FINAL TECHNICAL REPORT

Federal Agency to which Report is submitted: DOE EERE – Wind & Water Power Program

Recipient: Pennsylvania State University, 003403953

Award Number: DE-EE0005481

Project Title: A HPC "Cyber Wind Facility" Incorporating Fully-Coupled CFD/CSD for Turbine-Platform-Wake Interactions with the Atmosphere and Ocean

Project Period: 1 Oct 11 – 30 August 15 (including a no-cost extension)

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Report Submitted by: PI

Report Date: 14 April 2017

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Acknowledgment: This material is based upon work supported by the Department of Energy EERE under Award Number DE-EE0005481.

EXECUTIVE SUMMARY

The central aims of the DOE-supported "Cyber Wind Facility" project center on the recognition that wind turbines over land and ocean generate power from atmospheric winds that are inherently turbulent and strongly varying, both spatially over the rotor disk and in temporally as the rotating blades pass through atmospheric eddies embedded within the mean wind. The daytime unstable atmospheric boundary layer (ABL) is particularly variable in space time as solar heating generates buoyancy-driven motions that interact with strong mean shear in the ABL "surface layer," the lowest 200 - 300 m where wind turbines reside in farms. With the "Cyber Wind Facility" (CWF) program we initiate a research and technology direction in which "cyber data" are generated from "computational experiments" within a "facility" akin to a wind tunnel, but with true space-time atmospheric turbulence that drive utility-scale wind turbines at full-scale Reynolds numbers. With DOE support we generated the key "modules" within a computational framework to create a first generation Cyber Wind Facility (CWF) for single wind turbines in the daytime ABL—both over land where the ABL globally unstable and over water with closer-to-neutral atmospheric conditions but with time response strongly affected by wave-induced forcing of the wind turbine platform (here a buoy configuration).

The CWF must also capture correctly the modulating effects of nonsteady blade and rotor loadings on the mechanisms that generate the highly turbulent rotor wake, another important source of nonsteady turbulent forcing of downstream wind turbines in wind farms. Thus the central modules of the CWF are (1) the atmospheric boundary layer generation module in which true atmospheric boundary layer turbulence eddies (~100 m) and mean winds are generated using high-accuracy large-eddy simulation (LES) to interact with a wind turbine, (2) the aerodynamics module which incorporates the ABL-LES turbulent winds to predict accurately, with all key physical elements included, the spatio-temporal variations in blade loads highly resolved in both blade length (~70 m) and chord (~ 4m) to scales necessary to capture the nonsteady responses of the extremely thin boundary layers (~ microns) on the blade surfaces, (3) the elastic response of the blades to spanwise nonuniform and highly nonsteady aerodynamic loadings, (4) the production of wake turbulence behind wind turbine rotors in response to space-time-varying loads that impact downstream wind turbines in wind farms, and (5) the 6 degree-of-freedom (6DOF) motions of the platform/tower/rotor in the ocean environment in response both to atmospheric turbulence at the roto and ocean waves at the platform/buoy. These developments can only be envisioned in context with state-of-the-art high-performance computing using state-of-the-art algorithms and models. Therefore much of the effort in the DOE Cyber Wind Facility program was directed at development and validation of the 5 individual modules.

In addition, a great deal of analysis was carried out with each of the individual modules that incorporated other important elements of the Cyber Wind Facility development from which a great number of new discoveries and advancements in understanding were made. The wake module, for example, made great contributions to the accuracy of actuator line models which are needed to predict wind turbine wake

structure and fluctuation level and the Cyber Wind Facility in full blade-boundary-layer-resolved mode was used to evaluate the extent to which the advanced actuator line models developed within the CWF program capture the nonsteady response of blade torque/power. The application of the CWF made in this program showed the existence of important ramp-like response events that likely contribute to bearing fatigue failure on the main shaft. Given the extreme computational expense and time requirements to carry out full blade-boundary-layer-resolved resolutions, we seek a computationally cheaper model that, when accurately implemented with sufficient resolution, will capture these ramp-like response dynamics well. Long-time analysis uncovered distinctive key dynamics that explain primary mechanisms that underlie potentially deleterious load transients. We have shown that whereas the commonly applied “blade element momentum theory” (BEMT) model cannot properly capture these strong repetitive transients, the advanced ALM method developed here can (with a time delay that is understood). Integrating the advanced model with the ABL inflow of the full CWF, we show that the temporal modulations of blade loadings from atmospheric turbulence modulate also the development of the rotor wake. We also show that blade bend-twist coupling plays a central role in the elastic responses of the blades and that atmospheric turbulence-elastic-blade interactions appear to cause opposing twisting motions that impact blade loads and turbine power.

Validation of the CWF is inherently difficult given that, unlike nearly all studies in the literature, the CWF is directed at the details of nonsteady response rather than statistics collected during quasi-stationary periods. At the highest level of fidelity it is not practical and computationally too expensive to generate long-time statistics with the blade-boundary-layer-resolved CWF. The CWF team worked closely with our industrial partner, GE Global Research (Munich) to obtain and analyze data from a unique field campaign in which details of the flow around a GE 1.5 MW wind turbine blade were measured in the daytime ABL. These data, when integrated with CWF and ALM computational experiments, show clearly the existence of three important time scales characterizing nonsteady response of wind turbine rotors to atmospheric turbulence: a longer time scale associated with the advection of energy-containing atmospheric turbulence eddies through the rotor plane (~30-90s), the once-per-revolution time scale associated with the period of blade rotation (3-5 s depending on the rated rotor RPM), and a short time scale associate with the ramp-like time responses (~1 s) that result from the passage of the blades through the internal structure of the atmospheric eddies.

As importantly, from these data we were able to uncover the characteristics within the winds that directly impact nonsteady turbine response to atmospheric turbulence. The CWF and ALM simulations made clear the importance of time changes in local flow angle that, using the field data analysis, are largely (but not totally) in response to strong turbulence fluctuations in the wind component perpendicular to the turbine rotor. Furthermore, direct comparison of field data with equivalent CWF and CWF/ALM simulations showed a high level of correspondence between spectral and statistical characteristics of field vs. cyber blade-local data, effectively validating the CWF and showing the CWF-ALM captures primary time response characteristics.

Overall we argue that the DOE-funded CWF program was a success at many levels. The primary objectives of the program were met within the limited resources available, both financially and especially in terms of computational resources available. In particular, each module was successfully developed and fully integrated with atmospheric boundary layer LES (with the exception of Subtask 1.3 which suffered from Dr. Paterson’s move from Penn State to VA Tech in the middle of the CWF program). The application of these modules produced a wide-ranging series of important results and discoveries. The primary disappointment was lack of necessary computational resources, and the large amount of time to obtain and maintain computational resources (primarily through the NSF XSEDE program). As a result there were insufficient time and resources to develop a 3-bladed rotor blade-boundary-layer-resolved simulation integrated with the blade elasticity and offshore dynamics. The technical knowledge obtained for future developments of blade-boundary-layer-resolved simulation within atmospheric turbulence large-eddy simulation (see appendix), advanced actuator line blade modeling, nonsteady elastic blade response modeling, and platform-wave coupling, however, points the way to future endeavors. The scientific and technical knowledge obtained in regards nonsteady wind turbine response to atmospheric turbulence, lower-order-model accuracy for predicting nonsteady response, "meso-micro" atmospheric response to weather events, elastic blade response to atmospheric turbulence and wake response dynamics to atmospheric turbulence is unparalleled. Furthermore, we have broken new ground in validation of nonsteady response using a unique dataset from a GE field campaign which both contributed to our knowledge of wind turbine function in a real atmospheric boundary layer and to future approaches to validation of time-local response dynamics.

Acronyms:

ABL: atmospheric boundary layer
ALM: actuator line model
BEMT: Blade Element Momentum Theory;
CAD: computational aero dynamics (hybrid URANS-LES over blades);
CHD: computational hydro dynamics (hybrid URANS-LES over platform);
CFD: computational fluid dynamics (CAD, CHD); COE: cost of energy;
CWF: Cyber Wind Facility;
HPC: high-performance computing;
LES: large-eddy simulation;
(U)RANS: (Unsteady) Reynolds-averaged Navier-Stokes simulation

References within Text

References within the text may be found are given in the final section of Final Technical Report, "Products Developed". In the text above these references are categorized using the acronyms JP. WP, GT, MP, IP and WP according to the titles of the subsections:

JP: Journal Publications and Refereed Proceedings
GT: Graduate Theses
MP: Meeting Presentations and Abstracts
IP: Invited Presentations
WP: Workshop Participation and Meeting Organization

PROJECT OBJECTIVES

Our primary objectives are to develop and validate a computational "Cyber Wind Facility" (CWF) in a high performance computing (HPC) environment to be used to design "cyber experiments" at the level of complexity and fidelity of field experiments on wind turbines over land and water responding to true atmospheric environments, but at levels of specificity and control, and with extraordinary numbers of sensors, impossible to obtain in the field. With this capability we aimed to quantify and analyze details of the interactions between wind turbine loadings and daytime atmospheric turbulence useful in future designs and control systems. The cyber data are to include, for example, simultaneous quantifications of the 4D turbulent winds in the land/marine atmospheric boundary layer (modulated by mesoscale weather), local stochastic loadings resolved along the blade surfaces in space/time, the time varying nature of torque/power and bending moments that enter the drivetrain, time-resolved blade deformations in response to wind load variations, and for offshore configurations, the 6 degree-of-freedom (DOF) motions of the platform, tower and rotor from wave-platform interactions. The CWF program also focused on interaction between atmospheric and wake turbulence with the development of advanced actuator line models for prediction of wake dynamics, and on the incorporation of aero-elastic blade response to atmospheric forcing. The full high-fidelity CWF is to be used to analyze the extent to which the advanced ALMs developed within this program can capture the nonsteady responses to loadings from daytime atmospheric turbulence.

AVAILABLE RESOURCES

RESEARCH TEAM: DOE VS OTHER SUPPORT.

The lead developers of this program were Profs. Brasseur (PI), Schmitz (coPI), Campbell (coPI) and Paterson (coPI), all from Penn State with the exception of Prof. Paterson who moved from Penn State to take the chair position in Aerospace and Ocean Engineering at VA Tech in the middle of the CWF project. In order to maintain the important expertise that departed with Prof. Paterson, when he left we brought into the program Dr. Brent Craven, a Research Associate at the Applied Research Lab who has a high level of experiment with OpenFOAM. Dr. Craven took over Dr. Paterson’s role as the go-to person when major issues with OpenFOAM arose. Dr. Sue Haupt (National Center for Atmospheric Research, NCAR) was a paid collaborator in the CWF effort. As a mesoscale meteorologist, Dr. Haupt worked with Brasseur in the development of the meso-micro coupling aspect of the atmospheric boundary layer module (subtask 1.1 below). All researchers above received DOE/EERE support.

Student and postdoctoral support was roughly half through the DOE and half through other mechanisms. Two of the three students Tarak Nandi (subtask 1.2), Pankaj Jha (Subtask 1.4) and Javier Motta-Mena (subtask 1.5) received stipend and tuition support from the DOE with the third from Penn State matching through the Penn State Institutes of Energy and the Environment (PSIEE) and the Penn State departments of Aerospace and Mechanical Engineering. Ganesh Vijayakumar (Subtask 1.2) was funded by a previous NSF grant and through additional grant support obtained from the Penn State College of Engineering. Vijayakumar and Nandi also carried out teaching assistantships for additional financial support when DOE support was depleted. Alex Dunbar (Subtask 1.4) and Adam Lavely (Subtask 1.2) were generously funded through the Penn State Applied Research Lab Walker Fellowship program. The primary postdoctoral researcher in the program, Dr. Balaji Jayaraman, was funded under the DOE award. After Prof. Paterson left Penn State for VA Tech, he brought graduate student Di Zhang into the program supported at Virginia Tech on a GRA. Zhang worked within the CWF program from about a year before changing thesis topics.

In addition, Prof. Schmitz advised M.S. student Zhixiang Wang from August 2013, funded through a Teaching Assistantship, on wind-related research peripherally aligned with the CWF program, and with two undergraduates Jessica Bashioum and Sarah Aguasvivas in the development of computer visualization. Profs. Brasseur and Schmitz obtained support from the Penn State College of Engineering for undergraduate Sarah Aguasvivas to develop a high-quality complex research-oriented animation that played a large role in analyses developed under the aerodynamics and wake modules [subtasks 1.2 and 1.4]. Finally a postdoctoral researcher, Amir Mehdizadeh, joined Brasseur’s team in the last two years of the CWF program on a Fellowship from Germany. As discussed below, the theme of Mehdizadeh’s research interfaced with the Subtask 1.2 “New hybrid RANS-LES model formulation”) developments.

In summary, the financial and material support applied to the development of the CWF program extended well beyond the DOE award.

COMPUTATIONAL SUPPORT.

One of the greatest practical difficulties in developing and carrying out the development and application of the Cyber Wind Facility concept was the large time requirements to obtain, maintain, and learn to use the CPU and hardware/software systems required for an effort of this magnitude. Many proposals were written to XSEDE (NSF, Blacklight at PSC, Kraken and Darter at NICS, Stampede at TAAC), the DOE (Titan at Oak Ridge) and to NREL/DOE for use of Peregrine. Whereas the highly valued CPU time awarded on the NREL Peregrine platform came at a critical time in CWF development, it was subsequently removed by the DOE Wind Program when it was determined that other priorities took precedence. Similarly, whereas the personnel at Oak Ridge were extremely helpful and significant discretionary computer time was granted we were unsuccessful in obtaining an award for major CPU on the DOE Titan machine through the ALCC and INCITE programs because it is not possible to provide scaling into the tens and hundreds of thousands of cores with highly nonlinear multicomponent simulations on complex geometries within the OpenFOAM environment, as required for the use of DOE ASCR Facilities at Oak Ridge and Argonne National Labs. Consequently most of the CPU support used for this far-reaching DOE-funded research program was provided by the NSF-funded XSEDE program.

SUMMARY OF RESEARCH ACTIVITIES

We organize the description of research activities carried out under this program according to the tasks outlined in the "Statement of Project Objectives" (SOPO) develop ed December 2011. The primary Task 1, the Development of Individual Cyber Wind Facility (CWF) Components, is separated into 5 subtasks, each one of the components of the CWF system, with validation (task 2), integration into a functional Cyber Wind Facility (task 3) and application to the analysis of the response of the utility scale wind turbine and its wake to atmospheric turbulence (task 4). An important sub-aim was interaction with industry, specifically GE Global Research (task 5) who's data played a major role in validation (task 2).

Subtask 1.1 Atmospheric Boundary Layer (ABL) Large-Eddy Simulation (LES) Module (Led by Dr. Brasseur)

AIMS SUMMARIZED/EDITED FROM SOPO: Our aims are the development of large-eddy simulation of canonical daytime atmospheric boundary layers over land and ocean consistent with the wind turbine environment to couple directly to the aerodynamics loadings module (task 1.2) and the platform computational hydrodynamics module (subtask 1.3). The ABL simulations are to be very well resolved to accommodate a reduction in scale that takes place within the domain of the computational aero dynamics module (from of order the blade chord on the domain boundaries to the boundary layer on the surfaces of the wind turbine blades). In addition, the ABL module will be designed to assimilate time-dependent wind and surface energy flux forced at the mesoscale by WRF weather prediction runs appropriate to notional daytime environments over land and water (task 4.0). The coupled ABL - aerodynamics (task 1.2) software modules form the core CWF capability.

PERSONNEL

There are two sub-elements of research under this subtask. The first is the development of high-resolution large-eddy simulations for incorporation into the aerodynamics wind turbine module (subtask 1.2) for predicting the nonsteady responses of blade boundary layer and loads on a utility-scale wind turbine rotor due to the passage of true daytime atmospheric turbulence eddying structures as they sweep through the rotor plane. The atmospheric boundary layer simulations for these applications were developed by the three PhD students, Ganesh Vijayakumar, Tarak Nandi and Adam Lavely. The second sub-element is the development and analysis of ABL turbulence eddying structure as a function of atmospheric stability state and on the nonstationary modulations of atmospheric turbulence by the local passage of mesoscale eddies. These simulations and studies were developed and carried out by Dr. Balaji Jayaraman working with Prof. Brasseur. Of the researchers above, Jayaraman and Nandi were directly supported by DOE funding. Vijayakumar was funded primarily from a previous NSF grant and with support from the Penn State College of Engineering. Lavely was supported by the Penn State Applied Research Lab under a Walker Fellowship.

LARGE-EDDY SIMULATION ABL DEVELOPMENTS.

As mentioned above, each of the students who developed simulations and analysis with the Cyber Wind Facility module (subtask 1.2) developed high-resolution high-quality large-eddy simulations of the daytime ABL being careful to validate against previous simulations and the literature. In order that the grid cells be of order the blade chord (2-3 chord), Vijayakumar's precursor LES for CWF simulations was on a 512 x 512 x 256 grid (GT: Vijayakumar 2015, JP: Vijayakumar *et al*. 2016) while the CWF-GE simulation developed by Nandi applied 768 x 768 x 258 grid resolution to his precursor simulation (GT: Nandi 2017). Ganesh Vijayakumar, in particular, has not only created a high-resolution/accuracy LES of the daytime ABL, he has carefully compared the effect of algorithm on the well-known deviations from LOTW in the surface layer that recently been explained (Brasseur & Wei 2010). As a result of this work (JP: Vijayakumar et al. 2012), both the precursor simulations and the CWF simulations of all three students (Vijayakumar, Nandi, Lavely) have been designed taking into account the approach developed by Brasseur & Wei (2910) with the results of Vijayakumar *et al*. to minimize deviations from law-of-the-wall in the ABL surface layer.

Lavely and Vijayakumar also carried out major studies to compare LES of the neutral vs. moderately convective (daytime) atmospheric boundary layer in relationship to nonsteady response of utility scale wind turbine to the passage of ABL turbulence eddying structures through the rotor disk (JP: Lavely, *et al*. 2011, GT: Vijayakumar 2015, Lavely 2017). Specifically they quantified the differences in convective time scales associated with the passage of the energy-dominant integral scale eddies through the rotor plane as well as a wide range of statistical characteristics ((JP: Lavely, *et al*. 2011). All CWF simulations were carried out with precursor ABL large-eddy simulations characterizing the typical daytime atmospheric boundary layer which is moderately convective.

ATMOSPHERIC TURBULENCE MODULATED BY ATMOSPHERIC STABILITY STATE AND BY MESO-SCALE FORCING OF THE MICRO SCALE TURBULENCE.

The last statement in the previous paragraph—that the typical daytime atmospheric boundary layer is moderately convective, is strongly confirmed by an in-depth analysis carried out by Jayaraman and Brasseur in which the stability state of the equilibrium ABL was systematically varied from neutral into the moderately convective state, as characterized by the ratio of boundary layer depth z_i to the Obukhov length scale L, which is negative in the daytime unstable ABL state with magnitude that characterizes the height at which the boundary layer transitions from shear to buoyancy dominant. Thus $-z_i/L > 0$ characterizes increasing effects of buoyancy relative to the buoyancy-free neutral state ($-z_i/L = 0$). In Jayaraman & Brasseur (2014) we show that with even slight levels of solar-generated surface heat flux, the ABL transitions to a state in which the energy-containing turbulence eddies dramatically change in size and structure in comparison to the neutral state. Thus, it is highly unlikely that the ABL is ever in a stability state characterized by the commonly used neutral model in the vast majority of wind turbine simulations and wind turbine experiments. Our analysis further adds much to the understanding of the generation of "large-scale rolls," an atmospheric phenomenon that has been observed and discussed for decades in the micrometeorology literature. We show the existence of an "optimal roll coherence state" at $-z_i/L \approx 1$ where "coherence" involves a combination of spatial and temporal correlations (or deviations therefrom).

Commonly applied examples are the kinematic models of atmospheric turbulence embedded within the NREL TurbSim software commonly applied in the United States, and in the Mann kinematic model commonly applied in Europe. Both of these models aim to characterize atmospheric turbulence fluctuations in fully shear-dominated turbulent flow. As part of our CWF program, Lavely *et al*. (2012) showed the major differences in turbulence structure given by the TurbSim kinematic model in comparison to our large-eddy simulations of the daytime (moderately convective) atmospheric boundary layer.

Furthermore, all models of the micrometeorological turbulence structure of the ABL used in wind turbine simulations assume, of necessity by current state-of-the-art, that the ABL is in an equilibrium state -- quasi stationary and characterized entirely by the stability parameter z_i/L, latitude (Coriolis-to-large-eddy time scale), Reynolds number, and roughness. However, the ABL occupies the lower 1-2 km or the troposphere is forced from above by mesoscale motions in the free troposphere where weather events pass over the location of the wind turbine or wind farm creating nonstationary nonequilibrium responses in the ABL. The eddying structure at the mesoscale is at horizontal scales orders of magnitude larger than the scale of the largest vertical motions in the ABL, but have a frontal behaviors that creates changes in time over horizontal domains larger than the typical computational domain if ABL LES (3-5 km). Of potential importance to wind turbine function is the magnitude and nature of the response of the ABL mean flow, turbulence statistics and turbulence structure. The characteristics and magnitude of "meso-micro-scale coupling" on daytime ABL turbulence was the central theme of a major effort by Jayaraman and Brasseur in collaboration with collaborator Sue Haupt (and her colleagues) at the National Center for Atmospheric Research. Because this research was developed towards the end of the CWF research program it has not yet been written up in a paper but has been presented at scientific conferences and in invited presentations (MP: Jayaraman, *et al*. 2016, 2015, 2014; Brasseur, *et al*. 2015; IP, Brasseur: Dec 2015, Oct 2015, June 2015). Aspects of this work were also presented in an invited joint presentation (with Jeff Mirocha, LLNL) at the A2e High-Fidelity Modeling Wind Plant Physics Planning Meeting in Feb 2015.

