SAND2019-0178C

NREL NATIONAL RENEWABLE ENERGY LABORATORY — Sandia National Laboratories — OAK RIDGE National Laboratory — TEXAS The University of Texas at Austin

ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling

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DRAFT

EXASCALE COMPUTING PROJECT

Project Overview

Objective: Create a predictive physics-based simulation capability that will provide a validated "ground truth" foundation for wind plant siting, operational controls, and reliably integrating wind energy into the grid

Motivation: Validated, predictive wind plant simulations will reduce the cost of energy by providing

- a path to better understanding of wind plant flow physics, which will lead to
  - new plant layout design in complex terrain
  - new turbine technologies to optimize plant performance
- a foundation for improved computer-aided engineering models, which will enable better design optimization
- quantified and reduced uncertainty in predicted plant performance

Primary Application Codes:

- **Nalu-Wind**
  - https://github.com/exawind/nalu-wind
  - Unstructured-grid computational fluid dynamics (CFD) code
  - Based on the SNL-supported Nalu code
  - C/C++
  - Built on Trilinos/STK/HYPRE/TIOGA
- **OpenFAST**
  - https://github.com/openfast/openfast
  - Whole-turbine simulation code; blades, control system, tower, etc.
  - Fortran 90; dedicated Intel Parallel Computing Center (IPCC) for parallelization

Software/Library Partnerships in Nalu-Wind

- ***Trilinos***, https://trilinos.org/
  - ***MueLu:*** provides templated aggregation-based multigrid preconditioners
  - ***Ifpack2:*** provides SOR-based, polynomial and incomplete factorization preconditioners
  - ***Kokkos-Kernels:*** provides shared memory algorithms: graph-coloring, SpMV, SPMM, iterative and incomplete factorization preconditioners
  - ***Tpetra:*** provides distributed memory, templated sparse linear algebra objects
  - ***Belos:*** provides templated Krylov and recycling solvers
  - ***Amesos2:*** provides sparse direct solvers
  - ***Sierra Toolkit (STK):*** provides an unstructured-mesh in-memory, parallel-distributed database
- ***HYPRE***, https://github.com/LLNL/hypre
  - Multigrid solvers and preconditioners based on classic Ruge-Stüben AMG algorithm
- ***Kokkos***, https://github.com/kokkos
  - Programming model in C++ for writing performance portable applications targeting all major HPC platforms
- ***TIOGA***, https://github.com/jsitaraman/tioga
  - Library for overset-grid assembly on parallel distributed systems
- ***VTK-m***, https://gitlab.kitware.com/vtk/vtk-m
  - New *in situ* visualization and analysis capabilities
- **Spack**, https://github.com/spack/spack
  - Package manager for exascale software

ECP Key Performance Parameter (KPP-2)

Challenge Problem:

Predictive simulation of a wind farm with tens of megawatt-scale wind turbines dispersed over an area of 50 square kilometers

Minimum Requirements:

- 3x3 array of megawatt-scale turbines operating at rated speed
- 4 km x 4 km domain with height of 1 km
- Hybrid-RANS/LES model
- At least 30-billion gridpoints (and 150 billion degrees of freedom); near-blade grid spacing will be such that the viscous sub-layer is resolved
- Demonstrate that we can simulate at least one domain transit time (500 s) with four weeks of system time

Keys to Success

- Enable large time steps (restricted by accuracy rather than stability)
- Minimize time per timestep:
  - Optimize strong scaling to utilize as much of the system as possible
  - Optimize linear-system solver algorithms

Programmatic Partnerships

The DOE Wind Energy Technology Office (WETO) is a core partner, with three supporting projects under the Atmosphere to Electrons (A2e) Initiative:

(1) **High-Fidelity Modeling (HFM)**
- Ensure that Nalu-Wind is equipped with appropriate math models

(2) **Wake Dynamics**
- Ensure that Nalu-Wind is validated at multiple scales

(3) **Meso-scale Micro-Scale Coupling (MMC)**
- Ensure that Nalu-Wind has appropriate large-scale forcing

Nalu-Wind Mathematical Models

- **Acoustically incompressible low-Mach-number formulation**
  - Turbine simulations have peak Mach number of 0.3 (at blade tip)
  - Requires pressure-Poisson solve for mass continuity
- **Available RANS/LES models**
  - One-equation subgrid-scale models, residual-based implicit LES
  - K-omega SST RANS model
- **Under-development hybrid RANS-LES turbulence model**
  - Hybrid-RANS/LES formulation ensuring consistency between resolved & modeled turbulence, and accounting for grid & turbulence anisotropy

