freedom. Instead of solving the original problem directly, we solve a sequence of smaller sub-problems. The sub-problems consider only constraints in the working set, which is a small sub-set of all constraints. After each sub-problem, we compute all constraint function values for the current design and add critical constraints to the working set. The algorithm terminates once an optimal point to a sub-problem is found that satisfies all constraints of the original problem. We tested the approach on several reproducible problem instances and demonstrate that the approach finds optimal points to the original problem by only considering a very small fraction of all constraints. The proposed approach drastically reduces the memory storage requirements and computational expenses of the linear algebra in the optimization solver and the computational cost of the design sensitivity analysis. Consequently, the approach can efficiently solve large-scale optimization problems with several hundred millions of constraints.

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Blade-Pitch Control for Wind Turbine Load Reductions

Large wind turbines are subjected to the harmful loads that arise from the spatially uneven and temporally unsteady oncoming wind. Such loads are the known sources of fatigue damage that reduce the turbine operational lifetime, ultimately increasing the cost of wind energy to the end-users. In recent years, a substantial amount of studies has focused on blade pitch control and the use of real-time wind measurements, with the aim of attenuating the structural loads on the turbine blades and rotor. However, many of the research challenges still remain unsolved. For example, there are many classes of blade individual pitch control (IPC) techniques, but the link between these different but competing IPC strategies was not well investigated. In addition, another example is that many studies employed model predictive control (MPC) for its capability to handle the constraints of the blade pitch actuators and the measurement of the approaching wind, but often, wind turbine control design specifications are provided in frequency domain that is not well taken into account by the standard MPC. To address the missing links in various classes of the IPCs, this thesis aims to investigate and understand the similarities and differences between each of their performance. The results suggest that the choice of IPC designs rests largely with preferences and implementation simplicity. Based on these insights, a particular class of the IPCs lends itself readily for extracting tower motion from measurements of the blade loads. Thus, this thesis further proposes a tower load reduction control strategy based solely upon the blade load sensors. To tackle the problem of MPC on wind turbines, this thesis presents an MPC layer design upon a predetermined robust output-feedback controller. The MPC layer handles purely the feed-forward and constraint knowledge, whilst retaining the nominal robustness and frequency-domain properties of the predetermined closed loop. Thus, from an industrial perspective, the separate nature of the proposed control structure offers many immediate benefits. Firstly, the MPC control can be implemented without replacing the existing feedback controller. Furthermore, it provides a clear framework to quantify the benefits in the use of advance real-time measurements over the nominal output-feedback strategy.

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Calibrating a wind turbine model using diverse datasets
This paper presents a model calibration investigation using a wide range of available data. The wind turbine under investigation was the V52 research turbine located at Denmark Technical University (DTU) Risø campus. The data included drawings and static and dynamic tests for both the entire wind turbine and the isolated blades. Each set of data was used to calibrate some aspect of the final model. There are three main parts of this paper. First, the different data sources are outlined, including an overview of the experimental procedures and the key results. Second, the model
calibration procedure for each set of experimental data is explained. Third, recommendations for the calibration procedure are presented for future researchers and the key outcomes of our calibration investigation are discussed.

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**Comparison of Aero-Elastic Simulations and Measurements Performed on NENUPHAR's 600kW Vertical Axis Wind Turbine: Impact of the Aerodynamic Modelling Methods: Paper**
Aero-elastic solver predictions are compared to measured data from the NENUPHAR’s 1HS prototype, with a focus on the blade loads. Two solvers are investigated, namely the HAWC2 solver, and DeepLinesWindTM, respectively based on a linear and a non-linear formulation of the Timoshenko beam theory. Various aerodynamic models are used, from simple Multiple Streamtube models up to the Actuator-Cylinder flow model and 2D/3D Vortex flow solvers. A special attention is also given to the influence of the dynamic stall on the results. Aero-elastic solvers predictions are accurate and fit well with the measured blade loads, but this work emphasizes the fact that suitable aerodynamic model and stall model should be used.

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Comparison of Fuga and RANS in complex terrain

Modeling wind turbine wakes and wind resources in complex terrain is challenging. High fidelity Computational Fluid Dynamics (CFD) methods can produce accurate results of long term averaged speed up factors for flow over complex terrain although user uncertainty can create large differences between CFD model results [1]. Engineering wake models are often not suited to model wakes in complex terrain because they are developed for wind farms in flat terrain [2]. Fuga [3] is a fast linearized CFD model developed to model wake effects in wind farms for flat terrain and uniform roughness lengths. The base flow in Fuga is an atmospheric surface layer following Monin-Obukhov Similarity Theory [4] and the effect of a wind turbine wake is added as a linear perturbation. Recent work has been carried out to develop a linearized terrain flow model in Fuga. The linearity of this terrain flow model implies that the model can only predict first order perturbations of the terrain and cannot predict flow separation and recirculation zones. In unpublished work, a comparison between the terrain flow model of Fuga and a Reynolds-averaged Navier-Stokes (RANS) model as implemented in EllipSys3D [5, 6] has been made for the flow over an axisymmetric Gaussian hill with a moderate maximum slope angle of 17° using eight test cases. This moderate slope angle was chosen to avoid flow separation. The comparison showed that the streamlines of Fuga and EllipSys3D compare well for all eight test cases. Results of this study are presented in Section 3.1 and the comparison is extended with results of speed up factor contours and profiles. In this report, we would like to continue the comparison between the terrain flow model of Fuga and RANS (without wind turbine wakes) for additional test cases that are designed to answer the following three research questions:

1. How well do the wind turbine wake streamlines follow the terrain streamlines?
2. For which slope angles does the terrain flow model of Fuga start to deviate significantly from RANS in terms of streamlines and speed up factors for an axisymmetric Gaussian hill?
3. How well does the terrain flow model of Fuga compare with RANS for a real complex terrain site in terms of speed up factors and velocity profiles?

The methodology and test cases are presented in Section 2. The results are discussed in Section 3.

Conceptual jacket design by structural optimization

We present an approach for sizing optimization of jacket structures and apply it to investigate the conceptual design of jackets for offshore wind turbines. Conceptual design is an input to early structural and financial models, and we assume simplified analysis and load models. A four-legged jacket for the DTU 10-MW wind turbine in 50-m water depth is modelled by Timoshenko beam finite elements, and the structural dimensions of the beam cross sections are considered as continuous design variables. A structural optimization problem is formulated to minimize the jacket mass, with constraints on fatigue and ultimate limit states. The optimal design problem is then used to investigate how the optimized mass depends on the number of bays and the jacket leg distance. The conceptual design investigation led to a new conceptual design with 14% lower mass compared with the original conceptual design. We conclude that structural optimization can provide useful insights in the conceptual design phase and lead to a better starting point for the further design and planning processes.
Cyclic soil loads on an offshore wind turbine during storm
Offshore wind turbines are subjected to combined static and cyclic loads due to its self weight, wind, current and waves. For the design of support structures, a point of concern is whether the highly varying loads may cause cyclic degradation of the soil leading to a permanent undesired pile settlement and tilting for the wind turbine. In particular during a severe storm, the large cyclic loads are being more critical as the wind and waves are typically from a single direction. The DTU 10MW wind turbine supported by a jacket at 33 m water depth is considered in this study, where the piles are axially loaded in order to bear the moment under wind and wave actions. This paper investigates the cyclic loads using traditional linear irregular waves and fully nonlinear irregular waves realized from the wave solver OceanWave3D previously validated until near-breaking wave conditions. This study shows that the nonlinear irregular waves introduce more extreme cyclic loads, which result in significantly larger pile settlement than using linear wave realizations. For the case in this study, linear wave theory underestimates pile settlement at least 30% compared to nonlinear wave realizations.

