Design optimization of offshore wind farms with multiple types of wind turbines

Most studies on offshore wind farm design assume a uniform wind farm, which consists of an identical type of wind turbines. In order to further reduce the cost of energy, we investigate the design of non-uniform offshore wind farms, i.e., wind farms with multiple types of wind turbines and hub-heights. Given a set of different types of wind turbines with a different default hub height for each type, we can specify the design of a wind farm by the types of turbines, number of turbines for each type, and turbine locations. We consider the optimization of such design to minimize the levelized cost of energy, which is calculated using a capital cost model that covers the turbine cost and the balance of plant cost. An empirical wind turbine design cost and scaling model is utilized to model the cost of turbines with different sizes. Constraints on wind farm boundary, wind turbine proximity and total capacity are also included. We solve the problem with a newly developed extended random search algorithm and tested it in a realistic design optimization problem based on the Horns Rev 1 offshore wind farm in Denmark. The optimized non-uniform designs are compared with their uniform counterparts. We find that a non-uniform design can achieve a lower levelized cost of energy than its uniform counterparts, when the capital cost per MW is slightly lower for the smaller size turbine. Comparison with the mixed-discrete particle swarm optimization algorithm is also carried out for a non-uniform wind farm design problem with a fixed number of turbines, which shows the effectiveness and superiority of the proposed algorithm. Finally, the advantages and possible disadvantages of non-uniform design are also identified and discussed.
Consistent modelling of wind turbine noise propagation from source to receiver

The unsteady nature of wind turbine noise is a major reason for annoyance. The variation of far-field sound pressure levels is not only caused by the continuous change in wind turbine noise source levels but also by the unsteady flow field and the ground characteristics between the turbine and receiver. To take these phenomena into account, a consistent numerical technique that models the sound propagation from the source to receiver is developed. Large eddy simulation
with an actuator line technique is employed for the flow modelling and the corresponding flow fields are used to simulate sound generation and propagation. The local blade relative velocity, angle of attack, and turbulence characteristics are input to the sound generation model. Time-dependent blade locations and the velocity between the noise source and receiver are considered within a quasi-3D propagation model. Long-range noise propagation of a 5MW wind turbine is investigated. Sound pressure level time series evaluated at the source time are studied for varying wind speeds, surface roughness, and ground impedances within a 2000m radius from the turbine.

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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.

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Design of the OffWindChina 5 MW Wind Turbine Rotor

The current article describes the conceptual design of a rotor for a 5 MW machine situated at an offshore site in China (OffWindChina). The OffWindChina 5 MW rotor design work was divided into two parts between the Technical University of Denmark (DTU) and the Chong Qing University (CQU). The two parts consist of the aeroelastic and structural design phases. The aeroelastic part determines the optimal outer blade shape in terms of cost of energy (COE), while the structural part determines the internal laminate layup to achieve a minimum blade mass. Each part is performed sequentially using in-house optimization tools developed at DTU and CQU. The designed blade yields a high energy
Development of an aeroelastic code based on three-dimensional viscous–inviscid method for wind turbine computations

Aerodynamic and structural dynamic performance analysis of modern wind turbines are routinely estimated in the wind energy field using computational tools known as aeroelastic codes. Most aeroelastic codes use the blade element momentum (BEM) technique to model the rotor aerodynamics and a modal, multi-body or the finite-element approach to model the turbine structural dynamics. The present work describes the development of a novel aeroelastic code that combines a three-dimensional viscous–inviscid interactive method, method for interactive rotor aerodynamic simulations (MIRAS), with the structural dynamics model used in the aeroelastic code FLEX5. The new code, called MIRAS-FLEX, is an improvement on standard aeroelastic codes because it uses a more advanced aerodynamic model than BEM. With the new aeroelastic code, more physical aerodynamic predictions than BEM can be obtained as BEM uses empirical relations, such as tip loss corrections, to determine the flow around a rotor. Although more costly than BEM, a small cluster is sufficient to run MIRAS-FLEX in a fast and easy way. MIRAS-FLEX is compared against the widely used FLEX5 and
FAST, as well as the participant codes from the Offshore Code Comparison Collaboration Project. Simulation tests consist of steady wind inflow conditions with different combinations of yaw error, wind shear, tower shadow and turbine-elastic modeling. Turbulent inflow created by using a Mann box is also considered. MIRAS-FLEX results, such as blade tip deflections and root-bending moments, are generally in good agreement with the other codes.

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In this paper, we investigate the sound propagation from a wind turbine considering the effects of wake-induced velocity deficit and turbulence. In order to address this issue, an advanced approach was developed in which both scalar and vector parabolic equations in two dimensions are solved. Flow field input was obtained using the actuator line (AL) technique with Large Eddy Simulation (LES) to model the wind turbine and its wake and from an analytical wake model. The effect of incoming wind speed and atmospheric stability was investigated with the analytical wake input using a single point source. Unsteady acoustic simulations were carried out with the AL/LES input for three cases with different incoming turbulence intensity, and a moving source approach to mimic the rotating turbine blades. The results show a non-negligible effect of the wake on far-field noise prediction. Particularly under stable atmospheric conditions, SPL amplification reaches up to 7.5dB at the wake centre. Furthermore, it was observed that when the turbulence intensity level of the incoming flow is higher, the SPL difference between the moving and the steady source is lower.
Improved fixed point iterative method for blade element momentum computations

The blade element momentum (BEM) theory is widely used in aerodynamic performance calculations and optimization applications for wind turbines. The fixed point iterative method is the most commonly utilized technique to solve the BEM equations. However, this method sometimes does not converge to the physical solution, especially for the locations near the blade tip and root where the failure rate of the iterative method is high. The stability and accuracy of aerodynamic calculations and optimizations are greatly reduced due to this problem. The intrinsic mechanisms leading to convergence problems are addressed through both theoretical analysis and numerical tests. A term from the BEM equations equals to zero at a critical inflow angle is the source of the convergence problems. When the initial inflow angle is set larger than the critical inflow angle and the relaxation methodology is adopted, the convergence ability of the iterative method will be greatly enhanced. Numerical tests have been performed under different combinations of local tip speed ratio, local solidity, local twist and airfoil aerodynamic data. Results show that the simple iterative methods have a good convergence ability which will improve the aerodynamic or structural design of wind turbines.
Blade element momentum theory, Convergence, Fixed point iteration problem, Wind turbine aerodynamics

Modeling of wind turbine vortex generators in considering the inter-effects between arrays

Vortex generators (VGs) are commonly placed on wind turbine blades to delay flow separation in the boundary layer. VGs can be parametrically modeled in computational fluid dynamics for effective and efficient simulations of wind blade flow fields. Many researchers have studied the vortex circulation created by VGs and created various parametric models used with the Navier-Stokes equations, but most of them are based on a single winglet of VGs and do not include the inter-
effects between the winglets. This paper proposes a parameterized VG array model based on counter-rotating VGs, which properly takes into account the inter-effects between winglets. Two cases, i.e., a plate with a pair of VGs and a DU-W2-250 blade segment with five pairs of VGs, are investigated to validate this model; the array type parametric model is in closer agreement with experimental data than traditional models. Compared to the solid VG model, the array type model has similar streamlines and surface pressure coefficients on the suction surface. The array type VG model can effectively reduce the number of grid points and yield highly accurate predictions of wind turbine blade aerodynamic characteristics.

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Numerical Study of Wind Turbine Wake Modeling Based on a Actuator Surface Model
In the Actuator Surface Model (ALM), the turbine blades are represented by porous surfaces of velocity and pressure discontinuities to model the action of lifting surfaces on the flow. The numerical simulation is implemented on FLUENT platform combined with N-S equations. This model is improved on the basis of actuator line model(ALM). By using ASM, the model of turbine can be simplified and the quantity of grids and computing time can be significantly reduced. A linear distribution model and a ASM Grid identification method are presented. This paper compares the ASM with ALM by computing both near and far wake of a Nibe A wind turbine, which combines wake velocity, turbulent intensity and vortex structure. Results show that ASM has better prediction accuracy and verify it's feasibility on numerical simulation of wind turbine wake.
Prediction of multi-wake problems using an improved Jensen wake model

The improved analytical wake model named as 2D_k Jensen model (which was proposed to overcome some shortcomings in the classical Jensen wake model) is applied and validated in this work for wind turbine multi-wake predictions. Different from the original Jensen model, this newly developed 2D_k Jensen model uses a cosine shape instead of the top-hat shape for the velocity deficit in the wake, and the wake decay rate as a variable that is related to the ambient turbulence as well as the rotor generated turbulence. Coupled with four different multi-wake combination models, the 2D_k Jensen model is assessed through (1) simulating two wakes interaction under full wake and partial wake conditions and (2) predicting the power production in the Horns Rev wind farm for different wake sectors around two different wind directions. Through comparisons with field measurements, results from Large Eddy Simulations (LES) as well as results from other commercial codes, it is found that the predictions obtained with the 2D_k Jensen model exhibit good to excellent agreements with experimental and LES data.

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Horns Rev wind farm, Multiple wakes interaction, Power losses, Wake model, Wind turbine wakes
Study on variable pitch strategy in H-type wind turbine considering effect of small angle of attack

Variable-pitch (VP) technology is an effective approach to upgrade the aerodynamics of the blade of an H-type vertical-axis wind turbine (VAWT). At present, most of the research efforts are focused on the performance improvement of the azimuth angle owing to the large angle of attack (AoA). On the blade circular path of an H-type VAWT, there are two azimuth positions where torques are negative, and the performance is the poorest. The vicinity zones of the two azimuths also have low performance and greatly weaken the overall productivity of VAWT. In this paper, we propose a new technology that, unlike the traditional VP-technology, focuses mainly on the aerodynamics improvement of the azimuth position with small AoA. The purpose of this novel approach is to widen the band of azimuth positions with high performance and eventually enhance the power efficiency of the overall VAWT. The performance of the new VP-VAWT is predicted using the Double Multiple Streamtubes model and Prandtl's mathematics to evaluate the blade tip loss.

Compared with the fixed-pitch (FP) blade, the VP-blade has a wider zone of the max AoA and tangential force in the upwind half-circle and yields the two new larger max values in the downwind half-circle. The new VP-strategy considerably narrows the two low-torque zones near the 0° and 180° azimuths and markedly widens the high-torque azimuth zone; the torque distribution appears in a trapezoidal shape in the upwind region and an M-like shape in the downwind region. The power distribution in the swept area of turbine changes from an arched shape of the FP-VAWT into a rectangular shape of the VP-VAWT. At last, an 18.9% growth in power efficiency is achieved. All of the above results confirm that the new VP-technology can effectively improve VAWT performance and also widens the highest performance tip speed ratio zone which makes the turbines capable of running with high efficiency in wider zones.

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Verification of a novel innovative blade root design for wind turbines using a hybrid numerical method

To enhance the performance of horizontal axis wind turbines, it is proposed to place a cylindrical disc in front of the rotor in order to lead the incoming flow from the inner part to the outer part of the rotor blades. This is expected to increase the power output, as the kinetic energy is mainly captured at the outer part of the blades, where the relative wind speed is high. To assess the impact of this novel design idea, a hybrid numerical technique, based on solving the Reynolds-averaged Navier-Stokes equations, is utilized to determine the aerodynamic performance. The in-house developed EllipSys3D code, which is employed as basic numerical solver, is combined with an actuator disc representation of the wind turbine rotor and an immersed boundary technique for representing the upstream cylindrical disc. The impact of the disc on the rotor performance is assessed by systematically changing the size of the circular disc and its axial distance to the rotor. Based on a numerical study of a Megawatt size commercial wind turbine, it is found that up to 1.5% additional energy can be captured by placing a circular disc with a suitable diameter upstream of the rotor plane.

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Wind farm power production in the changing wind: Robustness quantification and layout optimization

Wind farms operate often in the changing wind. The wind condition variations in a wide range of time scales lead to the variability of wind farms' power production. This imposes a major challenge to the power system operators who are facing a higher and higher penetration level of wind power. Thus, wind farm developers/owners need to take the variability into consideration in the designing/planning stage, in addition to the conventional main objective of maximizing the expected power output under a fixed wind distribution. In this study, we first propose a new metric to evaluate the variability of wind power based on the characteristics of the wind farm and its local wind conditions. Then a series of robustness metrics are proposed to quantify wind farm's ability to produce power with high mean value and low variability under changing wind, considering both short-term and long-term wind condition variations. Based on these metrics, wind farm layout optimization is performed to maximize the robustness of a real offshore wind farm in Denmark. The results demonstrate that the robustness metrics are more flexible and complete than the conventional metrics for characterizing wind farm power production, such as mean power output or wind power variability alone, and it is feasible to design wind farms to produce power with high mean value and low variability.

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Actuator disk model of wind farms based on the rotor average wind speed

Due to difficulty of estimating the reference wind speed for wake modeling in wind farm, this paper proposes a new method to calculate the momentum source based on the rotor average wind speed. The proposed model applies volume correction factor to reduce the influence of the mesh recognition of disk regions. The coefficient $C_4\varepsilon$ of the turbulent source term is also discussed and modified to improve the simulation accuracy. To validate the model, results are presented for the Nibe-B wind turbine and Horns Rev I offshore wind farm and show a good agreement with the measurements.

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Aeroacoustic calculations of a full scale Nordtank 500kW wind turbine

The Actuator Line/Navier-stokes technique is used to compute the incompressible flow around a full scale Nordtank 500kW wind turbine under different complex flow conditions such as atmospheric turbulence and wind shear. The flow field is used as an input to aeroacoustic calculations based on; a semi empirical noise model; and a Navier-Stokes based computational aeroacoustic code (CAA). The Navier-Stokes based approach is solving acoustic perturbation equations and is capable of taking propagation and ground effects into account, but is limited to low frequency noise due to feasible mesh resolution, and due to the simplification in the actuator line method using body forces to represent the blade. Noise levels are compared to field measurements of a Nordtank 500kW wind turbine at different wind speeds and in flow profiles.
Aeroacoustic Calculations of Wind Turbine Noise with the Actuator Line/Navier-Stokes Technique

Noise regulations in many countries are becoming extremely strict and wind turbine noise is thus becoming a barrier for further development of onshore wind turbines. Low noise wind turbine airfoil and blade design is an important technique for noise reduction. However, the ow situation of a wind turbine in wind farms is very complicated. In order to accurately model the noise generation and propagation from wind turbines in wind farms, it is urgent to develop a high-fidelity noise model to predict the noise features in complex situations. In the present study, we develop a flow-acoustic splitting technique where the wind turbine ow is calculated by using the in-house actuator line/LES/Navier-Stokes technique and the acoustics is obtained by solving the acoustic perturbation equations. In the ow solver, the wind turbine blades are modelled by rotating lines with body forces determined according to the local conditions and airfoil data. In the acoustic solver, the aeroacoustics is simulated by: (1) calculating the noise source using the improved engineering model (IBPM) based on the model developed by Brook, Pope and Marcolini (BPM); (2) introducing the noise source with an expected range of frequencies along the blade lines in the acoustic solver; (3) solving the acoustic perturbation equations with the introduced source and the source captured in the ow. The model can be used to study the prediction and propagation of low-frequency noise in complex situations. Noise generated by a wind turbine with and without yaw under wind shear and in ow turbulence will be presented in the paper.

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Aerodynamic wind-turbine rotor design using surrogate modeling and three-dimensional viscous-inviscid interaction technique

In this paper a surrogate optimization methodology using a three-dimensional viscous-inviscid interaction code for the aerodynamic design of wind-turbine rotors is presented. The framework presents a unique approach because it does not require the commonly-used blade element momentum (BEM) method. The three-dimensional viscous-inviscid interaction code used here is the accurate and fast MIRAS code developed at the Technical University of Denmark. In comparison with BEM, MIRAS is a higher-fidelity aerodynamic tool and thus more computationally expensive as well. Designing a rotor using MIRAS instead of an inexpensive BEM code represents a challenge, which is resolved by using the proposed surrogate-based approach. As a verification case, the methodology is applied to design a model wind-turbine rotor and is compared in detail with the one designed with BEM. Results demonstrate that nearly identical aerodynamic performance can be achieved using the new design method and that the methodology is effective for the aerodynamic design of wind-turbine rotors.
Extension of Goldstein's circulation function for optimal rotors with hub

The aerodynamic interaction or interference between rotor blades and hub body is usually very complicated, but some useful simplifications can be made by considering the hub with an infinite cylinder. Various attempts to find the optimum distribution of circulation by the lifting vortex lines method have been previously proposed to describe the blade interaction with the hub modeled by the infinite cylinder. In this case, the ideal distribution of bound circulation on the rotor blades is such that the shed vortex system in the hub-area is a set of helicoidal vortex sheets moving uniformly as if rigid, exactly as in the case where there is no influence of the streamtube deformations by the central hub-body. In the present investigation, we consider a more specific problem of the rotor-hub interaction where the initial flow streamtubes and the rotor slipstream submitted strong deformations at the nose-area of the semi-infinite hub.
Improved blade element momentum theory for wind turbine aerodynamic computations

Blade element momentum (BEM) theory is widely used in aerodynamic performance predictions and design applications for wind turbines. However, the classic BEM method is not quite accurate which often tends to under-predict the aerodynamic forces near root and over-predict its performance near tip. The reliability of the aerodynamic calculations and design optimizations is greatly reduced due to this problem. To improve the momentum theory, in this paper the influence of pressure drop due to wake rotation and the effect of radial velocity at the rotor disc in the momentum theory are considered. Thus the axial induction factor in far downstream is not simply twice of the induction factor at disc. To calculate the performance of wind turbine rotors, the improved momentum theory is considered together with both Glauert's tip correction and Shen's tip correction. Numerical tests have been performed for the MEXICO rotor. Results show that the improved BEM theory gives a better prediction than the classic BEM method, especially in the blade tip region, when comparing to the MEXICO measurements. (C) 2016 Elsevier Ltd. All rights reserved.
Improvement of airfoil trailing edge bluntness noise model

In this article, airfoil trailing edge bluntness noise is investigated using both computational aero-acoustic and semi-empirical approach. For engineering purposes, one of the most commonly used prediction tools for trailing edge noise are based on semi-empirical approaches, for example, the Brooks, Pope, and Marcolini airfoil noise prediction model developed by Brooks, Pope, and Marcolini (NASA Reference Publication 1218, 1989). It was found in previous study that the Brooks, Pope, and Marcolini model tends to over-predict noise at high frequencies. Furthermore, it was observed that this was caused by a lack in the model to predict accurately noise from blunt trailing edges. For more physical understanding of bluntness noise generation, in this study, we also use an advanced in-house developed high-order computational aero-acoustics technique to investigate the details associated with trailing edge bluntness noise. The results from the numerical model form the basis for an improved Brooks, Pope, and Marcolini trailing edge bluntness noise model.

General information

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Large Wind Turbine Rotor Design using an Aero-Elastic / Free-Wake Panel Coupling Code
Despite the advances in computing resources in the recent years, the majority of large wind-turbine rotor design problems still rely on aero-elastic codes that use blade element momentum (BEM) approaches to model the rotor aerodynamics. The present work describes an approach to wind-turbine rotor design by incorporating a higher- fidelity free-wake panel aero-elastic coupling code called MIRAS-FLEX. The optimization procedure includes a series of design load cases and a simple structural design code. Due to the heavy MIRAS-FLEX computations, a surrogate-modeling approach is applied to mitigate the overall computational cost of the optimization. Improvements in cost of energy, annual energy production, maximum ap-wise root bending moment, and blade mass were obtained for the NREL 5MW baseline wind turbine.
LES tests on airfoil trailing edge serration

In the present study, a large number of acoustic simulations are carried out for a low noise airfoil with different Trailing Edge Serrations (TES). The Ffowcs Williams-Hawkings (FWH) acoustic analogy is used for noise prediction at trailing edge. The acoustic solver is running on the platform of our in-house incompressible flow solver EllipSys3D. The flow solution is first obtained from the Large Eddy Simulation (LES), the acoustic part is then carried out based on the instantaneous hydrodynamic pressure and velocity field. To obtain the time history data of sound pressure, the flow quantities are integrated around the airfoil surface through the FWH approach. For all the simulations, the chord based Reynolds number is around 1.5x10^6. In the test matrix, the effects from angle of attack, the TE flap angle, the length/width of the TES are investigated. Even though the airfoil under investigation is already optimized for low noise emission, most numerical simulations and wind tunnel experiments show that the noise level is further decreased by adding the TES device.

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Organisations: Department of Wind Energy, Fluid Mechanics
Authors: Zhu, W. J. (Intern), Shen, W. Z. (Intern)
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Scopus rating (2014): SJR 0.253 SNIP 0.344 CiteScore 0.32
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
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ISI indexed (2013): ISI indexed no
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Multi-objective random search algorithm for simultaneously optimizing wind farm layout and number of turbines

A new algorithm for multi-objective wind farm layout optimization is presented. It formulates the wind turbine locations as continuous variables and is capable of optimizing the number of turbines and their locations in the wind farm simultaneously. Two objectives are considered. One is to maximize the total power production, which is calculated by considering the wake effects using the Jensen wake model combined with the local wind distribution. The other is to minimize the total electrical cable length. This length is assumed to be the total length of the minimal spanning tree that connects all turbines and is calculated by using Prim's algorithm. Constraints on wind farm boundary and wind turbine proximity are also considered. An ideal test case shows the proposed algorithm largely outperforms a famous multi-objective genetic algorithm (NSGA-II). In the real test case based on the Horn Rev 1 wind farm, the algorithm also obtains useful Pareto frontiers and provides a wide range of Pareto optimal layouts with different numbers of turbines for a real-life wind farm developer.

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Authors: Feng, J. (Intern), Shen, W. Z. (Intern), Xu, C. (Ekstern)
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BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 0.45 SJR 0.24 SNIP 0.383
A new CFD RANS based method to predict the far field sound pressure emitted from an aerofoil with serrated trailing edge has been developed. The model was validated by comparison to measurements conducted in the Virginia Tech Stability Wind Tunnel. The model predicted 3 dB lower sound pressure levels, but the tendencies for the different configurations were predicted correctly. Therefore the model can be used to optimise the serration geometry. A disadvantage of the new model is that the computational costs are significantly higher than for the Amiet model for a straight trailing edge. However, it is by decades faster than LES methods.

