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CONFERENCE ABSTRACTS

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The Wind Engineering, Energy & Environment (WindEEE) Research Institute, Western University, Canada
University of Wyoming College of Engineering and Applied Science
University of Wyoming Department of Mechanical Engineering

Conference Information

The generation of electricity via wind has grown rapidly, in Europe, in North America, and now worldwide with China having the largest amount of installed capacity of any country in the world. Despite the success of the wind energy industry to date, many challenges still exist including reliability, overall wind farm performance, and offshore wind to name just a few. This conference focus is on addressing those technology developments necessary for wind turbines and wind farms to continue improving. The session topics include Blade manufacturing processes, Blade Materials, Wind Turbine Aerodynamics, Turbine reliability, Structural Design, Wind resource assessment, and Enabling technologies for wind energy integration.

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CONFERENCE ABSTRACTS

(in order of presentation)

Wind Turbine Rotor R&D; an OEM Perspective

Kevin Standish, Siemens (Invited)
Edward Mayda, John Obrecht, Kristian Dixon, Alonso Zamora, Luis Mailly, Ryan Sievers and Manjinder Singh

Rotor blades largely dictate the annual energy production of a wind turbine and the loading levels that all other turbine components must be designed to sustain. Blade design is therefore an area of significant R&D investment for any OEM trying to maintain both profitability and competitiveness. A simple and efficient approach to R&D is necessary to develop successful and reliable products. Examples of simple and efficient R&D practices employed by Siemens are collocated multidisciplinary design teams, advanced numerical optimization tools, the IntegralBlade manufacturing process, smart and effective blade add-ons, and comprehensive testing and validation. This paper offers Siemens' perspectives on Rotor R&D and also lists ways in which the research community can contribute to the advancement of future wind turbine rotors.

Aerodynamic Testing of Unsteady Airfoils

John Strike, University of Wyoming
Michael Hind, Manjinder Singh, Ashli Babbitt, Andrew Magstadt, Pourya Nikoueeyan, and Jonathan Naughton

Wind turbine aerodynamics are largely governed by unsteady flows. While experimental investigations of unsteady airfoils have been conducted for decades, the complexity and cost of the experiments generally limit the resulting information obtained. Researchers at the University of Wyoming Wind Energy Research Center (WERC) have developed an experimental apparatus to investigate the unsteady flows in a 2-D pitching environment. A method to obtain robust and cost effective high temporal resolution pressure measurements from conventional tap-tubing systems utilizing electronically scanning pressure (ESP) modules was implemented. By taking advantage of rapid prototyping technology, airfoils were manufactured quickly at low cost, and high spatial resolution pressure information were obtained due to embedded tubing channels in the airfoils. The flow fields were examined through the use of a dual-laser, dual-camera particle image velocimetry (PIV) system that allowed the full near-field flow structures to be imaged simultaneously. The combination of high resolution pressure measurements and PIV flow field information allowed both the airfoil forces and moments and the causal physics to be examined. This presentation will outline the capabilities developed and some of the challenges incurred in developing and utilizing the unsteady aerodynamic testing system at the University of Wyoming.

Mechanics Challenges in Cost-effective Manufacturing of Composite Turbine Blades

Ramesh Talreja, Texas A&M (Invited)

As the wind turbine blades increase in size, their manufacturing cost becomes increasingly significant part of the total turbine cost. Since the manufacturing technology for the blades is still largely labor intensive, defects are unavoidable. Reducing the defects with measures common in aircraft structures would add unaffordable cost. Therefore the challenge is to allow certain amount of defects by knowing their effects on the blade performance. This presentation will discuss how this challenge translates into mechanics analyses of damage, fatigue and failure of composite materials accounting for defects. An approach to effects of defects will be described where observed defects such as voids are explicitly incorporated and analyzed in an integrated manner along with the composite constituents. A few cases will be considered to illustrate the approach.

Alterations in Aerodynamic Loading on Dynamically Pitching Airfoil

Andrew S. Magstadt, University of Wyoming
Pourya Nikoueeyan, Luiz F. Soares and Jonathan W. Naughton,

The aerodynamic impacts of pitch axis location in dynamically oscillating wind turbine blades have been experimentally investigated. Pitch axis location was varied for multiple flow cases representative of real-world aerodynamics of wind turbines, whose blade's flexural axis is recognized to vary as a function of rotor radius. Unsteady surface pressure data were collected in the University of Wyoming's low-speed wind tunnel, from which changing aerodynamic loading has been determined. As aeroelastic instabilities are becoming an increasing concern with the next generation of turbines, aerodynamic damping is a particular quantity of interest and has been calculated for correlation with pitch axis location.

Variation of pitch axis location led to the following observations: *i)* the sectional moment coefficient increases in magnitude as the pitch axis is positioned closer to the leading edge, *ii)* the aerodynamic damping linearly decreases with aftward position of the pitch axis, suggesting that *iii)* under most circumstances the unsteady flow structures around this airfoil are relatively insensitive to the different pitch axis locations investigated. Negative aerodynamic damping found in particular test configurations reveals the emergence of possible system instabilities, a noteworthy artifact when considering the blade's aeroelastic behavior.

Key Words: Wind Turbine Aerodynamics, Dynamic Stall, Pitch Axis

Increasing Prototype Airfoil Fabrication Efficiency Through Use of Sectional Molds

Adam Karges, University of Wyoming
David E. Walrath

Airfoil development has always been important in the aeronautics industry. Current airfoil development techniques are being applied to design larger and more efficient wind turbine blades. Although complex computational simulation is beneficial for design and scale model sections can be tested in small wind tunnels, a prototype blade must be built and tested to produce full scale test results. Current wing or blade structures are fabricated using traditional molding techniques. These large molds, particularly those used for wind turbine blades, are fabricated from composite materials formed over a master shape. This process can be time and material intensive.

This project develops the techniques and methodology to build larger cavity molds using sectional pieces directly fabricated by computer numerically controlled milling. A cavity in the mold was machined into the tooling foam using computer numerically controlled milling. This process allowed for the creation of the mold without a master airfoil. A major benefit of producing a sectional mold is the ability to create a mold for large airfoils using relatively small milling machines. The employment of several mold sections makes the machining process much easier and allows for smaller, less equipped machine shops to produce larger, previously unfeasible, airfoil molds.

Characterization of Dynamic Stall on 9-12% Thick Airfoils Through Flow-Field and Surface Pressure Measurements

Phillip Davidson, University of Wyoming
John A. Strike, Michael D. Hind, Jay Sitaraman, and Jonathan W. Naughton

Dynamic stall is a complicated phenomenon faced by rotorcraft and wind turbines. By more fully understanding and predicting dynamic stall of helicopters and wind turbines, future designs could be more efficient and reliable, thereby enhancing performance and decreasing the cost of energy. To mimic the unsteadiness that blades experience in a cycle of rotation, a classic airfoil, the NACA 0012, was pitched at different frequencies in a sinusoidal pattern. Pressure data was taken with the pitch angle constant, as well as with an oscillating pitch angle for both the tripped and un-tripped airfoil. Flow-field data were acquired using particle image velocimetry.

The cases studied were based upon what helicopters and wind turbines experience focusing on separated and stalled flow. The experiment delivered the unsteady pressure data and flow field data necessary to calculate force and moment coefficients, vortex movement, separation, and re-attachment. While the un-tripped and tripped static aerodynamic coefficients were quite similar except at the stall angle, the dynamically pitched aerodynamic coefficients were noticeably different throughout the cycle. This data was compared against other experimental results as well as CFD to better understand dynamic stall of thin airfoils.

Automated Manufacturing of High Curvature Blade Geometry via Controlled Deformation of Composite Fabric by Shifting

Siqi Zhu, Iowa State University
Corey J. Magnussen, Matthew C. Frank, and Frank E. Peters

This work presents a novel automated fabric layup solution based on a new method to manipulate fiberglass fabric, referred to as *shifting*, for the layup of non-crimp fabric (NCF) plies. The shifting method is intended for unidirectional fabric, where the fabric is sequentially constrained and then rotated about a deformation angle to approximate curvature. Shifting is done in a 2D plane, making the process easier to control and automate, but can be applied for fabric placement in 3D models; directly, or after a ply kitting process and then manually placed. Preliminary tests have been conducted in order to evaluate the physical plausibility of the shifting method. The layup tests show that shifting can produce layups with accurate two-dimensional geometry while avoiding out-of-plane deformation. In addition, coupon material tests have shown that shifting has minimal impact on the fatigue life and stiffness of fiber glass when the shift angle is small. The intent of the automated layup technique is to pre-form the fabric to approximate shape of the mold by shifting and then depositing the fabric onto the mold. In this way the layup process can be completed with very little human interaction.