DeepWind Innovative VAWT

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Design of offshore windfarms WP6.3 - D63.3 Offshore wind turbine control

This deliverable presents control algorithms for offshore wind turbines that can reduce the cost of energy by mitigating loads on the tower and support structure as well as unwanted swings and motions of the tower and nacelle. In turn, this can lead to reduced initial investments and thus to reduced levelized cost of energy. As a reference wind turbine, the 10 MW DTU reference wind turbine is selected, and adjusted to two support structures. A monopile is used to represent a bottom-mounted wind turbine, and a triple spar floating platform is used for simulations with floating wind turbines. For both cases, baseline controllers were adapted and tuned, with an option of using additional control loops for load reduction, such as individual pitch control, and control algorithms for reduction of tower loads based on collective blade pitching, generator torque, and individual blade pitching. Besides showing load reductions achievable by the proposed control concepts, the deliverable also discusses their possible industrial exploitation, showing that mostly software updates are required with no or only modest updates to the standard sensor equipment or actuators of modern multi-megawatt wind turbines. Load reduction with different control algorithms is analysed in aeroelastic simulations in GH Bladed under various atmospheric and sea states, which are obtained by lumping over 20 years of measurement data. It is concluded that some control algorithms achieve higher load reduction in certain operating conditions, meaning that - by identifying such conditions and using an adaptive activation strategy - actuator activity can be reduced without significantly reducing load reduction. As an example, when activating individual pitch controller only in selected atmospheric and sea states, one can reduce the actuator duty cycle over 25 % by losing only 15 % of the maximal achievable tower load reduction. Additionally, a significant impact on the support structure lifetime, and therefore on the levelized cost of energy, is shown as a function of the control effort, i.e. of the actuator duty cycle. It is shown that avoiding additional pitch activity in 50 % of the cases can already lead to the threefold increase of the support structure lifetime, indicating that further reductions in material are possible. To achieve even further load reduction, a series of different control loops for load reduction is replaced with a single optimal state space controller, LQR, which takes care of the wind turbine power control, reduction of blade loads, nacelle motion, and tower loads. This enables a better synchronisation among different control objectives, and more coordinated control actions towards achieving control objectives. The controller and the state estimator are designed based on a linearized mathematical model in the d-q coordinate system, and tested in aeroelastic simulations with turbulent wind conditions and irregular waves. It is shown that the more coordinated control actions can achieve further load reductions, with up to 5 % damage equivalent load (DEL) reduction of the fore-aft tower bending moment, and up to 1 % DEL reduction of the side-to-side tower bending moment compared to the baseline controller extended with standard control algorithms for load reduction. Additionally, the proposed control concept achieves slight reductions in the actuator activity (up to 1.5 %) and the standard deviation of the generated power (up to 13 %). The deliverable also presents a control strategy based on the predictive observer-based feedforward control, which can effectively reduce wind turbine loads in extreme operating conditions, and help in avoiding shutdown procedures. Such an approach can lead to reductions in the blade root flapwise bending moment of more than 30 %, which has an important impact on the loads envelope and the blade design. Furthermore, it is shown that the floating platform pitch tilt moment can be reduced by 15 %, the mooring anchor tension (1 m) can be reduced 13 %, and the fairlead around 8 %. Other loads are reduced in the range of 5 %, such as tower base fore-aft bending moment, and the mooring fairlead and anchor tensions at 2 m and 3 m. These results are obtained because the proposed controller anticipates risky situations, and either avoids a shutdown procedure, which additionally reduces the wind turbine downtime and thus increases the energy production, or it initiates a shutdown in a better condition and thus reduces ultimate loads. The obtained results show a possible reduction in blade weight and cost of up to 27 %, and a reduction of levelized cost of energy of up to 1.18 %, which is besides in material savings also driven by a slight increase of annual energy production. The unwanted swings and motions of floating wind turbines can cause the generator speed control loop using conventional blade pitch controller to become unstable at above rated wind speeds. To minimise such swings and motions, the blade pitch demand, produced by the basic controller, is augmented by an additive adjustment in response to tower fictitious forces at frequencies below tower natural frequency. Tower fictitious forces are apparent forces acting on the nacelle mass, when the WT is mounted on a non-stiff structure, which produces fore-aft and side-to-side unwanted motions described using a non-inertial reference frame. The developed control task is independent of the platform and wave dynamics and the strongly WT aerodynamic gain can be counteracted by global gain-scheduling. Besides guaranteeing stability, the control algorithm is extended to alleviate tower fatigue loads and reduce power fluctuations on the drive-train components by reducing blade pitching activity in the vicinity of the tower fore-aft natural frequency. It is shown that such a control concept enables the use of lighter floating platforms, thus also leading to reductions in the initial investment costs and levelized cost of energy, without the need to redesign standard control algorithms. Finally, the deliverable discusses requirements on the wind turbine systems from the grid operators, and defines design cases which can be used to test the compatibility of control systems with the grid requirements.

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Dynamic inflow effects in measurements and high-fidelity computations

A wind turbine experiences an overshoot in loading after, for example, a collective step change in pitch angle. This overshoot occurs because the wind turbine wake does not immediately reach its new equilibrium, an effect usually referred to as dynamic inflow. Vortex cylinder models and actuator disc simulations predict that the time constants of this dynamic inflow effect should decrease significantly towards the blade tip. As part of the NASA Ames Phase VI experiment, pitch steps have been performed on a turbine in controlled conditions in the wind tunnel. The measured aerodynamic forces from these experiments seemed to show much less radial dependency of the dynamic inflow time constants than expected when pitching towards low loading. Moreover the dynamic inflow effect seemed fundamentally different when pitching from low to high loading, and the reason for this behavior remained unclear in previous analyses of the experiment. High-fidelity computational fluid dynamics and free-wake vortex code computations yielded the same behavior as the experiments. In the present work these observations from the experiments and high-fidelity computations are explained based on a simple vortex cylinder wake model.
Dynamic stall model modifications to improve the modeling of vertical axis wind turbines

The Beddoes-Leishman type dynamic stall model was originally implemented in HAWC2 with a focus on horizontal axis wind turbines. In case of HAWTs, some terms in the unsteady airfoil lift and drag are very small and can be neglected, which are very important for VAWTs. Furthermore, the angle of attack variations during normal operation of VAWTs are by far larger than those occurring on HAWTs. This posed a challenge to the Beddoes-Leishman-type dynamic stall model, which had previously been validated for small variations in angle of attack against CFD and measurements. This report contains some necessary modifications of the Beddoes-Leishman type dynamic stall model in HAWC2 to enable unsteady aerodynamic computations on VAWTs. A short validation against measurements of the NREL/NASA Ames Phase VI rotor in standstill is included. There, it is shown that the model changes have only a small, but beneficial effect at small angle of attack variations.

