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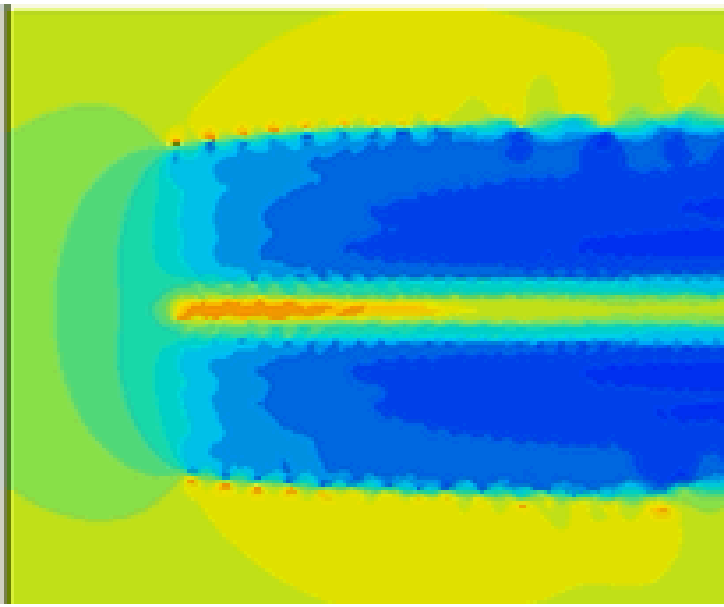

Wakes and Rotors: The National Rotor Testbed

David Maniaci

8/27/2014

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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Vision—SWiFT Experiment I: Inflow & Near-Wake Characterization

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- The Atmosphere to electrons (A2e) initiative has identified the evolution of wakes in turbulent inflow as the key physical process affecting the power production and turbine loads in multi-array wind plants.
- High-quality experimental data is necessary to *understand* the physical processes governing the generation and evolution of wakes and to *validate* high-fidelity computational models using a formal and systematic Verification and Validation (V&V) approach.

SWiFT Experiment Planning

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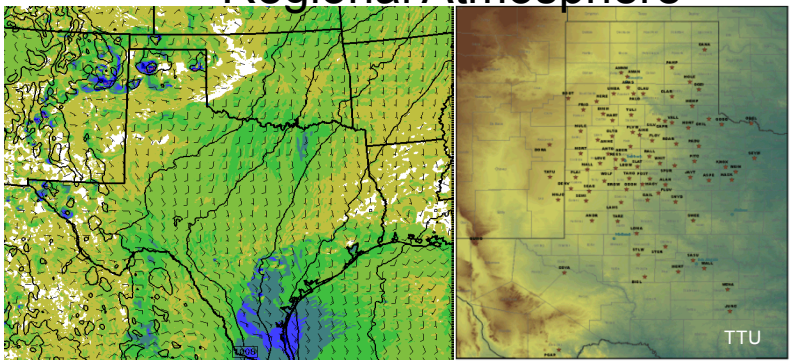
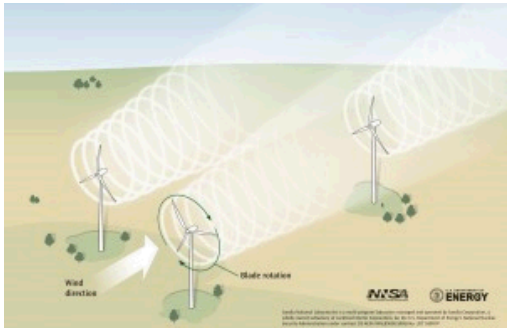
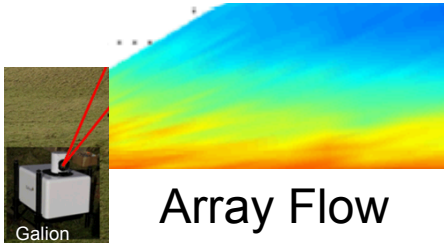
Regional Atmosphere



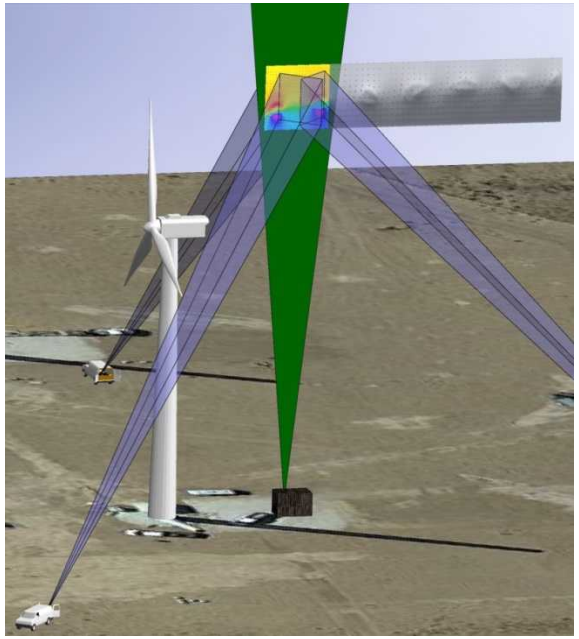
Atmospheric Boundary Layer



Wind Farm Flow



Array Flow



Wake Flow Structures

Why look at wakes?

Tech. Sergeant Russell E. Cooley IV - U.S. Air Force

Why look at wakes?

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Outdoor

Wind Tunnel

NREL Unsteady Aero Experiment

Why look at wakes?

