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High Fidelity Blade-Resolved Wind Plant Modeling

Andrew Kirby[1]

Professor Dimitri Mavriplis

[1] **2016-2017 Blue Waters Graduate Fellow**

2017 Blue Waters Symposium – Sunriver, Oregon

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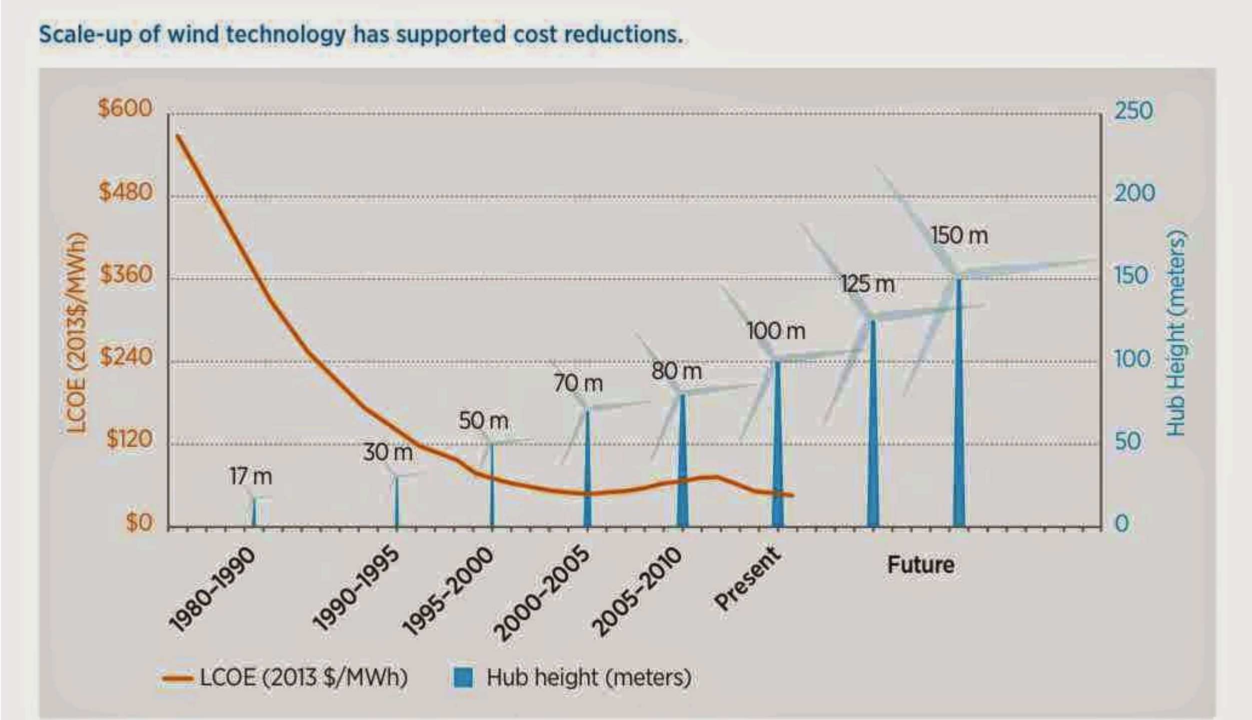
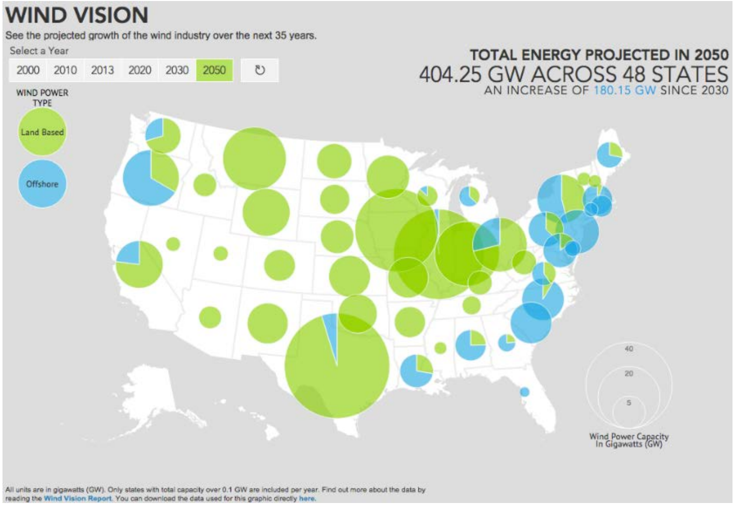
Motivation & Goals

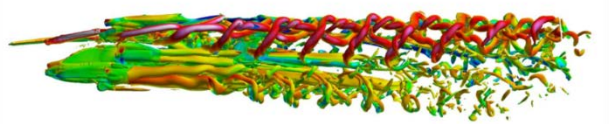


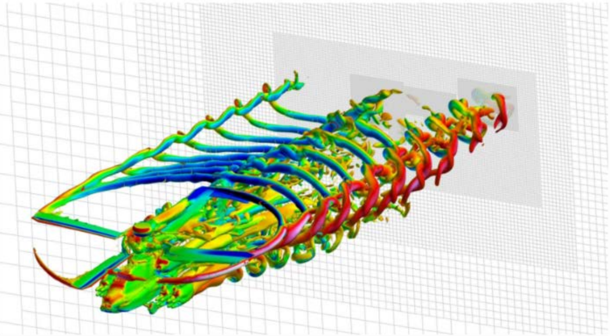
DoE Wind Vision: A New Era of Wind Power in the United States