**General information**

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Organisations: Department of Wind Energy, Aerodynamic design, Fluid Mechanics, LM Wind Power
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Journal: Journal of Physics: Conference Series (Online)
The collection of the main issues for wind farm optimisation in complex terrain

The paper aims at establishing the collection of the main issues for wind farm optimisation in complex terrain. To make wind farm cost effective, this paper briefly analyses the main factors influencing wind farm design in complex terrain and sets up a series of mathematical model that includes micro-siting, collector circuits, access roads design for optimization problems. The paper relies on the existing one year wind data in the wind farm area and uses genetic algorithm to optimize the micro-siting problem. After optimization of the turbine layout, single-source shortest path algorithm and minimum spanning tree algorithm are used to optimize collector circuits and access roads. The obtained results can provide important guidance for wind farms construction.

The collection of the main issues for wind farm optimisation in complex terrain

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General information
State: Published
Three-dimensional viscous-inviscid coupling method for wind turbine computations

In this paper, a computational model for predicting the aerodynamic behavior of wind turbine wakes and blades subjected to unsteady motions and viscous effects is presented. The model is based on a three-dimensional panel method using a surface distribution of quadrilateral sources and doublets, which is coupled to a viscous boundary layer solver. Unlike Navier-Stokes codes that need to solve the entire flow domain, the panel method solves the flow around a complex geometry by distributing singularity elements on the body surface, obtaining a faster solution and making this type of codes suitable for the design of wind turbines. A free-wake model has been employed to simulate the wake behind a wind turbine by using vortex filaments that carry the vorticity shed by the trailing edge of the blades. Viscous and rotational effects inside the boundary layer are taken into account via the transpiration velocity concept, applied using strip theory with the cross sectional angle of attack as coupling parameter. The transpiration velocity is obtained from the solution of the integral boundary layer equations with extension for rotational effects. It is found that viscosity plays a very important role in the predictions of blade aerodynamics and wake dynamics, especially at high angles of attack just before and after boundary layer separation takes place. The present code is validated in detail against the well-known MEXICO experiment and a set of non-rotating cases. Copyright © 2014 John Wiley & Sons, Ltd.
Wind turbine noise propagation modelling: An unsteady approach

Wind turbine sound generation and propagation phenomena are inherently time dependent, hence tools that incorporate the dynamic nature of these two issues are needed for accurate modelling. In this paper, we investigate the sound propagation from a wind turbine by considering the effects of unsteady flow around it and time dependent source characteristics. For the acoustics modelling we employ the Parabolic Equation (PE) method while Large Eddy Simulation (LES) as well as synthetically generated turbulence fields are used to generate the medium flow upon which sound propagates. Unsteady acoustic simulations are carried out for three incoming wind shear and various turbulence intensities, using a moving source approach to mimic the rotating turbine blades. The focus of the present paper is to study the near and far field amplitude modulation characteristics and time evolution of Sound Pressure Level (SPL).

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Scopus rating (2015): SJR 0.24 SNIP 0.373 CiteScore 0.35
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.253 SNIP 0.344 CiteScore 0.32
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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Article number: 032013
Aerodynamic performance of wind turbine under different yaw angles

A typical dynamic characteristic of horizontal axis wind turbine shows up under yaw condition. Prediction accuracy is low for momentum-blade element theory and related engineering prediction model. In order to improve the prediction accuracy of dynamic load characteristics, the whole wind turbine models, based on the experiment about MEXICO (model experiments in controlled conditions) rotor in 2006, are established by three-dimensional software called Pro/E. under different yaw conditions, i.e. yaw angle of 0, 15, 30 and 45 degree. ICEM CFD (integrated computer engineering and manufacturing code for computational fluid dynamics) is applied to grid division. The rotating domain containing rotor part is meshed into hexahedral grids, and the static domain containing part of wheel hub, tower and outflow field is meshed into tetrahedral grids. When the grid size of the first layer of blade surface is set as 5×10⁻⁶ m to ensure the first dimensionless size near the wall Y⁺<0.5 on the wall, the 2 numbers of grids are determined by the error of axial load on the airfoil in the 60% section of blades, which respectively are 6 572 451 and 2 961 385. The aerodynamic performance of models under rated condition is simulated by ANSYS CFX with the turbulence model of SST (shear stress transport), high resolution is chosen as advection scheme, and transient rotor stator as the domain interface method. The results are converted into data, processed and analyzed by MATLAB. Finally the following conclusions are drawn. The distributions of
pressure coefficients along the airfoil chord in different blade sections calculated by CFD method are in good agreement with the experimental measurements, and the error on the suction surface of airfoil is mainly caused by stall separation occurring on the pressure surface of airfoil. With the increasing of yaw angle, the pressure coefficients of the suction side are increasing and the location of minimum pressure coefficient moves to airfoil trailing edge slightly. For the pressure side, the pressure coefficients increase at first and then decrease, and the location of maximum pressure coefficient moves to airfoil leading edge slightly. The axial load coefficients and tangential load coefficients of blades first decrease and then increase and then decrease again with the increase of the azimuthal angle. With the increase of the yaw angle, the axial and tangential load coefficients are both reduced. When the yaw angle is within 30°, the relative error of axial load coefficients is in the range of ±5% and the relative error of tangential load coefficients is in the range of ±15%. CFD method is higher than BEM (blade element momentum) method in forecasting accuracy of dynamic load calculation. Under yaw condition, the hysteresis characteristic of airfoil lift and drag in blade root is more remarkable than blade tip, while the variation range of the angle of attack in blade root is much less than that in blade tip. This characteristic must be considered when BEM method is used to predict wind turbine performance. For axial inflow condition, CFD method can well predict the average speed, but restricted by turbulence model and the wake model, CFD calculation did not show the velocity characteristics of rotating vortex shedding from wind turbine impeller under yaw condition. The study provides a data support to build up the forecast model on the engineering and provides the basis for wind turbine design under yaw condition.

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Organisations: Department of Wind Energy, Fluid Mechanics
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Scopus rating (2010): SJR 0.264 SNIP 0.253
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Scopus rating (2006): SJR 0.104
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Scopus rating (2002): SJR 0.1
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Original language: Chinese
Airfoil Trailing Edge Noise Generation and Its Surface Pressure Fluctuation

In the present work, Large Eddy Simulation (LES) of turbulent flows over a NACA 0015 airfoil is performed. The purpose of such numerical study is to relate the aerodynamic surface pressure with the noise generation. The results from LES are validated against detailed surface pressure measurements where the time history pressure data are recorded by the surface pressure microphones. After the flow-field is stabilized, the generated noise from the airfoil Trailing Edge (TE) is predicted using the acoustic analogy solver, where the results from LES are the input. It is found that there is a strong relation between TE noise and the aerodynamic pressure. The results of power spectrum density show that the fluctuation of aerodynamic pressure is responsible for noise generation.

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Denmark Wind Energy Programme

In this chapter, a summary of some ongoing wind energy projects in Denmark is given. The research topics comprise computational model development, wind turbine (WT) design, low-noise airfoil and blade design, control device development, wake modelling and wind farm layout optimization.

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10.1007/978-3-319-17777-9_84
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In this chapter, two new airfoils with thickness to chord ratios of 30 and 36% are presented, which were designed with an objective of good aerodynamic and structural features. Airfoil design is based on a direct method using shape perturbation function. The optimization algorithm is coupled with the viscous/inviscid flow solver XFOIL.

Development and validation of a new two-dimensional wake model for wind turbine wakes

A new two-dimensional (2D) wake model is developed and validated in this article to predict the velocity and turbulence distribution in the wake of a wind turbine. Based on the classical Jensen wake model, this model is further employing a cosine shape function to redistribute the spread of the wake deficit in the crosswind direction. Moreover, a variable wake decay rate is proposed to take into account both the ambient turbulence and the rotor generated turbulence, different from a constant wake decay rate used in the Jensen model. The obtained results are compared to field measurements, wind tunnel experiments, and results of an advanced k-ω turbulence model as well as large eddy simulations. From the comparisons, it is found that the proposed new wake model gives a good prediction in terms of both shape and velocity amplitude of the wake deficit, especially in the far wake which is the region of interest for wind farm development projects.

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Design and Experimental Validation of Thick Airfoils for Large Wind Turbines

In this chapter, two new airfoils with thickness to chord ratios of 30 and 36% are presented, which were designed with an objective of good aerodynamic and structural features. Airfoil design is based on a direct method using shape perturbation function. The optimization algorithm is coupled with the viscous/inviscid flow solver XFOIL.

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Development of a Fast Fluid-Structure Coupling Technique for Wind Turbine Computations

Fluid-structure interaction simulations are routinely used in the wind energy industry to evaluate the aerodynamic and structural dynamic performance of wind turbines. Most aero-elastic codes in modern times implement a blade element momentum technique to model the rotor aerodynamics and a modal, multi-body, or finite-element approach to model the
turbine structural dynamics. The present paper describes a novel fluid-structure coupling technique which combines a threedimensional viscous-inviscid solver for horizontal-axis wind-turbine aerodynamics, called MIRAS, and the structural dynamics model used in the aero-elastic code FLEX5. The new code, MIRASFLEX, in general shows good agreement with the standard aero-elastic codes FLEX5 and FAST for various test cases. The structural model in MIRAS-FLEX acts to reduce the aerodynamic load computed by MIRAS, particularly near the tip and at high wind speeds.

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State: Published
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Authors: Sessarego, M. (Intern), Ramos García, N. (Intern), Shen, W. Z. (Intern)
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Main Research Area: Technical/natural sciences

Development of a high-fidelity noise prediction and propagation model for noise generated from wind turbines
An approach to combine the actuator line technique with the improved Brooks, Pope, and Marcolini (IBPM) model for wind turbine noise calculation is presented. The IBPM needs Mach number, local angle of attack and blade position as an input. These can be calculated accurately with the actuator line technique for any kind of flow conditions. We investigated laminar/ turbulent inflow, as well as wind shear and yaw of the 2.3 MW NM80 wind turbine. The turbulent case shows higher noise levels than the laminar one. Yaw changes the directivity from a dipole characteristic to an oval shape, inclined by the yaw angle.

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Authors: Debertshäuser, H. (Intern), Shen, W. Z. (Intern), Zhu, W. J. (Intern)
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Publication: Research - peer-review » Article in proceedings – Annual report year: 2015

Erratum: Validation of the actuator line method using near wake measurements of the MEXICO rotor

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Authors: Nilsson, K. (Ekstern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Breton, S. (Ekstern), Ivanell, S. (Ekstern)
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Fully Consistent SIMPLE-Like Algorithms on Collocated Grids
To increase the convergence rate of SIMPLE-like algorithms on collocated grids, a compatibility condition between mass flux interpolation methods and SIMPLE-like algorithms is presented. Results of unsteady flow computations show that the SIMPLEC algorithm, when obeying the compatibility condition, may obtain up to 35% higher convergence rate as compared to the standard SIMPLEC algorithm. Two new interpolation methods, fully compatible with the SIMPLEC algorithm, are presented and compared with some existing interpolation methods, including the standard methods of Choi [9] and Shen et al. [8]. Numerical results show that the time-step dependence of the standard methods may double the total discretization error at steady state. It is furthermore shown that the new methods are independent of time step and relaxation parameter at convergence. One of the new methods is shown to give a higher accuracy than the standard methods.
Reliable wind modelling is of crucial importance for wind farm development. The common practice of using sector-wise Weibull distributions has been found inappropriate for wind farm layout optimization. In this study, we propose a simple and easily implementable method to construct joint distributions of wind speed and wind direction, which is based on the parameters of sector-wise Weibull distributions and interpolations between direction sectors. It is applied to the wind measurement data at Horns Rev and three different joint distributions are obtained, which all fit the measurement data quite well in terms of the coefficient of determination R-2. Then, the best of these joint distributions is used in the layout optimization of the Horns Rev 1 wind farm and the choice of bin sizes for wind speed and wind direction is also investigated. It is found that the choice of bin size for wind direction is especially critical for layout optimization and the recommended choice of bin sizes for wind speed and wind direction is finally presented.

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ENERGY, SEARCH ALGORITHM, ENERGY ANALYSIS, PLACEMENT, TURBINES, DESIGN, Layout optimization, Wind modelling, Wind speed, Wind direction, Joint distribution, Sector-wise Weibull distribution
Numerical simulation of airfoil trailing edge serration noise
In the present work, numerical simulations are carried out for a low noise airfoil with and without serrated Trailing Edge. The Ffowcs Williams-Hawkings acoustic analogy is implemented into the in-house incompressible flow solver EllipSys3D. The instantaneous hydrodynamic pressure and velocity field are obtained using Large Eddy Simulation. To obtain the time history data of sound pressure, the flow quantities are integrated around the airfoil surface through the FW-H approach. The extended length of the serration is about 16.7% of the airfoil chord and the geometric angle of the serration is 28 degrees. The chord based Reynolds number is around 1.5x10^6. Simulations are compared with existing wind tunnel experiments at various angles of attack. Even though the airfoil under investigation is already optimized for low noise emission, numerical simulations and wind tunnel experiments show that the noise level is further decreased by adding the TE serration device.

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Numerical simulation of the aerodynamic field in complex terrain wind farm based on actuator disk model
Study on the aerodynamic field in complex terrain is significant to wind farm micro-siting and wind power prediction. This paper modeled the wind turbine through an actuator disk model, and solved the aerodynamic field by CFD to study the influence of meshing, boundary conditions and turbulence model on the calculation results. Comparison with the measured data of a wind farm was applied to find an appropriate method for simulating the aerodynamic field in the complex terrain wind farm. Related research can provide reference for wind farm micro-siting and wind power prediction.

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Solving the wind farm layout optimization problem using random search algorithm

Wind farm (WF) layout optimization is to find the optimal positions of wind turbines (WTs) inside a WF, so as to maximize and/or minimize a single objective or multiple objectives, while satisfying certain constraints. In this work, a random search (RS) algorithm based on continuous formulation is presented, which starts from an initial feasible layout and then improves the layout iteratively in the feasible solution space. It was first proposed in our previous study and improved in this study by adding some adaptive mechanisms. It can serve both as a refinement tool to improve an initial design by expert guesses or other optimization methods, and as an optimization tool to find the optimal layout of WF with a certain number of WTs. A new strategy to evaluate layouts is also used, which can largely save the computation cost. This method is first applied to a widely studied ideal test problem, in which better results than the genetic algorithm (GA) and the old version of the RS algorithm are obtained. Second it is applied to the Horns Rev 1 WF, and the optimized layouts obtain a higher power production than its original layout, both for the real scenario and for two constructed scenarios. In this application, it is also found that in order to get consistent and reliable optimization results, up to 360 or more sectors for wind direction have to be used. Finally, considering the inevitable inter-annual variations in the wind conditions, the robustness of the optimized layouts against wind condition changes is analyzed, and the optimized layouts consistently show better performance in power production than the original layout, despite of considerable variations in wind direction and speed. © 2015 Elsevier Ltd. All rights reserved.
This paper presented an improved computational fluid dynamics (CFD) model for simulating a horizontal-axis wind turbine wake. The model used the actuator disk model to simplify the wind turbine effect on the aerodynamic field by adding an extra momentum source and an improved term to correct the underestimation issue of the wind speed deficit when applying the STD k-ε model. In addition, the model also introduced a radial distribution function to assess the non-uniform load on the actuator disk and a coefficient $C_4\varepsilon$ of the turbulent source. To validate the model, the wind turbines of Nibe ‘B’ and Dawin 180/23 were checked by different wake models with multiple entrance velocities. Results show that the improved wake model has better prediction accuracy with experimental data and can be used for wind turbine wake calculation.
Validation of the actuator line method using near wake measurements of the MEXICO rotor

The purpose of the present work is to validate the capability of the actuator line method to compute vortex structures in the near wake behind the MEXICO experimental wind turbine rotor. In the MEXICO project/MexNext Annex, particle image velocimetry measurements have made it possible to determine the exact position of each tip vortex core in a plane parallel to the flow direction. Determining center positions of the vortex cores makes it possible to determine the trajectory of the tip vortices, and thus the wake expansion in space, for the analyzed tip speed ratios. The corresponding cases, in terms of tip speed ratios, have been simulated by large-eddy simulations using a Navier–Stokes code combined with the actuator line method. The flow field is analyzed in terms of wake expansion, vortex core radius, circulation and axial and radial velocity distributions. Generally, the actuator line method generates significantly larger vortex cores than in the experimental cases, but predicts the expansion, the circulation and the velocity distributions with satisfying results.

Additionally, the simulation and experimental data are used to test three different techniques to compute the average axial induction in the wake flow. These techniques are based on the helical pitch of the tip vortex structure, 1D momentum theory and wake expansion combined with mass conservation. The results from the different methods vary quite much,
especially at high values of . Copyright © 2014 John Wiley & Sons, Ltd.

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Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.637 SNIP 1.689
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.287 SNIP 0.9
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.528 SNIP 0.846
Validation of the Actuator Line Model for Simulating Flows past Yawed Wind Turbine Rotors

The Actuator Line/Navier-Stokes model is validated against wind tunnel measurements for flows past the yawed MEXICO rotor and past the yawed NREL Phase VI rotor. The MEXICO rotor is operated at a rotational speed of 424 rpm, a pitch angle of −2.3˚, wind speeds of 10, 15, 24 m/s and yaw angles of 15˚, 30˚ and 45˚. The computed loads as well as the velocity field behind the yawed MEXICO rotor are compared to the detailed pressure and PIV measurements which were carried out in the EU funded MEXICO project. For the NREL Phase VI rotor, computations were carried out at a rotational speed of 90.2 rpm, a pitch angle of 3˚, a wind speed of 5 m/s and yaw angles of 10˚ and 30˚. The computed loads are compared to the loads measured from pressure measurement.

Aerodynamic Analysis of Trailing Edge Enlarged Wind Turbine Airfoils

The aerodynamic performance of blunt trailing edge airfoils generated from the DU-91-W2-250, DU-97-W-300 and DU-96-W-350 airfoils by enlarging the thickness of trailing edge symmetrically from the location of maximum thickness to chord to the trailing edge were analyzed by using CFD and RFOIL methods at a chord Reynolds number of 3 × 106. The goal of this study is to analyze the aerodynamic performance of blunt trailing edge airfoils with different thicknesses of trailing edge and maximum thicknesses to chord. The steady results calculated by the fully turbulent k-ω SST, transitional k-ω SST model and RFOIL all show that with the increase of thickness of trailing edge, the linear region of lift is extended and the maximum lift also increases, the increase rate and amount of lift become limited gradually at low angles of attack, while the drag increases dramatically. For thicker airfoils with larger maximum thickness to chord length, the increment of lift is larger than that of relatively thinner airfoils when the thickness of blunt trailing edge is increased from 5% to 10% chord length. But too large lift can cause abrupt stall which is profitless for power output. The transient characteristics of blunt trailing edge airfoils are caused by blunt body vortices at low angles of attack, and by the combined effect of separation and blunt body vortices at large angles of attack. With the increase of thickness of blunt trailing edge, the vibration amplitudes of lift and drag curves increase. The transient calculations over-predict the lift at large angles of attack and drag at all angles of attack than the steady calculations which is likely to be caused by the artificial restriction of the flow in two dimensions.
A quasi-3D viscous-inviscid interaction code: Q3UIC

A computational model for predicting the aerodynamic behavior of wind turbine airfoils under rotation and subjected to steady and unsteady motions developed in [1] is presented herein. The model is based on a viscous-inviscid interaction technique using strong coupling between the viscous and inviscid parts. The rotational effects generated by centrifugal and Coriolis forces are introduced in Q3UIC via the streamwise and spanwise integral boundary layer momentum equations. A special inviscid version of the code has been developed to cope with massive separation. To check the ability of the code wind turbine airfoils in steady and unsteady conditions for a large range of angles of attack are considered here. Further, the new quasi-3D code Q3UIC is used to perform a parametric study of a wind turbine airfoil under rotation confined to its boundary layer.

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A strong viscous–inviscid interaction model for rotating airfoils

Two-dimensional (2D) and quasi-three dimensional (3D), steady and unsteady, viscous–inviscid interactive codes capable of predicting the aerodynamic behavior of wind turbine airfoils are presented. The model is based on a viscous–inviscid interaction technique using strong coupling between the viscous and inviscid parts. The inviscid part is modeled by a 2D panel method, and the viscous part is modeled by solving the integral form of the laminar and turbulent boundary-layer equations with extension for 3D rotational effects. Laminar-to-turbulent transition is either forced by employing a boundary-layer trip or computed using an envelope transition method. Validation of the incompressible 2D version of the code is carried out against measurements and other numerical codes for different airfoil geometries at various Reynolds numbers, ranging from 0.9⋅10⁶ to 8.2⋅10⁶. In the quasi-3D version, a parametric study on rotational effects induced by the Coriolis and centrifugal forces in the boundary-layer equations shows that the effects of rotation are to decrease the growth of the boundary-layer and delay the onset of separation, hence increasing the lift coefficient slightly while decreasing the drag coefficient. Copyright © 2013 John Wiley & Sons, Ltd.
Denmark Wind Energy Programme
In this paper, a summary of some ongoing wind energy projects in Denmark is given. The research topics comprise computational model development, wind turbine design, low noise airfoil and blade design, control device development, wake modelling, and wind farm layout optimization.

