U.S. DEPARTMENT OF ENERGY

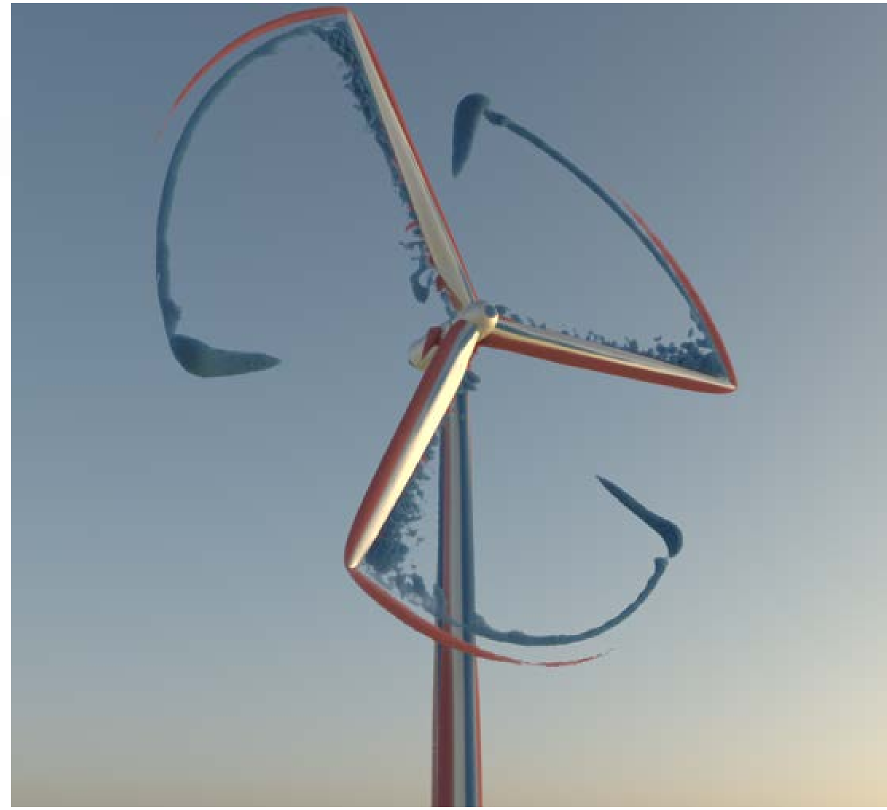
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

High-Fidelity Modeling

Project ID #T6

Michael A. Sprague

National Renewable Energy Laboratory



FY17-FY18 Wind Office Project Organization

“Enabling Wind Energy Options Nationwide”

Technology Development	Market Acceleration & Deployment
Atmosphere to Electrons	Stakeholder Engagement, Workforce Development, and Human Use Considerations
Offshore Wind	Environmental Research
Distributed Wind	Grid Integration
Testing Infrastructure	Regulatory and Siting
Standards Support and International Engagement	
Advanced Components, Reliability, and Manufacturing	

Analysis and Modeling (cross-cutting)

Project Overview

T6: High-Fidelity Modeling

Project Summary

- Creating an open-source, high- and multi-fidelity predictive modeling and simulation (ModSim) capability for wind turbines and plants
- Performing simulations designed to create new understanding of complex flow physics and turbine dynamics

Project Objective & Impact

- High-fidelity modeling (HFM), combined with high-performance computing (HPC), will enable new understanding of flow and turbine dynamics both on and offshore
- HFM/HPC will expose new pathways to, e.g., reducing levelized cost of energy (LCOE), increasing energy capture, and reducing loads
- HFM simulations will serve as a foundation for creating new, highly efficient engineering models for, e.g., optimization and uncertainty quantification

Project Attributes

Project Principal Investigator(s)

Michael A. Sprague
David Maniaci (FY17-FY18)
Paul Crozier (FY19+)

