Wind Energy Science Leadership Series

Discussions on the leading edge of wind energy science.

The Future of High-Performance Computing for Wind Energy

Thursday, July 30
9:00 to 10:15 a.m. MT
The future of high-performance computing for wind energy

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Overview: Speakers and topics

- **Mike Sprague**, PI for the DOE ExaWind and High-Fidelity Modeling Projects
  - Motivation for predictive high-fidelity modeling for wind energy
  - Overview of our team efforts and open-source software stack
- **Shreyas Ananthan**, Senior Research Scientist, ExaWind Chief Software Architect
  - Next-generation high-performance computing
- **Ganesh Vijayakumar**, Research Engineer
  - Model validation: Building confidence in our simulated reality
- **Luis 'Tony' Martínez Tossas**, Research Engineer
  - HPC and HFM as the foundation for next-generation engineering models
Motivation for next-generation high-fidelity models (which require HPC)

• More wind energy at low cost is a good thing
• High penetration of wind energy requires large wind farms composed of megawatt-scale turbines
  • Both land-based and offshore
• Wind farm flow dynamics and coupled turbine structural dynamics are extremely complex and models are lacking
  • Relevant dynamics span many orders of magnitude
• Only when we can model well the wind system can we optimize that system
  • Maximize energy extraction
  • Maximize turbine life, minimize downtime

Grand challenges in the science of wind energy
https://science.sciencemag.org/content/366/6464/eaau2027
HFM & HPC can illuminate the path to reducing the cost of wind energy

Can we **predict** and understand:

- Impact of wakes on downstream turbines?
- Evolution of the wakes?
- Formation of the wakes?

... and all in a highly complex, dynamic metocean environment

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

DOE Advanced Scientific Computing Research (ASCR) workshop highlighted predictive wind farm simulation as a grand-challenge requiring next-gen **exascale-class** supercomputers

http://www.nrel.gov/docs/fy17osti/67648.pdf
Primer: What is high-fidelity modeling (HFM)?

- **Mathematical model**: a description of a system using mathematical concepts
  - *i.e., an equation or a bunch of equations*
- For HFM of wind farms, we strive to adhere to **first-principles** to increase **predictivity**
  - Conservation of mass
  - Newton’s second law of motion
- The accepted model for many fluid motions is embodied in the **Navier-Stokes equations**, e.g.,

```plaintext
\[ \rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \mu \nabla^2 u + g \alpha (T - T_0) \]
\[ \nabla \cdot u = 0 \]
\[ \frac{\partial T}{\partial t} + u \cdot \nabla T = \kappa \nabla^2 T \]
```

**Set of non-linear, partial-differential equations governing fluid velocity, pressure, and temperature**
Primer: Can we solve Navier-Stokes for wind energy systems?

• Analytical solutions only exist for the **most simple laminar** problems

• **Turbulence** brings in orders more complexity (many scales to be captured)

  “Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity.” -- Lewis Richardson

The wind energy system is extremely **NOT SIMPLE**, and **HIGHLY TURBULENT**

The only way to solve the Navier-Stokes equations for wind energy flows is:

• **Introduce some approximations**

• “Discretize” the equations (millions to billions of equations)

• Solve on high-performance computing (HPC, e.g., supercomputers)

*This can be very difficult.*
Development efforts are focused on the open-source ExaWind software stack

**ExaWind:** An open-source multi-fidelity modeling & simulation software stack designed to run on **laptops** and **next-gen supercomputers**

**Nalu-Wind**
- [https://github.com/exawind/nalu-wind](https://github.com/exawind/nalu-wind)
- Incompressible-flow computational fluid dynamics (CFD) code
- Unstructured-grid finite-volume discretization
- Closely tied to Trilinos & **hypre** libraries
- Blade-resolved and actuator-type simulations