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Design and validation of the high performance and low noise CQU-DTU-LN1 airfoils

This paper presents the design and validation of the high performance and low noise Chong Qing University and Technical University of Denmark LN1 (CQU-DTU-LN1) series of airfoils for wind turbine applications. The new design method uses target characteristics of wind turbine airfoils in the design objective, such as airfoil lift coefficient, drag coefficient and lift-drag ratio, and minimizes trailing edge noise as a constraint. To express airfoil shape, an analytical expression is used. One of the main advantages of the present design method is that it produces a highly smooth airfoil shape that can avoid the problem of curvature discontinuity. An airfoil profile with discontinuous curvature can produce a discontinuous pressure gradient (i.e., local flow acceleration or deceleration), which enhances flow separation and thus decreases the airfoil performance. By combining the design method with the blade element momentum theory, the viscous-inviscid XFOIL code and an airfoil self-noise prediction model, an optimization algorithm has been developed for designing the high performance and low noise CQU-DTU-LN1 series of airfoils with targets of maximum power coefficient and low noise emission. To validate the airfoil design, CQU-DTU-LN118 airfoil has been tested experimentally in the acoustic wind tunnel located at the Virginia Polytechnic Institute and State University (Virginia Tech), USA. To show the superiority of the CQU-DTU-LN1 airfoils, comparisons on aerodynamic performance and noise emission between the CQU-DTU-LN118 airfoil and the National Advisory Committee for Aeronautics (NACA) 64618 airfoil, which is used in modern wind turbine blades, are carried out. Copyright © 2013 John Wiley & Sons, Ltd.

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Scopus rating (2014): SJR 1.272 SNIP 3.75 CiteScore 3.42
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Scopus rating (2013): SJR 1.275 SNIP 2.464 CiteScore 2.75
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Scopus rating (2011): SJR 1.024 SNIP 2.718 CiteScore 2.49
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.487 SNIP 2.013
Web of Science (2010): Indexed yes
This paper presents the aerodynamic design of low noise wind turbine blades using Betz and Joukowski concepts. The aerodynamic model is based on Blade Element Momentum theory whereas the aeroacoustic prediction model is based on the BPM model. The investigation is started with a 3MW baseline/reference turbine rotor with a diameter of 80 m. To reduce the noise emission from the baseline rotor, the rotor is reconstructed with the low noise CQU-DTU-LN1 series of airfoils which has been tested in the acoustic wind tunnel located at Virginia Tech. Finally, 3MW low noise turbine rotors are designed using the concepts of Betz and Joukowski, and the CQU-DTU-LN1 series of airfoils. Performance analysis shows that the newly designed turbine rotors can achieve an overall noise reduction of 6 dB and 1.5 dB(A) with a similar power output as compared to the reference rotor.
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Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.253 SNIP 0.321
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.265 SNIP 0.294
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Editorial : Special issue on aerodynamics of offshore wind energy systems and wakes

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Direct numerical solutions of the Navier-Stokes equations using Computational Fluid Dynamics methods are recognized as some of the most advanced and accurate methods for prediction of flows around wind turbines. The ability of these methods to capture the dynamics of the complex flow properties appearing in the immediate vicinity of a wind turbine rotor makes them invaluable tools in the field of wind energy. Since direct computations of a fully resolved flow around a wind turbine are computationally expensive, a typical requirement for a good CFD method is that it is able to predict the flow...
field efficiently without jeopardizing the accuracy. In this thesis, some fundamental developments of direct CFD methods are presented to provide a platform for the development of sliding grid method for wind turbine computations. As one of the most prospective CFD methods for incompressible wind turbine computations, collocated grid-based SIMPLE-like algorithms are developed for computations on block-structured grids with nonconformal interfaces. A technique to enhance both the convergence speed and the solution accuracy of the SIMPLE-like algorithms is presented. The erroneous behavior, which is typical for some commonly used mass flux interpolations, is estimated, and a new interpolation technique, which eliminates these errors, is developed together with fully consistent SIMPLE-like algorithms. For the algorithms, both the accuracy and the convergence rate are shown to be higher than standard versions of the SIMPLE algorithm. The new technique is implemented in an existing conservative 2nd order finite-volume scheme flow solver (EllipSys), which is extended to cope with grids with nonconformal interfaces. The behavior of the discrete Navier-Stokes equations is discussed in detail and the developed technique, which exhibits both low implementation costs and high efficiency of the numerical scheme, is presented. A Geometric Multigrid method of the EllipSys flow solver is fully extended to block-structured grids with nonmatching blocks. An Optimized Schwarz method employed for the Incomplete Block LU relaxation scheme is shown to possess several optimal conditions, which enables to preserve high efficiency of the multigrid solver on both conformal and nonconformal grids. The developments are done using a parallel MPI algorithm, which can handle multiple numbers of interfaces with multiple block-to-block connectivity.
Hybrid wake model for free vortex viscous-inviscid simulations

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Integrated airfoil and blade design method for large wind turbines

This paper presents an integrated method for designing airfoil families of large wind turbine blades. For a given rotor diameter and a tip speed ratio, optimal airfoils are designed based on the local speed ratios. To achieve a high power performance at low cost, the airfoils are designed with the objectives of high Cp and small chord length. When the airfoils are obtained, the optimum flow angle and rotor solidity are calculated which forms the basic input to the blade design. The new airfoils are designed based on a previous in-house designed airfoil family which was optimized at a Reynolds number of 3 million. A novel shape perturbation function is introduced to optimize the geometry based on the existing airfoils which simplifies the design procedure. The viscous/inviscid interactive code XFOIL is used as the aerodynamic tool for airfoil optimization at a Reynolds number of 16 million and a free-stream Mach number of 0.25 near the tip. Results show that the new airfoils achieve a high power coefficient in a wide range of angles of attack (AOA) and are extremely insensitive to surface roughness. Finally, a full blade analysis using computational fluid dynamics (CFD) and blade element momentum (BEM) technique proves the reliability of the integrated design method. © 2014 Elsevier Ltd.

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Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.983 SNIP 2.687 CiteScore 4.51
Web of Science (2014): Indexed yes
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Scopus rating (2013): SJR 2.066 SNIP 2.767 CiteScore 4.63
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Scopus rating (2012): SJR 1.852 SNIP 2.745 CiteScore 3.97
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Investigation of modified AD/RANS models for wind turbine wake predictions in large wind farm

Average power losses due to multiple wind turbine wakes in the large offshore wind farm is studied in this paper using properly modified k-ω SST turbulence models. The numerical simulations are carried out by the actuator disc methodology implemented in the flow solver EllipSys3D. In these simulations, the influence of different inflow conditions such as wind direction sectors are considered and discussed. Comparisons with measurements in terms of wake speed ratio and the corresponding power outputs show that the modified turbulence models had significant improvements; especially the SST-Csust model reflects the best ability in predicting the wake defect. The investigations of various inflow angles reveal that the agreement between predicted and measured data is improved for the wider sector case than the narrow case because of the wind direction uncertainty.

General information

State: Published
Organisations: Department of Wind Energy, Fluid Mechanics, Nanjing University of Aeronautics and Astronautics
Authors: Tian, L. L. (Intern), Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Zhao, N. (Ekstern)
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Large Eddy Simulation of Turbulent Flows In Wind Energy

This research is devoted to the Large Eddy Simulation (LES), and to lesser extent, wind tunnel measurements of turbulent flows in wind energy. It starts with an introduction to the LES technique associated with the solution of the incompressible Navier-Stokes equations, discretized using a finite volume method. The study is followed by a detailed investigation of the Sub-Grid Scale (SGS) modeling. New SGS models are implemented into the computing code, and the effect of SGS models are examined for different applications. Fully developed boundary layer flows are investigated at low and high Reynolds numbers, and thereafter, the fully-developed infinite wind farm boundary later simulations are performed. Sources of inaccuracy in the simulations are investigated and it is found that high Reynolds number flows are more sensitive to the choice of the SGS model than their low Reynolds number counterparts. Wind tunnel measurements of an airfoil at Reynolds numbers ranging from 40,000 to 400,000 are carried out. The measurements include detailed surface pressure as well as force balance measurements for obtaining the lift, drag and pressure distribution over the airfoil. Measurements are performed in the upstroke and downstroke pitching for angles of attack between $-10^\circ$ and $+25^\circ$ and the static stall hysteresis phenomenon is investigated experimentally. Following the wind tunnel measurements, LES of the airfoil is performed using a numerical wind tunnel for Re=40,000 and Re=100,000 at a range of angles of attack. Laminar-turbulent transition, generation of laminar boundary layer separation, and formation of stall cells are investigated. The simulated airfoil characteristics are validated against measurements. It is concluded that the LES computations and
wind tunnel measurements are in good agreement, should the mesh resolution, numerical discretization scheme, time averaging period, and domain size be chosen wisely. A thorough investigation of the wind turbine wake interactions is also conducted and the simulations are validated against available experimental data from external sources. The effect of several parameters on the wake structures and blade loadings is investigated. In particular, the role of SGS modeling on the flow structures and wind turbine loadings is quantified in great detail. It is found that, for the studied cases (using body-force to represent wind turbines), when a fine mesh is used to capture the tip vortices somewhat accurately, the particular choice of the SGS model is not a determining factor in simulation accuracy. To increase the role of SGS models therefore, one needs to coarsen the computational mesh, which, in return, results in poor wake predictions.

General information
State: Published
Organisations: Department of Wind Energy, Fluid Mechanics
Authors: Chivaee, H. S. (Intern), Sørensen, J. N. (Intern), Mikkelsen, R. F. (Intern), Shen, W. Z. (Intern)
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Large Eddy Simulation, Sub-grid Scale modeling, Atmospheric Boundary Layer, Airfoil Aerodynamics, Wind Turbine Wakes
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Large_Eddy_Simulation_of_Turbulent_Flows_in_Wind_Energy.pdf
Publication: Research › Ph.D. thesis – Annual report year: 2014

Numerical Investigation of Flow Control Feasibility with a Trailing Edge Flap
This paper concerns a numerical study of employing an adaptive trailing edge flap to control the lift of an airfoil subject to unsteady inflow conditions. The periodically varying inflow is generated by two oscillating airfoils, which are located upstream of the controlled airfoil. To establish the control system, a standard PID controller is implemented in a finite volume based incompressible flow solver. An immersed boundary method is applied to treat the problem of simulating a deformable airfoil trailing edge. The flow field is solved using a 2D Reynolds averaged Navier-Stokes finite volume solver. In order to more accurately simulate wall bounded flows around the immersed boundary, a modified boundary condition is introduced in the k-ω turbulence model. As an example, turbulent flow over a NACA 64418 airfoil with a deformable trailing edge is investigated. Results from numerical simulations are convincing and may give some highlights for practical implementations of trailing edge flap to a wind turbine rotor blade.

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Organisations: Department of Wind Energy, Fluid Mechanics
Authors: Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
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Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.24 SNIP 0.373 CiteScore 0.35
Operating wind turbines in strong wind conditions by using feedforward-feedback control

Due to the increasing penetration of wind energy into power systems, it becomes critical to reduce the impact of wind energy on the stability and reliability of the overall power system. In precedent works, Shen and his co-workers developed a re-designed operation schema to run wind turbines in strong wind conditions based on optimization method and standard PI feedback control, which can prevent the typical shutdowns of wind turbines when reaching the cut-out wind speed. In this paper, a new control strategy combing the standard PI feedback control with feedforward controls using the optimization results is investigated for the operation of variable-speed pitch-regulated wind turbines in strong wind conditions. It is shown that the developed control strategy is capable of smoothening the power output of wind turbine and avoiding its sudden showdown at high wind speeds without worsening the loads on rotor and blades.

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State: Published
Organisations: Department of Wind Energy, Fluid Mechanics
Authors: Feng, J. (Intern), Shen, W. Z. (Intern)
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Main Research Area: Technical/natural sciences
Prediction of the wind turbine performance by using BEM with airfoil data extracted from CFD

Blade element momentum (BEM) theory with airfoil data is a widely used technique for prediction of wind turbine aerodynamic performance, but the reliability of the airfoil data is an important factor for the prediction accuracy of aerodynamic loads and power. The airfoil characteristics used in BEM codes are mostly based on 2D wind tunnel measurements of airfoils with constant span. Due to 3D effects, a BEM code using airfoil data obtained directly from 2D wind tunnel measurements will not yield the correct loading and power. As a consequence, 2D airfoil characteristics have to be corrected before they can be used in a BEM code. In this article, we consider the MEXICO (Model EXperiments In
Controlled conditions) rotor where airfoil data are extracted from CFD (Computational Fluid Dynamics) results. The azimuthally averaged velocity is used as the sectional velocity to define the angle of attack and the coefficient of lift and drag is determined by the forces on the blade. The extracted airfoil data are put into a BEM code without further corrections, and the calculated axial and tangential forces are compared to both computations using BEM with Shen's tip loss correction model and experimental data. The comparisons show that the recalculated forces by using airfoil data extracted from CFD have good agreements with the experiment. © 2014 Elsevier Ltd.
Simulation and Prediction of Wakes and Wake Interaction in Wind Farms

The highly turbulent wake and the wake interaction of merging wakes between multiple wind turbines are modelled using Large Eddy Simulation (LES) in a general Navier-Stokes solver. The Actuator Line (AL) technique is employed to model the wind turbines, and the aeroelastic computations are fully coupled with the flow solver. The numerical simulations include the study of the far wake behind a single turbine, three idealised cases of infinitely long rows of turbines and finally three infinite wind farm scenarios with different spacings. The flow characteristics between the turbines, turbine performance, and principal turbulent quantities are examined for the different scenarios. The study focuses on the large coherent structures and movements of the wake behind and between wind turbines. The large coherent structures are analysed using Proper Orthogonal Decomposition (POD). POD constitutes the basis for two proposed dynamic wake models of the turbulent wake deep inside large wind farms. The first model is based on a direct reconstruction using POD, while the other model (REDOMO) is based on an additional reduction by only including the most dominant frequencies. The flow fields derived from the two wake models are assessed and verified by comparing turbine performance and loads to those derived from the flow extracted from the numerical simulations. The most comprehensive model yields excellent agreement for small and intermediate turbine spacing, while the simpler version is unable to resolve the complex dynamics due to severe temporal filtering. The models have difficulties capturing the more extreme and spurious events for larger turbine spacings. The performance is also compared to stochastically generated Mann turbulence, which gives better results for larger spacings. The comparison also reveals how much information should be retained by the POD models to add more value than simply applying homogeneous turbulence as inflow.

General information
State: Published
Organisations: Department of Wind Energy
Authors: Andersen, S. J. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern), Mikkelsen, R. F. (Intern)
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Publication: Research › Ph.D. thesis – Annual report year: 2014

Simulations of the Yawed MEXICO Rotor Using a Viscous-Inviscid Panel Method
In the present work the viscous-inviscid interactive model MIRAS is used to simulate flows past the MEXICO rotor in yawed conditions. The solver is based on an unsteady three-dimensional free wake panel method which uses a strong viscous-inviscid interaction technique to account for the viscous effects inside the boundary layer. Calculated wake velocities have been benchmarked against field PIV measurements, while computed blade aerodynamic characteristics are compared against the load calculated from pressure measurements at different locations along the blade span. Predicted and measured aerodynamic forces are in overall good agreement, however discrepancies appear in the root region which could be related to an underestimation of the rotational effects arising from Coriolis and centrifugal forces.
The predicted wake velocities are generally in good agreement with measurements along the radial as well as the axial traverses performed during the experimental campaign.
Study of tip loss corrections using CFD rotor computations

Tip loss correction is known to play an important role for engineering prediction of wind turbine performance. There are two different types of tip loss corrections: tip corrections on momentum theory and tip corrections on airfoil data. In this paper, we study the latter using detailed CFD computations for wind turbines with sharp tip. Using the technique of determination of angle of attack and the CFD results for a NordTank 500 kW rotor, airfoil data are extracted and a new tip loss function on airfoil data is derived. To validate, BEM computations with the new tip loss function are carried out and compared with CFD results for the NordTank 500 kW turbine and the NREL 5 MW turbine. Comparisons show that BEM with the new tip loss function can predict correctly the loading near the blade tip.
Validation of a three-dimensional viscous-inviscid interactive solver for wind turbine rotors

MIRAS is a newly developed computational model that predicts the aerodynamic behavior of wind turbine blades and wakes subject to unsteady motions and viscous effects. The model is based on a three-dimensional panel method using a surface distribution of quadrilateral singularities with a Neumann no penetration condition. Viscous effects inside the boundary layer are taken into account through the coupling with the quasi-3D integral boundary layer solver Q3UIC. A free-wake model is employed to simulate the vorticity released by the blades in the wake. In this paper the new code is validated against measurements and/or CFD simulations for five wind turbine rotors, including three experimental model rotors [20-22], the 2.5 MW NM80 machine [23] and the NREL 5 MW virtual rotor [24]. Such a broad set of operational conditions and rotor sizes constitutes a very challenging validation matrix, with Reynolds numbers ranging from 5.0·10^4 to 1.2·10^7.

General information
State: Published
Organisations: Department of Mechanical Engineering, Fluid Mechanics, Department of Wind Energy
Authors: Ramos García, N. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
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Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.983 SNIP 2.687 CiteScore 4.51
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Scopus rating (2013): SJR 2.066 SNIP 2.767 CiteScore 4.63
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Validation of the CQU-DTU-LN1 series of airfoils
The CQU-DTU-LN1 series of airfoils were designed with an objective of high lift and low noise emission. In the design process, the aerodynamic performance is obtained using XFOIL while noise emission is obtained with the BPM model. In this paper we present some validations of the designed CQU-DTU-LN118 airfoil by using wind tunnel measurements in the acoustic wind tunnel located at Virginia Tech and numerical computations with the inhouse Q3uic and EllipSys 2D/3D codes. To show the superiority of the new airfoils, comparisons with a NACA64618 airfoil are made. For the aerodynamic features, the designed Cl and Cl/Cd agrees well with the experiment and are in general higher than those of the NACA airfoil. For the acoustic features, the noise emission of the LN118 airfoil is compared with the acoustic measurements and that of the NACA airfoil. Comparisons show that the BPM model can predict correctly the noise changes.

General information
State: Published
Organisations: Department of Wind Energy, Fluid Mechanics, Aeroelastic Design, LM Wind Power, Chongqing University
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Number of pages: 10
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Conference: The science of Making Torque from Wind 2012, Oldenburg, Germany, 09/10/2012 - 09/10/2012
BFI conference series: European Academy of Wind Energy : The Science of Making Torque from Wind (5010078)
Wind farm layout optimization in complex terrain: A preliminary study on a Gaussian hill

One of the crucial problems for wind farm (WF) development is wind farm layout optimization. It seeks to find the optimal positions of wind turbines (WTs) inside a WF, so as to maximize and/or minimize a single objective or multiple objectives, while satisfying certain constraints. Although this problem for WFs in flat terrain or offshore has been investigated in many studies, it is still a challenging problem for WFs in complex terrain. In this preliminary study, the wind flow conditions of
complex terrain without WTs are first obtained from computational fluid dynamics (CFD) simulation, then an adapted
Jensen wake model is developed by considering the terrain features and taking the inflow conditions as input. Using this
combined method, the wake effects of WF in complex terrain are properly modelled. Besides, a random search (RS)
algorithm proposed in previous study is improved by adding some adaptive mechanisms and applied to solve the layout
optimization problem of a WF on a Gaussian shape hill. The layout of the WF with a certain number of WTs is optimized to
maximize the total power output, which obtained steady improvements over expert guess layouts.

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Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.24 SNIP 0.373 CiteScore 0.35
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.253 SNIP 0.344 CiteScore 0.32
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.231 SNIP 0.272 CiteScore 0.25
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.28 SNIP 0.354 CiteScore 0.33
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.292 SNIP 0.352 CiteScore 0.43
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.288 SNIP 0.344
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.253 SNIP 0.321
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.265 SNIP 0.294
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.257 SNIP 0.39
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Web of Science (2006): Indexed yes
Accurate wind turbine aero-acoustics by high-order schemes

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Organisations: Department of Wind Energy, Fluid Mechanics
Authors: Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
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Main Research Area: Technical/natural sciences

Advanced Time Approach of FW-H Equations for Predicting Noise
An advanced time approach of Flowcs Williams-Hawkins (FW-H) acoustic analogy is developed, and the integral equations and integral solution of FW-H acoustic analogy are derived. Compared with the retarded time approach, the transcendental equation need not to be solved in the advanced time approach, on the other hand, computational cost can be saved using the approach due to no demand of pre-storing lots of aerodynamic data. To further validate the efficiency of the advanced time approach for predicting noise, unsteady flow fields are firstly simulated for air around square cylinder and NACA0012 airfoil, then unsteady calculations are used as input for FW-H equations, and numerical predictions are made for noise induced by vortex shedding of square cylinder and NACA0012 airfoil using the advanced time approach. Finally, the retarded time approach and the advanced time approach are compared.

General information
State: Published
Organisations: Department of Wind Energy, Fluid Mechanics, Nanjing University of Aeronautics and Astronautics, China Aerodynamics Research and Development Center
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Scopus rating (2013): SJR 0.293 SNIP 0.559 CiteScore 0.3
ISI indexed (2013): ISI indexed no
Scopus rating (2012): SJR 0.165 SNIP 0.447 CiteScore 0.21
ISI indexed (2012): ISI indexed no
Scopus rating (2011): SJR 0.153 SNIP 0.45 CiteScore 0.24
ISI indexed (2011): ISI indexed no
Analysis of turbulent wake behind a wind turbine

The aim of this study is to improve the classical analytical model for estimation of the rate of wake expansion and the decay of wake velocity deficit in the far wake region behind a wind turbine. The relations for a fully turbulent axisymmetric far wake were derived by applying the mass and momentum conservations, the selfsimilarity of mean velocity profile and the eddy viscosity closure. The theoretical approach is validated using the numerical results obtained from large eddy simulations with an actuator line technique at 0.1% and 3% ambient turbulence level and ambient wind velocity of 10 m/s, and 0.1% ambient turbulence level and ambient wind velocity of 7 m/s. The obtained results showed that neglecting the nonlinear term of velocity in the momentum equation in the far wake region cannot be a fair assumption, unlike what is generally assumed in most of text books of fluid mechanics. Therefore the theoretical determination of the power law for the wake expansion and the decay of the wake velocity deficit may not be valid in the case of the wake generated behind a wind turbine with low ambient turbulence and high thrust coefficient. Although at higher ambient turbulence levels or lower ambient wind velocities (higher thrust coefficients), this trend may be improved due to the faster recovery of the wake and therefore closer values to the theoretical approach may be obtained. In addition, the assumption of self-similarity behavior of the mean velocity profile, when scaled with center line velocity deficit, could be correct in the far wake region of a wind turbine and low ambient turbulence levels.

