Wind Turbine Rotor Design and Analysis Tools

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SMART Wind Composite Meeting – Blade Design

28 October 2015

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Overview

- Importance of rotor design tools with an emphasis on aero-/fluid-dynamics.
- Tools:
  - 2D Airfoil Analysis Tools
  - 3D Blade/Rotor Analysis Tools

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Key Issues - I

- Rotor design space is constrained by tools used in design and analysis of airfoil section shapes, blades, and rotors. These tools may limit innovation.
- Innovation is key to long-term success of wind energy:
  - "Incrementalism is innovation's worst enemy! We don't want continuous improvement, we want radical change." Sam Walton, Walmart founder
  - "Innovation is the only answer, there's no easy way around." Jim McNerney, Boeing's former CEO

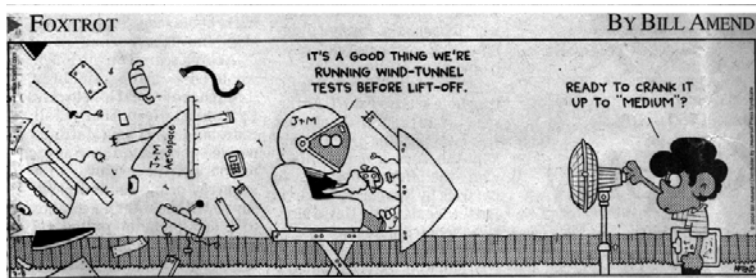
Key Issues - II

Tools must be able to capture or model:

- Airfoil/blade boundary layer transition
- Airfoil/blade surface roughness
- Airfoil/blade flow separation
- Airfoil/blade flow unsteadiness
- Airfoil/blade flow modifiers (VGs, stall strips, trailing edge tabs, etc)
- Inflow disturbances (turbulence)

Key Issues - III

- Depending on size, difficult to impossible to test wind turbine blade/rotor in wind tunnel at conditions approaching/ matching full scale.
- As a result, we are often faced with jump from computational design and analysis to full-scale field testing without intermediate step. Field-based trial & error testing can be frustrating and costly



The Davis Enterprise, July 8, 2004

Computational Aero-/Fluid-Dynamic Tools

- 2D Airfoil Analysis Tools
  - XFOIL
  - MSES
  - OVERFLOW – 2D
- 3D Blade/Rotor Analysis Tools
  - WT_Perf
  - FAST
  - OVERFLOW – 3D
  - SOWFA

XFOIL

- Airfoil aerodynamic analysis code developed by Mark Drela
  - Lift and drag prediction up to stall
  - Automated drag polar computation
  - Airfoil blending capability
  - Interactive airfoil re-design from user input
- Coupled viscous/inviscid interaction
  - Inviscid linear-vorticity stream function panel method
  - Integral boundary layer formulation with e^N transition criterion
- Specify fixed or free transition
- Minimal computational overhead
- Plus:
  - Well validated. Zero cost
- Minus:
  - Steady flow solver. Single element airfoils only

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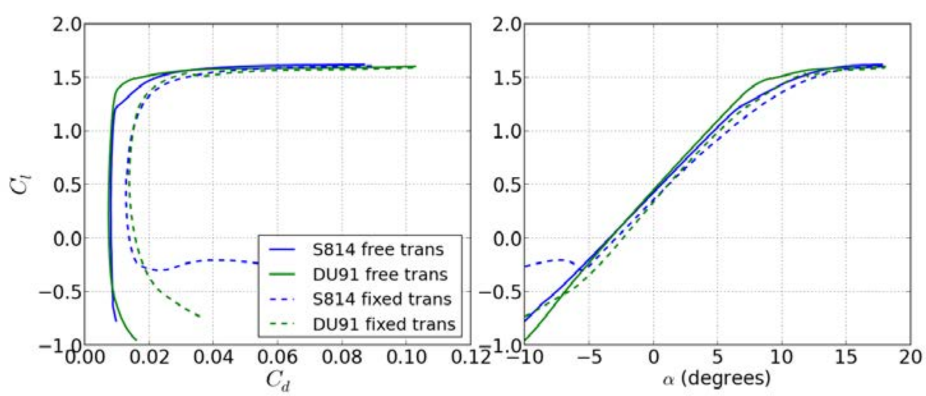
XFOIL- Free vs Fixed Transition

