SAND2012-7151P

Scientific Computing Challenges in Wind Energy

CSRI Summer Seminar Series

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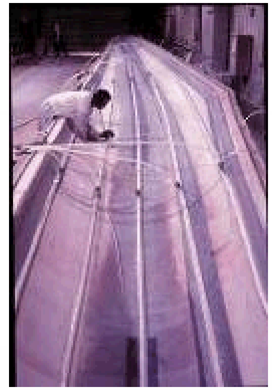
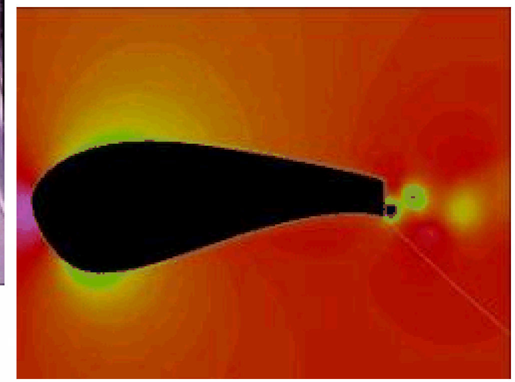
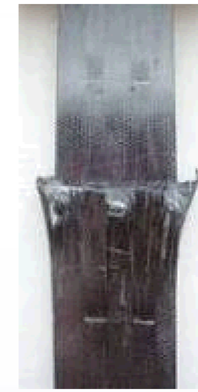
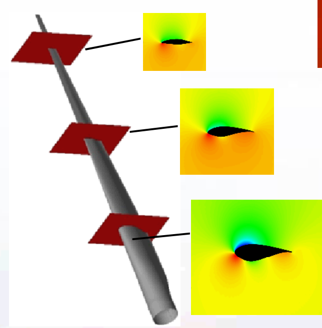
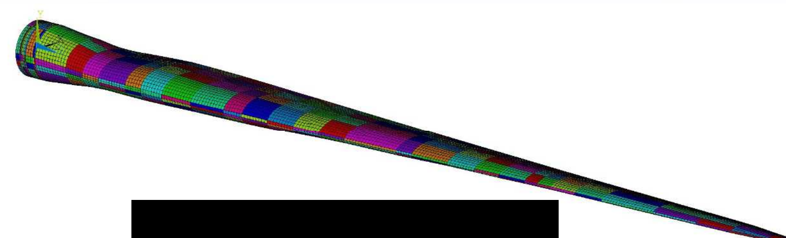
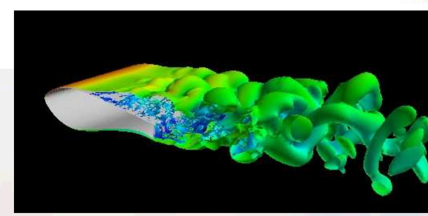
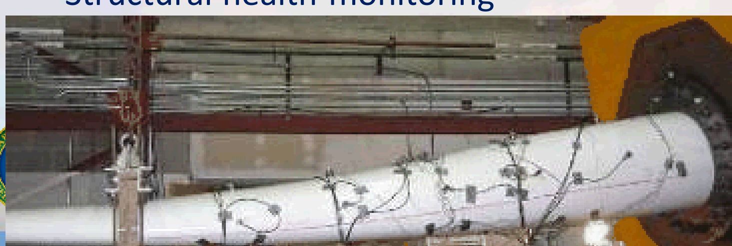
Presentation Outline

- **Overview of wind energy**
- **Challenge 1 : Wind farm aerodynamics**
- **Challenge 2 : Wind turbine extreme design loads**
- **Challenge 3 : Wind turbine noise**

Goal: Give an overview of scientific computing applications in wind energy, with examples.

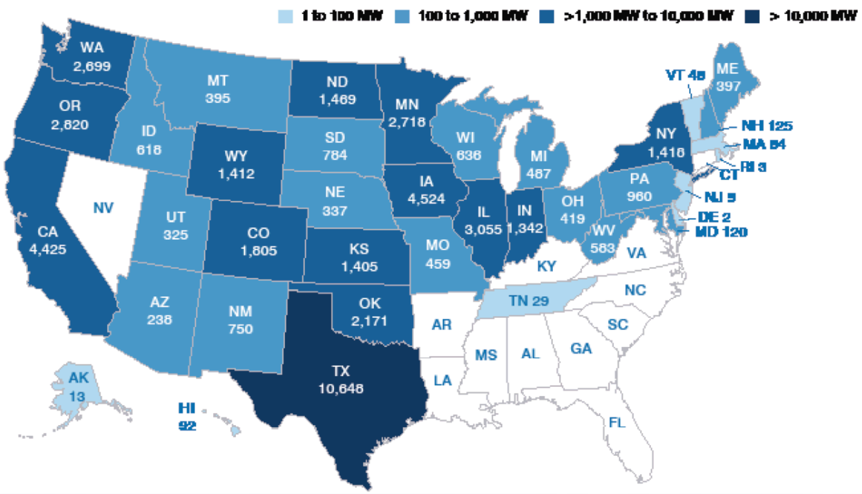
SNL's Wind Energy Program

- **Wind Technology**
  - Materials and Manufacturing
  - Structural, Aerodynamic, and Full System Modeling
  - Sensors and Structural Health Monitoring
  - Advanced Blade Concepts
  - Lab - Field Testing and Data Acquisition
- **System Reliability**
  - Industry Data Collection
  - Improve reliability of the existing technology and future designs
  - Blade Reliability Collaborative
- **System Integration**
  - Wind/RADAR Interaction
  - Integration Assessment
- **Offshore Wind**
  - Floating vertical-axis wind turbine research
  - Sediment transport around foundations
  - Structural health monitoring

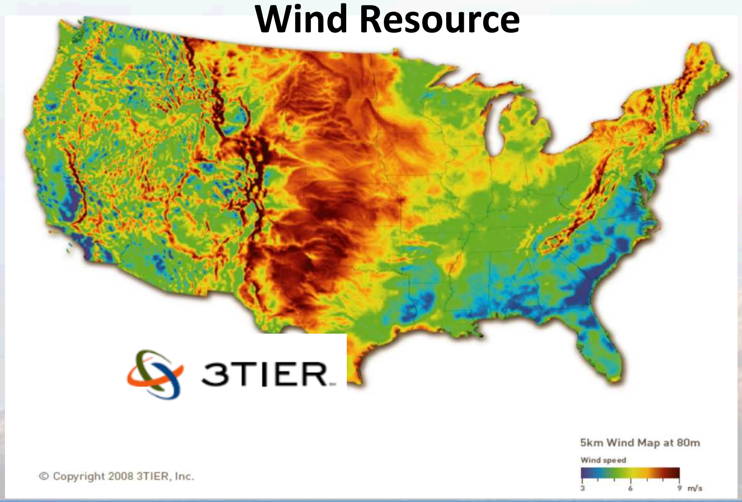









Wind Energy in the U.S.