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Engineering an optimal wind farm using surrogate models: EOWF using SUMO

A framework for optimal design of wind farm layouts using a surrogate-based Dynamic Wake Meandering model is presented. The optimization platform is set-up as a hybrid strategy combining genetic search with the gradient-based algorithm. The design variables are the number of turbines in the layout and their relative position within the bounded area. The objective function is defined as the net present value of the wind farm's profit, thus including the relevant expenditures throughout the farm's lifespan. Results show that an optimal design is reached by maximizing investment and accepting a minor sacrifice of the wind farm performance.

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Evaluation of the Effect of Spar Cap Fiber Angle of Bending-Torsion Coupled Blades on the Aero-Structural Performance of Wind Turbines

This paper presents a comprehensive study of the evaluation of the effect of spar cap fiber orientation angle of composite blades with induced bending-torsion coupling (IBTC) on the aero-structural performance of wind turbines. Aero-structural performance of wind turbines with IBTC blades is evaluated with the fatigue load mitigation in the whole wind turbine system, tower clearances, peak stresses in the blades, and power generation of wind turbines. For this purpose, a full E-glass/epoxy reference blade has been designed, following the inverse design methodology for a 5-MW wind turbine. An E-glass/epoxy blade with IBTC and novel, hybrid E-glass/carbon/epoxy blades with IBTC have been designed and aeroelastic time-marching multibody simulations of the 5-MW turbine systems, with the reference blade and the blades with IBTC, have been carried out using six different randomly generated turbulent wind profiles. Fatigue-equivalent loads (FELs) in the wind turbine have been determined as an average of the results obtained from the time response of six different simulations. The results reveal that certain hybrid blade designs with IBTC are more effective in fatigue load mitigation than the E-glass-epoxy blade with IBTC, and besides the fiber orientation angle, sectional properties of hybrid blades must be adjusted accordingly using proper number of carbon/epoxy layers in the sections of the blade with IBTC, in order to simultaneously reduce generator power losses and the FEL.

Fast trailed and bound vorticity modeling of swept wind turbine blades

Passive load alleviation can be achieved through geometric bend-twist coupling, for example, by sweeping the blade backwards. The influence of the blade sweep on the trailing vorticity and bound vorticity is not modelled in the current fast aeroelastic wind turbine codes suitable for certification. A near wake trailed vorticity model which was coupled with a blade element momentum theory based aerodynamic model has been modified to take into account the blade sweep. The extended model is compared with the original near wake model, a blade element momentum (BEM) model and full rotor computational fluid dynamics (CFD) results for the modified IEA 10MW reference wind turbines. The steady-state loadings calculated from the extended model are in better agreements with CFD compared to the original model and the BEM for four different swept blades. It is also shown that the influence of the blade sweep on normal loading is not correctly modelled by BEM and this error will be inherited to the near wake model results. Thus, further modification to BEM will likely improve the predicted normal loading for swept blades, even if no near wake model is used.
Free flow wind speed from a blade-mounted flow sensor

This paper presents a method for obtaining the free-inflow velocities from a 3-D flow sensor mounted on the blade of a wind turbine. From its position on the rotating blade, e.g. one-third from the tip, a blade-mounted flow sensor (BMFS) is able to provide valuable information about the turbulent sheared inflow in different regions of the rotor. At the rotor, however, the inflow is affected by the wind turbine, and in most cases the wind of interest is the inflow that the wind turbine is exposed to, i.e. the free-inflow velocities. The current method applies a combination of aerodynamic models and procedures to estimate the induced velocities, i.e. the disturbance of the flow field caused by the wind turbine. These velocities are subtracted from the flow velocities measured by the BMFS to obtain the free-inflow velocities. Aeroelastic codes, like HAWC2, typically use a similar approach to calculate the induction, but they use it for the reversed process, i.e. they add the induction to the free inflow to get the flow velocities at the blades, which are required to calculate the resulting aerodynamic forces. The aerodynamic models included in the current method comprise models based on blade element momentum (BEM) for axial and tangential induction, a radial induction model and tip loss correction, and models for skew and dynamic inflow. It is shown that the method is able to calculate the free-inflow velocities with high accuracy when applied to aeroelastic HAWC2 simulations with a stiff structural model while some deviations are seen in simulations with a flexible structure. Furthermore, the method is tested on simulations performed by a flexible structural model coupled with a large-eddy simulation (LES) flow solver. The results of this higher-fidelity verification confirm the HAWC2-based conclusion.
High fidelity simulation of multi-MW rotor aerodynamics by using a multifan

During the last decades the offshore wind energy sector has experienced large developments. Despite bottom fixed wind turbines have been widely used, some their limitations have brought to scout and develop concepts based on floating support structures. The behavior of such structures is affected by forces of different nature, so the analysis of these structural systems becomes complex and requires an accurate definition of their dynamics. This is one of the reasons for which the numerical simulations can be highly improved from experimental tests at reduced scale. The interaction between hydrodynamic forces and the structure is investigated experimentally by means of wave tank tests. In these circumstances the correct representation of the aerodynamic forces is not trivial due to laboratory scale law conflicts. These issues can be eased by using hybrid systems. This work aims to describe a hybrid system developed by IH Cantabria. The system is meant to define the most significant aerodynamic loads affecting the dynamic performance of a floating wind turbine by using an aerodynamic model (BEM), while their generation in the scaled model is obtained by using a multi-fan system. This approach successfully satisfies issues related to the scalability of the aerodynamic forces and their variability due to the turbine controller and wind variability. Nevertheless, some shrewdness have to be taken in order to comply with the following matters. The correct representation of the dynamic effects relative to the aerodynamic forces requires high frequency calculations. For this reason some simplifications on the aerodynamic model must be taken. This work explains the criteria used to define the simplifications to be adopted, showing the low impact they have on the tests results. On the present paper it will be demonstrated the capabilities of the multi-fan that was chosen to reproduce the rotor aerodynamics. Moreover, it will evidence the high fidelity of the forces developed by the multi-fan, both in terms of amplitude and reactivenss on the forces fluctuations. The final section will prove the ability of the hybrid system to reproduce with high fidelity and large flexibility the aerodynamic load conditions desired in lab scale wave tank tests.