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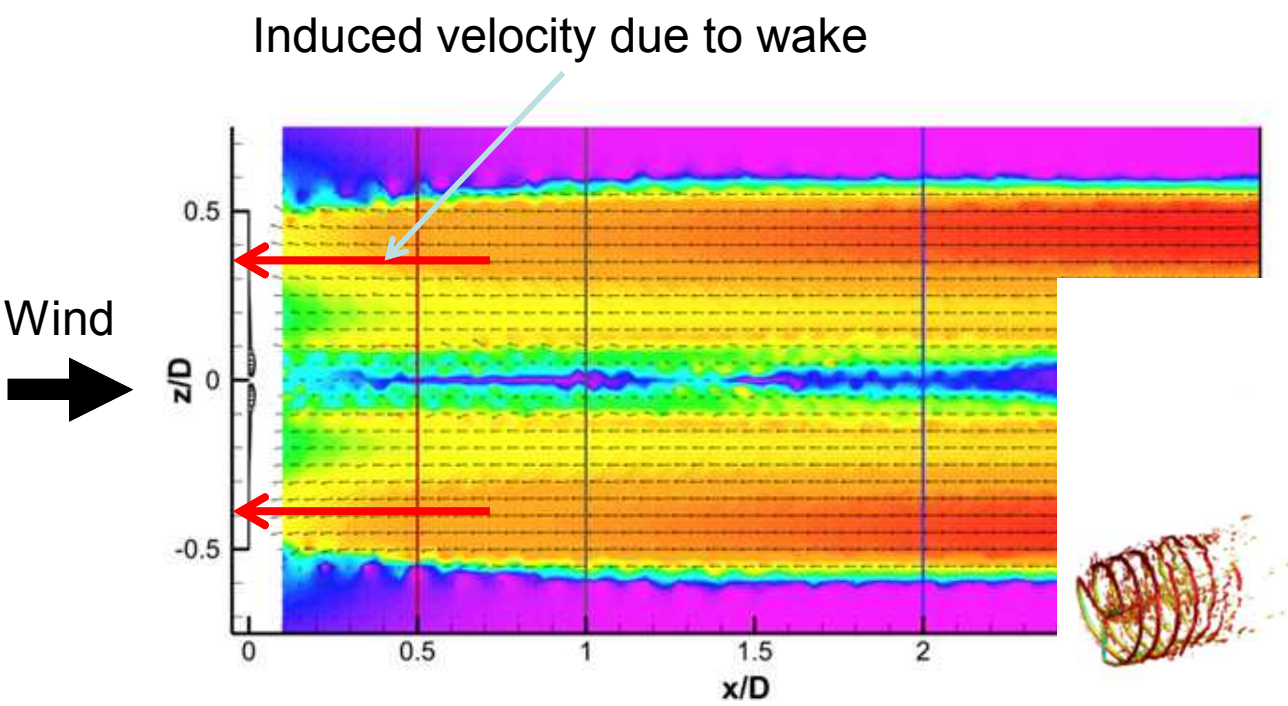
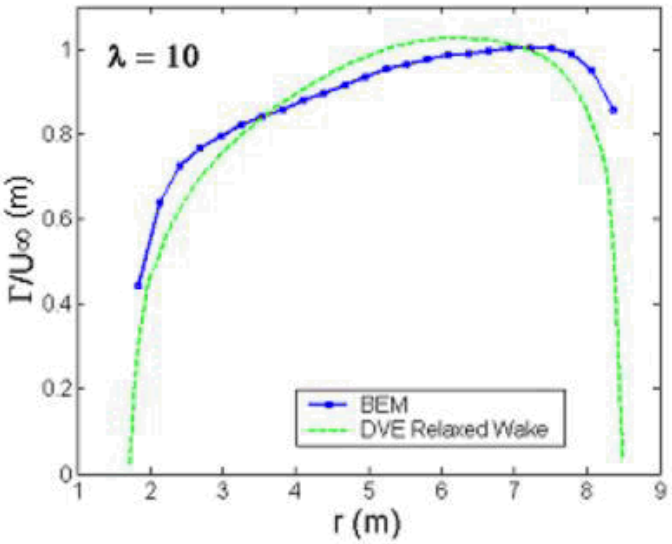
Why look at wakes?

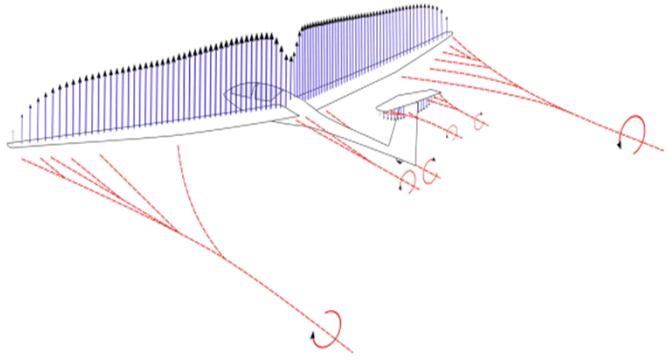
- The power a wind turbine and wind farm are able to extract from the wind is directly proportional to wake strength, evolution, and energy recovery
- The strength of the wake depends on the amount of power exchanged with the wind

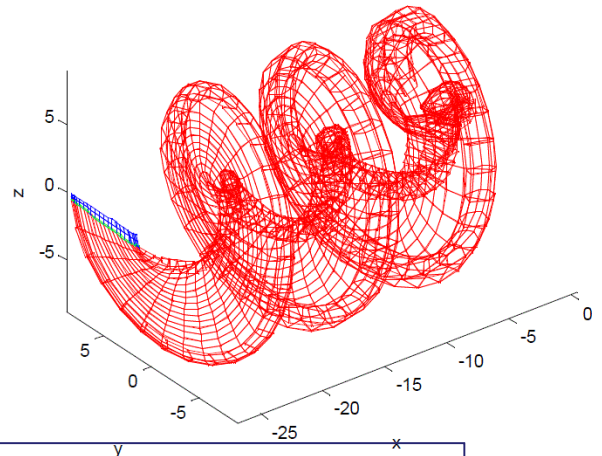


Circulation and Wake Formation

- The shape of the circulation distribution along the rotor span is a driver for near- and mid-wake character