**OpenFAST**
- [https://github.com/openfast](https://github.com/openfast)
- Whole-turbine simulation code

**AMR-Wind**
- [https://github.com/exawind/amr-wind](https://github.com/exawind/amr-wind)
- Incompressible-flow CFD code
- Structured-grid finite-volume atmospheric-boundary-layer “background solver”
- Built on AMReX libraries
- Coupled to Nalu-Wind through overset meshes

Software described in NAWEA 2019 paper
ExaWind modeling approach defined in 2015 meeting of experts

DOE Strategic Planning meetings established the modeling and simulation requirements for predictive wind farm simulations

- Compressible- or incompressible-flow model
- Geometry-resolving meshes
- Fluid-structure interaction
- Hybrid RANS/LES modeling
- Nonlinear structural dynamics

https://www.nrel.gov/docs/fy16osti/64697.pdf
HPC performance portability is central to ExaWind development

Supercomputer architecture is evolving rapidly
- U.S. Department of Energy (DOE) supercomputers are increasingly relying on Graphical Processing Units (GPUs) for computational speed at low power
- The first exascale supercomputers will all have hybrid CPU-GPU architectures
  - Coming online in 2021-2022
  - Aiming for power requirements below 30 MW
- Hybrid CPU-GPU architecture is expected to become more common amongst all clusters
- CFD codes will need to be able to utilize GPUs!

Exascale systems will be at least 5 times faster, but require no more than 3 times the power
ExaWind development is funded by two DOE offices

DOE Wind Energy Technologies Office:
- “High-Fidelity Modeling” project
- Period of performance: 2016-2023
- Partnership between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL)

DOE NNSA/SC Exascale Computing Project:
- “ExaWind” project; [https://www.exawind.org/](https://www.exawind.org/)
- Period of performance: 2016-2023
- Partnership between NREL, SNL, Oak Ridge National Laboratory, University of Texas at Austin, & Parallel Geometric Algorithms, Inc.
The ExaWind-HFM team: 40+ researchers

- M. Sprague, HFM & ExaWind PI
- S. Ananthan
- R. Binyahib
- M. Brazell
- M. Churchfield
- G. Deskos
- A. Glaws
- K. Gruchalla
- M. Henry de Frahan
- R. King
- J. Jonkman
- T. Martinez
- P. Mullowney
- M. Natarajan
- R. Mudafort
- J. Rood
- A. Sharma
- K. Swirydowicz
- S. Thomas
- G. Vijayakumar
- S. Yellapantula

- P. Crozier, ExaWind & HFM co-PI
- L. Berger-Vergiat
- M. Blaylock
- L. Cheung
- D. Glaze
- A. Hsieh
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- I. Yamazaki

- J. Turner
- A. Prokopenko
- R. Wilson

- J. Sitaraman

Parallel Geometric Algorithms, Inc.
- R. Moser
- J. Melvin
Next-generation high-performance computing

Shreyas Ananthan
DOE high-performance computing (HPC) systems

Petascale systems

EERE

NREL Eagle
8 PF; ~1 MW
51 in HPC Top500

ANL Theta
11.6 PF
34 in HPC Top500

ORNL Summit
200 PF; ~10 MW
2 in HPC Top500

NERSC Cori
27.8 PF; ~4 MW
16 in HPC Top500

NREL Peregrine
2.24 PF; ~700 kW
Retired 2019

ORNL Titan
27 PF
Retired 2019

ORNL Frontier
~ 1.5 Exaflops

ANL Aurora
> 1 Exaflops

1 Petaflop = $10^{15}$ calculations per second

Exascale systems

2021 – 2023

DOE Leadership Computing Facilities (LCF)

1 Petaflop = $10^{15}$ calculations per second
DOE HPC systems present an unprecedented opportunity for unlocking novel insights into wind farm physics

However, wind research has not fully harnessed all the available computing power

Existing wind-energy codes are not suited for running on state-of-the-art HPC systems
Supercomputer hardware is very different

Summit node layout

Most wind-energy codes are designed to run on these chips

Almost all computing power in modern supercomputers on these chips
Supercomputer hardware is very different