To analyze the influence of nonstationary forcing at the mesoscale on ABL mean flow and turbulence structure, we developed a model that couples mesoscale transients to the evolution of the microscale (one-way coupling). Applying the quite justifiable approximation of horizontal homogeneity over the LES computational domain, we show that the "geostrophic wind" and "mesoscale wind" vectors are the same only in the equilibrium quasi-stationary limit and that the deviations between the two increases with increasing levels of nonstationarity in the mesoscale winds. By coupling a WRF simulation of warm and cold front passage over Kansas (developed by Haupt and colleagues at NCAR) with LES of the atmospheric boundary layer (through the geostrophic wind), we show that the deviations in the mesoscale from stationarity produce major deviations from equilibrium in the evolution of the ABL. The mean flow velocity, turbulence statistics and turbulence structure are strongly affected by passage of these typical fronts over Kansas. Non-stationarity at the mesoscale arises from both the time changes in mesoscale wind velocity vector (magnitude and direction) as weather fronts pass over the location of the wind turbine/farm, and also in the diurnal change in surface heat flux between sun up (zero flux), solar maximum (max flux) and sun down (zero flux again). We show that in the interplay between deviations from the stationary state in buoyancy force, arising from solar heating, and in horizontal winds as the mesoscale, produce interesting deviations from equilibrium behaviors that, for example, manifest in different turbulence eddying structure at the same equilibrium stability state parameter, z_i/L.

The data generated under the meso-micro coupling study is yet to be fully analyzed and has not yet been written up in manuscript form. Whereas the other research that discovered the high levels of sensitivity between atmospheric turbulence structure and deviations from the neutral ABL state into the moderately convective daytime ABL state has been written in manuscript form as an AIAA paper, this research has been written into a more compressive manuscript for submission to a major scientific journal. We hope to submit within the next month or two.

Subtask 1.2 Aerodynamic Loadings Computational Aerodynamics Module (Led by Dr. Brasseur)

AIMS SUMMARIZED/EDITED FROM SOPO: The coupled ABL (task 1.1) - aerodynamics software modules form the core CWF capability to predict the interaction between atmospheric turbulence and the spatio-temporal loadings on the wind turbine. We aim to develop the computational aerodynamics module within the OpenFOAM framework using on a hybrid URANS-LES formulation form the blade on a grid rotating with the turbine rotor coupled to an ABL grid fixed relative to the ground. The design of the rapid transition in scale from a structured high aspect ratio URANS grid adjacent to the blade surface to an LES grid away from the blade surface, the coupling between the inner rotating and outer fixed grids, and the change in grid scale within the outer fixed grid will be analyzed for accuracy.

PERSONNEL

Whereas this module was led by Prof. Brasseur, there was a great deal of advisory help from Prof. Paterson and Dr. Craven, experts in the application of the OpenFOAM computational platform. The primary researchers involved in the creation of the Cyber Wind Facility (CWF) aerodynamic module were the three PhD students, Ganesh Vijayakumar, Adam Lavely and Tarak Nandi and the postdoctoral researcher Balaji Jayaraman. Of the four, only Nandi and Jayaraman received funding form the DOE. As mentioned above, Vijayakumar was supported by the NSF and Lavely by a Walker Fellowship from the Penn State Applied Research Lab.

Towards the end of the research program, Profs. Brasseur and Schmitz submitted a successful proposal to the Penn State College of Engineering under the newly established "College of Engineering Innovation Grant Program" entitled "Application of the Penn State High Performance Computing "Cyber Wind

Facility" to Design Atmosphere-Informed Controls of Wind Turbines within Wind Plants to Lower Levelized Cost of Energy." This program provided a significant level of support to Ganesh Vijayakumar and allowed us to "hire" and undergraduate student, Sarah Aguasvivas, to develop an animation from our CWF simulations. Her work is discussed under "Task 4.0 Application of the CWF."

DEVELOPMENT OF SOLVER ON COUPLED MOVING AND FIXED GRIDS

The solver that underlay the core of the Cyber Wind Facility (CWF) was developed primarily by Ganesh Vijayakumar and Adam Lavely with significant help from Balaji Jayaraman and Tarak Nandi. As discussed below (Task 2) Nandi also play the primary role in validation of the CWF while Vijayakumar, Lavely and Jayaraman played major roles in the verification of the grid design.

The details of the solver design for a utility scale wind turbine within LES of the daytime ABL and resolved well down to the viscous sublayer adjacent to the rotor blades are described in detail in the PhD thesis of Vijayakumar (2015). Descriptions are also given in the thesis of Lavely (2017) for the NREL 5 MW wind turbine with rotor diameter of 120 m. Nandi applied all that was learned by Vijayakumar and Lavely in the development of a CWF simulation for the GE 1.5 MW wind turbine with 77 m diameter rotor. The CWF design is therefore also described in the PhD thesis of Nandi (2017). The design of the CWF for blade-boundary-layer-resolved wind turbine rotor simulation within the daytime ABL are described, at various levels of development, in the following publications listed below under journal publications (JP): Vijayakumar, *et al*. 2016, 2014; and Lavely, *et al*. 2014. Details of the solver development were presented in a number of scientific meetings and invited presentations (see the section "Products Developed"). The many difficulties and complications associated with the CWF development are described in an attachment at the end of the technical report entitled "Issues Related to Creating an OpenFOAM High-Fidelity Modeling Environment for Blade-Boundary-Layer-Resolved Wind Turbine Simulations" by Brasseur (2014), a document that also describes details of the CWF computational environment.

The CWF was develop within the OpenFOAM computational framework with the pseudo-spectral LES of the daytime ABL as a precursor simulation from which a location and time period was selected for the placement of the rotor for the blade-boundary-layer-resolved simulation. Whereas the pseudo-spectral domain (~ 5 km x 5 lm x 2 km) was designed to accommodate the energy-dominant large-eddy structure of the atmospheric surface layer, the much smaller CWF domain (~300 m x 300 m x 500 m) was designed to accommodate a single NREL 5 MW wind turbine. In the absence of the wind turbine, however, the computational domain was designed as an atmospheric boundary layer simulator with precisely the same modeling details as the pseudo-spectral ABL LES.

The CWF-ABL, like the pseudo-spectral ABL, carried both the momentum and temperature equations applied the Boussinesq approximation for buoyancy force, and contained the Coriolis term with corresponding mean pressure gradient represented through a geostrophic wind vector. Most importantly, the same surface stress model was applied at the lower surface of the computational domain, which posed particularly difficult problem within the OpenFOAM framework and required special treatment developed by Vijayakumar. Vijayakumar and Brasseur worked with Matt Churchfield at the NREL National Wind Technology Center to help him develop a similar ABL solver within OpenFOAM that is currently referred to with the acronym SOFWA, an open-source code that has been used by many researchers. The initial reports from NREL acknowledge the involvement of Vijayakumar and Brasseur in its development (Churchfield *et al*. 2010, 2012).

Whereas the CWF-ABL solver contained the same elements as the pseudo-spectral solver, in order for the higher accuracy and to avoid the extreme expense of predicting a 5 km x 5 km x 2 pm domain within OpenFOAM, the much smaller CWF-ABL domain applied Dirichlet boundary conditions at the inflow obtained from the precursor pseudo-spectral ABL large-eddy simulation. Furthermore, the wind turbine rotor in the LES was contained within a cylindrical domain with fixed grid that rotated relative to the earth-fixed external CWF-ABL domain. The fixed and rotating grids were coupled using the "Arbitrary Mesh Interface" interpolation utility within OpenFOAM. A great deal of effort was placed into testing the accuracy of the CWF-ABL by passing ABL turbulence through an "empty" CWF-ABL domain with rotating cylindrical domain being sure to design the grid with sufficient resolution and structure to minimize numerical dissipation of the atmospheric eddies (Vijayakumar *et al*. 2012).

Details of the solver design are given in the references and thesis of Vijayakumar and in the document by Brasseur at the end of the Technical Report, and are further summarized in what follow.

NEW HYBRID RANS-LES MODEL FORMULATION

An important advance that was made in the design of the CWF solver was the integration of the LES of the atmospheric boundary layer with blade-boundary-layer-resolved simulations of the wind turbine rotor. An LES cannot remain an LES down to the blade surface and into the viscous sublayer adjacent to the blade; near the surface the simulation must transition either to a direct numerical simulation (DNS) within the lower inertial layer and the viscous sublayer, where all turbulence scales are resolved, or to an unsteady Reynolds-averaged Navier-Stokes (URANS) model where the viscous and inertial wall layers are resolved normal to the blade surface but the integral scale turbulence motions are fully unresolved by the grid geometry parallel to the surface. DNS is impractical so URANS is the only viable option. However, the transition between URANS adjacent to the surface and LES outside the boundary layer is problematic and a major area of research in its own right. Vijayakumar developed a novel solution to the problem by coupling Mentor's k-ω SST-SAS URANS model with the 1-equation LES subfilter-scale (SFS) model used in our ABL LES. Mentor's "scale-adaptive" (SAS) extension to his SST model allows the URANS model to transition naturally into "scale-resolving" mode akin to LES before transitioning into a formal LES structure a chord or more from the blade (see Vijayakumar *et al*. 2016, 2014; Lavely *et al*. 2014 and the PhD thesis of Vijayakumar (2015); as well as the Brasseur Appendix to this report). Vijayakumar's model represents a significant advance, both for blade-boundary-layer-resolved simulation of wind turbine blades and for aerodynamics LES in general.

It should also be mentioned that in the final two years of the CWF program, Dr. Amir Mehdizadeh joined Brasseur's research group on a German Fellowship with a focus on the theory and modeling details behind hybrid RANS-LES methods (Mehdizadeh 2015). Although Mehdizadeh's research was not directly applied within the CWF program, his interactions with Ganesh Vijayakumar helped in the application of Vijayakumar's hybrid RANS-LES approach within the CWF module, and Vijayakumar's model developments influenced the direction of Mehdizadeh's research.

NEW HYBRID RANS-LES WITH TRANSITION MODEL FORMULATION

One of the two foci of the PhD research of Tarak Nandi was the analysis of the role of transition on utility scale wind turbine blades (the other focus is analysis of the GE field data in context with CWF validation, discussed under Tasks 2 and 4). To develop this aim it was necessary for Nandi to put considerable effort into the development, verification and validation of a state-of-the-art transition model. We chose the Langtry & Mentor (2009) transition model in part because it is a well-known state-of-the-art model and in part because it is designed on top of the k-ω SST model and therefore has the potential to be extended to the k-ω SST-SAS model. As describe in his thesis, Nandi (2017) worked closely with Jayaraman to develop and test the Langtry-Mentor transition model on the flat place turbulent boundary layer and discovered an error in the 2009 Langtry & Mentor paper that required reconciliation with previous versions of correlations presented therein (these errors were communicated to Langtry and Mentor). Nandi then applied the revised transition model to a large series of simulations of the nonsteady oscillating airfoil flow (JP: Nandi *et al*. 2016, GT: Nandi 2017)) measured on the S809 airfoil by the University of Glasgow, from whom the raw data from their experiments were obtained. Because these simulations also applied the fully turbulent k-ω SST model, they also played a role in the validation effort for the CWF (task 2.0 below).

However the most major advance of Nandi was his fusion of the k-ω SST-SAS model (GT: Nandi 2017) with the Langtry-Mentor transition model which had never before been attempted. Nandi's successful fusion was applied in his CWF-GE simulations of the GE 1.5 MW wind turbine in the presence of daytime atmospheric boundary layer turbulence. This important computational experiment is discussed under Task 4 below.

GRID DEVELOPMENT AND PRACTICAL ISSUES

As discussed in the document at the end of this report, "Issues Related to Creating an OpenFOAM High-Fidelity Modeling Environment for Blade-Boundary-Layer-Resolved Wind Turbine Simulations," there are serious practical issues that create major obstacles to the successful development of a "Cyber Wind Facility" concept. One is the development of the highly complex grid that must satisfy a number of essential requirements simultaneously: (1) the grid must compress from the grid scale required to resolve the integral scales in atmospheric turbulence, an order of magnitude larger than the chord scale and multiple orders of magnitude larger than the scale of the viscous layer adjacent to the blade surfaces, at a rate that allows the representation of smaller scales without numerical error or instability, (2) the grid must be structured and well-designed tetrahedral elements within a chord of the blade, (3) the grid scale must be an order of magnitude smaller than the integral scales in the wake of the blades and must be designed to minimize numerical dissipation, (4) the grid within the rotating cylindrical zone surrounding the rotating blade must be close to the same size and structure as the grid cells external to the cylindrical region in the fixed ABL domain, and (5) the complexity of the grid geometry at the junction between the wind turbine blade and nacelle and the complexity in transition between the near-surface grid and the grid away from the blade must be somehow accommodated. Whereas the grid scale was a few meters at the inflow, at the surface of the blade the distance between grid cells normal to the blade surface was only 5 μm in order to resolve well the viscous sublayer!

As discussed in the document at the end of this report, to "extrude" a grid adjacent to the surface at these extremely small dimensions with the curvature of the blade, especially around the trailing edge and tips of the blades, was extremely difficult. The students (Vijayakumar and Lavely) literally spend months generating and regenerating grids as they learned the subtleties of the grid-generating software (Pointwise). Indeed, at one point in the program, we almost decided that the inability to generate a grid of sufficient quality to maintain numerical stability without destroying the important turbulence eddying motions with numerical dissipation would lead to failure of the CWF module. However, with a great deal of perseverance, practice, and help from experts, Vijayakumar and Lavely ultimately succeeded in developing the required grid, after several months of effort! The knowledge and expertise gained in this process served Nandi well as he used their methods to develop his grid for the GE-CWF simulation.

In addition to the document in the Appendix at the end of this report, detailed descriptions may be found in the PhD theses of Vijayakumar (2015), Lavely (2017) and Nandi (2017). Journal publications that describe the grid as part of the CWF development include Vijayakumar *et al*. (2016, 2012) and Lavely *et al*. (2014).

SELECTABLE FIDELITY: DEVELOPMENT OF LOWER ORDER MODELS WITH THE CWF FOR COMPARISON WITH FULL BLADE-BOUNDARY-LAYER-RESOLVED SIMULATION

One of the arguments made for the creation of the Cyber Wind Facility concept is its application to the analysis of lower-order models by comparing with the highest fidelity model possible -- the blade-boundary-layer-resolved CWF simulation. To make such one-on-one comparisons, however, it is necessary that the higher and lower fidelity CWF simulation be carried out with the same ABL inflow and with minimal changes in the CWF structure and grid. The blade boundary layer simulations of Vijayakumar were compared to ALM and BEMT simulations using this approach by Lavely (JP: Lavely *et al*. 2014, GT: Lavely 2014). Lavely's important comparisons are described briefly under Task 4 below. Subsequently Nandi developed the GE-CWF for the GE 1.5 MW wind turbine rotor for comparison with the GE field data (JP: Nandi *et al*. 2017) both as part of the validation process (Task 2) and the analysis process (Task 4). Nandi also compared ALM with full blade-boundary-layer-resolved simulation (GT: Nandi 2017).

VERIFICATION & VALIDATION AND ANALYSIS OF GE FIELD CAMPAIGN

Verification and validation are summarized below under "Task 2.0 Benchmark and Validation."

APPLICATIONS

Applications of the CWF module are summarized below under "Task 4.0 Application of the CWF."

Subtask 1.3 Platform Computational Hydro Dynamics (CHD) Module (Led by Dr. Paterson)

AIMS SUMMARIZED/EDITED FROM SOPO: The aim is to develop a software module within the OpenFOAM environment that incorporates well-resolved computational hydro dynamics of wave-induced loadings on a wind turbine platform into the CWF in order to predict six degree-of-freedom (6-DOF) platform motions in response to modeled wave structure and forces/moments on the rotor and tower. Free-surface waves will be resolved using volume-of-fluid and level-set methods. Relatively simple models for surface wave motion will be developed that incorporates basic kinematic models for ocean wave fields with incorporates met/buoy data for application in the current program. The surface wave model will also be applied in the MABL submodule of subtask 1.1. With this module the CWF aims to have the capability to predict atmosphere-rotor interactions in the offshore marine environment with buoy-type platforms.

PERSONNEL

The development of this the CHD module was directed by Eric Paterson, Penn State Applied Research Lab and Department of Mechanical Engineering, who moved during the course of the program to VA Tech to become Department Head of Aerospace and Ocean Engineering. CHD module development and application was hampered by several major personnel changes and change of academic plans. The team consisted of 2 faculty (Eric Paterson and Brent Craven) and 2 PhD students (Alex Dunbar and Di Zhang). During the execution of the CWF, Dr. Paterson moved from Penn State to Virginia Tech in 2012, and Dr. Craven moved from Penn State to the US Food & Drug Administration in 2015. In addition, Alex Dunbar ended his PhD studies on this topic and earned a M.S. with the paper option. Di Zhang, who was supported at Virginia Tech on a GRA to support the VT HPC center, was forced to change topics when that funding disappeared. Di is finishing his PhD in 2017 on a non CHD-Module wind-energy topic inspired by the CWF, but on funding provided by the VT Institute for Critical Technology and Applied Sciences (ICTAS). Because of these changes, technical advancement of the CHD Module was limited in scope and did not meet the objectives of the proposal.

SOLVER FOR SIMULATING FLOATING OFFSHORE WIND TURBINE PLATFORMS

Simulations of offshore floating wind turbine platform dynamics typically utilize engineering tools that include simplified modeling assumptions. In our CHD Module work, an open-source CFD/6-DOF solver is developed using OpenFOAM for high-fidelity simulation of offshore floating wind turbine platforms. The solver tightly couples the fluid and 6-DOF equations of motion using sub-iterations and dynamic relaxation to eliminate the artificial added mass instability. Validation of the tightly coupled CFD/6-DOF solver was carried out on a benchmark case of the free decay of a heaving cylinder. The solver was then used in simulations of the DeepCwind semi submersible platform and compared with FAST, a NREL engineering tool. The CFD/6-DOF solver and FAST were compared in four cases including both rotational and translational motion. Overall, the results demonstrated that the tightly coupled solver compared well with FAST. The tightly coupled CFD/6-DOF solver represents an advance in modeling of offshore wind turbine platform dynamics using open-source software that may be used for wind turbine research, design, and analysis. This work is described in detail in a journal publication (JP: Dunbar *et al*. 2015).

WAVE AND MARINE BUOY MODEL DEVELOPMENT

Work on mooring-line and wave modeling was to be the focus of Di Zhang's PhD work. Unfortunately, due to funding challenge, he made little advancement on these topics, and there is nothing to report.

Subtask 1.4 Advanced Wake Actuator Line Methods Wake Turbulence Module (Led by Dr. Schmitz)

AIMS SUMMARIZED/EDITED FROM SOPO: This software module will predict the turbulence in the wake of the wind turbine rotor from the interactions between atmospheric turbulence and the rotating rotor-blades. The aim of the task is to improve current actuator line approaches and to generalize the actuator line methods with the "Actuator Vortex Embedding" (AVE) method. (Note that in this new approach is slightly modified in name and application from the "actuator vortex body embedding" (AVE) method described in the proposal and SOPO). The advanced actuator line models are to be incorporated into ABL LES within the OpenFOAM environment (task 1.2). The AVE method will be compared with current actuator line and disk methods. Expected outcomes include a more accurate generalized formulation than classical actuator line and disk methods and detailed analysis of wake turbulence from atmosphere-turbine interactions.

PERSONNEL

In addition to the co-PI, Dr. Schmitz, the DOE supported a graduate student, Dr. Pankaj Jah to develop his PhD thesis with Dr. Schmitz based on subtask 1.4 research objectives (GT: Jha 2015). An additional M.S. student Zhixiang Wang joined Dr. Schmitz in August 2013, funded through a Teaching Assistantship. Two undergraduate student volunteers, Jessica Bashioum and Sarah Aguasvivas, made significant contributions to flow visualizations that were presented at the Gallery of Fluid Motion at APS Division of Fluid Dynamics meetings (MP: Jha, Bashioum, *et al*. 2013, Aguasvivas, *et al*. 2014). In 2015, Sarah worked within a team lead by Dr. Brasseur and Dr. Schmitz to develop a analysis-oriented scientific visualization with PhD student Adam Lavely, presented at the 2015 APS Division of Fluid Dynamics annual meeting (MP: Aguasvivas, *et al*. 2015). Dr. Schmitz and his team collaborated with Dr. Matt Churchfield (NREL) and Dr. Earl Duque (Intelligent Light) that resulted in co-authored publications (JP: Jha, Duque, *et al*. 2015, 2014).

DEVELOPMENT OF AN ADVANCED ACTUATOR LINE MODEL

The CWF Wake Module focused on improved Actuator Line Modeling of wind turbines in the atmospheric boundary layer. Results from the wake module have been transferred to other CWF modules. Pankaj started working in early 2012 on the CWF project and spent the summer at NREL (hosted by Matt Churchfield). After his return to Penn State, he focused his attention on assessing the accuracy of the actuator line method to date (Fall 2012). Papers were presented at the AIAA meeting in January 2013 and 2014 (JP: Jha, Churchfield, *et al*. 2013, 2014). During the course of this work, Sven and Pankaj developed simple consistent rules to improve the capability of the actuator line method in predicting sectional blade loads. These studies were primarily performed in uniform inflow. Validation cases included an elliptically-loaded wing and the NREL Phase VI rotor in rotating and parked conditions. The results of this work were subsequently published in the ASME Journal of Solar Energy Engineering (JP: Schmitz *et al*. 2013). A summary "guide" to improved actuator line models for wind turbine representation with large-eddy simulation was published in 2014 (JP: Jha, Churchfield, *et al*. 2014).

The simulations applied to quantify and improve state-of-the-art ALM in predicting spanwise blade loads, rotor thrust and power were performed with steady and uniform inflow on LES-type grids with grid aspect ratio close to unity, and on stretched grids). A rigorous study on assessing ALM accuracy through comparison against available data, classical lifting-line solutions, and a blade-element momentum (BEM) method was performed. The sensitivity of computed sectional blade loads as well as integrated rotor thrust and power on the major ALM parameters was analyzed. An assessment of accuracy of the state-of-the-art ALM with regards to the ALM parameters was performed by studying an elliptically loaded wing with two different planforms, and the NREL Phase VI rotor under parked and rotating conditions. A new method was developed in which the Gaussian radius is based on an equivalent elliptic blade planform of the same *AR* as the actual blade. The basic idea of the new method was inspired by the work of Schrenk (1940) used in the fixed-wing community and leads to a set of universal criteria to be used for the ALM parameters on LES-type grids. Available data for the NREL Phase VI rotor and BEM results were used for quantitative comparisons with the new ALM models to optimize parameter choices. Comparisons among parameters with proposed new criteria were performed for the cases for which an accuracy assessment was performed. It was found that the new method for the Gaussian radius and guidelines for the grid spacing and actuator spacing yield improved and consistent predictions for sectional blade loads. Also, ALM simulations were performed for the NREL 5-MW turbine using the new method and compared to BEM results and other

ALM approaches. It was again found that the new method in which the Gaussian radius is determined by an equivalent elliptic blade planform gives consistent and improved predictions of 41 sectional blade loads.