DOE Lead

Michael Derby

Project Partners/Subs

National Renewable Energy Laboratory
- About 10 people

Sandia National Laboratories
- About 7 people

University of Colorado at Boulder
Northwest Research Associates

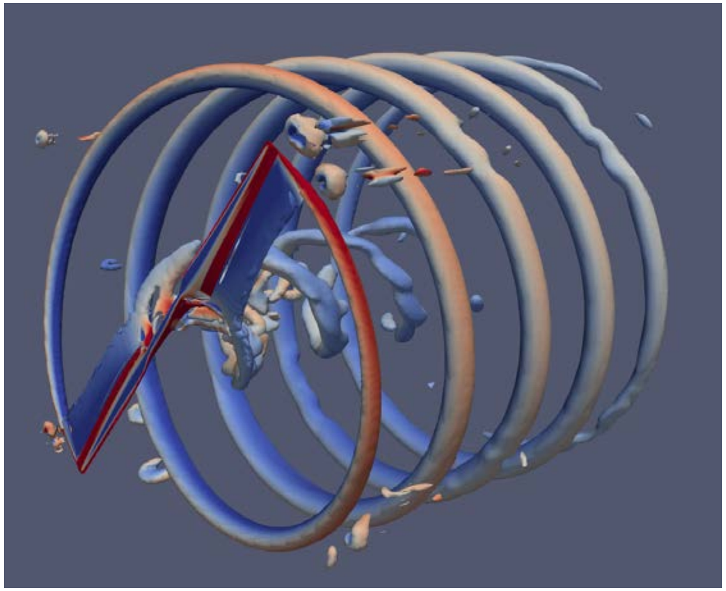
Project Duration

6.6 years (3/1/2016–9/30/2022)

Technical Merit and Relevance

Our lack of understanding and inability to predict the complex flow and dynamic responses within wind farms is restricting the pace of technology innovation and wide-scale deployment of wind energy

Photo by Gitte Nyhus Lundorff, Bel Air Aviation Denmark – Helicopter Services



Validated, predictive modeling and simulation enable researchers and engineers to

- expose new, disruptive, pathways to lowering the cost of energy
- create a foundation for next-generation HFM & engineering models for optimization and uncertainty quantification

Nalu-Wind simulation of the NREL Phase VI turbine (Ananthan)

Technical Merit and Relevance

Photo by Gitte Nyhus Lundorff, Bel Air Aviation Denmark – Helicopter Services

Can we predict, and understand, e.g.,

Impact of wakes on downstream turbines?

Evolution of the wakes?

Formation of the wakes?

HFM & HPC on DOE supercomputers are keys

Approach and Methodology

- **HFM modeling & simulation pathway established in 2015 A2e Strategic Planning Meeting of experts selected the Nalu large-eddy simulation (LES) computational fluid dynamics (CFD) code and the FAST v8 whole-turbine simulation code as our starting points**
- **Nalu chosen because it**
  - is open source
  - is <u>highly scalable on modern supercomputers</u>
  - was designed with sustainable software engineering methods
  - leverages well-supported libraries (e.g., linear solvers)

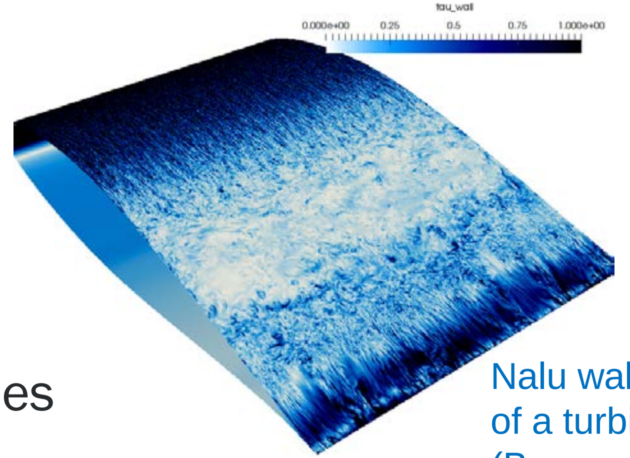
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

A2e High Fidelity Modeling: Strategic Planning Meetings

Steven W. Hammond and Michael A. Sprague
National Renewable Energy Laboratory

David Womble and Matt Barone
Sandia National Laboratories

http://www.nrel.gov/docs/fy16osti/64697.pdf



Nalu wall-resolved LES study of a turbine blade section (Barone, Trinity Open Science project)

Approach and Methodology

- Created Nalu-Wind, a wind-specific code based on Nalu
- Implemented and demonstrated midfidelity capabilities established in SOWFA:
  - Atmospheric boundary layer
  - Actuator-line turbines
  - Coupling to OpenFAST
- Created a modern ModSim environment for FAST v8, called OpenFAST
- Implemented capabilities for high-fidelity blade-resolved turbine simulations to capture wake development and fluid-structure (rotor and tower) interactions