- Lift and drag prediction using e^N criteria (free) and fixed transition location



Comparison of lift and drag prediction using fixed and free transition criteria in XFOIL, S814 and DU91-W2-250 airfoils, $Re_c = 2.4 \times 10^6$

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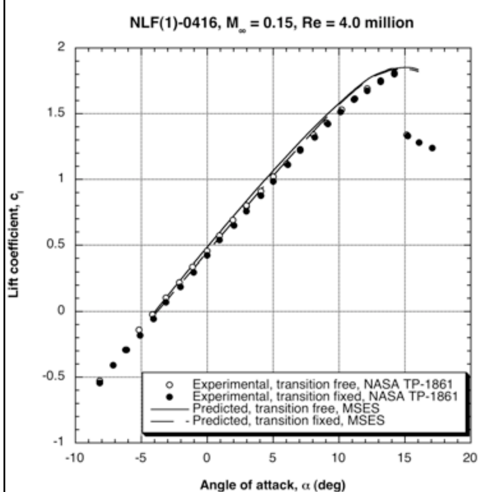
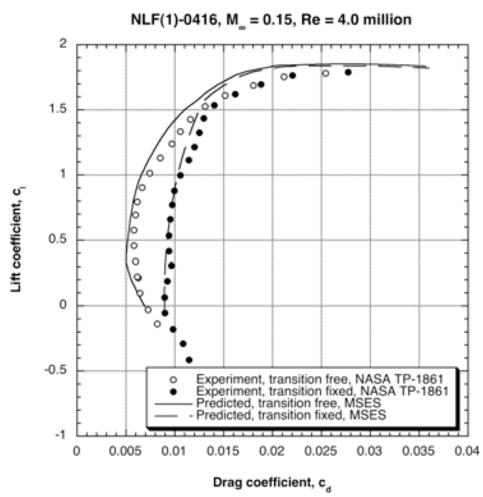
MSES

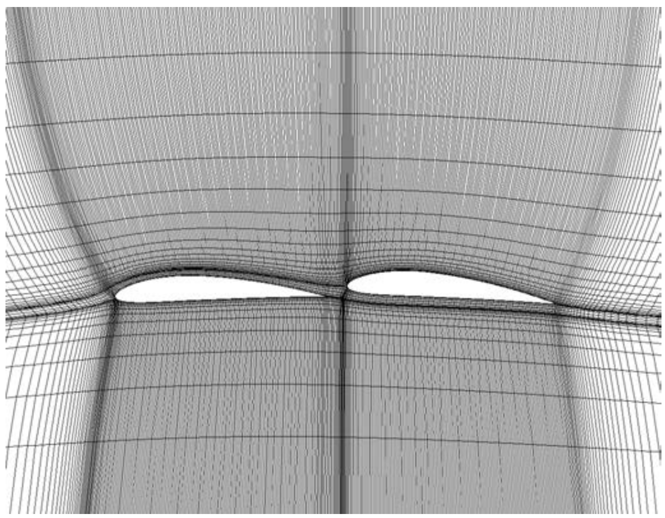
- Multi-element airfoil aerodynamic analysis code developed by Mark Drela
- Coupled viscous-inviscid method
  - Euler equations, full potential flow, or hybrid of both
    - Inviscid, compressible
  - Integral boundary layer equations
  - Transition model - e^n. Manual trip specification available
- Multiple options for far field boundary conditions
  - Infinite, solid wall
- Plus:
  - Well validated. Multi-element airfoil capability. But no confluent boundary layer model. Zero cost for academic use.
- Minus:
  - Steady flow solver. Costly for non-academic use. Solution process often not very robust.