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Organisations: Department of Mechanical Engineering, Thermal Energy, Department of Wind Energy, Fluid Mechanics
Authors: Kermani, N. A. (Intern), Andersen, S. J. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
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Analysis_of_turbulent_wake_behind.pdf
Publication: Research - peer-review › Article in proceedings – Annual report year: 2013

A Research on Wind Farm Micro-sitting Optimization in Complex Terrain

Wind farm layout optimization in complex terrain is a pretty difficult issue for onshore wind farm. In this article, a novel optimization method is proposed to optimize the layout for wind farms in complex terrain. This method utilized Lissaman and Jensen wake models for taking the terrain height and the wake loss from the upstream turbines into the wind turbine power output calculation. Wind direction is divided into sixteen sections, and the wind speed is processed using the Weibull distribution. The objective is to maximize the total wind farm power output and the free design variables are the wind turbines' park coordinates which subject to the boundary and minimum distance conditions between two wind turbines. A Cross Particle Swarm Optimization (CPSO) method is developed and applied to optimize the layout for a certain wind farm case. Compared with the uniform and experience method, results show that the CPSO method has a higher optimal value, and could be used to optimize the actual wind farm micro-sitting engineering projects.

General information
Development of an AD/RANS model for predicting wind turbine wakes

The wake flow behind a single wind turbine is studied in this paper using the standard k-ω SST turbulence model with three different modifications: (1) adding sustain terms to maintain ambient turbulence level; (2) modifying the coefficients of the turbulence model; (3) combining the first two methods together. The simulations are performed by using the in-house flow solver EllipSys3D coupled with the actuator disc (AD) methodology. The main objective of the proposed model is to control the turbulence decay caused by the intrinsic property of the two-equation turbulence model and further increasing the predicted turbulence intensity through correcting the destruction terms. To validate the proposed method, comparisons are carried out between measurements and other numerical simulations for the Nibe B wind turbine. Results show that the newly developed model can provide satisfactory predictions for the wind speed deficit and the turbulence intensity.

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Organisations: Department of Wind Energy, Fluid Mechanics, Nanjing University of Aeronautics and Astronautics
Authors: Tian, L. (Ekstern), Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Zhao, N. (Ekstern)
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Main Research Area: Technical/natural sciences
Design loads, Spherical joint, Semi floating platform, Mooring system
Links:
http://www.ewea.org/offshore2013/
Publication: Research - peer-review › Article in proceedings – Annual report year: 2013

Development of a Three-Dimensional Viscous-Inviscid coupling Method for Wind Turbine Computations

MIRAS, a computational model for predicting the aerodynamic behavior of wind turbine blades and wakes subject to unsteady motions and viscous effects has been developed. The model is based on a three-dimensional panel method using a surface distribution of quadrilateral singularities with a Neumann no penetration condition. Viscous effects inside the boundary layer are taken into account through the coupling with the quasi-3D integral boundary layer solver Q^3UI.C. A free-wake model is employed to simulate the vorticity released by the blades in the wake. In this paper simulations are presented in an effort to validate the code for three different rotor geometries, the MEXICO experiment rotor, the DELFT rotor and the NREL 5MW rotor.

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Organisations: Department of Wind Energy, Fluid Mechanics
Authors: Ramos García, N. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
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Host publication information
Effect of non-uniform mean flow field on acoustic propagation problems in computational aeroacoustics

Acoustic propagation in the presence of a non-uniform mean flow is studied numerically by using two different acoustic propagating models, which solve linearized Euler equations (LEE) and acoustic perturbation equations (APE). As noise induced by turbulent flows often propagates from near field to far field in a non-quiescent medium, the effect of non-uniform mean flows on the propagation of acoustic waves is important to be considered. In this paper, 4 different non-uniform mean flows are considered. Results show that the non-uniform mean flows can modify both the amplitude and shape of the acoustic waves as compared to the uniform mean flow. From the numerical point of view, the APE model can predict almost the physical behaviors with a difference in amplitude which is dependent on location, as compared to LEE. On the other hand, APE solves one equation less and thus is computationally less expansive.
In this paper, a hybrid immersed boundary technique has been developed for simulating turbulent flows past airfoils with moving trailing-edge flaps. Over the main fixed part of the airfoil, the equations are solved using a standard body-fitted finite volume technique, whereas the moving trailing-edge flap is simulated using the immersed boundary method on a curvilinear mesh. An existing in-house-developed flow solver is employed to solve the incompressible Reynolds-Averaged Navier-Stokes equations together with the k-ω turbulence model. To achieve consistent wall boundary conditions at the immersed boundaries the k-ω turbulence model is modified and adapted to the local conditions associated with the immersed boundary method. The obtained results show that the hybrid approach is an efficient and accurate method for solving turbulent flows past airfoils with a trailing-edge flap and that flow control using an adjustable trailing-edge flap is an efficient way to regulate the aerodynamic loading on airfoils. Copyright © 2012 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved.
This paper presents an integrated method for designing airfoil families of large wind turbine blades. For a given rotor diameter and tip speed ratio, the optimal airfoils are designed based on the local speed ratios. To achieve high power performance at low cost, the airfoils are designed with an objective of high Cp and small chord length. When the airfoils are obtained, the optimum flow angle and rotor solidity are calculated which forms the basic input to the blade design. The new airfoils are designed based on the previous in-house airfoil family which were optimized at a Reynolds number of 3 million. A novel shape perturbation function is introduced to optimize the geometry on the existing airfoils and thus simplify the design procedure. The viscos/inviscid code Xfoil is used as the aerodynamic tool for airfoil optimization where the Reynolds number is set at 16 million with a free-stream Mach number of 0.25 at the blade tip. Results show that these new airfoils achieve high power coefficient in a wide range of angles of attack (AOA) and they are extremely insensitive to surface roughness.

**General information**

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**Organisations:** Department of Wind Energy, Fluid Mechanics

**Authors:** Zhu, W. J. (Intern), Shen, W. Z. (Intern)

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**Host publication information**
Multigrid technique and Optimized Schwarz method on block-structured grids with discontinuous interfaces

An Optimized Schwarz method using Robin boundary conditions for relaxation scheme is presented in the frame of Multigrid method on discontinuous grids. At each iteration the relaxation scheme is performed in two steps: one step with Dirichlet and another step with Robin boundary conditions at inner block boundaries. A Robin parameter that depends on grid geometry and grid discontinuity at block interfaces is introduced. The general solution algorithm is based on SIMPLE method and a conservative finite-volume scheme on block-structured grids with discontinuous interfaces. The multigrid method is used to obtain the solution of pressure-correction equation where an Incomplete Block LU factorization is used as the relaxation scheme. Solution on the coarsest grid is done with an Incomplete Block LU preconditioned Conjugate Gradient method. Results from computations of laminar flows around a circular cylinder on grids with nonmatching interfaces are presented.
Optimization of Wind Farm Layout in Complex Terrain

Microscopic site selection for wind farms in complex terrain is a technological difficulty in the development of onshore wind farms. This paper presented a method for optimizing wind farm layout in complex terrain. This method employed Lissaman and Jensen wake models, took wind velocity distribution law and wake loss between different turbines into consideration and calculated the sheltering area effect of wake loss from upstream wind turbines on downstream wind turbines. Wind direction was divided into sixteen sections, and the wind speed was processed by the Weibull distribution. To calculate the output of each section, we used the wind speed distribution and its probability density as well as the wake loss between wind turbines for every section. The objective function is maximization of the whole wind farm's power output and the free variables are the wind turbines' coordinates which are subject to boundary conditions and minimum distance conditions. The improved genetic algorithm (GA) for real number coding was used to search the optimal result. Then the optimized result was compared to the result from the experienced layout method. Results show the advantages of the present method, and the limitations of the experienced method. © 2013 Chin. Soc. for Elec. Eng.
Prediction of aerodynamic performance for MEXICO rotor

The aerodynamic performance of the MEXICO (Model EXperiments In Controlled cOnditions) rotor at five tunnel wind speeds is predicted by making use of BEM and CFD methods, respectively, using commercial MATLAB and CFD software. Due to the pressure differences on both sides of the blade, the tip-flow will produce secondary flow along the blade, consecutively resulting in decreases of torque. To overcome the above-mentioned issue, a variety of tip-correction models are developed, while most models overestimate the axial and tangential forces. To optimize accuracy, a new correction model summarized from CFD results by Shen is adopted in this paper. In order to accurately simulate the separation point and the separation area which is caused by the adverse pressure gradient, the CFD method using SST turbulence model is used to solve the three-dimensional Reynolds averaged equations. The first order upwind is used for the advection schemes, and the discrete equations are solved with simple algorithms. In addition, uniform velocity and static temperature are given as inlet boundary conditions, and static pressure is given as the circumferential outer boundary condition and the outlet boundary condition. The boundaries of fan-shaped both sides are defined as rotationally periodic connection, and the freeze rotor model is applied at the interface of the rotating and stationary domains, which means the relative position of rotating and stationary domains is fixed when calculating the flow field. Speed no-slip conditions are applied to solid walls such as blades. In this paper, two different meshing methods are used to generate a hexahedral grid for the rotating domain and a tetrahedral grid for stationary domain, between which comparison of the deviation of axial force on 60% blade cross section under the design condition (Vtun=15 m/s) leads to a clear decision of the better mesh method with less deviation. Taking the better mesh method into consideration, the final number of rotating domain grids is calculated according to verification of grid independence, with an amount of 2,961,385. The conclusion of this paper will be illustrated from the following points: first, the comparison of the calculated and the experimental angle of attack distribution along the span direction shows that the maximum relative errors of the attack angle calculated by BEM and CFD respectively are -0.402 and 0.099; it further illustrates that the experimental results are substantially between the results obtained by the two methods, and closer to the result of CFD at the blade tip. Meanwhile, the axial force on the blade increases with increasing radius, while the tangential force shows small change. All of the axial and tangential force in each section increases with increasing wind speed. Additionally, the maximum relative errors of axial force calculated by BEM and CFD respectively are -0.139 and -0.096. In a word, the experimental data are in good agreement with the results calculated by BEM and CFD, confirming the reliability of the MEXICO data. Second, the SST turbulence model can better capture the flow separation on the blade and has high aerodynamic performance prediction accuracy for a horizontal axis wind turbine in axial inflow conditions. Finally, the comparisons of the axial and tangential forces as well as the contrast of the angle of attack indicate that the prediction accuracy of BEM method is high when the blade is not in the stall condition. However, the airfoil characteristic becomes unstable in the stall condition, and the maximum relative error of tangential force calculated by BEM is -0.471. As a result, prediction accuracy of the BEM method needs to be further improved.

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Prediction of the aerodynamic performance of the Mexico rotor by using airfoil data extracted from CFD

Blade Element Momentum (BEM) theory is a widely used technique for prediction of wind turbine aerodynamics performance, but the reliability of airfoil data is an important factor to improve the prediction accuracy of aerodynamic loads and power using a BEM code. The airfoil characteristics used in BEM codes are mostly based on 2D wind tunnel measurements of airfoils with constant span. However, a BEM code using airfoil data obtained directly from 2D wind tunnel measurements will not yield the correct loading and power. As a consequence, 2D airfoil characteristics have to be corrected by using some models before they can be used in a BEM code. In this article, the airfoil data for the MEXICO (Model EXperiments in Controlled cOnditions) rotor are extracted from CFD (Computational Fluid Dynamics) results. The azimuthally averaged velocity is used as the sectional velocity to define the angle of attack and the coefficient of lift and drag is determined by the forces on the blade. The extracted airfoil data are put into a BEM code without corrections of rotational or tip effects, and the calculated axial and tangential forces are compared to both computations using BEM with Shen’s tip loss correction models and experimental data. The comparisons show that the present method of determination of angle of attack is correct, and the re-calculated forces have good agreements with the experiment.

Prediction of wind energy distribution in complex terrain using CFD

Based on linear models, WAsP software predicts wind energy distribution, with a good accuracy for flat terrain, but with a large error under complicated topography. In this paper, numerical simulations are carried out using the FLUENT software on a mesh generated by the GAMBIT and ARGIS software to predict wind speed distribution in complex terrain. TECPLOT
software post-processing is used to get the whole wind flow field, the wind speed distribution characteristics and distribution of wind energy. The obtained results are compared with the results of WAsP software and are also more accordance with the actual conditions.

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Conference: International Conference on aerodynamics of Offshore Wind Energy Systems and wakes (ICOWES 2013), Lyngby, Denmark, 17/06/2013 - 17/06/2013
Wind farm, Complex terrain, Wind energy resources evaluation, CFD numerical simulation

Structural optimization study of composite wind turbine blade
In this paper the initial layout of a 2. MW composite wind turbine blade is designed first. The new airfoils families are selected to design a 2. MW wind turbine blade. The finite element parametric model for the blade is established. Based on the modified Blade Element Momentum theory, a new one-way fluid-structure interaction method is introduced. A procedure combining finite element analysis and particle swarm algorithm to optimize composite structures of the wind turbine blade is developed. The procedure proposed not only allows thickness variation but also permits the spar cap location variation over the structure. The results show that, compared to the initial blade, the mass of the optimized blades is reduced and especially for the scheme II (the location of blade spar cap is seen as one of the variables) which exhibit more mass saving. This present study has important significance for the structural design and optimization of wind turbine blades. © 2012.

General information
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Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 2.418 SNIP 3.474 CiteScore 4.36
Web of Science (2014): Indexed yes
The aerodynamics of wind turbines

In the paper we present state-of-the-art of research in wind turbine aerodynamics. We start be giving a brief historical review and a survey over aerodynamic research in wind energy. Next, we focus on some recent research results obtained by our wind energy group at Department of Mechanical Engineering at DTU. In particular, we show some new results on the classical problem of the ideal rotor and present a series of new results from an on-going research project dealing with the modelling and simulation of turbulent flow structures in the wake behind wind turbines.

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Wind turbine pitch control using ICPSO-PID algorithm

For the traditional simplified first-order pitch-control system model, it is difficult to describe a real dynamic characteristic of a variable pitch action system, thus a complete high order mathematical model has to be developed for the pitch control of wind turbine generation (WTG). In the paper, a pitch controller was designed based on power and wind speed and by considering the inertia and delay characteristics of a pitch-control system to achieve a constant power output when a wind speed was beyond the rated one. A novel ICPSO-PID control algorithm was proposed based on a combination of improved cooperative particle swarm optimization (ICPSO) and PID, subsequently, it was used to tune the pitch controller parameters; thus the difficulty in PID tuning was removed when a wind speed was above the rated speed. It was indicated that the proposed optimization algorithm can tune the pitch controller parameters quickly; and the feed-forward controller for wind speed can improve dynamics of a pitch-control system; additionally the power controller can allow a wind turbine to have a constant power output as a wind speed is over the rated one. Compared with a conventional PID, the controller with ICPSO-PID algorithm has a smaller overshoot, a shorter tuning time and better robustness. The design method proposed in the paper can be applied in a practical electro-hydraulic pitch control system for WTG.

General information

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Actuator line/Navier–Stokes computations for the MEXICO rotor: comparison with detailed measurements

In the European collaborative MEXICO (Model Experiments in Controlled Conditions) project, a series of experiments was carried out on a 4.5 m diameter wind turbine rotor to validate numerical diagnostics tools. Here, some of the measured data are compared with computations of the combined actuator line/Navier–Stokes (AL/NS) model developed at the Technical University of Denmark. The AL/NS model was combined with a large eddy simulation technique and used to compute the flow past the MEXICO rotor in free air and in the DNW German-Dutch wind tunnel for three commonly defined test cases at wind speeds of 10, 15 and 24 m s⁻¹. Two sets of airfoil data were used. Comparisons of blade loadings showed that the AL/NS technique with the modified airfoil data is in better agreement with the measurements than with the original 2D airfoil data. Comparisons of detailed near-wake velocities showed good agreement with the measurements. Computations including the influence of the geometry of the wind tunnel showed that tunnel effects are not significant and the effect of the geometry of the wind tunnel only results in a speedup of 3% at a thrust coefficient of CT = 1.

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Analysis of Mexico wind tunnel measurements: Final report of IEA Task 29, Mexnext (Phase 1)

This report describes the work performed within the first phase of IEA Task 29 Mexnext. In this IEA Task 29 a total of 20 organisations from 11 different countries collaborated in analysing the measurements which have been taken in the EU project ‘Mexico’. Within this Mexico project 9 European institutes carried out a wind tunnel experiment in the Large Low Speed Facility (LLF) of the German DutchWind Facilities DNW on a rotor with a diameter of 4.5 m. Pressure distributions were measured at five location along the blade along with detailed flow field measurements around the rotor plane using stereo PIV.

Comparisons between LES and Wind Tunnel Hot-Wire Measurements

Large-eddy simulations (LES) are carried out for flows over a NACA 0015 airfoil at AoA = 8° and a chord based Reynolds number of 1.71 × 10^6. To accurately simulate the complex flow on the suction side of the airfoil, a reasonably large number of grid points is required. The computational mesh is constructed in a wind tunnel similar to the LM wind tunnel where the experiment for an NACA 0015 airfoil was carried out. The goal of this study is to validate the mixed scale SGS turbulence model against detailed measurements. Simulations are performed with the in-house EllipSys3D code on high performance computers. The stability and accuracy of the LES simulations are studied on various mesh configurations. The spanwise grid spacing is found important to produce correct flow disturbances along the airfoil span, which can affect the turbulent energy distribution.

General information

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Comparisons between LES and wind tunnel hot-wire measurements of a NACA 0015 airfoil

Large-eddy simulations (LES) are carried out for flow over a NACA 0015 airfoil at AoA = 8° and chord based Reynolds number of 1.71106. To accurately simulate the complex flow at the suction side of the airfoil, a reasonably large number of grid points are required. The computational mesh is constructed in a wind tunnel similar as the condition where the experiments were carried out. The goal of this study is to validate the LES model against detailed measurements. The simulations are performed with in-house EllipSys3D code on high performance computers. Numerical study are focused on the stability and accuracy of the LES simulations on various mesh configurations. The spanwise grid spacing was found important to produce correct flow disturbance along the airfoil span, which further affects the turbulent energy distribution.

Control of variable speed pitch-regulated wind turbines in strong wind conditions using a combined feedforward and feedback technique

Due to the increasing penetration of wind energy into power systems, it becomes critical to reduce the impact of wind energy on the stability and reliability of the overall power system. In precedent works, Shen and his co-workers developed a re-designed operation schema to run wind turbines in strong wind conditions based on optimization method and standard PI feedback control, which can prevent the typical shutdowns of wind turbines when reaching the cut-out wind speed. In this paper, a new control strategy combing the standard PI feedback control with feedforward controls using the optimization results is investigated for the operation of variable-speed pitch-regulated wind turbines in strong wind conditions. It is shown that the developed control strategy is capable of smoothening the power output of wind turbine and avoiding its sudden showdown at high wind speeds without worsening the loads on rotor and blades.
Fatigue distribution optimization for offshore wind farms using intelligent agent control

A novel control approach is proposed to optimize the fatigue distribution of wind turbines in a large-scale offshore wind farm on the basis of an intelligent agent theory. In this approach, each wind turbine is considered to be an intelligent agent. The turbine at the farm boundary communicates with its neighbouring downwind turbines and organizes them adaptively into a wind delivery group along the wind direction. The agent attributes and the event structure are designed on the basis of the intelligent agent theory by using the unified modelling language. The control strategy of the intelligent agent is studied using topology models. The reference power of an individual wind turbine from the wind farm controller is re-dispatched to balance the turbine fatigue in the power dispatch intervals. In the fatigue optimization, the goal function is to minimize the standard deviation of the fatigue coefficient for every wind turbine. The optimization is constrained such that the average fatigue for every turbine is smaller than what would be achieved by conventional dispatch and such that the total power loss of the wind farm is restricted to a few percent of the total power. This intelligent agent control approach is verified through the simulation of wind data from the Horns Rev offshore wind farm. The results illustrate that intelligent agent control is a feasible way to optimize fatigue distribution in wind farms, which may reduce the maintenance frequency and extend the service life of large-scale wind farms. Copyright © 2012 John Wiley & Sons, Ltd.

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Investigation of Load Prediction on the Mexico Rotor Using the Technique of Determination of the Angle of Attack

Blade element moment (BEM) is a widely used technique for prediction of wind turbine aerodynamics performance, the reliability of airfoil data is an important factor to improve the prediction accuracy of aerodynamic loads and power using a BEM code. The method of determination of angle of attack on rotor blades developed by SHEN, et al is successfully used to extract airfoil data from experimental characteristics on the MEXICO (Model experiments in controlled conditions) rotor. Detailed surface pressure and particle image velocimetry (PIV) flow fields at different rotor azimuth positions are examined to determine the sectional airfoil data. The present technique uses simultaneously both PIV data and blade pressure data that include the actual flow conditions (for example, tunnel effects), therefore it is more advantageous than other techniques which only use the blade loading (pressure data). The extracted airfoil data are put into a BEM code, and the calculated axial and tangential forces are compared to both computations using BEM with Glauert's and SHEN's tip loss correction models and experimental data. The comparisons show that the present method of determination of angle of attack is correct, and the re-calculated forces have good agreements with the experiment.

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Laminar-Turbulent transition on Wind Turbines

The present thesis deals with the study of the rotational effects on the laminar-turbulent transition on wind turbine blades. Linear stability theory is used to formulate the stability equations that include the effect of rotation. The mean flow required as an input to stability computations is obtained by a similarity transformation technique. This approach allows to transform the boundary layer equations that have included the effect of the Coriolis and centrifugal forces into a set of coupled partial differential equations, that are more convenient to solve numerically.