Future supercomputers will have more exotic architectures

NVIDIA, AMD, Intel are all making their own GPUs

Tomorrow’s NREL system might look a lot like today’s Summit

To run efficiently on current & exascale systems, codes must be able target different types of hardware
Running on different kinds of hardware is a key priority for ExaWind codes

- Laptops, workstations
- NREL Eagle
- ORNL Summit
- ORNL Frontier (2021)

Cloud computing
- Amazon EC2
- Microsoft Azure

Containerization
- Docker
- Singularity
**Strong-scaling** – a way to measure how well we are utilizing the supercomputer

- **Run time**
- **Double the resources**
- **Ideal scaling**
- **Reality**

Closing the gap between ideal and reality is a big focus of ExaWind project.
Performance-measurement example

• Atmospheric-boundary-layer simulation
• Compute the complex flow in which turbines operate
• Simulated using millions of grid points
• Double compute resources (cores) and measure run time

Complex atmospheric flow over a 3 sq. km area
ExaWind strong-scaling performance on Eagle

- Measure performance of Nalu-Wind and AMR-Wind on Eagle
- 25 million grid points where equations are solved
- Starts trailing-off when we use large portions of the machine
- AMR-Wind is 5x faster than Nalu-Wind on the same problem
Comparing performance for CPUs and GPUs on Summit

3D flow field from ABL simulations

Strong-scaling study for the ABL LES precursor simulation on a 3 km x 3 km x 2 km domain with uniform mesh resolution on ORNL Summit

AMR-Wind Strong-scaling performance
Model validation: Building confidence in our simulated reality

Ganesh Vijayakumar
Validation is key to establishing predictivity of wind-energy simulations

Validation – Are the equations a true representation of the physics?

Comparison to experimental results

Exawind framework – solve model equations on HPC for wind-energy problems

How can we trust Exawind framework results?

- Yawed inflow for wind-farm control
- High shear + veer inflow
- Atmospheric turbulence
- Floating platform motion
- Highly flexible bend-twist coupled blades
- Unsteady aerodynamics in nominal mode of operation
- Local aerodynamic devices for flow control
Hierarchy of validation studies for increasing complexity

International Benchmark Working Group from industry and universities to frame benchmark validation cases.

- **Comparison of turbulence models for the NASA validation case of a 2D wall mounted hump (Moser)**
- **Full-scale wind farm simulations, e.g., Lillgrund wind farm (Churchfield)**
- **Single turbine simulation in uniform inflow (Ananthan)**
- **ABL simulation (Brazell)**
- **Single turbine simulation in ABL (Churchfield)**
McAlister-Takahashi fixed-wing wind-tunnel validation

NACA0012 airfoil benchmark problem from NASA Langley Turbulence modeling resource
k-w-SST – RANS turbulence model

Aerodynamic performance:
Lift and drag coefficients with grid refinement

Pressure profiles along wing
Tip vortex capture

1 - https://turbmodels.larc.nasa.gov/naca0012_val_sst.html
Unsteady Aerodynamic Experiments in the 1990s in NASA Ames wind tunnel\(^1\)

Two-bladed extremely stiff teetering turbine with fixed rpm/pitch
10m diameter
Compare with detailed measurements on blade
k-w-SST RANS turbulence model

Integrated rotor torque

Pressure profiles at different points along the blade

\( r/R = 0.3 \)
\( r/R = 0.63 \)
\( r/R = 0.9 \)

IEA Task 29: Dan-Aero 2-MW NM-80 turbine field experiment

Three-bladed upwind turbine with full rpm and pitch control
International group focused on validation and code-to-code comparison
Collaboration with DTU: Use very similar grids, algorithm and turbulence model

1 – Grinderslev et. al., Validation of blade-resolved computational fluid dynamics for a MW-scale turbine rotor in atmospheric flow, To be presented at Torque 2020.
Reference turbine established by NREL in 2009\textsuperscript{1}

Three-bladed upwind turbine with full rpm and pitch control

No validation data: Compare to other codes in literature

k-w-SST RANS turbulence model

\textsuperscript{1} Jonkman et. al., Definition of a 5-MW reference wind turbine for offshore system development, Tech. Rep. NREL/TP-500-38060, 2009.
Current work

Fluid-Structure Interaction

Bridging length scales using hybrid-RANS/LES turbulence modeling

Demonstration using NREL 5MW turbine with k-w-SST RANS turbulence model

Ongoing validation with IEA Task 29

Generator power

Rotor thrust

Exawind framework is built on a strong validation base with increasing levels of complexity.