DEVELOPMENT OF THE ACTUATOR CURVE EMBEDDING' (ACE) MODEL

An integral part of the original proposal was the development of novel idea for actuator modeling based on Sven's earlier work on vorticity embedding for helicopter hover flows. (The original concept of vorticity embedding was first developed by Prof. John Steinhoff in the late 1980s.) The conceptual idea of discretizing an actuator line at once, rather than having a sequence of actuator points with overlapping volumetric force fields, was named 'Actuator Curve Embedding' (ACE) where 'Curve' is used to indicate that this method works independent of the (structural) deformation of the lifting (or actuator) line. Sven programmed the idea in Fortran source code in 2012 and passed it on to Pankaj in 2013 for implementation into OpenFOAM. The first preliminary results were presented at the APS Division of Fluid Dynamics meeting in 2013 in Pittsburgh PA (MP: Jha & Schmitz 2013). Since then, Pankaj has performed a number of simulations with validations against an elliptically-loaded wing and the rotating and parked NREL Phase VI rotor as well as the NREL 5-MW turbine (comparison to other ALM approaches). These results are documented in Pankaj's Ph.D. thesis (GT: Jha 2015).

The ACE approach is based on the previously discovered need to avoid the overlap of Gaussian spheres with classical and improved ALMs. Since the state-of-the-art ALM as well as the modified ALM uses a 3D Gaussian kernel function to project the blade force (per unit volume) on the volumetric grid, the blade force is spread onto the grid cells in all three coordinate directions with equal weighting which causes the higher blade force inboard of a blade tip to influence cells near the blade tip. This non-physical force overlap produces spuriously high net body force in cells near the tip and the resulting velocity field at the few outer actuator points is influenced by the inner actuator points more than they should be. To avoid this, we develop an approach that avoids the spanwise spreading around an actuator point by using a 2D Gaussian kernel function. The blade force computed at each of the actuator points along the arc (or locus of actuator points) is spread in a disk normal to the local arc. Moreover, instead of looping over each actuator point to compute the contribution to body force from each sphere of influence, a reverse approach is followed: the entire flow field sees the influence of a blade/wing as a whole. The details fo the algorithm are given in the PhD thesis of Pankaj Jha (*GT: Jha 2015*). The blade force and projected body force are computed in each grid cell associated with a unique actuator point on the curve rather than visited by multiple actuator points; thus the issue of overlap is avoided.

APPLICATIONS TO WIND TURBINE WAKE ANALYSIS

In late 2013, Pankaj developed actuator line simulations in the atmospheric boundary layer in a turbine-turbine interaction problem and (in 2014) a small wind farm consisting of 5 wind turbines arranged in two staggered arrays. Quantitative analyses were conducted of Reynolds stress distributions along horizontal/vertical/spanwise lines to better understand the recovery patterns of the wake momentum deficit in the atmosphere in neutral and unstable conditions. The collaboration with Earl Duque was very productive; a post-processing infrastructure was set up that allowed undergraduate students Jessica Bashioum and Sarah Aguasvivas to create insightful flow visualizations of turbulent wake flows. These fluid movies were presented at two APS Division of Fluid Dynamics (Gallery of Fluid Motion) meetings (Jha, Bachioum, *et al*. 2013, Aguasvivas, *et al*. 2014, 2015). Associated analyses were published in the *Energies* journal in June 2015 (Jha, *et al*. 2015). Conference papers were presented at AIAA SciTech meetings, one that compares actuator line models within ABL LES (Jha, *et al*. 2014) and one extending the model to include the nacelle (Churchfield *et al*. 2015), and at the American Helicopter Society (AHS) Forum applying the advanced actuator line models developed for wind turbine wake prediction (Jha, Duque, *et al*. 2014) as well as to other rotorcraft (Schmitz & Jha 2013). Recent publications apply their advanced actuator line models to study blade unsteadiness and turbulence when wind turbines interact (Jha *et al*. 2016).

Subtask 1.5 Aeroelasticity Computational Solid Dynamics Module with Fluid-Structure Interaction (led by Dr. Campbell)

AIMS SUMMARIZED/EDITED FROM SOPO: The aim is to develop a software module based on computational solid dynamics and fluid-structure-interaction (FSI) modeling of blade and tower deformations in the presence of space-time varying surface stresses from the computational aerodynamics module using efficient linear modeling where possible combined with nonlinear modeling on structural components undergoing large deformations. The module will incorporate a novel FSI solver with disparate solid and fluid meshes and an overlapping "auxiliary" mesh with variable rigidity in mesh elements so as to force the fluid mesh to remain relatively rigid with respect to the blade surface while allowing the fluid grid to deform away from the blade within the rotating domain. The longer-term aim is for the CWF to predict fluid-structure interactions from local aerodynamic forces to capture deformations associated with atmospheric turbulence.

PERSONNEL

Dr. Campbell advised graduate student Javier Motta-Mena, supported by the DOE, to develop the research in subtask 1.5. Mr. Motta-Mena began his research program intending to complete a PhD thesis under the CWF program but later changed to a Master of Science thesis with the aim to enter industry. He completed his M.S. thesis, graduated August 2015 and currently works as a Systems Engineer for Ford Motor Company.

DEVELOPMENT OF SOLVERS FOR ELASTIC BLADE DEFORMATION

This work is described in detail in Javier Motta-Mena's M.S. thesis (GT: Motta-Mena 2015). The developments were summarized in presentations at the APS Division of Fluid Dynamics meeting of 2013 (MP: Campbell, *et al*. 2013, Motta-Menna, *et al*. 2013) and the 32nd ASME Wind Energy Symposium in 2014 (JP: Motta-Mena, *et al.* 2014).

A reduced order, partitioned FSI solver was developed to assess the importance of blade flexibility on the performance of a 5 MW wind turbine in the presence of atmospheric boundary layer (ABL) turbulence. The FSI solver was implemented with a partitioned approach that incorporates an existing OpenFOAM-based actuator line method (ALM) solver and a modal structural dynamics solver. This reduced-order solver incorporates a tightly coupled framework using a fixed-point iteration to ensure proper convergence of the flow field and structural displacements at each solution time step.

The OpenFOAM-based ALM solver and author-developed, modal-based structural dynamics solver were developed with a strong emphasis on the solver's ability to incorporate blade bending and twisting motion to ensure the blade's bend-twist coupling features were captured properly. The tight coupling and incorporation of blade twisting are solver features that are currently not widely available in wind turbine analysis software.

The flow solver is a variation of OpenFOAM's pimpleDyMFoam solver, which is a transient solver based on the hybrid Pressure Implicit Split Operator - Semi-Implicit Method for Pressure Linked Equations (PISO-SIMPLE) algorithm, which also includes dynamic mesh motion capabilities. The ALM solver applied was that developed under subtask 1.4 summarized herein. The existing pimpleDyMFoam source code was modified to include additional terms required to accurately model ABL turbulence (the Coriolis force due to planetary rotation and the buoyancy force) and the wind turbine via the ALM ("ablActuatorDyMFoam").

The structural solver developed is based on a modal summation formulation, wherein an arbitrary number of eigenvectors and eigenvalues determined for the fixed reference frame are used to describe the motion of the structure as it deforms. The implementation employed here is similar to that of the aero-elastic module in FAST except that the analysis is not restricted in the number or type of modes employed and bend-twist coupling effects can be included provided the simulation basis set includes such information. Although the original ALM formulation does not incorporate an aerodynamic pitching moment calculation in its framework, the necessary modifications were made to include it for this module. However, its effect on the fluid-structure interaction is only partially implemented—the effect of the pitching moment on the structure is considered, but not the effect on the flow. To properly account for the effect of gravitational, Coriolis and centrifugal forces on the blades, the finite element principle of work-equivalent loads is implemented in the structural solver.

The bend-twist coupling effect is a consequence of the principal material direction of laminas being skewed with respect to the blade axis. It is important to model this effect as accurately as possible, as it plays a crucial role in predicting the structure’s response and its interaction with the flow around it. The structural solver uses the flap-wise component of displacement of the LE and TE, as well as the local chord, to compute the twist due to deformation.

Javier coupled the flow and structural solvers in a partitioned manner, relying on sub-iterations every time step to tightly converge the solutions. Simulations were performed with various degrees of coupling, from loose (no sub-iterations) to tight (fully converged) to assess the importance of using tight coupling. The solver represents a reduced-order FSI solver (selectable fidelity) capable of simulating several minutes of turbine operation in a few hundred computational hours.

Validation and verification of the solver was performed in several steps during the development of the flow solver (Subtask 1.4), the structural solver, and then the coupled solver. The validation and verification process is summarized below in the Task 2.0 section. Features of the final solver include:

- The solver requires an arbitrary number of rotor structural mode shapes, which can be based on a finite element model of the rotor with any degree of complexity and resolution (but limited to linear response); mass normalized mode shapes, resonance frequencies, and finite element mesh are all that is required. The mode shapes for this work were obtained from an ABAQUS model of the NREL 5 MW rotor.
- The rotor structural model incorporates gravitational, Coriolis, and centrifugal forces; the full structural mesh is used for this, with nodal masses computed for each finite element node.
- A Newmark time integration scheme (implicit, average acceleration method that is unconditionally stable) is used to perform the time integration at each solution step.
- A fixed-point iteration is used at each time step to ensure tight coupling of the solver (or no sub-iterations for a loosely coupled simulation).

ANALYSIS OF ELASTIC RESPONSE OF WIND TURBINE BLADES

Prior to the analysis with ABL turbulence inflow, a uniform and steady flow analysis was performed to gain initial insight into the rotor’s structural response and its effect on the turbine’s aerodynamics. The effect of various things, such as tight coupling, bend/twist, pitching moment, etc. were evaluated for a uniform inflow case. It was determined that there is a significant difference in the turbine’s operation when blade flexibility is enabled. Mainly, the aerodynamic loads and estimated power output have lower values in the flexible blade cases compared to the rigid blade cases. This analysis also revealed that the difference between rigid blade and flexible blade cases is largely due to the blade bend-twist coupling. (A non-discernible difference was observed when comparing rigid blade results to flexible blade results without blade twisting.) The importance of including the aerodynamic pitching moment in the formulation of the structural solver was also demonstrated. The response of the rotor is substantially different when this load is omitted, which leads to an incorrect solution.

Upon completion of the preliminary analysis, the main analysis focusing on ABL turbulence inflow was conducted. Simulations were performed using turbulent inflow conditions consistent with the daytime (moderately convective) ABL. Simulations were performed using the full solver and the solver without the effect of blade twist. Using the same moderately convective ABL flow conditions, the simulation was repeated, but this time with a single rotating blade that was been initialized with uniform inflow conditions and results compared to the “single-blade-rotating-in-atmosphere” (SRBiA) simulation by Ganesh Vijayakumar (task 1.2).

Results showed that the structural response of the rotor is significantly more complex than in the uniform and steady flow analysis, as anticipated due to complex nature of the unsteady spatial-varying loadings caused by turbulent-eddy passage in the ABL. Special focus was placed on a 20 second period of the simulation, where the rotor deforms upwind past the tower for short periods of time, a phenomenon not present in uniform and steady flow conditions. Turbulence-elastic-blade interactions appear to cause opposing twisting motions from the first flapwise bending mode and the first edgewise bending mode. The loads on the blades and the turbine's estimated generated power are both lower in the flexible blade case. The ABL analysis revealed that blade flexibility plays a substantial role in the overall operation of the turbine, given its effects on the turbine's loads and power output.

The analyses are described in detail in Javier Motta-Mena's M.S. thesis (GT: Motta-Mena 2015). Analysis was summarized in a presentation at the APS Division of Fluid Dynamics meeting of 2015 (MP: Motta-Menna, *et al*. 2015).

Task 2.0 Benchmark and Validation

AIMS SUMMARIZED/EDITED FROM SOPO: The aim is to individually benchmark and validate each module with experimental or computational data from the literature or other studies. Because validation will be particularly difficult for the integrated CWF the outcome of the component validation exercise is important. The project team will work closely with the project's industrial partner and shall develop interactions with NREL (Moriarty).

[1.1] Atmospheric Boundary Layer Module

The development and validation of the atmospheric boundary layer module was summarized above under Subtask 1.1 "Atmospheric Boundary Layer (ABL) Large-Eddy Simulation (LES) Module." The long history of ABL LES has previously validated predictions with the exception of the important near-surface region where LES of the ABL generally does not properly predict law-of-the-wall. As explained above, the precursor ABL pseudo-spectral large-eddy simulations were carefully designed to satisfy the requirements to satisfy law-of-the-wall at a reasonable level using the method described in Brasseur & Wei (2010). These efforts are described in JP: Vijayakumar *et al*. (2012) and in GT: Vijayakumar (2015). The research of Jayaraman (JP: Jayaraman & Brasseur 2014) indicates that the daytime ABL is moderately convective: therefore the precurser simulations were all for the moderately convective daytime atmospheric boundary layer.

[1.2] Aerodynamics HPC Module

A great deal of effort has gone into the various processes underlying verification and validation for the development of the Cyber Wind Facility. Indeed, given the fact that blade-boundary-layer-resolved CWF simulations are both extremely expensive and extremely time-consuming and difficult to generate (see Brasseur 2014 in the Appendix), a great deal of discussion went into the question what is validation and how to validate a simulation strategy that aims to capture the key nonsteady variations in local blade and integrated rotor loads in response to the passage of atmospheric eddies through the rotor plane. Given that we would, at best, be able to carry out one or two blade-boundary-layer-resolved simulations with atmospheric turbulence within the Cyber Wind Facility over only a couple blade rotations—insufficient for statistical analysis—we recognized early on that for verification and validation (V & V) of nonsteady response predictions we had to largely rely on V & V associated with the development of different components. Some of these component analyses are discussed in detail in the appendix. These are briefly described below.

However, when simulations could be carried on sufficiently long to capture statistics, more traditional validation was carried out. This was the case for the ALM simulations within the CWF framework developed by Lavely and Nandi. Nandi, in particular, was able to made statistical comparisons of integrated loads with the GE database. These comparisons were quite favorable as discussed Nandi's PhD thesis.

Nandi's research thesis (GT: Nandi 2017) specifically addressed V & V for time response of blade loads, ad briefly discussed below.

GRID DESIGN AND RESOLUTION

The design process for the fully complexity of a multi-zone multi-scale grid that could simultaneously capture ABL turbulence and nonsteady blade boundary layer response down to the viscous layer was extremely difficult and time-consuming, as described in the document in the Appendix "Issues Related to Creating an OpenFOAM High-Fidelity Modeling Environment for Blade-Boundary-Layer-Resolved Wind Turbine Simulations." It was essential to design the grid adjacent to the blade surfaces in carefully and, for obvious practical reasons, outside the fully complexity of at CWF simulation. As described in the appendix, Jayaraman, Vijayakumar, and Lavely used a park NREL 5 MW rotor blade at high angle-of-attack (designed for the boundary layer to separate from the middle of the suction surface) to analyze different grids that can resolved (i) high gradients at the leading and trailing edges, (ii) separation of the shear layer form the suction surface, and (iii) spanwise instabilities and ABL-with-blade-boundary-layer-resolved CWF simulations of Vijayakumar and Nandi, as reported in JP: Vijayakumar *et al.* 2016, 2014; Lavely *et al.* 2014 and the PhD theses of Vijayakumar (2015) and Nandi (2017).

HYBRID RANS-LES WITH TRANSITION MODEL

As described in JP: Nandi *et al.* (2016) and in GT: Nandi (2017), Nandi carried out a detailed series of simulations and analyses of the transitional oscillating S809 airfoil, a case with data from the Universities of Glasgow and Delft as well and Ohio State. We obtained to most extensive database, that from Glasgow, to allow for V & V of our hybrid RANS-LES-with-transition-model simulations described above under subtask 1.2. The aims were threefold: (1) validate the Langtry-Mentor transition model for our applications, (2) analyze the predictions of the fully turbulent k-ω SST model against the k-ω SST model enhanced with the transition model with nonsteady separating boundary layers akin to what might be expected on wind turbine blades, and (3) obtain important physical understanding of the likely nonsteady properties of utility scale wind turbines by related appropriate nondimensional parameter ranges between the S809 database and the NREL 5 MW wind turbine studied by Vijayakumar and Lavely.

Validation of the Blade-Boundary layer-Resolved CWF by Comparison with GE Field Campaign Data

Nandi (with Brasseur) were the leads on a major long-term effort to analyses an experimental dataset from our industrial collaborator, GE Global Research, of a unique field experiment carried out in northwest Germany. The interesting analysis of these data is described in a recent publication in the *Phil. Trans. R. Soc. A* (Nandi, Herrig, Brasseur 2017). In addition to the advances in nonsteady dynamics uncovered in this study, Nandi made comparisons with both ALM and blade-boundary-layer-resolved CWF simulations of the GE 1.5 MW wind turbine used. These validation studies were overall very successful and are described in the *Phil. Trans.* paper and in Nandi's thesis (2017). A particularly important discovery from the analysis of the data from the GE field campaign, integrated with the CWF blade-boundary-layer-resolved simulations of Vijayakumar and the actuator-line-blades-in-atmosphere simulations of Nandi is the existence of three important time scales that characterize the nonsteady response of the wind turbine rotor to atmospheric turbulence: a longer time scale associated with the advection of energy-containing atmospheric turbulence eddies through the rotor plane (~30-90s), the once-per-revolution time scale associated with the period of blade rotation (3-5 s depending on the rated rotor RPM), and the short time scale associate with the ramp-like time responses (~1 s) that result from the passage of the blades through the internal structure of the atmospheric eddies.

[1.3] Hydrodynamics Platform Module

Algorithm stability posed significant challenge in the development of the CHD module. To demonstrate stability of the tightly coupled CFD/ 6-DOF solver, we performed simulations for the benchmark case of free heave decay of a two-dimensional circular cylinder. By studying effects of time step size, the tightly coupled solver was shown to have unconditional stability and to eliminate the non-physical oscillations in velocity and force which were observed in the loosely-coupled formulation.

To verify the numerical simulations, we performed grid and time step convergence studies to ensure that the tightly coupled CFD/6-DOF solutions for free heave decay of a two-dimensional circular cylinder are independent of the mesh resolution and time step size. Specifically, we uniformly refined the computational mesh of the two-dimensional cylinder and performed simulations using three meshes: coarse, medium, and fine that contain approximately 50,000, 80,000, and 150,000 computational cells, respectively. Simulations of free heave decay were performed and the solutions compared for each mesh. The CHD algorithm demonstrated monotonically convergent solutions with increasing mesh resolution and decreasing time step size, with relatively small differences between each of the solutions. Quantitatively, to estimate the numerical error in the simulation results, we calculated the grid and time step convergence indices. The convergence indices for both amplitude and period are less than about 1.5%, thereby demonstrating that the numerical error in the computed results is small and the solution is insensitive to mesh resolution and time step size for the fine mesh and small time step case.

To validate the CHD solver, we performed simulations of the benchmark heaving cylinder case using the fine mesh and small time step and compared the results with theoretical solutions of Maskell and Ursell (1970) and experimental data of Ito (1977). The theoretical solutions were derived using potential theory to solve for the position of the freely heaving cylinder over time, and Ito (1977) conducted an experiment that was designed to validate the theoretical solutions of Maskell and Ursell (1970). Our results showed that the the CHD simulation closely matches the theoretical and experimental data. Quantitatively, the percent difference between the CFD/6-DOF solution and experimental data is small (less than about 3%), thereby validating our solver.

[1.4] Advanced Actuator Line Model Wake Module

In the development process of the AVE method, careful verification & validation studies were performed. In particular, the volumetric body-force spreading of AVE was verified by means of volume integrals over the affected grid cells to ensure conservation of momentum (subtask 1.4a). These fundamental verification studies are documented in the dissertation of PhD student Pankaj Jha. Furthermore, validation studies were conducted against available exact solutions from classical lifting-line theory (elliptic wing) and, in particular, the NREL Phase VI rotor in parked and rotating conditions; the NREL Phase VI data proved to be a valuable validation database as the data were acquired in controlled wind tunnel conditions (subtasks 1.4bc). The originally proposed Tjaerborg turbine was not included in the validation study due to higher data uncertainties that would conflict with accuracy assessment studies of ALM and AVE. Comparison of computed near wakes by both the standard ALM and newly developed AVE were performed (subtask 1.4d) and published (Jha *et al.* 2016). A direct comparison to wake data from large wind farms (subtask 1.4e) could not be performed due to lack of computational resources needed for ABL-LES simulations of wind farms with 30+ turbines, primarily a result of grid requirements found to be necessary for accurate blade load and wake computations. Therefore, a generic 5-turbine (NREL 5-MW) wind farm was constructed in subtask 1.4e, showing array effects very similar to larger wind farms (Jha, Duque *et al.* 2014), in addition to steady validation of NREL 5-MW turbine loads.

[1.5] Aeroelastic Blade Deformation Module

While there is no formal validation of the ALM-FSI solver because of a lack of experimental data, each component of the solver is validated against other solver results. The structural solver was validated by comparing its response to that of a commercial solver (ABAQUS). The ALM-FSI solver was tested by disabling all of the new features and effectively reducing it to a loosely coupled, rigid blade solver. A modal dynamic analysis was performed in both the structural solver and ABAQUS, using the same initial representative aerodynamic forces and moments. The comparisons between the results of these analyses focused on flap-wise displacement and blade twist. Comparisons of trailing and leading edge displacement and twist at the blade tip between the modal static solution and the ABAQUS simulation were compared. The results show that the structural solver is in very good agreement with ABAQUS’s modal dynamic solver. The flow and structural solver coupling was validated in part against various FAST simulations, including a parked rotor case to allow blade vibration ring-down and comparisons of rigid and flexible blades with uniform flow while disabling enhanced features of the ALM-FSI solver (such as bend-twist coupling). Cases with uniform and non-uniform inflow were evaluated to assess the effect of loose and tight coupling, blade pitching moments, and blade bend/twist coupling. Details are given in the Motta-Mena M.S. thesis (GT: Motta-Mena 2015).