Nalu-Wind Numerical Methods

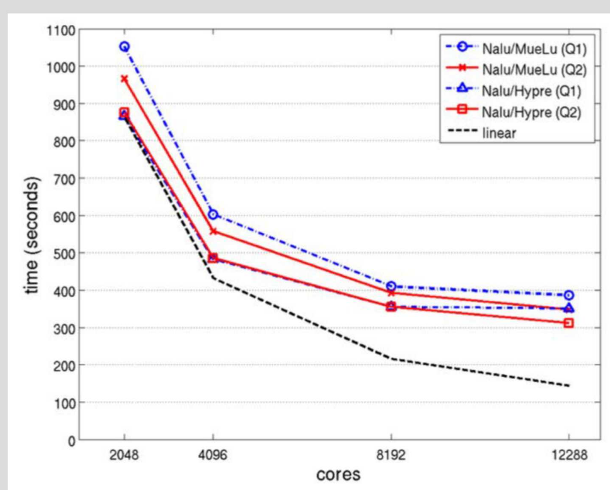
- **Unstructured-grid solver**
  - Second-order control-volume finite element method (CVFEM) or edge-based vertex centered (EBVC) finite-volume scheme
  - Low-dissipation advection operators with either classic Peclet blending approaches or residual-based entropy/viscosity stabilization
  - Equal-order interpolation with pressure stabilization
  - Approximate pressure projection method with controlled splitting errors
- **High-order schemes**
  - P-promotion properties of FEM and Conservation Properties of FVM
  - Nonlinear Stabilization Operator based on hybrid Shakib/Guermond DCO/entropy-viscosity approach
- **Dynamic mesh motion (for moving turbine components)**
  - ALE capability for deforming meshes
  - Hybrid CVFEM/DG-based sliding mesh interface
  - Overset mesh capability
- **Typical solvers configurations**
  - Time/Advection/Diffusion/SRC: GMRES + SGS || ILUT preconditioner
  - Pressure Poisson (continuity): GMRES + AMG preconditioner

Model Coupling: Nalu-Wind 🡨 🡪 OpenFAST

- Fluid-structure-interaction coupling with OpenFAST; loose coupling
- Future work will couple WRF coupling for meso-scale forcing

FY18Q2: *Decrease time-to-solution through improved linear-system setup and solve*

- Improved configurations of the HYPRE-BoomerAMG and Trilinos/MueLu AMG preconditioners for the pressure-Poisson system for a KW-scale-turbine simulation
- Significant improvement in setup and solve times for the Trilinos/MueLu preconditioner at all core counts compared to FY18 Q1
- Significant improvement in setup and solve times for the HYPRE preconditioner at 12K cores compared to FY18 Q1
- Implemented BDDC (Balancing Domain Decomposition by Constraints) as a new preconditioner capability

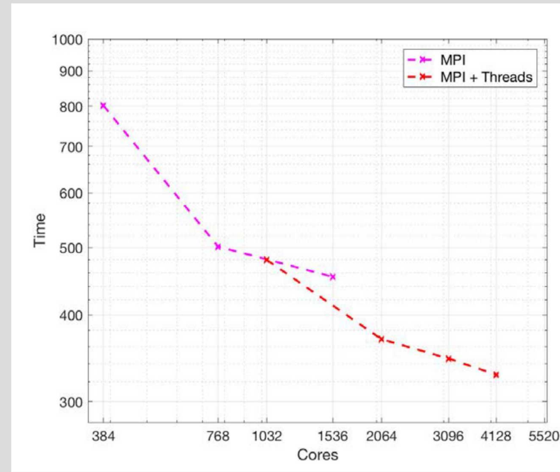


Poisson-system setup and solve times for a simulation of a fully-resolved KW-scale turbine for which the rotor resides in an embedded, rotating "disk" of fluid that is coupled to the surrounding fluid via a sliding-mesh interface. Shown are strong-scaling timing results from MueLu and HYPRE comparing new settings with those reported in FY18 Q1 for setup and solve of the Poisson system.

Team: Hu, Thomas, Dohrmann, Ananthan, Domino, Williams, Sprague

FY18Q3: *Deploy threading in Nalu solver stack*

- Explored the trade-space of MPI ranks vs. threads in the Trilinos solver stack (via Kokkos) and the HYPRE stack (via straight OpenMP)
- Showed how threading can take strong scaling to new levels when work per MPI rank becomes too low
- Demonstrated how offloading linear solver work to GPUs can accelerate time to solution O(10x) GPUs
- Successful collaboration with the LLNL HYPRE team