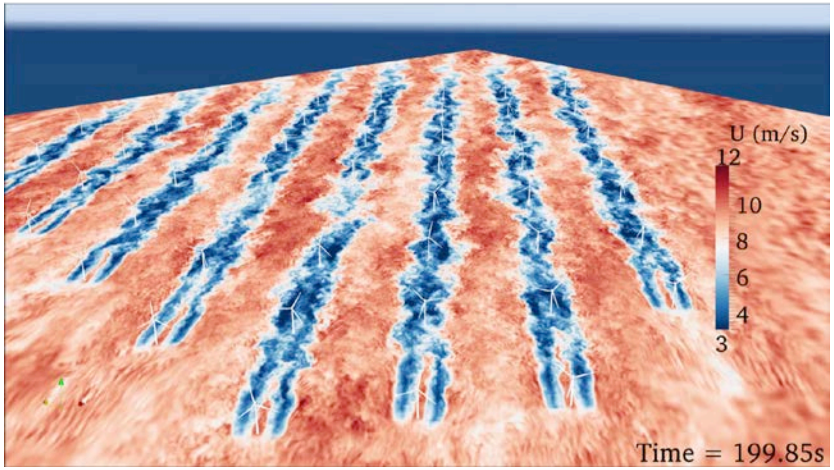
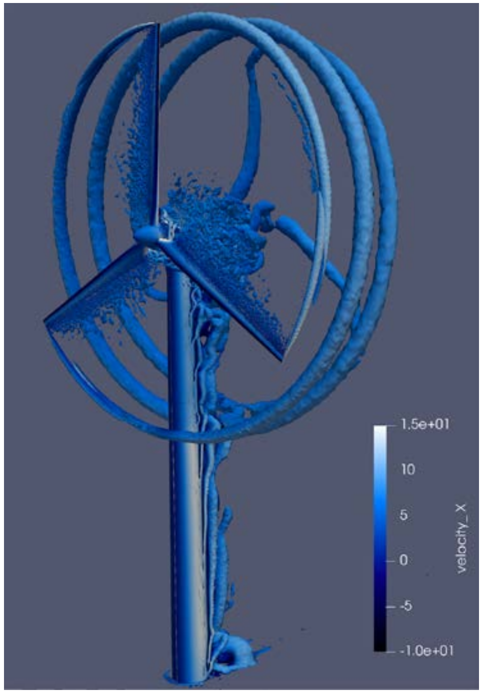


Image of Lillgrund offshore wind farm and associated SOWFA simulation (Churchfield, NREL)

Approach and Methodology

We are evolving an LES research code to handle "production" wind-energy simulations and DOE supercomputers

Nalu



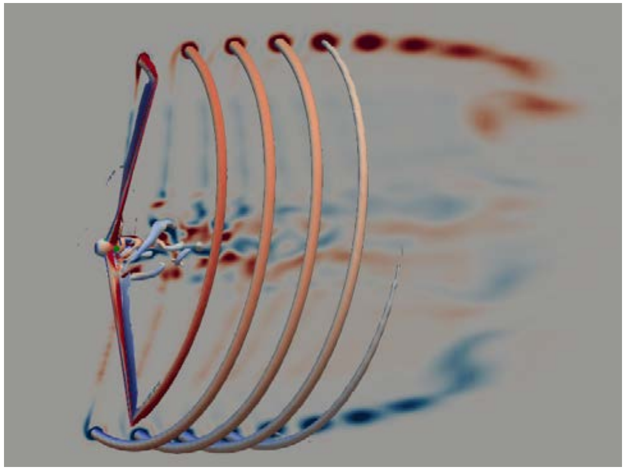
Vestas V27 Turbine

- LES-focused code
- **Development philosophy:** emphasis on maintaining design-order accuracy

Image from *ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling;* poster presented at the ECP Annual Meeting, Knoxville, TN, 2018, SAND2018-1050D

Nalu-Wind

- ***Development philosophy:*** balance accuracy with robustness and practical time to solution
- **Quantities of interest drive algorithm design**



NREL 5-MW Turbine

Image from *Blade-resolved, overset-mesh turbine simulations using Nalu-Wind*, Ananthan et al.; abstract submitted to WESC 2019

Approach and Methodology

- **Development activities are closely linked with multiple WETO projects in applied sciences, including**
  - Wake Dynamics
  - Integrated Systems Design & Analysis (ISDA)
  - Meso-Scale Micro-Scale Coupling (MMC)
- **Adhering to modern software engineering practices to maintain a robust, portable, open-source modeling and simulation environment**
  - Automated testing
  - Multiplatform build system
  - Online documentation
  - Software version control
- **Enabling multifidelity models in the Nalu-Wind/OpenFAST environment**
  - Needed capability for industry wind turbine and plant technology innovation
  - Key for uncertainty quantification and validation

Accomplishments and Progress

- **All ten FY17-FY18 milestones have been completed, but there were delays**
  - FY17 Q1 completion delayed 2.5 months (implementation of SOWFA capabilities)
  - FY17 Q2 & Q3 milestones delayed and reconfigured into FY18 milestones (demonstration of SOWFA capabilities)
  - FY18 Q2 & Q3 milestones were delayed
- **In short, equipping and converting a research-focused CFD code (Nalu) into one capable of realistic wind energy simulations (Nalu-Wind) was much more difficult than expected**
- **The Nalu-Wind code is now on track**
  - Validation-quality blade-resolved simulations are now being performed