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High-resolution periodic mode shapes identification for wind turbines
The stability analysis of in-operation wind turbines is a very important topic, that has received considerable attention in the last years. Many identification algorithms have been developed to estimate frequencies and damping ratios, but very few papers have been dedicated to the mode shapes. The knowledge of high-resolution mode shapes could be exploited for several applications including model validation, accurate description of the vibratory content of a machine and spatially-accurate damage detection. In this work, we will present a procedure to compute the high-resolution periodic mode shapes of a wind turbine, and apply it to a high-fidelity wind turbine model. The results show that this methodology is able to identify the first low-damped modes of the system with good accuracy.

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This paper presents a study on derating wind turbine power levels in a wind farm and the associated loads on downwind placed wind turbines. This is done by derating the wind farm power output for certain periods of time. Derating can be done in different ways by adjusting the rotor speed and blade pitch on the individual turbines which also has a direct impact on the turbine component loads. The paper studies three characteristic derating strategies on the upstream wind turbine (WT) and the corresponding load impact on the downstream one. These are defined as minimum/maximum rotor speeds (minRS, maxRS) and minimum thrust (minT) modes. Derating factors of 20% and 40% on available power are applied together with 4 and 7 diameters WT interspace. The study is based on aeroelastic simulations of a 2MW generic WT model including wake effects. The results show that below rated wind speed (8m/s) the downstream WT blade flap fatigue loads are minimized when the upfront WT is derated with the minRS or minT strategy. The maxRS mode returns around 2% percent higher loads. The load levels for minRS and minT strategies are almost equal. Above rated wind speed (16m/s) the trend is the same as at 8m/s with a bit higher difference on load levels, up to 6% percent at tighter interspace between maxRS strategy and the other two. The fore-aft fatigue loads on the tower base and the main bearing yaw moment follow the same trends as the blade for both below and above rated wind speed. Finally, it is also found that there is a correlation on the load levels and the wind deficit values. In all cases up to around ±10 degrees incoming wind direction the wake deficit from the maxRS control strategy is higher and the load levels follow the same trend. This is an important outcome and links the control strategies directly to the wake deficit due to the upstream WT operation.
Impact on wind turbine loads from different down regulation control strategies

Three characteristic derating strategies on the upstream wind Turbine are studied and the load impact to the downstream one is assessed. These are defined as minimum/maximum rotor speeds (minRS, maxRS) and minimum thrust (minT) modes. Derating factors of 20% and 40% on available power are applied together with 4 and 7 diameters WT interspace. The study is based on aeroelastic simulations of a 2MW generic WT model including wake effects. The results show that below rated wind speed (8m/s) the downstream WT blade flap fatigue loads are minimized when the upfront WT is derated with the minRS strategy. The maxRS mode returns always the highest loads. When the WTS are aligned with the wind direction (full wake situation) the load levels for minRS and mint strategies are almost equal. Above rated wind speed (16m/s) the tendency is the same as at 8m/s. Finally, the fore-aft fatigue loads on the tower base and the main bearing yaw moment follow the same trends as the blade for both below and above rated wind speed.

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Contributors: Galinos, C., Larsen, T. J., Mirzaei, M.
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Improved modelling of fatigue loads in wind farms under non-neutral ABL stability conditions

The purpose of this study is improve the predictive capability of the Dynamic Wake Meandering (DWM) model generalized to non-neutral atmospheric boundary layer (ABL) conditions in general and under stable ABL stratification in particular. The emphasis is on rotating wind turbine components, and the model improvement in focus is intimately linked to a newly developed refinement of the classic Monin-Obukhov theory, which, for stable ABL stratification, primary results in less pronounced mean wind shear outside the surface layer, where most modern wind turbines are operating. The model improvements are validated against a huge set of full-scale data, which allows for a one-to-one comparison of wind turbine load simulations and measurements conditioned on ABL stability conditions.

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

The power and load performance of wind turbines are both crucial for the development and expansion of wind energy. The power and loads are highly dependent on the inflow conditions, which can be measured using different types of sensors mounted on nearby met masts, on the nacelle, at the spinner or at the blade. Each combination of sensor type and mounting position has advantages and shortcomings. To characterise the inflow that results in high and low fatigue loads, information about the temporal and spatial variations within the rotor area is required. This information can be obtained from a blade-mounted flow sensor, BMFS, e.g. a five-hole pitot tube, which has been used in several research experiments over the last 30 years. The BMFS measured flow velocity is, however, located inside the induction zone and thereby influenced by the aerodynamic properties, the control strategy and the operational status of the turbine. In this project, a method to estimate the free-inflow velocity from the BMFS measured flow velocity has been developed and implemented. The method is based on the aerodynamic engineering models that are used in well-established aeroelastic codes to describe the relation between the free-inflow and the velocity at the blades. Before these models can be applied, the measured local flow must be compensated for flow deflection and change of flow speed near the airfoil. Furthermore, the sensor velocity must be subtracted and the resulting absolute flow must be mapped into fixed ground coordinates. In these steps, uncertainty is introduced because the actual velocity and orientation of the BMFS are unknown due to the deflection and torsion of the blade. The introduced uncertainties have been investigated using HAWC2 simulations and simulations performed by Flex5 coupled with the LES flow solver, EllipSys3D. The uncertainties should, however, be considered in relation to the advantages of measuring the flow at the blade: a BMFS yaws with the turbine, measures the inflow at the rotor plane and sweeps different parts of the rotor. It is thereby exposed to exactly the same inflow conditions as the turbine (including wake effects from upstream turbines) and able to provide valuable information about the instant inflow velocity as well as variations within the rotor plane, and that goes for all wind directions. From the BMFS measurements, estimates of the local aerodynamic forces, the angle-of-attack and relative flow speed, the rotor-plane velocity and the free-inflow velocity can be obtained. Applications of these measures have been investigated. It is concluded that a BMFS provides valuable information about the inflow, which can be used for the control of load alleviating concepts like individual pitch and trailing edge flaps, to investigate the complex relation between the inflow and the power and loads, to characterise the inflow conditions that yield high loads, and as input for aeroelastic simulations to improve the correlation between the measured and simulated loads.

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Measured aerodynamic forces on a full scale 2MW turbine in comparison with EllipSys3D and HAWC2 simulations

Design loads on turbines are normally simulated with an aeroelastic model using an engineering BEM type model with the turbulent inflow generated with a turbulence model like the Mann model. There are several fundamental uncertainties in this approach, e.g. how well the unsteady induction in response to the turbulent flow is computed. However, within the last few years full 3D CFD rotor computations with turbulent inflow have been performed which can provide detailed insight into this complex load response. In the present work we present computations with the EllipSys3D solver on the 80m diameter NM80 turbine used in the DANAERO project where surface pressure measurements at four radial positions were conducted. The aerodynamic loads integrated from the pressure distributions have been derived and compared with computations by the aeroelastic code HAWC2. Overall a very good correlation is found by comparing PSD spectra of the measured sectional blade forces with HAWC2 simulations using specific flow input from the meteorology mast at six heights. In another comparison using purely turbulent inflow for the simulations on the NM80 rotor some deviations between the force spectra are found between EllipSys3D results and HAWC2 simulations at the inboard part of the blade and at high frequencies.