The solution have been parametrized and adapted to an wind turbine rotor geometry. The blade is resolved in radial sections along which calculations are performed. The obtained mean flow is classified according to the parameters used on the rotating configuration, geometry and operational conditions. The stability diagrams have been obtained by solving the stability equations as an eigenvalue problem. The Keller box Scheme that is second order accurate was used as a numerical method. Have found to be stable and effective in terms of computing time. The solution of the eigenvalue problem provide connection between the parameters used to define the resultant wave magnitude and direction. The propagation of disturbances in the boundary layers in three dimensional flows is relatively a complicated phenomena. The report discusses the available methods and techniques used to predict the transition location. Some common wind turbine airfoils are selected to performe parametrical studies with rotational effects. Finally a wind turbine rotor is used for comparison with transition experiments. The relative motion between the flow and the blade geometry defines the response of the flow to disturbances. Have been found that flow on the suction side of the blade has a stabilizing effect, while on the region from the stagnation point to the rotor plane has a destabilizing effect on the boundary layer. The tendency is that rotational effect stabilize the boundary layer on the wind turbine blade.
Operation Design of Wind Turbines in Strong Wind Conditions

In order to reduce the impact on the electrical grid from the shutdown of MW wind turbines at wind speeds higher than the cut-out wind speed of 25 m/s, we propose in this paper to run the turbines at high wind speeds up to 40 m/s. Two different operation designs are made for both constant speed and variable speed pitch regulated wind turbines. The variable speed design is more suitable for wind turbines to run at very high wind speeds which can help the turbine braking system to stop the turbine at the new "cut-out" wind speed. Reference power, rotational speed and pitch angle have been designed optimally. In order to reduce the possible increased loading, fatigue due to the wind gusts, control strategies have been considered for both constant speed and variable speed pitch regulated wind turbines. The control study shows that the designed controllers can reduce the standard deviations efficiently for wind turbines at some selected wind high speeds.

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Validations and improvements of airfoil trailing-edge noise prediction models using detailed experimental data

This paper describes an extensive assessment and a step by step validation of different turbulent boundary-layer trailing-edge noise prediction schemes developed within the European Union funded wind energy project UpWind. To validate prediction models, measurements of turbulent boundary-layer properties such as two-point turbulent velocity correlations, the spectra of the associated wall pressure fluctuations and the emitted trailing-edge far-field noise were performed in the laminar wind tunnel of the Institute of Aerodynamics and Gas Dynamics, University of Stuttgart. The measurements were carried out for a NACA643-418 airfoil, at Re = 2.5 × 10^6, angle of attack of −6° to 6°. Numerical results of different prediction schemes are extensively validated and discussed elaborately. The investigations on the TNO-Blake noise prediction model show that the numerical wall pressure fluctuation and far-field radiated noise models capture well the measured peak amplitude level as well as the peak position if the turbulence noise source parameters are estimated properly including turbulence anisotropy effects. Large eddy simulation based computational aeroacoustic computations show good agreements with measurements in the frequency region higher than 1 kHz, whereas they over-predict the sound pressure level in the low-frequency region. Copyright © 2011 John Wiley & Sons, Ltd.

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Experimental characterization of airfoil boundary layers for improvement of aeroacoustic and aerodynamic modeling

The present work aims at the characterization of aerodynamic noise from wind turbines. There is a consensus among scientists that the dominant aerodynamic noise mechanism is turbulent boundary trailing edge noise. In almost all operational conditions the boundary layer flow over the wind turbine blades makes a transition from laminar to turbulent. In the turbulent boundary layer eddies are...
created which are a potential noise sources. They are ineffective as noise source on the airfoil surface or in free flow, but when convecting past the trailing edge of the airfoil their efficiency is much increased and audible sound is radiated. We performed measurements of the boundary layer velocity fluctuations and the fluctuating surface pressure field in two different wind tunnels and on three different airfoils. The first wind tunnel is the one of LM Wind Power A/S following the classic concept for aerodynamic wind tunnels with a hard wall test section. Acoustic far field sound measurements are not possible in this tunnel due to the high background noise. The second wind tunnel is owned by Virginia Tech University. The test section has Kevlar walls which are acoustically transparent and it is surrounded by an anechoic chamber. In this experiment the far field sound was measured with a microphone array placed in the anechoic chamber. The measurements were compared to predictions with an analytical model for trailing edge noise. The analytical model is divided into two steps. First the fluctuating velocity field is related to the fluctuating surface pressure field, then the far field trailing edge noise is related to the surface pressure field close to the trailing edge of the airfoil. The data base of measurements was used to evaluate the different parts of the original analytical trailing edge noise model and to improve it, because the predictions gave in general too low far field noise levels. Our main finding is that the acoustic formulations to relate the fluctuating surface pressure field close to the trailing edge of airfoil to the radiated far field sound give excellent results when compared to far field sound measurements with a microphone array and measured surface pressure statistics as input up to a frequency of about 2000-3000Hz. The fluctuating surface pressure field can be measured in a wind tunnel with high background noise due to the high level of the fluctuating surface pressure field. Hence, trailing edge noise can be evaluated by means of measured surface pressure field, even in cases where a direct measurement of trailing edge noise is not possible. This opens up great new vistas, i.e. by testing new airfoils in a standard industrial wind tunnel or by testing new wind turbine rotors in the field. The main difficulty for trailing edge noise modeling is to predict the fluctuating surface pressure field correctly and one uncertainty of the original model was the assumption of isotropic turbulence. This was investigated in the present work and a new model to relate the boundary layer velocity field to the surface pressure field accounting for an anisotropic turbulence spectrum was proposed. The results were very similar compared to the original model and underestimated the measured one point surface pressure spectrum, even though the prediction of the one point velocity spectra was improved.

General information
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Simulation of Moving Trailing Edge Flaps on a Wind Turbine Blade using a Navier-Stokes based Immersed Boundary Method
As the rotor diameter of wind turbines increases, turbine blades with distributed aerodynamic control surfaces promise significant load reductions. Therefore, they are coming into focus in relation to research in academia and industry. Trailing edge flaps are of particular interest in terms of control surfaces. The unsteady flow around such flaps is usually investigated by applying linearized unsteady aerodynamic models or by solving the two dimensional unsteady Reynolds averaged Navier-Stokes equations. The latter method is usually applied in combination with moving or interpolated body conforming meshes. A more flexible method would open up an opportunity to investigate the flow features of complex moving flap geometries in great detail. The immersed boundary method offers this flexibility, as the geometry is represented through the introduction of additional forcing terms in the governing equations. This approach allows for simulation of arbitrary geometries in fixed meshes that do not need to conform to the body geometry. The flow solver EllipSys has previously been extended with a base implementation of an immersed boundary method. The present work developed the necessary tools to handle trailing edge flap geometries in two and three dimensions. Validation cases were
presented for the circular cylinder in a Cartesian mesh topology as well as in a topology similar to a standard body fitted mesh. To simulate trailing edge flaps, a hybrid approach was developed that modeled only the moving flap as an immersed boundary, while the rest of the airfoil was represented by a conventional body-fitted mesh. The results from the hybrid approach were validated against published wind tunnel measurements and improvement over a thin-airfoil based flow model was proven. A load alleviation control in a changing inflow was presented for a divided flap action, i.e. a segmented flap with independent actuation rates. It has been demonstrated that the total flap deflection can be divided into two separate deflections without deteriorating control authority. The results suggested that the combined use of two independent flap actuators was beneficial when dealing with complex inflows. Full scale turbine measurements were presented and indicated that the flap hinge moment provided suitable input for load control. A novel way of using the hinge moment of a moving flap for load alleviation control was presented. Simulations demonstrated the feasibility and robustness of the approach. The hybrid immersed boundary approach proved to be able to handle 3D airfoil sections with span-wise flap gaps. The flow around and in the wake of a deflected flap at a Reynolds number of 1.63 mio was investigated for steady inflow conditions. A control for two span-wise independent flaps was implemented and first load reductions could be achieved. The hybrid method has demonstrated to be a versatile tool in the research of moving trailing edge flaps. The results shall serve as the basis for future investigations of the unsteady flow field around trailing edge flaps.

**General information**

**State:** Published

**Organisations:** Department of Mechanical Engineering, Fluid Mechanics, Department of Wind Energy, Aeroelastic Design

**Authors:** Behrens, T. (Intern), Shen, W. Z. (Intern), Zhu, W. J. (Intern), Sørensen, J. N. (Intern), Sørensen, N. N. (Intern)

**Number of pages:** 131

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**Original language:** English

**Main Research Area:** Technical/natural sciences

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- Source: orbit
- Source-ID: 318958

**Publication:** Research › Ph.D. thesis – Annual report year: 2012

**Quasi-3d aerodynamic code for analyzing dynamic flap response**

A computational model for predicting the aerodynamic behavior of wind turbine airfoil profiles subjected to steady and unsteady motions has been developed. The model is based on a viscous-inviscid interaction technique using strong coupling between the viscous and inviscid parts. The inviscid part is modeled using a panel method whereas the viscous part is modeled by using the integral form of the the laminar and turbulent boundary layer equations and with extensions for 3-D rotational effects. Laminar to turbulent transition can be forced with a boundary layer trip or computed with a modified e9 transition model. Validation of the steady two dimensional version of the code has been carried out against experiments for different airfoil geometries and Reynolds numbers. The unsteady version of the code has been benchmarked against experiments for different airfoil geometries at various reduced frequencies and oscillation amplitudes, and generally a good agreement is obtained. The capability of the code to simulate a trailing edge flap under steady or unsteady flow conditions has been proven. A parametric study on rotational effects induced by Coriolis and centrifugal forces in the boundary layer equations shows that the effect of rotation is to decrease the growth of the boundary layer, delay the onset of separation, and hence increase the lift coefficient and decrease the drag slightly.

**General information**

**State:** Published

**Organisations:** Fluid Mechanics, Department of Mechanical Engineering

**Authors:** Ramos García, N. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)

**Publication date:** Sep 2011

**Publication information**

**Place of publication:** Kgs. Lyngby, Denmark

**Publisher:** Technical University of Denmark (DTU)

**Original language:** English

**Main Research Area:** Technical/natural sciences

**Electronic versions:**

- PhDThesis_NestorRamosGarcia.Library_FB.pdf
- Source: orbit
- Source-ID: 313743

**Publication:** Research › Ph.D. thesis – Annual report year: 2011
Actuator Line/Navier-Stokes Computations for Flows past the Yawed MEXICO Rotor

In the paper the Actuator Line/Navier-Stokes model has been used to simulate flows past the yawed MEXICO rotor. The computed loads as well as the velocity field behind the yawed rotor are compared to detailed pressure and PIV measurements which were carried out in the EU funded MEXICO project. The computed loading follows in general the experimental counterpart in a period of rotation with a slight overprediction on the mean loading which probably is caused by the inaccuracy of the airfoil data. The predicted wake velocity agrees well with the experiments in the near wake region. Computations with the DNW wind tunnel for the yawed rotor are also performed and show that the tunnel effects are very small in the loading and in the near wake field behind the rotor whereas in the far wake region (>1D) the influence becomes important.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Yangzhou University
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Yang, H. (Ekstern)
Publication date: 2011

Design og optimering af vingetipper for vindmøller: Slutrapport

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Aeroelastic Design, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Authors: Sørensen, J. N. (Intern), Shen, W. Z. (Intern), Zhu, W. J. (Intern), Borbye, J. (Intern), Okulov, V. (Intern), Mikkelsen, R. F. (Intern), Gaunaa, M. (Intern), Réthoré, P. M. (Intern), Sørensen, N. N. (Intern)
Number of pages: 10
Publication date: 2011

Determination of the tip vortex trajectory behind the MEXICO rotor

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Gotland University
Authors: Nilsson, K. (Ekstern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Ivanell, S. (Ekstern)
Pages: 94-99
Publication date: 2011
Extraction of airfoil data using PIV and pressure measurements

A newly developed technique for determining the angle of attack (AOA) on a rotating blade is used to extract AOs and airfoil data from measurements obtained during the MEXICO (Model rotor EXperiments in COntrolled conditions) rotor experiment. Detailed surface pressure and Particle Image Velocimetry (PIV) flow fields at different rotor azimuth positions are examined for determining sectional airfoil data. The AOA is derived locally by determining the local circulation from pressure data and subtracting the induction of the bound circulation from the local velocity. The derived airfoil data are compared to 2D data from wind tunnel experiments and XFOIL computations. The comparison suggests that the rotor is subject to severe 3D effects originating from the geometry of the rotor, and explains why the Blade Element Momentum technique with 2D airfoil data over-predicts the loading of the rotor. The extraction technique is verified by employing the derived airfoil characteristics as input to computations using the BEM technique and comparing the calculated axial and tangential forces to the measured data. The comparison also demonstrates that the used technique of determining the AOA is a reliable tool to extract airfoil data from experimental data. Copyright © 2010 John Wiley & Sons, Ltd.
In this paper, the flow/acoustics splitting method for predicting flow-generated noise is further developed by introducing high-order finite difference schemes. The splitting method consists of dividing the acoustic problem into a viscous incompressible flow part and an inviscid acoustic part. The incompressible flow equations are solved by a second-order finite volume code EllipSys2D/3D. The acoustic field is obtained by solving a set of acoustic perturbation equations forced by flow quantities. The incompressible pressure and velocity form the input to the acoustic equations. The present work is an extension of our acoustics solver, with the introduction of high-order schemes for spatial discretization and a Runge–Kutta scheme for time integration. To achieve low dissipation and dispersion errors, either Dispersion-Relation-Preserving (DRP) schemes or optimized compact finite difference schemes are used for the spatial discretizations. Applications and validations of the new acoustics solver are presented for benchmark aeroacoustic problems and for flow over an NACA 0012 airfoil. Copyright © 2010 John Wiley & Sons, Ltd.
Modeling of Airfoil Trailing Edge Flap with Immersed Boundary Method

The present work considers incompressible flow over a 2D airfoil with a deformable trailing edge. The aerodynamic characteristics of an airfoil with a trailing edge flap is numerically investigated using computational fluid dynamics. A novel hybrid immersed boundary (IB) technique is applied to simulate the moving part of the trailing edge. Over the main fixed part of the airfoil the Navier-Stokes (NS) equations are solved using a standard body-fitted finite volume technique whereas the moving trailing edge flap is simulated with the immersed boundary method on a curvilinear mesh. The obtained results show that the hybrid approach is an efficient and accurate method for solving turbulent flows past airfoils with a trailing edge flap and flow control using trailing edge flap is an efficient way to regulate the aerodynamic loading on airfoils.
Q3UIC – A new aerodynamic airfoil tool including rotational effects

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Ramos García, N. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Publication date: 2011

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Electronic versions:
ris-r-1796.pdf
Source: orbit
Source-ID: 313897
Publication: Research › Sound/Visual production (digital) – Annual report year: 2011

Simulation of vortex sound using the viscous/acoustic splitting approach
A numerical viscous/acoustic splitting approach for the calculation of an acoustic field is applied to study the sound generation by a pair of spinning vortices and by the unsteady interaction between an inviscid vortex and a finite length flexible boundary. Based on the unsteady hydrodynamic information from the known incompressible flow field, the perturbed compressible acoustic terms are calculated and compared with analytical solutions. Results suggest that the present numerical approach produces results which are in good agreement with the analytical solutions. The present investigation verifies the applicability of the viscous/acoustic approach to flow structure-acoustic interaction.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Sichuan University, Hong Kong Polytechnic University
Authors: Zheng, T. H. (Ekstern), Tang, S. K. (Ekstern), Shen, W. Z. (Intern)
Pages: 39-56
Publication date: 2011
Main Research Area: Technical/natural sciences

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Journal: Canadian Society for Mechanical Engineering. Transactions
Volume: 35
Issue number: 1
ISSN (Print): 0315-8977
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BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.22 SNIP 0.413 CiteScore 0.42
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.222 SNIP 0.534 CiteScore 0.43
BFI (2014): BFI-level 1
Study on wind turbine arrangement for offshore wind farms

In this paper, the separation distance between two neighboring offshore wind turbines has been carried out by using the Actuator Line/Navier-Stokes technique developed at the Technical University of Denmark (DTU). Under offshore atmospheric conditions, Large Eddy Simulation has been performed for two Tjæreborg 2 MW wind turbines in tandem with separation distances of 4D, 5D, 6D, 7D, 8D and 10D at the design wind speed of 10 m/s. The power performance of the wake turbine showed to be about 23% of the first turbine at a separation distance of 4D while its performance reached about 50% at 7D due to the turbulence mixing. This study hints that the optimal separation distance between neighboring turbines for offshore wind farms should be 7 rotor diameters.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Mikkelsen, R. F. (Intern)
Publication date: 2011
The affect of wind turbine nacelle geometry on near wake structure

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Monash University, Universite de Toulouse
Authors: Sherry, M. (Ekstern), Sheridan, J. (Ekstern), Shen, W. Z. (Intern), LoJacono, D. (Ekstern)
Pages: 106-110
Publication date: 2011

TOPFARM - next generation design tool for optimisation of wind farm topology and operation

The present report is the publishable final activity report for the EU project TOPFARM. The project has been running from 1st December 2007 to 30th November 2010, and has successfully addressed optimization of wind farm topology and control strategy based on aero-elastic modeling of loads as well as of power production as seen in an economical perspective. Crucial factors in this regard are the overall wind climate at the wind farm site, the position of the individual wind turbines, the wind turbine characteristics, the internal wind farm wind climate, the wind turbine control/operation strategy for wind turbines interacting through wakes, various cost models, the optimization strategy and a priori defined constraints imposed on the wind farm topology. In TOPFARM, the object function used in the optimization platform is formulated in economical terms, thus ensuring the optimal balance between capital costs, operation and maintenance costs, cost of fatigue lifetime consumption and power production output throughout the design lifetime of the wind farm. The report describes the project consortium and the project activities, which has been organized in 9 Work Packages. A summary description of the results is given, and reference is made to a large number of publications resulting from the project.

General information
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Number of pages: 95
Publication date: 2011
**Airfoils and method for designing airfoils**

The present invention relates to airfoils and design and design optimization of airfoils, in particular airfoils of rotor blades for wind turbines. One aspect of the invention relates to an airfoil with an external shape provided by an airfoil profile defined by a limited number of parameters, such as a set of parameters. Another aspect of the invention relates to a method for designing an airfoil by means of an analytical airfoil profile, said method comprising the step of applying a conformal mapping to a near circle in a near circle plane, wherein the near circle is at least partly expressed by means of an analytical function, said conformal mapping transforming the near circle in the near circle plane to the airfoil profile in an airfoil plane.

**General information**

State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Department of Physics
Authors: Zhu, W. J. (Intern), Wang, X. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern), Cheng, J. (Intern), Chen, J. (Ekstern)
Publication date: 2010

**Publication information**

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Date: 01/12/2010
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Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 274068
Publication: Research › Patent – Annual report year: 2010

**Coupling analysis of wind turbine blades based on aerelastics and aerodynamics**

The structural dynamic equations of blades were constructed for blades of wind turbines. The vibration velocity of blades and the relative flow velocity were calculated using the structural dynamics model. Based on the BEM (Blade Element Momentum) theory and traditional aerodynamics, the coupling model for wind turbines including the aeroelastic and aerodynamics was developed. Finally, the computation was completed for a 2MW wind turbine. The vibration deflection, speed, acceleration and load of the blades are computed at the rating wind speed. The aerodynamic model of wind turbines becomes more accurate because of the coupling analysis between the vibration speed of blade and the wind speed. The results have very significance to the design of wind turbines.

**General information**

State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Wang, X. (Ekstern), Chen, J. (Ekstern), Zhang, S. (Ekstern), Shen, W. Z. (Intern), Zhu, W. (Ekstern)
Pages: 96-100
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Main Research Area: Technical/natural sciences

**Publication information**

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Scopus rating (2015): SJR 0.166 SNIP 0.329 CiteScore 0.22
Scopus rating (2014): SJR 0.206 SNIP 0.514 CiteScore 0.26
Scopus rating (2013): SJR 0.194 SNIP 0.505 CiteScore 0.27
ISI indexed (2013): ISI indexed no
Scopus rating (2012): SJR 0.218 SNIP 0.729 CiteScore 0.32
Determination of the angle of attack on the Mexico rotor using experimental data

The reliability of airfoil data is an important factor to improve the prediction accuracy of aerodynamic loads and power using a Blade Element Momentum (BEM) code. The method of determination of angle of attack on rotor blades developed by Shen et al. was successfully used to extract airfoil characteristics from experimental data on the MEXICO (Model Experiments in controlled Conditions) rotor. Detailed surface pressure and Particle Image Velocimetry (PIV) flow field at different rotor azimuth positions were examined for determining the sectional airfoil data. It is worthwhile noting that the present technique uses simultaneously both PIV data and blade pressure data that include the actual flow conditions (for example, tunnel effects), so it is advantageous over other techniques that use only the blade loading (pressure data). The extracted airfoil data is put into a BEM code and the calculated axial and tangential forces are compared to those from BEM computations with Glauert's and Shen's tip loss correction models and experimental data. The comparisons show that the present method of determination of AOA is correct, and the recalculated forces have good agreement with the experiment.