Accomplishments and Progress

Start of the HFM project in mid-FY16 was key to securing the ExaWind Exascale Computing Project (ECP)

- ExaWind ECP is funded at about $3.5M/year, FY17 – FY22
- Preparing Nalu-Wind for next-generation exascale supercomputers
- HFM and ExaWind are in close collaboration and are dependent on each other

EXASCALE COMPUTING PROJECT

OLCF Summit Supercomputer

Importance of ExaWind/HFM Collaboration: Consider *Summit*, at the DOE Oak Ridge Leadership Computing Facility (OLCF)

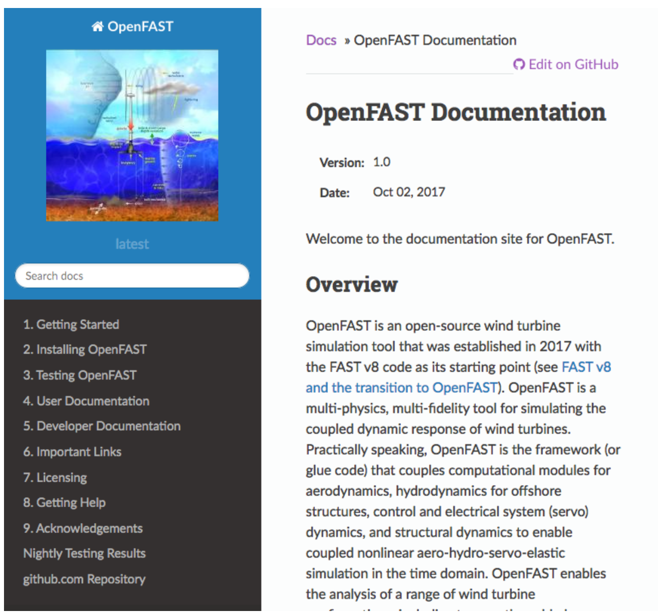
- World's fastest supercomputer
- 200 PetaFLOPs machine
- Codes must be able to effectively execute on **Graphical Processing Units** (GPUs) to get compute time

Accomplishments and Progress

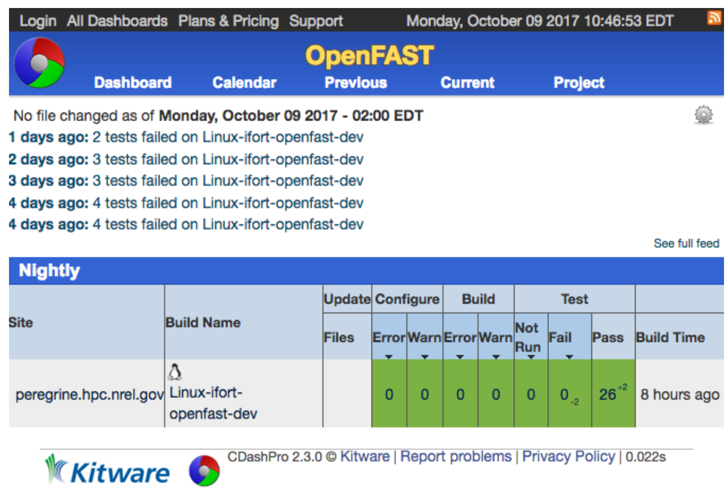
Established web presence for Nalu-Wind and OpenFAST

- Includes documentation, code repository, and results from nightly automated testing

	Nalu-Wind	OpenFAST
Documentation	https://nalu-wind.readthedocs.io/	https://openfast.readthedocs.io/
Code repository	https://github.com/exawind/nalu-wind	https://github.com/openfast/openfast
Code testing	https://my.cdash.org/index.php?project=Nalu-Wind	https://my.cdash.org/index.php?project=OpenFAST