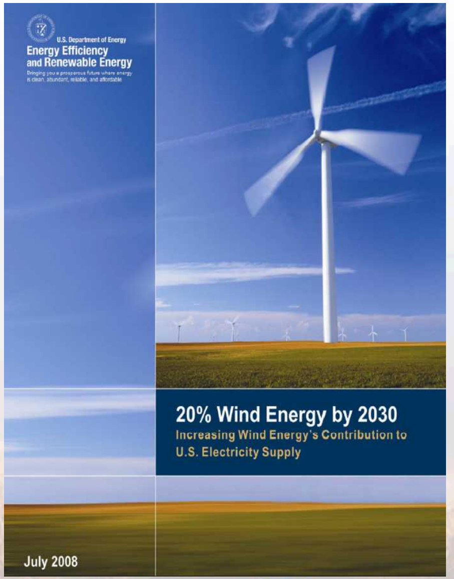
(MW as of June 30, 2012)
1 MW powers ~300 homes



Wind Resource



- **Wind Energy Today**
  - Total installed capacity: >50,000MW (38 States)
  - >2.5% of U.S. electricity generation
  - Installed cost: ~7¢/kWh (2010 capacity-weighted cost)
- **DOE Wind Program Focus: 20% wind generation by 2030**
  - 50,000 MW offshore



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Wind Power Plant

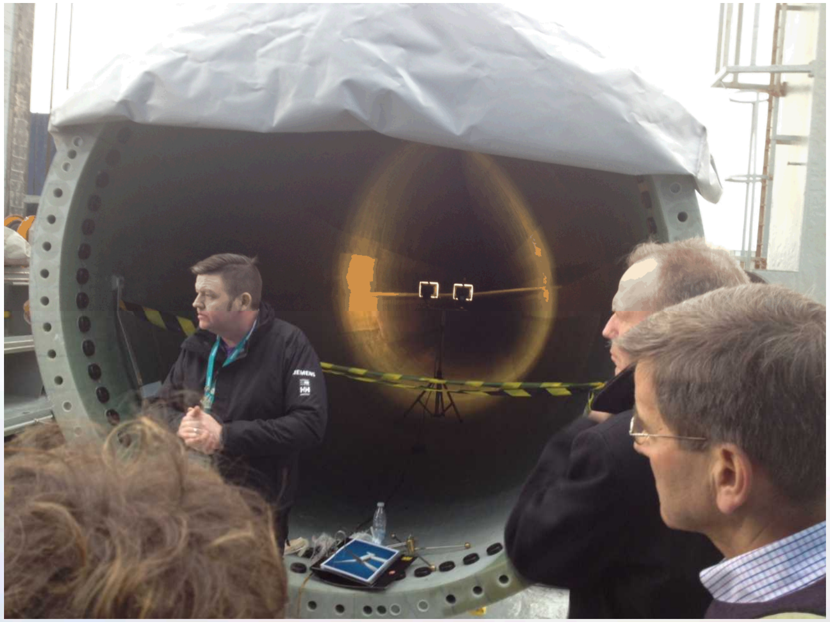
Representative Modern Turbine:

- GE 2.5 – 103
- Rated Power: 2.5 MW
- Hub height: 100 meters
- Rotor diameter: 103 m

Wind Farm:

- From several to several *hundred* turbines
- Spaced 3-10 rotor diameters apart

Wind Turbine Blade



Wind Turbine Performance

Air Density — Rotor Area — Wind Speed

$$Power, P = \frac{1}{2}\rho A C_P V_\infty^3$$

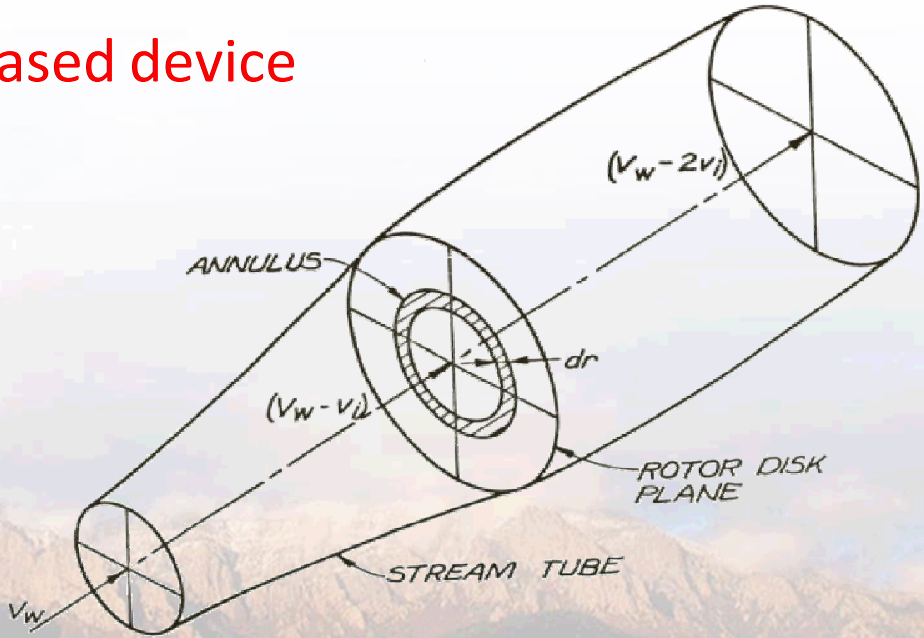
Wind Power output is proportional to wind speed cubed.

Power Coefficient

$$C_{P\max} \cong 0.3$$ Drag-based device

$$C_{P\max} \cong 0.59$$ Lift-based device

The Betz Limit



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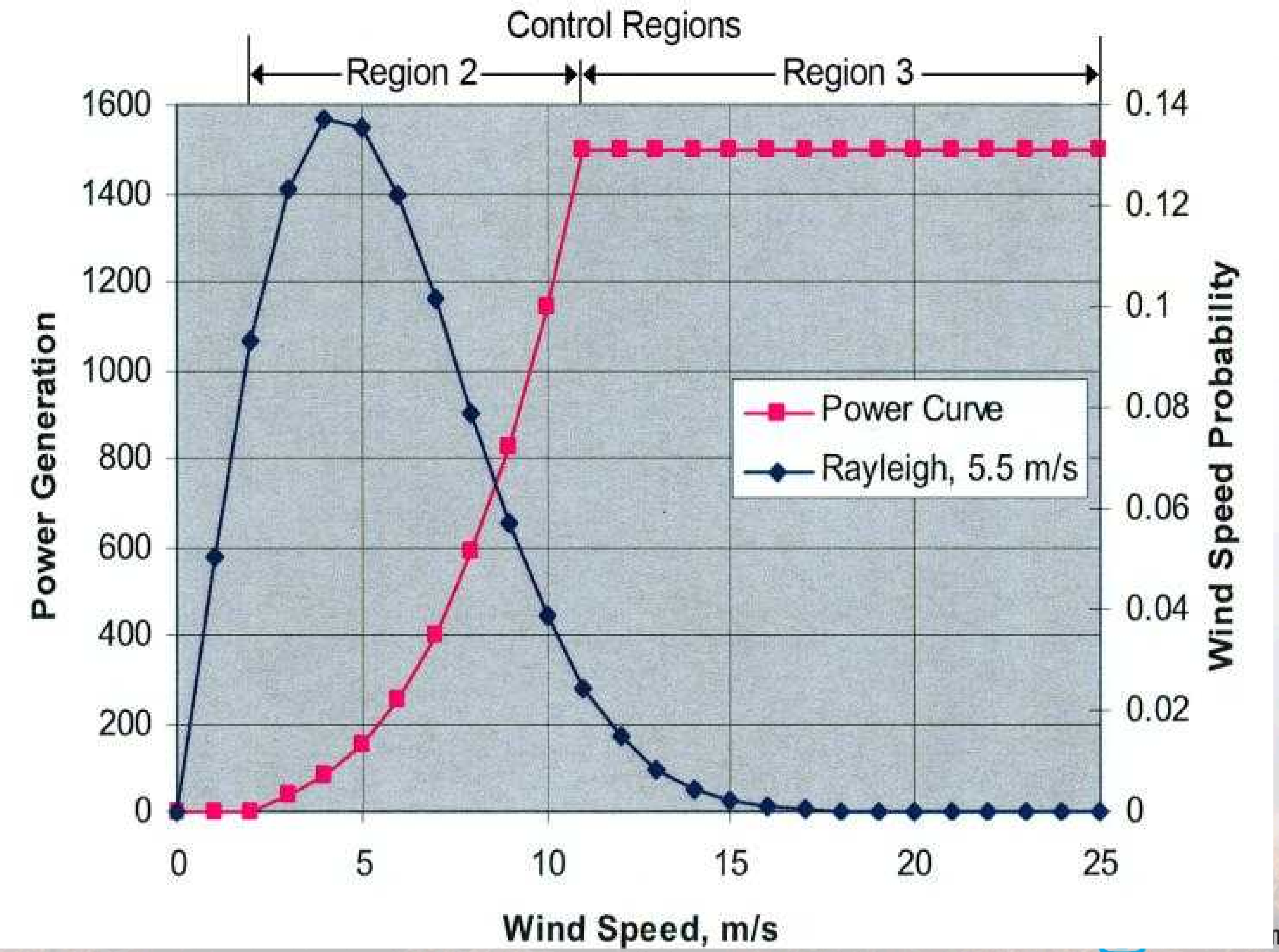
Basics of Wind Turbine Performance