INTEGRATION, DEVELOPMENT AND APPLICATION OF CWF

Task 3.0 Integration of Modules into a Complete CWF

AIMS SUMMARIZED/EDITED FROM SOPO: The project team aims to develop and contrast fully and partially coupled methods to dynamically integrate the CWF modules described in Task 1.0 and evaluate performance and efficiency on highly parallelized HPC platforms. Full coupling the ABL spectral LES and aerodynamics finite volume modules will be a technological advance. An alternative may be to run both ABL and aerodynamics modules within the OpenFOAM environment. The team shall test the hypothesis that one-way coupling from ABL LES using a spectral code to the aerodynamics CAD using a finite volume code (OpenFOAM) will be sufficiently accurate to allow this approach to be used with full CWF cyber experiments. We shall explore the concept of "Selectable Fidelity"—the ability to exchange some high-fidelity CWF modules with lower level models such as AeroDyn/FAST and actuator line/disk models as a basis for the improvement of engineering-level design tools.

INTEGRATION OF CWF MODULES: PRACTICAL ISSUES

As has been described in task 1 above, 4 modules have been developed: 1.1 Atmospheric Boundary Layer with LES, 1.2: Aerodynamic Loadings Computational Aerodynamics, 1.3: Platform Computational Hydro Dynamics, and Subtask 1.4: Advanced Wake Actuator Line Methods and Wake Turbulence. In these modules LES of the atmospheric boundary layer (module 1.1) was integrated with a simulation of aerodynamic loads (1.2), hydrodynamics (1.3) and wake development (1.4) as described in the papers and PhD theses referred to in the sections above. These integrations have led to major advances in our understanding of wind turbine dynamics and function (task 4 below). Furthermore, the ALM module (1.4) has been integrated with the aerodynamics module (1.2).

There was insufficient time, however, to integrate beyond the integrations described above. It has turned out to be overly ambitious to produce, within the allotted time and resources available, and the limits associated with typical knowledge and technical levels of new graduate students, a fully integrated CWF. The many difficulties associated with the development of a fully integrated "Cyber Wind Facility" with a 3-bladed rotor modeled with high fidelity blade-boundary-layer-resolved hybrid URANS-LES and fully resolved elastically deforming blades embedded within high-resolution atmospheric boundary layer large-eddy simulation lead to extreme levels of complexity that required much more rapid computational turnaround time to resolve in a three-year period that was available for this program (see Appendix). This conclusion is especially true in the envisioned marine environment with a high-fidelity URANS-wave model and 6 degrees-of-freedom rotor-tower-platform motions.

Given that reality, we feel that we have made tremendous advances within the limits of the funded program and have not only generated a first generation CWF and a great trove of new valuable knowledge, we have shown the path forward if there were a desire to learn from our efforts and organize a direction, with sufficient resources and technology level, to create a fully functional Cyber Wind Facility as envisioned here. The technical knowledge obtained for future developments of blade-boundary-layer-resolved simulation within atmospheric turbulence large-eddy simulation (see appendix), advanced actuator line blade modeling, nonsteady elastic blade response modeling, and platform-wave coupling, however, points the way to future endeavors. The scientific and technical knowledge obtained in regards nonsteady wind turbine response to atmospheric turbulence, lower-order-model accuracy for predicting nonsteady response, "meso-micro" atmospheric response to weather events, elastic blade response to atmospheric turbulence and wake response dynamics to atmospheric turbulence is unparalleled. Furthermore, we have broken new ground in validation of nonsteady response using a unique dataset from a GE field campaign which both contributed to our knowledge of wind turbine function in a real atmospheric boundary layer and to future approaches to validation of time-local response dynamics.

Task 4.0 Application of the CWF

AIMS SUMMARIZED/EDITED FROM SOPO: The team will apply the CWF to a notional offshore and onshore configuration and carry out cyber experiments addressing a range of issues. Of particular interest is space-time load generation associated with atmospheric turbulence , rigid vs. deformable turbine blades, over land vs. over water, etc. An objective is to use cyber experiments with the CWF to isolate loadings for strategies for load mitigation.

Application of the CWF to Blade-Boundary-Layer-Resolved Simulations of a NREL 5MW Wind Turbine Rotor Blade Embedded within ABL Turbulence

Ganesh Vijayakumar applied the Cyber Wind Facility to analyze the nonsteady responses of the rotating blade boundary layer to true daytime atmospheric boundary layer turbulence. Given the high level and number of technical difficulties that must be addressed to develop the CWF, and the extreme level of computational resources and time required to carry out a simulation of ABL turbulence interacting with a rotating three-bladed NREL 5 MW 120 m diameter wind turbine rotor over many rotations of the blade, he was able to simulate a single rotor over 2-3 blade rotations. Thus Vijayakumar focused, in his analysis, on the time scales of blade response at the rotation time scale and shorter. The longer time scale analyze would be left to Adam Lavely to study (below). Vijayakumar's analyses, some of which were in collaboration with Lavely, are reported in these publications: JP: Vijayakumar *et al.*, 2016, 2014, 2012; and Vijayakumar's thesis (2015). Although a number of important advances in knowledge were developed, perhaps two of the particularly important ones are:

(1) The loads (forces and bending moments) on the hub and drivetrain due to the passage of the wind turbine blade through an energetic atmospheric eddy display ramp-line events in which the load changes by large values (40-50% of the mean) at the second time scale. We conclude that as the eddy passes through the rotor plane at a time scale an order of magnitude or more longer than the blade rotation time scale, the blade passes through the internal eddy structure to create large rapid excursions in moments that could impulsively pass through the drivetrain and contribute to fatigue damage on low-speed shaft bearings.

(2) The primary mechanism for the time changes in blade loads are not due, as one might expect, to changes in wind speed, but rather to time changes in the sectional angle-of-attacks.

A great deal more was learned that is described in the papers and thesis identified above.

Application of the Selectable Fidelity Feature of the CWF to Evaluate Ability of BEMT and ALM Rotor/Blade Models to Capture Nonsteady Rotor Response from Atmospheric Turbulence

Adam Lavely applied to CWF to two purposes, firstly to analyze how well the BEMT and ALM models can predict the nonsteady responses of the blade and rotor loads to atmospheric turbulence, and secondly to study the longer time characteristics and mechanics of rotor response to atmospheric turbulence. As reported in his thesis (GT: Lavely 2017) and in JP: Lavely, *et al*. (2014) and MP: Brasseur, *et al*. (2016), tremendous advances have been made in our understanding of the mechanisms that generate nonsteady integrated loadings, in particular thrust vs. bending moments. Furthermore based on the characteristic of "selectable fidelity" in which the full blade-boundary-layer-resolved rotor can be replaced with a lower order model, Lavely's analyses have shown that BEMT does not capture the ramp-like nonsteady responses uncovered by Vijayakumar, but high-fidelity ALM does. As a result of this important discovered a number of statistical studies of long term nonsteady response were carried out by Lavely (GT: Lavely 2017; MP: Brasseur *et al*. 2016) and by Nandi (JP: Nandi *et al*. 2017; GT: Nandi 2017).

The Lavely study, in particular, describes the physics underlying what are likely the dominant contributors to potentially deleterious drive-train loads impacting reliability. What turned out to be a critical element in this analysis was the quantitative animation developed by Aguasvivas in a collaboration between

Brasseur and Schmitz funded by the Penn State College of Engineering (MP: Aguasvivas, *et al*. 2015). Complete details of the analyses can be found in Lavely's PhD thesis (GT: Lavely 2017).

Multi-Scale Time Responses to Wind Turbine Loadings Analyzed with Combined Field and CWF Simulation Data

As has been mentioned, Nandi (and Brasseur) worked closely with colleagues at GE Global Research in Munich Germany in a far-reaching analysis of a GE field campaign with corresponding ABL-CWF simulation using the advanced actuator line model. The important results and conclusions are described in a recent publication by Nandi *et al*. (2017). These results combine with the computational experiments of Vijayakumar and Lavely to characterize three primary times scales associated with nonsteady blade and rotor responded to daytime atmospheric turbulence: the convective time scales associated with the passage or energy-dominant atmospheric eddies through the rotor plane, the rotation time scale associated with the passage of the blade through eddy structure, and a short ~1 sec time scale associated with the ramp-like structure discovered by Vijayakumar in his CWF simulations (JP: Vijayakumar *et al*. 2016, 2015) and, using ALM by Lavely (GT: Lavely 2017).

Wake and Turbine-Turbine Interaction Analyses

The application of CWF simulation using the advanced ALM models developed by Jha and Schmitz are described above under Subtask 1.4. These analyses have been published in a number of papers by Jha and Schmitz, with colleagues, and are summarized in Jha's PhD thesis (2015).

Elastic Response of Blades to Atmospheric Turbulence

Motta-Mena and Campbell studied the elastic response of the NREL 5 MW wind turbine blade to atmospheric turbulence using the same inflow ABL as Lavely with the actuator line model representation of the wind turbine blades developed in subtask 1.4. These studies are summarized in the M.S. thesis of Javier Motta-Mena (2015).

Task 5.0 Industry Interactions

AIMS SUMMARIZED/EDITED FROM SOPO: The project's industry partner will provide industry input in three primary ways: (1) through the running of code to test the CWF modules and the integrated CWF, (2) providing feedback from the testing process to make the modules more valuable from an industry perspective and to develop industry-friendly documentation, and (3) participate in regular meetings by teleconference. The industry partner will identify data specific to field tests with their wind turbines that can be used for validation of the CWF.

ANALYSIS OF GE FIELD CAMPAIGN DATA FOR PHYSICS AND FOR VALIDATION

As has been mentioned several times above, our collaborations with our industry partner, GE Global Research in Munich Germany, have been extremely fruitful. GEGR provided a unique dataset which was analyzed in detail to extranet useful new physics, and which formed the primary dataset used for validation of the CWF. For the latter, Nandi developed a CWF simulation of the GE 1.5 MW wind turbine used in the GE field campaign. A great effort was made to select data appropriate to comparison with an LES of the dry-air ABL in quasi-steady state, which occurs for 2-3 hours after noon. Nandi also developed an ABL LES that closely mimics that ABL experienced by the wind turbines in the GE field campaign, with the GE wind turbine represented using the advanced actuator line model of Jha & Schmitz (task 1.4). The experimental analysis clearly shows the existence of three characteristic time scales, plus a spectrally local depression of turbulent kinetic energy due to rotation. The comparison with the ALM simulation shows a rather amazing correspondence between simulation and experiment, an important validation as well as providing additional physical understanding. This work was recently published in *Phil. Trans. R. Soc. A* (JP: Nandi, Herrrig & Brasseur 2017) and is also found in GT: Nandi 2017.

PRODUCTS DEVELOPED

Below we summarize the "products" developed under this research program. In the text above these references are categorized using the acronyms JP. WP, GT, MP, IP and WP according to the titles of the subsections below:

- JP: Journal Publications and Refereed Proceedings
- GT: Graduate Theses
- MP: Meeting Presentations and Abstracts
- IP: Invited Presentations
- WP: Workshop Participation and Meeting Organization

JP: Journal Publications and Refereed Proceedings

Nandi, T.N., Herrig, A., Brasseur, J.G. 2017 Nonsteady wind turbine response to daytime atmospheric turbulence. *Phil. Trans. R. Soc. A* 375: 20160103. http://dx.doi.org/10.1098/rsta.2016.0103 (25 pgs)

Jha, P. K., Churchfield, M. J., and S. Schmitz, 2016 Blade Load Unsteadiness and Turbulence Statistics in an Actuator-Line Computed Turbine-Turbine Interaction Problem, ASME *Journal of Solar Energy Engineering* 138(3):031002 (13 pages).

Vijayakumar, G., Brasseur, J.G., Lavely, A., Jayaraman, B., Craven, B.C. 2016 Interaction of Atmospheric Turbulence with Blade Boundary Layer Dynamics on a 5MW Wind Turbine using Blade-Boundary-Layer-Resolved CFD with hybrid URANS-LES. AIAA SciTech, 4-6 Jan 2016, San Diego, CA, AIAA2016-0521.

Nandi, T., Brasseur, J.G., Vijayakumar, G. 2016 Prediction and Analysis of the Nonsteady Transition and Separation Processes on an Oscillating Wind Turbine Airfoil using the γ-Re_θ Transition Model. AIAA SciTech, 4-6 Jan 2016, San Diego, CA, AIAA2016-0520.

Dunbar, A. J., Craven, B. A., & Paterson, E. G. 2015 Development and validation of a tightly coupled CFD/6-DOF solver for simulating floating offshore wind turbine platforms. *Ocean Engineering*, 110, 98-105. doi:10.1016/j.oceaneng.2015.08.066

Jha, P. K., Duque, E. P. N., Bashioum, J. L., and S. Schmitz, S. 2015 Unraveling the Mysteries of Turbulence Transport in a Wind Farm, *Energies* 8(7):6468-6496.

Churchfield, M. J., Wang, Z., S. Schmitz, S. 2015 Modeling Wind Turbine Tower and Nacelle Effects within an Actuator Line Model, AIAA-2015-0214. (19 pages).

Zhang, D., & Paterson, E. G. 2015 A study of wave forces on an offshore platform by direct CFD and Morison equation. In M. J. Churchfield (Ed.), 2nd Symposium on OPENFOAM(R) In *Wind Energy* Vol. 5 (pp. 12 pages). Natl Renewable Energy Lab, Boulder, CO: E D P SCIENCES. doi:10.1051/c3sconf/20150504002

Mehdizadeh, A., Brasseur, J.G., Nandi, T., Foroutan, H. 2015 Analysis of Scale Adaptive Approaches Based on the Rotta Transport Equation. In: S. Girimaji et al. (eds.), *Progress in Hybrid RANS-LES Modelling*, Notes on Numerical Fluid Mechanics and Multidisciplinary Design 130, DOI 10.1007/978-3-319-15141-0_23.

Jayaraman, B., Brasseur, J. 2014 Transition in Atmospheric Turbulence Structure from Neutral to Convective Stability States, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0868.

Vijayakumar, G., Lavely, A., Jayaraman, B., Craven, B., Brasseur, J.G. 2014 Blade Boundary Layer Response to Atmospheric Boundary Layer Turbulence on a NREL 5MW Wind Turbine Blade with

Hybrid URANS-LES, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0867.

Lavely, A., Vijayakumar, G., Craven, B., Jayaraman, B., Jha, P., Nandi, T., Paterson, E.G., Brasseur. J.G. 2014 Toward a Blade-Resolved Hybrid URANS-LES of the NREL 5-MW Wind Turbine Rotor within Large Eddy Simulation of the Atmospheric Boundary Layer, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0869.

Motta-Mena, J., Campbell, R.L., Schmitz, S., Brasseur, J.G. 2014 Wind Turbine Fluid-Structure Interaction using an Actuator Line Solver and a Structural Dynamics Solver in a Tightly-Coupled Implementation, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0717.

Jha, P., Churchfield, M. J., Moriarty, P. J., Schmitz, S. 2014 Guidelines for Actuator Line Modeling of Wind Turbines on Large-Eddy Simulation-type Grids. *ASME Journal of Solar Energy Engineering* 136:031003 (11 pages).

Jha, P., Churchfield, M. J., Moriarty, P. J., Schmitz, S. 2014 The Effect of Various Actuator-Line Modeling Approaches on Turbine-Turbine Interactions and Wake-Turbulence Statistics in Atmospheric Boundary-Layer Flow, 2nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD,, AIAA-2014-0710. (21 pages).

Jha, P., Duque, E. P. N., Bashioum, J. L., Schmitz, S. 2014 Turbulent Transport Phenomena in the Wakes of Wind Turbines, Proceedings of the American Helicopter Society 70th Annual National Forum. (16 pages).

Schmitz, S., Jha, P.K. 2013 Modeling the Wakes of Wind Turbines and Rotorcraft Using the Actuator-Line Method in an OpenFOAM – LES Solver, Proceedings of the American Helicopter Society 69th Annual National Forum. (8 pages).

Jha, P., Churchfield, M. J., Moriarty, P. J., Schmitz, S. 2013 Accuracy of State-of-the-Art Actuator-Line Modeling for Wind Turbine Wakes, AIAA-2013-0608. (19 pages).

Vijayakumar, G., Brasseur, J.G., Lavely, A.W., Kinzel, M.P., Paterson, E.G., Churchfield, M.J., Moriarty, P.J. 2012 Considerations in coupling LES of the atmosphere to CFD around wind turbines, *Proc. 50th AIAA Aerospace Sciences Meeting*, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0817.

Lavely, A.W., Vijayakumar, G., Brasseur, J.G., Paterson, E.G., Kinzel, M.P. 2012 Comparing Unsteady Loadings on Wind Turbines using TurbSim and LES Flow Fields, *Proc. 50th AIAA Aerospace Sciences Meeting*, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0818.

Churchfield, M.J., Moriarty, P.J., Martínez, L.A., Leonardi, S., Vijayakumar, G., Brasseur, J.G. 2012 Large-Eddy Simulations of Wind-Plant Aerodynamics, *Proc. 50th AIAA Aerospace Sciences Meeting*, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0537.

Jha, P., Brillembourg, D., Schmitz, S. 2012 Wind Turbines under Atmospheric Icing Conditions – Ice Accretion Modeling, Aerodynamics, and Control Strategies for Mitigating Performance Degradation, *Proc. 50th AIAA Aerospace Sciences Meeting*, 9-12 Jan 2012, Nashville, TN, AIAA-2012-1287. (11 pages)

Lavely, A. W., Vijayakumar, G., Kinzel, M.P., Brasseur, J.G., Paterson, E.G. 2011 Space-Time Loadings on Wind Turbine Blades Driven by Atmospheric Boundary Layer Turbulence. *Proc. 49th AIAA Aerospace Sciences Meeting*, 4-7 Jan 2011, Orlando, FL, AIAA Paper 2011-635.

Churchfield, M.J., Vijayakumar, G., Brasseur, J.G., Moriarty, P.J. 2010 Wind Energy-Related Atmospheric Boundary Layer Large-Eddy Simulation Using OpenFOAM. NREL Report CP-500-48905 (National Renewable Energy Laboratory), and *Proc. 19th AMS Symp. Boundary Layers and Turbulence*, Keystone, CO, paper 1B.6, Aug. 2010.

GT: Graduate Theses

Nandi, Tarak. 2017 Effects of Blade Boundary Layer Transition with Daytime Atmospheric Turbulence on Wind Turbine Performance Analyzed with Blade-Resolved Simulation and Field Data. PhD Thesis, Pennsylvania State University, May 2017.

Lavely, Adam. 2017 Effects of Daytime Atmospheric Boundary Layer Turbulence on The Generation of Nonsteady Wind Turbine Loadings and Predictive Accuracy of Lower Order Models, PhD Thesis, Pennsylvania State University. August 2017.

Vijayakumar, Ganesh. 2015 *Non-steady Dynamics of Atmospheric Turbulence Interaction with Wind Turbine Loadings through Blade Boundary Layer Resolved HPC*. PhD Thesis, Department of Mechanical Engineering, Pennsylvania State University, University Park, PA, May 2015.

Jha, Pankaj K. 2015 *Characterization of Wake Turbulence in a Wind Turbine Array Submerged in Atmospheric Boundary Layer Flow*, PhD Thesis, The Pennsylvania State University, August 2015, https://etda.libraries.psu.edu/files/final_submissions/11125.

Motta-Mena, Javier. 2015 Fluid-structure Interaction Simulations of a Wind Turbine with Consideration of Atmospheric Boundary Layer Turbulence, M.S. Thesis, The Pennsylvania State University, 88 pages, August 2015.

MP: Meeting Presentations and Abstracts

Brasseur, J.G., Lavely, A., Nandi, T. 2016 Fundamental Distinctions in Physics underlying Nonsteady Forcings of Wind Turbine Power vs. Drivetrain by Atmospheric Turbulence. (abstract) Bull. Amer. Phys. Soc.: http://meetings.aps.org/Meeting/DFD16/Session/G2.1. Ann. Meeting of the APS Division of Fluid Dynamics, Portland, OR.

Jayaraman, B. Brasseur, J.G., Haupt, S., Lee, J. 2016 Deviations from Equilibrium in Daytime Atmospheric Boundary Layer Turbulence arising from Nonstationary Mesoscale Forcing. (abstract) Bull. Amer. Phys. Soc.: http://meetings.aps.org/Meeting/DFD16/Session/M13.3. Ann. Meeting of the APS Division of Fluid Dynamics, Portland, OR

Motta-Mena, J., Campbell, R., Lavely, A., Jha, P. 2015 Reduced-order FSI simulation of NREL 5 MW wind turbine in atmospheric boundary layer turbulence, (abstract) American Physical Society, 68th Annual Division of Fluid Dynamics Meeting, Boston, MA, 22-24 November, 2015.

Brasseur, J.G., Jayaraman, B., Haupt, S., Lee, J. 2015 Nonequilibrium Response of the Daytime Atmospheric Boundary Layer to Mesoscale Forcing. (abstract) Bull. Amer. Phys. Soc. 60 (21): http://meetings.aps.org/link/BAPS.2015.DFD.E21.1. Ann. Meeting of the APS Division of Fluid Dynamics, Boston, MA.

Vijayakumar, G., Lavely, A., Jayaraman, B., Craven, B., Brasseur, J.G. 2015 Dominant mechanism of load fluctuations on a wind turbine in a realistic atmosphere through Hybrid URANS-LES. (abstract) Bull. Amer. Phys. Soc. 60 (21): http://meetings.aps.org/link/BAPS.2015.DFD.D28.4. Ann. Meeting of the APS Division of Fluid Dynamics, Boston, MA.

Zhang, D., Paterson, E., *et al*. 2015 System-Level Simulation of Floating Platform and Wind Turbine Using High-Fidelity and Engineering Models. (abstract) In North American Wind Energy Academy 2015 Symposium. Virginia Tech.