EXASCALE COMPUTING PROJECT

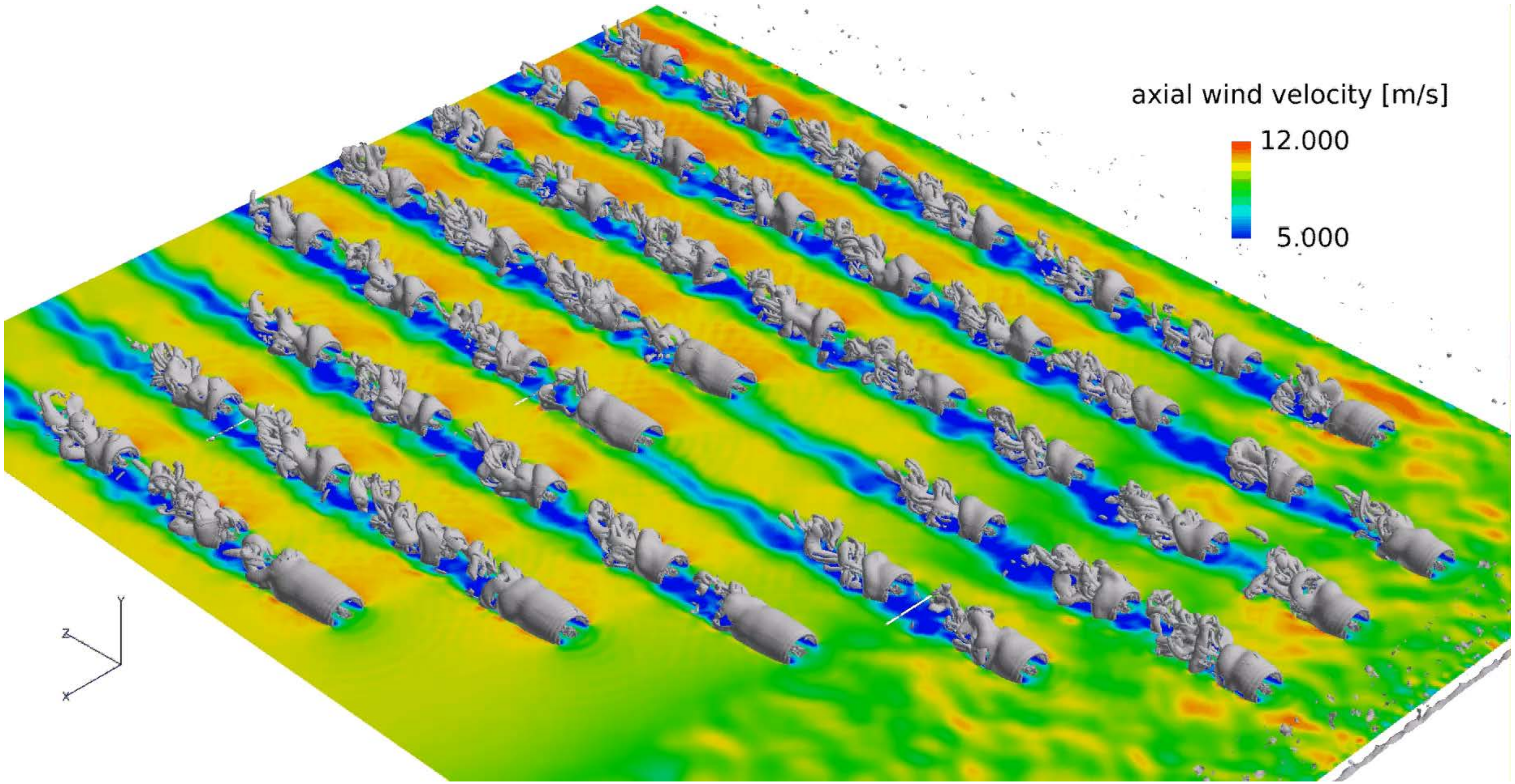
Previous Work





University of Wyoming

- Jay Sitaraman-2013
  ARMY's HELIOS



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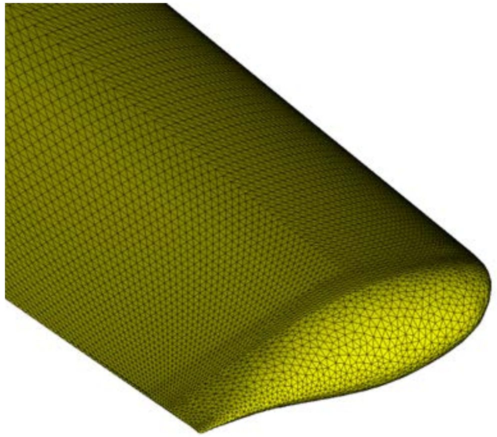
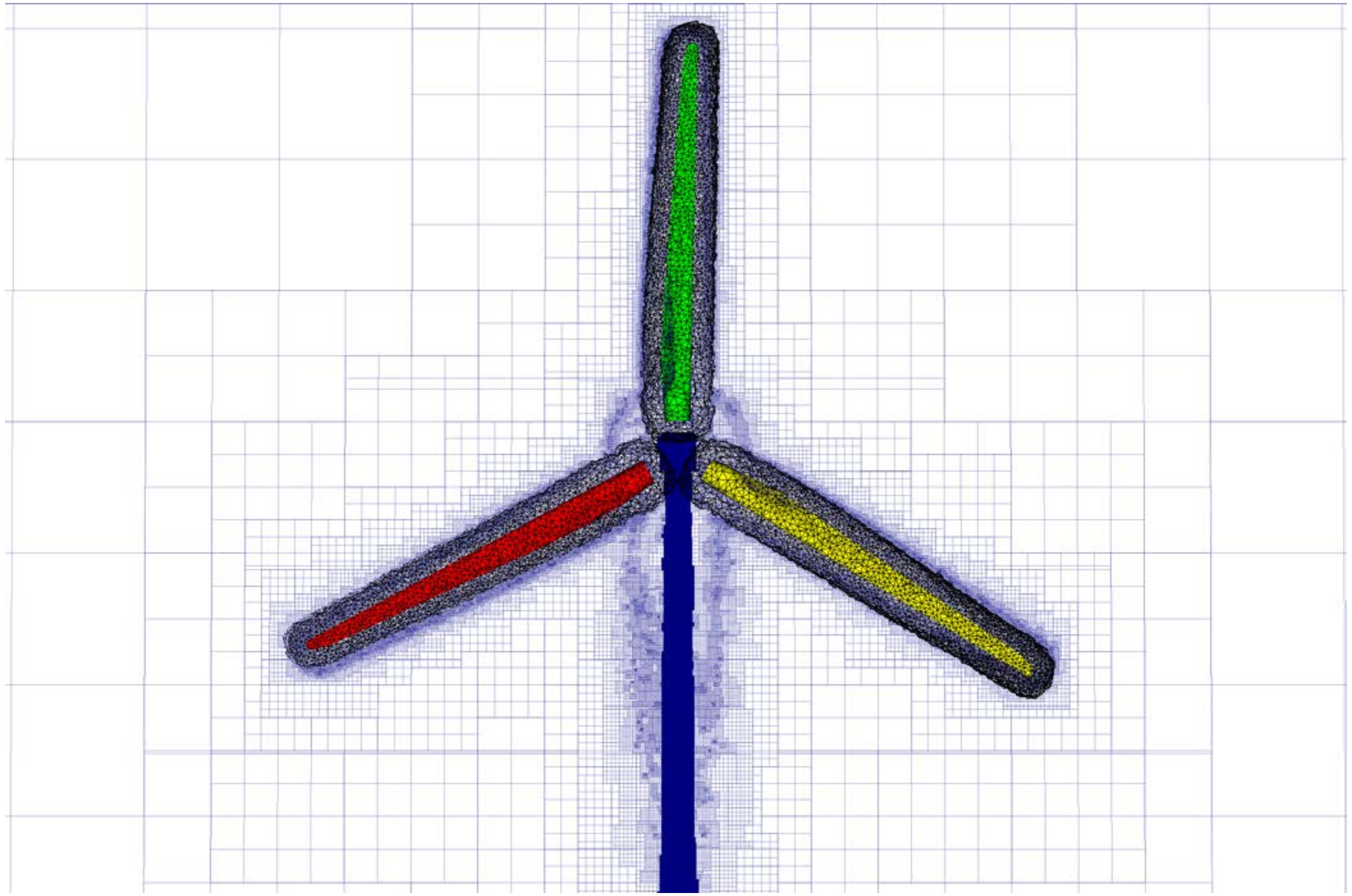
Multi-Mesh, Multi-Solver Paradigm

Near-Body Mesh:

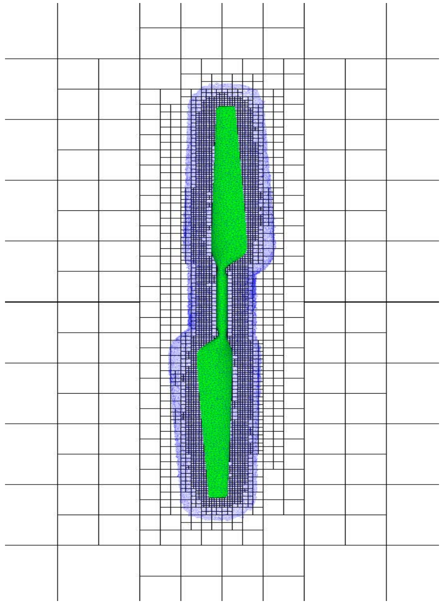
- Complex geometries
- Commercially-available grid generation
- Targets near-wall viscous turbulent flow





Off-Body Mesh:

- High-order accuracy
- Solution adaption
- Targets far-field wake



Multi-Mesh, Multi-Solver Paradigm

Near-Body Mesh:

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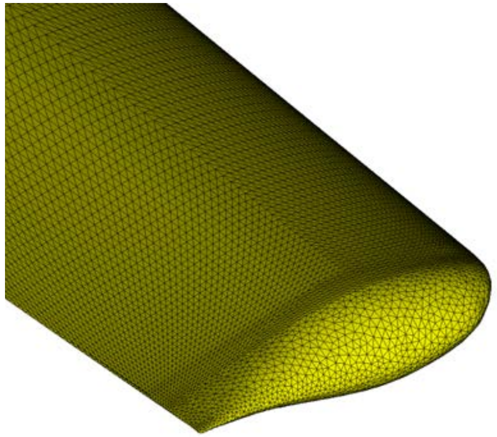
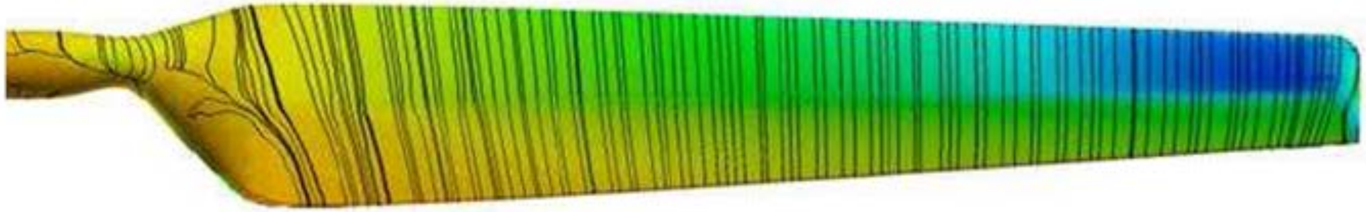
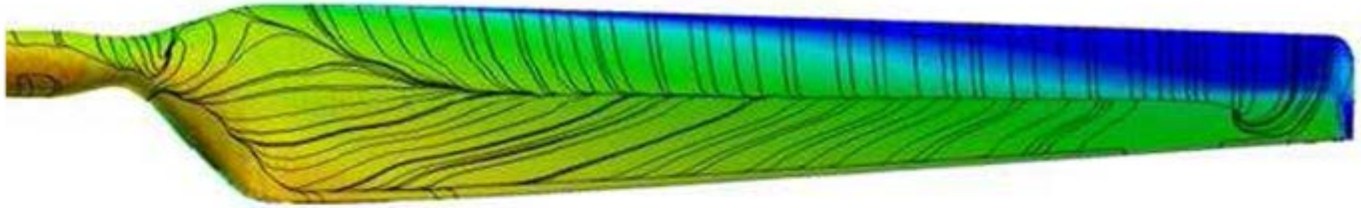




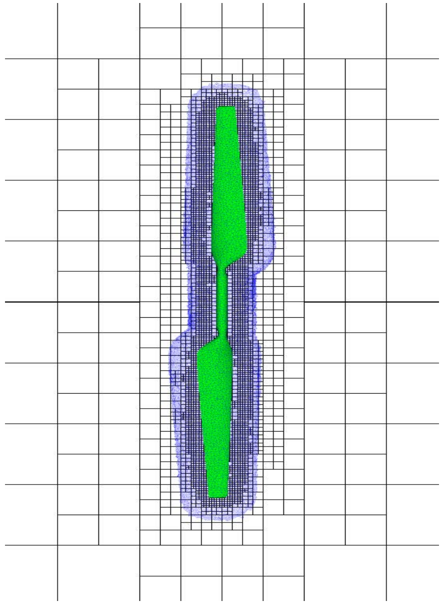
(a) $V = 7m\ s^{-1}$



(b) $V = 10m\ s^{-1}$

Off-Body Mesh:

- High-order accuracy
- Solution adaption
- Targets far-field wake



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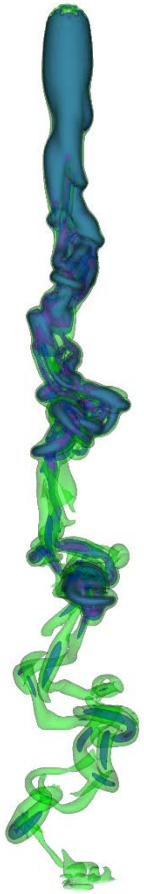
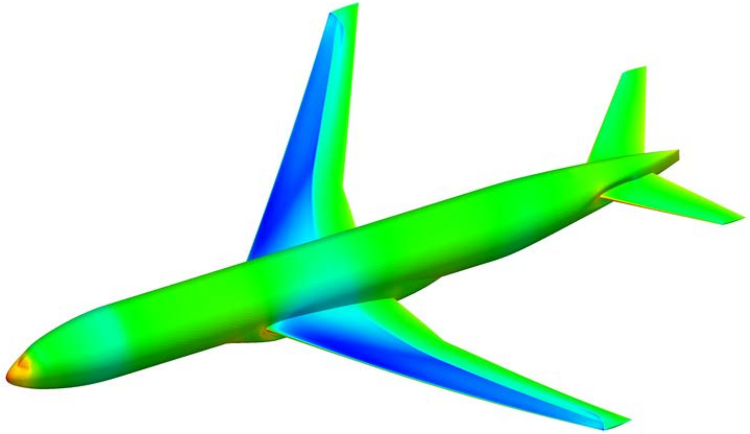
Solvers