Steady and Unsteady Flow Characteristics of Wind Turbine Blades with Gurney Flaps

Pourya Nikoueeyan, University Wyoming
John A. Strike, Andrew S. Magstadt, Michael D. Hind, and Jonathan W. Naughton

The turbulent atmospheric boundary layer imposes significant unsteady aerodynamic conditions on wind turbine blades. This results in unwanted oscillatory loads and accompanying deflections that cause stall, and reduced aerodynamic efficiency. This study addresses the flow control capabilities of the Gurney flap as a fast response, and low cost approach for controlling wind turbine blades. Effects of flap height on the lift and moment coefficients have been explored by integrating time-resolved pressure measurements taken on a DU97-W-300 flatback airfoil at a Reynolds number of 430,000. Data were acquired statically and for three different pre and post stall dynamic regimes caused by oscillating the airfoil at a reduced frequency of 0.14(10Hz). The experimental results for static and dynamic flow conditions show a significant change in lift and moment coefficients because of the Gurney flap implementation. In the moderate and deep stall regimes, the addition of a Gurney flap to the pressure side of the airfoil can significantly increase C_L, although stall behavior is not affected. Implementing a Gurney flap on the suction side can reduce C_L, and significantly change the stall hysteresis pattern. In conclusion, the Gurney flap provides substantial authority for flow control in the pre-stall regimes along with levels of effectiveness in post stall.

Avoiding Waves in Longitudinal Blade Elements via Pre-Shearing of Unidirectional Fabrics

Wade Johans, Iowa State University
Luke Schlanglen, Frank E. Peters, Matthew C. Frank, John K. Jackman

On Optimal Large-Scale Wind Turbine Design

M. Platzer,
N. Sarigul-Klijn, U.C. Davis
J. Young, J.C.S. Lai, University of New South Wales, Canberra

The need to transition from fossil-based power generation to renewable energy systems has led to the construction of wind turbines with rapidly increasing rotor diameters. The question therefore arises whether there is a limit to the scaling up of the current standard rotary wind turbines. For optimal power generation a rectangular flow capture area is preferable to a circular area for kinetic energy conversion in shallow rivers and tidal flows, as demonstrated at the Laval University in Canada and by Pulse Tidal Ltd in the United Kingdom. Their turbines use the oscillating-wing principle whereby a wing is forced to oscillate in a pitch and heave motion with a 90 degree phasing between the two motions. We showed in small prototype tests and in computational analyses that the proper phasing can be obtained aerodynamically, resulting in a robust power extraction device, with efficiencies comparable to modern wind turbines. It is our contention that oscillating-wing power generators have advantages for large-scale wind power generation, arising from the fact that they allow simpler construction, transportation, installation, operation, maintenance and repair.

Simulation of Wind Turbine Wakes

Jens N. Sørensen (Invited)
Department of Wind Energy, Technical University of Denmark

Wind turbines operating in clusters are always subject to the influence wakes of neighboring turbines. As the wake behind a wind turbine has a lower mean wind speed and an increased turbulence level, wake interaction leads to a decreased total power production and increasing fatigue loads. The modeling of wakes can be carried out using models of different levels of complexity. The simplest models assume linearly expanding wakes and are described by simple integral momentum equations, while the most complex models make use of computational fluid dynamics (CFD) and state of the art representations of the rotor blades. For an extensive list of different wake models, the reader is referred to Crespo et al. [1], Vermeer et al. [2] and Sørensen [3]. In the past years, wakes behind wind turbine blades have been extensively studied both experimentally and numerically, using analytical tools as well as numerical simulations based on RANS or LES methodologies combined with actuator disc or line techniques. From these studies it has been shown that wind turbine wakes are inherent unstable and that the flow inside a wind farm both depends on the mixing properties of the turbines as well as on the ambient turbulence and the stability properties of the atmospheric boundary.

In the presentation we describe the ingredients in the modeling of wind turbine wakes, including a general description of the challenges of wake modeling and a description of the various models in use today. Furthermore, we present mechanisms for initial breakdown of the vortex pattern in the near wake and show results from studies of wake interaction and the interaction between wind farms and the atmospheric boundary layer.

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Comparing Computational Methods and Full-Scale Tests for Ultimate Failure of Blades

Kim Branner (Invited)
Department of Wind Energy, Technical University of Denmark
P. Berring, A. Tesauro, M.A. Eder & P.H. Nielsen, Technical University of Denmark

Today, wind turbine blade certification tests are based on flapwise and edgewise loading only. However, some results have indicated that loads in other directions than pure flap- or edgewise may have major importance. A thorough analysis of the behavior of wind turbine blades in different loading direction validated by testing is needed in order to improve their structural design and move the design limits.

These issues are studied in a Danish national funded project "Experimental Blade Research – phase 2". This talk will present recent results from that project with main focus on Finite Element Analysis (FEA) and comparison with full-scale tests for ultimate failure.

The tests presented were performed on a 34m long blade from SSP technology A/S. The blade has been tested ultimately to failure. The blade was tested in a flapwise load direction pressure towards suction, with 30 degree towards trailing edge. In this direction the blades failed at 55% load, with 100% being its load carrying capacity in other load directions.

On the Mechanisms of Wake Meandering in Axial Flow Turbines: Insights Gained by Large-Eddy Simulation

Fotis Sotiropoulos, University of Minnesota (Invited)
Xiaolei Yang and Seokkoo Kang, University of Minnesota

In this talk I will introduce the University of Minnesota ***V****irtual* ***Wi****nd* ***S****imulator* (*VWiS*), a state-of-the-art, multi-resolution, large-eddy simulation (LES) framework for simulating atmospheric turbulence past land-based and offshore wind-farms. I will also present results from a recent application of the *VWiS* aimed at elucidating the physics of wake meandering in axial flow turbines. Turbine-geometry-resolving LES (LES-TR) and LES with actuator disk (AD) and actuator line (AL) models are carried out for an axial flow turbine in a fully-developed turbulent boundary layer. LES-TR reveals very complex large-scale dynamics in the near wake, which appear to influence not only the flow in the immediate vicinity of the turbine but also trigger and dramatically impact the structure and dynamics of meandering motions in the far wake. LES-AD and LES-AL cannot capture these geometry-induced near wake phenomena and are shown to yield far wake dynamics that are qualitatively and quantitatively different than in the actual turbine. I will discuss the implications of these findings for simulating utility-scale wind farms and underscore the need for improving the fidelity of actuator-type models.

Wind Turbine Blade Reliability - Effects of Defects

Douglas S. Cairns, Montana State University (Invited)
Jared W. Nelson, W. Trey Riddle, Montana State University

Modern wind turbines are large, expensive structures. Some are over 60m in length, and failures are expensive. Most premature failures occur at manufacturing defects. Continued development of wind energy necessitates an improved understanding of the effects of defects and what is needed to mitigate premature failures. The DOE sponsored, Sandia led, Blade Reliability Collaborative has been formed to perform comprehensive studies to improve wind turbine blade reliability. One of these studies is to characterize common manufacturing defects, and to establish damage growth and validation tools to quantify wind turbine blade reliability. In this presentation, we propose a probabilistic reliability infrastructure, as well as damage models to understand the progressive damage nature of a defect in wind turbine blades. Uncertainties at all levels of a composite structure, and in the fatigue load spectrum render standard deterministic approaches to structural response evaluations inadequate for reliability estimation. A probabilistic approach for quantifying reliability is developed and presented, consistent with a damage tolerance philosophy for wind turbine blades.

Two models for damage are developed and presented; continuum damage modeling and discrete damage modeling. Examples are given and validated, from laboratory coupons through wind turbine blades.