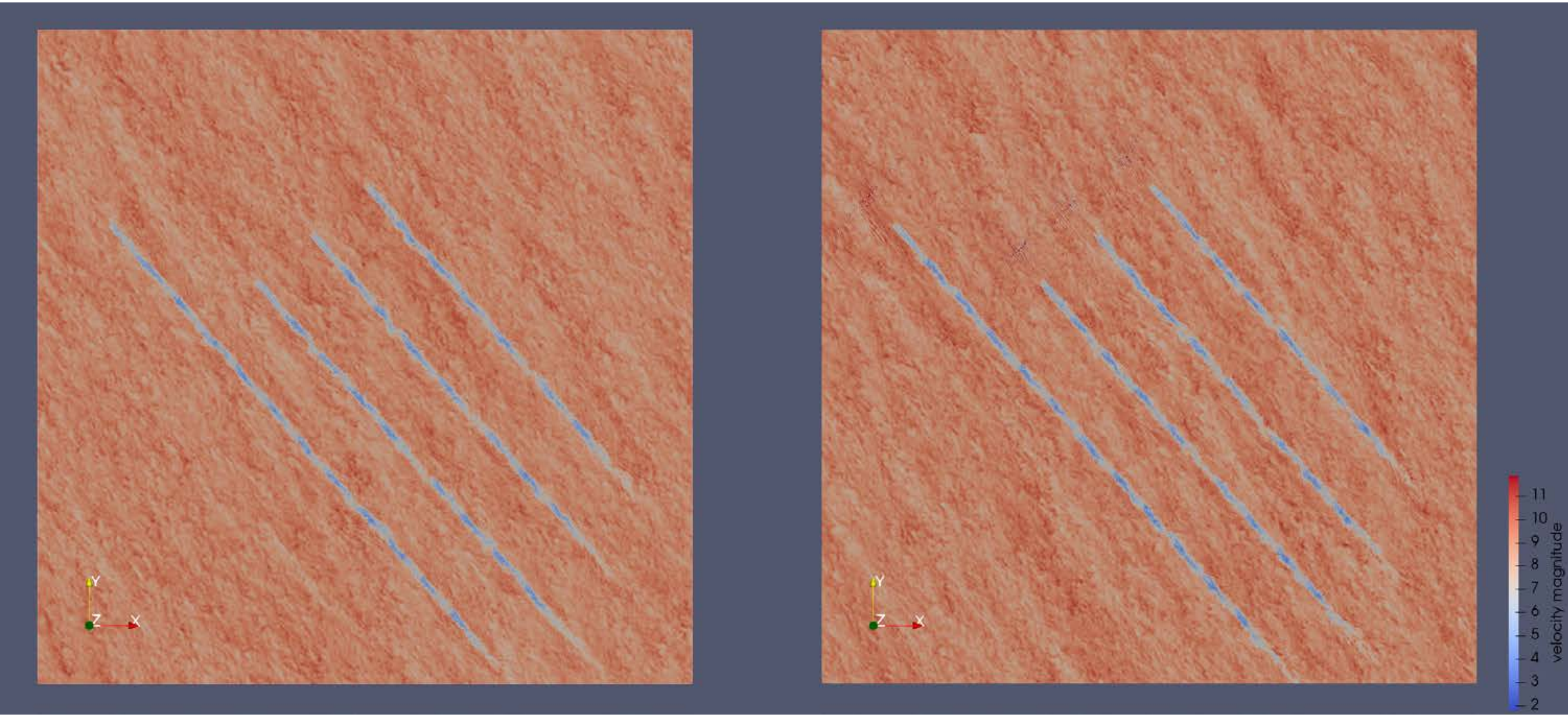
Screenshot of the new OpenFAST documentation site



Screenshot of the new OpenFAST nightly testing reporting site

Accomplishments and Progress

Established in Nalu-Wind the key features of SOWFA for midfidelity actuator-line wind farm simulations

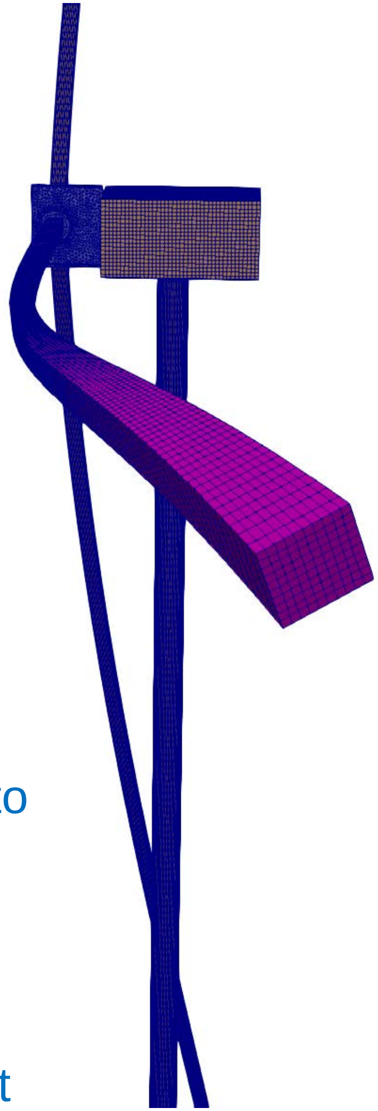


Velocity magnitude at hub height (70 m) for Nalu-Wind (left) and SOWFA (right) simulations for the OWEZ wind farm (after initialization with atmospheric-boundary-layer precursor)