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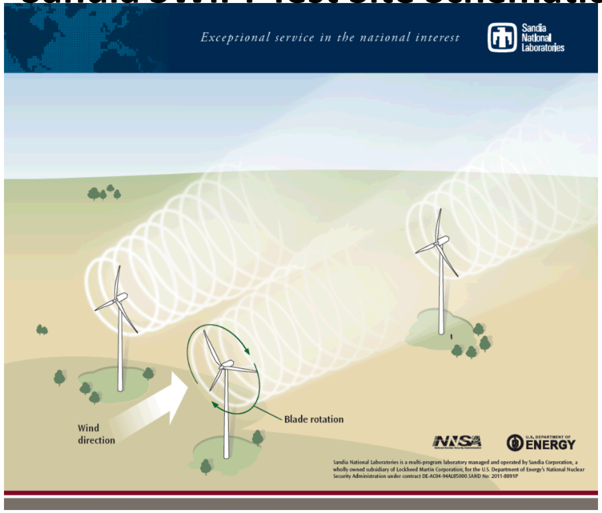
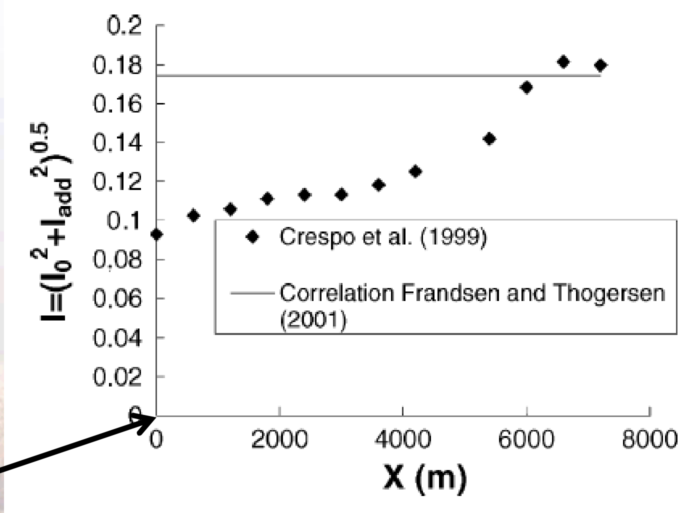
Challenge: Wind Farm Aerodynamics

- Turbines within a wind farm operate within one another's wakes
- Power losses can be significant
  - >50% for individual turbines
  - Up to 20% for the wind farm as a whole
- Increased fatigue loads on the turbines
  - Increased turbulence intensity within wakes
  - Partial immersion within meandering wakes
  - Decreased turbine reliability

Sandia SWiFT Test Site Schematic



Turbulence intensity within a wind farm



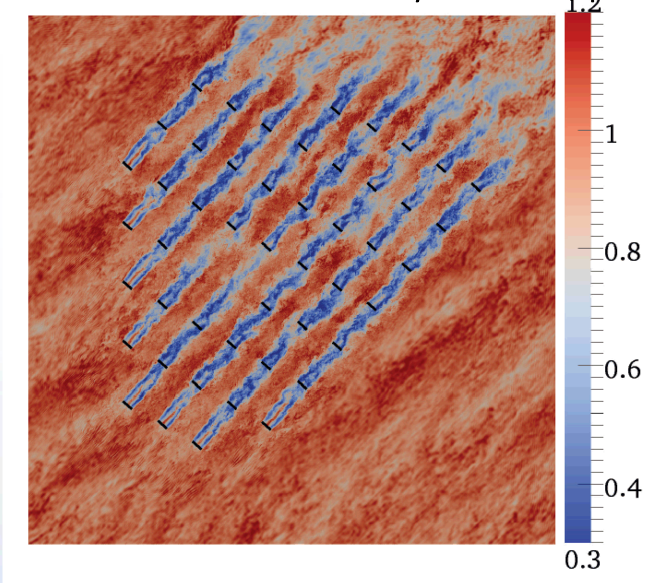
Leading edge of wind farm

High-Fidelity Simulation of Wind Turbine Wakes

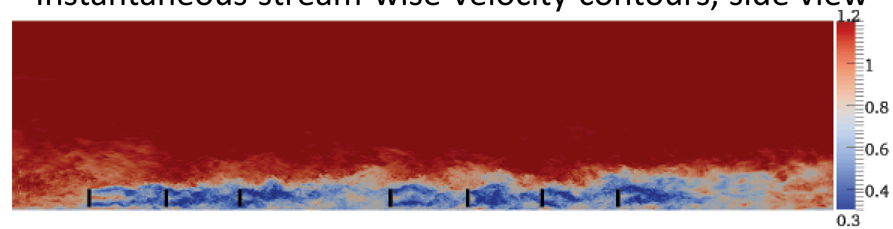
LES of Wind Farm Performance

From: Churchfield *et al.*, "A Large-Eddy Simulation of Wind-Plant Aerodynamics, AIAA 2012-0537, 2012. Results from NREL researchers using the Red Mesa supercomputer.