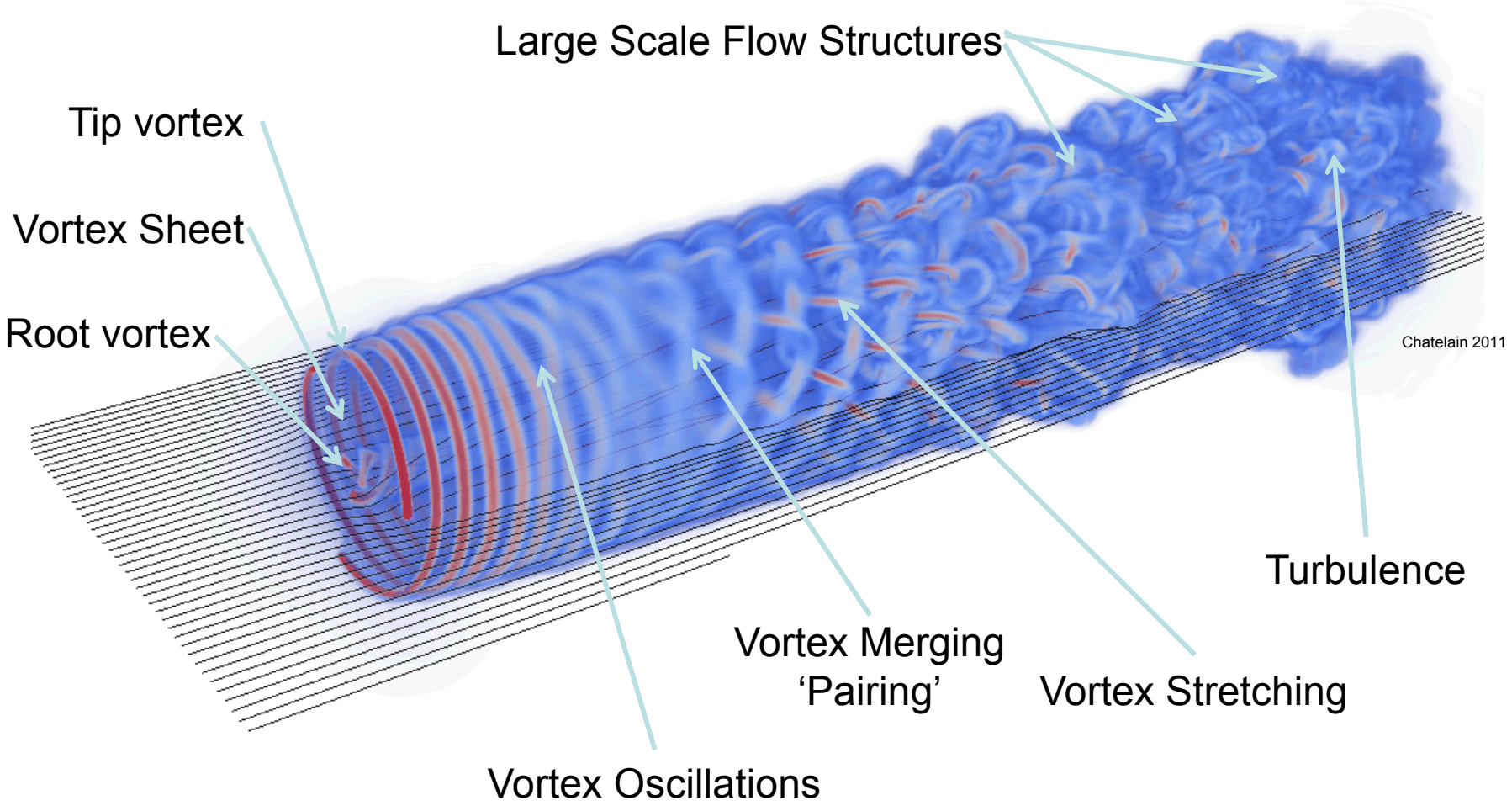




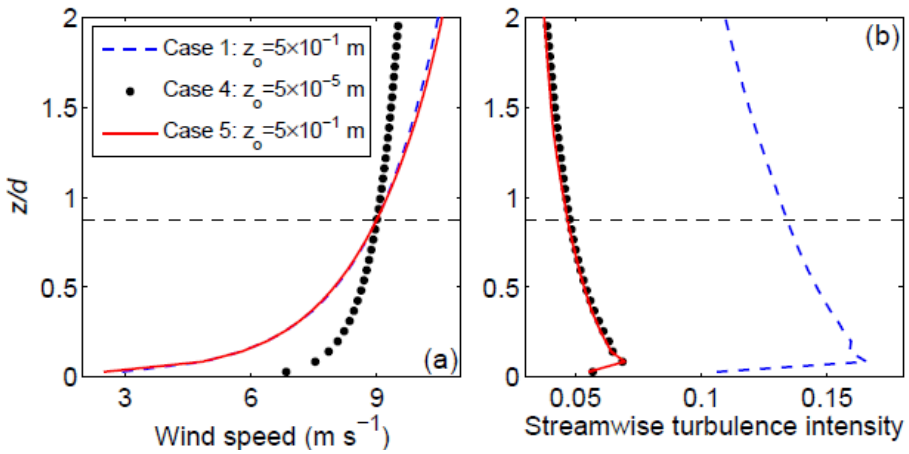


Circulation varies along span → Wake is shed in proportion to change In circulation → Wake vorticity causes change in velocity at the lifting surface