Accomplishments and Progress

Established a new mapping algorithm necessary for coupling OpenFAST and Nalu-Wind in fluid-structure interaction calculations

- Algorithm designed to map motion and forces between different mesh topologies
- E.g., mapping between an OpenFAST BeamDyn blade model (line elements) and the fluid (surface elements)



Cartoon turbine model used to verify the mapping algorithm between OpenFAST and the body-resolved fluid mesh in Nalu-Wind for large blade deflections and rotations/twist (Vijayakumar)

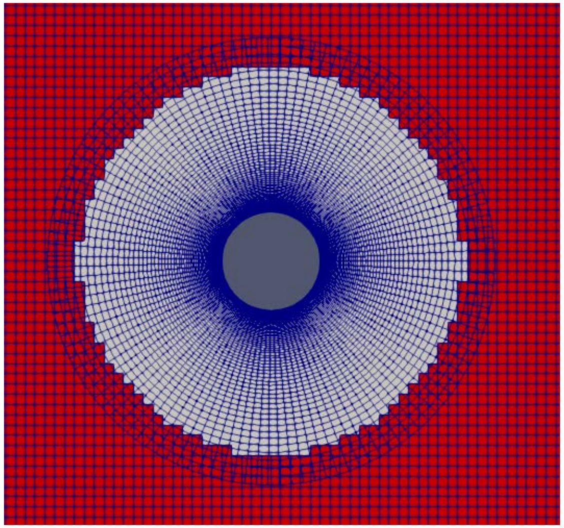
Accomplishments and Progress

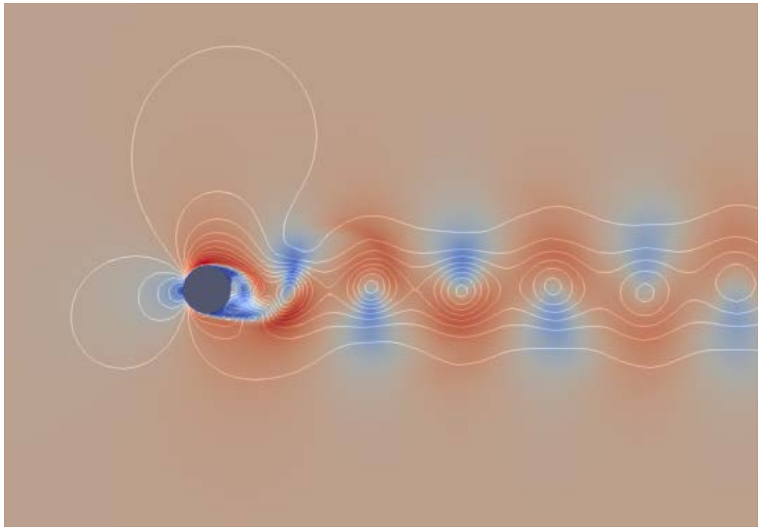
Established overset-mesh capabilities through the Topology Independent Overset Grid Assembler (TIOGA)

- Collaboration between A2e-HFM, ExaWind ECP, and J. Sitaraman

Overset-mesh capability

- Greatly simplifies creation of high-quality hex-dominant fluid meshes
- Simplifies fluid-structure interaction calculations