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Research output: Contribution to journal › Conference article – Annual report year: 2018 › Research › peer-review
On the Architecture of Wind Turbine Control Required for Induction-based Optimal Wind Farm Control

In wind farms, the aerodynamic interaction of wind turbines results in power loss of up to 40% and up to 80% larger fatigue loads at downstream turbines. In simulation studies, induction-based wind farm control is observed to mitigate this effect. The approach is to reduce the power, induction and thrust of upstream turbines, thereby weaken the upstream turbines’ wake and as a result potentially reduce the power loss and fatigue loads of downstream turbines. This work investigates the design of turbine control required to enable such wind farm control. The current standard approach for turbine control is unsuited and therefore a new control approach is presented in this work. The proposed controller realizes a reduced thrust by changing the blade pitch angle. Turbine controller tests on a single turbine set-up and a wind farm scale set-up are conducted using a dynamic simulation tool that models turbine dynamics, wind farm flow aerodynamics and wind farm control. The simulation results show the suitability of the proposed wind turbine control approach for induction-based wind farm control.

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Contributors: Kazda, J., Mirzaei, M., Cutululis, N. A.
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On wind turbine down-regulation control strategies and rotor speed set-point

The use of down-regulation or curtailment control strategies for wind turbines offers means of supporting the stability of the power grid and also improving the efficiency of a wind farm. Typically, wind turbine derating is performed by modifying the power set-point and subsequently, the turbine control input, namely generator torque and blade pitch, are acted on to such changes in the power reference. Nonetheless, in addition to changes in the power reference, derating can be also performed by modifying the rotor speed set-point. Thus, in this work, we investigate the performance of derating strategies with different rotor speed set-point, and in particular, their effect on the turbine structural fatigue and thrust coefficient were evaluated. The numerical results obtained from the high-fidelity turbine simulations showed that compared to the typical derating strategy, the derated turbines might perform better with lower rotor speed set-point but it is crucial to ensure such a set-point does not drive the turbine into stalled operations.

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Optimal Aero-Elastic Design of a Rotor with Bend-Twist Coupling

Passive Bend-Twist Coupling (BTC) can be used in blades to alleviate loads and generate more Annual Energy Production (AEP). However, BTC is inherently aero-elastic, thus difficult to incorporate into the design with sequential design process. Multi-disciplinary Design Optimization (MDO) is an attractive approach for overcoming these challenges. This paper presents the re-design of a 100kW BTC rotor using the MDO rotor design package HAWTOpt2. In the preliminary design phase, MDO was used to assess the differences between elastic BTC (i.e. off-axis fibers) and geometric BTC (i.e. sweep). This work found that aero-elastic design optimization without BTC was able to achieve a 16% improvement, then with sweep a 18% improvement and with material coupling a 17% improvement. Due to the reduced stiffness of off-axis fibers, material coupled designs had more difficulty satisfying the tip deflection constraint. The geometric BTC concept was chosen for the final design. The design optimization was repeated with additional manufacturing constraints. The final design achieved a 12% improvement.

Optimal design of cathodic protection systems for offshore wind turbine support structures

Cathodic protection (CP) can be defined as preventing a metal surface to corrode by making that surface the cathode of an electrochemical cell. Cathodic protection is one of the common methods for corrosion protection of offshore wind turbine support structures. Improper corrosion protection of offshore wind turbine support structures can lead to significant lifetime degradation of these structures. One could say that the corrosion uncertainty is one of the most influential parameters on residual fatigue lifetime of monopile support structures [1]. Furthermore, if the corrosion protection system must be repaired, the associated cost can be much higher than the initial installation cost of the corrosion protection system [2]. Hence an efficient and cost-effective design of a CP system is of crucial importance. Current manual design of
CP systems using standards can be time-consuming as well as lead to a costly CP design. Moreover, the positions of the anodes on the support structure, as an influential parameter on the performance of the CP system, are not determined in the design standards. The current study addresses the optimal design process of a CP system for offshore wind turbine support structures. The optimization process is carried out in two steps. First, the mass/cost of the CP system is minimized by formulating an optimization problem with number and dimensions of the anodes as design variables, and the criteria in the design standard as non-linear design constraints. Second, the positions of the anodes on the structure are determined in such a way that the protective potential criteria on the structure are satisfied. The non-linear optimization problem is modelled in MATLAB and the protective potential on the structure is calculated using boundary element method (BEM). Using BEM for calculating the protective potential instead of finite element method reduces the computational cost, considerably. The obtained results show the efficiency of the proposed optimization procedure for reducing the cost of CP systems as well as improving their performance.

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Optimal yaw strategy for optimized power and load in various wake situations: Paper
The interaction between nearby wind turbines in a wind farm modifies the power and loads compared to their stand-alone values. The increased turbulence intensity and the modified turbulence structure at the downstream turbines creates higher fatigue loading, which can be mitigated by wind farm and/or wind turbine control. To alleviate loads and maximize power possible strategies such as wake steering, where the turbine is yawed to redirect the wake such that it does not impinge the downstream turbine, have been studied. The work presented here focuses on situations where the wake is nevertheless affecting the downstream turbine, and more specifically how high loads can be avoided by yawing the wake-affected turbine. The analysis is conducted on a 2.3 MW machine, and the flow field is simulated using the Dynamic Wake Meandering model. The study investigates the impact on power and loads for different longitudinal interspacing and turbulence intensities. Optimal yaw strategies are defined for above rated regions where no power loss occurs. The potential load alleviation for different load sensors are studied, but the presentation is focussed on the blade root flapwise fatigue loading. For full wake at 3D interspacing and turbulence intensity of 5 %, around 35 % of load reduction on the 1 Hz Damage Equivalent Loads can be achieved at high wind speeds. Smaller reductions are achieved for higher atmospheric turbulence; the analogue case with 15 % turbulence intensity shows 17 % potential alleviation. The alleviation on the wind turbine lifetime is also calculated and compared for different turbulence intensities and mean wind speeds. Small reductions are achieved for sites with low mean wind speed and high turbulence intensity, but high reductions, of around 19 %, are accomplished in low turbulence intensity with high mean wind speed.