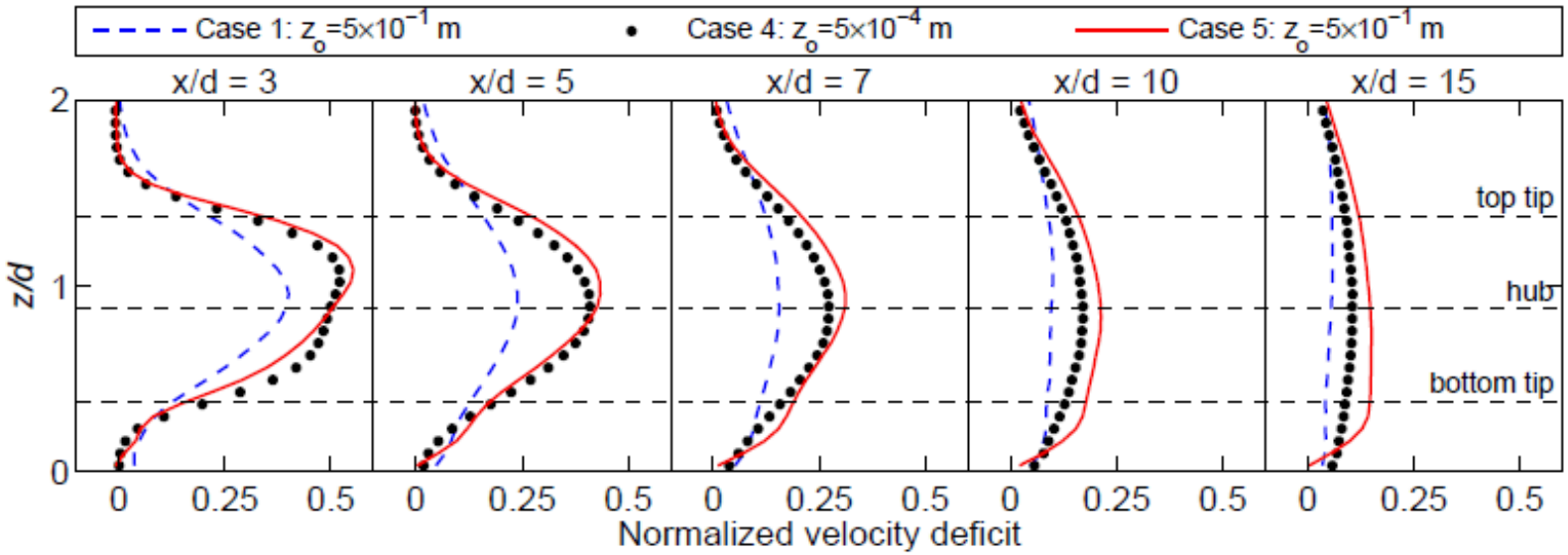
Wake Structure



Atmospheric Effects on Wake

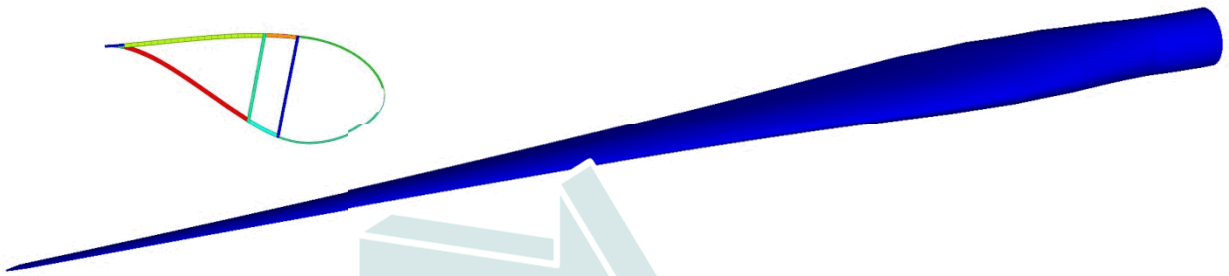


- Inflow characteristics are directly related to wake development
- Stability, shear, veer, turbulence intensity



Atmospheric Turbulence Effects on Wind-Turbine Wakes: An LES Study; Wu, Yu-Ting, 2012

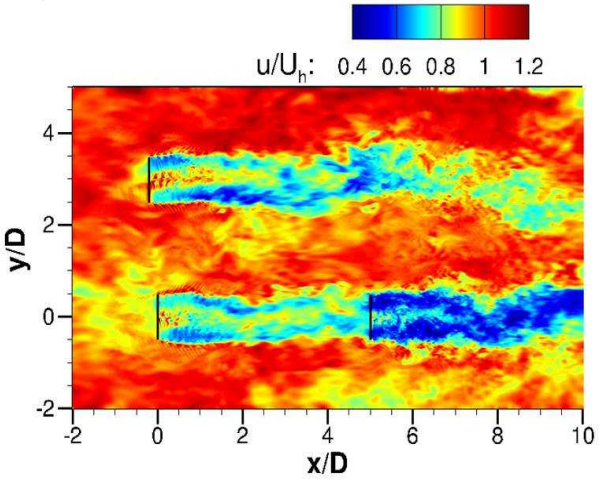
National Rotor Testbed: Vision



Aero-structural rotor design

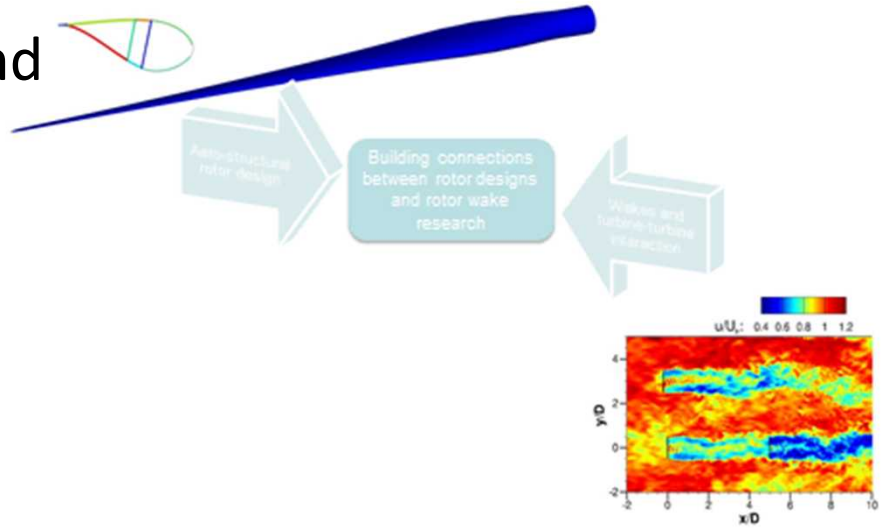
Building connections between rotor designs and rotor wake research

Wakes and turbine-turbine interaction



High Level Rotor Design Goals

- Retrofit to the existing SWiFT turbines
  - Loads and rotational speed constraints
- Replicate rotor loads and wake formation of a utility scale turbine to support turbine-turbine interaction research at SWiFT;
  - Produce wakes of similar geometry, velocity deficit and turbulence intensity.



NRT Wake Research

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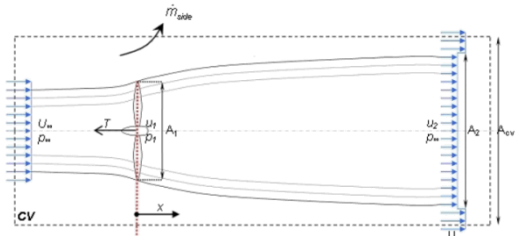
- Predict the wake behavior of the NRT rotor relative to a full-scale machine using models of multiple fidelities
- Determine if rotor loading effects wake development
- Determine sensitivity of wake development to rotor loading
- Support planning by identifying the most valuable experiments for validation
  - Show the limits (and strengths) of the available analysis methods

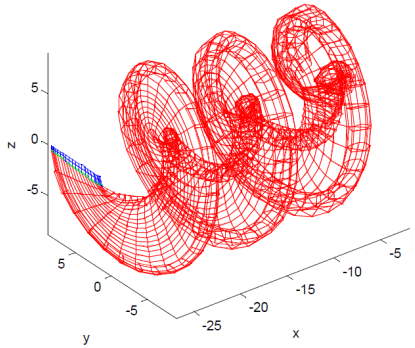
NRT Wake Research

- Predict the wake behavior of the NRT rotor relative to a full-scale machine using models of multiple fidelities
  - BEMT (Blade Element Momentum Theory): initial blade design and loads calculation
  - FWVM (Free Wake Vortex Method): Analysis of near- and mid-wake regions
  - AL-LES (Actuator Line Large Eddy Simulation): detailed wake simulation and calibration of other models

BEMT



FWVM



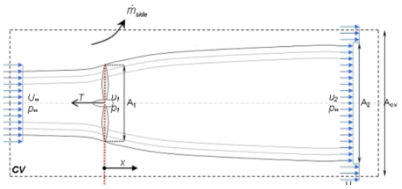
AL-LES

UMN
VWiS

Comparison of BEMT and FWVM

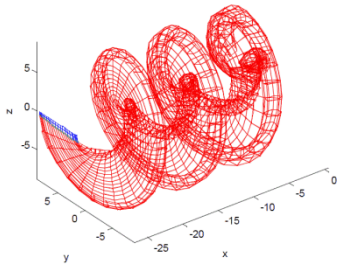
BEMT and FWVM predict similar values at certain TSR (λ)