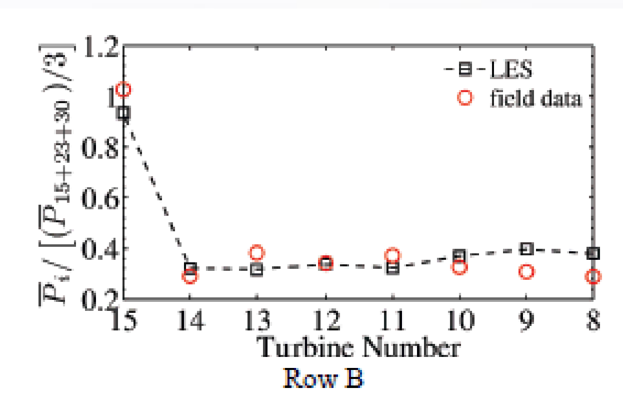
Instantaneous stream-wise velocity contours, plan view



Instantaneous stream-wise velocity contours, side view



Normalized average rotor power



Computational Resources:
315 million grid cells
1 million processor hours for a ten-minute simulation

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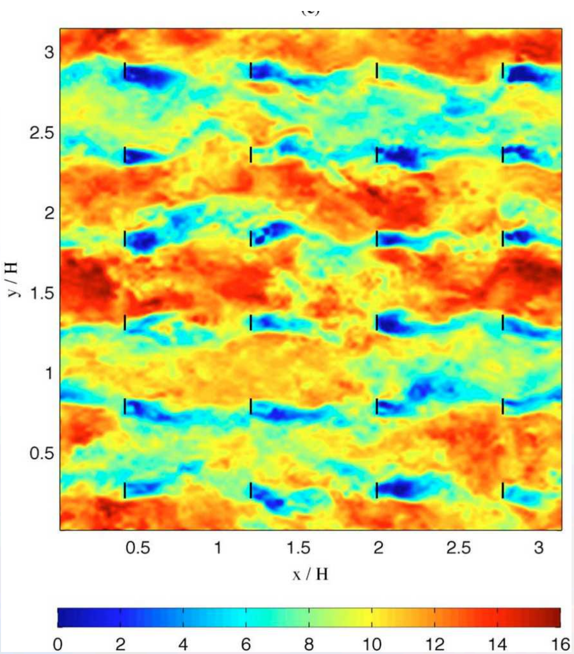
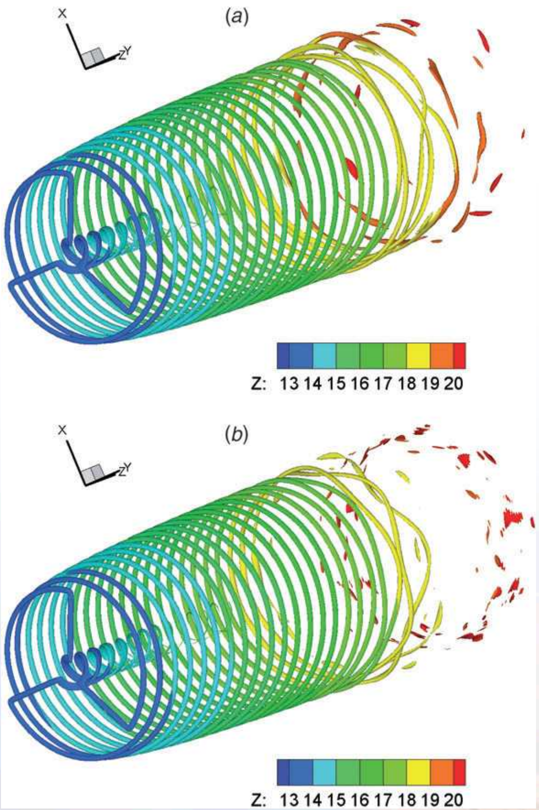
LES of Infinitely Large Wind Farms

From: Calaf, Meneveau, and Myers, "Large eddy simulation study of fully developed wind-turbine array boundary layers", *Phys. Fluids*, 22, 2010.



- **Fully developed wind turbine / atmospheric boundary layer flow:**
  - Turbines modeled using an actuator disk approach
  - Periodic boundary conditions in the horizontal plane approximates "very large" wind farm
  - **Major Finding**: Vertical flux of kinetic energy of the same order of magnitude as power extracted by the turbines

Stability of Wind Turbine Wakes



- **Near-wake of a wind turbine dominated by helical tip and hub vortex system**
- **Ivanell *et al. (Wind Energy 13, 2010)* conducted numerical experiments investigating stability of helical wind turbine wakes**
- **Outstanding questions on wake stability and breakdown**
  - Effect of free-stream turbulence
  - Effect of vertical wind shear

Wind Farm Aerodynamics: Remaining Issues

- **Detailed experimental data suitable for wind farm LES predictions (including turbine fatigue loads)**
- **High-fidelity models of inter-farm wake effects**
- **LES of wind farms under a variety of atmospheric conditions**
- **LES of wind farms with complex terrain**
- **Design of turbines/farms to mitigate wake effects**
  - Manipulation of the near wake to enhance wake mixing and recovery
  - Automated wind turbine siting tools based on high-fidelity wake models

Challenge: Wind Turbine Design

- **Objective: Minimum cost of energy**
  - Minimum capital cost of the turbine & installation
  - Minimum operations & maintenance cost
  - Minimum financing cost (driven by uncertainty!!)
  - Maximum energy capture
- **Constraints**
  - Structural reliability
  - Noise
  - Size constraints (transportation of components)
  - Manufacturability
  - Aesthetics

Some Uncertainties in Wind Turbine Design

Environment

- Mean wind distribution
- Turbulence intensity distribution
- Turbulence spectrum
- Shear distribution
- Topography effects
- Upwind turbine wake effects

Turbine

- Structural shape
- Aerodynamic shape
- Material properties (load resistance)
- Blade soiling/erosion
- Structural damage
- Rotor/pitch system imbalance
- Extreme wind loads

SNL Wind Turbine Uncertainty Quantification Project

(1400, 1500, 6100, with Stanford U. and Purdue U.)

- ***Motivation:***
  - Computational assessment of failure probability or life expectancy of turbine components is hindered by the presence of large uncertainties
    - environmental conditions, blade structure, model form (e.g., turbulence)
  - Rigorous UQ can fundamentally improve the state-of-the-art in computational predictions and, as a result, aid in the design of more cost-effective devices
- ***UQ methodologies:***
  - Stochastic expansion methods on structured grids
    - adaptive refinement, adjoint enhancement
  - unstructured grids
    - simplex collocation, compressive sensing
  - error balance
  - multifidelity UQ
- ***Simulations:***
  - Low fidelity: EOLO, FAST, CACTUS
  - High fidelity: time spectral, DG LES