Aguasvivas, S., Lavely, A., Vijayakumar, G., Brasseur, J.G., Schmitz, S., Duque, E. 2015 Nonsteady Wind Turbine Loading Response to Passage of Daytime Turbulence Eddies. (abstract) Gallery of Fluid Motion, Ann. http://gfm.aps.org/meetings/dfd-2015/55f598c069702d060d7e0300. Meeting of the APS Division of Fluid Dynamics, Boston, MA.

Jayaraman, B., Brasseur, J.G. 2015 Analysis of the Relationship Between Mesoscale-driven Atmospheric Boundary Layer Turbulence and Temporal Variations in Local Flow Angles Relevant to Wind

Turbine Function Using LES. (abstract) Proceedings of the Conference on Model Integration across Disparate Scales in Complex Turbulent Flow Simulation (ICMIDS), Pennsylvania State University, June 2015.

Vijayakumar, G., Lavely, A., Jayaraman, B., Craven, B.A.,, Brasseur, J.G. 2015 Interaction of Atmospheric Turbulence with Blade Boundary Layer Dynamics on a 5MW Wind Turbine using Blade-boundary-layer-resolved CFD with hybrid URANS-LES (abstract) Proceedings of the Conference on Model Integration across Disparate Scales in Complex Turbulent Flow Simulation (ICMIDS), Pennsylvania State University, June 2015.

Lavely, A., Vijayakumar, G., Brasseur, J.G. 2015 Comparisons of Lower-order Wind Turbine Models with Blade-Boundary-Layer Resolved CFD for Unsteady Wind Turbine Loading Response to Atmospheric Turbulence (abstract). Proceedings of the Conference on Model Integration across Disparate Scales in Complex Turbulent Flow Simulation (ICMIDS), Pennsylvania State University, June 2015.

Nandi, T., Brasseur, J.G., Vijayakumar, G. 2015 Analysis of Nonsteady Transitional Boundary Layer Dynamics for Flow over an Oscillating S809 Airfoil using the γ-Re_θ Transition Model. (abstract) 2015 Proceedings of the Conference on Model Integration across Disparate Scales in Complex Turbulent Flow Simulation (ICMIDS), Pennsylvania State University, June 2015.

Aguasvivas, S., Plummer, J., Jha, P., Schmitz, S., Duque, E.P.N. 2014 Turbulent Transport in the Wakes of Wind Turbines. (abstract) 67th Annual Meeting of the American Physical Society (APS) Division of Fluid Dynamics, Gallery of Fluid Motion. http://gfm.aps.org/meetings/dfd-2014/541657b869702d585c610100, San Francisco, CA.

Brasseur, J., Vijayakumar, G., Lavely, A., Jayaraman, B., Paterson, E., Sullivan, P. 2014 Two Key Discoveries on Atmospheric Turbulent Wind Forcing of Nonsteady Wind Turbine Loadings, from HPC. (abstract) Bull. Amer. Phys. Soc. 59 (20). http://meetings.aps.org/link/BAPS.2014.DFD.L30.3. Ann. Meeting of the APS Division of Fluid Dynamics, San Francisco, CA.

Dunbar, A., Paterson, E., Craven, B., and Brasseur, J. 2014 Application of a Tightly- Coupled CFD/6-DOF Solver for Simulating Offshore Wind Turbine Platforms. (abstract) Second Symposium on OpenFOAM in Wind Energy, Boulder, CO, 19-21 May

Jayaraman, B., Brasseur, J., McCandless, T., Haupt, S. 2014 Nonequilibrium Behavior of the Daytime Atmospheric Boundary Layer, from LES. (abstract) Bull. Amer. Phys. Soc. 59 (20), http://meetings.aps.org/link/BAPS.2014.DFD.L25.11. Ann. Meeting of the APS Division of Fluid Dynamics, San Francisco, CA.

Jha, P., Bashioum, J. L., Schmitz, S., Duque, E.P.N. 2013 Wake Turbulence of Two NREL 5-MW Wind Turbines Immersed in Neutral Atmospheric Boundary-Layer Flow. (abstract) 66th Annual Meeting of the American Physical Society (APS) Division of Fluid Dynamics, Gallery of Fluid Motion. http://arxiv.org/abs/1310.3294, Pittsburg, PA.

Jha, P., and S. Schmitz. 2013 An Actuator Curve Embedding Method to Model Wind Turbine Wakes, (abstract) Bull. Amer. Phys. Soc. 58. 66th Annual Meeting of the American Physical Society (APS) Division of Fluid Dynamics, Gallery of Fluid Motion, Pittsburg, PA.

Vijayakumar, G., Lavely, A., Jayaraman, B., Craven, B., Brasseur, J.G. 2013 Forcing of Wind Turbine Blade Boundary Layer Dynamics by Atmospheric Turbulence with Hybrid URANS-LES. (abstract) Bull. Amer. Phys. Soc. 58 (18): http://meetings.aps.org/link/BAPS.2013.DFD.E5.1. Ann. Meeting of the APS Division of Fluid Dynamics, Pittsburg, PA

Nandi, T., Jayaraman, B., Lavely, A., Vijayakumar, G., Paterson, E., Brasseur, J.G. 2013 Numerical Study of the Interaction between Nonsteady Transition and Separation on Oscillating Airfoils.

(abstract) Bull. Amer. Phys. Soc. 58 (18): http://meetings.aps.org/link/BAPS.2013.DFD.E5.5. Ann. Meeting of the APS Division of Fluid Dynamics, Pittsburg, PA

Lavely, A., Vijayakumar, G., Craven, B., Jayaraman, B., Nandi, T., Paterson, E., Brasseur, J.G. 2013 HPC of Loading Transients on a 5-MW Wind Turbine Rotor by Atmospheric Turbulence Eddies. (abstract) Bull. Amer. Phys. Soc. 58 (18): http://meetings.aps.org/link/BAPS.2013.DFD.E5.2. Ann. Meeting of the APS Division of Fluid Dynamics, Pittsburg, PA

Jayaraman, B., Brasseur, J.G. 2013 An LES Study of Transition in Atmospheric Boundary Layer Turbulence Structure from Neutral to Convective Stability States. (abstract) Bull. Amer. Phys. Soc. 58 (18): http://meetings.aps.org/link/BAPS.2013.DFD.R36.2. Ann. Meeting of the APS Division of Fluid Dynamics, Pittsburg, PA

Campbell, R., Jayaraman, B., Lavely, A., Motta-Mena, J., Vijayakumar, G. 2013 Fluid-structure Interaction Simulations of a Parked Wind Turbine Rotor Blade under Steady and Unsteady Inflow Conditions. (abstract) Proceedings of American Physical Society, 66th Annual Meeting of the APS Division of Fluid Dynamics, Pittsburgh, PA, November 2013

Motta-Mena, J., Jha, P., Campbell, R., Schmitz, S., Brasseur, J.G. 2013 Coupling the Actuator Line and Finite Element Methods to Model Fluid Structure Interaction of a Commercial Wind Turbine in the Atmosphere. (abst) Bull. Amer. Phys. Soc. 58 (18): meetings.aps.org/link/BAPS.2013.DFD.E5.3, Ann. Meeting of the APS Division of Fluid Dynamics, Pittsburg, PA

Dunbar, J.J., Paterson, E.G., Craven, B.A., Brasseur, J.G. 2013 CFD Experiments for Wind-Turbine-Platform Seakeeping Models and Flow Physics. (abstract) Bull. Amer. Phys. Soc. 58 (18): http://meetings.aps.org/link/BAPS.2013.DFD.L31.7. Ann. Meeting of the APS Division of Fluid Dynamics, Pittsburg, PA

Jha, P. , Churchfield, M., Moriarty, P., Schmitz, S. 2012 Accuracy of Current Actuator-Line Modeling Methods in Predicting Blade Loads and Wakes of Wind Turbines, (abstract) Bull. Amer.Phys. Soc. 57(17): 43. Ann. Meeting of the APS Division of Fluid Dynamics, San Diego, CA.

Brasseur, J., Vijayakumar, G., Lavely, A., Nandi, T., Jayaraman, B., Jha, P., Dunbar, A., Motta-Mena, J., Haupt, S., Craven, B., Campbell, R., Schmitz, S. Paterson, E. 2012 The Penn State "Cyber Wind Facility." (abstract) Bull. Amer. Phys. Soc. 57 (17), 241. Ann. Meeting of the APS Division of Fluid Dynamics, San Diego, CA.

Brasseur, J., Vijayakumar, G., Churchfield, M., Lavely, A., Paterson, E., Moriarty, P. 2011 Designing LES of the High Reynolds Surface Layer to Account for Numerical Friction in the Algorithm. (abstract) Bull. Amer. Phys. Soc. 56 (18): 400. Ann. Meeting of the APS Division of Fluid Dynamics, Baltimore, MD.

Lavely, A., Vijayakumar, G., Brasseur, J., Paterson, E., Kinzel, M. 2011 Inherent Variability in Short-time Wind Turbine Statistics from Turbulence Structure in the Atmospheric Surface Layer. (abstract) Bull. Amer. Phys. Soc. 56 (18): 185. Ann. Meeting of the APS Division of Fluid Dynamics, Baltimore, MD.

Vijayakumar, G., Lavely, A., Brasseur, J., Paterson, E., Kinzel, M. 2011 Influences of Atmospheric Stability State on Wind Turbine Aerodynamic Loadings. (abstract) Bull. Amer. Phys. Soc. 56 (18): 185. Ann. Meeting of the APS Division of Fluid Dynamics, Baltimore, MD.

Paterson, E., Lavely, A., Vijayakumar, G., Brasseur, J., 2011 Influence of transition on steady and unsteady wind-turbine airfoil aerodynamics. (abstract) Bull. Amer. Phys. Soc. 56 (18): 233. Ann. Meeting of the APS Division of Fluid Dynamics, Baltimore, MD.

Lavely, A., Kinzel, M., Vijayakumar, G., Brasseur, J., Paterson, E., Lindau, J. 2010 Influence of a recent Transition Model on Complex Nonsteady Boundary Layer Flows with Dynamic Stall and Multiple

Phases. (abstract) Bull. Amer. Phys. Soc. 55 (16): 77. Ann. Meeting of the APS Division of Fluid Dynamics, Long Beach, CA.

Vijayakumar, G., Brasseur, G, Churchfield, M., Lavely, A., Moriarty, P., Kinzel, M., Paterson, E. 2010 The Role of the Algorithm in the Design of LES. (abstract) Bull. Amer. Phys. Soc. 55 (16): 118. Ann. Meeting of the APS Division of Fluid Dynamics, Long Beach, CA.

IP: Invited Presentations

Brasseur:

Nov 2016	Pennsylvania State University, Fluid Dynamics Research Consortium Seminar Series, "Nonsteady Forcing of Wind Turbine Drivetrains by the Passage of Daytime Atmospheric Turbulence Eddies, analyzed with Field and Computational Data"
Aug 2016	Boulder Fluid and Thermal Sciences Seminar Series, University of Colorado, "Nonsteady Forcing of the Wind Turbine Drivetrain by the Passage of Daytime Atmospheric Turbulence Eddies Analyzed by Combining Field and Computational Data."
July 2016	NREL National Wind Technology Center, "Nonsteady Forcing of the Wind Turbine Drivetrain by the Passage of Daytime Atmospheric Turbulence Eddies Analyzed by Combining Field and Computational Data."
June 2016	EUROMECH Colloquium 576: Wind Farms In Complex Terrains, KTH Royal Institute Of Technology, Stockholm, Sweden, "Nonsteady Forcing of the Wind Turbine Drivetrain by the Passage of Daytime Atmospheric Turbulence Eddies."
May 2016	WINDFARMS 2016, University of Texas at Dallas, invited Plenary Presentation, "Nonsteady Forcing of the Wind Turbine Drivetrain by the Passage of Daytime Atmospheric Turbulence Eddies."
Dec 2015	NREL National Wind Technology Center, "Two Oddities related to transitions in Atmospheric Turbulence Structure from External Forcing at the Mesoscale"
Oct 2015	Boulder Fluid and Thermal Sciences Seminar Series, "Two Oddities related to the Transition in Atmospheric Turbulence Structure from External Forcing."
Sept 2015	GE Global Research, Münich, Germany, "Applications of the Penn State Cyber Wind Facility with GEGR Collaboration."
June 2015	Conference on Model Integration across Disparate Scales in Complex Turbulent Flow Simulation (ICMIDS), Penn State University, invited plenary seminar with Jeffrey Mirocha (LNNL) "Interaction between Meso and Microscale Atmospheric Turbulence Dynamics: from the Meso Down and from the Micro Up."
June 2015	2015 Symposium of the North American Wind Energy Academy (NAWEA), VA Tech, Invited Plenary Presentation, "High Performance Computing Analysis of Wind Turbine Response to Atmospheric Eddy Passage."
June 2015	KTH Mechanics, Stockholm, Sweden, "Nonsteady Wind Turbine Responses to Daytime Atmospheric Turbulence."
Feb 2015	The Johns Hopkins University Department of Mechanical Engineering Seminar Series, " Nonsteady Wind Turbine Response to the Passage of Turbulence Eddies within the daytime Atmospheric Boundary Layer from High Performance Computing."
Feb. 2015	A2e High-Fidelity Modeling Wind Plant Physics Planning Meeting, Arlington, VA, with Jeffrey Mirocha (LNNL): "Physics and Computational Challenges at the Mesoscale-Microscale Interface."

Jan 2015	GE Global Research, Niskayuna, NY. "The Penn State Cyber Wind Facility (CWF) Program."
June 2014	NREL National Wind Technology Center, "Interactions between Atmospheric Eddies and Wind Turbine Blades analyzed using Blade-Boundary-Layer-Resolved Simulations within the Penn State Cyber Wind Facility."
June 2014	National Oceanographic and Atmospheric Administration (NOAA), Physical Sciences Division Seminar, "The Transition in Atmospheric Boundary Layer Turbulence Structure from Neutral to Moderately Convective Stability States."
April 2014	National Wind Resource Center Seminar, Texas Tech University, "Transition in Atmospheric Boundary Layer Turbulence Structure from the Neutral to Convective Stability States in Relationship to Wind Turbine Response."
Nov 2013	Symposium on Frontiers of Fluid Dynamics, Puerto Rico, "Transition in Atmospheric Boundary Layer Turbulence Structure with Stability State Relevant to Wind Turbine Function."
Sept 2013	Keynote speaker, Argonne National Lab, Workshop on Atmospheric Modeling at LES Scales: Opportunities and Challenges, "Challenges and State of the Art in Wind Energy High Performance Computing."
Aug 2013	National Center for Atmospheric Research (NCAR), Research Applications Laboratory (RAL) Seminar Series, Boulder, CO. "The Surprising Transition in Atmospheric Boundary Layer Turbulence Structure from Neutral to Convective Stability States."
March 2013	GE Global Research, Münich, Germany, "The Penn State Cyber Wind Facility."
March 2013	Invited lecturer, von Karman Institute for Fluid Dynamics (VKI), Rhode-Saint-Genèse, Belgium. Lecture series entitled "Atmospheric Boundary Layer Modelling for Wind Engineering Applications." Presented 4.5 hours of lectures on three topics: (1) Introduction to Microscale Meteorology (with application to wind energy); (2) Large-eddy Simulation Methods for the Atmospheric Boundary Layer; (3) CFD Application to Wind Energy using Large-eddy Simulation.
Nov 2012	Sandia National Laboratory, Albuquerque, NM, "Interactions between Atmospheric Turbulence and Wind Turbine Loadings as a Central Component to the Penn State 'Cyber Wind Facility'."
Oct 2012	Virginia Tech. University, Department of Aerospace and Ocean Engineering, "Interactions between Atmospheric Turbulence and Wind Turbine Loadings as a Central Component to the Penn State 'Cyber Wind Facility'."
April 2012	University of Wyoming, Department of Mechanical Engineering and Wind Energy Research Center, "Interactions between Atmospheric Turbulence and Wind Turbine Loadings from Large-Eddy Simulation of the Atmospheric Boundary Layer Coupled with AeroDyn."
Feb 2012	GE Global Research, Münich, Germany, "Interactions between Atmospheric Turbulence and Wind Turbine Loadings from Large-Eddy Simulation of the Atmospheric Boundary Layer Coupled with AeroDyn."
Jan 2012	NREL National Wind Technology Center (NWTC) "Designing Large-Eddy Simulation of the Atmospheric Boundary Layer to Predict the Law-of-the-Wall, Part II: The Influence of the Surface Stress Model and Numerical Dissipation, and the Prediction of the von Kárman Constant."
Nov 2011	NREL National Wind Technology Center (NWTC), Boulder, CO, "Interactions between Atmospheric Turbulence and Wind Turbine Loadings."

Nov 2011	NREL National Wind Technology Center (NWTC), Boulder, CO, "Designing Large-Eddy Simulation of the Atmospheric Boundary Layer to Predict the Law-of-the-Wall."
Sept 2011	Texas Tech University and the National Wind Resource Center, Lubbock, TX, "Interactions between Atmospheric Turbulence and Wind Turbine Loadings."
Sept 2011	Texas Tech University and the National Wind Resource Center, Lubbock, TX, "Structure of Atmospheric Boundary Layer Turbulence from Large-Eddy Simulation."
June 2011	6th AIAA Theoretical Fluid Mechanics Conference Honolulu, Hawaii, "Influences of Atmospheric Boundary Layer Turbulence Structure on the Space-time Variability in Wind Turbine Blade and Shaft Loadings."
May 2011	Risø National Laboratory for Sustainable Energy Technical University of Denmark, "Designing of Large-Eddy Simulation of the Atmospheric Boundary Layer to Predict the Law-of-the-Wall: Influence on Wind Turbine Aerodynamics."
Feb 2011	Universidad del Turabo, Caguas, Puerto Rico, NSF Workshop on "Wind Energy & Turbulence," "Penn State & NREL Wind Energy Collaborations."

Schmitz

Sept 2015	Schmitz, S., Fluid Mechanics Seminar Series, University of Illinois, Urbana-Champaign IL, "Wind Turbine Aerodynamics – Current Challenges & Future Opportunities," Invited.
Jan 2015	Schmitz, S., AIAA SciTech 2015, Kissimmee FL, "Breezy' Mysteries - Using FieldView XDB's to extract greater understanding of Wind Turbine Wake Interactions." Presentation in Exhibition Hall invited by 'Intelligent Light'.
Oct 2013	Jha, P. K., Churchfield, M. J., Moriarty, P. J., Schmitz, S. (Presenter), International Conference on Future Technologies for Wind Energy, University of Wyoming, Laramie WY, "On Turbine-Turbine Interactions Subject to Atmospheric Boundary-Layer Inflow - The Effect of Various Actuator-Line Approaches,"
Jan 2013	Schmitz, S., Fluid Dynamics Research Consortium (FDRC), The Pennsylvania State University, "Accuracy of Current Actuator-Line Modeling Methods in Predicting Wind Turbine Blade Loads."
June 2012	Schmitz, S. (Presenter), National Wind Technology Center (NWTC), Boulder CO, "Modeling the Wakes of Wind Turbines and Rotorcraft".

Paterson

June 2014	Paterson, E.G., (2014). Update on the development of an OpenFOAM-basedCyber Wind Facility. 9th OpenFOAM Workshop, Zagreb, Croatia 23-26 June 2014.
June 2012	Brasseur, J., Campbell, R., Dunbar, A., Jayaraman, B., Jha, P., Lavely, A., Motta-Mena, J., Nandi, T., Paterson (presenter), E, Schmitz, S., Vijayakumar, G. 2012 Development of a Cyber-Wind Facility for Terrestrial and Offshore Wind-Energy Applications. 7th OpenFOAM Workshop, Center of Smart Interfaces, Technische Universitat Darmstadt, Germany, 24-28 June 2012.

WP: Workshop Participation and Meeting Organization

NREL Drivetrain Reliability Collaborative Workshop, 21-22 Feb 2017, National Renewable Energy Lab, Golden, CO: Brasseur, attendee

Symposium of the North American Wind Energy Academy (NAWEA), Virginia Tech University June 2015: Paterson, primary organizer.

Conference on Model Integration across Disparate Scales in Complex Turbulent Flow Simulation (ICMIDS), Pennsylvania State University, June 15-17, 2015: Brasseur, primary organizer.

DOE A2e Workshop on Wind Plant Physics and Modeling, Arlington, VA, Feb 2015: Brasseur, Invited attendee and speaker.

DOE A2e High Fidelity Modeling: ModSim Environment Strategic Planning Meeting. Denver, CO, Jan 2015: Brasseur, invited attendee.

DOE A2e High Fidelity Modeling Working Group Meeting. NREL, Golden, CO, April 2014: Brasseur, invited attendee.

DOE A2E High-Fidelity Modeling Working Group Workshop, 23 January 2013, Sandia National Laboratory, Albuquerque, NM: Brasseur, invited attendee.

Invited address at Argonne National Lab, Workshop on Atmospheric Modeling at LES Scales, Sept 2013: Brasseur, invited attendee and keynote speaker.

DOE Wind Program Complex Flows Workshop, January 17-19th, 2012, Boulder, CO: Brasseur, invited attendee.

Scoping Workshop for a North America Wind Energy Academy (NAWEA), Nov. 17-18 2011, Boulder, CO: Brasseur, invited attendee.

Animation and Education

As discussed under subtask 1.2 and task 4 above, we have developed a well-done animation that is both highly valuable scientifically and pedagogically useful to teach students a variety of higher-level concepts surrounding wind turbine aerodynamics, function and high-performance computing. This animation was displayed at the 2015 annual meeting of the Division of Fluid Dynamics of the American Physical Society (MP: Aguasvivas, *et al*. 2015) and will continue to be useful well into the future. The animation is available to DOE personnel and others on request.

NUMERICAL AND PRACTICAL ISSUES FOR FUTURE BLADE-BOUNDARY-LAYER-RESOLVED SIMULATIONS OF WIND TURBINES AND WIND FARMS.