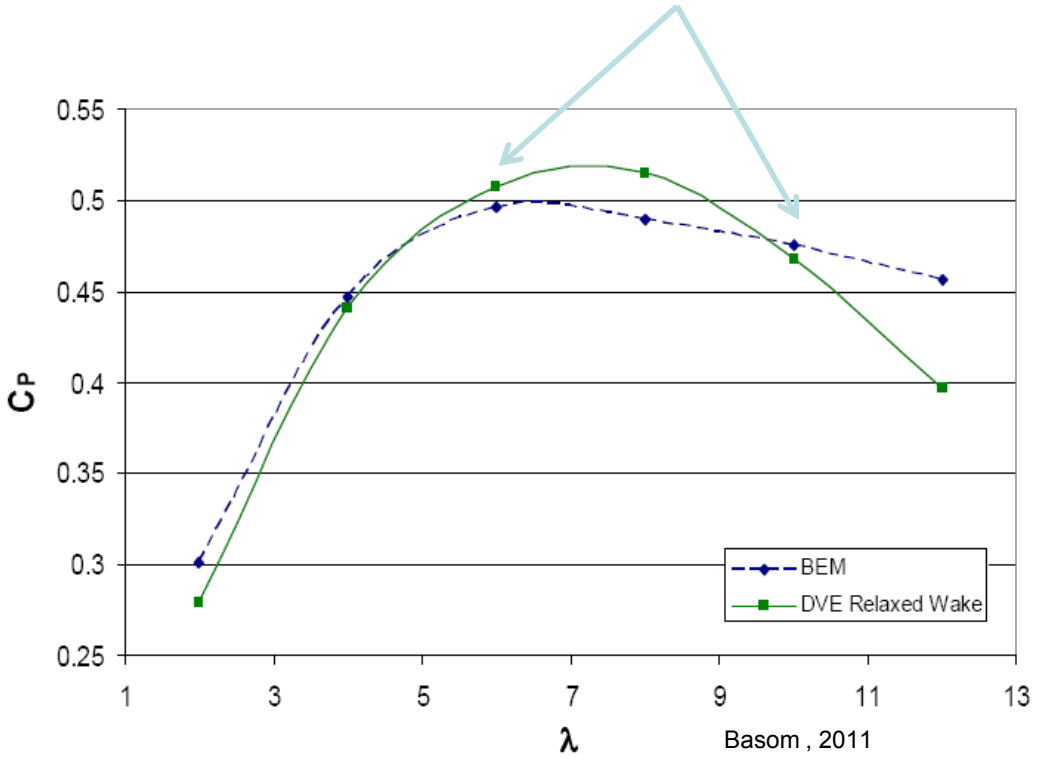
BEMT



U Strathclyde

FWVM



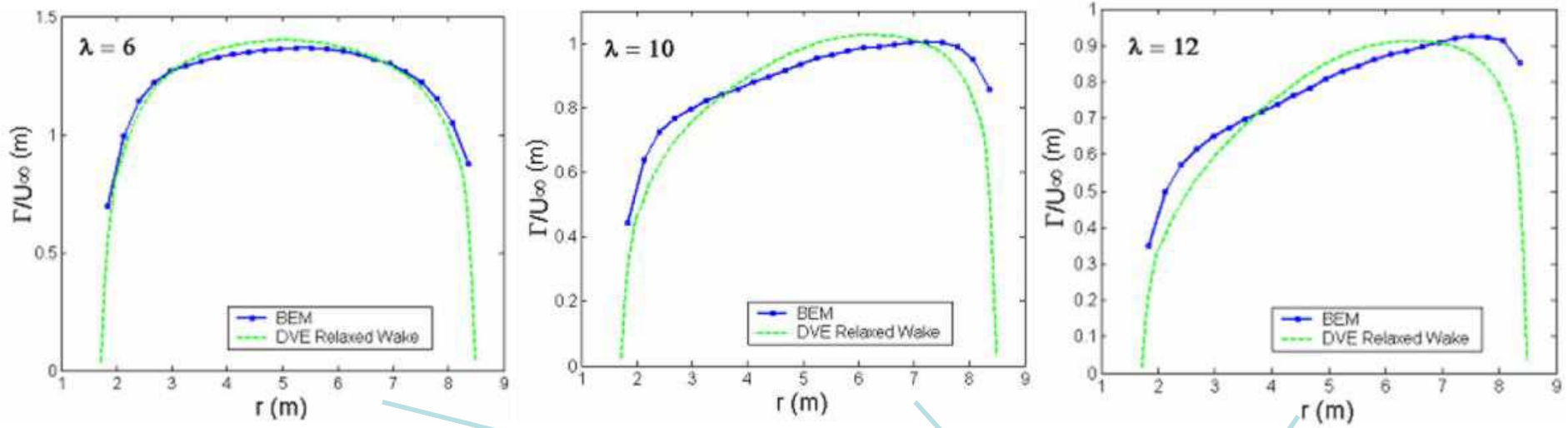


Basom , 2011

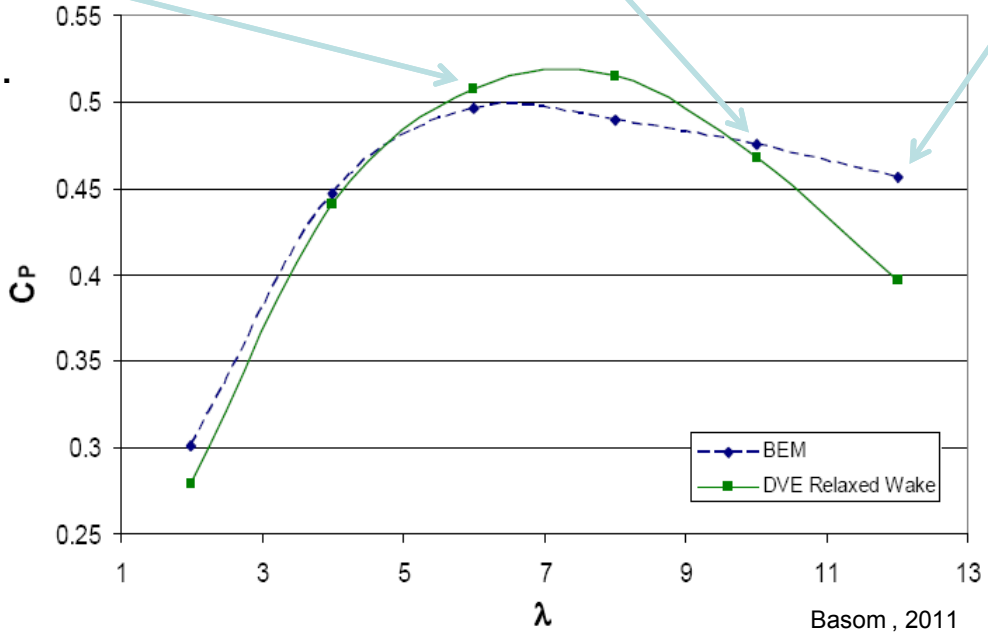
Comparison of power coefficient vs. tip-speed ratio predicted by a BEMT analysis and a fully relaxed-wake vortex method analysis.