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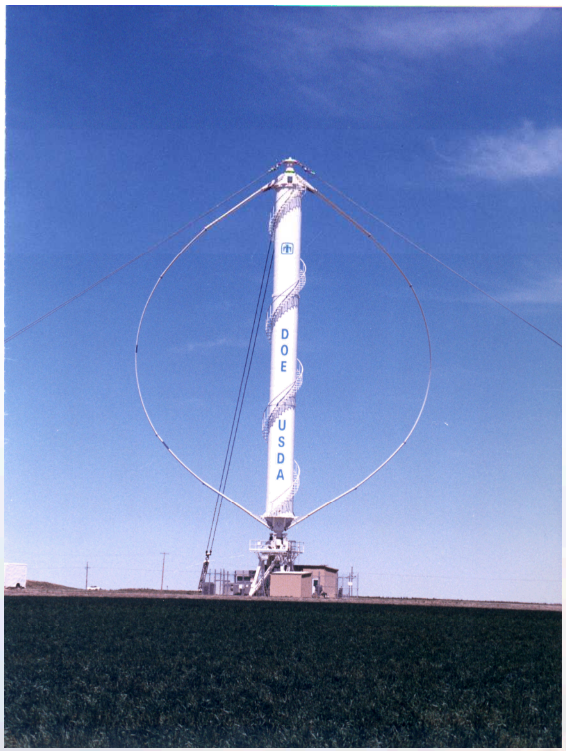
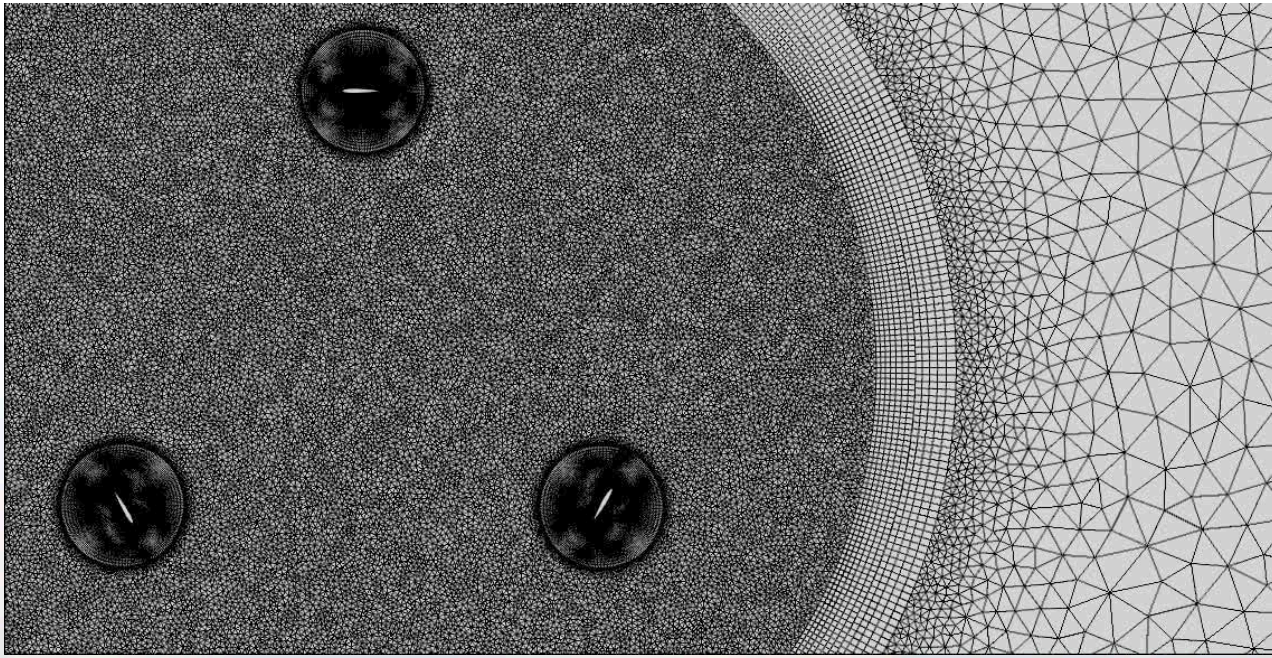
High-fidelity CFD modeling of wind turbine aerodynamics

- **Demonstration of a new halo cell sliding mesh algorithm on a 2D vertical-axis wind turbine problem with hybrid mesh**





Ksgs constant coef LES model

Prediction of Wind Turbine Extreme Loads

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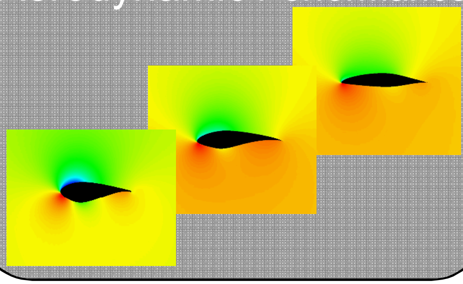
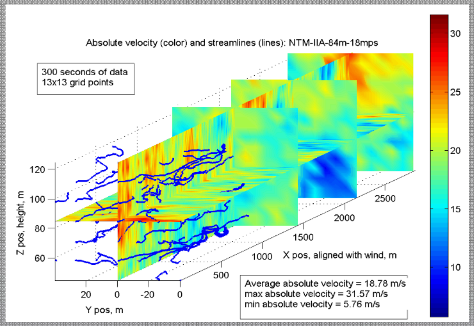
Aeroelastic Simulation