MSES





MSES Multi-Element Airfoil Analysis



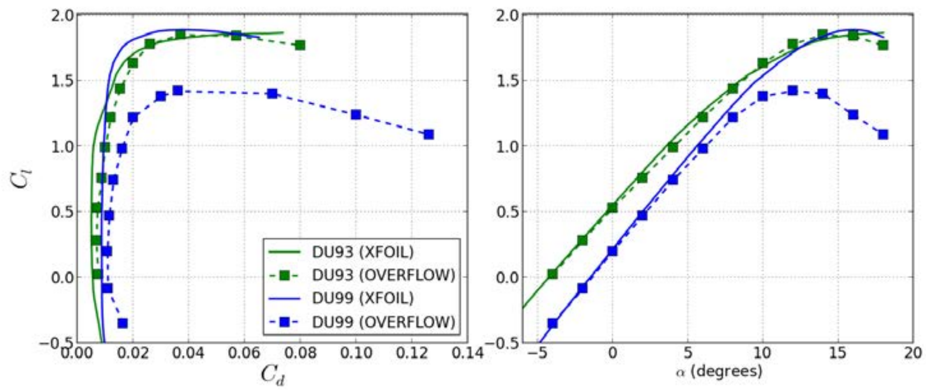
OVERFLOW2 – 2-D CFD

- Airfoils from NREL 5-MW turbine analyzed using OVERFLOW 2.2e
  - Spatially discretized using 6th order Euler central differencing
  - Beam-Warming pentadiagonal scheme
  - Matrix Dissipation
  - Langtry-Menter γ-$Re_{\theta t}$ transition model with Menter's SST k-ω turbulence model
- DU-93-W-210
  - $Re_c = 8.14 \times 10^6$
  - 21% thick

- DU-99-W-350
  - $Re_c = 5.23 \times 10^6$
  - 35% thick

NREL Airfoil Prediction

- Lift and drag prediction from OVERFLOW-2, comparison to XFOIL results shown



DU93-W-210 (Re_c = 8.14 x 10^6) and DU99-W-350 (Re_c = 5.23 x 10^6) airfoils, free transition set in XFOIL

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WT_Perf

- NWTC Design Code (no longer officially supported)
  - Developed by Marshall L. Buhl Jr. at NREL
  - Derived from the PROP code (Oregon State)
- Blade element and momentum theory (BEM) code
  - Iterates on axial and tangential induction factors
  - Assumes ideal 2-D flow with no spanwise interaction
  - Steady-state
- Horizontal axis wind turbines (HAWT) performance analysis
  - Basic and fast geometry descriptions
    - Number of blades, radius, hub size, coning, yaw, tilt
    - SI or English units
  - Hub and Prandtl-tip loss models
  - 2-D airfoil performance tables are required
  - Fast parametric sweeps on blade pitch, wind speed/TSR, and rotor RPM
  - Outputs rotor power, torque, thrust, C_p, root flap-bending moment

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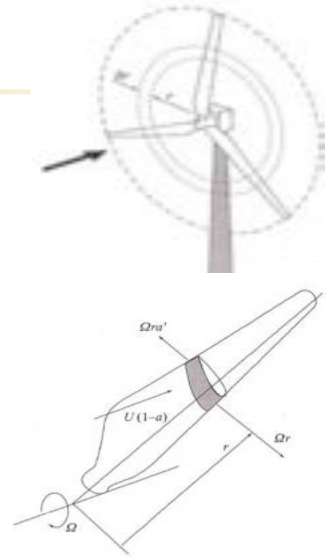
FAST

- NREL's primary computer aided engineering tool for simulating the coupled dynamic response of wind turbines.
  - Simulates one turbine at a time.
  - Simulates only horizontal axis turbines.
- Well established in the wind power community.
- Independently evaluated and certified. Low computational cost:
  - A 10 minute long FAST simulation can be run in ~3 minutes on a single processor.

https://nwtc.nrel.gov/FAST
https://nwtc.nrel.gov/SimulatorCertification



Burton et al, *Wind Energy Handbook*, 2nd ed., Wiley, 2011

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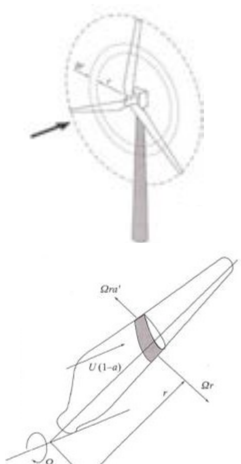
FAST



Burton et al, *Wind Energy Handbook*, 2nd ed., Wiley, 2011

- Structural dynamics are modeled as a combination of modal dynamics and multi-body dynamics.
  - Multi-body dynamics are calculated using Kane's method.
- Aerodynamic loading is modeled using blade element-momentum theory.
- Can interface with TurbSim for statistically accurate, stochastic, full-field turbulent wind inflow.
- Can interface with turbine controllers modeled in Simulink.