Rotor designed for λ = 6.

Comparison of BEMT and FWVM



Rotor designed for λ = 6.

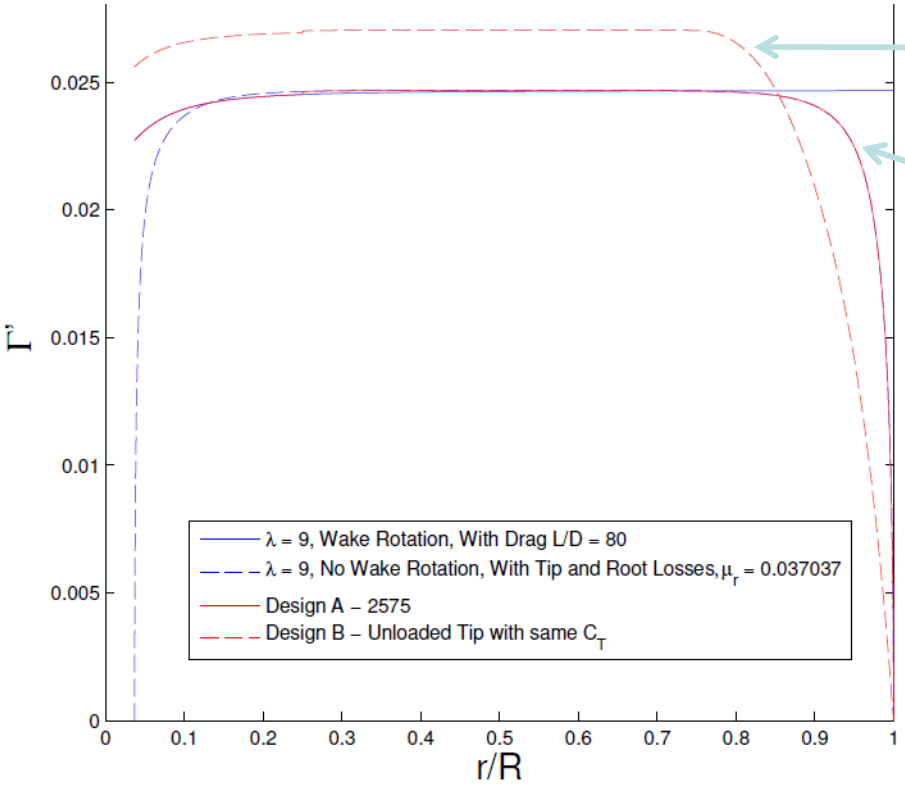


Basom , 2011

NRT Wake Research

- Determine if rotor loading effects wake development
  - Design two blades with the same total thrust and different load distributions and show the effect on wake development
  - Rotors designed with BEMT and analyzed with FWVM and AL-LES

Non-dimensional Circulation Distribution



Design B

Design A

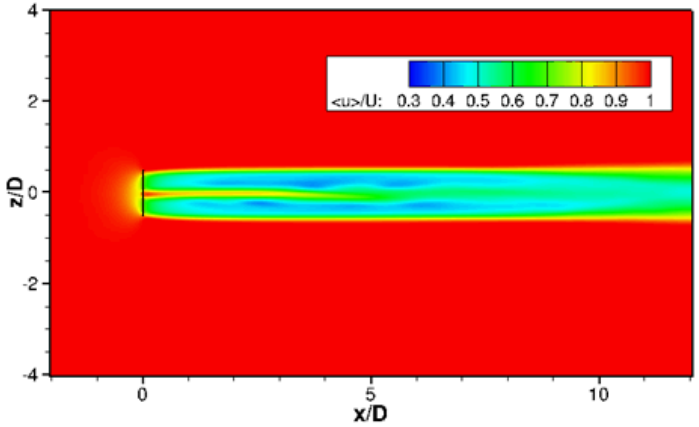
Paper by Chris Kelley to be presented at AIAA/ASME Wind Symposium 2015

