An open-source incompressible-flow hybrid-solver framework for massively parallel blade-resolved wind farm simulations under atmospheric inflow

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1 Introduction & Approach

The biggest challenge associated with high-fidelity blade-resolved simulations of wind turbines in realistic atmospheric conditions is to create a solver framework that can efficiently simulate both the flow around the moving complex blade geometry as well capture the wake formation and interaction with the atmospheric boundary layer. To achieve this, we present an open-source hybrid-solver framework comprising of the unstructured incompressible-flow solver Nalu-Wind [1] and the block-structured adaptive mesh refinement background solver AMR-Wind [2] coupled using TIOGA's [3] overset grid connectivity capabilities [2]. Nalu-Wind is designed to handle body-fitted unstructured meshes, and is responsible for resolving the thin boundary layers around the turbine geometry. AMR-Wind is constructed on top of AMReX [5], and is designed for solving massively parallel block structured meshes which reduces the computational cost and memory footprint compared to a uniform mesh while preserving the local descriptions of various physical effects associated with complex fluid flow. Coupled through overset, the two CFD solvers allow us to simulate flows across a range of length scales that are eight orders of magnitude apart from $\approx 10\mu m$ in the blade boundary layer to $O(1)km$ km in the atmospheric boundary layer. In addition to acoustically incompressible fluid dynamics, the hybrid-solver framework is equipped to capture all relevant physics for wind energy applications including a hybrid Reynolds-averaged Navier-Stokes/LES (RANS/LES) turbulence modeling scheme, and one-way coupling to weather-scale forcing (e.g., numerical weather prediction) for simulating the atmospheric boundary layer (ABL). To keep up with the next-generation of exascale systems with different architectures, all the software is performance portable, i.e. the same codebase runs on varying GPU and CPU architectures.

2 Preliminary Results

Preliminary results are presented for the NREL 5-MW rotor operating under uniform inflow of $u = 8m/s$ in a fluid with density and viscosity set to that of air. For the purposes of this study, the turbine geometry was simplified by ignoring the tower and nacelle structures; only the three blades and the

[1]https://github.com/Exawind/nalu-wind.git
[2]https://github.com/Exawind/amr-wind.git
[3]https://github.com/jsitaraman/tioga.git

hub were modeled. The unstructured Nalu-Wind mesh is a blend of of wedge, hexahedral, tetrahedral, and pyramid elements for a total of 870,000 elements with the smallest element size of $\approx 10^{-5}m$. The background AMReX mesh depicted in Fig. 1 spans a domain of $1.9 \times 1 \times 1$ km^3, and consists of 5 levels of refinement with the coarsest level mesh size set to ≈ 7.3 m. The first 4 levels of refinement serve to accurately model the turbine wake and cover the wake region including the turbine. The finest level of refinement spans only the near-body turbine mesh for effective overset interpolation. All levels of refinement combine for a total of ≈ 311 million cells. Figure 2 presents the power and thrust evolution for the turbine using a fixed timestep size such that the blade rotates 0.25° at each timestep. The converged values therein can be compared to match data in the literature [4].