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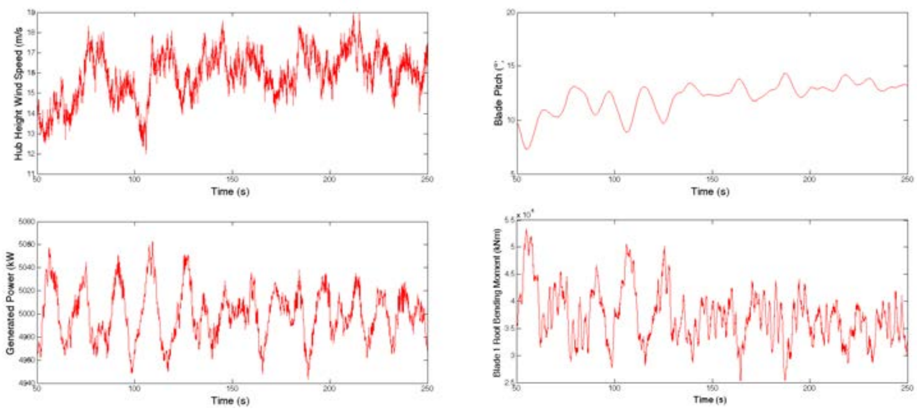
Example: NREL 5-MW turbine in turbulent wind



- FAST can output time series data for 286 Simulation parameters, including the four shown here.

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OVERFLOW2 - 3-D CFD

- Developed and maintained by Pieter Buning at NASA Langley
- 3-D Unsteady Reynolds-averaged Navier-Stokes (URANS)
  - Numerical schemes
    - High order schemes (up to 6^{th})
    - Central, Roe upwind, TVD, HLLC, HLLE
    - Full multigrid, WENO, MUSCL
  - Time advancement schemes
    - Explicit, Newton sub-iterations, dual-time stepping
  - Turbulence models
    - Spalart-Allmaras, Menter's *k-ω* SST, SA-DES, wall functions
    - γ-$Re_{\theta t}$-SA, Langtry-Menter transition models
- Rotor Dynamics
  - Prescribed or 6-DOF solid body dynamics
  - Rotational source term to model rotation
- Chimera/overset grid topology

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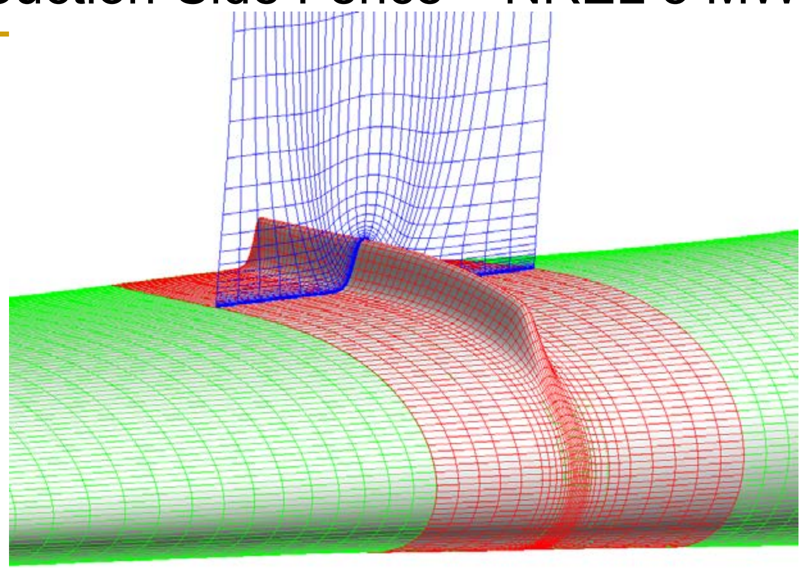
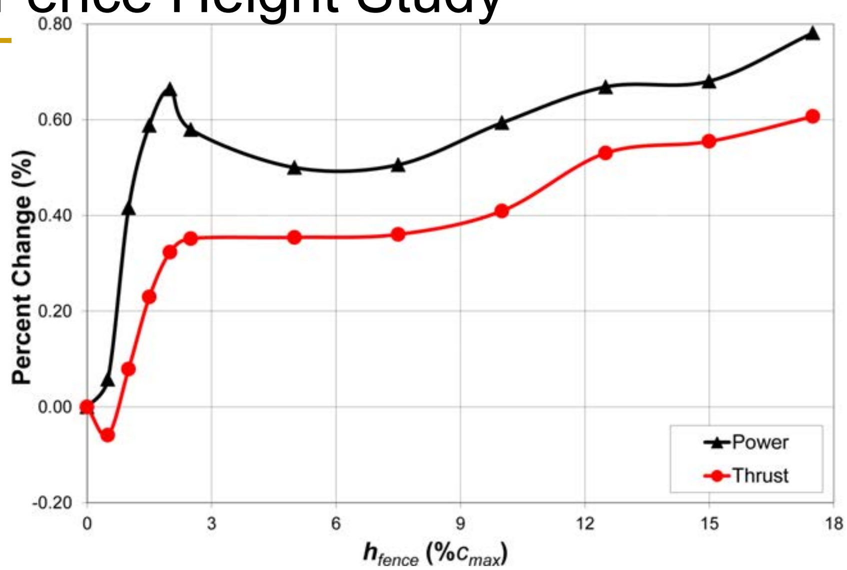
Suction-Side Fence – NREL 5 MW