NRT Wake Research

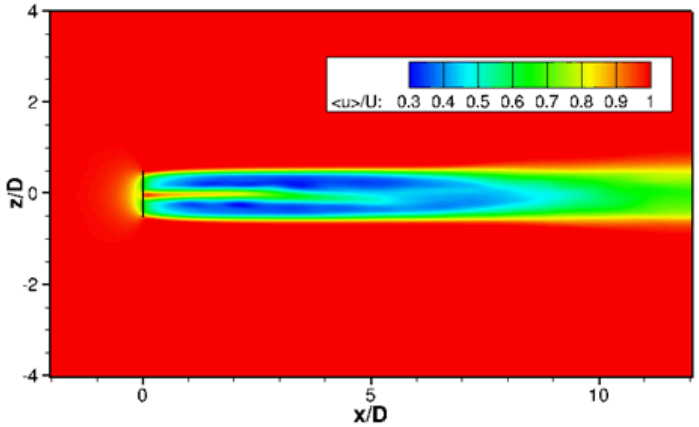
Sandia National Laboratories

AL-LES

Design A

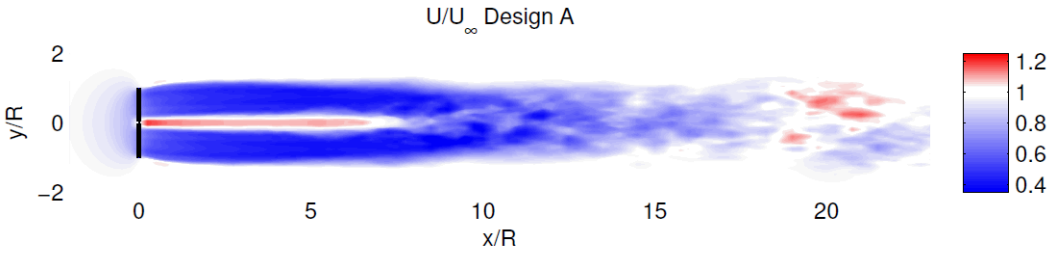


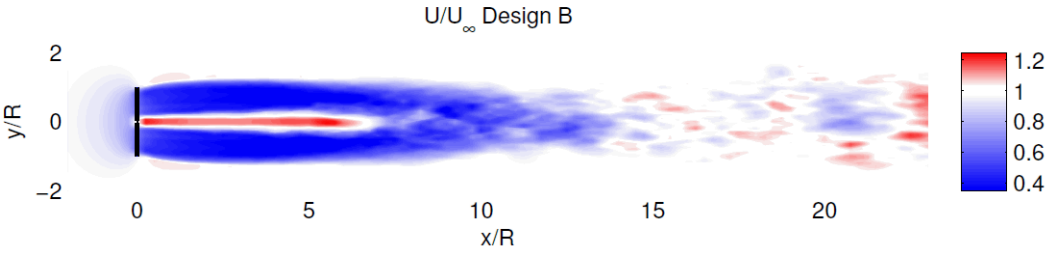
Design B



(a) <u>

FWVM





Where to go from here

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- Analyze effect of shear and atmospheric turbulence on the relative wake development of the NRT and full-scale rotors
  - Focus on LES analysis
- Determine sensitivity of wake development to rotor loading
  - Link FWVM to DAKOTA and utilize HPC resources to perform many simulations
  - No experimental data exists to validate the effect of rotor loading on wake development
- Support planning of experiments by showing the limits (and strengths) of the available analysis methods

Acknowledgements

- Fellow Sandians involved in research: Matt Barone, Jon Berg, Phillip Chiu, Brandon Ennis, Tommy Herges, Chris Kelley, Brian Resor
- Researchers at UMN: Xiaolei Yang, Aaron Boomsma, and Fotis Sotiropoulos
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Thank You

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Wake effect from wind turbine Picture © Riso National Laboratory, Denmark

Back-Up Slides

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Wake character from vortex method

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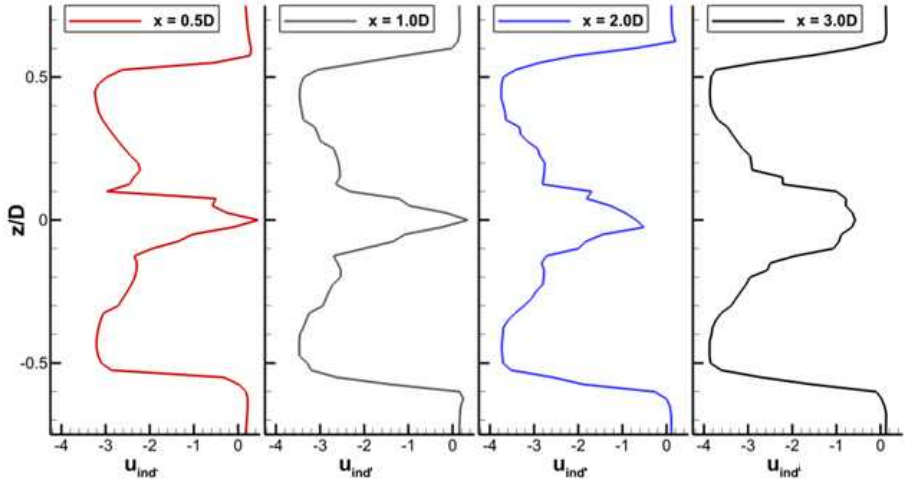
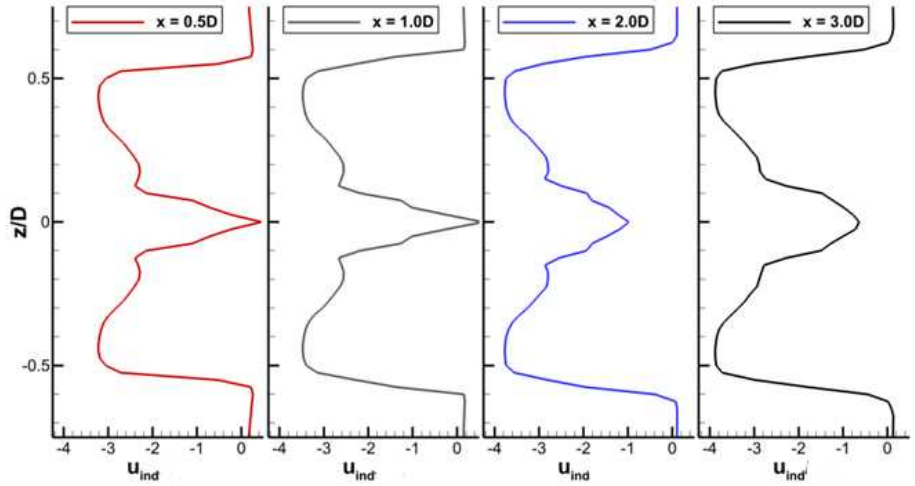
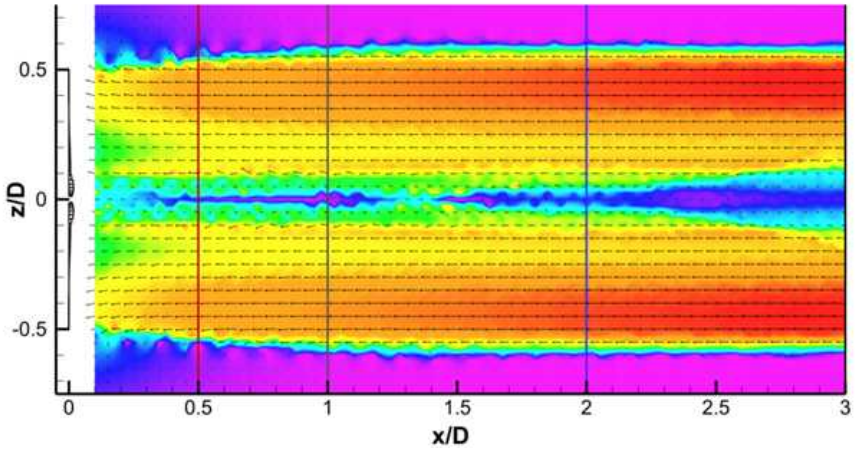
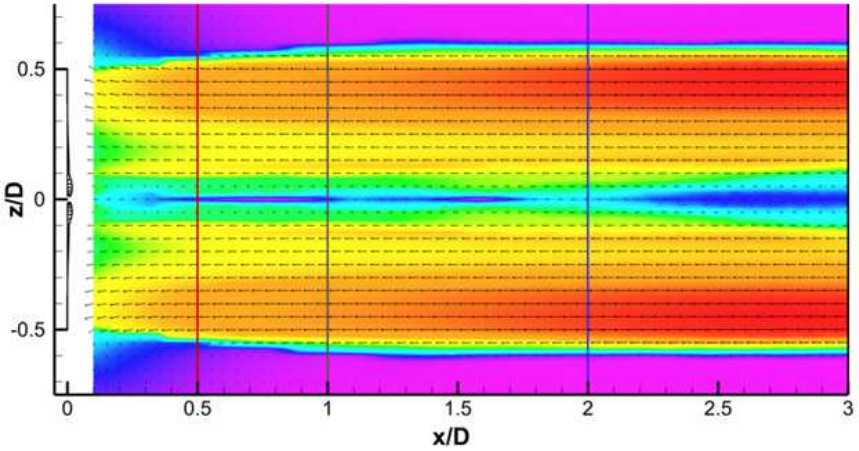
Instantaneous induced velocities