Optimization design of blade shapes for wind turbines

For the optimization design of wind turbines, the new normal and tangential induced factors of wind turbines are given considering the tip loss of the normal and tangential forces based on the blade element momentum theory and traditional aerodynamic model. The cost model of the wind turbines and the optimization design model are developed. In the optimization model, the objective is the minimum cost of energy and the design variables are the chord length, twist angle and the relative thickness. Finally, the optimization is carried out for a 2 MW blade by using this optimization design model. The performance of blades is validated through the comparison and analysis of the results. The reduced cost shows that the optimization model is good enough for the design of wind turbines. The results give a proof for the design and research on the blades of large scale wind turbines and also establish the foundation for further research and industrial application of wind turbines. © 2010 Journal of Mechanical Engineering.
General information
State: Published
Organisations: Department of Mechanical Engineering, Fluid Mechanics, Chongqing University
Authors: Chen, J. (Ekstern), Wang, X. (Intern), Shen, W. Z. (Intern), Zhu, W. J. (Intern), Zhang, S. (Ekstern)
Pages: 131-134
Publication date: 2010
Main Research Area: Technical/natural sciences

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Journal: Jixie Gongcheng Xuebao
Volume: 46
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ISSN (Print): 0577-6686
Ratings:
Web of Science (2017): Indexed Yes
Scopus rating (2016): CiteScore 0.88
Scopus rating (2015): CiteScore 0.87
Scopus rating (2014): CiteScore 0.88
Scopus rating (2013): CiteScore 0.91
ISI indexed (2013): ISI indexed no
Scopus rating (2012): CiteScore 0.84
ISI indexed (2012): ISI indexed no
Scopus rating (2011): CiteScore 0.79
ISI indexed (2011): ISI indexed no
Original language: English
Blades of wind turbines, Aerodynamics, Cost of energy, Optimization design
DOIs:
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Source-ID: 269220
Publication: Research - peer-review › Journal article – Annual report year: 2010

Shape optimisation of wind turbine blades

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern)
Pages: 90-92
Publication date: 2010
Main Research Area: Technical/natural sciences

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Journal: Modern Energy Review
Volume: 2
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ISSN (Print): 2041-9570
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ISI indexed (2012): ISI indexed no
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Original language: English
Source: orbit
Source-ID: 270798
Publication: Research › Journal article – Annual report year: 2010

Study of airfoil trailing edge bluntness noise
This paper deals with airfoil trailing edge noise with special focus on airfoils with blunt trailing edges. Two methods are employed to calculate airfoil noise: The flow/acoustic splitting method and the semi-empirical method. The flow/acoustic splitting method is derived from compressible Navier-Stokes equations. It provides us possibilities to study details about noise generation mechanism. The formulation of the semi-empirical model is based on acoustic analogy and then curve-fitted with experimental data. Due to its high efficiency, such empirical relation is used for purpose of low noise airfoil
design or optimization. Calculations from both methods are compared with exist experiments. The airfoil blunt noise is found as a function of trailing edge bluntness, Reynolds number, angle of attack, etc.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
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Publication date: 2010

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Conference: The Science of Making Torque from Wind 2010, Heraklion, Crete, Greece, 01/01/2010
Airfoil trailing edge blunt noise, Aeroacoustics
Electronic versions:
TORQUE 2010 Full paper.pdf
Source: orbit
Source-ID: 265725
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Validation of the actuator line/Navier Stokes technique using mexico measurements
This paper concerns the contribution of DTU MEK in the international research collaboration project (MexNext) within the framework of IEA Annex 29 to validate aerodynamic models or CFD codes using the existing measurements made in the previous EU funded project MEXICO (Model Experiments in Controlled Conditions). The Actuator Line/Navier Stokes (AL/NS) technique developed at DTU is validated against the detailed MEXICO measurements. The AL/NS computations without the DNW wind tunnel with speeds of 10m/s, 15m/s and 24m/s. Comparisons of blade loading between computations and measurements show that AL/NS with original 2D airfoil data over-predicts the blade loads. To take into account the effects on a rotating blade, a set of modified airfoil data is used instead. Comparisons show that AL/NS with modified airfoil data agrees much better (for example, the maximum over prediction at the win speed of 15m/s is decreased from 17% to 8% at 60%R). The discrepancy may be due to severe 3D effects caused essentially by the blade geometry where different types of airfoils are used. Comparisons of detailed near wake velocity show good agreements.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Zhu, W. J. (Intern), Sørensen, J. N. (Intern)
Number of pages: 876
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Publication date: 2010

Host publication information
Title of host publication: The Science of Making Torque from Wind 2010
Main Research Area: Technical/natural sciences
Conference: The Science of Making Torque from Wind 2010, Heraklion, Crete, Greece, 01/01/2010
Rotor aerodynamics, wakes
Source: orbit
Source-ID: 265730
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Aeroacoustic Computations for Turbulent Airfoil Flows
The How-acoustic splitting technique for aeroacoustic computations is extended to simulate the propagation of acoustic waves generated by three-dimensional turbulent flows. In the flow part, a subgrid-scale turbulence model (the mixed model) is employed for the large-eddy simulations. The obtained instantaneous How solution is employed as input for the acoustic part. At low Mach numbers, the differences in scales and propagation speed between the flow and the acoustic field are quite large, and hence different meshes and time steps can be used for the two parts. The model is applied to compute flows past a NACA 0015 airfoil at a Mach number of 0.2 and a Reynolds number of 1.6 x 10(5) for different angles of attack. The flow solutions are validated by comparing lift and drag characteristics with experimental data. The comparisons show good agreements between the computed and measured airfoil lift characteristics for angles of attack up to stall. For the acoustic solutions, predicted noise spectra are validated quantitatively against experimental data. A parametrical study of the noise pattern for flows at angles of attack between 4 and 12 deg shows that the noise level is small for angles of attack below 8 deg, increases sharply from 8 to 10 deg, and reaches a maximum at 12 deg.

General information
Analysis of numerical models for cavitation on 2D hydrofoil

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Fluid Mechanics
Authors: Shin, K. W. (Intern), Andersen, P. (Intern), Shen, W. Z. (Intern)
Publication date: 2009

Host publication information
Title of host publication: Proc. 12th Numerical Towing Tank Symposium
Editor: Bertram, V.
Main Research Area: Technical/natural sciences
Conference: 12th Numerical Towing Tank Symposium, Cortona, Italy, 01/01/2009

Blade optimization for wind turbines

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Chongqing University
Authors: Wang, X. D. (Ekstern), Shen, W. Z. (Intern), Zhu, W. J. (Intern), Sørensen, J. N. (Intern), Chen, J. (Ekstern)
Number of pages: 10
Publication date: 2009

Host publication information
Title of host publication: Proceedings of EWEC 2009
Volume: PO 181
Main Research Area: Technical/natural sciences
Conference: 2009 European Wind Energy Conference and Exhibition, Marseille, France, 16/03/2009 - 16/03/2009

Calculations of Flow around an Airfoil with a Trailing Edge Flap by Use of an Immersed Boundary Method

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Aeroelastic Design, Wind Energy Division, Risø National Laboratory for Sustainable Energy, VESTAS Wind Systems A/S
Authors: Behrens, T. (Ekstern), Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Sørensen, N. N. (Intern), Wedel-Heinen, J. J. (Ekstern)
Publication date: 2009

Host publication information
Title of host publication: EWEC 2009 Proceedings online
Publisher: EWEC
Main Research Area: Technical/natural sciences
Conference: 2009 European Wind Energy Conference and Exhibition, Marseille, France, 16/03/2009 - 16/03/2009
Wind energy, Aeroelastic Design
Electronic versions: 2009_54.pdf
Source: orbit
Source-ID: 241685
Publication: Research › Article in proceedings – Annual report year: 2009
**Computational Aerodynamics and Aeroacoustics for Wind Turbines**

To analyse the aerodynamic performance of wind turbine rotors, the main tool in use today is the 1D-Blade Element Momentum (BEM) technique combined with 2D airfoil data. Because of its simplicity, the BEM technique is employed by industry when designing new wind turbine blades. However, in order to obtain more detailed information of the flow structures and to determine more accurately loads and power yield of wind turbines or cluster of wind turbines, it is required to resort to more sophisticated techniques, such as Computational Fluid Dynamics (CFD). As computer resources keep on improving year by year (about ten times every five years from statistics over the last twenty years), CFD has now become a popular tool for studying the aerodynamics of wind turbines. The present thesis consists of 19 selected papers dealing with the development and use of CFD methods for studying the aerodynamics and aero-acoustics of wind turbines. The papers are written in the period from 1997 to 2008 and numbered according to the list in page v. The work consists of two parts: an aerodynamic part based on Computational Fluid Dynamics and an aero-acoustic part based on Computational Aero Acoustics for wind turbines. The main objective of the research was to develop new computational tools and techniques for analysing flows about wind turbines. A few papers deal with applications of Blade Element Momentum (BEM) theory to wind turbines. In most cases the incompressible Navier-Stokes equations in primitive variables (velocity-pressure formulation) are employed as the basic governing equations. However, since fluid mechanical problems essentially are governed by vortex dynamics, it is sometimes advantageous to use the concept of vorticity (defined as the curl of velocity). In vorticity form the Navier-Stokes equations may be formulated in different ways, using a vorticity-stream function formulation, a vorticity-velocity formulation or a vorticity-potential-stream function formulation. In [1] - [3] two different vorticity formulations were developed for 2D and 3D wind turbine flows. In [4] and [5] numerical techniques for avoiding pressure oscillations were developed when solving the velocity-pressure coupling system in the in-house EllipSys2D/3D code, which originally was developed in a cooperation between DTU (Michelsen, 1992) and Risø (Sørensen, 1995). In [6] – [8] different actuator disc techniques combined with CFD are presented. This includes actuator disc, actuator line and actuator surface techniques, which were developed to simulate flows past one or more wind turbines. In [9] and [10] a tip loss correction method that improves the conventional models was developed for use in combination with BEM or actuator/Navier-Stokes computations. A simple and efficient technique for determining the angle of attack for flow past a wind turbine rotor was developed in [11], and in [12] tunnel wall corrections for wind tunnels with closed or open test sections were developed. The second part of the thesis deals with Computational Aero-Acoustics (CAA). With the spread of wind turbines near urban areas, there is an increasing need for accurate predictions of aerodynamically generated noise. Indeed, noise has become one of the most important issues for further development of wind power, and the ability of controlling and minimising noise emission may be advantageous when competing on the world energy market. To predict generation and propagation of aerodynamic noise, it is required to solve the compressible Navier-Stokes equations. As the scales of the flow and the acoustic waves are quite different (about 1/M, M=Mach number=U/c), it is difficult to resolve them together at the same time. Hardin and Pope proposed a non-linear two-step (viscous incompressible flow and inviscid acoustic perturbation) splitting procedure for computational aero-acoustics that is suitable for both generation and propagation. The advantage of the splitting approach, as compared to the acoustic analogies, is that the source strength is obtained directly and that it accounts for sound radiation as well as scattering. In [13] and [14] an inconsistency in the original formulation of Hardin and Pope 1994 was analysed and a consistent formulation was proposed and applied to laminar flows. An aero-acoustic formulation for turbulent flows was in [15] developed for Large Eddy Simulation (LES), Unsteady Reynolds Averaged Navier-Stokes Simulation (URANS) and Detached Eddy Simulation (DES). In [16] a collocated grid / finite volume method for aero-acoustic computations was developed and implemented in the EllipSys2D/3D code. In [17] and [18] three dimensional flow-acoustic computations were carried out. Finally, the aero-acoustic formulation using high order Finite Difference schemes (Dispersion Relation Preserving (DRP) / Optimized Compact schemes) was developed in [19] and implemented in the EllipSys2D/3D code.

**General information**

State: Published

Organisations: Fluid Mechanics, Department of Mechanical Engineering

Authors: Shen, W. Z. (Intern)

Number of pages: 352

Publication date: 2009

**Publication information**

Place of publication: Kgs. Lyngby, Denmark

Publisher: Technical University of Denmark (DTU)

ISBN (Print): 978-87-89502-87-8

Original language: English

Main Research Area: Technical/natural sciences

wind turbine; rotor aerodynamics; wakes; aeroacoustics; Navier-Stokes equations; vorticity-velocity formulation; SIMPLEC; computational fluid dynamics (CFD); computational aeroacoustics (CAA); flow-acoustic splitting technique; large eddy simulation (LES); actuator disc; actuator line; actuator surface; tip loss correction

Source: orbit

Source-ID: 255206

Publication: Research › Doctoral thesis – Annual report year: 2009
**Determination of the angle of attack on rotor blades**

Two simple methods for determining the angle of attack (AOA) on a section of a rotor blade are proposed. Both techniques consist of employing the Biot-Savart integral to determine the influence of the bound vorticity on the velocity field. In the first technique, the force distribution along the blade and the velocity at a monitor point in the vicinity of the blade are assumed to be known from experiments or CFD computations. The AOA is determined by subtracting the velocity induced by the bound circulation, determined from the loading, from the velocity at the monitor point. In the second method, the full pressure distribution on the blade is assumed to be known and used to determine the local distribution of circulation along the surface contour of the blade. Using the local distribution of circulation to determine the influence of the bound vorticity enables the velocity monitor points to be located closer to the blade, and thus to determine the AOA with higher accuracy. Data from CFD computations for flows past the Tellus 95 kW wind turbine at different wind speeds are used to test both techniques. Comparisons show that the proposed methods are in good agreement with existing techniques. The advantage of the proposed techniques, as compared with existing techniques, is that they can be used to determine the AOA on rotor blades under general flow conditions (e.g., operations in yaw or with dynamic inflow).

**General information**

State: Published  
Organisations: Fluid Mechanics, Department of Mechanical Engineering  
Authors: Shen, W. Z. (Intern), Hansen, M. O. L. (Intern), Sørensen, J. N. (Intern)  
Pages: 91-98  
Publication date: 2009  
Main Research Area: Technical/natural sciences

**Publication information**

Journal: Wind Energy  
Volume: 12  
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ISSN (Print): 1095-4244  
Ratings:  
BFI (2017): BFI-level 2  
Web of Science (2017): Indexed yes  
BFI (2016): BFI-level 2  
Scopus rating (2016): CiteScore 3.37 SJR 1.104 SNIP 2.306  
Web of Science (2016): Indexed yes  
BFI (2015): BFI-level 2  
Scopus rating (2015): SJR 1.196 SNIP 2.086 CiteScore 3.06  
Web of Science (2015): Indexed yes  
BFI (2014): BFI-level 2  
Scopus rating (2014): SJR 1.272 SNIP 3.75 CiteScore 3.42  
Web of Science (2014): Indexed yes  
BFI (2013): BFI-level 2  
Scopus rating (2013): SJR 1.275 SNIP 2.464 CiteScore 2.75  
ISI indexed (2013): ISI indexed yes  
Web of Science (2013): Indexed yes  
BFI (2012): BFI-level 2  
Scopus rating (2012): SJR 1.126 SNIP 2.39 CiteScore 2.36  
ISI indexed (2012): ISI indexed yes  
Web of Science (2012): Indexed yes  
BFI (2011): BFI-level 2  
Scopus rating (2011): SJR 1.024 SNIP 2.718 CiteScore 2.49  
ISI indexed (2011): ISI indexed yes  
Web of Science (2011): Indexed yes  
BFI (2010): BFI-level 2  
Scopus rating (2010): SJR 1.487 SNIP 2.013  
Web of Science (2010): Indexed yes  
BFI (2009): BFI-level 2  
Scopus rating (2009): SJR 1.124 SNIP 1.448  
Web of Science (2009): Indexed yes
Integration study on airfoil profiles for wind turbines

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Chongqing University
Authors: Wang, X. D. (Ekstern), Chen, J. (Ekstern), Shen, W. Z. (Intern), Zhang, S. (Ekstern)
Pages: 211-213
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Main Research Area: Technical/natural sciences

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Journal: Zhongguo Jixie Gongcheng
Volume: 20
Issue number: 2
ISSN (Print): 1004-132X
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Scopus rating (2016): SJR 0.263 SNIP 0.426 CiteScore 0.34
Scopus rating (2015): SJR 0.253 SNIP 0.407 CiteScore 0.33
Scopus rating (2014): SJR 0.298 SNIP 0.724 CiteScore 0.33
Scopus rating (2013): SJR 0.323 SNIP 0.722 CiteScore 0.34
ISI indexed (2013): ISI indexed no
Scopus rating (2012): SJR 0.155 SNIP 0.531 CiteScore 0.2
ISI indexed (2012): ISI indexed no
Scopus rating (2011): SJR 0.147 SNIP 0.543 CiteScore 0.24
ISI indexed (2011): ISI indexed no
Scopus rating (2010): SJR 0.155 SNIP 0.464
Scopus rating (2009): SJR 0.154
Scopus rating (2008): SJR 0.141 SNIP 0
Scopus rating (2007): SJR 0.123 SNIP 0
Scopus rating (2006): SJR 0.117 SNIP 0
Scopus rating (2005): SJR 0.108
Scopus rating (2004): SJR 0.105
Scopus rating (2003): SJR 0.107
Scopus rating (2002): SJR 0.11
Numerical Study on Turbulent Airfoil Noise with High-Order Schemes

High-order finite difference schemes are introduced in the flow/acoustics splitting technique for predicting flow generated noise. The flow equations are solved by a second-order finite volume method whereas the acoustic equations are solved by high-order finite difference schemes. At each time step, the incompressible pressure and velocity form input to the acoustic equations. In this paper, sound generation from a NACA 0012 airfoil in turbulent flow condition is studied. The noise source regions are found at the trailing edge and the strength of the sources is depended on the Reynolds number and the angle of attack.

Shape Optimization of Wind Turbine Blades

This paper presents a design tool for optimizing wind turbine blades. The design model is based on an aerodynamic/aero-elastic code that includes the structural dynamics of the blades and the Blade Element Momentum (BEM) theory. To model the main aero-elastic behaviour of a real wind turbine, the code employs 11 basic degrees of freedom corresponding to 11 elastic structural equations. In the BEM theory, a refined tip loss correction model is used. The objective of the optimization model is to minimize the cost of energy which is calculated from the annual energy production and the cost of the rotor. The design variables used in the current study are the blade shape parameters, including chord, twist and relative thickness. To validate the implementation of the aerodynamic/aero-elastic model, the computed aerodynamic results are compared to experimental data for the experimental rotor used in the European Commission-sponsored project Model Experiments in Controlled Conditions, (MEXICO) and the computed aero-elastic results are examined against the FLEX code for flow post the Tjereborg 2 MW rotor. To illustrate the optimization technique, three wind turbine rotors of different sizes (the MEXICO 25 kW experimental rotor, the Tjareborg 2 MW rotor and the NREL 5 MW virtual rotor) are applied. The results show that the optimization model can reduce the cost of energy of the original rotors, especially for the investigated 2 MW and 5 MW rotors. Copyright (C) 2009 John Wiley & Sons, Ltd.
Simulation of Flow Past Wind Turbines Located on a Hill by a Hybrid Actuator/Navier-Stokes Method

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Mikkelsen, R. F. (Intern)
Number of pages: 10

DOI: 10.1002/we.335
Source: orbit
Source-ID: 253904
Publication: Research - peer-review › Journal article – Annual report year: 2009
The Actuator Surface Model: A New Navier-Stokes Based Model for Rotor Computations

This paper presents a new numerical technique for simulating two-dimensional wind turbine flow. The method, denoted as the 2D actuator surface technique, consists of a two-dimensional Navier-Stokes solver in which the pressure distribution is represented by body forces that are distributed along the chord of the airfoils. The distribution of body force is determined from a set of predefined functions that depend on angle of attack and airfoil shape. The predefined functions are curve fitted using pressure distributions obtained either from viscous-inviscid interactive codes or from full Navier-Stokes simulations. The actuator surface technique is evaluated by computing the two-dimensional flow past a NACA 0015 airfoil at a Reynolds number of $10^6$ and an angle of attack of 10 deg and by comparing the computed streamlines with the results from a traditional Reynolds-averaged Navier-Stokes computation. In the last part, the actuator surface technique is applied to compute the flow past a two-bladed vertical axis wind turbine equipped with NACA 0012 airfoils. Comparisons with experimental data show an encouraging performance of the method.
Aero-Acoustic Computations of Wind Turbines

A high-order finite difference method to predict flow-generated noise is introduced in this thesis. The technique consists of solving the viscous incompressible flow equations and inviscid acoustic equations using an incompressible/acoustic splitting technique. The incompressible flow equations are solved using the in-house flow solver EllipSys2D/3D which is a second-order finite volume code. The acoustic equations are solved using high-order finite difference schemes. The incompressible flow equations and the acoustic equations are solved at the same time levels where the pressure and the velocities obtained from the incompressible equations form the input to the acoustic equations. To achieve low dissipation and dispersion errors, either Dispersion-Relation-Preserving (DRP) schemes or optimized compact finite difference schemes are used for spatial discretizations of the acoustic equations. The acoustic solver consists of numerical schemes from fourth-order up to tenth-order accuracy, the use of different schemes are case dependent. In practice, at high Reynolds numbers when flow becomes turbulent, schemes with the highest order of accuracy are always used to resolve the small waves. For time integration, the classical 4-stage Runge-Kutta scheme is applied. Non-centered high-order schemes at numerical boundaries and high-order filter schemes are also discussed due to their importance. The method was validated against a few test cases and further applied for flows around a cylinder and an airfoil both for laminar and turbulent flows. Results have shown that sound generation is due to the unsteadiness of the flow field and the spectrum of sound has a strong relation with fluctuating forces on the solid body. Flow and acoustic simulation were also carried out for a wind turbine where general trends of sound generation from blades was found.
Aero-Acoustic Modeling using Large Eddy Simulation

The flow-acoustic splitting technique for aero-acoustic computations is extended to simulate the propagation of acoustic waves generated by three-dimensional turbulent flows. In the flow part, a sub-grid-scale turbulence model (the mixed model) is employed for Large-Eddy Simulations. The obtained instantaneous flow solution is employed as input for the acoustic part. At low Mach numbers the differences in scales and propagation speed between the flow and the acoustic field are quite large, hence different meshes and time-steps can be utilized for the two parts. The model is applied to compute flows past a NACA 0015 airfoil at a Mach number of 0.2 and a Reynolds number of for different angles of attack. The flow solutions are validated by comparing lift and drag characteristics to the experiments of Shedhal and Klimas. The comparisons show good agreement between computed and measured airfoil characteristics for angles of attack up to stall.