Simulation of the Flow of Wind-Plant: RANS OpenFoam Solver and Wake Model

Mihaela Popescu, SINTEF
Balram Panjwani, Jon Samseth, Ernst Meese, SINTEF Material and Chemistry, Trondheim, Norway
Jafar Mahmoudi, International Research Institute of Stavanger (IRIS), Stavanger, Norway

The work presented is part of the prediction tools for offshore wind energy generation called "Offwind ToolKit", which is under development. The numerical simulation of plant aerodynamics is developed in two different levels: i) Engineering Level (based on empirical equations); ii) Advanced Level (based on WRF and CFD)

Engineering method uses the Jenson approach, which it is based on velocity deficit approach. CFD approach is carried out using the actuator line technique combined with the 3D Navier Stokes solver and a k-ε turbulence model. Unsteady PisoFoam solver is extended to account for wind turbines, where each turbine is modeled as a sink term in the momentum equation. Turbine modeling is based on actuator line concepts derived from SOWFA code, where each blade of the turbine is represented as a line. The loading on each line/blade of the turbine is estimated with Blade Element Method (BEM). The inputs for the solver are tabulated airfoil aerodynamic data, dimension and height of the wind turbine, wind magnitude and direction. The computation of the CFD and engineering approach is validated for a real wind farm - Lillgrund offshore facility in Sweden/Denmark operated by Vattenfall Vindkraft AB. The simulated power production is compared to the field data and large-eddy simulation. The simulation shows the significant decreases of the power for those turbines that were in the wake.

Benchmarking of Lamina Failure Tests from WWFE-I and WWFE-II With a Three Parameter Micromechanics Based Matrix Failure Theory

Kedar Malusare, University of Wyoming
Ray S. Fertig III

The use of fiber reinforced composites in the wind energy industry is growing rapidly. Owing to their increasing importance, it is critical to develop tools to accurately predict their complex behavior under different loading conditions. However, their heterogeneous microstructure and inherent anisotropy make failure prediction very difficult. Two well-known composite failure benchmarks, World-Wide Failure Exercise – I (WWFE-I) and World-Wide Failure Exercise-II (WWFE-II) compared leading failure theories from around the world with one another and with actual test results. This paper presents a three-parameter micromechanics-based composite failure theory which uses constituent-level stresses to predict matrix-dominated composite failure. A representative volume element (RVE) of the microstructure is used to extract constituent stresses for use with the failure theory. The merit of the failure theory lies in its simplistic calibration which requires just three parameters that can be obtained from three standard composite failure tests (transverse tension, transverse compression and in-plane shear). This theory is benchmarked against lamina failure test data from WWFE-I and WWFE-II and compared with the failure theories that performed comparatively well in WWFE-I and WWFE-II. Our results show that for most of the test cases the predictions of the theory were in close agreement with the test data.

Blade Boundary Layer Response to Convective Atmospheric Boundary Layer Turbulence on a NREL 5MW Wind Turbine Blade with Hybrid URANS-LES

James Brasseur, Penn State University
Ganesh Vijayakumar, Adam Lavely, Balaji Jayaraman, Brent Craven

We study the spatio-temporal changes in blade boundary layer structure in response to the passage of atmospheric boundary layer (ABL) turbulence eddies through the rotor of commercial wind turbines, and the resulting temporal changes in blade surface stress distribution underlying transients in blade loadings. Our

previous studies show that the advective time scales of ABL eddies are multiple blade rotations, and that blade load transients result from large changes in blade angle-of-attack. To quantity eddy-blade interaction events, we developed fully blade-resolved computer simulations for the 3-bladed 5 MW NREL wind turbine rotor using a blended hybrid URANS-SAS-LES within OpenFOAM and embedded within a typical moderately convective clear-air daytime ABL simulated with a low-dissipation spectral solver. To resolve the blade viscous layer and 3D transient attached and separated boundary layers, we apply a new hybrid URANS-LES approach that blends the k-w-SST-SAS URANS model near the blade with well-resolved ABL LES away from the blades. I present preliminary results using a single rotating blade model as a predecessor to full rotor "Cyber Wind Facility" (CWF) calculations in process. These CWF simulations will be used to inform corresponding actuator line models currently under development to improve predictive accuracy and to quantify wake-turbine interactions.

Strength Distribution Comparison of Aerospace and Wind Energy Carbon Fiber Reinforced Epoxy

Eric Jensen, University of Wyoming
Ray S. Fertig III

As wind turbines continue to grow in size, the wind energy industry increasingly looks to carbon fiber composites as a way to meet demanding weight and stiffness requirements. In general, wind energy carbon fiber tends to be large-tow standard-modulus carbon fiber manufactured as economically as possible. This focus has the potential to produce properties and property distributions unique to wind energy material. Unfortunately, limited distribution data is available and even less addresses behavior unique to the wind energy industry. In this study 90° off-axis tensile strength distributions were measured from micro-tensile tests performed on wind energy and aerospace preimpregnated carbon/epoxy. This data is important for predicting reliability of components and highlights any unique characteristics of wind energy material that must be taken into consideration during the design process. In addition, specimen microstructures were imaged using fluorescent optical microscopy to identify microstructural defects which may influence the strength distributions. This could lead to the identification of processing parameters which could improve reliability of wind turbines in the future.

On Turbine-Turbine Interactions Subject to Atmospheric Boundary-Layer Inflow - The Effect of Various Actuator-Line Approaches

Sven Schmitz, Penn State University
Pankaj K. Jha, Penn State University
Matthew J. Churchfield and Patrick J. Moriarty, National Renewable Energy Laboratory

The objective of this study is to investigate how different volumetric body-force projection techniques within an actuator-line wind turbine rotor model affect the wake characteristics and blade loads in a turbine-turbine interaction problem. Three techniques for the body-force projection width are used that are based on either i) the grid spacing, ii) the actual blade chord, or iii) an equivalent elliptic blade planform. Recent work by the authors has shown that method iii) predicts sectional blade loads at a higher accuracy when compared to measured data. Here an array of two NREL 5-MW turbines separated by seven rotor diameters is simulated within an OpenFOAM-based large-eddy simulation (LES) solver subject to neutral and moderately- convective atmospheric boundary-layer inflow typical of flat terrain. Preliminary results of computed power histories and selected Reynolds stresses in the turbine wakes suggest that time- varying blade loads and wake turbulence statistics reveal a measurable sensitivity to the way in which the body-force projection width is determined along the blades. The findings from this work will be applied to detailed comparisons against fully blade-resolved computations within the “Cyber Wind Facility” (CWF) to further improve all actuator-type methods for both wake and blade loading predictions in wind plants.

Facilities for In-Situ and Dynamic Testing of Residential Wind Turbine Blades

Charles Schmidt, University of Wyoming
David E. Walrath

A high altitude test facility for studying residential wind power generation on the high plains provides a resource for engineers, scientists, and residents to study the potential for renewable power generation. Development, implementation, and maintenance protocols for a residential-scale wind turbine blade testing platform have been developed. The facility will accommodate interchangeable turbine blades, different blade instrumentation, and calculation platforms for analyzing turbine performance. A Kestrel e400nb wind turbine installed in an off-grid configuration was demonstrated to be a viable platform for baseline power production and for comparison to future tests. Using documented wind conditions the Wind Energy Research Center meteorological tower and turbine production levels demonstrate the potential to annually produce 9,000 kWh of electricity for a single wind turbine. Test methods and procedures are defined for sustainable use of this turbine as a viable test platform and an example for potentially larger-scale turbine test facilities.