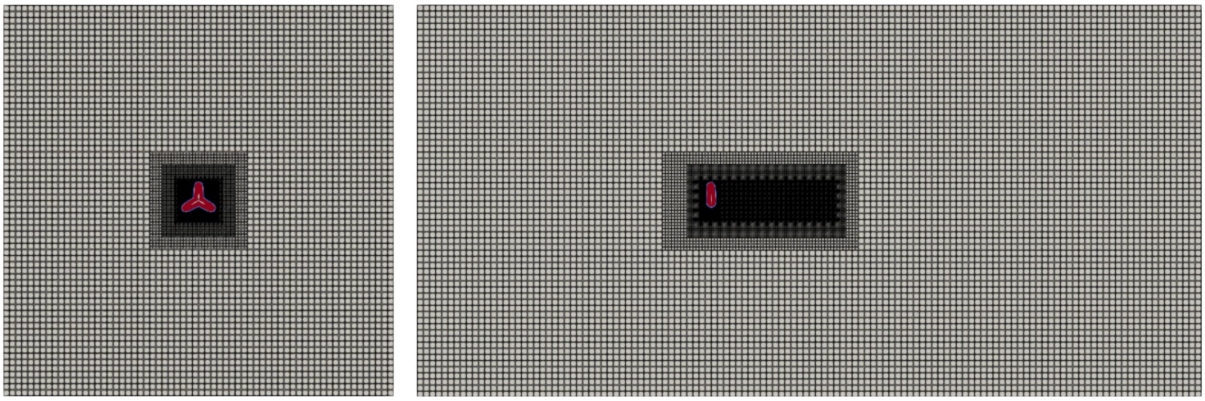

Figure 1: AMReX grids and local refinement boxes overlapping the unstructured NREL 5-MW turbine mesh (red).

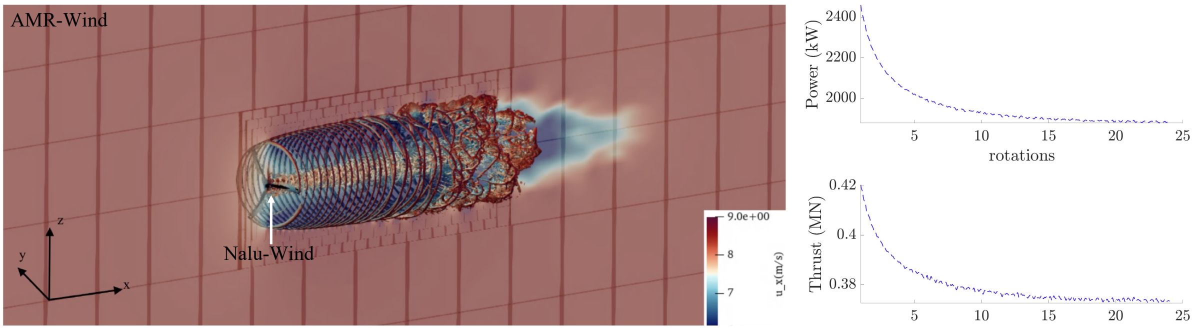

Figure 2: Left: Isocontours of Q-criterion with velocity visualized in the wake for NREL 5-MW turbine operating under uniform inflow wind speed of 8 m/s; Right: Power and thrust evolution.

3 Full Paper

The final paper will present the full details for the new hybrid-solver framework including:

- An overset Additive Schwarz-like algorithm to decouple the global linear system into smaller solver-specific linear systems corresponding to the individual meshes associated with Nalu-Wind and AMR-Wind.
- Validation studies using canonical problems with analytical solution as well as blade-resolved turbine simulations focusing on the NM-80 [3] and NREL 5-MW rotors [1].
- Discussions on scalability of the code-base in preparation for next-generation of exascale systems.
- Multi-turbine simulations under atmospheric inflow.

References

[1] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-mw reference wind turbine for offshore system development. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2009.

[2] B. Roget and J. Sitaraman. Robust and efficient overset grid assembly for partitioned unstructured meshes. *Journal of Computational Physics*, 260:1–24, 2014.

[3] J. Schepers, K. Boorsma, H. A Madsen, G. Pirrung, G. Bangga, G. Guma, T. Lutz, T. Potentier, C. Braud, E. Guilmineau, et al. Iea wind tcp task 29, phase iv: Detailed aerodynamics of wind turbines. 2021.

[4] M. Sprague, S. Ananthan, G. Vijayakumar, and M. Robinson. Exawind: A multi-fidelity modeling and simulation environment for wind energy. In *Proceedings of NAWEA WindTech*, 2019.

[5] W. Zhang, A. Almgren, V. Beckner, J. Bell, J. Blaschke, C. Chan, M. Day, B. Friesen, K. Gott, D. Graves, M. Katz, A. Myers, T. Nguyen, A. Nonaka, M. Rosso, S. Williams, and M. Zingale. AMReX: a framework for block-structured adaptive mesh refinement. *Journal of Open Source Software*, 4(37):1370, May 2019.