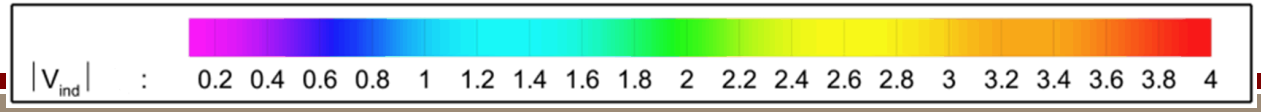


Averaged induced velocities

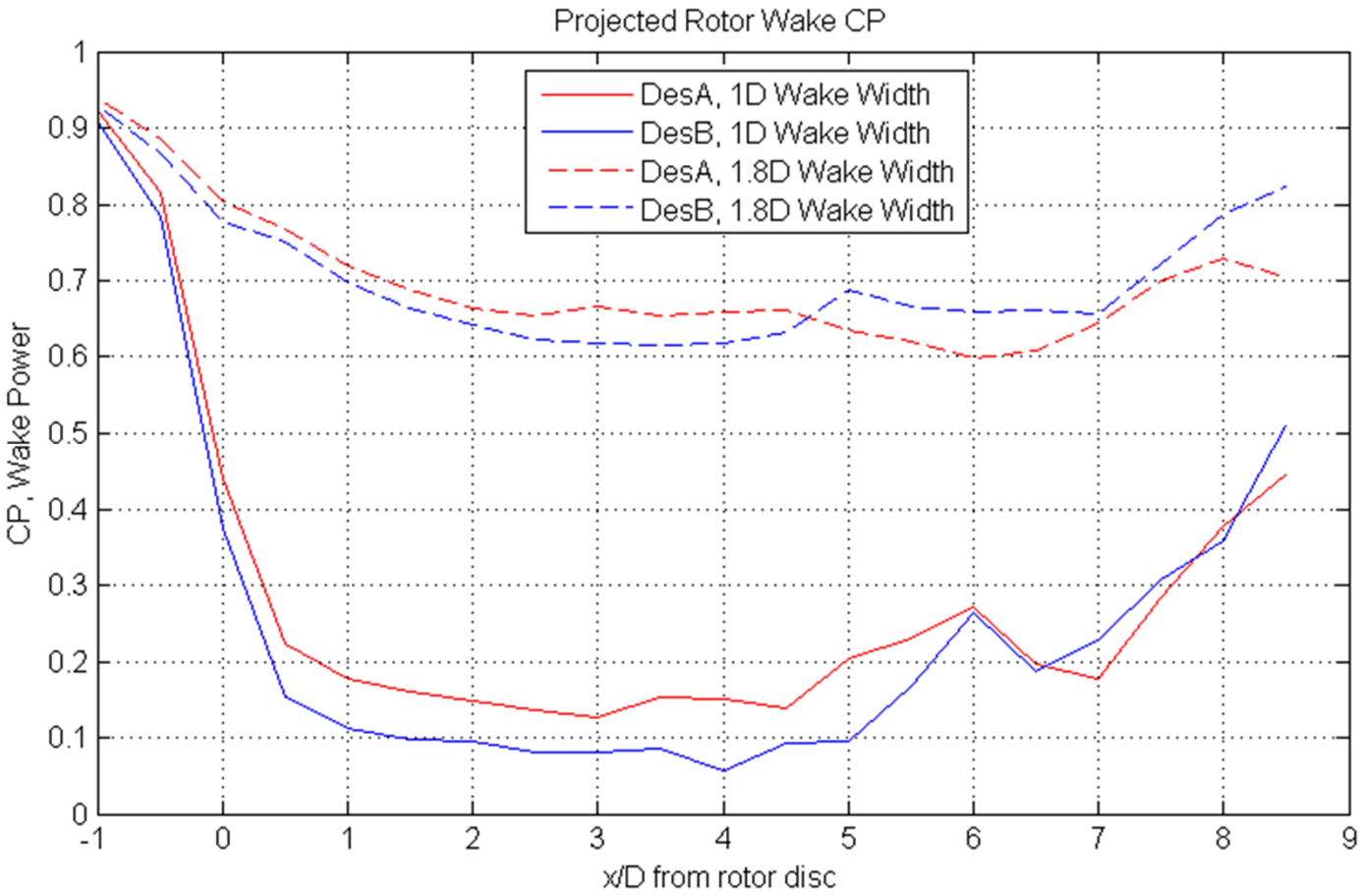








FWVM (WindDVE) Results



Vision—SWiFT Experiment I: Inflow & Near-Wake Characterization

Sandia National Laboratories

- Objectives
  - Detailed characterization of the turbulent inflow conditions and atmospheric boundary layer profiles at the SWiFT Facility.
  - Design, build, and test a scaled wind turbine rotor capable of reproducing the wake characteristics observed in utility-scale turbines; verify scaling capability.
  - Detailed characterization of the near-wake coherent structures (primarily tip vortices), the turbulent wake breakdown process in the intermediate range, and the preliminary stages of fully turbulent Gaussian far-wake profile.
  - Utilize data in conjunction with high-fidelity models through formal and systematic Verification and Validation (V&V) process developed within the A2e initiative.
  - Complement other A2e experimental campaigns in the wind tunnel and utility-scale wind farms to understand the impact of scaling on rotor aerodynamics.
- Success Criteria
  - Able to quantify model bias and uncertainties in turbulent inflow and near-wake region.
  - High-quality experimental data for use in V&V exercises to develop and improve high-fidelity inflow and wake models.