Study of Wake of Two Rotor System

A.R. Sudhamshu, Amrita Vishwavidyapeetham
C.P. Manik, M. Vivek, and V. Ratnakishore, Amrita Vishwavidyapeetham

The paper studies the performance of Horizontal axis wind turbine, NREL Phase VI turbine in the wake of another wind turbine. Also wake-wake interaction is studied. The different configurations of two rotor systems are 5R , 5R,R (offset coaxially) and 3R, where R is the radius of the rotor are used. The performance parameters considered are the power developed and the thrust experienced. The study is benchmarked against NREL Phase VI wind turbine on a single rotor system. The same method is used to study two rotor system. Contour of velocity magnitude is obtained for the vertical position of blade on a plane passing through blade for all three configurations. Reduction in power loss due to offsetting the wind turbine as a consequence of wake is observed. Also, closer the downstream turbine is to the upstream turbine, lower will be the extent of wake convection. This study may be extended to different offset distances so as to obtain optimal distance which can be useful for micro siting

Key words- *NREL, Pitch angle, Wake-effect, Micro siting , SST k-ω*

Relating the Stability of the Atmospheric Boundary Layer to Fluctuating Surface Pressure Statistics

Gregory Lyons, University of Mississippi
Nathan E. Murray, University of Mississippi

Wind resource assessment and power output forecasting could be improved by knowledge of stability, but determination from nacelle-based measurements of TKE has proven to be unreliable. Here we present the statistics of turbulent surface-pressure fluctuations as a complimentary method for assessing atmospheric stability. In the atmospheric boundary layer, the fluctuating pressure equation includes three distinct sources: turbulence self-interactions, turbulence interactions with the mean shear, and buoyancy fluctuations. Therefore, by definition, atmospheric stability will affect the relative contributions of the mean-shear and buoyancy terms to the fluctuating pressure. An analysis of these contributions is performed using field data collected over a 44-hour period at Reese Technology Center, located in the Llano Estacado mesa region of West Texas. Pressure measurements were made with a 60-meter array of 96 piezoelectric bimorphs designed for atmospheric infrasound sensing. Profiles of wind velocity, temperature, humidity, and barometric pressure were recorded simultaneously at eight elevations by a 200-meter meteorological tower. The statistical characteristics of the surface pressure and their relationship to atmospheric stability are presented, and physical mechanisms for these observations are discussed. The results lead to suggestions for methods of predicting stability from surface pressures.

Promotion of Wind Energy in Germany Consequences Arising out of the EEG-Report 2011

Rainald Kasprik, University of Heilbronn

According to scientific evidence, the EU and other industrialized regions must reduce domestic greenhouse gas emissions by 25%-40% identified by the IPCC to give us a 50% chance of avoiding the 2°C temperature rise. In Germany, the Act on granting priority to renewable energy sources (Renewable Energy Sources Act – EEG), brought into effect in 2000, revised in 2004, 2008 and 2012, brought a tremendous increase of installed wind energy plants (2000: 6.097 MW; 2012: 31.315 MW [31.035 MW on-shore, 280 MW off-shore]).

The EEG-Report 2011, written by experts for the federal government, showed the benefits and shortcomings of EEG 2008 (http://dip21.bundestag.de/dip21/btd/17/060/1706085.pdf). The presentation will concentrate on the most important findings and the lessons learned from German experience in the field of wind energy integration.

Key Words: *Promotion of Wind Energy in Germany, Renewable Energy Sources Act, incentive policies*

Structural Design of Adhesive Joints for Wind Turbine Rotor Blades - On the Use of Cohesive Laws

Bent F. Sørensen (Invited)
Department of Wind Energy, Technical University of Denmark

Most wind turbine rotor blades are made of several parts joined by adhesives bonds. A relative new way of designing adhesive joints is by the use of cohesive laws. A cohesive law is a traction-separation law that describes the fracture process zone. Cohesive laws constitute a new type of material law that incorporates both strength and fracture energy and can thus be used for the modeling of both crack initiation and propagation. The approach requires both experimental characterizing of cohesive laws of a given adhesive joint and the implementation of cohesive laws in modeling tools such as finite element models.

The presentation will review some of the still existing challenges, such as the accurate determination of mixed mode cohesive laws from experiments and the gab between real cohesive laws measured experimentally and idealized cohesive laws used in finite element software packages.

A critical issue of the cohesive law approach is the testing of whether the approach is capable of making accurate strength predictions of larger structures from cohesive laws determined from test specimens. The presentation will present examples of such studies and will give an overview of the potential use of cohesive laws for adhesive joints in wind turbine blades.

High Fidelity Analysis and Optimization of Wind Turbine Blades

Asitav Mishra, University of Wyoming
Dimitri Mavriplis, Karthik Mani, Jay Sitaraman

A tightly coupled aero-elastic simulation capability is described that uses a moving and deforming unstructured mesh Reynolds-averaged Navier Stokes capability coupled to a beam structural model to simulate aeroelastic rotating blade systems. At each time step, the coupled aero-elastic problem is solved using a number of outer coupling iterations where each coupling consists of partially converging the flow equations, computing the beam deflection due to aerodynamic forces, and solving the mesh deformation equations. Further, each coupling iteration involves solution information transfer between each of these components that form the whole coupling formulation. The analysis formulation is utilized as an effective tool to analyze a model wind turbine (NREL 5MW) rotor system with slender flexible blades. The formulation successfully resolves the aero-elastic behavior of the wind turbine rotor, both qualitatively and quantitatively. An aero-structural blade shape optimization capability is also described based on an adjoint approach that efficiently computes the sensitivities of the fully coupled aeroelastic analysis problem to performance objectives.

Testing Composites For Wind Turbine Blades

Lars P. Mikkelsen (Invited)
Department of Wind Energy, Technical University of Denmark

Opposite aerospace structures, the load carrying part of a wind turbine blade is essentially made of uni-directional fiber reinforced polymer. This is due to the fact that the main design criteria designing a wind turbine blade are the material stiffness and fatigue properties in the axial direction of the blade. Testing high strength unidirectional composites in the fiber direction is a major challenge. A challenge due to the high tensile-compressive strength compared with the 10-20 times lower shear strength and a challenge even more pronounced during fatigue loading of the material. Together with the fact that the axial loading in the gauge section are introduced into the test coupons though shear loading in the tap section special attention performing the tests are required. In the presented study, these challenges have been addressed comparing results from finite element simulations with experimental measurements using thermography, digital image correlation and acoustic emission. Experimental techniques making it possible exploring local material deformation and failure mechanism during material testing. The experimental techniques are used for statically as well as fatigue loading. In addition to these results, prediction of the compressive strength of unidirectional composites is presented using an advanced non-linear composite material law.

Understanding the Flow Dynamics of Turbulent Wake of Wind Turbine

Mithu Debnath, U. Texas, San Antonio
Kiran Bhaganagar, U. Texas, San Antonio
Fazle Hussain, Texas Tech University, Lubbock, TX

Large Eddy Simulation (LES) has been used to simulate two in-line tall, multi-megawatt 3-blade wind turbines (WT) in unstable atmospheric boundary layer (ABL). The results have revealed the initial spiral vortex shed by rotating blades of the WT breakdown to smaller scale structures. It is clear that turbulent wake is dominated by the competing roles of stratification, shear, turbulence and wind turbines. To get a better understanding of the individual roles of these physical processes, we conduct the following idealized numerical experiments: (i) include only uniform wind speed without effects of walls, shear or buoyancy generated turbulence, (ii) include uniform shear, (iii) include shear generated turbulence. The numerical experiments clarify the effect of shear and turbulence on vortex evolution and dynamics in the wake-region of single WT in neutral ABL.

Experimental Assessments and Analysis of Steel Fibre/Polyester Composites - Interface and Compression Failures

R.T. Durai Prabhakaran, Hans Lilholt, Lars P. Mikkelsen, and Bent F. Sørensen
Department of Wind Energy, Technical University of Denmark

Steel fibre reinforced polyester composites are having good scope for future industrial research in developing advanced engineering structures. The composite performances will mainly depend on the constituents and its interface design. The present work describes various trials performed experimentally with the unidirectional (UD) steel fibre/polyester composites. The main objective of this experimental investigation was to study the failure behavior of steel fibre reinforced polyester composites during in-plane compression loading at macro level, followed by another experimental study i.e. fibre/matrix interface characterization at micro level. The failure phenomena were observed by a high speed camera imaging under compression loadings. The results were analyzed in terms of various failure modes, such as elastic micro buckling of steel fibres, delamination of fabric layers from a polymer matrix, and matrix cracks due to poor interface debonding. At micro level, the fibre/matrix interface characteristics were studied by pullout test method. The experimental tool developed can allow user to visually observe the debonding along the fibre/matrix interface. The advanced modeling tool developed was used to evaluate the interface parameters of the fibre/matrix interface.

Aeroelastic, Time-spectral Method for Wind Energy Applications

Nathan Mundis, University of Wyoming
Dimitri J. Mavriplis

Periodic and quasi-periodic time-spectral methods, which show great promise for improved efficiency over currently state-of-the-art, time-implicit methods, are applied to the demanding problem of aeroelastic gust response. Both a standard time-implicit method and time-spectral methods are developed that take into account the coupling among the three fundamental aspects of computational aeroelastic calculations: unsteady flow equations, time dependent structural response to aerodynamic loads, and moving meshes. Results from the time-implicit and time-spectral methods are then compared in order to demonstrate the capability of time-spectral methods to solve aeroelastic gust response problems. These results are presented for two-dimensional representations of wind-turbine blade aeroelastic response under different conditions and to variable gust parameters. It is shown that time-spectral based methods can be used to solve every reasonable combination of airfoil motion and gust response that has thus far been attempted.