In the appendix we attach an analysis issues that will need to be faced in future developments of highly resolved couple blade boundary layer - atmospheric boundary layer simulations. In addition we wish to point out important practical issues that seriously interfered with the rate or progress:

- As mentioned early on in the final technical report, one of the greatest practical difficulties in developing and carrying out the development and application of the Cyber Wind Facility concept was the huge amount of time required to obtain, maintain, and learn to use the CPU and hardware/software systems required for an effort of this magnitude. Many proposals were written to XSEDE (NSF, Blacklight at PSC, Kraken and Darter at NICS, Stampede at TAAC), the DOE (Titan at Oak Ridge) and to NREL/DOE for use of Peregrine. Each of these efforts consumed a great deal of valuable time that could have been spent on development. As importantly, each of these platforms had their own issues and difficulties that made them suitable for some purposes and not for others and required a new and different learning curve with new and different personnel. The Penn State CWF program would have made much more rapid progress and with much less frustration if the DOE-funded program had been accompanied with good computational resources for a program that centers on the development of a state-of-the-art high-performance computing facility.
- Another practical difficulty of some importance surrounds the potential of a typical new graduate student to master wide ranges of highly complex new knowledge and technologies that are sometimes better suited to a professional who has already obtained wide experience in algorithm development, complex gridding, parallelization, and applications on multiple hardware platforms with different computational architectures.

- Whereas the resources to hire students and postdoctoral researchers was clearly necessary and invaluable to develop this program, these resources were not sufficient; it would not have been possible to make the progress we made had it not been for person power brought into the program from two Walker Fellowships (Adam Lavely and Alex Dunbar), support from the departments of Aerospace Engineering, Mechanical Engineering and the Penn State Institutes of Energy and the Environment which covered expenses for a graduate student (Motta-Mena) and substantial support from the National Science Foundation and the College of Engineering for a key student in this effort, Ganesh Vijayakumar. Future efforts must consider more realistically both person-power and computational resources required to successfully develop a program at the high levels of technological, scientific and modeling knowledge required.

Given the high level resources and time available we feel that our development of the Cyber Wind Facility program has been both a major success and, perhaps more importantly, has shown what is possible if the direction initiated here is pursued to its logical conclusion in the future. Although there are many advances still necessary to make the Cyber Wind Facility concept a practical, as well as scientific, success, this program has shown that it is both possible and doable, given the right level of resources required and the time and support necessary to make the far-reaching advances begin with the current COE-funded Penn State Cyber Wind Facility Program.

APPENDIX

Issues Related to Creating an OpenFOAM High-Fidelity Modeling Environment for Blade-Boundary-Layer-Resolved Wind Turbine Simulations

(following pages)

Issues Related to Creating an OpenFOAM High-Fidelity Modeling Environment for Blade-Boundary-Layer-Resolved Wind Turbine Simulations

James G. Brasseur[1]

based on the research of

Ganesh Vijayakumar, Adam Lavely and Balaji Jayaraman

Department of Mechanical and Nuclear Engineering
Pennsylvania State University

2 October 2014

1. Introduction

The purpose of the informal manuscript is to lay out the essential difficulties and issues associated with developing complex computational fluid dynamics (CFD) simulations of blade-boundary-layer-resolved simulations of wind turbine rotors. There are many essential issues that make this CFD particularly difficult. The dynamics that must be captured by the simulations are exceptionally multiscale in nature in both space and time, and output is required that is resolved to capture both very large and very small spatial and temporal scales simultaneously. Correspondingly there exists a high degree of complexity associated with different dominant physics: in the highly turbulent atmospheric boundary layer (ABL) flow surrounding the wind turbine with energy-dominant at the wind turbine rotor scale vs. the aerodynamic interactions with highly nonsteady spatially-evolving boundary layer dynamics adjacent to moving wind turbine blade surfaces. The exceptionally high blade chord Reynolds number creating viscous layers within the blade boundary layer that are 6-7 orders of magnitude smaller in scale than the turbulent atmospheric eddies, both dynamics of which must be captured accurately. The geometric complexity of long thin blades larger than a jet liner but rotating and cutting through the atmospheric eddies creates practical difficulties in capture relative motions of blades to outer flow. Finally there are a myriad of issues specific to the application of the OpenFOAM computational environment. These issues are summarized in this document from several years of experience in the development of the Penn State "Cyber Wind Facility" (CWF), a blade-boundary-layer-resolved simulation of an NREL 5 MW reference rotor in the daytime atmospheric boundary layer created with large-eddy simulation (LES).

2. CAD Model and Near-surface Grid Generation Issues

Grid generation is both central and difficult in all complex geometry CFD. The requirement that the viscous layers near the surface of the blades be resolved in order to capture three-dimensional time-dependent blade boundary layer dynamics, especially nonsteady boundary layer separation and dynamic stall, create extreme resolution requirements for the cells adjacent and near to the blade surface. Normal to the blade surface, the grid must resolve the thinnest viscous layer with 5-10 levels, so that the first grid must be of order 1 plus unit from the surface, or less, at the blade airfoil section with the highest chord Reynolds number. On the NREL 5 MW wind turbine (based on the RePower 5 MW wind turbine with LM Glasfiber blade) the highest chord Reynolds number is $\sim 1.2 \times 10^7$ which creates a viscous layer of order 25 μm thick within a boundary layer of order a mm or less. For $y^+ \approx 1$ resolution adjacent to the surface at max Re_c, our first grid level is 5.2 μm (!) on a blade that is 62.7 m in length. The horizontal scale of atmospheric eddies in the daytime ABL is typically of order 30-100 m from the lower to upper margin of the rotor disk from late morning to later afternoon. Thus the scale of the atmospheric eddy scale is of order the rotor radius or diameter, so a blade-boundary-layer-resolving grid must capture motions separated in scale by of order 10^7 from the blade surface into the atmospheric eddy-resolving part of the computational domain.

However, to capture, with first principles predictions, the primary boundary layer dynamics that contribute to nonsteady blade loadings, it is necessary to resolve the nonsteady dynamics of three-dimensional blade boundary layer separation (fig. 1). For this, the span-wise resolution of the grid

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adjacent to the surface must be sufficiently high (and the numerical algorithm sufficiently nondissipative) to allow the discretized dynamics to respond to spanwise instabilities of separating shear layers over the suction surface of the blade (figs. 1a,c). In the chordwise direction the grid must be sufficiently fine over the suction blade surfaces to resolve the shear layer that is in process of separation (fig. 1b,c). Using parked rotor simulations (fig. 1), we find that this concentration of vorticity is rather thicker than is often presented in textbooks in the shear layer mid-chord, where boundary layer separation tends to occur. Chordwise resolution around the leading and trailing edges must be particularly fine (fig. 1d). Our finest resolution is at the leading and trailing edges where grid resolution is 1/1000 chord, while the grid expands to 0.03 chord in the mid-chord regions, as shown in fig. 2. The blade span is resolved with 709 grid cells root to tip, with the finest resolution being near the tip (1/10 the resolution near the tip vs. the hub with relatively gradual reduction in grid scale until near the tip, where grid resolution increases more rapidly). As a result, 85% of the total number of grid cells for our "Cyber Wind Facility" simulations (158 M) are within three chords of the blade surfaces.

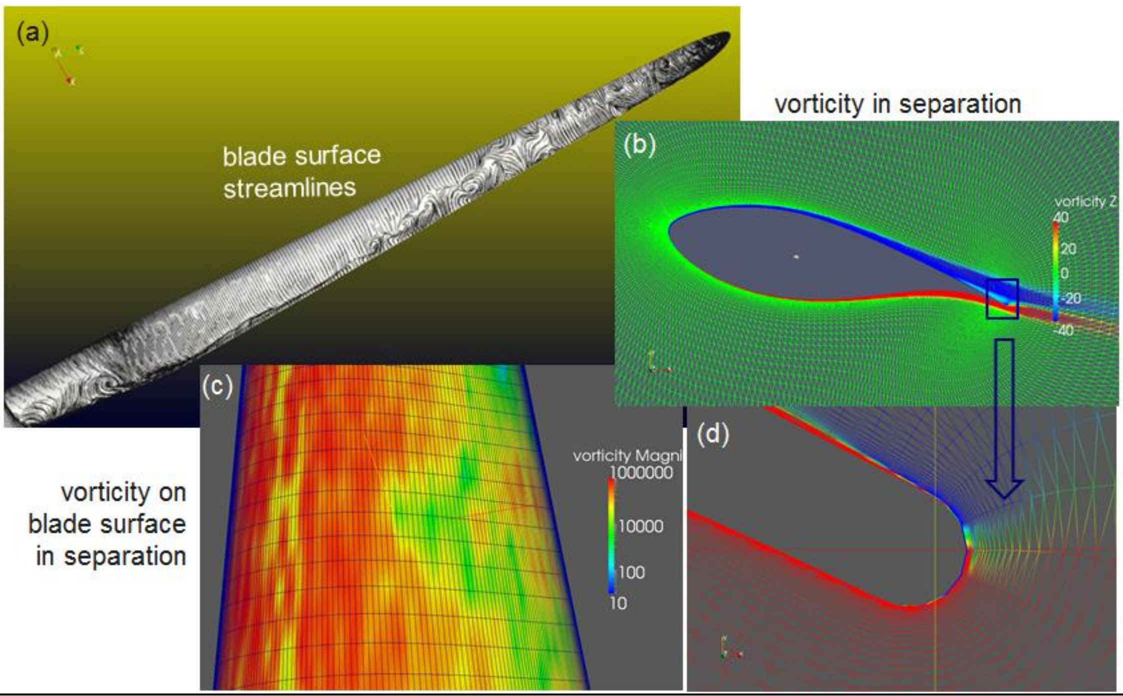

Figure 1. Development of the surface grid taking into account blade boundary layer separation using parked rotor simulations. (a) Blade surface streamlines showing the spanwise variations in separation and 3D nature of the separated region; (b) Showing he relatively broad region of vorticity gradient representing the separating shear layer; (c) The 3D nature of the vorticity gradient in the separating shear layer; (d) The need for high resolution at the trailing edge.

Difficult and serious practical challenges surround the need for accurate simulation on extremely find grids necessary to resolve the very thin separating viscous layers adjacent to the blade surfaces grids on large blades that operate at extremely high chord Reynolds numbers. A major practical problem is the need to generate a high quality structured grid with hexahedral cell structure near the blade surface so as to minimize numerical dissipation and maximize accuracy in the most dynamically critical region of the blade boundary layer (see fig. 2). Tetrahedral grids require more complex interpolations that introduce additional numerical dissipation. As importantly, the lack of surface orthogonality to inflow velocity vectors and lack of parallel faces perpendicular to local flow vectors reduces accuracy of discretized terms.

Our grid is generated using Pointwise mesh generating software (http://www.pointwise.com/). To generate a structured grid adjacent to the blade surface, one "extrudes" a grid normal to the surface from a surface grid which is itself generated from a CAD model. The extreme resolution of the near-surface grid

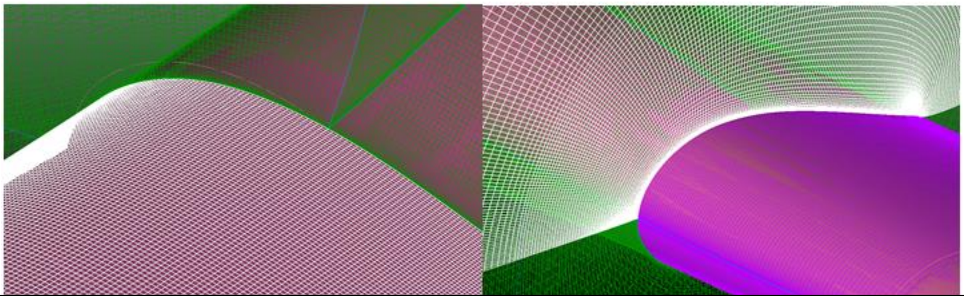

Figure 2. The near-surface grid. To minimize numerical dissipation and maximize accuracy in predicting the blade-boundary-layer at the extreme resolutions required, the grid near the surface must be hexahedral and of exceptional quality.

makes the extrusion process extremely sensitive to the smoothness of the surface grid, and therefore the CAD model. Slight "bumps" in surface curvature easily cause extruded mesh lines to cross, creating a singularity in the solution of the elliptic equations upon which the extrusion process is built. For this reason, it is necessary to create an exceptionally high-quality CAD model of the blade surface with extreme smoothness. On this smooth surface the surface grid is defined and forms the boundary condition for the extrusion process. Ganesh Vijayakumar learned the SolidWorks CAD software package (http://www.solidworks.com/) to develop our refined model of the NREL 5 MW model turbine rotor. The software interpolated between airfoil sections that are defined for the NREL wind turbine blade in Jonkman et al. (2009). However, before this could be done, it was necessary to obtain two airfoil sections not listed in the report for proprietary reasons. This was (eventually) provided by N. Timmer at Delft University and, through our efforts, is now freely available as an excel file from the NREL Wind Forum[2].

Several iterations of progressively smoother CAD models generated in SolidWorks were required until extrusion of a near-surface structured hexahedral grid, used in figs. 1 and 2, was successful. Figure 3 shows the final CAD design for a single blade and fig. 4b shows all 3 blades. These figures, and particularly figure 4a and d, also show the interface between the hub and blade. This is a particularly problematic region for generating the grid.

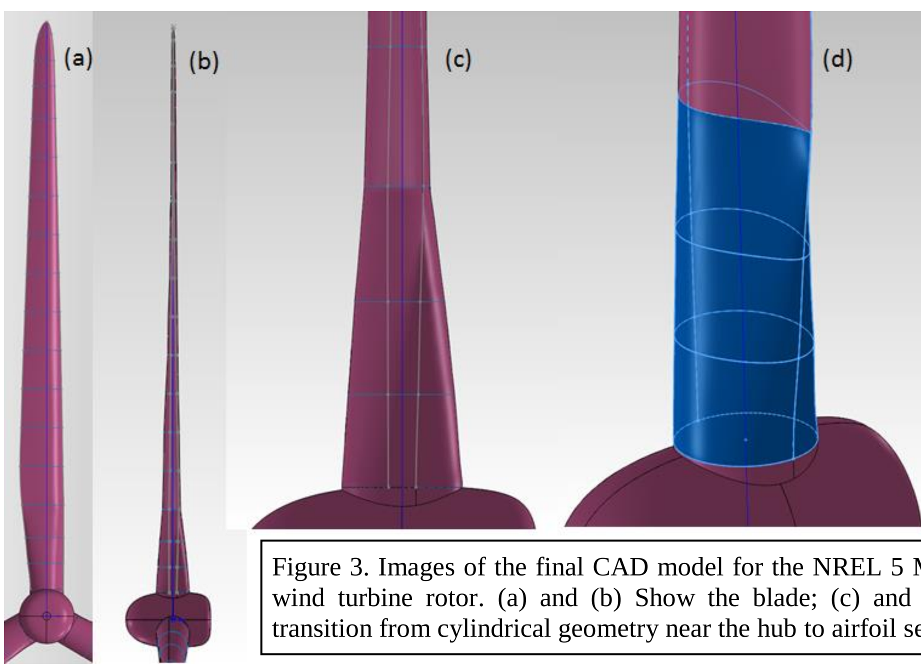

Figure 3. Images of the final CAD model for the NREL 5 MW reference wind turbine rotor. (a) and (b) Show the blade; (c) and (d) show the transition from cylindrical geometry near the hub to airfoil sections.

[2] https://wind.nrel.gov/forum/wind/viewtopic.php?f=2&t=440&p=1811&hilit=DU+airfoil#p2416

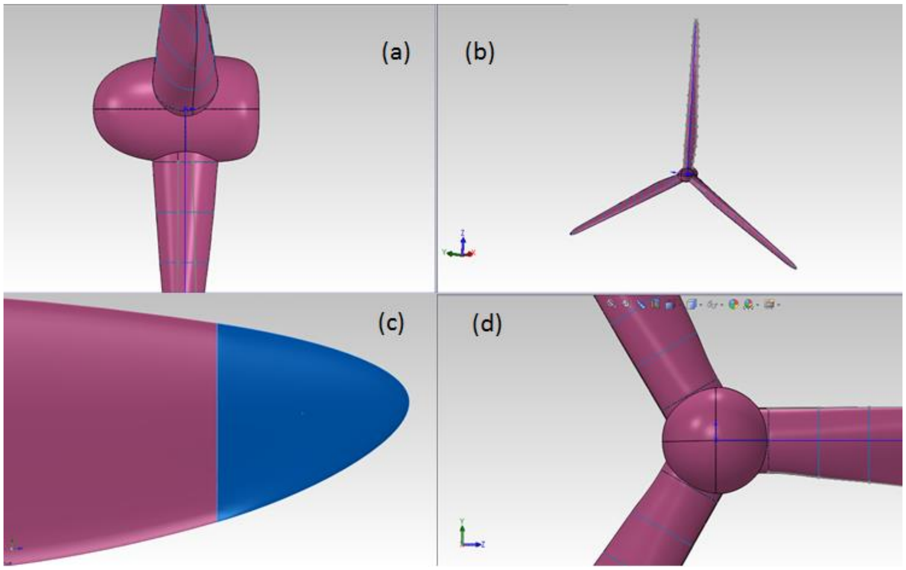

Figure 4. The final CAD model of the NREL 5 MW reference rotor. (a) and (d): the interface between the rotor and hub; (b): the three blades; (c): the tip.

The surface grid is shown in fig. 5a and the extrusion in fig. 5b. To couple the blade and hub grids at the interface between them, it was necessary to slightly "over-resolve" near the hub and fill in spaces with structured grid cells.

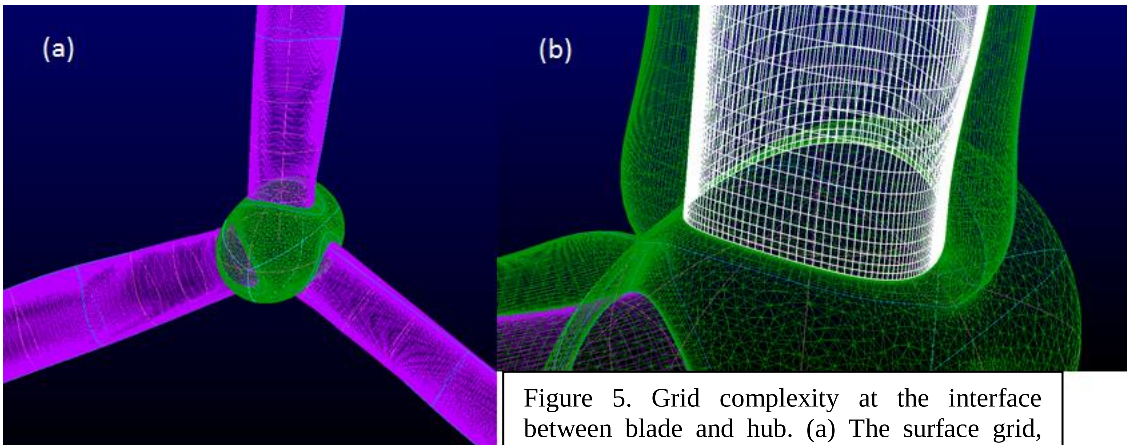

Figure 5. Grid complexity at the interface between blade and hub. (a) The surface grid, generated from the CAD model shown in figs. 3 and 4; (b) Extrusion from the surface grids.

Another problematic grid region is the tip of the blades, beginning with the fact that Jonkman et al. (2009) do not specify a tip. Thus one has be designed. We both designed our own tip and borrowed a tip designed by Raymond Chow and Case Van Dam at UC Davis. Ultimately we used our own design, shown in fig. 4c. The grid surrounding the tip posed special challenges. In particular, the grid around the tip and blade body was extruded as a unit. This process is illustrated in fig. 6. Fig. 6a shows the surface grid at the tip which must be generated within particularly high resolution to capture the large surface pressure and vorticity gradients there and the tip vortex generation and rollup process. From this surface grid the grid in the interior is extruded, as shown in figs. 6b and 6c, where the tip extrusion is shown adjacent to the surface grid on the body of the blade. Due to the high curvatures around the tip, the interior structure is also highly curved, as shown in fig. 6d where an interior surface of grid cells extruded from the blade surface is shown to be highly curved.

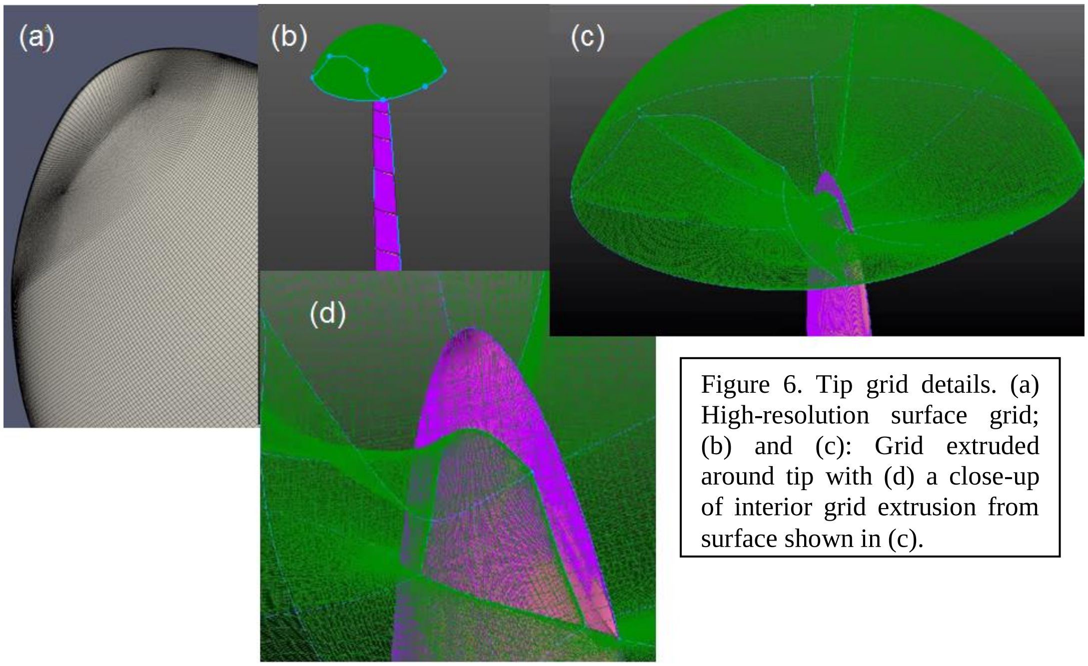

Figure 6. Tip grid details. (a) High-resolution surface grid; (b) and (c): Grid extruded around tip with (d) a close-up of interior grid extrusion from surface shown in (c).

