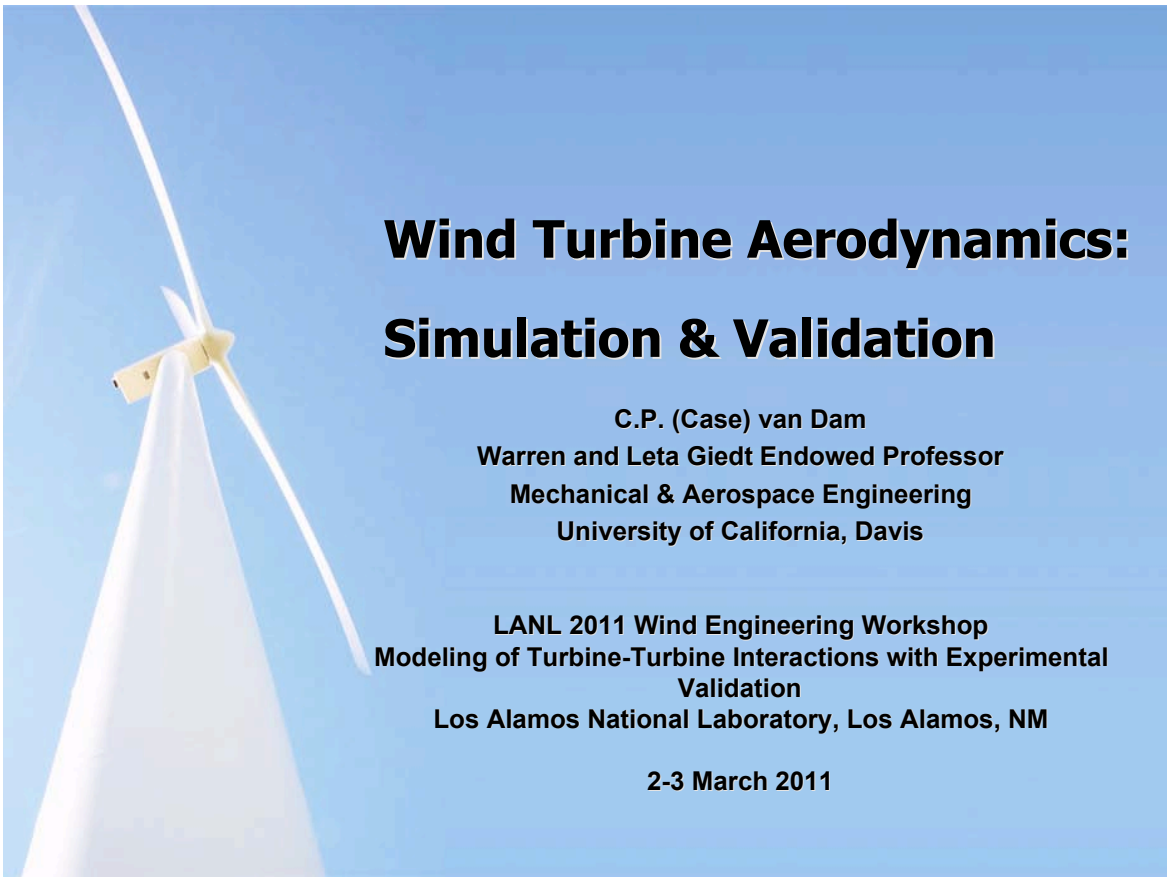

Wind Turbine Aerodynamics: Simulation & Validation

C.P. (Case) van Dam
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Mechanical & Aerospace Engineering
University of California, Davis

LANL 2011 Wind Engineering Workshop
Modeling of Turbine-Turbine Interactions with Experimental Validation
Los Alamos National Laboratory, Los Alamos, NM