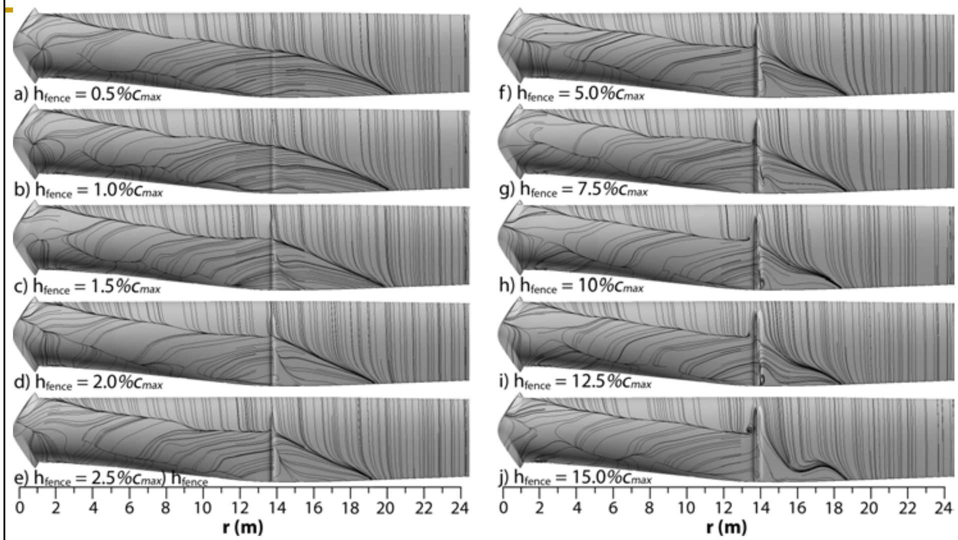


Fence Height Study



Constant spanwise location: $r_{fence} = r(c_{max}) = 13.7m$

Fence Height Study



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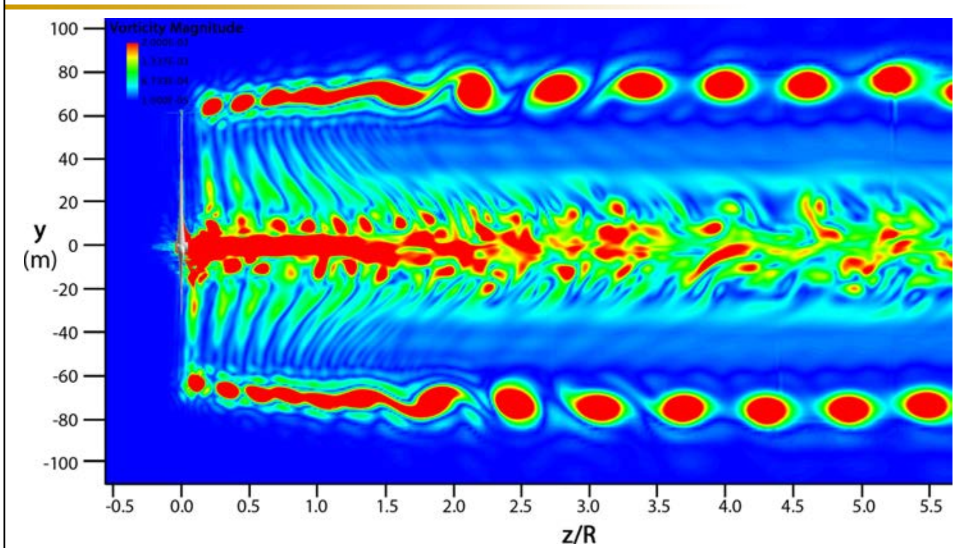
Constant spanwise location: $r_{fence} = r(c_{max}) = 13.7$m