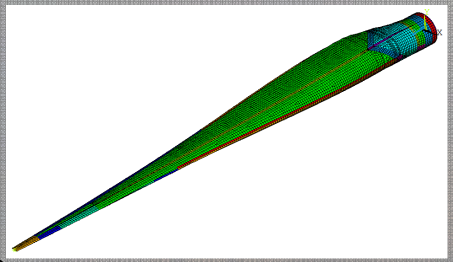
Aerodynamic Performance



Turbulent Wind Input



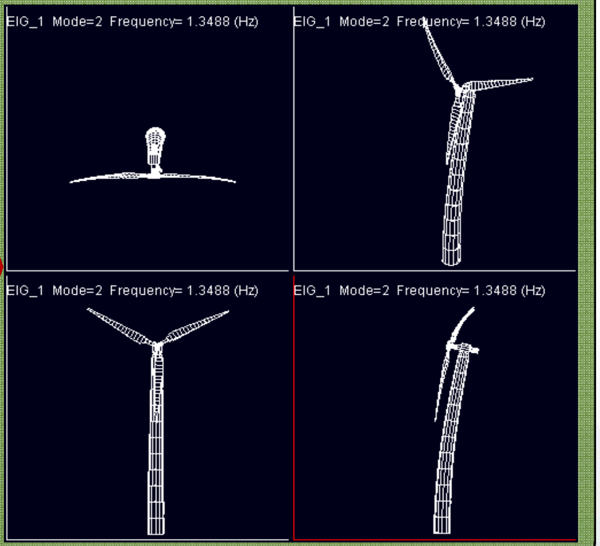
Structure and Materials



FAST

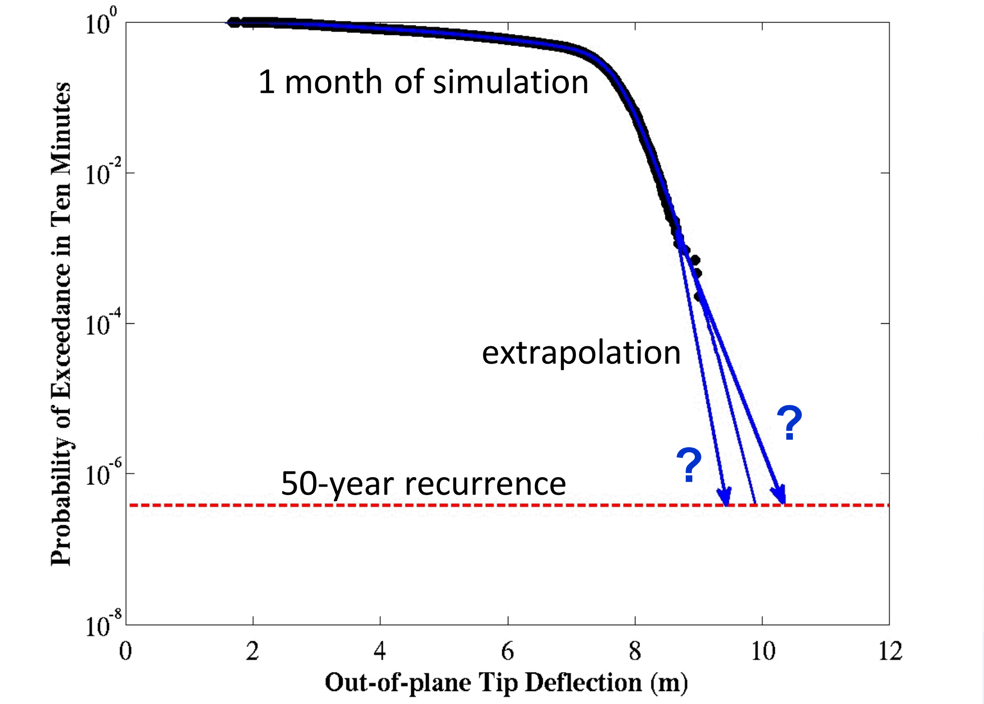
Wind Turbine System Dynamics Model

Dynamics



Output: Power and Loads

Wind Turbine Extreme Load Extrapolation



From: IEC 61400-1 Ed. 3 – Wind Turbine Design Standards

For DLC 1.1 the characteristic value of load shall be determined by a statistical load extrapolation and correspond to an exceedance probability, for the largest value in any 10-min period, of less than or equal to 3.8 x 10-7, (i.e. a 50-year recurrence period) for normal design situations.

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Aero-elastic Load Simulations

DAKOTA

- Simulation framework developed at SNL
- Enables large-scale parameter studies, sensitivity analysis, optimization, and UQ
- dakota.sandia.gov

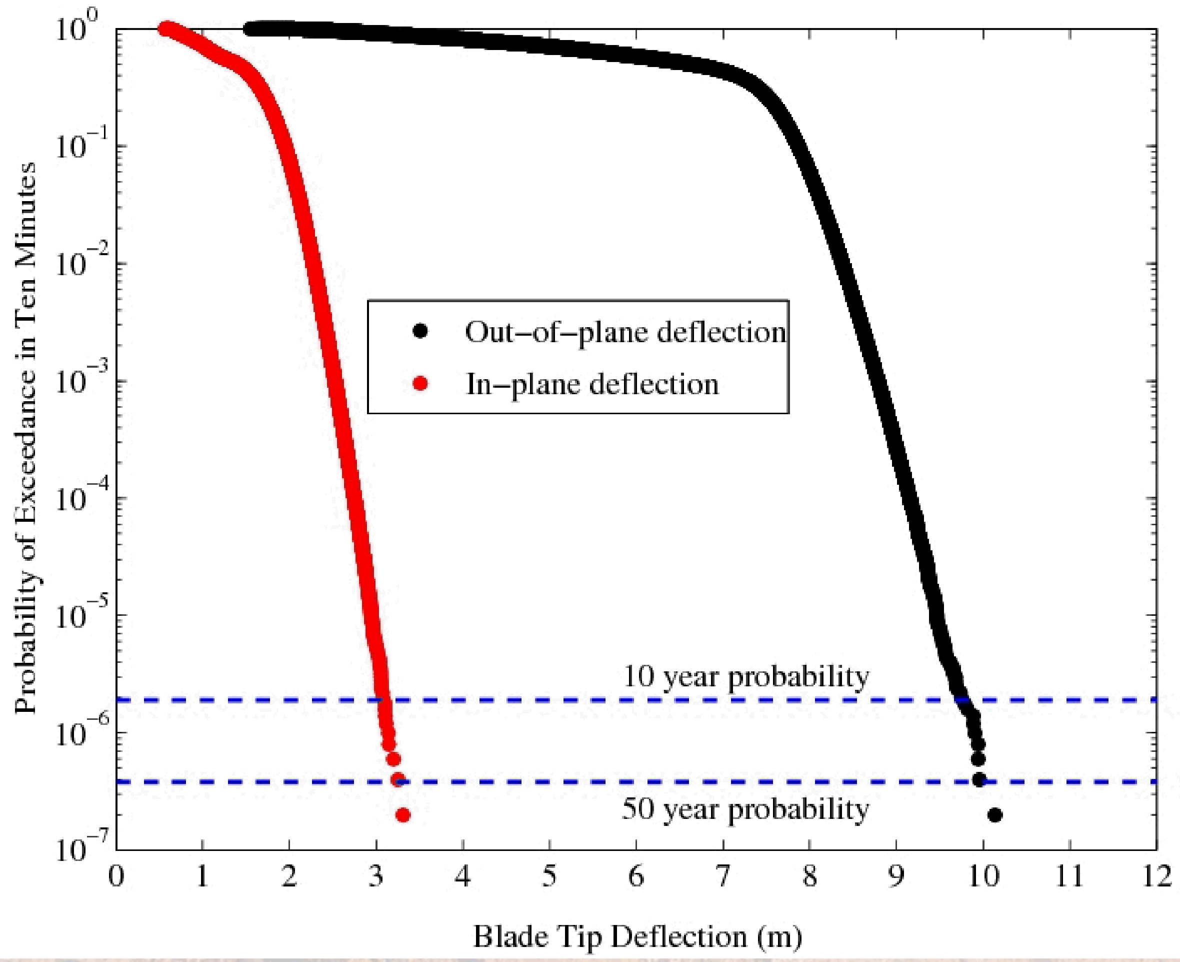
Simulation Procedure

- DAKOTA samples two random wind seeds and mean wind speed for each sim using a Latin Hypercube sampling method
- DAKOTA asynchronously schedules a simulation on each available core
- TurbSim, FAST, Crunch are run in sequence for each simulation
- Random seeds, mean wind speed, and 10-minute extreme values are saved by DAKOTA

Stats

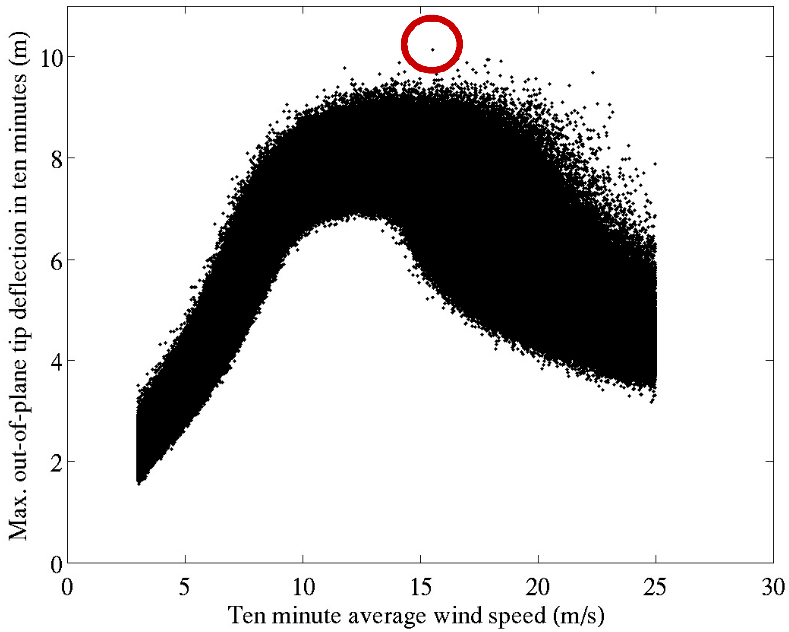
- 5,020,189 simulations performed (~96 years) in six separate batches
- 1028 cores used on Red Sky
- 4.5 days of total wall-clock time

