ExaWind: Then and Now

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ExaWind Objective: To create an open-source 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

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

ExaWind Partnership: Development has been jointly funded by the U.S. Department of Energy (DOE) Exascale Computing Project (ECP) and the DOE Wind Energy Technologies Office (WETO) since 2016

ExaWind 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: 2 × 2 array of megawatt-scale turbines, 3 km × 3 km × 1 km domain, at least 30-billion grid points

Then (2016)

Approach: Create computational fluid/structure dynamics (CFD and CSD) codes for Reynolds-averaged Navier-Stokes (RANS)/large-eddy simulations (LES) where wind turbine geometry and blade boundary layers are resolved and include moving meshes, fluid-structure interaction, and atmospheric turbulence

Starting-Point Codes:

Nalu: https://github.com/nalucfd/

- Unstructured-grid, incompressible-flow CFD
- LES turbulence model
- C/C++
- Built on Trilinos STK, Tpetra/Belos/MueLu solvers, and Kokkos
- Mesh rotation achieved through a sliding-mesh interface

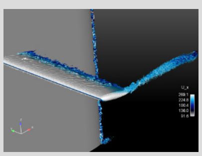
OpenFAST: https://github.com/openfast/

- Whole-turbine simulation code (structural dynamics, control)
- Fortran90

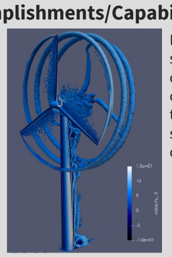
Challenges:

- Target problem requires resolving spatial scales going from blade boundary layers (e.g., 10^{-5} m) to the wind farm domain (e.g., 10^{3} m), i.e., at least eight orders of magnitude
- Finite volumes with extreme aspect ratios (e.g., 10,000), which are necessary for hybrid-RANS/LES, were a serious challenge linear-system solvers
- Time-integration scheme required impractically small time-step sizes (e.g., 10^{-6} s) for production simulations
- Sliding-mesh approach presented mesh-creation challenges and no clear pathway for yaw motions

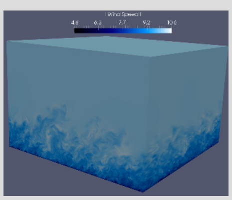
Then (2017): Nalu Example Accomplishments/Capabilities



Nalu simulation of the McAlister-Takahashi blade, which has extensive wind-tunnel experimental data. 68- and 300-million grid point meshes examined, with RANS and LES.



Nalu LES results for a fully resolved kilowatt-scale turbine in uniform flow; isosurfaces of Q-criterion colored by the streamwise-component of velocity; mesh motion achieved through a sliding-mesh interface; for a simulation with 45-million grid points on 4096 cores, 48-hour wall-clock time per rotation.



Nalu LES results for a neutrally stable atmospheric boundary layer (ABL).

Systems Employed

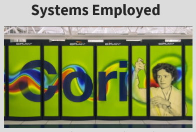


Image: DOE, National Energy Research Scientific Computing Center (NERSC)

Image: DOE, National Renewable Energy Laboratory

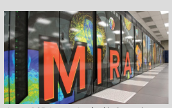
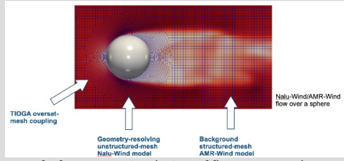


Image: DOE, Argonne Leadership Computing Facility (ALCF)

Now (2023)

Shift in Approach: Added AMR-Wind as a background solver and made Nalu-Wind the near-body solver; coupling via overset meshes



Proof-of-concept simulation of flow over a sphere using the hybrid Nalu-Wind/AMR-Wind solver.

Primary Application Codes:

Nalu-Wind

- https://github.com/exawind/nalu-wind
- Wind-specific offshoot from Nalu; primarily used for near-body flows
- *hypre* is primary linear-system-solver package
- Hybrid-RANS/LES with time integrator that enables practical time step sizes
- Overset meshes (via TIOGA, https://github.com/jsitaraman/tioga) is primary method for moving meshes
- Performant on NVIDIA GPUs; Advanced Micro Devices, Inc. (AMD) GPUs are in progress

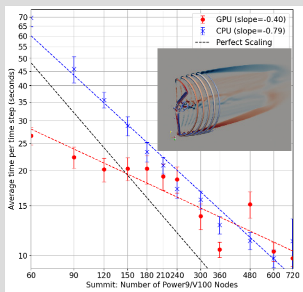
AMR-Wind

- https://github.com/exawind/amr-wind
- Structured-grid adaptive mesh refinement (AMR) CFD code; background solver
- C++ and built on the AMReX library
- Performant on NVIDIA and AMD GPUs

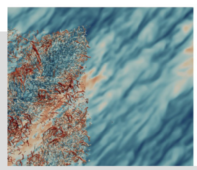
OpenFAST

- No pathway to support parallelization or GPUs
- Starting new FY23 WETO project to create replacement: OpenTurbine https://github.com/exawind/openturbine

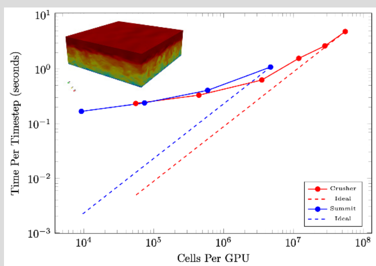
Now (2023): ExaWind Example Accomplishments/Capabilities



Nalu-Wind strong-scaling results for blade-resolved simulations of the a 5-megawatt turbine on the Summit supercomputer; model had 640-million grid points; GPU and CPU calculations used all GPUs and all CPU cores, respectively, on each node.



Hybrid AMR-Wind/Nalu-Wind simulation of a small wind farm in a stable ABL; isosurfaces of Q-criterion colored by velocity magnitude; for a simulation with 650-million grid points on 6046 CPU cores, 3.6-hour wall-clock time per rotation.



AMR-Wind strong-scaling plot for ABL simulations on Summit (NVIDIA) and Crusher (AMD) GPUs. Simulations of different model sizes were run on a fixed resource of 16 Crusher nodes (128 GCDs) or 16 Summit nodes (96 GPUs). The largest models were 0.5- and 7-billion grid points on Summit and Crusher, respectively.

Takeaways

- The shift to a new Nalu-Wind time integration scheme and overset-enabled loose coupling between AMR-Wind and Nalu-Wind was a game changer
- Blade-resolved wind farm simulations that span eight orders of magnitude in spatial scales have been achieved with practical simulation times and up to 10-billion grid points
- Nalu-Wind and AMR-Wind on Summit GPUs outperform CPUs by a wide margin for many grid points per GPU
- Nalu-Wind GPU strong-scaling limit is about 300,000 grid points per Summit GPU
- AMR-Wind on Crusher scales well to about 2-million cells per AMD Graphics Complex Die (GCD)

Key Remaining Challenges

- Fluid-structure interaction capabilities are currently being tested; required for challenge problem
- Porting Nalu-Wind to Crusher/Frontier AMD GPUs has been challenging, e.g., building and linking Nalu-Wind dependencies on Crusher with HIP relocatable device code

Ongoing and Future Directions

Reduce time to solution, tighten coupling between Nalu-Wind and AMR-Wind, couple to the mesoscale Energy Research and Forecasting (ERF) code; offshore wind energy (two-phase fluid dynamics, floating-platform offshore turbines), concentrated solar power

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