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Parameter estimation of a breaking wave slamming load model using Monte Carlo simulation: Paper

For offshore wind turbines (OWTs) located in relatively shallow water, the design is influenced by the occurrence of breaking waves. The strongly nonlinear properties associated with the wave breaking process result in challenges in modelling their impact loads on the structures. The total impact loads are normally calculated as the sum of a slowly varying quasi-static load and an impulsive slamming load. The quasi-static load is normally calculated using Morison's equation and the slamming load is approximated by the Goda model or the Wienke-Oumeraci model. Given the dynamic properties of OWTs, structural resonances might be excited by the impulsive slamming load. Therefore, there is a clear need to evaluate the response effect excited by the slamming load. In this paper, the response of a vertical pile subjected to a severe breaking wave case is investigated by a combination of data from a large-scale experiment and numerical simulations. The slowly varying quasi-static load obtained in a non-breaking wave packet is modelled using Morison’s equation with the wave kinematics obtained from a fully nonlinear potential flow solver OceanWave3D. The governing parameters used in a slamming load model are estimated using the Monte Carlo method and verified by comparing the experimental data with the numerical simulation results. It is found that the slamming coefficient and the curling factor are close to the values found by the Wienke-Oumeraci model, however the impact duration is significantly larger than the values found by the Goda model and the Wienke-Oumeraci model, which is important for the assessment of the dynamic responses of OWTs.

PyConTurb: an open-source constrained turbulence generator

This paper presents an open-source tool that can be used to simulate turbulence boxes constrained by measured data, which is useful for wind turbine model validation. The tool, called PyConTurb for "Python Constrained Turbulence", uses a novel algorithm based on the Kaimal Spectrum with Exponential Coherence method, and the algorithm can efficiently generate turbulence boxes under a wide variety of measurement constraints. The theoretical background for the technique is presented along with a few notes on its implementation in Python. The utility of PyConTurb is demonstrated using real data measured using three-dimensional sonic anemometers at the Denmark Technical University Risø campus. The presented results demonstrate that PyConTurb can successfully generate turbulence boxes from real measured data, including recreating the desired spatial coherence relationships between the simulated and measured time series. PyConTurb is shown to be a promising tool for investigating new spatial coherence models and for future one-to-one wind turbine validation studies.
Response Analysis of Poseidon P-37 – An Offshore Platform Mounted with Wave Absorbers and Wind Turbines

In this document results from analysis of the measurements data from the floating platform, Poseidon P37 equipped with wave energy absorbers and wind turbines, are presented. When wave absorber activity is little sensitive misalignment as long as the relative angle between waves and platform is less than approximately 50°. The platform primarily aligns with the wind and only the waves when these also aligns with the wind. It was not possible to determine a significant influence of turbine or absorber activity on the platform motion, besides a slight tendency to yaw with the wind depending on turbine activity. A method of producing Response Amplitude Operator-curves have been provided.

Simplification and Validation of a Spectral-Tensor Model for Turbulence Including Atmospheric Stability

A spectral-tensor model of non-neutral, atmospheric-boundary-layer turbulence is evaluated using Eulerian statistics from single-point measurements of the wind speed and temperature at heights up to 100 m, assuming constant vertical gradients of mean wind speed and temperature. The model has been previously described in terms of the dissipation rate epsilon, the length scale of energy-containing eddies L, a turbulence anisotropy parameter Gamma, the Richardson number Ri, and the normalized rate of destruction of temperature variance eta(θ) equivalent to epsilon(θ)/epsilon. Here, the latter two parameters are collapsed into a single atmospheric stability parameter z/L using Monin-Obukhov similarity theory, where z is the height above the Earth's surface, and L is the Obukhov length corresponding to Ri eta(θ). Model outputs of the one-dimensional velocity spectra, as well as cospectra of the streamwise and/or vertical velocity components, and/or temperature, and cross-spectra for the spatial separation of all three velocity components and temperature, are compared with measurements. As a function of the four model parameters, spectra and cospectra are reproduced quite well, but horizontal temperature fluxes are slightly underestimated in stable conditions. In moderately unstable stratification, our model reproduces spectra only up to a scale similar to 1 km. The model also overestimates coherences for vertical separations, but is less severe in unstable than in stable cases.
Stability analysis of wind turbines with bend-twist coupled blades

Over the last years, bend-twist coupling (BTC) has become one of the most important passive load reduction techniques in wind turbine blades. The kind and amount of BTC is often decided on the basis of the load reduction, often forgetting the related stability implications. In this work we perform the stability analysis of a very large wind turbine, where the BTC is obtained by rotating the fibers of the spar caps. The study focuses first on the isolated blade, and then on the complete wind turbine. The findings show that this BTC leaves some modes unaffected, but reduces the damping of the collective edgewise mode.
Steady State Comparisons HAWC2 v12.5 vs HAWCStab2 v2.14: Integrated and distributed aerodynamic performance

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TOPFARM Examples. Work Package 62, Deliverable number D62.9
This deliverable summarizes the current state of TOPFARM and presents two examples to demonstrate TOPFARM’s utility in benchmarking different wake models for different wind farms. Thanks in part to efforts in this deliverable, TOPFARM has been recently redesigned to not only be compatible with the newest version of OpenMDAO but also to facilitate the definition of user-defined cost and wake models. It is hoped that these development efforts will maximize the utility of TOPFARM into the future and also encourage collaborative research efforts between different institutions. The first example presented within this deliverable is an AEP calculation for Horns Rev with two different wake models: the GCL model (open-source) and the Fuga model (proprietary). The resulting AEP values indicate that, for this wind farm, the GCL wake model produces a substantially lower AEP. The second presented example optimizes the layout for a three-turbine wind farm with wind coming from a single inflow direction. The three turbines are initially oriented parallel to the wind flow, and the expectation is that the optimized layout will be arranged such that turbines are perpendicular to the flow. The example is simple, but the expected output is intuitive and it therefore allows a “sanity check” that the optimization procedure produces expected results. The resulting layouts were optimized with both the GCL wake model and with the Fuga wake model, and the results from both cases were as expected. The final AEP for the optimized wind farm layouts were similar. In both examples, the AEP calculation for Horns Rev and the three-turbine optimization, the GCL model was found to run substantially slower than the Fuga model (13x slower for the three-turbine optimization, 200x slower for the Horns Rev AEP calculation). This difference is due in part to a suboptimal implementation of the GCL model, but is likely primarily due to differences in the wake models themselves. Future work is underway to update the GCL wake model in the FUSED-Wake interface, as well as to modify the Fuga software to allow the extraction of turbine-specific information during AEP calculations. This will allow for better benchmarking in the future.

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Towards the understanding of vertical-axis wind turbines in double-rotor configuration

Vertical-axis wind turbines (VAWTs) in double-rotor configuration, meaning two rotors in close proximity, have the ability to enhance the power performance. In this study, we work towards the understanding of vertical-axis wind turbines in double-rotor configuration. Numerical simulations are performed to gain insight in the physics behind the double-rotor concept. Furthermore, a parametric study is performed to explore the effect of the double-rotor lay-out, rotor loading, rotor spacing and wind direction on the flow characteristics and the power generation.