Finite Element Model for Aero-elastically Tailored Residential Wind Turbine Blade Design

Eric Robinson, University of Wyoming
David E. Walrath

Passive wind turbine control systems permit wind turbines to achieve higher efficiencies and operate in wider inflow conditions. Aeroelasticly tailored bend-twist coupled blades are one method of achieving passive control by designing blades that twist to feather due to bending. To adequately model such blades for design, may require modeling large deformations, nonlinear material behavior, and variable aerodynamic loading.

To aid in passive wind turbine blade design, an iterative finite element based aeroelastic model capable of computationally predicting blade deflection under loading was constructed. The model was based on solving for an optimum composite laminate orientation and structure to meet the turbine design torque at elevated wind speeds. The approach was to model a preexisting pitch controlled small scale (3.5kW) turbine design as a basis for designing a passive pitch control replacement system that would operate in a similar fashion. Three different aerodynamic loading schemes were implemented so that results could be compared. A replacement blade has been designed for prototype fabrication and field testing.

Analysis of Vertical Axis Wind Turbine Aerodynamics by Using a Multi-fidelity Approach

Yi Han, University of Wyoming
Jayanarayanan Sitaraman, University of Wyoming
Yong Dan, Northwest University, Xi'an, Shaanxi Province, China

In the presentation, two analytical methods will be applied in the prediction and analysis of the aerodynamic performance of straight-blade vertical axis wind turbine (VAWT): Double-multiple streamtube (DMST) model and potential flow 3-D vortex panel model. DMST model is mainly based on the Blade Element Momentum Theory (BEMT) which has been widely used in the analysis of horizontal axis wind turbine (HAWT). An angular induction factors is also introduced into the original DMST model which establishes a pair of iterative equations in relation to upwind and downwind streamwise induction factors. The potential flow 3-D vortex panel method is based on the Weissinger theory (extended lifting line theory). The blade will be divided into several panels and the elliptic spanwise distribution of the circulation will be obtained by solving the boundary condition that zero flow across the thin wing's solid surface. The computational results including non-dimensional normal and tangential forces during the whole revolution obtained by two approaches will be compared with experimental data and VDART2 program data. In addition, the velocity field near the rotor and the wake structure will be shown under different operational cases.

Wind Resource and Wakes - Results from the 3D Wind Experiment

Rebecca Barthelmie, Indiana University Bloomington (Invited)
SC Pryor, H Wang, P Crippa

As wind turbines and farms increase in size, the challenge of integrating measurements and modeling of wind characteristics for both resource assessment and wind farm control become more difficult. Even offshore or in relatively homogeneous landscapes, there are typically significant gradients of both wind speed and turbulence. Adding the impact of wind turbine wakes that introduce wind speed deviations of about the same order as gradients gives a complex and rapidly evolving wind and turbulence fields. Our project integrates remote sensing and in situ measurements with model simulations to produce a 3D wind field on wind farm scales. We are evaluating experimental and processing strategies for wind and turbulence measurement platforms such as traditional mast-based anemometers, anemometers on tethersondes, sonic anemometers on masts and Unmanned Aerial Vehicles (UAV), vertically-pointing lidar, scanning Doppler lidar, satellite-derived wind speeds from synthetic aperture radar and scatterometers. Our first experiment combined measurements with Weather Research and Forecast (WRF) modeling at a large wind farm in Indiana. Our second experiment in May 2013 combines measurements and modeling around the coast and offshore at Lake Erie. These campaigns will be described in detail, with a view to evaluating optimal strategies for offshore measurement campaigns.

Physical Modeling for Wind Energy Applications

Horia Hangan, Western (Invited)

Although wind turbines and wind farms are now a long standing reality, many aspects in their design are based on numerical modeling from the mesoscale, microscale to the aerodynamic levels. The interactions among these massive wind turbines and the turbulent atmospheric boundary layer (ABL) are still not fully understood. The ability to predict the flow kinetic energy extraction decreases due to complex wind turbine interactions, terrain roughness and topography.

Physical simulations can be used to improve the models, however, they have their set of limitations. Wind Tunnel simulations of array interference are presently generic with no clear geometric, kinematic and dynamic similarities between the small-scale models and reality. Usually wind tunnel topographic effect studies are conducted at scales that lack the required resolution.

New, larger multi-fan facilities are presently emerging at cross-disciplinary interfaces. Herein we explore the possibility to develop improved wake and topographic/terrain models through novel physical simulations in the newly constructed Wind Environment, Energy and Engineering (WindEEE) Dome at Western University. The 25 meters in diameter WindEEE Dome is capable of generating various kinds of wind system at large-scales, over complex topographic and forested terrain. Inputs for validation will be received from available field measurements and the results will be used to improve existing linear and non-linear wind farm models.

Multi-Fidelity Wind Farm Simultions on Massively Parallel Compute Systems

Jayanarayanan Sitaraman, University of Wyoming (Invited)
Dimitri Mavriplis

Simulation of wind farms operating under turbulent inflow conditions poses a unique challenge of accurately resolving multiple spatial and temporal scales consisting of the largest scales of the atmospheric flows to the smallest scales of the blade boundary layer. Furthermore, complex interactional aerodynamics dictates the power production, loads and vibration of individual turbines. In this work, we will present efforts to model this multi-scale problem using three incrementally complex approaches (1) full rotor model for wind turbines with turbulent inflow included using meso-scale coupling (2) actuator line model for wind turbines with turbulent inflow included using meso-scale coupling and synthetically generated flow and (3) free vortex wake model for wind turbines also with turbulent inflow. This work will present one of the first large scale calculations using full rotor models for a wind farm using detached eddy simulation and solution based adaptive mesh refinement.

Moving Towards Damage Tolerant Design of Wind Turbine Blades

Josh Paquette, Sandia National Laboratories (Invited)
Dennis Roach, Sandia National Laboratories
Doug Cairns (Montana State University)

As the wind industry has matured, standards have been developed to ensure reliability of components and the overall system. Wind turbine blades have been a particularly difficult component to address given the high and variable loading they encounter along with a very tight cost envelope to be economically viable. To further complicate matters, blades are some of, if not the largest composite structures being manufactured in the world. Currently, blades are designed using a safe-life methodology, where an analysis is performed of the expected loading regime over a 20-year operational life and compared to the expected structural resistance, using a set of safety factors. This is akin to the methodology used to design aircraft components decades ago. However, as understanding of loads and failure mechanisms have progressed, aviation has moved towards a damage tolerance approach to design. This requires the designer to assume that damage or defects exists to the extent that inspection methods cannot detect it. Then, throughout operation, the component is inspected at regular intervals and if damage is found, an assessment is made as to the criticality and severity of the damage, along with how that damage may progress until the next inspection interval. A decision can then be made to repair, replace, or wait until the next inspection. This method of design has been shown to both increase reliability and decrease cost in aviation and other industries. This presentation with discuss how this practice may lend itself to better blade design.

Microscale Wind Simulations over Arbitrarily Complex Terrain Using Cartesian Methods and GPUS

Inanc Senocak, Boise State University
Rey DeLeon and Clancy Umphrey

Utility companies and balancing authorities need accurate wind power forecasting methods to balance the variable wind energy generation with other energy resources. To address this practical need, we develop a multi-GPU accelerated microscale computational fluid dynamics (CFD) simulation that resolves arbitrarily complex terrain with an immersed boundary approach and with spatial resolutions on the order of ten meters. An MPI-CUDA implementation is used to execute the incompressible solver with a geometric multigrid method on clusters of graphics processing units (GPU). The implementation overlaps GPU to CPU data copy operations and cluster communication with computations on the GPU. In the incompressible solver, the large-eddy simulation paradigm with a localized Lagrangian dynamic subgrid scale model is used to resolve wind profiles over complex terrain. The immersed boundary method with a direct forcing approach is extended to represent the arbitrarily complex terrain in the computations. GPU accelerated incompressible solver is compared against the OpenFOAM CFD model to assess the parallel performance in terms of execution speed and accuracy of adopted approaches. The differences between the Cartesian approach and the terrain-fitted approach of OpenFOAM are investigated using well-known complex terrain experiments.