2-3 March 2011

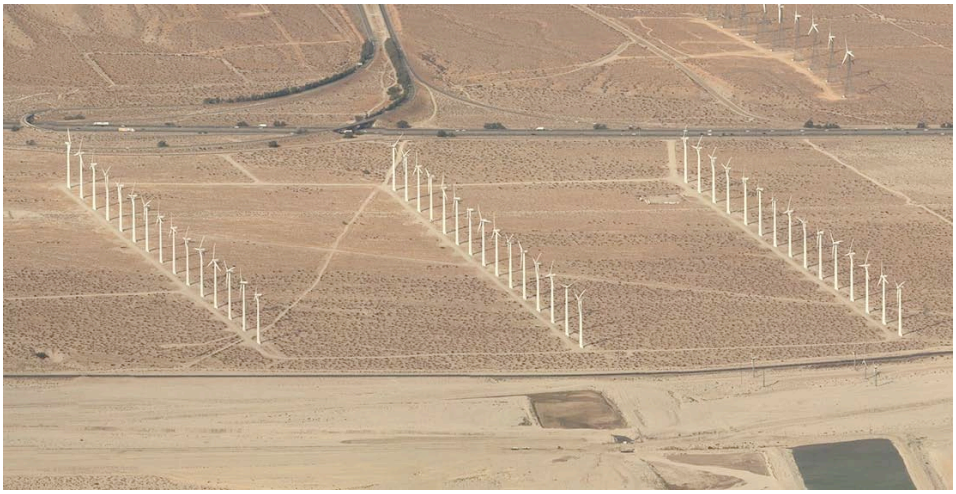
Acknowledgments

- Raymond Chow
  - PhD student UC Davis, CFD simulations
- Matt Brunner
  - MS student UC Davis, white paper “Advances in Wind Turbine Far-Wake Computations and Measurements”
- Syta Saephan
  - PhD UC Davis, now consultant, initial NREL 5-MW grid generation & simulations
- NREL, ECN, Risø
  - NREL Phase VI database
  - NREL 5-MW/UpWind rotor information
- Funding
  - Sandia National Laboratories, Albuquerque
  - PIER program, California Energy Commission

Wind Turbine Aerodynamics: Simulation & Validation

- Overview
- NREL Phase VI Experiment
- Mexico Experiment
- NREL 5-MW Turbine
- Concluding Remarks

Turbine - Turbine Interactions



San Gorgonio Wind Resource Area
Source: Field, 2008

Turbine - Turbine Interactions

Horns Rev windplant
Source: www-ict.aeolus.eu

Turbine-Turbine Interactions

- Turbine-turbine aerodynamic interactions can be strong depending on:
  - Turbine spacing
  - Rotor tip speed ratio (TSR)
  - Rotor aerodynamic loading
  - Atmospheric conditions
- Problem has been recognized since development of first windfarms in 1980s
- Recently moved back to the forefront because of underperformance of large windplants
- Focus of this presentation is on validation of turbine aerodynamics

Validation Study:

NREL Phase VI Rotor

Validation: NREL Phase VI Rotor

- NREL UAE dataset
- Tested in 80 ft x 120 ft closed test section of National Full-Scale Aerodynamics Complex at NASA Ames
- Upwind & downwind 2-bladed rotor
- 10.06 m diameter
- S809 airfoil
- Linear twist
- Linear taper
- 72 RPM