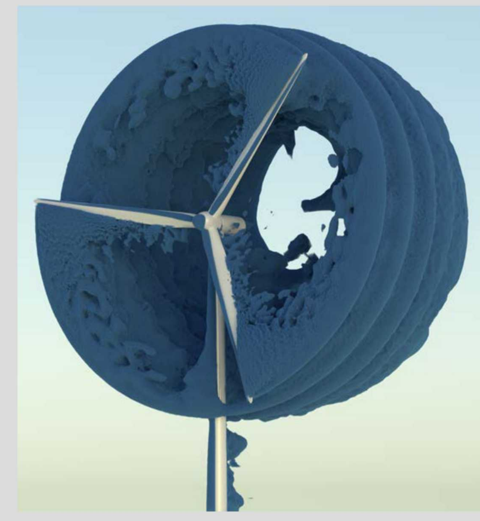
Strong scaling plot for a 29M gridpoint model of a KW-scale turbine on Haswell cores; MPI + OpenMP threading enables scaling improvements to 7000 DOF per core (HYPRE solver).

Team: Prokopenko, Thomas, Swirydowicz, Ananthan, Hu, Williams, Sprague

FY18Q4: *Blade-resolved single-turbine simulations under atmospheric flow*

- Established the NREL 5-MW reference turbine as our target system
- Demonstrated that the Nalu-Wind solver stack is capable of simulating a body-resolved MW-turbine with turbulent inflow
- Established the model that will be the proving ground for upcoming improvements in hybrid-RANS/LES modeling, new solver algorithms, and acceleration on next- generation architectures

Team: Lawson, Melvin, Ananthan, Gruchalla, Rood, Sprague

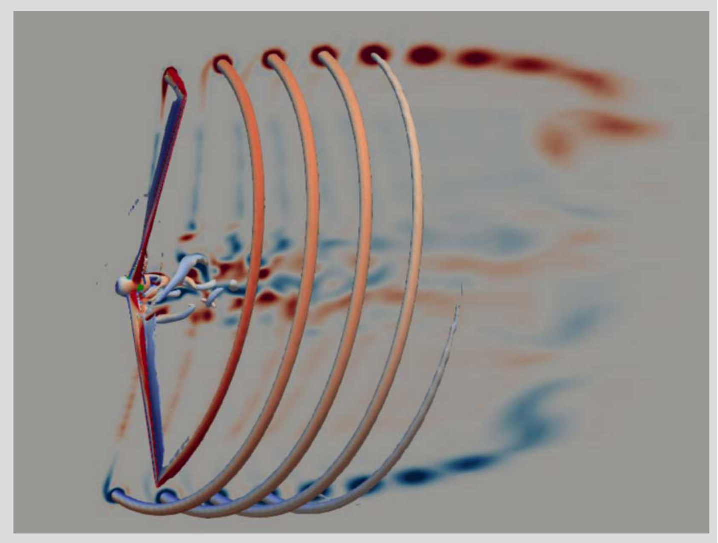


Demonstration simulation of the notional NREL 5-MW reference turbine for multiple revolutions with uniform inflow. The simulation shown used a coarse mesh (25M DOF), but a refined mesh (6B DOF) have been simulated simulation on Mira including strong scaling studies.

Recent Highlights

Time-update algorithm and overset meshes enable validation-quality simulation of the NREL 5-MW turbine

- New time-update algorithm enables simulation with URANS turbulence model with **necessary large time steps**
- Overset capability enables use of high-quality elements throughout domain (still have extreme aspect ratios in boundary layers)
- New algorithm enables simulation of one revolution in about 14 hours (at 20,000 gridpoints per MPI rank)
- Fluid-structure interaction, hybrid –RANS/LES, and turbulent inflow to be added in FY19 Q2
- Partnership effort with DOE WETO project



Simulation of NREL 5-MW turbine with new time-update algorithm and overset meshes. Simulation performed on the NREL Eagle system with 1080 MPI ranks. HYPRE pressure solve and Trilinos momentum solve.

Team: Ananthan, Vijayakumar, Sitaraman

Solvers team dramatically reduces solve time for Nalu-Wind pressure-Poisson systems with moving meshes

- Early Nalu-Wind simulations had majority of wall-clock time devoted to the pressure-Poisson system setup and solve
- Pressure system setup & solve times have been reduced to less than 20% of total time (for test problem); momentum system is now the tall pole
- Improvements were demonstrated in both the HYPRE and Trilinos solver stacks
- Details found in Thomas et al., "A comparison of classical and aggregation-based algebraic multigrid preconditioners for high-fidelity simulation of wind-turbine incompressible flows," *SIAM Journal on Scientific Computing* (under revision)

Team: Thomas, Ananthan, Yellapantula, Hu, Lawson, Sprague

NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This report followed the Sandia National Laboratories formal review and approval process (SAND2019-XXXX). As such, the technical report is suitable for unlimited release.

Exascale Computing Project Annual Meeting
Houston, TX
January 14-17, 2019