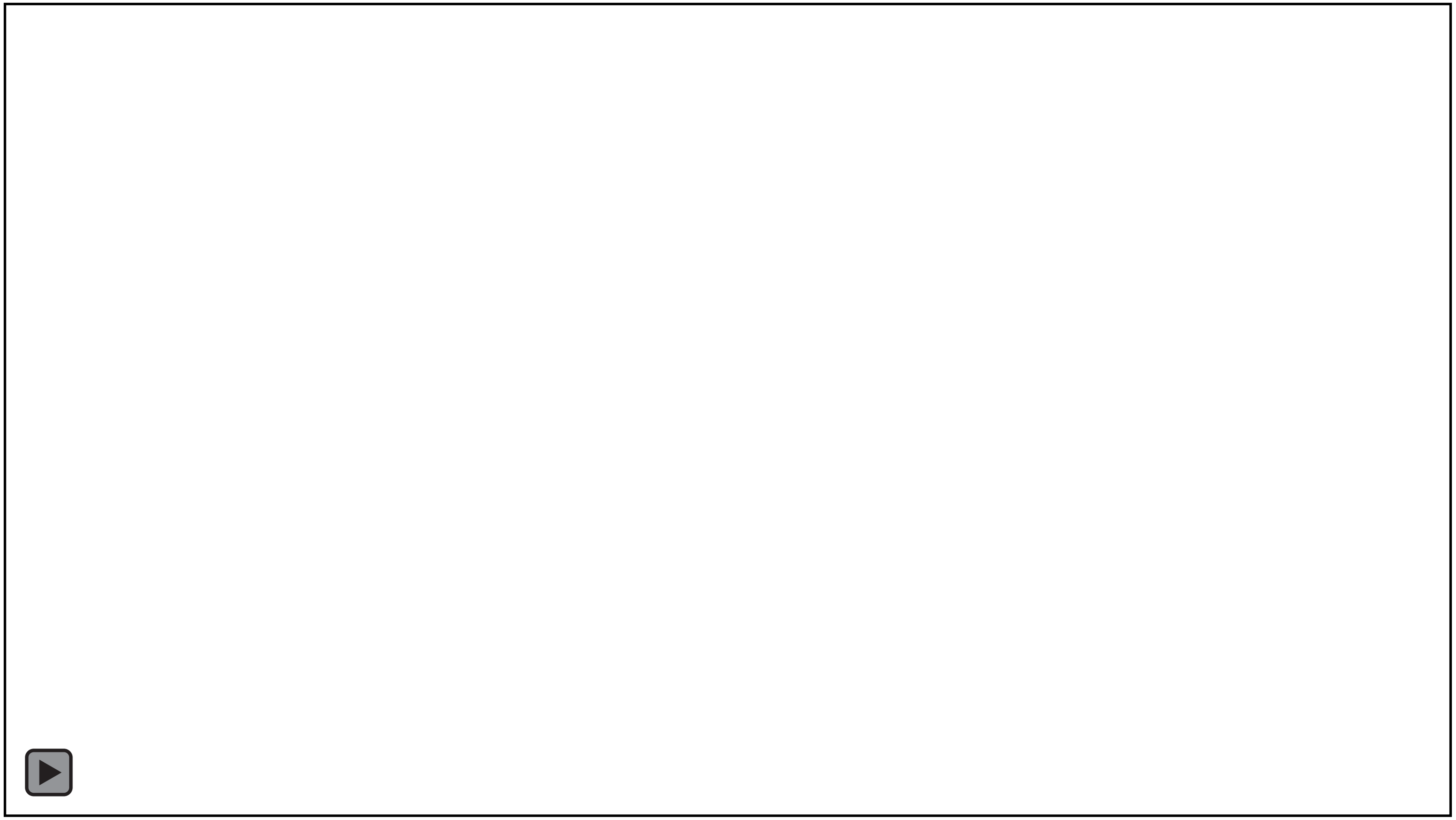




Nalu-Wind simulation of flow over a cylinder demonstrating the new overset-mesh capability (Ananthan)

Accomplishments and Progress

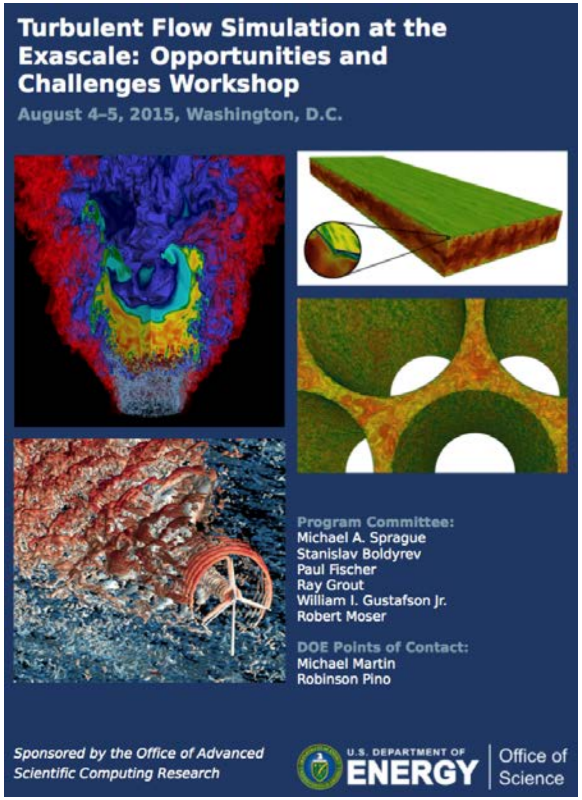
In collaboration with ExaWind, established proof-of-concept, reduced-physics blade-resolved simulation capability



NREL 5-MW turbine simulation under uniform inflow of 8 m/s. Sliding-mesh interface. Simulation performed on the NERSC Cori machine.