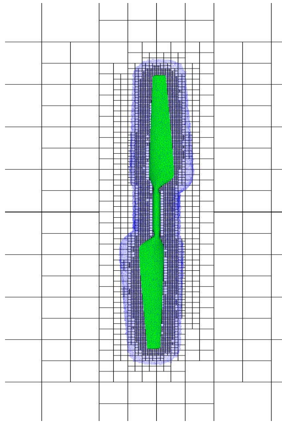
Near-Body Solver: NSU3D

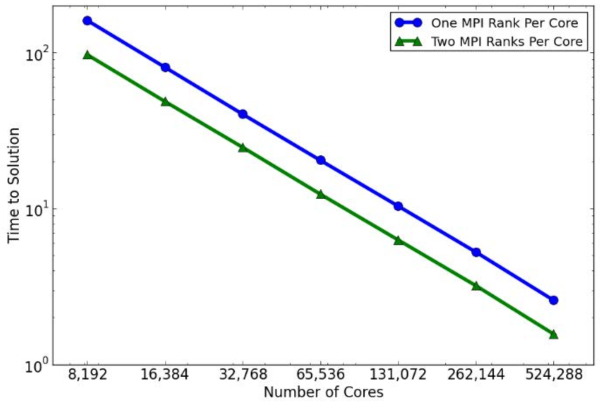
- Finite-Volume 2nd-order accuracy
- RANS SA / DDES turbulence models
  - Rotation correction
- Agglomeration multigrid
- Line-implicit solution acceleration

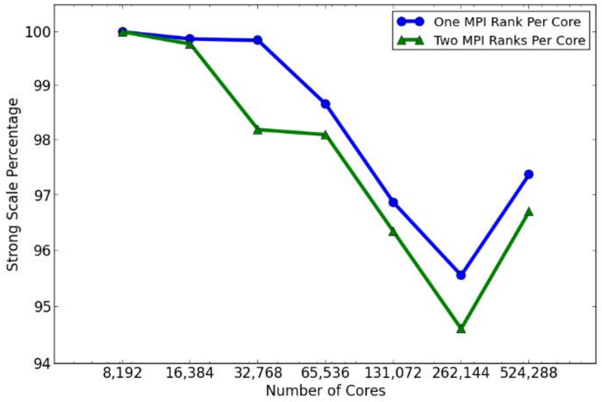


Off-Body Solver: dg4est

- High-Order DG FEM
  - High computational efficiency
- AMR: p4est
  - *hp*-adaption
- LES
- Coriolis & Gravity







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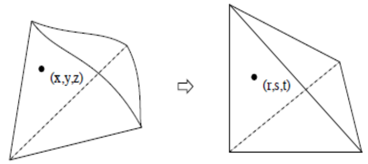
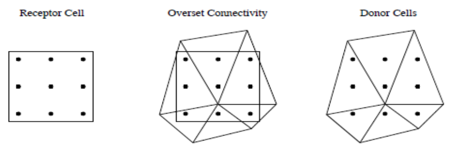
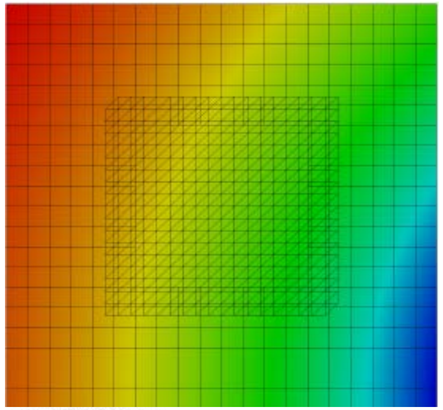
High-Order Overset Mesh Interpolation

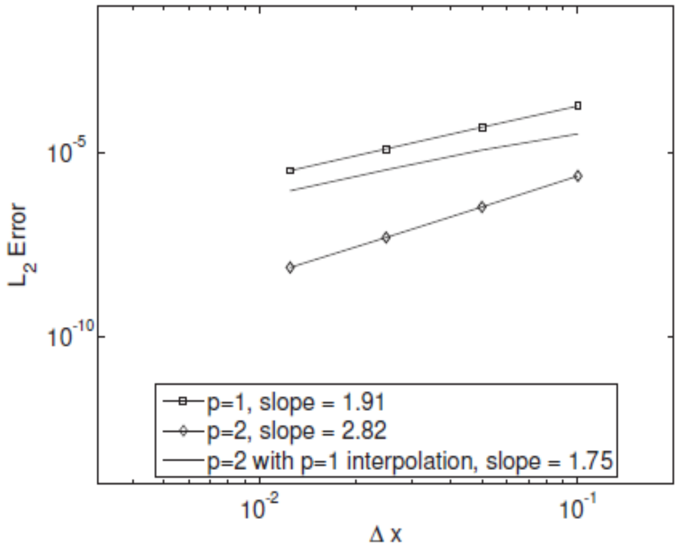
TIOGA - Topology Independent Overset Grid Assembler

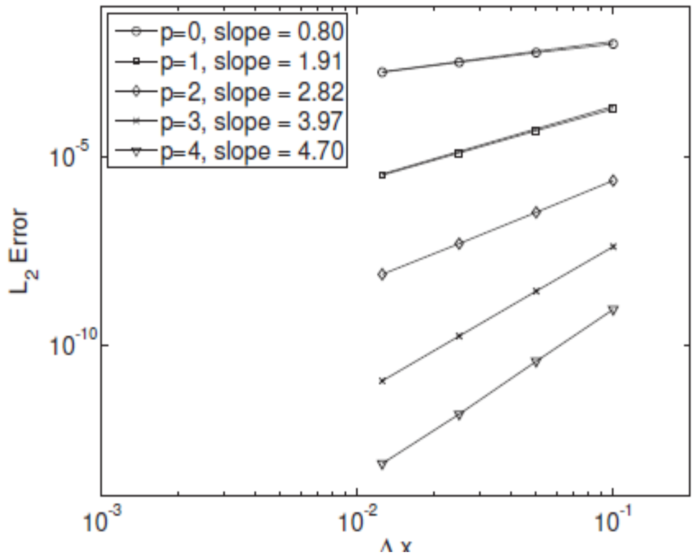
- Generate receptor node lists
- High-order donor inclusion test
- High-order interpolation weights
- Convert interpolation weights







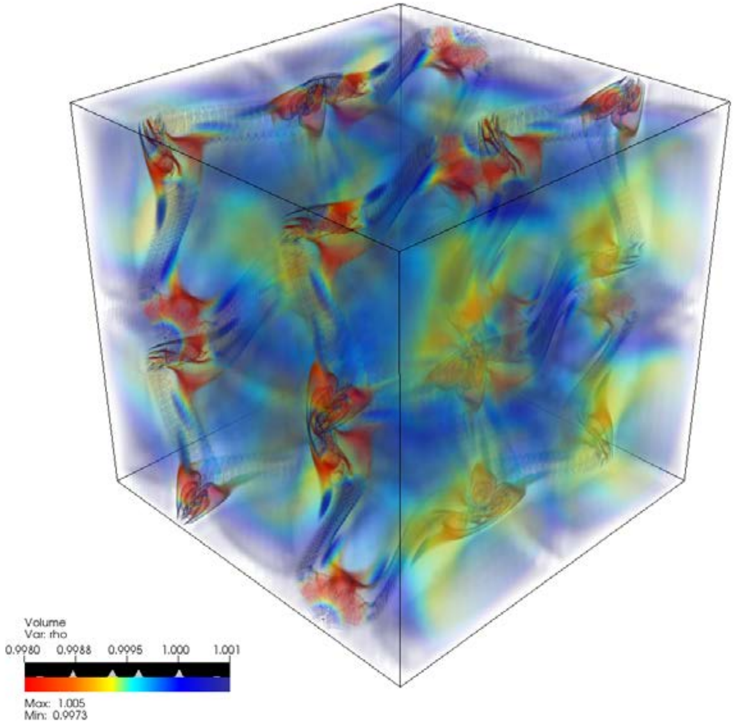


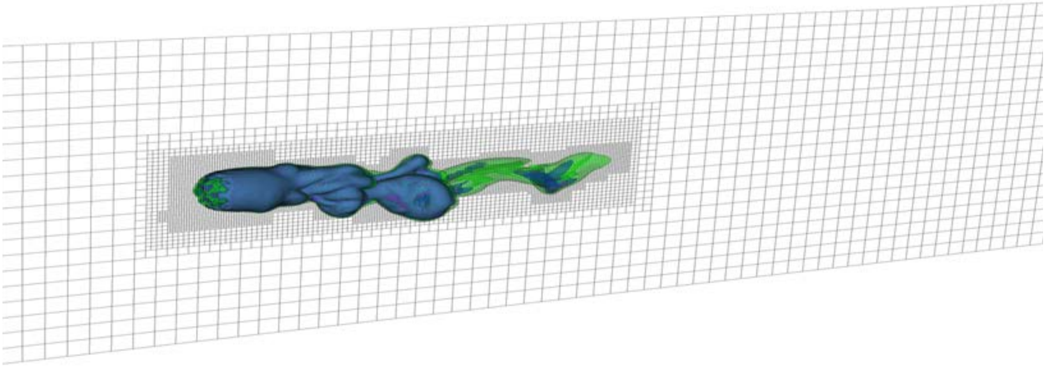


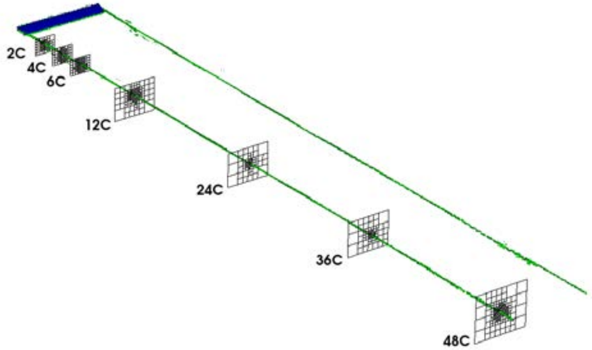
M. Brazell, J. Sitaraman and D. Mavriplis. An overset mesh approach for 3D mixed element high-order discretizations, Journal of Computational Physics, Oct. 2016.