For the acoustic solutions, predicted noise spectra are validated quantitatively against the experimental data of Brook et al. A parametrical study of the noise pattern for flows at angles of attack between 4 deg and 12 deg shows that the noise level is small for angles of attack below 8 deg, increases sharply from 8 deg to 10 deg and reaches a maximal at 12 deg.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Number of pages: 14
Publication date: 2008

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Title of host publication: Proceedings of The 37th International Congress & Exhibition on Noise Control Engineering : Inter.noise 2008
Place of publication: Shanghai, China
Main Research Area: Technical/natural sciences
Conference: 37th International Congress & Exhibition on Noise Control Engineering : Inter.noise 2008, Shanghai, China, 01/01/2008
Airfoil flow, Computational Aero-Acoustics, flow/acoustics splitting technique
Source: orbit
Source-ID: 228546
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

Analysis of induction near tip

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Aeroelastic Design, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Authors: Mikkelsen, R. F. (Intern), Madsen Aagaard, H. (Intern), Hansen, M. H. (Intern), Shen, W. Z. (Intern), Øye, S. (Intern)
Pages: 11-16
Publication date: 2008

Host publication information
Title of host publication: Research in aeroelasticity EFP-2007
Volume: Risø-R-1649(EN)
Place of publication: Roskilde
Publisher: Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi
Editor: Bak, D. C.
ISBN (Print): 978-87-550-3685-7

Series: Denmark. Forskningscenter Risoe. Risoe-R
Number: 1649(EN)
ISSN: 0106-2840
Multi-Agent Model for Fatigue Control in Large Offshore Wind Farm

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Tongji University, Aalborg University
Authors: Zhao, R. (Ekstern), Su, Y. (Ekstern), Knudsen, T. (Ekstern), Bak, T. (Ekstern), Shen, W. Z. (Intern)
Pages: 71-75
Publication date: 2008

Host publication information
Title of host publication: Proceedings of International Conference on Computational Intelligence and Security
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Publisher: IEEE Computer Society Press
ISBN (Print): 978-0-7695-3508-1
Main Research Area: Technical/natural sciences
Conference: 2008 International Conference on Computational Intelligence and Security, 01/01/2008
DOIs: 10.1109/CIS.2008.131
Source: orbit
Source-ID: 231692
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

Triplet of Helical Vortices

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Center for Fluid Dynamics
Authors: Okulov, V. (Intern), Naumov, I. (Ekstern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Pages: 281-290
Publication date: 2008

Host publication information
Title of host publication: IUTAM Symposium on Hamiltonian Dynamics, Vortex Structures, Turbulence : IUTAM Bookseries
Volume: 6
Publisher: Springer
ISBN (Print): 978-1-4020-6743-3
Main Research Area: Technical/natural sciences
Conference: IUTAM Symposium on Hamiltonian Dynamics, Vortex Structures, Turbulence held in Moscow, 25-30 August, 2006, 01/01/2006
Source: orbit
Source-ID: 208418
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

3D boundary layer study on a rotating wind turbine blade

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Hernández, G. G. M. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 1-8
Publication date: 2007
Actuator surface model for wind turbine flow computations

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, GE Energy Engineering Division
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Zhang, J. (Ekstern)
Publication date: 2007

Host publication information
Title of host publication: Proceedings of European Wind Energy Conference 2007
Main Research Area: Technical/natural sciences
Aero-acoustic modeling using large eddy simulation

The splitting technique for aero-acoustic computations is extended to simulate three-dimensional flow and acoustic waves from airfoils. The aero-acoustic model is coupled to a sub-grid-scale turbulence model for Large-Eddy Simulations. In the first test case, the model is applied to compute laminar flow past a NACA 0015 airfoil at a Reynolds number of 800, a Mach number of 0.2 and an angle of attack of 20 degrees. The model is then applied to compute turbulent flow past a NACA 0015 airfoil at a Reynolds number of 100 000, a Mach number of 0.2 and an angle of attack of 20 degrees. The predicted noise spectrum is compared to experimental data.
Airfoil noise computation use high-order schemes
High-order finite difference schemes with at least 4th-order spatial accuracy are used to simulate aerodynamically generated noise. The aeroacoustic solver with 4th-order up to 8th-order accuracy is implemented into the in-house flow solver, EllipSys2D/3D. Dispersion-Relation-Preserving (DRP) finite difference schemes and optimized high-order compact finite difference schemes are applied for acoustic computation. Acoustic equations are derived using so-called splitting technique by separating the compressible NS equations into viscous (flow equation) and inviscid (acoustic equation) parts. The viscous flow equations are solved using EllipSys2D/3D, the hydrodynamic variables are used as input to the inviscid acoustic equations at same time step.

General information
State: Published
Organisations: Department of Mechanical Engineering, Fluid Mechanics
Authors: Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Publication date: 2007

Analysis of counter-rotating wind turbines
This paper presents a study on the performance of a wind turbine with two counter-rotating (CRWT) rotors. The characteristics of the two counter-rotating rotors are on a 3-bladed Nordtank 500 kW rotor. The analysis has been carried out by using an Actuator Line technique implemented in the Navier-Stokes code EllipSys3D. The analysis shows that the Annual Energy Production can be increased to about 43.5 %, as compared to a wind turbine with a single rotor. In order to determine the optimal settings of the CRWT turbine, parameters such as distance between two rotors and rotational speed have been studied.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Appa Renewable Energy Systems Incorporated
Authors: Shen, W. Z. (Intern), Zakkam, V. A. K. (Ekstern), Sørensen, J. N. (Intern), Appa, K. (Ekstern)
Pages: 9 pages
Publication date: 2007
Main Research Area: Technical/natural sciences
Computational Aero-Acoustic Using High-order Finite-Difference Schemes

In this paper, a high-order technique to accurately predict flow-generated noise is introduced. The technique consists of solving the viscous incompressible flow equations and inviscid acoustic equations using a incompressible/compressible splitting technique. The incompressible flow equations are solved using the in-house flow solver EllipSys2D/3D which is a second-order finite volume code. The acoustic solution is found by solving the acoustic equations using high-order finite difference schemes. The incompressible flow equations and the acoustic equations are solved at the same time levels where the pressure and the velocities obtained from the incompressible equations form the input to the acoustic equations. To achieve low dissipation and dispersion errors, either Dispersion-Relation-Preserving (DRP) schemes or optimized compact finite difference schemes are used for spatial discretizations of the acoustic equations. The classical fourth-order Runge-Kutta time scheme is applied to the acoustic equations for time discretization.

General information
State: Published
Organisations: Department of Mechanical Engineering, Fluid Mechanics
Authors: Zhu, W. J. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Oscillatory instability in a closed cylinder with rotating top and bottom

A numerical investigation of oscillatory instability is presented for axisymmetric swirling flow in a closed cylinder with rotating top and bottom. The critical Reynolds number and frequency of the oscillations are evaluated as function of the
ratio of angular velocities of the bottom and the top. Earlier Linear Stability Analysis (LSA) using the Galerkin spectral method by Gelfgat et al. [Phys. Fluids, 8, 2614-2625 (1996)] revealed that the curve of the critical Reynolds number behaves like an “S” around in the co-rotation branch and around in the counter-rotation branch. Additional finite volume computations, however, did not show a clear “S” behaviour. In order to check the existence of the “S” shape, computations are performed using an axisymmetric finite volume Navier-Stokes code at aspect ratios 1.5 and 2.0. Comparisons with LSA at aspect ratio 1.5 show that the “S” shape does exist. At an aspect ratio, our results show that the critical Reynolds number curve has a “beak” shape in the counter-rotation region and a much wider “S” shape in the co-rotation region. This transformation of the “S” shape is caused by the change in aspect ratio from 1.5 to 2 and therefore the corresponding topological behaviour of the transition is different.
Prediction and reduction of noise from a 2.3 MW wind turbine

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Siemens Wind Power A/S
Authors: Leloudas, G. (Ekstern), Zhu, W. J. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern), Hjort, S. (Ekstern)
Pages: 1-9
Publication date: 2007
Main Research Area: Technical/natural sciences

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Volume: 75
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BFI (2017): BFI-level 1
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 0.45 SJR 0.24 SNIP 0.383
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.24 SNIP 0.373 CiteScore 0.35
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.253 SNIP 0.344 CiteScore 0.32
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.231 SNIP 0.272 CiteScore 0.25
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.28 SNIP 0.354 CiteScore 0.33
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.292 SNIP 0.352 CiteScore 0.43
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.288 SNIP 0.344
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.253 SNIP 0.321
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.265 SNIP 0.294
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.257 SNIP 0.39
Web of Science (2007): Indexed yes
Rotational Effects on wind turbine blades for transition prediction

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Hernández, G. G. M. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Publication date: 2007

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Title of host publication: 3nd PhD Seminar on Europe
Main Research Area: Technical/natural sciences
Conference: 3nd PhD Seminar on Europe, 01/01/2007
Source: orbit
Source-ID: 209516
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

The influence of imperfections on the flow structure of steady vortex breakdown bubbles

General information
State: Published
Organisations: Dynamical systems, Department of Mathematics, Fluid Mechanics, Department of Mechanical Engineering
, Center for Fluid Dynamics
Authors: Brøns, M. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Zhu, W. J. (Intern)
Pages: 453-466
Publication date: 2007
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Fluid Mechanics
Volume: 578
ISSN (Print): 0022-1120
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 2.82 SJR 1.671 SNIP 1.636
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.912 SNIP 1.676 CiteScore 2.57
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.865 SNIP 1.808 CiteScore 2.66
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.894 SNIP 1.915 CiteScore 2.71
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.731 SNIP 1.88 CiteScore 2.47
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Determination of Angle of Attack (AOA) for Rotating Blades

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Hansen, M. O. L. (Intern), Sørensen, J. N. (Intern)
Number of pages: 332
Pages: 205-209
Publication date: 2006

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Place of publication: Berlin Heidelberg
Publisher: Springer Verlag
ISBN (Print): 978-3-540-33865-9
Main Research Area: Technical/natural sciences
Conference: EUROMECH Colloquium 464b Wind Energy, Oldenburg, Germany, 04/10/2005 - 04/10/2005
Electronic versions:
Euromech_shen2006.pdf
Source: orbit
Source-ID: 193618
Effect of Mn-site vacancies on the magnetic entropy change and the Curie temperature of La0.67Ca0.33Mn1-xO3 perovskite

Single-phase polycrystalline samples of La0.67Ca0.33Mn1-xO3 (x = 0.00, 0.02, 0.04, 0.06) have been prepared using the sol-gel method. The structure, magnetocaloric properties and the Curie temperature of the samples with different Mn vacancy concentrations have been investigated. The experimental results show that vacancy doping at the Mn-sites has a significant influence on the magnetic properties of La0.67Ca0.33Mn1-xO3. The Curie temperature decreases monotonically with increasing the Mn-site vacancy concentration x. A remarkable enhancement of the magnetic entropy change has been obtained in the La0.67Ca0.33W0.98O3 sample. The entropy change reaches $\Delta S_M = 3.10 \text{ J kg}^{-1} \text{ K}^{-1}$ at its Curie temperature (264 K) under an applied magnetic field $H = 10 \text{ kOe}$, which is almost the same value as that of pure Gd.
Numerical study of swirling flow in a cylinder with rotating top and bottom

A numerical investigation of oscillatory instability is presented for axisymmetric swirling flow in a closed cylinder with rotating top and bottom. The critical Reynolds number and frequency of the oscillations are evaluated as function of the ratio of angular velocities of the bottom and the top ($\xi=\Omega_{\text{bottom}}/\Omega_{\text{top}}$). Earlier linear stability analysis (LSA) using the Galerkin spectral method by Gelfgat [Phys. Fluids, 8, 2614 (1996)] revealed that the curve of the critical Reynolds number behaves like an "S" around $\xi=0.54$ in the co-rotation branch and around $\xi=-0.63$ in the counter-rotation branch. Additional finite volume computations, however, did not show a clear S behavior. In order to check the existence of the S shape, computations are performed using an axisymmetric finite volume Navier-Stokes code at aspect ratios ($\lambda=H/R$) 1.5 and 2.0. Comparisons with LSA at $\lambda=1.5$ show that the S shape does exist. The S shape of the stability diagram predicted by LSA is thus confirmed by a finite-volume based Navier-Stokes solver. The additional computations at aspect ratio $\lambda=2$ show that the curve of critical Reynolds number has a wider S shape in the co-rotating branch for $\xi$ about 0.7 whereas a sharp "beak" appears in the counter-rotating branch for $\xi$ approximately -0.5.

General information

State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Michelsen, J. (Intern)
Pages: 064102
Publication date: 2006
Main Research Area: Technical/natural sciences

Publication information
Journal: Physics of Fluids
Volume: 18
Issue number: 6
ISSN (Print): 1070-6631
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.16 SJR 1.29 SNIP 1.291
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.366 SNIP 1.278
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.354 SNIP 1.348
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.42 SNIP 1.395
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.215 SNIP 1.356
In the paper we present a correction model for wall interference on rotors of wind turbines or propellers in wind tunnels. The model, which is based on a one-dimensional momentum approach, is validated against results from CFD computations using a generalized actuator disc principle. In the model the exchange of axial momentum between the tunnel and the ambient room is represented by a simple formula, derived from actuator disc computations. The correction model is validated against Navier-Stokes computations of the flow about a wind turbine rotor. Generally, the corrections from the model are in very good agreement with the CFD computations, demonstrating that one-dimensional momentum theory is a reliable way of predicting corrections for wall interference in wind tunnels with closed as well as open cross sections.

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An aerodynamic noise propagation model for wind turbines

A model based on 2-D sound ray theory for aerodynamic noise propagation from wind turbine rotating blades is introduced. The model includes attenuation factors from geometric spreading, sound directivity of source, air absorption, ground deflection and reflection, as well as effects from temperature and airflow. At a given receiver point, the sound pressure is corrected by taking into account these propagation effects. As an overall assumption, the noise field generated by the wind turbine is simplified as a point source placed at the hub height of the wind turbine. This assumption is reasonable, for the receiver is located in the far field, at distances from the wind turbine that are much longer than the diameter of the rotor.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Zhu, W. J. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 129-143
Publication date: 2005
Main Research Area: Technical/natural sciences

Publication information
Journal: Wind Engineering
Volume: 29
Issue number: 2
ISSN (Print): 0309-524X
Ratings:
BFI (2017): BFI-level 1
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.267 SNIP 0.515 CiteScore 0.58
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.369 SNIP 0.632 CiteScore 0.63
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.412 SNIP 1 CiteScore 0.78
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.382 SNIP 1.105 CiteScore 0.62
ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.325 SNIP 1.095 CiteScore 0.56
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.363 SNIP 0.762 CiteScore 0.74
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.379 SNIP 0.655
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.396 SNIP 0.724
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 0.282 SNIP 0.637
Scopus rating (2007): SJR 0.601 SNIP 0.777
Scopus rating (2006): SJR 0.438 SNIP 0.749
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.248 SNIP 0.655
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.235 SNIP 0.835
Modeling of Aerodynamically Generated Noise From Wind Turbines

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Zhu, W. J. (Intern), Heilskov, N. (Intern), Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Pages: 517-528
Publication date: 2005
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Solar Energy Engineering
Volume: 127
Issue number: 4
ISSN (Print): 0199-6231
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.46 SNIP 0.654 CiteScore 1.37
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.759 SNIP 1.024 CiteScore 1.65
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.737 SNIP 1.214 CiteScore 1.75
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.699 SNIP 1.373 CiteScore 1.35
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.546 SNIP 1.024 CiteScore 1.08
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.469 SNIP 1.25 CiteScore 1.01
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.548 SNIP 1.224
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.679 SNIP 1.123
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Tip Loss Correction for Actuator/Navier-Stokes Computations

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern), Mikkelsen, R. F. (Intern)
Pages: 209-213
Publication date: 2005
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Solar Energy Engineering
Volume: 127
Issue number: 2
ISSN (Print): 0199-6231
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.46 SNIP 0.654 CiteScore 1.37
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.759 SNIP 1.024 CiteScore 1.65
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.737 SNIP 1.214 CiteScore 1.75
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.699 SNIP 1.373 CiteScore 1.35
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.546 SNIP 1.024 CiteScore 1.08
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.469 SNIP 1.25 CiteScore 1.01
Tip loss corrections for wind research turbine computations

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering, Risø National Laboratory
Authors: Shen, W. Z. (Intern), Mikkelsen, R. F. (Intern), Sørensen, J. N. (Intern), Bak, C. (Ekstern)
Pages: 457-475
Publication date: 2005
Main Research Area: Technical/natural sciences

Publication information
Journal: Wind Energy
Volume: 8
Issue number: 4
ISSN (Print): 1095-4244
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.37 SJR 1.104 SNIP 2.306
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.196 SNIP 2.086 CiteScore 3.06
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.272 SNIP 3.75 CiteScore 3.42

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Michelsen, J. (Intern), Sørensen, J. N. (Intern)
Pages: 348-366
Publication date: 2004
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Computational Physics
Volume: 196
ISSN (Print): 0021-9991
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed yes
Tip loss correction for actuator / Navier Stokes computations
The new tip loss correction, initially developed for ID BEM computations [1], is now extended to 2D Actuator Disc / Navier-Stokes (AD/NS) computations and 3D Actuator Line / Navier-Stokes (AL/NS) computations. As shown in the paper, the tip loss correction is an important and necessary step for actuator / Navier-Stokes models. Comparisons of the present results with those obtained from a EM code with new tip correction and experimental data show that the tip loss correction is correctly implemented in the actuator / Navier-Stokes models. The results demonstrate also that difference between actuator line and actuator disc based models may increase especially for flows at low tip speed ratio. Since the flows at low...
tip speed ratio are far to be considered as axisymmetrical flows, the actuator disc models that are based on axisymmetrical flow behaviors may not be valid. Keywords: Actuator Disc, Actuator Line, Navier-Stokes equations, Tip loss correction.

Wall Correction Model for Wind Tunnels with Open Test Section
In th paper we present a correction model for wall interference on rotors of wind turbines or propellers in wind tunnels. The model, that is based on a onedimensional momentum approach, is validated against results from CFD computations using a generalized actuator disc principle. Generally, the corrections from the model are in very good agreement with the CFD computations, demonstrating that one-dimensional momentum theory is a reliable way of predicting corrections for wall interference in wind tunnels with closed as well as open cross sections. Keywords: Wind tunnel correction, momentum theory, CFD

An Improved SIMPLEC Method for Steady and Unsteady Flow Computations
A modified SIMPLEC scheme for flow computations on collocated grids has been developed. It is demonstrated that the standard SIMPLEC scheme (1) is inconsistent when applied on collocated grids. Hence, for steady computations the computed solution depends on the velocity underrelaxation parameter fu, whereas the solutions of unsteady computations for small time steps are polluted by unphysical wiggles. A revised scheme is proposed that extends the capability of the SIMPLEC method to cope with collocated grids in a general and consistent way. The efficiency of the new scheme is demonstrated by computing flows past a circular cylinder and an airfoil.
LDA-PIV Diagnostics and 3D Simulation of Oscillating Swirl Flow in a Closed Cylindrical Container

Results on unsteady vortex breakdown are obtained simultaneously using two diagnostics methods: a) determination of velocity fields by particle tracks (Particle Image Velocimeter - PIV), b) determination of velocity fields by Laser Doppler Anemometry (LDA), are presented. The experiments data are in some regimes supplemented by the 3D computations of the incompressible Navier-Stokes equations in cylindrical coordinates. Perfect agreements between calculation and experiment reveal efficiency of both diagnostics method for pulsating vortex breakdown and numerical method for solution to 3D unsteady Navier-Stokes equations.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Naumov, I. (Intern), Okulov, V. L. (Ekstern), Meyer, K. E. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 143-148
Publication date: 2003
Main Research Area: Technical/natural sciences
Recent Development of Non-Linear Aeroacoustic Model for Wind Turbine Computations

A numerical algorithm for simulation of acoustic noise generation, based on collocated grids, has been developed. The approach, that was originally developed using a viscous/inviscid decomposition technique, involved two steps comprising a viscous incompressible flow part and an inviscid acoustic part. On collocated grids the inviscid solution is found to be mesh dependent due to unavoidable extrapolations of the acoustic pressure and density at walls, differing from the case on staggered grid where no extrapolation is needed. The situation is most pronounced when a sharp body is considered. A viscous acoustic algorithm is proposed to overcome the difficulty. The model is currently applied to the problem of an airfoil exposed to a gust and results are compared to the numerical results of Lockard and Morris [AIAA J. 36(6) (1998) 907].

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Michelsen, J. (Intern), Sørensen, J. N. (Intern)
Publication date: 2003

Host publication information
Title of host publication: Proc. European Wind Energy Conference & Exhibition
Publisher: European Wind Energy Association (EWEA)
Edition: CD-ROM
Main Research Area: Technical/natural sciences
Workshop: 2003 European Wind Energy Conference and Exhibition, Madrid, Spain, 16/06/2003 - 16/06/2003
Links:
http://www.ewea.org
Source: orbit
Source-ID: 25649
Publication: Research - peer-review › Article in proceedings – Annual report year: 2003

Study of Tip-loss Using an Inverse 3D Navier-Stokes Method

The tip-correction for airscrews described by Prandtl (1919) and implemented into the Blade Element Momentum (BEM) theory by Glauert (1930), is founded on certain assumptions which the present analysis seeks to overcome. In the paper we propose a method to derive the tip-correction by solving the 3D Navier-Stokes equations combined with the actuator line technique where blade loading is applied using an inverse method. The numerical simulations shows that the method...
captures the tip-correction when comparing with the theories of Prandtl and Goldstein, however, the accuracy of the obtained results reveal that further refinements still is needed. Keywords: Tip-loss; Actuator line; 3D Navier-Stokes methods.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Mikkelsen, R. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern), Michelsen, J. (Intern)
Publication date: 2003

Host publication information
Title of host publication: Proc. European Wind Energy Conference & Exhibition
Place of publication: CD-ROM, www.ewea.org
Publisher: European Wind Energy Association (EWEA)
Main Research Area: Technical/natural sciences
Workshop: 2003 European Wind Energy Conference and Exhibition, Madrid, Spain, 16/06/2003 - 16/06/2003
Links:
http://www.ewea.org
Source: orbit
Source-ID: 25675
Publication: Research - peer-review › Article in proceedings – Annual report year: 2003

Validation of Tip Corrections for Wind Turbine computations
Tip loss effect of rotors plays an important role in predictions of wind turbine performance. Classical tip corrections, based on the Prandtl tip reduction function, including Glauert’s, Wilson & Lissaman’s and De Vries’ corrections are considered in the paper. In the proximity of the tip, these classical models fail to predict the physical behaviour. A new tip correction model is proposed. Comparisons between numerical and experimental data for flows past the NREL combined experiment rotor and the Swedish WG 500 rotor show that only the new model can predict correctly the force in the tip region.