Source: NREL

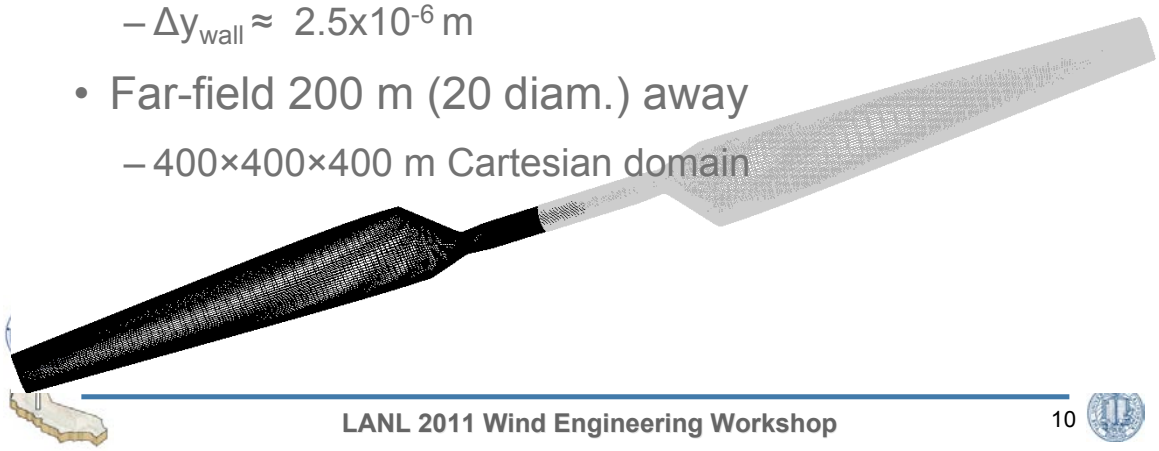
Validation: NREL Phase VI Rotor

0 deg pitch, 7 m/s, TSR = 5.4

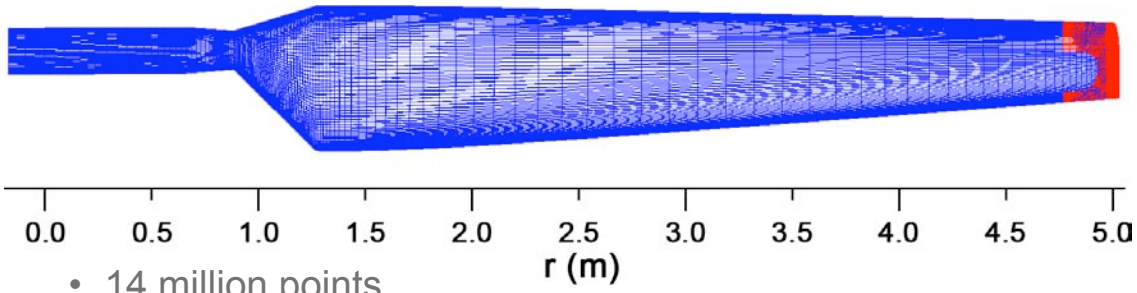
Source: NREL

Phase VI Grids

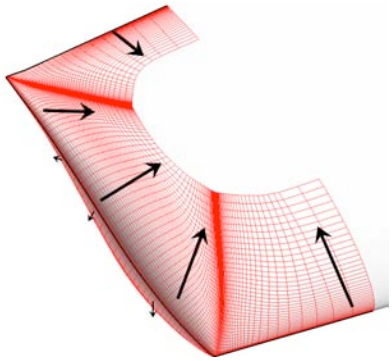
- Viscous wall spacing ~0.3 y^+
  - $U_{tip} \approx 40$ m/s
  - $Re_{tip} \approx 1.0 \times 10^6$
  - $y^+ \approx 7.4 \times 10^{-6}$ m
  - $\Delta y_{wall} \approx 2.5 \times 10^{-6}$ m
- Far-field 200 m (20 diam.) away
  - 400×400×400 m Cartesian domain