Extreme Tip Deflections

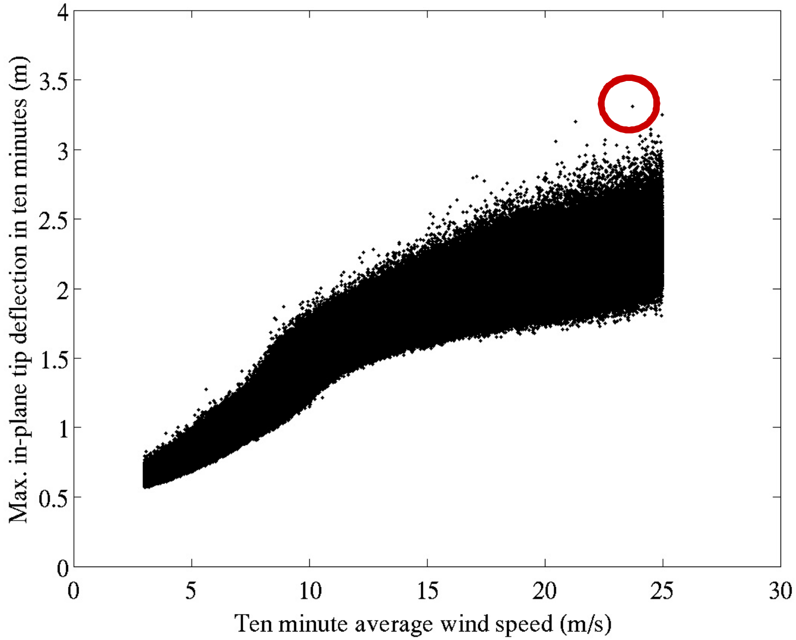


Extreme Tip Deflections vs. Wind Speed

Out-of-Plane

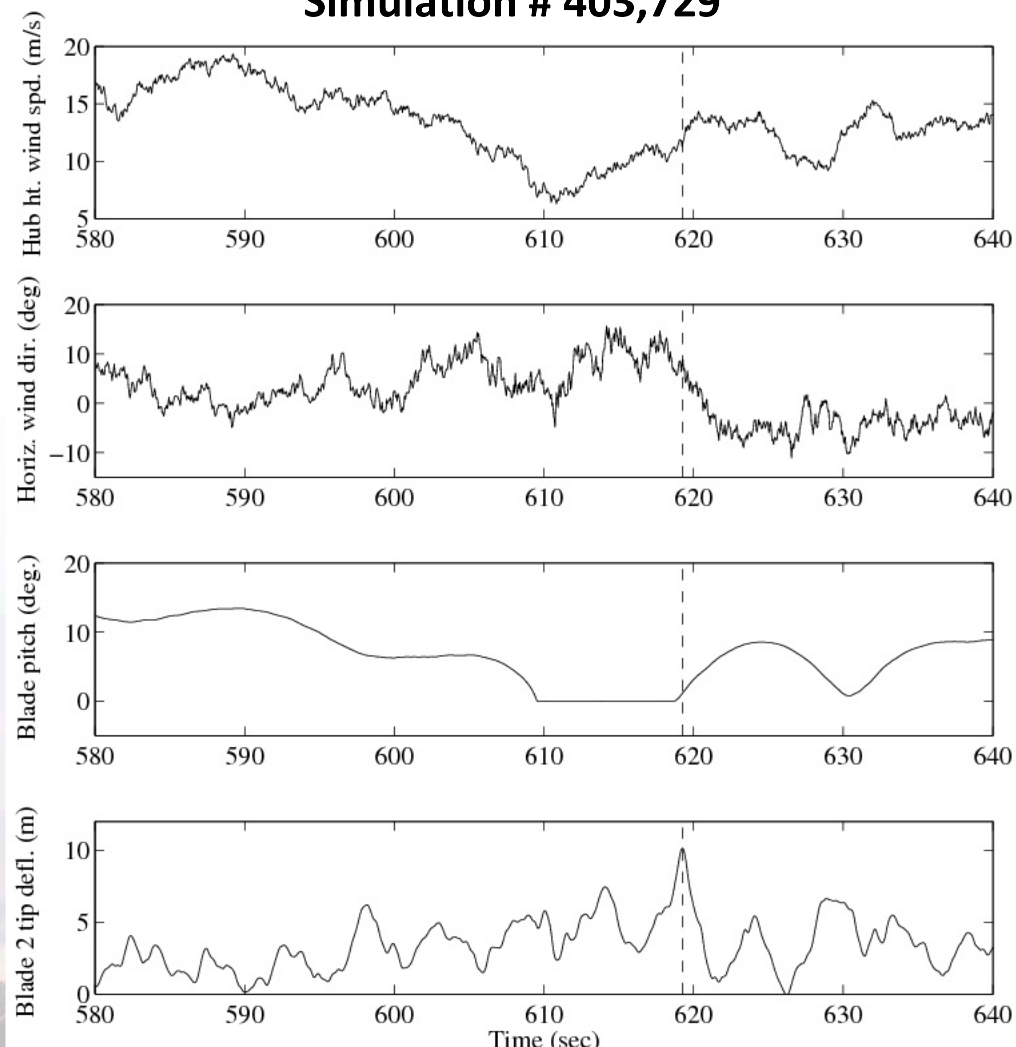


In-Plane



Max. Out-of-Plane Tip Deflection Case

Simulation # 403,729



Wind Speed

Horiz. Wind Direction

Blade Pitch

Blade 2 Tip Deflection

Extreme Design Loads: Remaining Issues

- **Need to treat other input variables non-deterministically**
  - Turbulence intensity
  - Vertical wind shear
  - For offshore, variables defining wave loading
- **Use the large database of loads to verify alternative load extrapolation techniques for design standards**
  - IEC wind turbine design standards committee has been engaged
- **More efficient ways of determining the random wind field that leads to highest load?**

Challenge: Wind Turbine Noise

- **Wind turbine noise provides both a *design constraint* and a *deployment barrier***
  - **Design constraint**: limits rotational speed of the turbine, driving up torque requirements for the gearbox and generator
  - **Deployment barrier**: limits viable sites for turbines near inhabited areas, leads to public perception problems
- **Three elements to wind turbine noise**
  - Noise sources
  - Propagation
  - Perception