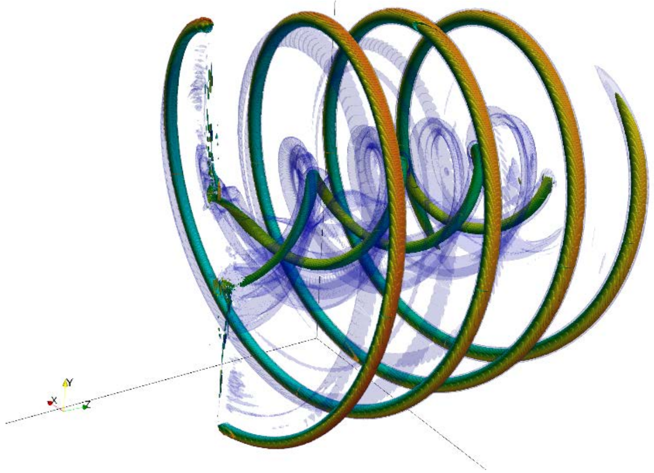
WwAaKE3D

Wyoming **W**ind and **A**erospace **A**pplications **K**omputation **E**nvironment





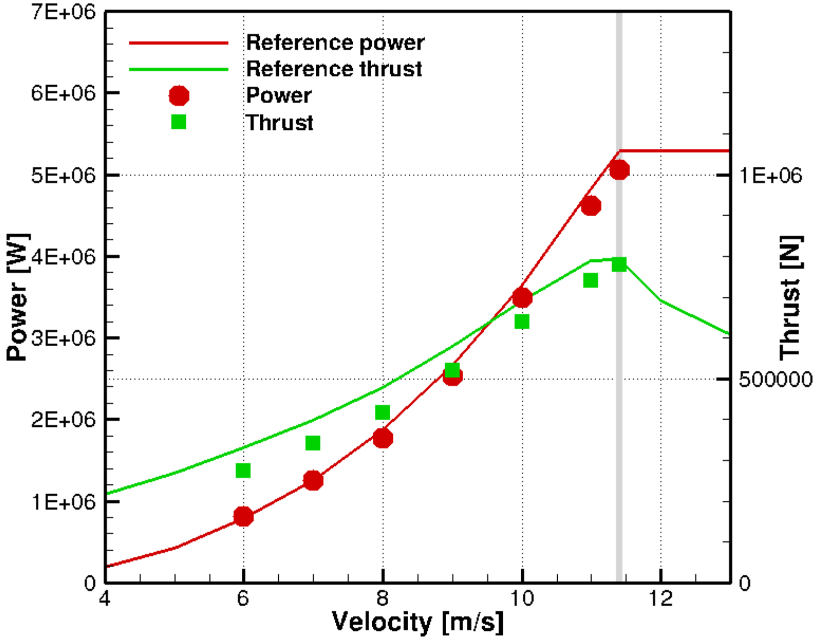


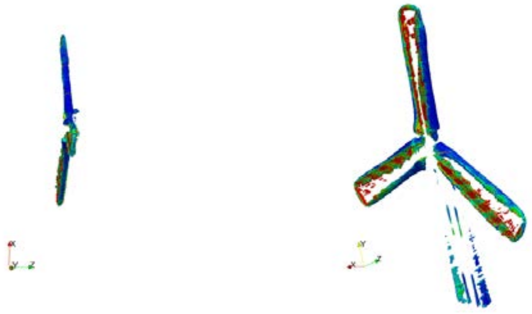


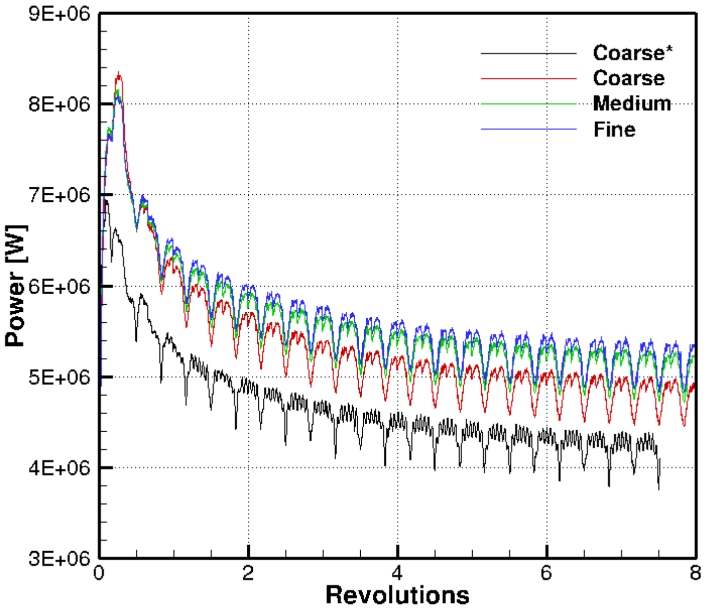
Results: NREL 5MW

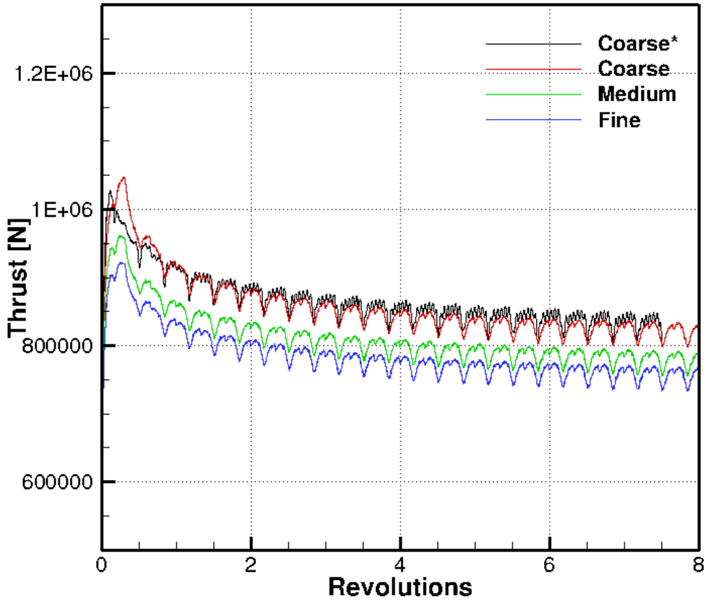
Mesh Refinement Study

Mesh	Mesh Points
Coarse*	474,383
Coarse	360,148
Medium	927,701
Fine	2,873,862





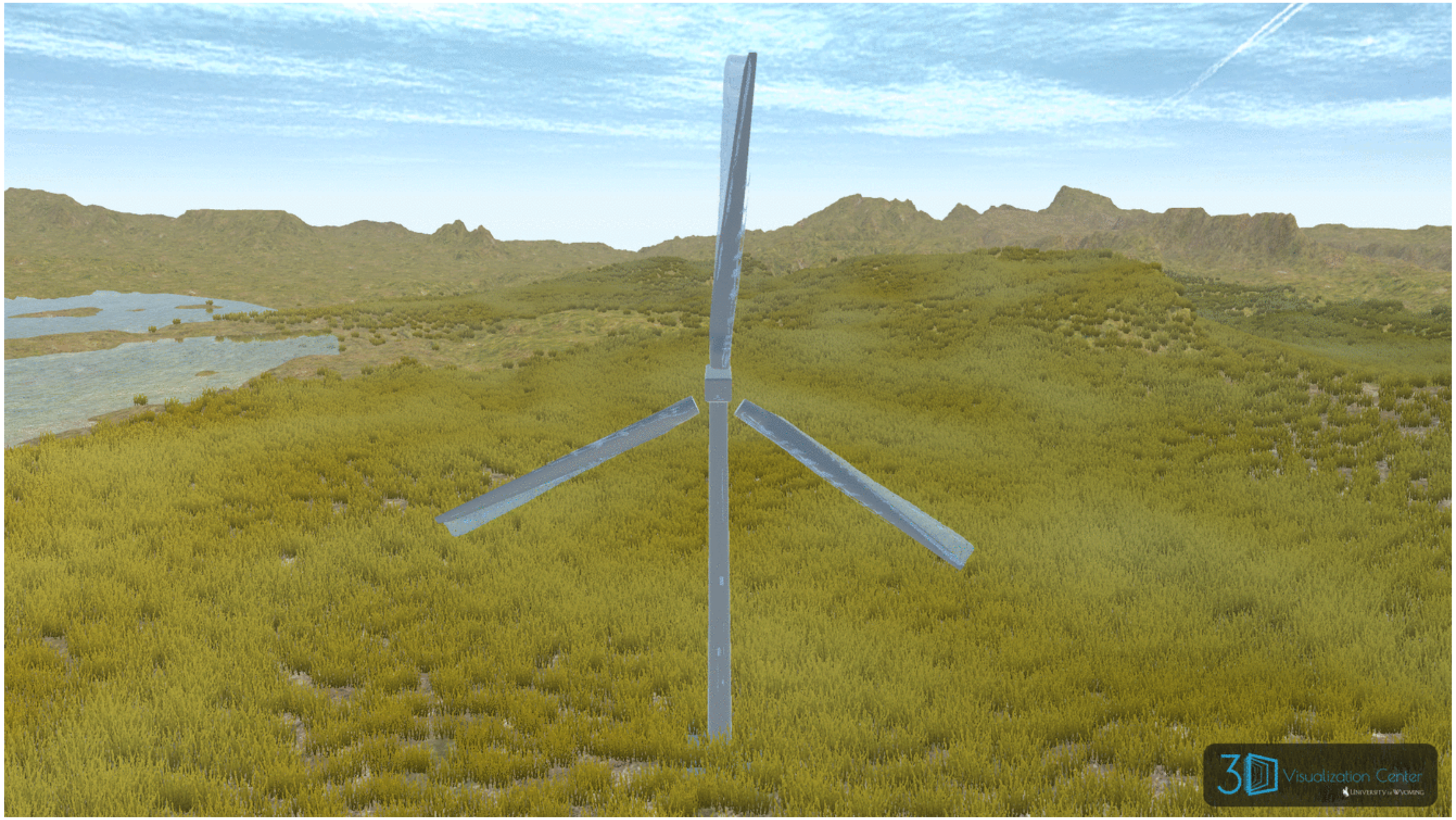




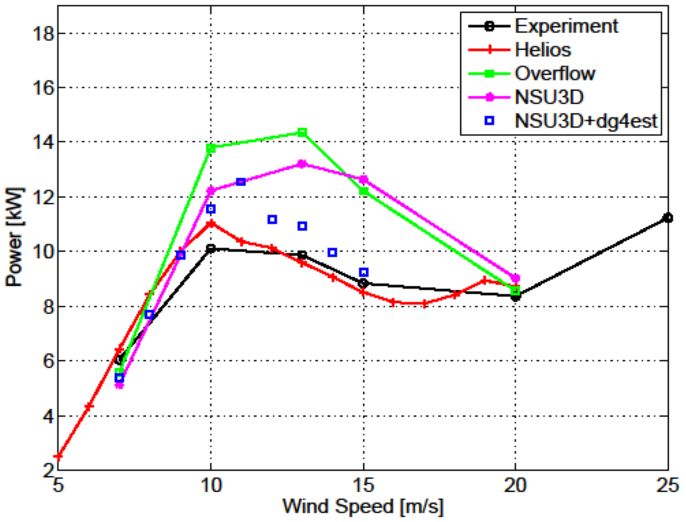
Results: NREL 5MW

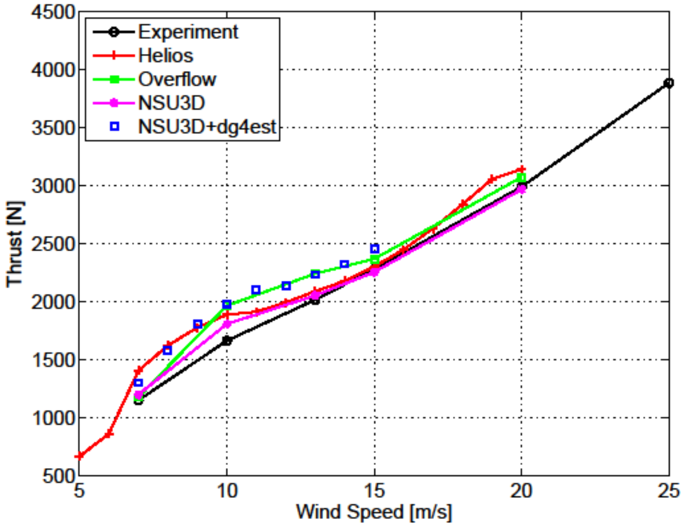
VisIt Libsim:

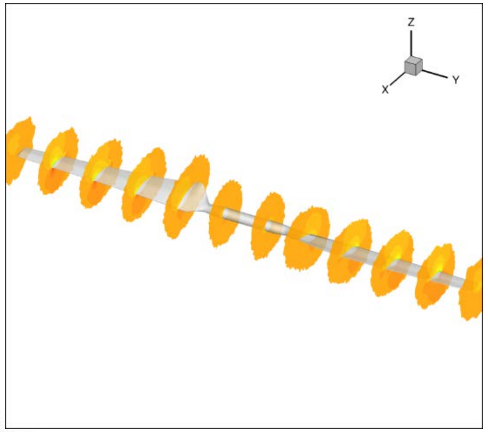
In-situ visualization

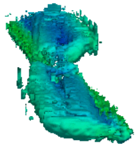


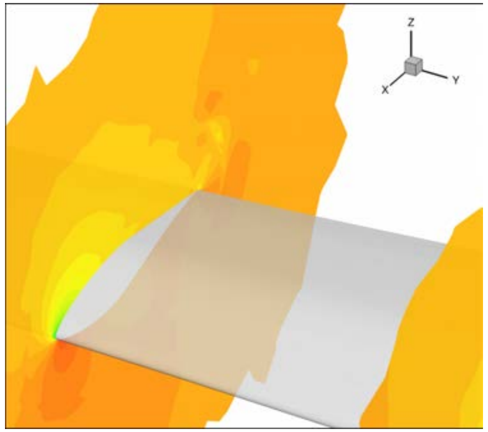
Results: NREL Phase VI



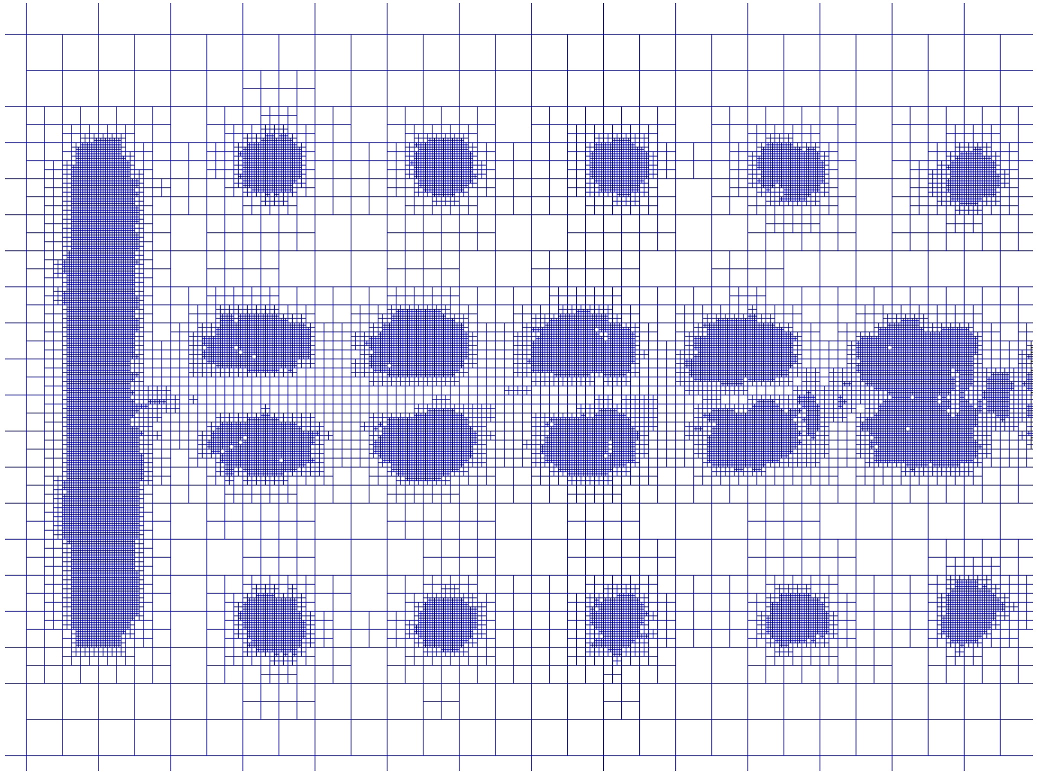




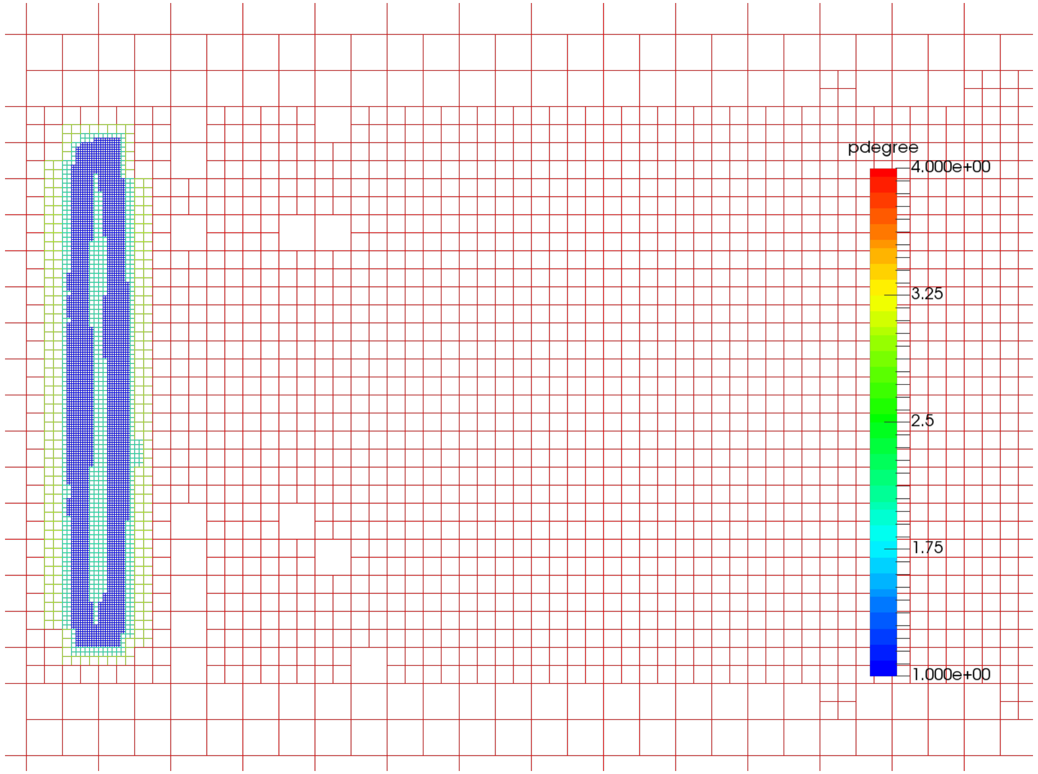




Results: NREL Phase VI

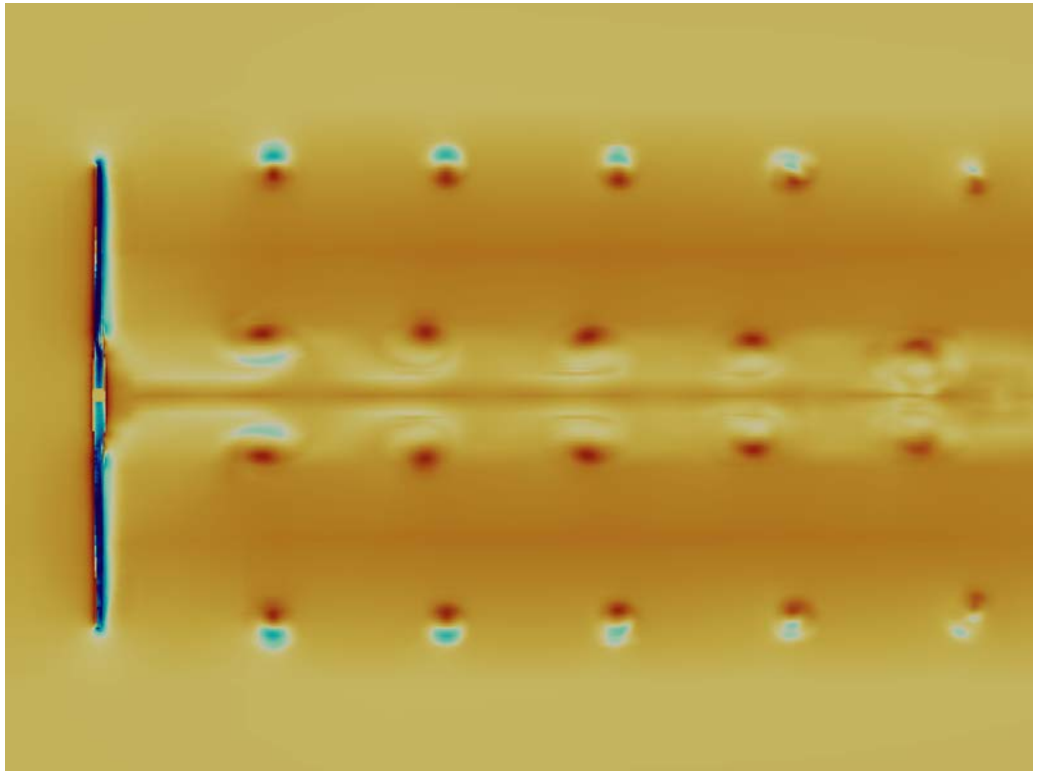


p= 1
2^{nd}-order

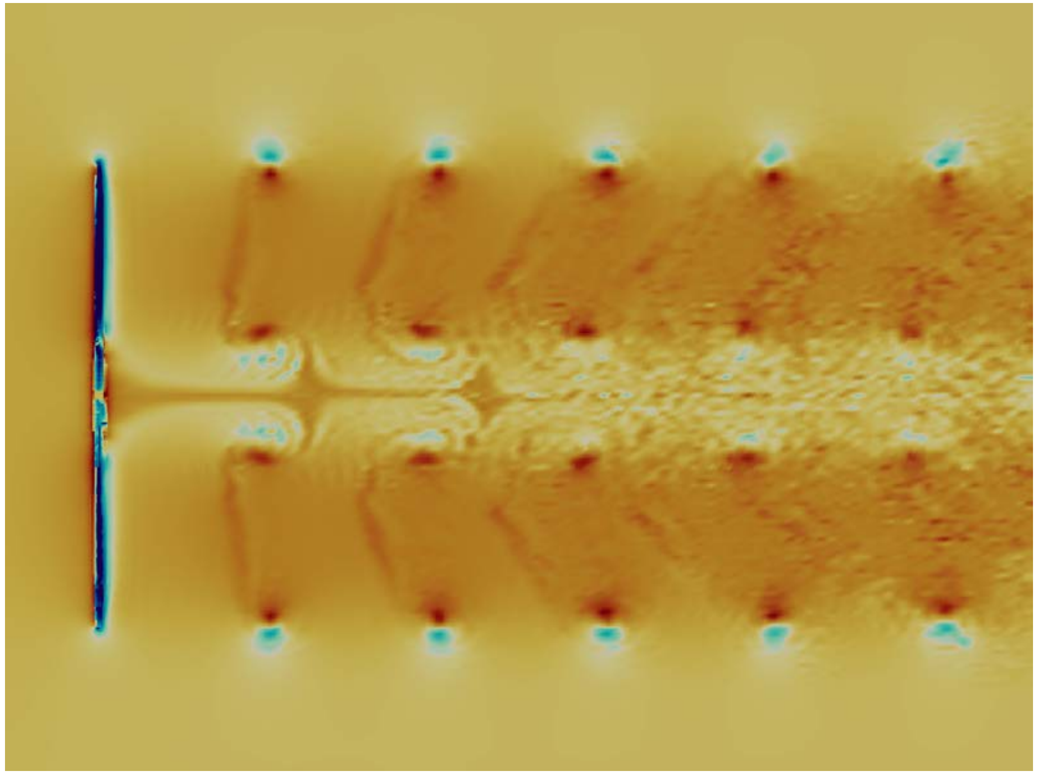


p= 1 - 4
2^{nd}- to 5^{th}-order

Results: NREL Phase VI

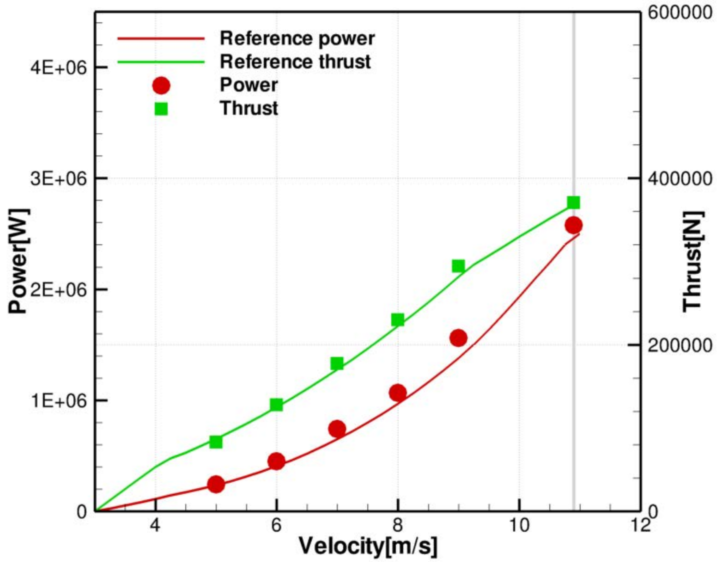


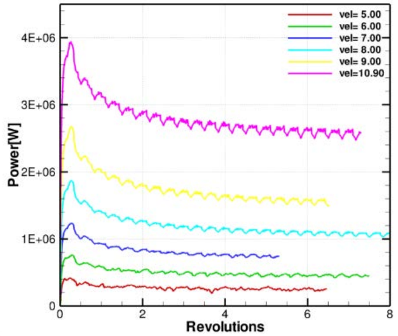
p=1
2nd-order

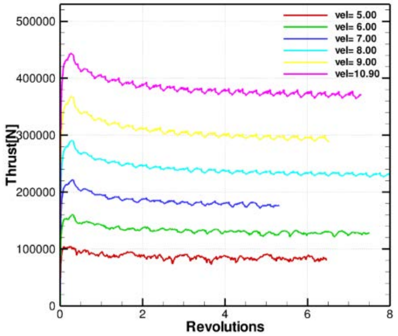


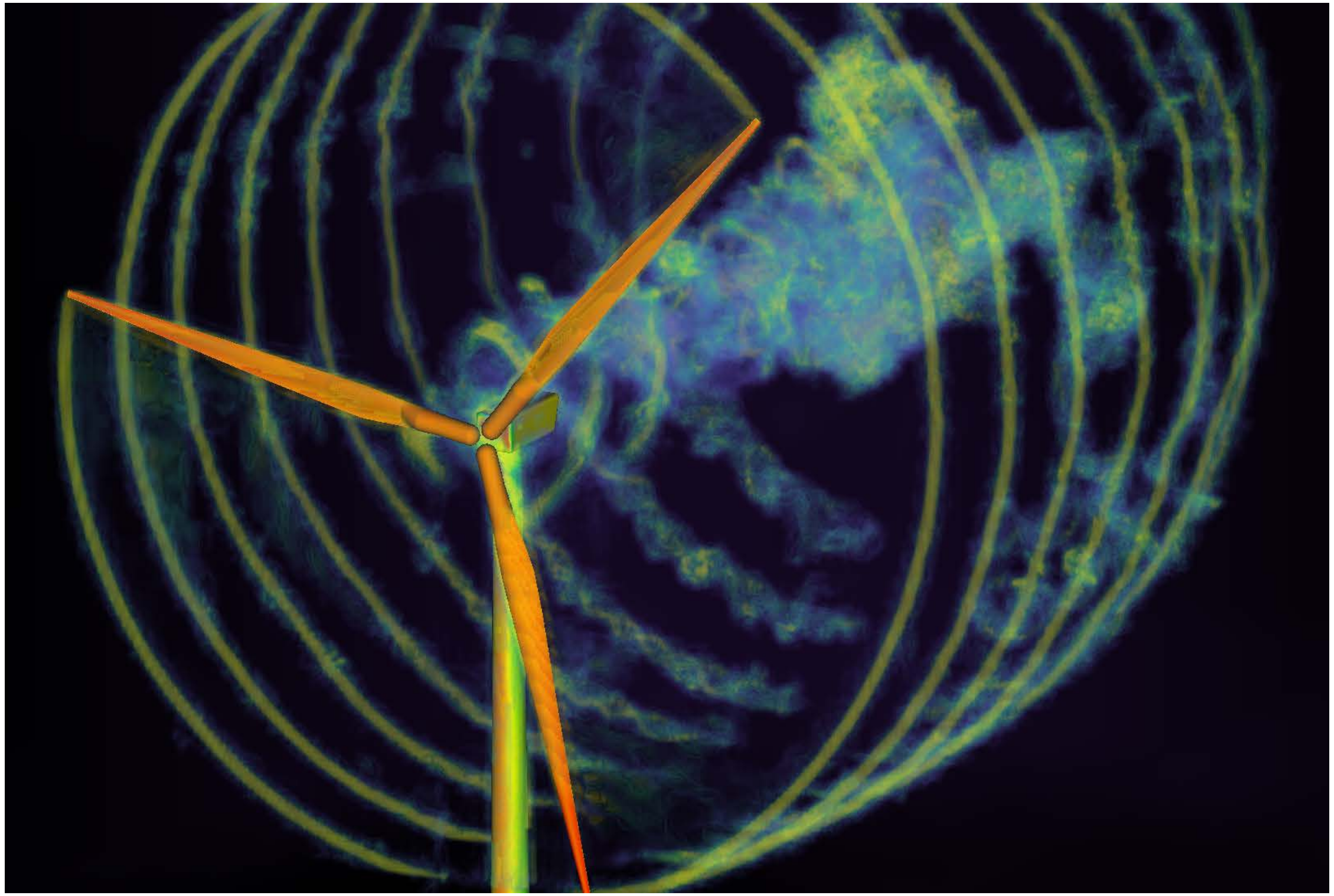
p=4
5th-order