Carbon Nanofibers for Strain Sensing in Wind Turbine Blades

J. Cai, Texas A&M University
M. Naraghi

Fast Multipole Accelerated Free-Vortex Simulations of The Lillgrund Wind Farm

K. Brown, University of Wyoming
Chris Gundling and Jayanarayanan Sitaraman

The free-vortex wake code (UWAKE), developed at the University of Wyoming, has been coupled with the Weather Research and Forecasting model (WRF) and also the Mann model to allow accurate representation of the turbulent atmospheric inflow. One of the specific goals was to produce a lower complexity physics based model that could be developed, tested and cross- compared concurrently with the higher complexity methods such as LES and detached eddy simulations (DES). Multilevel fast multipole methods (MLFMM) were used accelerate the computational speed of the code, providing fast and accurate wind farm simulations. The 48 wind turbines at the offshore Lillgrund site were simulated and power results are compared with experimental data. Qualitative observations are also made on wake deficits and results are compared to a steady inflow case. The main focus of the talk will be implementation of the MLFMM algorithm with the free-vortex wake equations and parallelization methods.

Investigation of Waviness in Wind Turbine Blades: Structural Health Monitoring

Sunil Chakrapani, Iowa State University
Vinay Dayal and Daniel Barnard

This paper presents the investigation of discrete, out-of-plane waviness(marcel) in thick composite plates with applications to wind turbine blades. The investigation was carried out with the help of air coupled ultrasonics and a two-step procedure was developed to assist production line implementation. The first step involved detection of marcels, and the second step involved the characterization of these marcels with the help of an index called aspect ratio. Based on the aspect ratio, the detected marcels are either accepted or rejected. A passive structural health monitoring approach has been presented here to monitor the accepted marcels above a threshold. The fatigue life of specimen is the most affected in the presence of a marcel. Hence this study focused on the damage evaluation during the fatigue testing. Monitoring was facilitated using piezo-film transducers which generate bulk waves.

Mesoscale to Turbine: Aspects and Techniques of Multi-Scale Wind Resource Modeling

Wayne Miller, Lawrence Livermore National Laboratory
Sonia Wharton, Matt Simpson, Katie Lundquist, Jeff Mirocha, Lawrence Livermore National Laboratory
Jay Sitaraman, University of Wyoming
Jennifer Newman, University of Oklahoma

We are developing and verifying methods for multi-scale modeling and forecasting of wind resources. The atmospheric scales of interest to wind power range from mesoscale (100-1000 km) to turbine (1-100 m) scales. No single tool is capable of resolving this huge range of scales, and so we rely on hybrid methods of overlaid domains. Each domain resolves flow features germane to its scale, and information is transferred between domains. Benefits of multi-scale forecasts include reducing the cost of energy by creating more accurate forecasts of wind farm power production and more accurate understanding of turbine performance and dynamic loads. Challenges include industry acceptance, computational burden, turbulence resolution, resolving terrain features and experimental verification. We are executing extensive field campaigns to compare atmospheric observations at rotor elevations to the predicted forecasts. We use these observations to extract turbulence data that is then used to seed the model turbulence input. Through collaboration with active commercial wind farms we are able to compare predicted turbine performance to actual SCADA data for the observational period.

A Computer-Based Inspection Method for Determining Surface Flaws of Wind Turbine Blades

Huiyi Zhang, Iowa State University
John Jackman

Wind turbine blades made from fiber-reinforced composite material and surface coating protection layers account for a significant portion of wind farm maintenance costs due to internal and surface damage that occurs during operation. Surface damage (e.g., erosion, cracking, or peeling) can occur during the transportation, installation, and operation stages. Small cracks (as small as hairline thickness) can be a sign of a more severe problem and represent a challenge for existing inspection methods. This study examined a rotor blades surface crack optical inspection method with image processing techniques that can identify and quantify hairline thickness cracks. The method was compared with a platform-based visual inspection method and the results demonstrated that the optical inspection method performed consistently with a significantly low time and cost. Further studies were addressed after the methods comparison, which include a best fit-crack image capturing algorithm, and a indentifying and eliminating environmental noises algorithm. These algorithms will be tested with both synthetic cracks and field images. Finally, a prototype rotor blades surface health inspection system with testing environment was described. This study is part of ongoing efforts to provide accurate and cost-effective inspection methods and these results support the feasibility of this approach.

Wind Turbine Blade Tip Vortex Characteristics using Data from Full Rotor CFD Simulations

Beatrice Roget, University of Wyoming
Jayanarayanan Sitaraman

The flow field of rotary wing systems such as helicopters and wind turbines are dominated by the presence of tip vortices. Wake deficits behind wind turbines are strongly influenced by the evolution and break down of tip vortices. In order to correctly model wind turbine interactions, it is therefore important to gain an understanding of the physics of tip vortex evolution. Detailed measurement of tip vortex evolution in scale test is an ongoing field of research. However, the complexities involved in measurements often limit the extent of availability of usable data. High-fidelity computational fluid dynamics analysis using full rotor-models provide an alternate path in this context. Detailed flow simulations using a hybrid RANS/LES type methodology can provide a reasonable database that can be mined to develop a physical understanding of tip vortex evolution. This presentation describes an algorithm to identify tip vortices in the CFD simulation data and use it to perform a detailed analysis of the evolution of the vorticity and core diffusion rate.

Smart Wind Farm Array

Suhas Pol, Texas Tech U.
A. Taylor, D. Mckeon, L. C. Castillo, J. Sheng, B. Aksak, F. Hussain
C. W. Westergard, Nextratech
G. Wang and M. Glauser, Syracuse University

The goal of National Wind Resource Center (NWRC) of Texas Tech University (TTU) is to perform cutting edge research in the field of wind energy by developing a unique experimental facility of scaled down wind farm to allow research of wind farm dynamics in unprecedented detail. This field site will initially consist of an array (3X5) of scaled down version of the Vestas V90 turbine (V2, nominal diameter: 2m). It will be replicating the control procedures of actual wind farms and will be equipped with advanced diagnostics such as Particle Image Velocimetery, multipoint measurements of micro-meteorological parameters with sonic anemometers, instantaneous power and rpm measurements. The presentation will cover theoretical analysis of a few salient aspects of wind turbine aerodynamics, especially, those that can be researched at this unique facility. Since, the Smart Wind Farm Array facility is a field site it is possible to consider wide range of data at various atmospheric stability conditions, create dynamically changing initial conditions for simulations, capture the role of unsteady initial condition on the evolution of the coherent vortical structures and turbulent transport of momentum from free stream in to the wind farm roughness layer. Further, it will be a test bed to validate control system

algorithms, smart blade design etc. that mitigate fatigue load and increase wind farm output. A description of planned experiments and the experimental setup will be covered. The inflow conditions will be measured using sonic anemometers distributed on a 10 m tower (nominal hub height) which can be compared with a 200 m meteorological tower located about 500 meters. Correlation studies with power and rpm measurements to establish the significance of fluctuating inflow conditions on power produced and ensuing aerodynamics of wind farms will be performed.

Using Mesoscale Weather Model Output as Boundary Conditions For Atmospheric Large-Eddy Simulations and Wind-Plant Aerodynamics Simulations

Matthew Churchfield, NREL
Michael A. Sprague, John Michalakes, Sang Lee, Caroline Draxl, Avi Purkayastha, and Patrick J. Moriarty, NREL
Brian Vanderwende, Julie K. Lundquist, Univeristy of Colorado, Boulder

Wind plant aerodynamics are directly affected by the microscale weather, which is directly influenced by the mesoscale weather. Microscale weather refers to processes that occur within the atmospheric boundary layer with the largest scales being a few hundred meters to a few kilometers depending on the atmospheric stability of the boundary layer. Mesoscale weather refers to large weather patterns, such as weather fronts, with the largest scales being hundreds of kilometers wide. Sometimes microscale simulations that capture mesoscale-driven variations (changes in wind speed and direction over time or across the spatial extent of a wind plant) are important in wind plant analysis. In this paper, we present our preliminary work in coupling a mesoscale weather model with a microscale atmospheric large-eddy simulation model. The coupling is one-way beginning with the weather model and ending with a computational fluid dynamics solver using the weather model in coarse large-eddy simulation mode as an intermediary. We simulate one hour of daytime moderately convective microscale development driven by the mesoscale data, which are applied as initial and boundary conditions to the microscale domain, at a site in Iowa. We analyze the time and distance necessary for the smallest resolvable microscales to develop.