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VAWT in double-rotor configuration: the effect on airfoil design
This work presents a study to identify the effect of double-rotor configuration on the airfoil selection of vertical-axis wind turbines (VAWTs). Simulations are performed using an inviscid panel/vortex model for two different counter-rotating layouts (counter-up and counter-down) and various tip speed ratios, solidities and rotor spacings are considered. The double-rotor configuration relatively enhances the power production and the flow characteristics revealed that this is due to the wake contraction, flow acceleration, and favourable angle of attack in between the rotors. With a multi-objective optimisation scheme airfoils are designed by balancing the aerodynamic and structural needs. The optimised airfoils outperform the airfoils from the initial generation and show the importance of an appropriate airfoil selection. The angle of attack encountered by the turbine in double-rotor configuration is only effected noticeably in between the rotors and therefore it is concluded that the double-rotor configuration does not significantly influence the airfoil design.

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Verification of a Numerical Model of the Offshore Wind Turbine From the Alpha Ventus Wind Farm Within OC5 Phase III

The main objective of the Offshore Code Comparison Collaboration Continuation, with Correlation (OC5) project, is validation of aero-hydro-servo-elastic simulation tools for offshore wind turbines (OWTs) through comparison of simulated results to the response data of physical systems. Phase III of the OC5 project analyzes the Senvion 5M wind turbine supported by the OWEC Quattropod from the alpha ventus offshore wind farm. This paper shows results of the verification of the OWT models (code-to-code comparison). A subsequent publication will focus on their validation (comparison of simulated results to measured physical system response data). Based on the available data, the participants of Phase III set up numerical models of the OWT in their simulation tools. It was necessary to verify and to tune these models. The verification and tuning were performed against an OWT model available at the University of Stuttgart – Stuttgart Wind Energy (SWE) and documentation provided by Senvion and OWEC Tower. A very good match was achieved between the results from the reference SWE model and models set up by OC5 Phase III participants.

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Wind turbine site-specific load estimation using artificial neural networks calibrated by means of high-fidelity load simulations

Previous studies have suggested the use of reduced-order models calibrated by means of high-fidelity load simulations as means for computationally inexpensive wind turbine load assessments; the so far best performing surrogate modelling approach in terms of balance between accuracy and computational cost has been the polynomial chaos expansion (PCE). Regarding the growing interest in advanced machine learning applications, the potential of using Artificial Neural-Network (ANN) based surrogate models for improved simplified load assessment is investigated in this study. Different ANN model architectures have been evaluated and compared to other types of surrogate models (PCE and quadratic response surface). The results show that a feedforward neural network with two hidden layers and 11 neurons per layer, trained with the Levenberg Marquardt backpropagation algorithm is able to estimate blade root flapwise damage-equivalent loads (DEL) more accurately and faster than a PCE trained on the same data set. Further research will focus on further model improvements by applying different training techniques, as well as expanding the work with more load components.

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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 flapwise 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 flapwise 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.

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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
Contributors: Niemann, H. H., Poulsen, N. K., Mirzaei, M., Henriksen, L. C.
Publication date: 8 Jun 2017
Aeroelastic Analysis of Olsen Wings 14.3m Blade-Blatigue 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 aero-elastic 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 ( Blatigue, 2020).

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Contributors: Galinos, C.
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Research output: Book/Report › Report – Annual report year: 2017 › Research › peer-review

Aeroelastic code validation - A mixed collection of examples

General information
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Organisations: Department of Wind Energy, Wind turbine loads & control
Contributors: Larsen, T. J.
Publication date: 2017
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Research output: Non-textual form › Sound/Visual production (digital) – Annual report year: 2017 › Research › peer-review

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%.

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Organisations: Department of Wind Energy, Wind turbine loads & control, Aerodynamic design, Fluid Mechanics
Contributors: Pavese, C., Tibaldi, C., Zahle, F., Kim, T.
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Publication information
A framework for medium-fidelity wake dynamics in moderately complex terrain

General information
Publication status: Published
Organisations: Department of Wind Energy, Wind turbine loads & control, Aerodynamic design, Resource Assessment Modelling
Contributors: Larsen, G. C., van der Laan, P., Ott, S.
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Event information
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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
Contributors: Tibaldi, C., Hansen, M. H., Stolpe, M.
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Electronic versions:
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Research output: Book/Report › Report – Annual report year: 2017 › Research › peer-review

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 $1.5 \times 1.5 \text{ m}^2$, 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 $0.8 \times 0.8 \text{ m}^2$ 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

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.

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.

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Organisations: Department of Wind Energy, Fluid Mechanics, Wind turbine loads & control, Siemens Wind Power US
Contributors: Poryzala, T., Mikkelsen, R. F., Kim, T.
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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2017 › Research › peer-review

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 programWAMIT 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.

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Organisations: Department of Wind Energy, Fluid Mechanics, Wind turbine loads & control
Contributors: Borg, M., Bredmose, H., Hansen, A. M.
Number of pages: 10
Publication date: 2017
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.

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.

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- Contributors: Stäblein, A. R., Hansen, M. H., Pirrung, G.
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**High-fidelity linear time-invariant model of a smart rotor with adaptive trailing edge flaps**
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.

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- Contributors: Bergami, L., Hansen, M. H.
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- Volume: 20
- Issue number: 3
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.

Inflow conditions and wake effects for wind turbines in forested terrain

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.
Inflow conditions and wake effects for wind turbines in forested terrain

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Organisations: Department of Wind Energy, Meteorology & Remote Sensing, Wind turbine loads & control, Technical University of Denmark
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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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Contributors: Meseguer Urban, A., Hansen, M. H.
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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.

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Contributors: Larsen, G. C., Larsen, T. J., Hansen, K. S.
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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.

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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.

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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 deflection 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.

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Modeling Atmospheric Turbulence via Rapid Distortion Theory: Spectral Tensor of Velocity and Buoyancy
A spectral tensor model is presented for turbulent fluctuations of wind velocity components and temperature, assuming uniform vertical gradients in mean temperature and mean wind speed. The model is built upon rapid distortion theory (RDT) following studies by Mann and by Hanazaki and Hunt, using the eddy lifetime parameterization of Mann to make the model stationary. The buoyant spectral tensor model is driven via five parameters: the viscous dissipation rate epsilon, length scale of energy-containing eddies L, a turbulence anisotropy parameter Gamma, gradient Richardson number (Ri) representing the local atmospheric stability, and the rate of destruction of temperature variance eta(θ). Model output includes velocity and temperature spectra and associated cospectra, including those of longitudinal and vertical temperature fluxes. The model also produces two-point statistics, such as coherences and phases of velocity components and temperature. The statistics of uniformly sheared and stratified turbulence from the model are compared with atmospheric observations taken from the Horizontal Array Turbulence Study (HATS) field program, and model results fit observed one-dimensional spectra quite well. For highly unstable stratification, however, the model has deficiencies at low wavenumbers that limit its prediction of longitudinal velocity component spectra at scales on the order of 0.6 km. The model predicts coherences well for horizontal separations but overestimates vertical coherence with increasing separation. Finally, it is shown that the RDT output can deviate from Monin-Obukhov similarity theory.
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Organisations: Department of Wind Energy, Meteorology & Remote Sensing, Resource Assessment Modelling, Wind turbine loads & control, University of Agder
Contributors: Chougule, A. S., Mann, J., Kelly, M. C., Larsen, G. C.
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Web of Science (2017): Impact factor 3.159
Web of Science (2017): Indexed yes
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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.