Similar difficulties occur at the trailing edge of the blade, as shown in fig. 1b and 1d. It is not possible to represent a sharp cusp, and a perfectly sharp trailing edge cannot exist in reality, so the trailing edge is rounded and covered with cells around the highly curved surface at high resolution, necessary to capture the high pressure and vorticity gradients around the trailing edge (fig. 1d).

The process of generating the grid around the blade is first to generate the grid surrounding one blade, including the tip and one third of the bug, then to rotate this blade ±120° to generate the grid around the other two blades. Although the process of copying the grid twice to create a perfectly symmetric grid design surrounding a 3-bladed rotor is supposed to be relatively straightforward in Pointwise, we had a great deal of difficulty make it work perfectly. The software often left a slight displacement in the positioning of the copied grids at the hub.

Some of the complexities could be reduced by use of overset grids, where the grid on each blade is be made individually and overlapping grids handled through Overset interpolation. Unfortunately the Overset software available at the time we were developing our CWF is ITAR restricted and was not released from that restriction as we had hoped. Furthermore, overset comes with its own difficulties in mass conservation, stability, and parallizability.

After the generation of a grid, it is essential to pass the grid through the "checkmesh" utility in OpenFOAM to check for grid faces that are sufficiently non-parallel to cause numerical difficulties. In practice, it was virtually impossible to generate a near-surface grid that passed checkmesh the first time through. After failure, the sometimes difficult task of identifying the cells with insufficient quality cell geometry and adjusting locally the cell geometry to pass checkmesh. Passing checkmesh does not guarantee a successful grid, but not passing checkmesh guarantees an unsuccessful grid. Identifying and fixing mesh problems was a major time sink. Indeed the difficulties faced in the development of a successful grid were many, varied, mostly unknown in advance, and extremely frustrating.

Two students (Adam Lavely and Ganesh Vijayakumar) have spent many months creating and testing grids, making many unintentional mistakes along the way, several severe enough to require staring over (albeit with much greater experience and ability). In other words, there is a serious learning curve for such severe resolution requirements with over such complex domains (sec. 3) that can only be obtained with experience that includes failures and restarts. The process of generating a successful grid is one of major problems that develop and must be solved, with major time sinks, in the course of development and testing as part of the process of creating blade-boundary-layer resolved simulations of wind turbine rotors in the atmospheric boundary layer. Furthermore, the grid issue is intertwined with algorithmic issues surrounding accuracy and numerical stability (sec. 5) and with parallelization issues surrounding domain decomposition and mapping (sec. 6).

3. Domain Grid Design Issues

Blade-boundary-layer resolved simulation must integrate the extreme-resolution near-surface viscous-layer-resolving grid described in section 2 with a near-surface outer domain that captures separating boundary layers, vortex roll-up, tip vortex formation and near wake that scales from boundary layer scale to chord scale. The grid must be designed correctly to handle this transition near the surface and to integrate with the turbulence model and solver applied in the simulation. In the Cyber Wind Facility construct we have been extremely careful to resolve this transition so as to transition from URANS in and near the viscous surface layers to effective LES in the outer and separating boundary layer regions where the transition from nonsteady RANS-like to LES-like is handled near the surface using the Menter/Ergonov k-ω SST-SAS model (sect. 4). This LES-like simulations then transitions to a full LES with a 1-equation eddy viscosity model within roughly three chord-lengths from the surface (sect. 4). For hybrid URANS-LES methods to correctly and accurately transition from URANS to full LES, the grid must transition correctly both in resolution grid aspect ratio. Specifically, near the surface grid aspect ratio must be large compared to 1, while in fully turbulent regions away from the surface simulated with LES the grid aspect ratio should be order one in all directions.

Figure 7 shows the process we used to design the grid in the transition region from the blade surface into the near wake. To confirm that grid resolution is adequate in both resolution and aspect ratio, parked blade simulation was carried out and the grid was overlaid on predicted turbulence structure visualized with vorticity and second invariant of velocity gradient (Q). Several adjustments in the grid, both in resolution and in design, resulted from a prolonged and careful series of simulations, visualizations and grid comparisons.

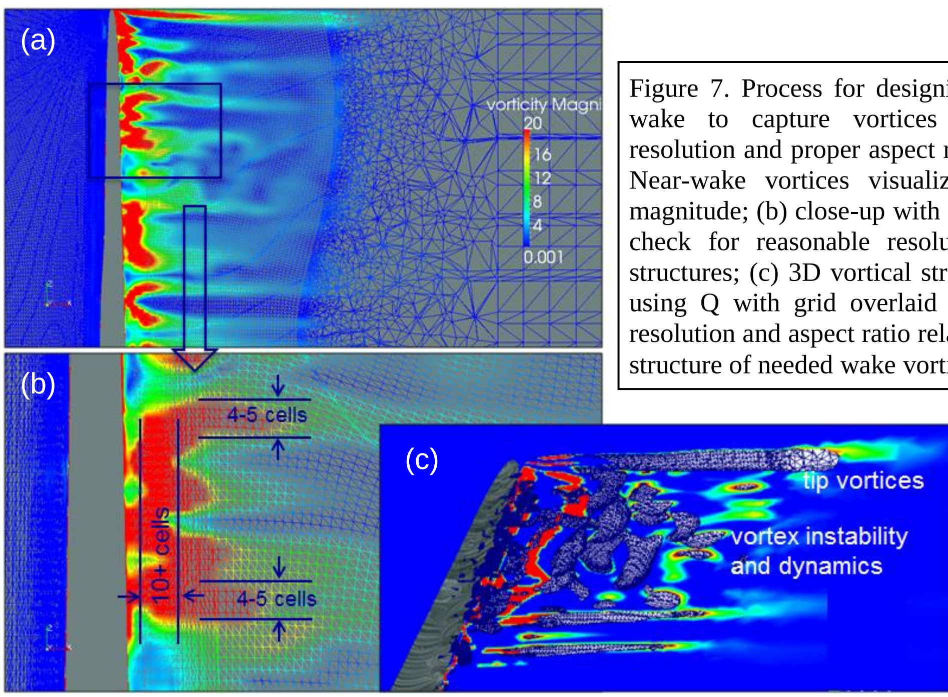

Figure 7. Process for designing grid in near-wake to capture vortices with sufficient resolution and proper aspect ratio for LES. (a) Near-wake vortices visualized by vorticity magnitude; (b) close-up with grid overlaid and check for reasonable resolution of vortical structures; (c) 3D vortical structure visualized using Q with grid overlaid to examine grid resolution and aspect ratio relative to scale and structure of needed wake vorticity.

Figure 8 shows a similar process that we applied to design adequate resolution and good transition in both the scale of the grid and the grid cell aspect ratio from adjacent to the blade surfaces (high aspect ratio URANS cells) into the near-surface region where boundary layer separation and vortex generation occur (aspect ratio approaching order one). We designed a parked rotor simulation specifically to stimulate nonsteady boundary layer separation on the suction side of the blade as expected near the hub when the blade boundary layer is responding atmospheric boundary layer turbulence.

The grid and rotor blades are embedded within a much larger domain that must accommodate the rotation of the rotor relative to an external domain with atmospheric boundary layer eddies passing through the rotor plane relative to the ground. As the rotor rotates it slices through pieces of atmospheric eddies, generating turbulence fluctuations at time scales shorter than the blade rotation time scale. Thus, the complexities of extruding extreme-resolution grids near blade surfaces from a high quality CAD model (figs. 1-4), coupling to a hub grid model fig. 5), and then extending the near-surface grid to the near blade region adjacent to the blade and in the near wake (figs. 6-8) must interface with the complexity of grids designed in outer domains.

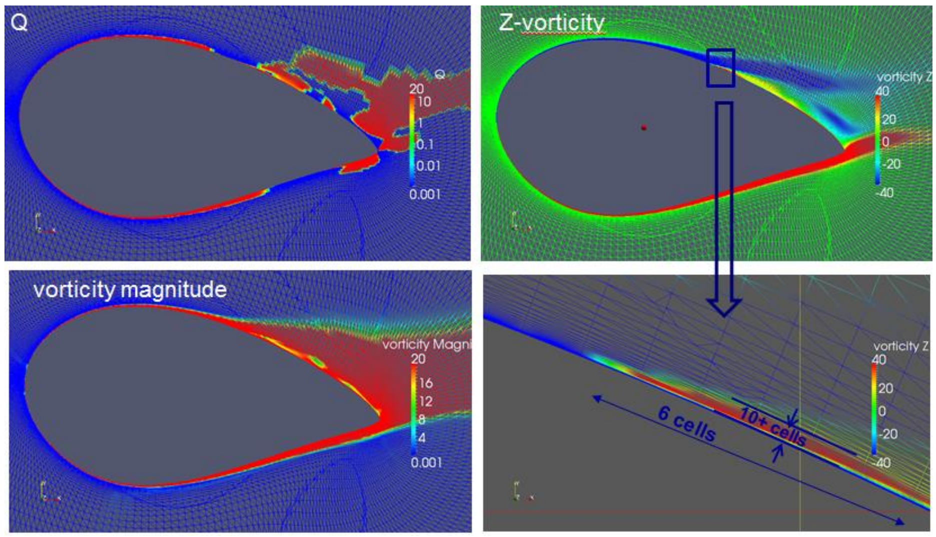

Figure 8. Demonstrating the design process near the blade surfaces to capture boundary layer separation and vortex formation with resolution sufficient for URANS-SAS and the transition to LES.

Figure 9 illustrates the global computational domain, including the blade and the near-blade grid elements discussed above and in sect. 2. The three-bladed rotor is fixed within a cylindrical domain that rotates as a unit at the blade rotation rate relative to an outer grid. At the inlet plane to the outer flow Dirichlet boundary conditions on velocity determine the specification of the mean and turbulent velocity field that passes through the rectangular domain, through the boundary of the rotating cylindrical domain with wind turbine rotor, and over the rotor blades generating blade surface stresses from nonsteady boundary layer dynamics in response to a highly nonsteady velocity field. In our Cyber Wind Facility we feed into the outer grid the flowfield generated from a low-dissipation high-resolution spectral large-eddy simulation of the daytime atmospheric boundary layer that requires surface heating, buoyancy force, a capping inversion, Coriolis force, and a surface stress model that includes effects of roughness. It is imperative that the wind turbine computation on the outer and inner sections of fig. 9 contain the same dynamics as the precursor simulation from which the inflow boundary conditions are obtained in order that the structures maintain the correct dynamical structure as they advect through the rotor disk and over the rotating turbine blades.

The "sleeve" regions surrounding each blade contain a structured grid from the blade surface to the sleeve boundary with rather dramatic changes in both grid resolution and grid cell aspect ratio as the grid transitions from the blade surface to the sleeve boundary. It is very important, both for computational accuracy and to minimize numerical dissipation, that the grid be structured and hexahedral adjacent to the blade surfaces, and as close to hexahedral as possible with faces perpendicular to the flow direction away from the surface. A well-designed near-surface grid is necessary to meet resolution requirements for the blade surface boundary layers to dynamically respond to high nonsteady inflow, especially separation and nonsteady vortex formation, and minimally dissipative so as to not damp near-wake vortex instability and the proper development of wake turbulence. As discussed above, the generation of this structured grid within the sleeve is difficult, time-consuming and involves a high level of "trial and error" as grid patches are designed, extruded, connected, tested for overly severe deviations from orthogonality using the OpenFOAM "check-mesh" utility, tested for potential grid-induced numerical instability, and then redesigned to resolved difficulties in any one of these areas.

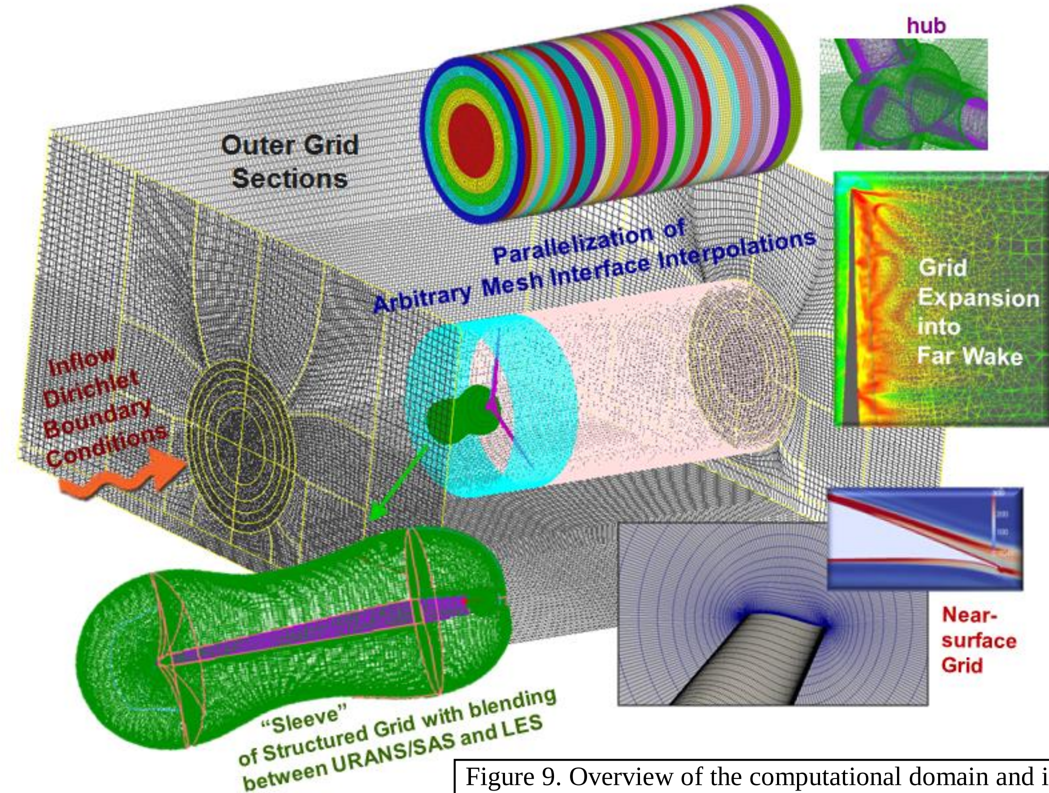

Figure 9. Overview of the computational domain and its sub elements. The blades form a rotor within a rotating cylindrical domain relative to fixed outer grid sections. A sleeve surrounds each blade at the edge of which the grid transitions from structured to unstructured. Operations at the the AMI surface are parallelized separately from the inner and outer domains.

Between the sleeve and the boundary of the cylindrical inner region is most easily designed if unstructured. This is partly because the grid should contain aspect ratio order one grid cells. As importantly, however, the grid within the rotating cylindrical domain must match the cells in the outer grid sections at the surface of the cylinder. This is necessary to allow for accurate and mass conserving interpolation using the Arbitrary Mesh Interface (AMI), built into the OpenFOAM framework. The need for grid interpolation puts demands on balancing parallelization. Specifically, for good scaling it is necessary for the domain to be decomposed (sect. 6) in balanced fashion among cores. That is, if one core has an order of magnitude more cells or fewer cells than others, the load imbalance creates major latency problems and reduces quality of scaling. However the decomposition at the AMI surface must be handled so as to allow the AMI software to access cells adjacent to and across the cylindrical surface. Thus these grid cells require special decomposition that does not fit into the standard decomposition approaches using Scotch or Metis (sect. 6) and special coding is required that integrated with Scotch or Metis.

External to the cylindrical "AMI surface" the grid must expand to the boundaries of the rectangular computational domain. As illustrated in fig. 9, we have done this in domain patches that match at their boundaries. The essential requirement is that the grid size at the inflow boundary be close to the grid size of the precursor simulation and that the rate of grid contraction from inflow to cylinder AMI surface, and then from AMI surface to sleeve, and finally from sleeve to blade surface, be sufficiently gentle to allow the dynamics to generate smaller-scale turbulence supported by the shrinking grid. A proper daytime ABL simulation requires a domain no smaller than 5 km × 5 km in the horizontal and 2 km in the vertical. Thus for the precursor LES grid to have resolution not too much larger than max blade chord (3-4 m) in order to capture most of the eddying motions with significant turbulent kinetic energy, the precursor grid must be quite large (we use a 760 × 760 × 256 grid before padding). In any event, it is important that the grid resolution in the outer grid be sufficiently refined to capture most of the turbulent kinetic energy in the atmospheric turbulence in the resolved scales of the LES.

The grid outside the rotating cylindrical domain containing the wind turbine rotor, in our simulations, is structured, necessitating the need for a dozen or so coupled sub-grid volumes (fig. 9). The grids within our sleeves are fully structured and extremely carefully designed. Currently the only unstructured nonhexahedral grid cells are between the sleeve and cylindrical AMI surface. This was necessitated by the need for the grid to match at both the sleeve and AMI surfaces and to expand relatively rapidly between the two. However, there are accuracy reasons why a future aim should be to generate a fully structured grid even in the transition between sleeve and cylinder. This is particularly the case in the wake where higher resolution and hexahedral grid cells are needed to both resolve the formation and capture the instabilities of trailing vortices from the blade tips within minimum numerical dissipation.

Grid-generation Software. To develop our grids we have used Pointwise mesh generating software (http://www.pointwise.com/). Pointwise has a user-friendly interface and can output directly in OpenFOAM format with the ability to set the boundary conditions at grid boundaries. The serious difficulties are in (1) the requirement to produce high-quality hexahedral cells of extraordinary resolution adjacent to the surface, (2) the need to transition between domains with very different grid resolution and aspect ratio requirements, (3) the value of scripting the development of the grid to allow for ease of modification and repetition, (4) the need to copy grid domains precisely (for example, from one blade to another), and (5) difficulties in nonorthogonality hexahedral grid faces leading to numerical instability. The learning curve for Adam and Ganesh was quite significant. They found particular difficulty with (1), (4) and (5). For example, Pointwise was supposed to allow copying, however the copy was not precise, producing small gaps between grid and surface that caused the code to break. Grid anomalies from (4) and (5) often had to be fixed by hand, requiring significant time.

We have since learned about GridPro, which may allow for the generation of higher quality fully structured more complex grids than Pointwise. We are told that this software has a steeper learning curve than Pointwise, in part because it has a less user friendly interface, However we are also told that it is a more advanced more sophisticated gridding approach than Pointwise that does not involve extrusion, a process for solving an elliptic equation for the grid that is sensitive to the smoothness of the blade surface geometry with the extremely fine grids needed to resolve the viscous surface layers. The other disadvantage of GridPro is the lack of a direct OpenFOAM interface, with consequent requirement to manually set boundary conditions and use a 3rd-party tool to output the grids in OpenFOAM format. Thus there are extra steps required compared to OpenFOAM. However to develop higher quality fully structured grids between the sleeve and cylindrical AMI surface, in future it may be advisable to explore its use.

4. Issues in the Transition in Simulation and Models: hybrid URANS-LES

Coupled to the design of the grid is the transition in the unsteady Reynolds-averaged Navier-Stokes (URANS) modeling of nonsteady three-dimensional turbulent boundary layer dynamics near blade surfaces to Large Eddy Simulation with sub-filter scale (SFS) models momentum and temperature in the atmospheric boundary layer turbulence away from the blades. In between these two limits it is necessary to capture accurately boundary layer separation and rollup within a chord of the blade surfaces, and the formation of trailing and wake vortices in the near-wake. To model the transition from URANS to LES requires a well-designed hybrid URANS-LES approach.

It is impossible to simulate the near-surface boundary layers using LES: the resolution requirements are astronomical. Thus it is necessary to model the boundary layers adjacent to the blade surfaces using high-quality URANS. In our application, the primary distinctions between URANS and LES are: (1) in URANS regions the energy-containing scales should <u>not</u> be resolved by the grid while in LES regions all energy-dominant eddies <u>should</u> be resolved by the effective grid (including implicit filtering from numerical and modeled dissipation), and (2) in the URANS regions the SFS model must be consistent with not resolving the energy-containing eddies (i.e., the modeled length and velocity scales in the eddy viscosity should be an appropriate integral scale and turbulent kinetic energy square root), while in the LES regions the SFS model decouples from the integral sales and the modeled eddy viscosity length and velocity scales should characterize the grid scale. However, to capture the dynamics of the near-surface boundary layer separation with high three-dimensionality and, especially, time-resolved to capture nonsteady behavior and dynamic stall, outside the viscous surface layer, the URANS model must transition rapidly to LES-like where the integral-scale motions are resolved by the grid. As discussed above, the grid must transition from very high aspect ratio in the viscous and transitional viscous-inertial surface layers, to order one aspect ratio in the outer inertial surface layer (with corresponding severe difficulties in grid generation).

As importantly, the SFS model must transition from RANS-like to LES-like, the latter containing length and velocity attached to the grid scale (rather than the integral scale). To effect this transition near the surface in the boundary layer is very difficult. We therefore use a two-step process. Seamless transition from viscous to inertial layer, especially including boundary layer separation and vortex formation in the boundary layer, is handled using the k-ω SST-SAS model of Ergorov and Mentor (2008). This model works particularly well when the boundary layer is highly unstable, as is the case with significant boundary layer separation. We then use our own blending method (developed by Vijayakumar 2014) to transition from URANS-SAS to full LES with a 1-equation SFS stress model. As discussed in sect. 4 and shown in fig. 9, the grid transitions from structured to unstructured grid outside the sleeve boundary. The blended transition between URANS-SAS below and pure 1-eq. LES above takes place within the sleeve and is controlled by a blending function that varies from 0 to 1. Figure 10a shows an isosurface of the blending function value 0.5. Figure 10b shows the cross section with the blending function transition from URANS-SAS within to pure LES without.