Results: Siemens SWT-2.3-93





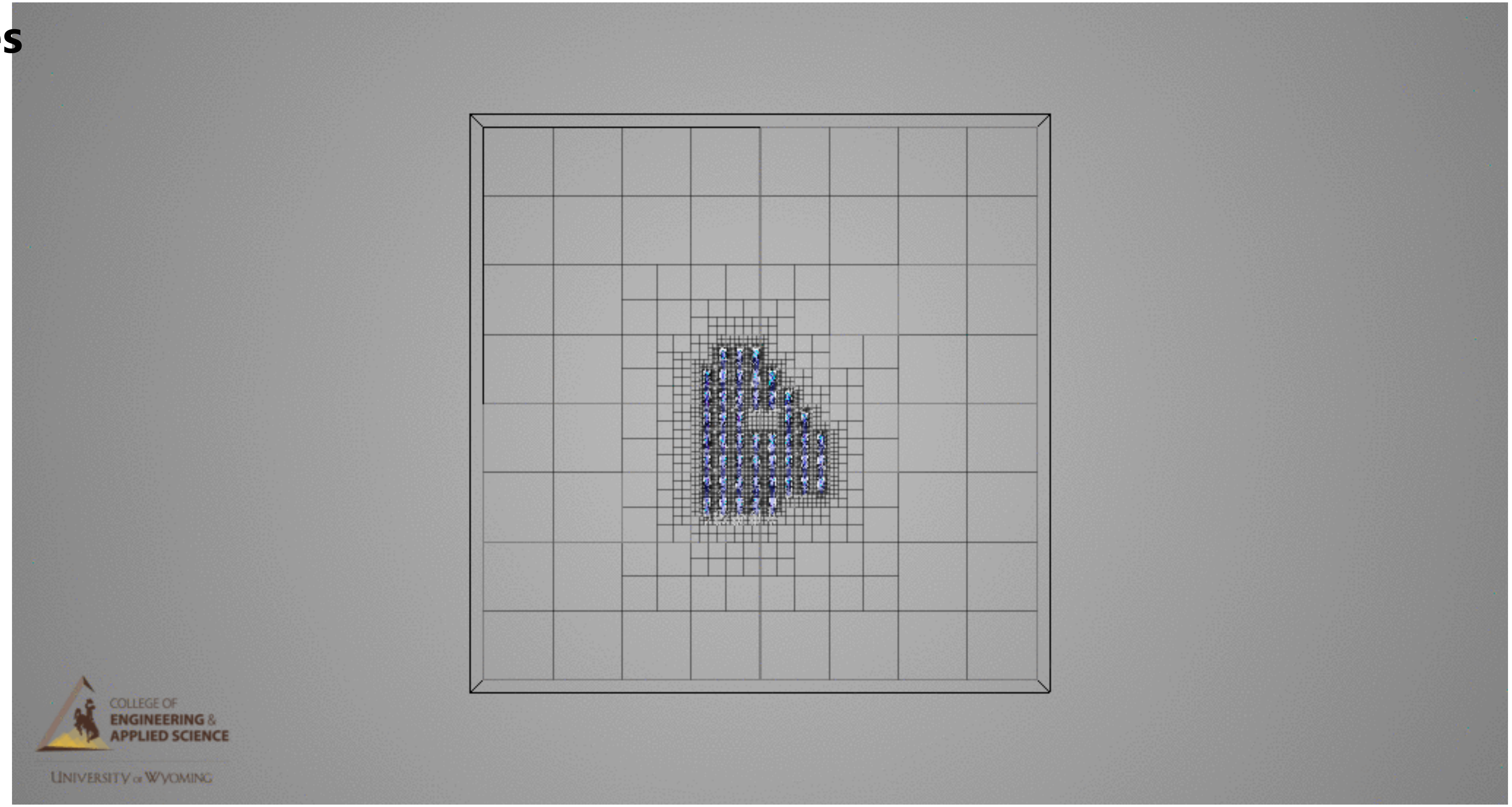




Results: Lillgrund Wind Farm

48 Wind Turbines

- **1.55 billion DOFs**
- **22,464 cores**
- **Domain**
  10 km x 10 km
- **Smallest Element**
  7E-6 m
  (7 micrometers)
- **10 magnitudes of spatial scales**

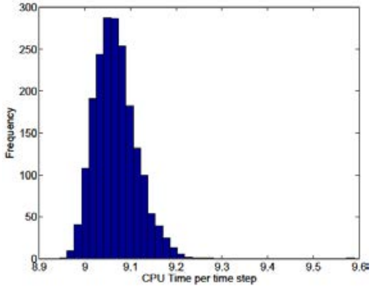


Results: Weak Scaling Study

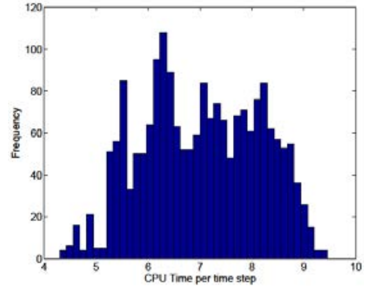
Turbine Count	Efficiency	Revs	Near-Body Cores	Off-Body Cores	Total Cores
6	1.0000	1.374	2,088	720	2,808
12	0.9874	1.360	4,176	1,440	5,616
24	0.9682	1.331	8,352	2,880	11,232
48	0.9333	1.283	16,704	5,760	22,464
96	0.8686	1.194	33,408	11,520	44,928