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Operational modal analysis on a VAWT in a large wind tunnel using stereo vision technique

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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Passive Loads Control in the Preliminary and Conceptual Design of Wind Turbine Blades

This thesis deals with the development of methodologies for the implementation of passive control strategies in the preliminary and conceptual design process of a wind turbine blade.

Reducing the cost of energy is a key concern for wind energy research and the ultimate goal for both academia and industry. An effective path to achieve this goal is to scale down the increase in total mass of the blades while designing
rotors with increasing size and energy yield. In this context, the capability to mitigate loads on the structure during operation becomes an attractive characteristic for the design of modern wind turbine blades.

One of the family of methods for the alleviation of loads on a wind turbine is called passive control, as it relies on the idea of designing a structure that, without any active mechanisms, deforms so as to reduce the unsteady loading generated by turbulent fluctuating wind inflow. The concept behind passive control for wind turbine blades is to produce a structural coupling between flap-wise bending towards the tower and torsion towards feathering. This coupling mitigates loads dynamically on the wind turbine structure due to a decrease in the angle of attack.

Researchers have been fascinated by the possibility to embed a form of control directly into the structural design of a wind turbine blade for decades. A wind turbine rotor that can mitigate loads passively can be considered a cost effective solution because the load mitigation effects allow the employment of lighter components without the addition of actuators and mechanical actively-controlled parts. The load mitigation effects can be also used to stretch the size of the rotor, increasing the energy yield by the machine.

Our contribution to the research in the topic of passive control for wind turbines is articulated as follows. First, we provide a validation of the aero-servo-elastic model used to perform the analysis throughout the work. Once the accuracy of the nonlinear aeroelastic models has been established, we focus on the subtle and complex interactions arising during the design process of passively controlled rotors, due to the mutual effects of aerodynamics, structure, and control. The aim is to provide a fair estimation of the load alleviation potential of different categories of passive control methods. The parametric study approach, where design parameters which trigger favourable structural coupling effects are changed individually, is not enough to ensure that the full potential of passive control is exploited. Even though parametric studies offer an estimation of load mitigation effects, they do not allow any control on whether standard design requirements have been met or not. Furthermore, these type of studies are not suited to convert the reduction in loads into factors that have a direct impact on the cost of energy, such as the decrease in blade mass or the increase in annual energy production.

We overcome these shortcomings by formulating the passively controlled wind turbine blade design process as an optimization problem using a multidisciplinary design optimization framework. From the application studies reported, we demonstrate how the integration of passive control as a design variable can open the path to the preliminary design of wind turbine rotors with not only considerable load alleviation potential, but also with substantially decreased blade mass or increased annual energy production.
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.
Validation of the dynamic wake meander model with focus on tower loads

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.
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 “Hamborg”. 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.

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.
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.

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A 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.

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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.

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 trailing edge which shows 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.
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.

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 wind speed and turbulence intensity.
Demonstration of a Basis for Tall Wind Turbine Design, EUDP Project Final Report

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 61400-1standard 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 Havsnæs 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.

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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, Thyborøn, 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.

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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.

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Design of an aeroelastically tailored 10 MW wind turbine rotor

Design of an aeroelastically tailored 10 MW wind turbine rotor
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.
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.
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 ±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.

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 atmospheric stability conditions on wind farm loading and production

The project has created a new basis for further development and optimization of WT’s designed for WF operation. This has been accomplished through developing of more realistic modelling of WF flow fields as well as of such fields interactions with WT’s under non-neutral ABL stability conditions. On this basis a verified model complex for prediction of structural loads as well as production losses for wind turbines operating in wind farm conditions, which takes into account the effects from ABL stability conditions, is established. Thereby the way to increased reliability and cost efficiency of future wind turbines as well as to more precise prediction of the WF power output is paved.

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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.

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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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Investigation of wake interaction using full-scale lidar measurements and large eddy simulation: Investigation of wake interaction using full-scale lidar measurements and LES

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.

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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.

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Mapping Wind Farm Loads and Power Production - A Case Study on Horns Rev 1

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.

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.
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 loads are estimated based on a reduced order model of the DTU 10-MW wind turbine.
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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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.

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Trailing vorticity modeling for aeroelastic wind turbine simulations in stand still

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
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 ($R_i$) representing the atmospheric stability and the rate of destruction of temperature variance ($\eta_\theta$).

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.

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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 aerelastic 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.

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Wake affected offshore tower and foundation loads

Based on the recorded data material basic mechanisms driving the increased loading experienced by WT’s operating in offshore wind farm conditions has been identified, characterized and modeled, and in general a very good agreement between predictions and measurements is obtained. However, for single wake situations the predictions seem to underpredict loading in the above rated wind speed regime. The, a priori, conjectured load peak in full wake loading cases, for a certain downstream spacing, has been identified in the simulations. As for the measurements, the considerable scatter in these prevents a firm conclusion on this issue. However, it can be concluded: 1) that tower bottom bending fatigue equivalent moments seem to level out in the range between 6D and 9D and decrease at longer downstream distances; and 2) that tower top yaw fatigue equivalent moments seem to level out in the range between 5D and 7D and decrease at longer downstream distances. Finally, generic WF studies combined with analyses of the Nysted II layout has revealed that, from a load perspective, it is recommended to avoid straight line topology layouts, at least if these lines is oriented along predominant wind directions.

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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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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.

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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.
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.

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Wind turbine wake models developed at the Technical University of Denmark: A review

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Wind turbine wake models developed at the Technical University of Denmark: A review

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WP8 Detailed Blade Modelling Implemented in Aero-Elastic load simulation

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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**Investigation of rotor imbalance on a NEG-Micon 80 Wind Turbine**

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Research output: Book/Report › Report – Annual report year: 2016 › Research

**LEX Project. Handbook - terms and definitions v. 4**
This document is aimed at helping all parties involved in the LEX project to get a common understanding of words, process, levels and the overall concept.

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**Fast Trailed 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 trailed 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 trailed 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 trailed 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 trailed vorticity effects on the aerodynamic work are found to be of the same order of magnitude as the shed vorticity effects. The trailed 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 stiffness are varied between 70% and 130% of their original value to obtain more general results. In all computed cases, the trailed 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 trailed vorticity modeling on fatigue and extreme loads. The model will further be implemented in the aeroelastic stability tool HAWCStab2.
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.