Tower Design Load Verification for a 3.5-kW Wind Turbine

Sina Erturk, University of Wyoming
Jennifer Tanner and Richard J. Schmidt

Current US design codes are focused on buildings that are generally quite stiff. Flexible structures present cases where it is difficult to correctly evaluate wind loads. Previous researchers have reported that the IEC 61400-2 is overly conservative in terms of small-scale tower design. As wind energy becomes more mainstream the need to optimize loads for small or mid-scale wind turbine towers grows in importance.
A unique opportunity exists at the University of Wyoming to instrument a steel wind turbine tower and compare tower behavior to measured wind speeds. The turbine has a rated capacity of 3.5 kW of electrical energy. Accelerometers and strain gages are mounted to the tower to collect tower response to wind loads and turbine operation. Structural dynamic models are proposed to compare tower response to measured wind speed.
In order to evaluate bending moment in the tower strain gages are placed at three different heights. Finally, three accelerometers are applied at various points on the tower.

The Role of Design Standards in Wind Plant Optimization

Paul Veers, NREL (Invited)
Andrew Ning, Matt Churchfield, and Katherine Dykes, NREL

When a turbine is optimized, it is done within the design constraints established by the objective criteria in the international design standards used to certify a design. Since these criteria are multifaceted, it is a challenging task to conduct the optimization, but it can be done. The optimization is facilitated by the fact that a standard turbine model is subjected to standard inflow conditions that are well characterized in the standard. Examples of applying these conditions to rotor optimization are examined. In other cases, an innovation may provide

substantial improvement in one area, but be challenged to impact all of the myriad design load cases. When a turbine is placed in a wind plant, the challenge is magnified. Typical design practice optimizes the turbine for stand-alone operation, and then runs a check on the actual site conditions, including wakes from all nearby turbines. Thus, each turbine in a plant has unique inflow conditions. The possibility of creating objective and consistent inflow conditions for turbines within a plant, for used in optimization of the turbine and the plant, are examined with examples taken from LES simulation.

Impacts of Stratification and Non-Equilirbum Winds/Waves on Hub-Height Winds Offshore

Ned Patton, National Center for Atmospheric Research (Invited)
Branko Kosovic, Peter Sullivan, Larry Mahrt, Mark Zagar, Jimy Dudhia, and Line Gulstad

Loads and Response of Offshore Wind Turbine Structures to Steep and Breaking Waves

Henrik Bredmose (Invited)
Department of Wind Energy, Technical University of Denmark
Bo Terp Paulsen, Signe Schløer
Flemming Schlütter, DHI, Denmark

As offshore wind turbines are installed at increasing larger depth, the hydrodynamic loads become increasingly important. At certain depths, the loads from extreme waves can be dimensioning for the substructure. At shallow depths, such extreme loads are caused by breaking waves. Also structural excitation by higher-harmonic wave forcing components can occur.

These effects are at the heart of the 'Wave loads' project (2010-2013) of DTU Wind Energy, DHI and DTU Mechanical Engineering. The project involves experiments, development of CFD tools and development of aero-elastic models. Some of the experiments were carried out with a flexible pile, enabling direct measurement of the structural response to steep and breaking waves.

The CFD tools are based on the OpenFOAM® toolbox. A coupling between a 3D Navier-Stokes VOF model and a fully nonlinear potential flow solver has been developed. to allow efficient CFD computation of loads from irregular waves travelling over varying depth. The aero-elastic developments involve application of fully nonlinear wave kinematics for monopile- and jacket-supported turbines.

The present talk gives an overview of the 'Wave loads' project with special focus on CFD results, the experimental investigation with a flexible pile and their numerical reproduction.

Experimental investigations on Wake Interference among Multiple Turbines in Onshore and Offshore Wind Farms

Hui Hu, Iowa State University (Invited)

The recent research progresses made in the speaker's research laboratory to investigate the wake interferences among multiple wind turbines in onshore and offshore wind farms will be introduced briefly. The experimental studies are conducted in a large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) Wind Tunnel available at Iowa State University. An array of scaled three-blade Horizontal Axial Wind Turbine (HAWT) models are placed in atmospheric boundary layer winds with different mean and turbulence characteristics to simulate the situations in onshore and offshore wind farms. The effects of the relative rotation directions of downstream turbines with respect to the upstream turbines, the yaw angles of the turbines with respect to the oncoming winds, array spacing and layout, and the terrain topology of wind farms on the turbine performances and the wake interferences among multiple wind turbines are investigated in detail. In addition to measuring dynamic wind loads (both forces and moments) and the power outputs of the scaled turbine models, a high-resolution Particle Image Velocity (PIV) system is used to conduct detailed flow field measurements to quantify the characteristics of the turbulent wake vortex flows and the wake interferences among the wind turbines sited over a flat (baseline case) and hilly terrains with non-homogenous surface winds. The detailed flow field measurements are correlated with the dynamic wind loads and power output measurements to elucidate underlying physics in order to gain further insight into the characteristics of the dynamic wind loads and wake interferences among multiple wind turbines for higher total power yield and better durability of the wind turbines in atmospheric boundary layer (ABL) winds.

Challenges in Wind Farm Optimization
Gunner Chr. Larsen (Invited)
Department of Wind Energy, Technical University of Denmark

To achieve the optimal *economic output* from a wind farm over its lifetime, an optimal balance between capital costs, operation and maintenance costs, fatigue lifetime consumption of turbine components and power production is to be determined on a rational basis. This has implications both for the wind turbine modeling, where *aeroelastic models* are required, and for the wind farm flow field description, where *in- stationary* flow field modeling is needed to capture the complicated mixture of atmospheric boundary layer (ABL) flows and upstream emitted meandering wind turbine wakes, which together dictates the fatigue loading of the individual wind turbines.

Within an optimization context, the basic challenge in describing the in-stationary wind farm flow field is *computational speed.* The Dynamic Wake Meandering (DWM) model includes the basic features of a CFD Large Eddy Simulation approach in an engineering manner by essentially treating wind turbine wakes as passive tracers emitted into an ABL field. Interfacing the DWM model with the aeroelastic code HAWC2 has facilitated development of the wind farm optimization platform TOPFARM. Features of the TOPFARM platform will be described, including full-scale validation examples of key elements as well as example applications, and recent developments and future plans will be touch on.

Unified RANS-LES and Dynamic LES Simulations of the Atmospheric Boundary Layer With and Without Wind Turbines
Ehsan Kazemi, University of Wyoming
Stephan Heinz

The paper reports the results of applications of linear and nonlinear dynamic LES and unified RANS-LES methods to neutrally stratified atmospheric boundary layer (NABL) simulations with and without wind turbines. The advantages of dynamic LES methods are their accuracy and the ability to account correctly for anisotropy and backscatter. The advantage of unified RANS-LES models is their ability to provide results like LES for much lower computational cost.

WindScanner.dk - a New Remote Sensing Based Research Infrastructure for On- and Offshore Wind Energy Research
Torben Mikkelsen (Invited)
Department of Wind Energy, Technical University of Denmark

Recent measurement achievements obtained with new 3D remote sensing based WindScanners will be presented.

Our new WindScanner research infrastructure (www.windscanner.dk) development based on remote sensing wind lidars will be presented and first results shown.

Wind velocity 3D vector measurements obtained in planetary boundary layer turbulent flow have been acquired from both ground-based and wind turbine-integrated space by time and space synchronized scanning lidars.
Results to date include: turbulent inflow over complex terrain scanned in a horizontal-vertical 2D scan plane, and 2-dimensional and 3-dimensional wind vector scan measurements obtained during various WindScanner boundary-layer field campaigns.

A special designed “2D upwind rotor plane scanning SpinnerLidar”, mounted in the rotating spinner, and able to provide the wind turbine control systems with detailed upwind feed-forward inflow information, is also investigated as a provider of rotor plane inflow for accurate power curve measurements.

Finally a brief presentation of the most recent on-going research infrastructure build up work at DTU is given, including our activities at DTU Wind Energy with both the short range (10 -200 m range) and the long-range (100 – 6000 m range) space and time synchronized 3D scanning wind lidar systems.