Large-Eddy Simulation of Trailing Edge Noise

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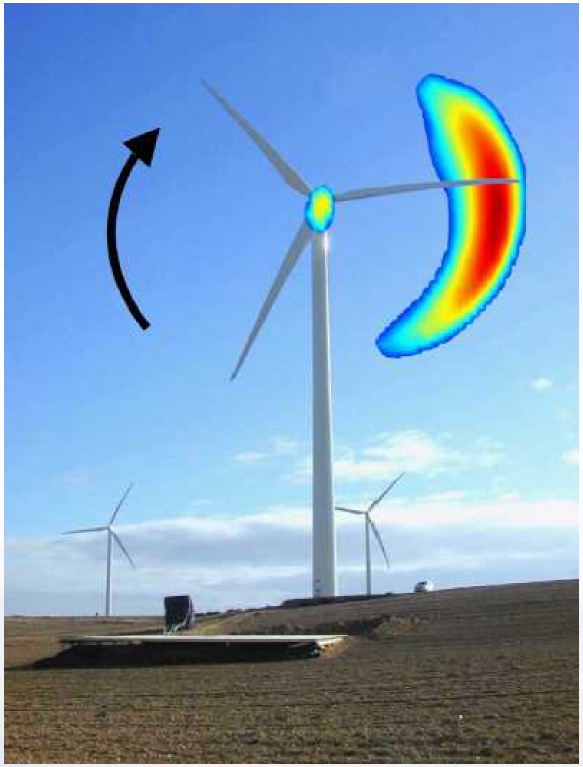
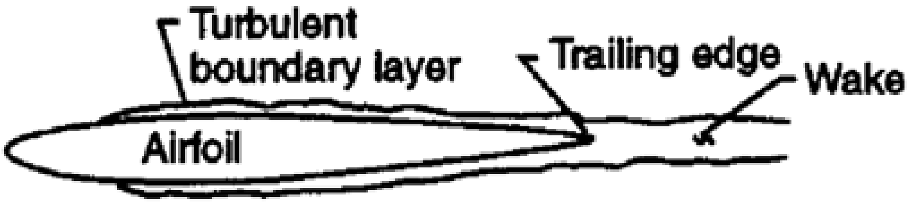
Wind Turbine Blade Trailing Edge Noise



Trailing edge noise is the dominant aeroacoustic noise source on modern utility-scale HAWTs.

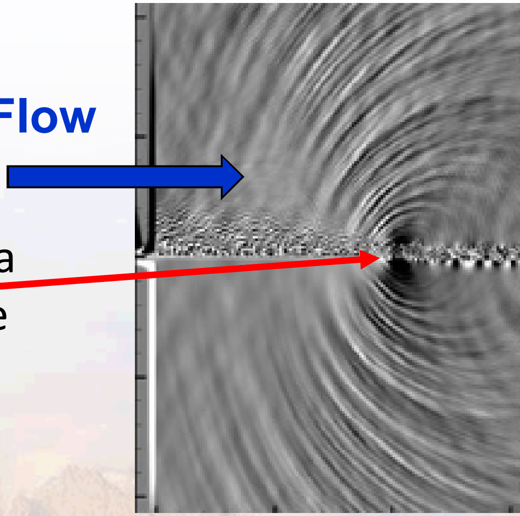
(S. Oerlemans, Ph.D. Thesis, U. of Twente, 2009)



Turbulent boundary layer - trailing edge (TBL-TE) noise

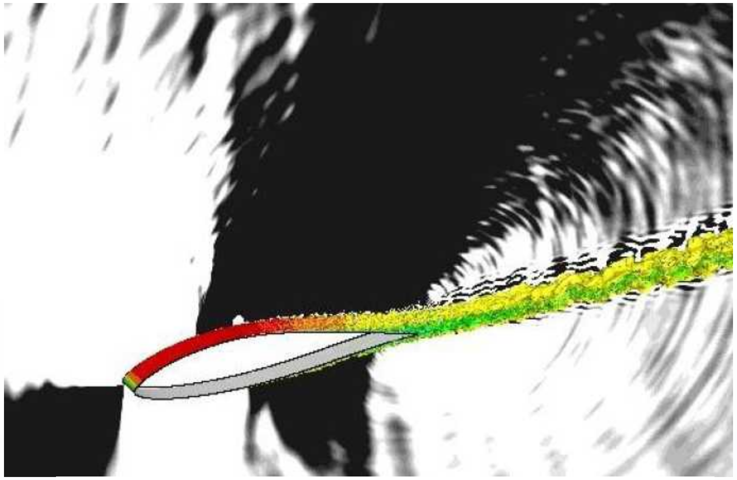
Simulation of a turbulent boundary layer interacting with a sharp edge to produce sound waves.

Sandberg & Sandham, J. Fluid Mech., 2008.

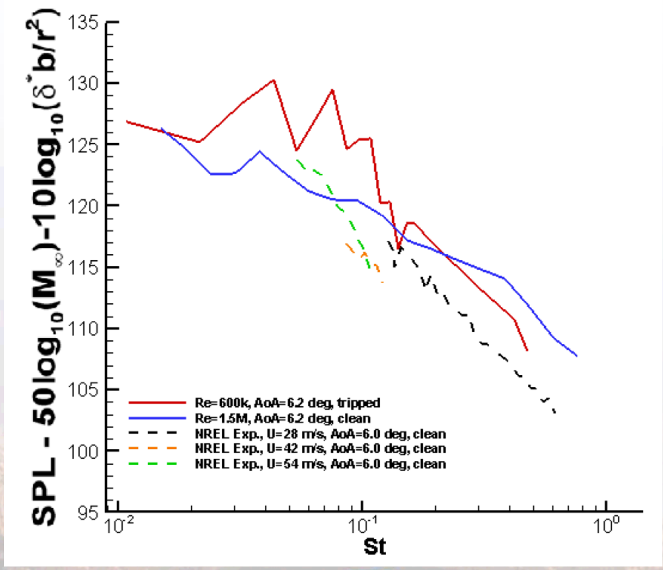


LES of Trailing Edge Noise

From: Wolf *et al*., "Investigation of noise generated by a DU96 airfoil", AIAA 2012-2055, 2012.
Results from Prof. Sanjiva Lele's group at Stanford U., with GE Global Research.



- **Large eddy simulation used to compute the hydrodynamic near field**
- **Two approaches for far-field noise prediction**
  - Compressible flow solver with Ffowcs Williams & Hawkings acoustic analogy (Re=600,000)
  - Incompressible flow solver with Amiet's theory (Re=1.5M)



Trailing Edge Noise Simulation: Remaining Issues

- Suitable wall models to increase computational efficiency of LES
- Modeling Trailing edge flows with complex geometries (serrations, brushes, etc.)
- 3D LES of the tip region, including both trailing edge noise and tip vortex noise

Other Potential Applications of Scientific Computing to Wind Energy

- **Wind farm interference with radar**
  - Major problem! Over 10,000 MW of planned installation delayed or abandoned in 2010 due to radar interference issues
  - Calculation of a single wind turbine radar cross-section is a formidable computational problem
    - Large ratio of turbine scale to radar wavelengths, O(1000)
    - Physical-optics methods are used
    - Results are very sensitive to turbine and blade orientation, details of the blade structure
- **Wind farm noise propagation**
  - Calculation of acoustic propagation through a turbulent atmospheric boundary layer in complex terrain
- **Wind forecasting for managing variability of the wind resource for the electrical grid**

Summary

- **Further advancements in wind energy will require sophisticated models and analysis methods**
- **Scientific computing is playing an increasing role in wind plant design and analysis, in the areas of:**
  - Wind farm aerodynamics, turbine-turbine interactions
  - Wind turbine design
  - Wind turbine and wind farm noise prediction
  - Wind/radar interference
  - Meteorological wind forecasting

Questions?