Communication, Coordination, and Commercialization

- **The High-Fidelity Modeling project is designed to be as open as possible, with feedback encouraged**
  - All code is maintained, developed, and documented in the open domain
  - The HFM team communicates regularly with DOE WETO projects (e.g., PRUF, MMC, ISDA, Wake Dynamics)
- **HFM and ExaWind are executed as close collaborations**
  - Access to Office of Science supercomputers will be key to success of HFM
- **HFM regularly communicates results through conference presentations, papers, and technical reports**
  - See summary document for details

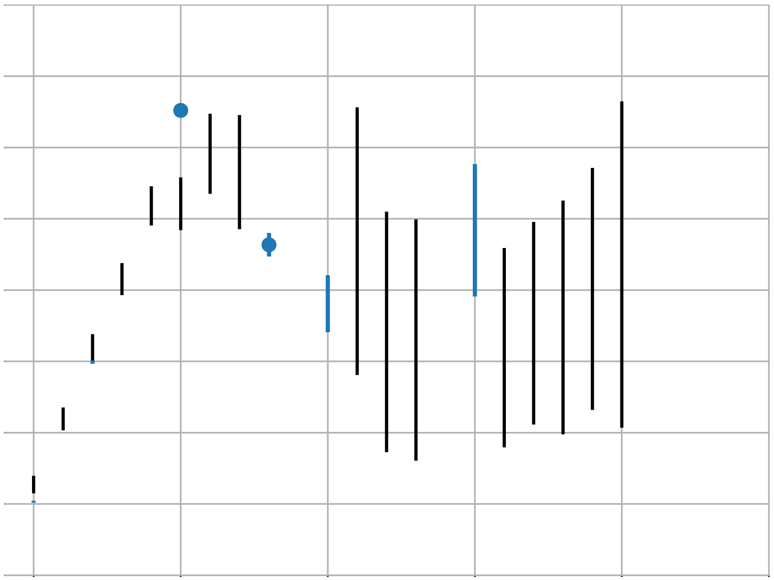


Predictive wind plant simulations are recognized as a simulation grand challenge

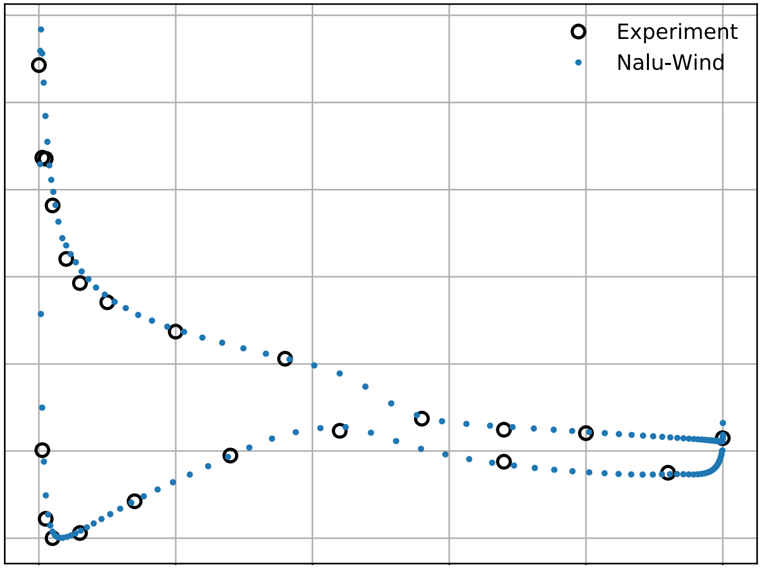
http://www.nrel.gov/docs/fy17osti/67648.pdf

Recent & Upcoming Project Activities

Performed first validation-quality Nalu-Wind unsteady Reynolds-averaged-Navier-Stokes (URANS) simulations of a turbine with appropriate grid resolution and moving meshes



Experimental and simulated average rotor torque of the NREL Phase VI turbine



Experimental and simulated coefficient of pressure C_p at 80% of blade length for NREL Phase VI turbine with mean flow velocity of 10 m/s

(Ananthan et al.)

Recent & Upcoming Project Activities

- **On track to have full, baseline turbine-resolved capabilities in place by mid-FY19**
- **FY19–FY22**
  - Establish international working group to define and execute benchmarks for demonstrating predictive HFM capabilities
  - Advance and validate Nalu-Wind models (e.g., turbulence, complex terrain, ABL boundary conditions for large wind farms)
  - Continue collaboration with ExaWind, enabling efficient simulations on next-generation supercomputers
  - Secure compute time and perform highest-fidelity simulations to date
- **FY20+: New focus on predictive simulation capabilities for <u>offshore wind</u>; high-fidelity models will include**
  - The offshore environment including hydrodynamics, air-sea interaction, the marine boundary layer, etc.
  - Floating platforms, mooring lines, etc.