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Mikkelsen, R. (Intern), Sørensen, J. N. (Intern), Bak, C. (Ekstern)
Publication date: 2003

Host publication information
Title of host publication: Proceedings CD-ROM. CD 2
Place of publication: CD-ROM, www.ewea.org
Publisher: European Wind Energy Association (EWEA)
Main Research Area: Technical/natural sciences
Workshop: 2003 European Wind Energy Conference and Exhibition, Madrid, Spain, 16/06/2003 - 16/06/2003
Source: orbit
Source-ID: 25683
Publication: Research - peer-review › Article in proceedings – Annual report year: 2003

Vorticity-velocity formulation of the 3D Navier Stokes equations in cylindrical coordinates

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Hansen, M. O. L. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 29-45
Publication date: 2003
Main Research Area: Technical/natural sciences

Publication information
Volume: 41
ISSN (Print): 0271-2091
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 1.398 SNIP 1.491 CiteScore 2.26
A numerical algorithm for acoustic noise generation is extended to 3D flows. The approach involves two parts comprising a viscous incompressible flow part and an inviscid acoustic part. In order to simulate noise generated from a wind turbine, the incompressible and acoustic equations are written in polar coordinates. The developed algorithm is combined with a so-called actuator-line technique in which the loading is distributed along lines representing the blade forces. Computations are carried out for the 500kW Nordtank wind turbine equipped with three LM19 blades.

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**Aero-acoustic Computations of Wind Turbines**

A numerical algorithm for acoustic noise generation is extended to 3D flows. The approach involves two parts comprising a viscous incompressible flow part and an inviscid acoustic part. In order to simulate noise generated from a wind turbine, the incompressible and acoustic equations are written in polar coordinates. The developed algorithm is combined with a so-called actuator-line technique in which the loading is distributed along lines representing the blade forces. Computations are carried out for the 500kW Nordtank wind turbine equipped with three LM19 blades.

©2001 The American Institute of Aeronautics and Astronautics, Inc. and ASME

**General information**

**State**: Published

**Organisations**: Fluid Mechanics, Department of Mechanical Engineering

**Authors**: Shen, W. Z. (Intern), Michelsen, J. (Intern), Sørensen, J. N. (Intern)

**Pages**: 216-222
Evaluation of the Prandtl Tip Correction for Wind Turbine Computations

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Mikkelsen, R. F. (Intern), Sørensen, J. N. (Intern), Bak, C. (Ekstern)
Publication date: 2002

Host publication information
Title of host publication: Global Windpower Conference and Exhibition
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 62533
Publication: Research - peer-review › Article in proceedings – Annual report year: 2002

Evaluation of Tip Correction Theories

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Mikkelsen, R. F. (Intern), Sørensen, J. N. (Intern), Bak, C. (Ekstern)
Publication date: 2002

Host publication information
Title of host publication: 15th IEA Symposium on the Aerodynamics of Wind Turbines
Place of publication: Sweden
Publisher: FOI Swedish Defence Research Agency
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 62594
Publication: Research › Article in proceedings – Annual report year: 2002

Numerical Modelling of Wind Turbine Wakes

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 393-399
Publication date: 2002
Main Research Area: Technical/natural sciences
Aero-acoustic modelling of low Mach-number flows

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Michelsen, J. (Intern), Sørensen, J. N. (Intern)
Publication date: 2001

Host publication information
Title of host publication: Proceedings of the 2001 European Wind Energy Conference and Exhibition
Aeroacoustic modelling of turbulent airfoil flows

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Fluid Mechanics
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Pages: 1057-1064
Publication date: 2001
Main Research Area: Technical/natural sciences

Publication information
Journal: A I A A Journal
Volume: 39
Issue number: 6
ISSN (Print): 0001-1452
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.58 SJR 0.884 SNIP 1.672
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.883 SNIP 1.756 CiteScore 1.99
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.875 SNIP 1.754 CiteScore 2.28
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.976 SNIP 1.837 CiteScore 2.25
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.949 SNIP 1.911 CiteScore 1.54
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.108 SNIP 1.725 CiteScore 1.44
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.902 SNIP 1.597
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.96 SNIP 1.519
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.014 SNIP 1.388
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.216 SNIP 1.601
Scopus rating (2006): SJR 1.057 SNIP 1.719
Web of Science (2006): Indexed yes
An improved Rhie-Chow interpolation for unsteady flow computations

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Shen, W. Z. (Intern), Michelsen, J. (Intern), Sørensen, J. N. (Intern)
Pages: 2406-2409
Publication date: 2001
Main Research Area: Technical/natural sciences

Publication information
Journal: A I A A Journal
Volume: 39
Issue number: 12
ISSN (Print): 0001-1452
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.58 SJR 0.884 SNIP 1.672
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.883 SNIP 1.756 CiteScore 1.99
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.875 SNIP 1.754 CiteScore 2.28
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.976 SNIP 1.837 CiteScore 2.25
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.949 SNIP 1.911 CiteScore 1.54
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.108 SNIP 1.725 CiteScore 1.44
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.902 SNIP 1.597
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.96 SNIP 1.519
Web of Science (2009): Indexed yes
Modelling and analysis of the flow field around a coned rotor

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Mikkelsen, R. F. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: pp. 1-15
Publication date: 2001
Main Research Area: Technical/natural sciences

Publication Information
Journal: Wind Energy
Volume: Vol. 4
ISSN (Print): 1095-4244
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.37 SJR 1.104 SNIP 2.306
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.196 SNIP 2.086 CiteScore 3.06
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.272 SNIP 3.75 CiteScore 3.42
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.275 SNIP 2.464 CiteScore 2.75
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.126 SNIP 2.39 CiteScore 2.36
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.024 SNIP 2.718 CiteScore 2.49
Modelling of aerodynamically generated noise

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Publication date: 2001

Host publication information
Title of host publication: Proceedings of 14th IEA Symposium on the Aerodynamics of Wind Turbines
Publisher: FFA
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 64210
Publication: Research - peer-review › Article in proceedings – Annual report year: 2001

Yaw analysis using a 3D actuator line model

General information
State: Published
Organisations: Fluid Mechanics, Department of Mechanical Engineering
Authors: Mikkelsen, R. F. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Publication date: 2001

Host publication information
Title of host publication: Proceedings of the 2001 European Wind Energy Conference and Exhibition
Publisher: WIP-Renewable Energies
Main Research Area: Technical/natural sciences
Aeroacoustic Modelling of Airfoils Flows

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Pages: 146-149
Publication date: 1999

Host publication information
Title of host publication: Proceedings of European Wind Energy Conference EWEC '99, Nice
Main Research Area: Technical/natural sciences
Conference: 1999 European Wind Energy Conference and Exhibition, Nice, France, 01/03/1999 - 01/03/1999
Source: orbit
Source-ID: 174864
Publication: Research - peer-review › Article in proceedings – Annual report year: 1999

Aeroacoustic Modelling of Lowspeed Flows

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Pages: 271-289
Publication date: 1999
Main Research Area: Technical/natural sciences

Publication information
Journal: Theoretical and Computational Fluid Dynamics
Volume: 13
ISSN (Print): 0935-4964
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.574 SNIP 0.836 CiteScore 1.42
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.795 SNIP 1.543 CiteScore 1.63
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.972 SNIP 1.637 CiteScore 2.06
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.923 SNIP 1.023 CiteScore 1.29
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.665 SNIP 0.874 CiteScore 0.96
ISI indexed (2012): ISI indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.747 SNIP 1.028 CiteScore 1.04
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.982 SNIP 1.321
Web of Science (2010): Indexed yes
Analysis of a coned rotor using an actuator disc model

General information
State: Published
Organisations: Department of Mechanical Engineering
Authors: Mikkelsen, R. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 119-132
Publication date: 1999

Host publication information
Title of host publication: Proceedings of the 13th IEA Symposium on the Aerodynamics of Wind Turbines
Publisher: Energy Technology Support Unit
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 176240
Publication: Research › Article in proceedings – Annual report year: 1999

Comment on the Aeroacoustic Formulation of Hardin and Pope

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Pages: 141-143
Publication date: 1999
Main Research Area: Technical/natural sciences

Publication information
Journal: AIAA Journal
Volume: 1

Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 2.58 SJR 0.884 SNIP 1.672
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.883 SNIP 1.756 CiteScore 1.99
BFI (2014): BFI-level 1
Computation of Wind Turbine Wakes using Combined Navier-Stokes/Actuator-line Methodology

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 156-159
Publication date: 1999

Host publication information
Title of host publication: Proceedings of European Wind Energy Conference EWEC '99, Nice
Main Research Area: Technical/natural sciences
Conference: 1999 European Wind Energy Conference and Exhibition, Nice, France, 01/03/1999 - 01/03/1999
Source: orbit
Source-ID: 174865
Publication: Research - peer-review › Article in proceedings – Annual report year: 1999
Simulation of a coned rotor using an actuator disc model.

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Mikkelsen, R. (Intern), Sørensen, J. N. (Intern), Shen, W. Z. (Intern)
Pages: 119-132
Publication date: 1999

Host publication information
Title of host publication: Proceedings of 13th IEA Symposium on the Aerodynamics of Wind Turbines, Stockholm, 29-30 November
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 174861
Publication: Research › Journal article – Annual report year: 1999

Analysis of wake states by a full-field Actuator disc model

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Shen, W. Z. (Intern), Munduate, X. (Ekstern)
Pages: 73-88
Publication date: 1998
Main Research Area: Technical/natural sciences

Publication information
Journal: Wind Energy
Volume: 1
ISSN (Print): 1095-4244
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.37 SJR 1.104 SNIP 2.306
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.196 SNIP 2.086 CiteScore 3.06
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.272 SNIP 3.75 CiteScore 3.42
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.275 SNIP 2.464 CiteScore 2.75
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Quasi-3D model for rotating and oscillating airfoil

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Shen, W. Z. (Intern), Sørensen, J. N. (Intern)
Pages: 440-447
Publication date: 1998

Host publication information
Title of host publication: Quasi-3D model for rotating and oscillating airfoil
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 174862
Publication: Research › Article in proceedings – Annual report year: 1998

A coupling finite difference/particle method for the resolution of 2D Navier-Stokes equations in velocity-vorticity form

General information
State: Published
Organisations: Department of Energy Engineering
Authors: Shen, W. Z. (Intern), Loc, T. (Ekstern)
Pages: 97-109
Publication date: 1997
A coupling finite difference/particle method for the resolution of 2D Navier-Stokes equations in velocity-vorticity form

Vortex ring state by full-field actuator disc model

Projects:

Development of an advanced noise propagation model for noise optimization in wind farm
Wind Farm Layout Optimization in Complex Terrain

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

Department of Wind Energy
Fluid Mechanics
Wind turbine loads & control
Resource Assessment Modelling

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

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

Modeling of low frequency noise from wind turbines

Department of Wind Energy
Period: 01/12/2013 → 31/05/2017
Number of participants: 7
Phd Student:
Debertshäuser, Harald (Intern)
Supervisor:
Sørensen, Jens Nørkær (Intern)
Zhu, Wei Jun (Intern)
Main Supervisor:
Shen, Wen Zhong (Intern)
Examiner:
Noise propagation and optimization from wind turbines in wind farm

Department of Wind Energy
Period: 01/12/2013 → 31/08/2014
Number of participants: 4
Phd Student:
Menicocci, Simone (Intern)
Supervisor:
Shen, Wen Zhong (Intern)
Sørensen, Jens Nørkær (Intern)
Main Supervisor:
Zhu, Wei Jun (Intern)

Design of Large wind turbines using fluid-structure coupling technique

Department of Wind Energy
Period: 01/11/2013 → 16/02/2017
Number of participants: 7
Phd Student:
Sessarego, Matias (Intern)
Supervisor:
Ramos García, Néstor (Intern)
Sørensen, Jens Nørkær (Intern)
Main Supervisor:
Shen, Wen Zhong (Intern)
Examiner:
Aagaard Madsen, Helge (Intern)
Madsen, Jesper (Ekstern)
Schepers, Gerard (Ekstern)

Development of Large Eddy Simulation Tools for Simulation of Atmospheric Boundary Layers in Wind Farms

Department of Wind Energy
Period: 01/11/2013 → 07/12/2017
Number of participants: 7
Phd Student:
Dag, Kaya Onur (Intern)
Supervisor:
Shen, Wen Zhong (Intern)
Sørensen, Niels N. (Intern)
Main Supervisor:
Aerodynamic and structural design of wind turbine blades

Department of Wind Energy
Period: 15/06/2012 → 30/09/2016
Number of participants: 4
Phd Student:
Hrgovan, Iva (Intern)
Supervisor:
Berggreen, Christian (Intern)
Sørensen, Jens Nørkær (Intern)
Main Supervisor:
Shen, Wen Zhong (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Research and Development of optimal Wind turbine rotors under offshore wind conditions in China

The scientific objectives of the project are to develop new aerodynamic and structural design tools, and control techniques for optimizing wind turbine rotors for offshore wind energy applications in China. During the past five years, DTU has established a strong research collaboration network with Chinese universities and research institutes in the area of wind energy. The present proposal will further strengthen the collaboration. To develop wind technology under offshore wind conditions in China, it demands the insights of the physics of wind turbine flows under local wind conditions and the development of novel computational techniques that are capable to design and predict the performance of wind turbines.

The goal is to make offshore wind energy production more competitive through fundamental insights into the interaction between atmospheric turbulence and wind turbines. Further, wind turbines under offshore conditions in China can be operated optimally through the design of efficient control systems.

Department of Wind Energy

Fluid Mechanics

Aerodynamic design
Period: 01/04/2012 → 30/06/2017
Number of participants: 4
Acronym: OffWindChina
Project ID: IFD-0603-00506B
Number of related Ph.D. students: 4
Project Manager, organisational:
Sørensen, Jens Nørkær (Intern)
Project Manager, academic:
Zhu, Wei Jun (Intern)
Aagaard Madsen , Helge (Intern)
Project Coordinator:
Shen, Wen Zhong (Intern)

Design of next generation wind turbine rotors

Department of Mechanical Engineering
LM Wind Power
Period: 01/07/2011 → 30/06/2014
Number of participants: 4
Acronym: NextRotor
Project ID: 76206
Project Manager, organisational:
Shen, Wen Zhong (Intern)
Sørensen, Jens Nørkær (Intern)
Zhu, Wei Jun (Intern)
Madsen, Jesper (Ekstern)

**Financing sources**
Source: Forskningsprojekter - Miljø- og Energiministeriet
Name of research programme: Forskningsprojekter - Miljø- og Energiministeriet
Amount: 16,716,501.00 Danish Kroner

**TURBOPT**
The project aims to develop the calculation of energy production and loads on wind turbines by develop and optimize integrated models, which is able to handle the multi-scale phenomena in complex terrain.

Department of Wind Energy
Aeroelastic Design
Fluid Mechanics

Chinese Academy of Sciences
Period: 01/04/2011 → 30/06/2014
Number of participants: 4
Acronym: 43033-4610
Project participant:
Henriksen, Lars Christian (Intern)
Fischer, Andreas (Intern)
Shen, Wen Zhong (Intern)
Project Manager, academic:
Aagaard Madsen , Helge (Intern)

**Simulation of flows past a wind turbine with wind shear using Navier-Stokes based sliding mesh technique**

Department of Wind Energy
Period: 01/02/2011 → 29/09/2014
Number of participants: 7
Phd Student:
Kolmogorov, Dmitry (Intern)
Supervisor:
Sørensen, Jens Nørkær (Intern)
Zhu, Wei Jun (Intern)
Main Supervisor:
Shen, Wen Zhong (Intern)
Examiner:
Zahle, Frederik (Intern)
Bijl, Hester (Ekstern)
Madsen, Jens Ingemann (Ekstern)

**Financing sources**
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD
Aerodynamics and optimization of wind turbines in complex terrain
This is a Sino-Danish collaboration project funded by DSF. The objective of the project is to develop numerical tools to simulate wind turbine flows in complex terrain, and optimize and control wind turbines in complex terrain.

Department of Mechanical Engineering
Period: 01/01/2011 → 31/12/2014
Number of participants: 4
Project Manager, organisational:
Shen, Wen Zhong (Intern)
Project Manager, academic:
Zhu, Wei Jun (Intern)
Sørensen, Jens Nørkær (Intern)
Aagaard Madsen, Helge (Intern)

Financing sources
Source: Forskningsrådene - Andre
Name of research programme: Forskningsrådene - Andre

Simulation and Modelling of Wakes and Wake Interaction in Offshore Wind Farms
Department of Wind Energy
Period: 01/01/2011 → 25/08/2014
Number of participants: 7
Phd Student:
Sarlak Chivaee, Hamid (Intern)
Supervisor:
Mikkelsen, Robert Flemming (Intern)
Shen, Wen Zhong (Intern)
Main Supervisor:
Sørensen, Jens Nørkær (Intern)
Examiner:
Walther, Jens Honore (Intern)
Davidson, Lars (Ekstern)
Olesen, Niels Anker (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.

Simulation and prediction of wakes and wake interaction in wind farms
Department of Wind Energy
Period: 01/06/2010 → 27/01/2014
Number of participants: 7
Phd Student:
Andersen, Søren Juhl (Intern)
Supervisor:
Mikkelsen, Robert Flemming (Intern)
Shen, Wen Zhong (Intern)
Main Supervisor:
Sørensen, Jens Nørkær (Intern)
Examiner:
Mann, Jakob (Intern)
Ivanell, Stefan S. A. (Ekstern)
Meyers, Johan (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: 1/3 FUU, 1/3 inst 1/3 Andet
Experimental characterization of airfoil boundary layers for improvement of aeroacoustic and aerodynamic modelling

Technical University of Denmark
Period: 01/10/2008 → 22/02/2012
Number of participants: 7
Phd Student: Fischer, Andreas (Intern)
Supervisor: Bertagnolio, Franck (Intern)
Shen, Wen Zhong (Intern)
Main Supervisor: Aagaard Madsen, Helge (Intern)
Examiner: Serensen, Jens Nørkær (Intern)
Keith, Graeme (Ekstern)
Roger, Michel (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Risø (Løn)
Project: PhD

Simulation of Moving Trailing Edge Flaps on a Wind Turbine Blade using Navier-Stokes based Immersed Boundary Method

Department of Mechanical Engineering
Period: 15/07/2008 → 21/12/2011
Number of participants: 8
Phd Student: Behrens, Tim (Intern)
Supervisor: Serensen, Jens Nørkær (Intern)
Serensen, Niels N. (Intern)
Wedel-Heinen, Jens Jakob (Ekstern)
Main Supervisor: Shen, Wen Zhong (Intern)
Examiner: Gaunaa, Mac (Intern)
Bijl, Hester (Ekstern)
Davidson, Lars (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Ansat eksternt
Project: PhD

Quasi-3d aerodynamic code for analyzing dynamic flap response

Department of Mechanical Engineering
Period: 01/04/2008 → 28/09/2011
Number of participants: 6
Phd Student: Ramos Garcia, Néstor (Intern)
Supervisor: Shen, Wen Zhong (Intern)
Main Supervisor: Serensen, Jens Nørkær (Intern)
Examiner:
Andersen, Poul (Intern)
Sun, Yuping (Ekstern)
Voutsinas, Spyros (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

3D Modelling of Laminar-Turbulent Transition on Wind Turbine Blades
Department of Mechanical Engineering
Period: 01/12/2005 → 09/11/2011
Number of participants: 6
Phd Student:
Martinez Hernandez, Gabriel Gerardo (Intern)
Supervisor:
Shen, Wen Zhong (Intern)
Main Supervisor:
Sørensen, Jens Nørkær (Intern)
Examiner:
Sørensen, Niels N. (Intern)
Matsubara, Masaharu (Ekstern)
Olesen, Niels Anker (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut/centerfinansieret
Project: PhD

DCAMM
Department of Mechanical Engineering
Period: 01/06/2004 → 07/03/2008
Number of participants: 6
Phd Student:
Zhu, Wei Jun (Intern)
Supervisor:
Sørensen, Jens Nørkær (Intern)
Main Supervisor:
Shen, Wen Zhong (Intern)
Examiner:
Sørensen, Niels N. (Intern)
Ekaterianris, Ioannis A. (Ekstern)
Thomsen, Per Grove (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

VISCWIND (EU) 3-D and dynamic stall modelling
Department of Energy Engineering
Period: 01/01/1996 → …
Number of participants: 3
Project participant:
Hansen, Martin Otto Laver (Intern)
Shen, Wen Zhong (Intern)
Project Manager, organisational:
Activities:

**Wind farm design in complex terrain - the FarmOpt methodology**
Period: 18 Oct 2017
Ju Feng (Invited speaker)
Wen Zhong Shen (Other)
Department of Wind Energy
Fluid Mechanics

**Description**
Invited speaker at the conference on 18th October in the session "Wind Farm Micro Siting".
Degree of recognition: International

**Documents:**
Wind farm design in complex terrain - the FarmOpt methodology _Ju Feng _DTU (2017)

**Related event**
China Wind Power 2017
17/10/2017 → 19/10/2017
Beijing, China
Activity: Talks and presentations › Conference presentations