Goal: Wind farm with flexible turbines in ABL with complex terrain/offshore

Single turbine in ABL with FSI
Single turbine in ABL
Single turbine in uniform inflow
Fixed wing
Airfoil
HPC and HFM as the foundation for next-generation engineering models

Luis 'Tony' Martínez Tossas
Image of SOWFA simulation of the Lillgrund offshore wind farm (Churchfield, NREL)

The challenge

How can we use high-fidelity modeling to design better engineering models?
Modeling-fidelity spectrum

Higher fidelity
More predictive (less tuning)
More computational expense

Best for:
• Untangling complex dynamics
• Exploring/demonstrating technology innovations
• Validating/creating lower-fidelity engineering models

Lower fidelity
Less predictive (more tuning)
Less computational expense

Best for:
• Optimization studies
• Sensitivity/uncertainty-quantification studies
• Certification studies

Need a modeling suite that spans the fidelity spectrum
Newton’s second law

\[ \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla \rho + \mu \nabla^2 \mathbf{u} + \mathbf{g} \alpha (T - T_0) \]

Many approximations
(lower fidelity)
inexpensive

Some approximations
(medium fidelity)
expensive

Zero approximations
(highest fidelity)
most expensive

Turbulence data obtained from the JHU database http://turbulence.pha.jhu.edu/
Computational cost vs model fidelity
Example 1: The curled wake

Example 1: The curled wake


Example 2: Flow over a fixed wing

Mcalister fixed wing simulation velocity magnitude highlighting the tip vortex

Cross-stream tip vortex velocity sampled along white line shown on the left figure

Comparison with experiments, high-fidelity simulations, and reduced-order models can expose pathways to next-generation design models & codes

Results presented at 2019 APS Division of Fluid Dynamics conference
C09.00010: Comparison of theory and large-eddy simulations with experiments of flow over a wing
Luis Martinez, Marc Henry de Frahan, Ganesh Vijayakumar, Shreyas Ananthan
Example 3: HFM results can be used to train neural-network models

New unsteady aerodynamics model using machine learning performs better than state-of-the-art unsteady aerodynamics models

Can be trained using Exawind framework CFD data.
Will improve fatigue load estimations for bigger wind turbines of the future on floating platforms

Measure of unsteadiness (reduced frequency) over the blade length for 4 commercially relevant wind turbines.

Comparison of the new ML unsteady aerodynamics model and state-of-the-art models against experimental data for a pitching N4415 airfoil.
Current work: High-thrust coefficient

- Wake models have a hard time predicting wakes for high-thrust conditions
- Can we simulate these conditions using HFM tools?
- How can we improve the current wake models to account for high thrust?
- Simulations using Nalu-Wind and OpenFAST (ExaWind)

Team: Luis A Martínez-Tossas, Emmanuel Branlard, Kelsey Shaler, Ganesh Vijayakumar, Shreyas Ananthan, Philip Sakievich, Jason Jonkman
What would the pioneers of wind energy say?

You imagine what we could do with supercomputers and high-fidelity modeling?

Progress will depend on a generation of scientists educated deeply in their own specialty as well as in the breadth of wind energy science. 

*Grand challenges in the science of wind energy*, Science 2019

**Ludwig Prandtl**
(1875 –1953)

**Albert Betz**
(1885 –1968)
Next frontier for ExaWind: Offshore wind

Simulation of wind over waves using the ExaWind/Nalu-Wind fluid solver. (G. Deskos)

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