Estimation of the Resolved Wind Inflow Using Sparse Measurements

Raj Rai, University of Wyoming
Jonathan Naughton

This present work develops a procedure that estimates a resolved wind inflow using sparse wind data sampled from wind inflows generated from the large eddy simulation (LES) of a neutral atmospheric boundary layer (ABL) in a manner similar to that a scanning Lidar records the wind velocities. The estimation of the wind inflow was performed using the proper orthogonal decomposition / linear stochastic estimation (POD/LSE) complementary approach. The quality of the estimated wind inflow was assessed employing the root mean square difference between the estimated and LES wind inflow. The results showed that the quality of the wind inflow estimate depends on the integral time scale of the wind inflow. As expected, the faster the wind velocity is scanned and the smaller the scan grid, the better the wind inflow estimation. However, as long as the total scanning time of the inflow plane occurs within the integral time scale, a good estimate of the wind inflow is achieved. The finding from this work can be used to determine the required scanning rate of a Lidar for a given grid size and desired spatial resolution.

Stable Adaptive Control of Wind Turbines in Regions 2&3

Mark Balas, University of Wyoming (Invited)

We will discuss the use of direct adaptive control on utility-sized wind turbines to enhance power capture and reduce dynamic loads. Adaptive Disturbance Tracking Control (ADTC) is introduced and used to control generator torque to track the Tip Speed Ratio (TSR) of 5 MW Horizontal Axis Wind Turbine (HAWT) in Region II and the blade pitch to regulate turbine speed in Region III. Adaptive control will also allow the turbine to transition smoothly between these two operating regions. The benefit of adaptive control is that exact knowledge of all the turbine parameters will not be needed. We will do this without direct wind speed measurement as well.

Since ADTC theory requires some wind speed information, a wind disturbance generator model must be combined with a very low order plant model to estimate the wind speed as well as the partial states of the wind turbine. In this paper, we will show the stability and convergence of ADTC theory with the low order estimator to create a completely adaptive way to control turbines without detailed knowledge of the turbine dynamics or the aerodynamic inflow.

Experimental Investigation of Swirl Effects on Axisymmetric Wakes

Michael Hind, University of Wyoming
Jonathan Naughton

Wind turbines often operate in the wakes of other turbines, and, as a result, swirling wakes are of interest for their strong influence on wind plant layout and ultimately plant power production. While much work has been done on axisymmetric wakes, little is available for swirling wakes, where validation of computational models is needed. This investigation applies two dimensional particle image velocimetry to verify the efficacy of a rotating honeycomb as a swirling wake generator and characterizes the axial velocity deficits of wakes with varying degrees of swirl. The current results demonstrate that the introduction of swirl increases momentum transfer between the wake and freestream. This increased level of momentum transfer results in faster wake evolution, as evident by accelerated wake growth and centerline velocity deficit decay. Also demonstrated is that, once minor flow features caused by honeycomb geometry decay, the velocity deficit profiles collapse when normalized with local centerline velocity deficit and wake half-width. These results verify the rotating honeycomb's ability to produce a relevant swirling wake, and they also emphasize the important differences between swirling and non-swirling wakes.

Wind Turbine Contingency Control Through Generator De-rating

Susan Frost, NASA-Ames Research Center
Kai Goebel, NASA-Ames Research Center
Mark Balas, University of Wyoming

Wind turbines are complex systems that operate in highly turbulent environments, leading to stress and strain on components. Faults detected in wind turbine components or subsystems might be such that the turbine could continue operating at some reduced capacity until maintenance can be performed to remedy the problem. The work reported herein explores the integration of condition monitoring of wind turbines with contingency control to balance the trade-offs between maintaining system health and energy capture. We demonstrate how de-rating the turbine's generator can lead to lower aerodynamic loads on its blades. We propose developing a contingency controller that de-rates the wind turbine, to enable continued operation before maintenance can be performed. A very simple economic model is used to demonstrate the benefit of operating at a reduced capacity until a scheduled maintenance procedure occurs, instead of ceasing operation and incurring the increased expenditure of an unscheduled maintenance activity.

Theoretical and Experimental Studies of Wind Turbines Wakes at Multiple Scales in the UNH Flow Physics Facility (FPF)

Martin Wosnik, University of New Hampshire
Kyle Charmanski, University of New Hampshire,
Nathaniel Dufresne, United States Coast Guard

Wind turbines at multiple model scales are being studied in the UNH Flow Physics Facility, a wind tunnel with a test section of 6m x 2.7m cross section and 72m length. The goal is to improve our understanding of wind turbine wakes and wind turbine array fluid dynamics.

The axisymmetric turbulent wake with rotation generated by a wind turbine was investigated analytically and experimentally. An equilibrium similarity theory was derived, with scaling functions obtained from the equations of motion. The axial and azimuthal (swirl) velocity fields were then measured in the wake of a single 3-bladed wind turbine with rotor diameter of 0.91m, up to 20 diameters downstream, using hot-wire anemometry with an X-wire sensor, to examine the validity of the derived scaling functions. First evidence for a new scaling function for the mean swirl (azimuthal velocity), $W_{\max} \propto x^{-1} \propto U_o^{3/2}$ was found, indicating that the mean swirl decays faster than the mean velocity deficit $U_o \propto (U_\infty - U_{cl}) \propto x^{-2/3}$.

Wind turbine arrays are studied at a smaller scale of D =0.25m. Preliminary studies were conducted with small arrays (1xN, 3x3). A study of the fully developed wind turbine array boundary layer with 100 turbines, using a combination of realistically scaled model turbines and porous discs, is underway.

Analysis, Design and Control of a DFIG Wind Farm Integrated DG-HVDC Power System

Kaushik Prasad, University of Wyoming
Margareta Stefanovic

DFIG wind turbines, Distributed Generation (DG) system and High Voltage DC (HVDC) technologies have been separately studied in depth but there is little information available on the integration of these technologies into a small scale power grid. A power system with a cascaded controller was designed in this study and the system stability in terms of maintaining constant DC grid voltage was achieved when the above technologies are utilized together. A DG system with a 9 MW DFIG wind farm transmitting power through a HVDC system was modeled using MATLAB. To analyze the power system performance in terms of voltage tracking and to guarantee stability of the system with varying wind speeds, random wind speed profile was generated. A cascaded controller was designed to regulate the DC voltage of the Internal Converter system of the DFIG wind farm.

In addition, harmonics elimination and constant DC voltage maintenance on the HVDC line was studied as it is important to eliminate harmonics present on the HVDC line for the overall stability of the system. Filters were designed to serve the purposes of eliminating the harmonics also appearing as large capacitor banks at fundamental frequency, thus providing reactive power compensation for the converter system.

A Pseudo Spectral Approach to the Vertical Entrainment of Mean Kinetic Energy in a Scaled Wind Farm

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A pseudo-spectral analysis was performed using a proper orthogonal decomposition of PIV collected from a scaled wind turbine data in order to examine the wavelength spectra of the vertical MKE flux by the Reynolds stresses. It was first found that the modes which contained large portions of the turbulent kinetic energy, also contributed largely to the Reynolds stresses. Further, less than 10 modes accounted over 50% of the total vertical flux of mean kinetic energy into the array. The nomenclature of idiosyncratic and Fourier modes is introduced. These are called as such since the former capture much of the inhomogeneity, and the latter because they decay like 1/n (like true Fourier modes). Idiosyncratic modes are dominant in terms of vertical MKE flux, with over 50\% of the total entrainment being done by these modes. Furthermore, the wavelengths associated with these individual modes were O(D), the rotor diameter.

Power Quality Improvement of Grid Connected DFIG through UPQC

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Two converter of DFIG are capable of controlling the active and reactive power transformation to grid by minimizing harmonics. The converter connected with stator terminals controls the stator voltage to predetermine level while other converter control the reactive power through common D C link. The power quality at grid gets disturbed due to nonlinear loads comprising of power electronics switching devices. This paper deals with unified power quality conditioners (UPQC's), which integrates the series-active and shunt-active filters, to compensate for voltage flicker/imbalance, reactive power, negative sequence current, and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation.

This paper also discusses the control strategy of the UPQC, with the flow of instantaneous active and reactive powers inside the UPQC. The detailed simulation based analysis and investigation on grid connected configuration of a 2 MW Doubly Fed Induction Generator in PSCAD/EMTDC (Power system Computer aided design software/Electromagnetic transients & control) , a dedicated power system simulator, has been investigated for power quality improvement through UPQC.