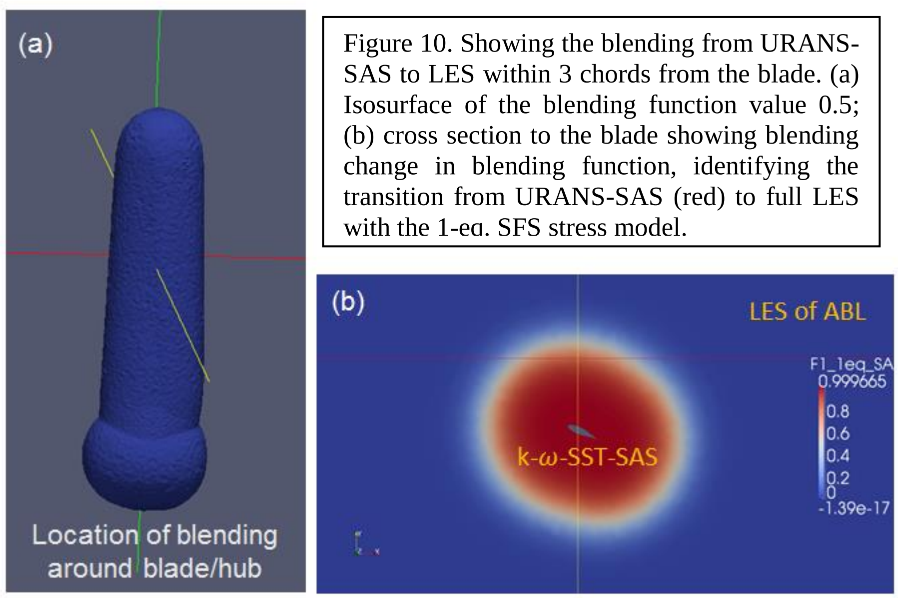

Figure 10. Showing the blending from URANS-SAS to LES within 3 chords from the blade. (a) Isosurface of the blending function value 0.5; (b) cross section to the blade showing blending change in blending function, identifying the transition from URANS-SAS (red) to full LES with the 1-eq. SFS stress model.

The grid resolution requirements in the transition from URANS to URANS-SAS to pure LES have been described above. To summarize, there are two essential requirements on the grid: grid cell size (resolution) and grid cell aspect ratio. Adjacent to the surface the grid cells must be very high aspect ratio with extreme resolution in the normal to the surface to capture the viscous wall layer, and well enough resolved along the blade surface to capture three-dimensional instabilities in the separating surface boundary layers and near-surface vortex rollup. Outside the blended region the grid should be aspect ratio order 1 and sufficiently fine to resolve all energy-dominant turbulence eddies. From a spectral perspective, the aim should be to resolve all integral-scale eddies to a factor of 5-10 smaller than the local integral scale. In the transition from the high grid cell aspect ratio viscous layer to the outer inertial boundary layer, the grid should be approaching order 1 aspect ratio and should be well enough resolved to capture the high vorticity layers in separating boundary layers, vortex rollup, and in the subsequent vortices after rollup.

5. Algorithmic and Simulation-specific Issues

Four issues dominate considerations for the solver to advance the velocity field in time and, correspondingly, predict accurately the nonsteady spatially-dependent details of blade surface boundary layer dynamics and blade surface stresses, particularly time variations in surface pressure and surface shear stress vector distribution over the blades which integrate to produce to all-important temporal variations in blade and shaft bending moments, rotor torque and rotor power. These issues are: numerical stability, numerical accuracy and numerical efficiency for time-resolved output, and practical limits on time-to-completion of simulation (related to time step and parallizability). The first three issues surround the solver method and limitations on time step for temporal accuracy. The last issue is directed at the practicalities and realities of carrying out the simulations on currently existing HPC platforms and the current realities of CPU allocation, job scheduling priorities, and competition for machine resources. The latter issue will be discussed in sect. 6. Here we focus on algorithmic and simulation-specific issues.

Since wind turbine aerodynamics is closely incompressible, the pressure-Poisson equation must be solved accurately to maintain local solenoidal velocity field. The pressure-Poisson equation is a fully elliptic 3D equation with solutions that couple the flowfield volume. Pressure-Poisson solvers require effective matrix inversion that limit parallelizability and severely restrict scalability to huge numbers of cores without severe loss of efficiency. The need to accurately solve the pressure-Poisson equation with small residuals in flowfields driven by high complexity in geometry, scale separation, and nonlinear dynamics, and requiring extremely complex grid design and the integration of multiple turbulence models that operate at disparate length scales puts blade-boundary-layer resolved simulations of wind turbines at a major disadvantage for use of DOE Advanced Scientific Computing Research (ASCR) resources. This is because simulations with such extreme levels of complexity are inherently limited in their ability to scale to very large numbers of cores while maintaining reasonable levels of efficiency.

To a large extent the limitations center on the sensitivity between numerical stability and the degree of precision by which a divergence-free velocity field can be maintained in the pressure solve. To maintain the requisite level of precision in discretized continuity often requires many iterations in the pressure solver, interfering with parallelization to huge numbers of cores with good efficiency. Practicalities of numerical stability and accuracy lead naturally to the requirement for semi-implicit time-advance methods where tradeoffs between stabilization from the implicit part of the time advance are balanced with spatio-temporal accuracy from the explicit part of the time advance. An alternative strategy to make the pressure solution much more amenable to parallelization is to apply either a compressible code in the low Mach number limit, or to solve pressure using a pseudo-compressibility strategy. The tradeoff, however, is the requirement for much smaller time steps with high loss of efficiency and unacceptable CPU cost. With such methods, stability can be maintained at larger time steps by applying costly preconditioning and reducing parallelizability. The inherent tradeoff between scalability and efficiency of incompressible solvers on highly complex geometries with highly multiscale complex grid structure is at the core of the difficulty with fully blade-boundary-layer resolved simulation of utility-scale wind turbine operating within LES of atmospheric boundary layer turbulence.

Within the OpenFOAM framework, the semi-implicit approach is based on a combination of the PISO algorithm for the pressure solve and the SIMPLE algorithm for time advance — what the OpenFOAM developers have labeled the "PIMPLE" algorithm. This is a finite-volume based solver. The practical tradeoffs in the application of the solver are:

(1) The number of corrector loops between the linearized predictor solution of the momentum equation and the pressure Poisson solution (SIMPLE);

(2) The number of loops to converge the pressure-Poisson solution to smaller tolerances on the solenoidal (continuity) requirement (PISO)

(3) The number of non-orthogonal corrector loops within the pressure-Poisson solution in order to improve estimates of derivatives in the source term within cells by improving estimates of cell face distances.

(4) The number of gradient limiters to artificially suppress instability from growth in gradients in momentum, temperature and/or turbulence prognostic variables* by placing local limits on gradients in variables of choice. The suppression of instability comes at the cost of increased

effective artificial dissipation. (*Turbulence variables are those calculated in prognostic equations for eddy viscosity: k (turbulent kinetic energy) and ω for the URANS model and e (SFS kinetic energy) for the LES SFS stress model.)

The first two steps above—inner pressure loops and outer velocity-pressure corrector loops—indirectly create a tradeoff between explicit and implicit time advance, implicitly improving stability; the second two steps above explicitly improve stability. When the simulation starts, initial "shocks" must be suppressed by reduction in time step (compared to later when the transients have settled down) and by the introduction of high levels of artificial (numerical) dissipation. The latter is done by increasing the number of gradient limiters and by changing to a first-order purely upwind solver. However, maintaining high levels of numerical dissipation suppresses the development of the smallest resolved fluctuations so that vortex formation, natural instability and turbulence are all suppressed, significantly affecting both the time-local accuracy and the temporal evolution of the flow-field. Thus, every attempt should be made to minimize numerical dissipation after the simulation passes through transients by changing to a second order scheme and reducing gradient limiters to the lowest possible number on the fewest number of variables. It is particularly important to remove limiters from velocity and temperature.

The inner-outer looping of the algorithm must be determined by trial and error in relationship to creating sufficiently strong coupling within the flow via more accurate solution of the pressure-Poisson equation (effectively integrating nonlocal information in the source term) and tighter coupling between the solution for pressure and the solution for velocity. Furthermore, due to the highly nonsteady and large-scale nature of the atmospheric turbulence passing through the rotor disk, a calculation that is stable over a few blade rotations can go unstable as the eddy inflow structure changes. For this reason, CWF-like simulations must be constantly monitored for impending loss of numerical stability and regularly the simulation must be stopped and restarted at an earlier time with change in time step, inner-outer PISO-SIMPLE loop structure, and/or gradient limiter level on different variables. This need to carefully monitor runs puts adds major human effort to a run and seriously limits the rate at which a major simulation can progress. Furthermore, accuracy and stability requirements must be balanced by the desire to minimize CPU cost—each additional loop comes with the price of additional cost.

For example, as shown in fig. 9, the wind turbine rotor in the CWF simulations is within a cylindrical region that rotates relative to a fixed outer gridded domain. As has been discussed, the grid reduces, in this region, from the chord scale (~ 1 m) to the viscous wall layer scale (~ 5 μm), 5-6 orders of magnitude. A serious consequence of the physical need for such a dramatic change in grid size is a corresponding difference in time step requirements and consequent stiffness in the coupling between inner vs. outer solution. We discovered, from trial and error, that if the number of inner and outer loops in the PISO-SIMPLE algorithm is not sufficiently large, the outer domain decouples from the inner domain and develops a serious incorrect temporal lag. Tight coupling is required. However, there is a strong need to minimize computational expense and clock time, so a series of parameter-variation studies were carried out to determine the optimal looping structure. Coincidentally, time step, the number of pressure loops and the number of non-orthogonal correctors in the pressure loop were chosen to maintain stability, again optimally to maintain minimum required CPU cost. The practical time requirements for this trial and error process combined with serious limitations in terms of CPU resources, system usage, and queuing biases, were among the more serious issues in developing and carrying out of simulations at the level of complexity required for blade-boundary-layer resolved wind turbine simulation.

6. Technical Aspects of Running OpenFOAM in Parallel on HPC Platforms

As was alluded to just above, there are a wide range of practical issues and limitations that make the development and carrying out of simulations at the complexity level of the Penn State Cyber Wind Facility extremely difficult and time-consuming in ways that extend well beyond algorithmic, modeling and physics issues. Some of these are summarized in this section.

Domain Decomposition, Mapping and Parallelization: RAM Requirements and AMI

To parallelize the simulation the domain must be decomposed so that the computational load is over the domain is carried by N cores over N subdomains of the grid with the aim to minimize the surface area between subdomains while maximizing subdomain volume. Standard utilities that automate the decomposition process that integrate with OpenFOAM are "Scotch" and "Metis." Although we have used both, Scotch is the primary utility of choice as it interfaces directly with OpenFOAM.

Quality domain decomposition directly impacts the quality of parallelization and scaling during simulations. The aim is to balance cells-per-core and minimize surface area to volume of decomposed patch as a function of number of cores (i.e., cells per core). There is some dependency on computational architecture and major dependency on the complexity and structure of the grid in relationship to the algorithmic details of the discretized dynamical system. Cell-count-balancing among cores is a major issue and is strongly impacted by the AMI interpolations illustrated in fig. 7. The central nature of a wind turbine simulation is a rotor rotating with respect to an atmospheric boundary layer flow which contains powerful energy-dominant turbulence eddies that sweep through the rotor disk and cause major time dependent wind turbine load responses that are at the heart of the types of simulations underlying this document.

Options for Resolving Rotating Blades. There are three options to consider in order to resolve the blade surface boundary layers on rotating wind turbine blades: (1) move the blade through a fixed grid (i.e., with immersed boundary methods), (2) rotate the entire grid with blades, and (3) rotate a grid local to the rotor relative to a grid fixed relative to the ground and tower. The first approach cannot work for blade-boundary-layer-resolved simulation since, to resolve the extremely thin blade boundary layer adjacent to blade surfaces, the grid would have to be extraordinarily refined over the entire rotor volume through which the blade passes, a wholly impractical approach. Option (2) would cause great difficulties in the specification of surface stress boundary conditions along the rough ground surface and on surfaces fixed relative to the ground, such as the tower and nacelle. Thus the only viable option is (3): rotate grids with the blades relative to fixed grids. This can be done using the Arbitrary Mesh Interface functionality within OpenFOAM or using grid overset methods which currently do not exist for OpenFOAM. Given the latter fact, we applied AMI interpolation across the cylindrical boundaries of the inner grid domain shown in fig. 7.

Parallelizing AMI Interpolations. Domain decomposition is hampered by the special requirements to interpolate between two grids, one rotating and one fixed. The grid cells involved in the interpolation must be specially handled with respect to decomposition and parallelization. To minimize inter-processor communication, cells involved in the interpolation should reside on the same processor. In fig. 7 we show the cylindrical AMI surface. This surface extends to the downstream boundary of the domain, but ends approximately 2-3 rotor diameters upstream of the rotor, before the inlet to the domain where Dirichlet boundary conditions in velocity are applied from the LES ABL simulation. The AMI surface is decomposed into N patches of cells across pieces of the AMI surface that are indicated by the different colors. The cylindrical surface, for example, is separated into cylindrical bands of axial width Δ_z. The cells involved in AMI interpolation across each band are assigned to a single processor. Similarly cells involved in AMI interpolation across the circular bands in the front of the AMI surface (fig. 7) are assigned to a single core. To incorporate these elemental surface patches into the decomposition using Scotch or Metis is not straightforward and for good scaling it is necessary that the cells/core be balanced among all cores. Balancing cells/core from the AMI surface patches with those from volumetric regions is a function of the number of the cores.

OpenFOAM interpolates data across overlapping AMI patches. To reduce communication overhead during the interpolation process, it is desirable to have the cells corresponding to the overlapping patches on the same processor. If the AMI surface patches across which interpolation takes place were dedicated to a single core, the number of patches would have to be adjusted each time the number of cores changes. To avoid this practical difficulty, Ganesh made a clever adjustment to OpenFOAM. The existing decomposition strategy in OpenFOAM uses Scotch to decompose the grid into the desired number of processors without any constraints and then modifies the decomposition for the cells containing the overlapping patches to be on the same processor. This leads to a non-optimal decomposition. Ganesh modified the strategy to agglomerate the cells surrounding each AMI patch before passing it to Scotch for decomposition. This allows Scotch to optimally decompose the mesh within the desired constraints.

Once grid decomposition is accomplished, this can be used on any parallel platform. However, a simulation cannot initiate until all simulation and boundary condition data are assigned to each cell on each core. We carry out this data decomposition as a second step. Both grid and data decomposition are accomplished by first placing all grid and data information required for the decomposition on a single processor. For this reason, the decomposition process requires a platform with large memory accessible by a single core. On the XSEDE network we have used, for this purpose, Blacklight at Pittsburgh Computer Center (PSC)—a machine with large shared memory—and Stampede at Texas Advanced Computing Center (TACC), one of the largest and most versatile HPC platforms on the XSEDE network with some nodes that can assess very large memory.

Occasionally, there is a need to interpolate data from one grid onto another, for example to initiate a more refined simulation with data from a coarser simulation. This requires use of the "mapping" tool within OpenFOAM and, depending on the number of variables mapped and the order of interpolation, the mapping process on the inherently unstructured OpenFOAM grids can consume several CPU hours and many more person hours.

File System Metadata Server Problems with OpenFOAM: the need for HDF5

As we developed our codes, we began serious production runs several months ago on 9M, 58M and 158M grids on XSEDE and DOE platforms using different levels of parallelization from <1000 to >4000 cores. A few months ago, our prime computational resource (the XSEDE Stampede platform with Lustre file system) was taken from us due to a problem with the way in which OpenFOAM writes and reads from disk. It turns out that when variables are output to disk from OpenFOAM, each variable is output in a separate file from each core. Thus if one is running on 1000 cores, for example, and one must 30 variables, then each time data are output, the file system must manipulate 30,000 files.

Because the focus of blade-boundary-layer resolved simulation is time-resolution of data output, it is necessary to output frequently, typically every 10-100 time steps. The output must be written also as input to restart the simulation if the calculation were to stop for some reason that does not allow for a final restart file to be written. (This is not an uncommon occurrence. With simulations this large, and with the practicalities of queue wait times and clock time restrictions in HPC schedulers, will we cannot continually start simulations over.) Therefore, every 10-100 time steps the metadata server within the Lustre filed system between RAM and disk must handle 30,000 files. With 4000 cores the number is 120,000 files, and if we are ever able to scale to 10,000 cores or more, the metadata server would have to handle over 300,000 files every 10-100 time steps. The result is that while it is handling such huge numbers of individual files, the metadata server is blocking the bandwidth between main memory and the file system. For this reason, the TACC XSEDE personnel have blocked our use of Stampede for large-core OpenFOAM usage until the problem is resolved.

To resolve the problem we have been working for the past several months with Dr. Anirban Jana of Pittsburgh Computer Center (PSC) and Dr. Si Liu of Texas Advanced Computing Center (TACC), financially supported by XSEDE to work with us, to incorporate the Hierarchical Data Format (HDF) Version 5 (http://www.hdfgroup.org/) into OpenFOAM with I/O structure specific to the data structure of our CWF simulations. As indicated on the HDF5 website, the HDF group of libraries was initiated at NCSA (University of Illinois) in 1987 and "HDF5 users and enthusiasts have created and are maintaining a variety of add-ons, high-level libraries, plugins, language bindings, and applications." Anirban is leading the effort to develop code to incorporate HDF5 applications in OpenFOAM that allow the output and input of all necessary data, including all information needed to specify the decomposed grid, grid boundary conditions, and data on the grid, on all cores, to restart the simulation from a single output/input file. Given the general nature of the decomposed grid and grid boundary conditions and the need to access all cores to both compile and redistribute this information to recreate all processes required to restart the run, this is a far from trivial exercise. The development is hopefully nearing the testing stage as new issues are uncovered. Ganesh and Balaji are working with Anirban to test code on relatively simple domains (e.g., 3D lid driven cavity flow) as developed. Ultimately, the HDF5 code must be incorporated into our CWF and tested on large numbers of cores. It is not clear how many more week are required for full implementation within CWF. Once complete, the code will be available to others to modify and adapt to their computational environments.

OpenFOAMs use of Dynamically Linked Libraries: Problems with Large Core Numbers

There exists another potential metadata server problem with OpenFOAM that, like the issue above, becomes increasingly severe as the number of cores used increases. OpenFOAM uses libraries that are dynamically linked at runtime and each core must search for library files on its own at startup. For example, typically 44 libraries are linked, so a simulation with 1000 cores produces 44,000 searches at runtime, swamping the metadata server. We aim to use several thousand cores, however as the number of cores is increases as required to run on major HPC platforms, the metadata server can completely clog. However, even with a couple thousand cores, when the metadata server is not clogged, the initiation of the simulation can be delayed by a couple hours as dynamic linking takes place. This not only wastes resources, but given that clock time is often limited to a few hours, dynamic linking with large numbers of cores, delaying start time, can often use a significant portion of total run time. Furthermore, the lack of an optimal executable in the compilation process increases run time.

Solving this problem requires altering the OpenFOAM environment to allow statically linked libraries. This reduces flexibility in the general applicability of OpenFOAM (the reason why dynamic linking is built in), but removes the startup barrier that will limit OpenFOAM usage as the number of cores increases into the thousands with many library calls.

Data Extraction and Analysis: a Serious Issue with Systems designed for Unstructured Grids

It should also be recognized that, because the OpenFOAM discretization environment is designed on an unstructured grid framework (even if the grid is structured), data are not stored in simple "i,j,k" format, accessible through relatively simple read statements into post-processing software that can easily identify and manipulate subsets of data. Instead, data are stored in patches in OpenFOAM format and can only be accessed using OpenFOAM-provided classes. This highly limits accessibility and flexibility in the way data are stored for subsequent data analysis. Custom classes must be designed for targeted data extraction. For example, to access volumetric data from the external atmospheric turbulence surrounding the wind turbine rotor, it was necessary to reduce resolution in some regions to make the data manageable. If the data were stored in structured grid format, the down-sampling could have been done in many ways in straightforward manner. However, this was not possible within the OpenFOAM environment. Instead we found it necessary to define another grid, much coarser than the simulation grid, onto which the data were interpolated using the OpenFOAM mapping utility. This coarse-grid dataset was then stored and later manipulated using other OpenFOAM data extraction tools. Data analysis requires runtime tiered data extraction, and data analysis requires the combined use of Paraview and python scripting at high levels of sophistication. Ganesh has developed a large suite of data-extraction analysis tools, in addition to volumetric regions, extract data from planes perpendicular to the blade axis, from cylinders surrounding each blade, from planes parallel and perpendicular to the rotor plane and ground, and from lines perpendicular to blade surfaces. All these data analysis tools were developed by Ganesh Vijayakumar.

Useful References

Churchfield, M.J., Moriarty, P.J., Martínez, L.A., Leonardi, S., Vijayakumar, G., Brasseur, J.G. 2012 Large-Eddy Simulations of Wind-Plant Aerodynamics, Proc. 50th AIAA Aerospace Sciences Meeting, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0537.

Jonkman, J., Butterfield, S., Musial, W., Scott, G. 2009 Definition of a 5-MW Reference Wind Turbine for Offshore System Development, NREL/TP-500-38060.

Lavely, A., Vijayakumar, G., Craven, B., Jayaraman, B., Jha, P., Nandi, T., Paterson, E.G., Brasseur. J.G. 2014. Toward a Blade-Resolved Hybrid URANS-LES of the NREL 5-MW Wind Turbine Rotor within Large Eddy Simulation of the Atmospheric Boundary Layer, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0869.

Lavely, A.W., Vijayakumar, G., Brasseur, J.G., Paterson, E.G., Kinzel, M.P. 2012 Comparing Unsteady Loadings on Wind Turbines using TurbSim and LES Flow Fields, Proc. 50th AIAA Aerospace Sciences Meeting, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0818.

Lavely, A. W., Vijayakumar, G., Kinzel, M.P., Brasseur, J.G., Paterson, E.G. 2011 Space-Time Loadings on Wind Turbine Blades Driven by Atmospheric Boundary Layer Turbulence. Proc. 49th AIAA Aerospace Sciences Meeting, 4-7 Jan 2011, Orlando, FL, AIAA Paper 2011-635.

Egorov, Y., Menter, F.2008 Development and application of SST-SAS turbulence model in the DESIDER project," in Advances in Hybrid RANS-LES Modelling, Springer, pp. 261-270.

Vijayakumar, G., Lavely, A., Jayaraman, B., Craven, B., Brasseur. J.G. 2014, Blade Boundary Layer Response to Atmospheric Boundary Layer Turbulence on a NREL 5MW Wind Turbine Blade with Hybrid URANS-LES, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0867.

Vijayakumar, G., Brasseur, J.G., Lavely, A.W., Kinzel, M.P., Paterson, E.G., Church, M.J., Moriarty, P.J. 2012 Considerations in coupling LES of the atmosphere to CFD around wind turbines, Proc. 50th AIAA Aerospace Sciences Meeting, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0817.