6 Turbines

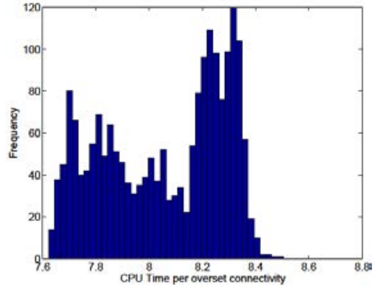
Near-Body



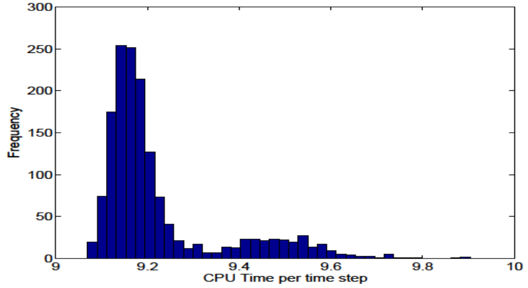
Off-Body

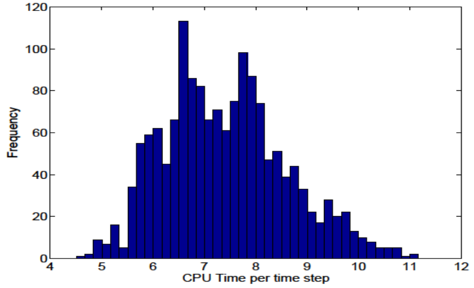


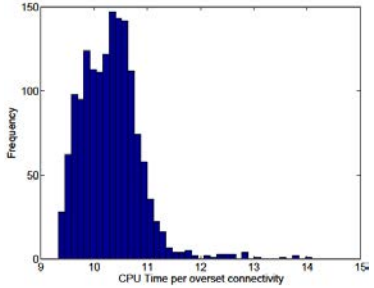
Overset



96 Turbines

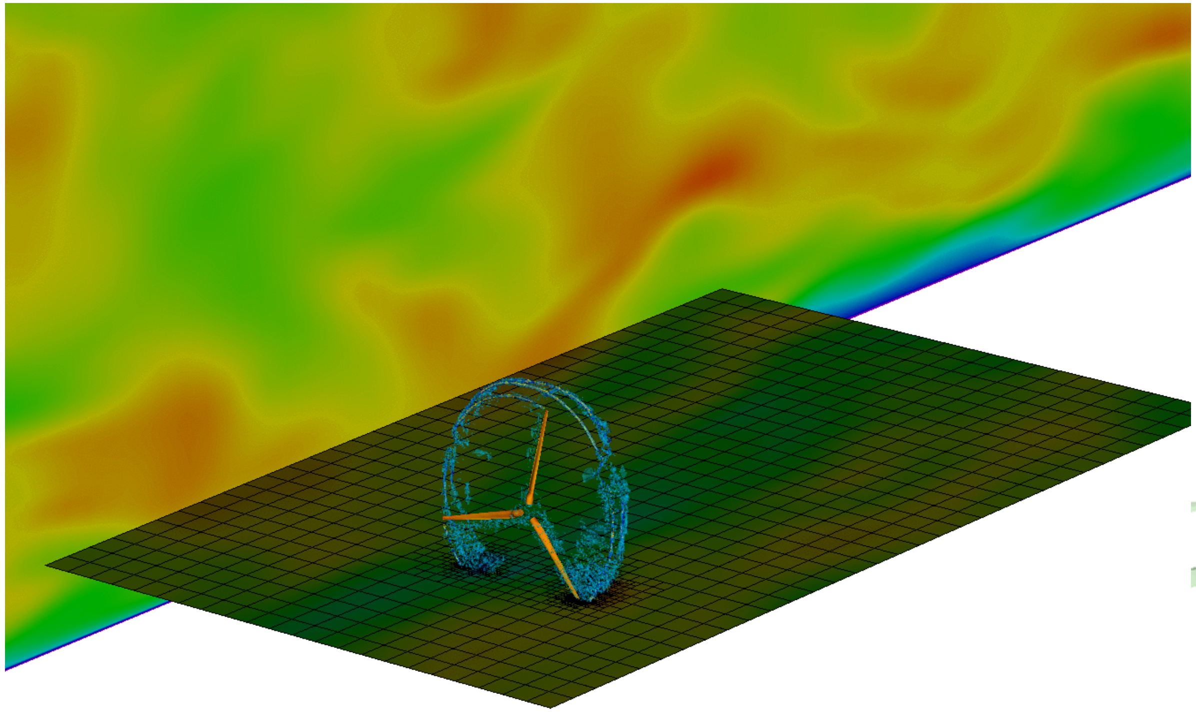


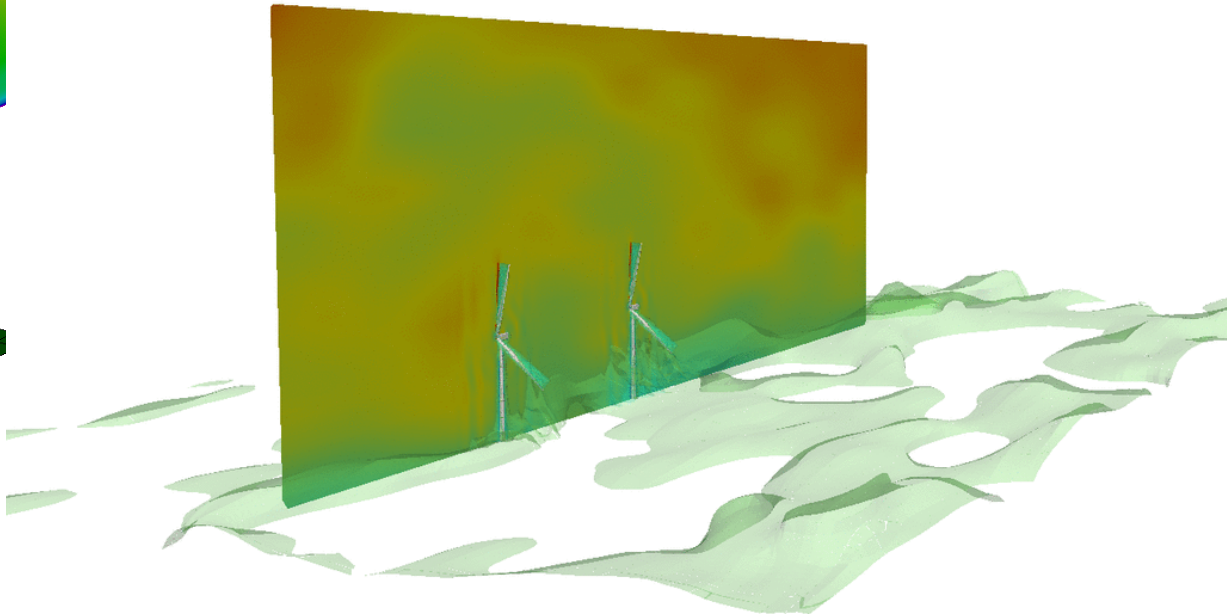




Results: CFD & Atmospheric Coupling

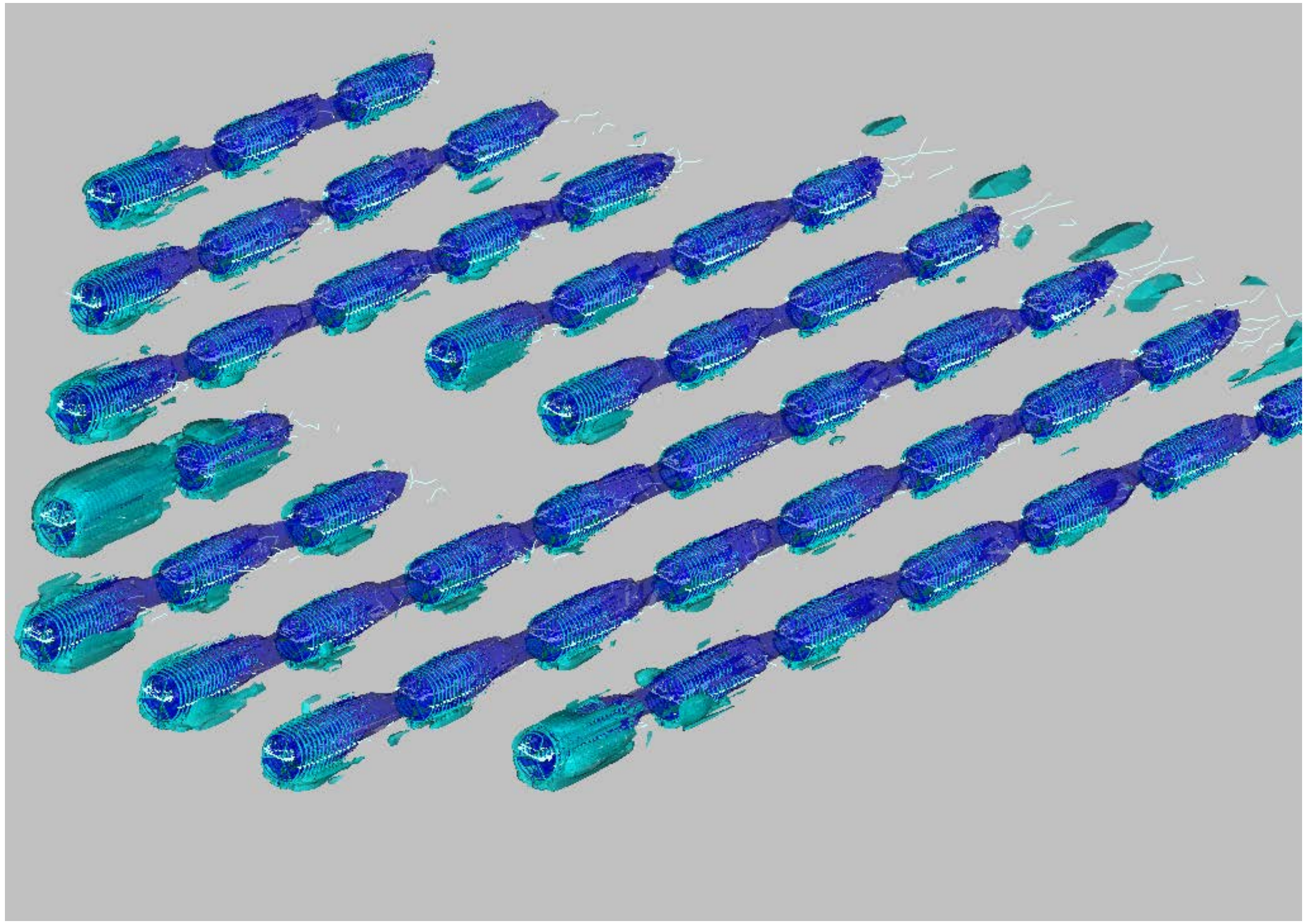
- NCAR WRF





Final Remarks

- Blue Waters Fellowship:
  - 50,000 Node-Hours
  - Perform 6 wind turbine case
- Blue Waters Proposal:
  - Moderate (50 Turbines)
    325,000 Node-Hours
  - Large (200 Turbines)
    1,000,000 Node-Hours



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Final Remarks

2017 AIAA AVIATION, Denver, CO

Wind Farm Simulations Using an Overset *hp*-Adaptive Approach with Blade-Resolved Turbine Models

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Department of Mechanical Engineering, University of Wyoming, Laramie, WY 82071, USA

Jay Sitaraman

Parallel Geometric Algorithms, LLC, Sunnyvale, CA 94087, USA

Blade-resolved numerical simulations of wind energy applications using full blade and tower models are presented. The computational methodology combines solution technologies in a multi-mesh, multi-solver paradigm through a dynamic overset framework. The coupling of a finite-volume solver and a high-order, *hp*-adaptive finite-element solver is utilized. Additional technologies including in-situ visualization and atmospheric micro-scale modeling are incorporated into the analysis environment. Validation of the computational framework is performed on the NREL 5MW baseline wind turbine, the unsteady aerodynamics experimental NREL Phase VI turbine, and the Siemens SWT-2.3-93 wind turbine. The power and thrust results of all single turbine simulations agree well with low-fidelity model simulation results and field experiments when available. Scalability of the computational framework is demonstrated using 6, 12, 24, 48, and 96 wind turbine wind plant set-ups including the 48 turbine wind plant known as Lillgrund. Demonstration of the coupling of atmospheric micro-scale and CFD solvers is presented using the NCAR WRF solver and the NREL SOWFA solver. Comprehensive validation with measurements will be the focus of future research of the computational framework.

A high-order discontinuous-Galerkin octree-based AMR solver for overset simulations

Michael J. Brazell[a], Andrew C. Kirby[b], and Dimitri J. Mavriplis[c]

Department of Mechanical Engineering

University of Wyoming