NREL 5-MW Rotor – U_∞=11 m/s



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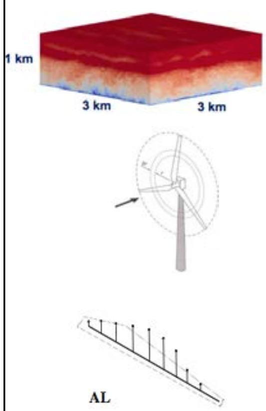
Vorticity contours over a coordinate plane slice

SOWFA

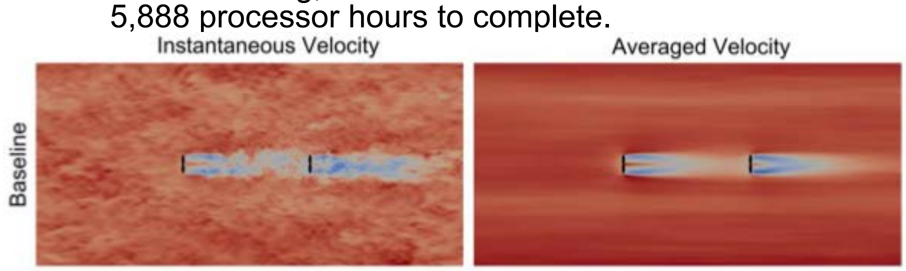


- NREL's Simulator for Wind Farm Applications is a windplant simulation tool.
- The flow field is modeled using a Large Eddy Simulation (LES) methodology based on the OpenFOAM CFD toolbox.
- Structural dynamics and aerodynamics of each turbine are modeled by a modified version of FAST.
  - Due to high Reynolds number flow, it would be impractical to model the turbine aerodynamics using LES.
- LES flow field model is coupled to FAST turbine model using an actuator line model.

Churchfield et al, 2012

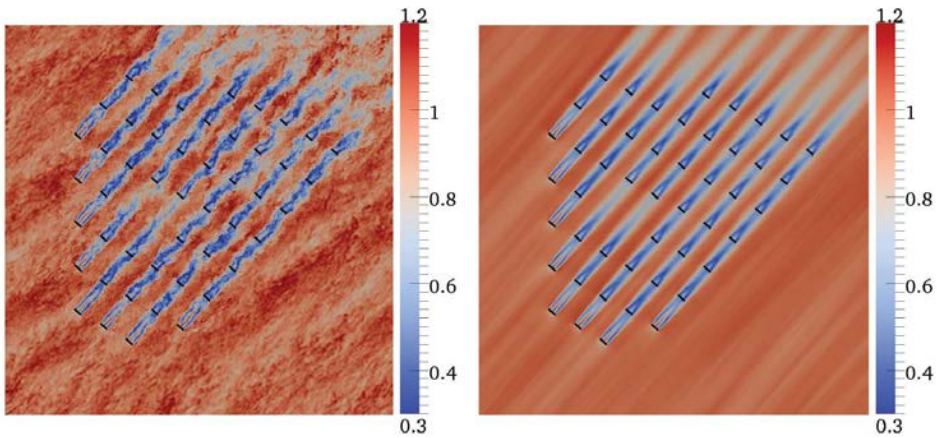
SOWFA

- Can model several turbines and their interactions.
  - Turbine to turbine wake interactions.
  - Plant level control systems.
  - Wind events propagating through the wind farm.
- Computationally expensive.
  - The 100s long, 2 turbine simulation shown below took 5,888 processor hours to complete.



Fleming et al., 2013

Example: 48 turbine simulation of the Lillgrund offshore wind farm



Churchfield et al, Journal of Turbulence, 2012

Conclusions

- As we explore the design and installation of turbines with more advanced rotor configurations and/or turbines in more complex environments, higher-order computational methodologies must be considered.
  - On the plus side, these design and analysis methods allow for simulation of more complex rotor configurations in more complex environments
  - On the minus side, these methods require significantly more computational resources and more setup and solution time.