The goal of this work is to develop a highly efficient off-body solver for use in overset simulations. Overset meshes have been gaining traction in recent years and are being used increasingly to simulate very complex large-scale problems. In particular we focus on a dual-mesh, dual-solver overset approach that combines specialized flow solvers in different regions of the flow domain: near-body and off-body. The near-body flow solver is designed to handle complicated geometry, anisotropic elements, and unstructured meshes. In contrast, the off-body solver is designed to be high-order, Cartesian, and use adaptive mesh refinement (AMR). The high-order discretization used for the off-body solver is based on the discontinuous Galerkin (DG) method. To get the most efficiency out of the method, a Cartesian grid is employed and tensor product basis functions are used in the DG formulation. The dense computational kernels allow this solver to obtain a near-constant cost per degree of freedom for a wide range of p-orders of accuracy. To further enhance the capabilities of the off-body solver, the DG solver in linked to an octree-based AMR library called `p4est`; this gives the ability for *h*-adaptation via non-conforming elements. *p*-adaption is also implemented in which each cell can be assigned a different polynomial degree basis. Combined h and p refinement is necessary for overlapping mesh problems where the off-body solver mesh must connect to the low-order near-body solver, since both mesh resolution and order of accuracy must be matched in the overlapping regions. To demonstrate the efficiency, accuracy, and capabilities of the DG AMR flow solver we simulate Ringleb flow and the Taylor-Green vortex problem. Finally, to demonstrate the overset capabilities a NACA 0015 wing case and a NREL PhaseVI wind turbine case are simulated.

Acknowledgements

- NCSA Staff: Blue Waters POC Galen Arnold
- 2016-2017 Blue Waters Fellowship
  - NSF awards OCI-0725070 and ACI-1238993
- Shell 3D Visualization Center at the University of Wyoming
  - Kyle Summerfield, Nikhil Shetty, Emma-Jane Alexander
- Intelligent Light (in-situ visualization)
  - Earl Duque & Brad Whitlock
- Compute Time
  - NSF Blue Waters (50,000 Node-Hours)
  - NCAR ASD Project (15,000,000 Core-Hours)
  - NCAR-Wyoming Alliance (Cheyenne: 38,000,000 Core-Hours, Yellowstone: 8,000,000 Core-Hours)
  - UWYO ARCC
- Office of Naval Research:
  - ONR Grant N00014-14-1-0045
  - ONR Grant N00014-16-1-2737
- U.S. Department of Energy, Office of Science, Basic Energy Sciences
  - Award #DE-SC0012671