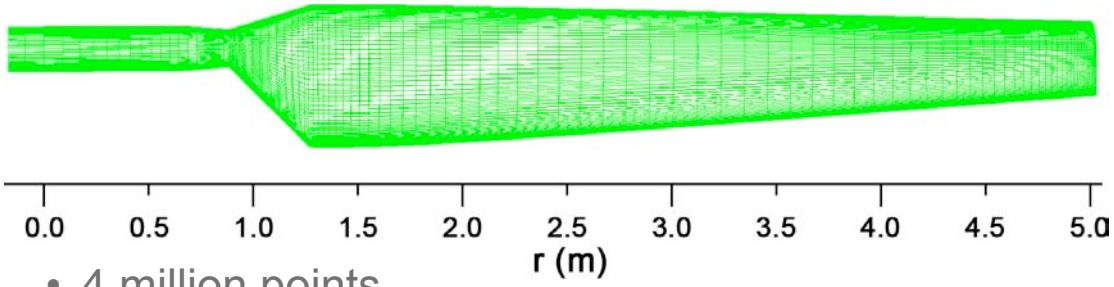
Phase VI – Fine Grid



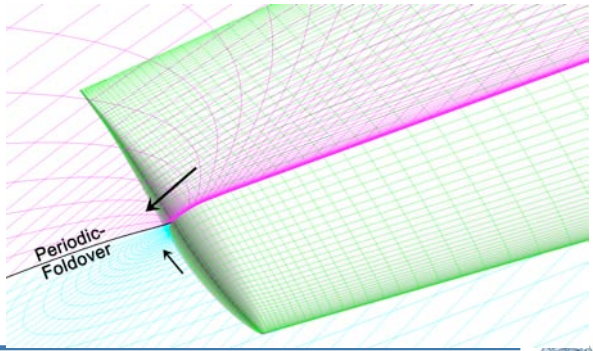
- 14 million points
- Blade grids
  - 209×128×150
- Tip-cap grids
  - 129×81×150
- Cartesian near-field
  - 141×141×61



Phase VI – Coarse Grid



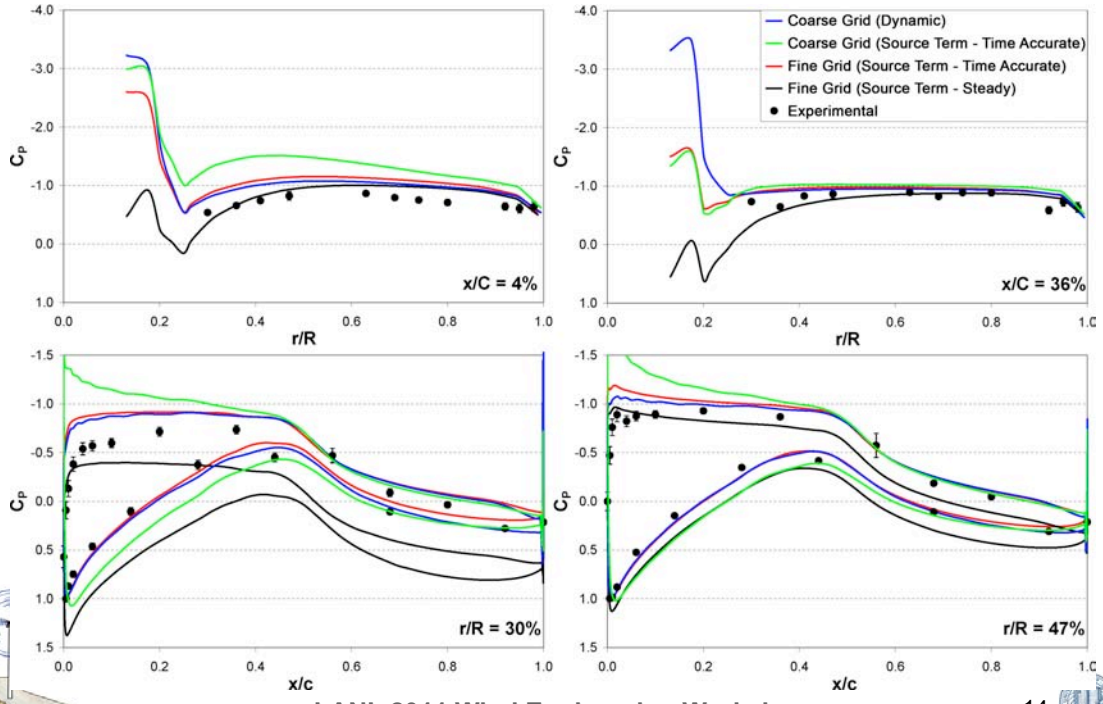
- 4 million points
- Blade grids
  - 141×102×80
- Cartesian near-field
  - 121×121×59



Flow Solver

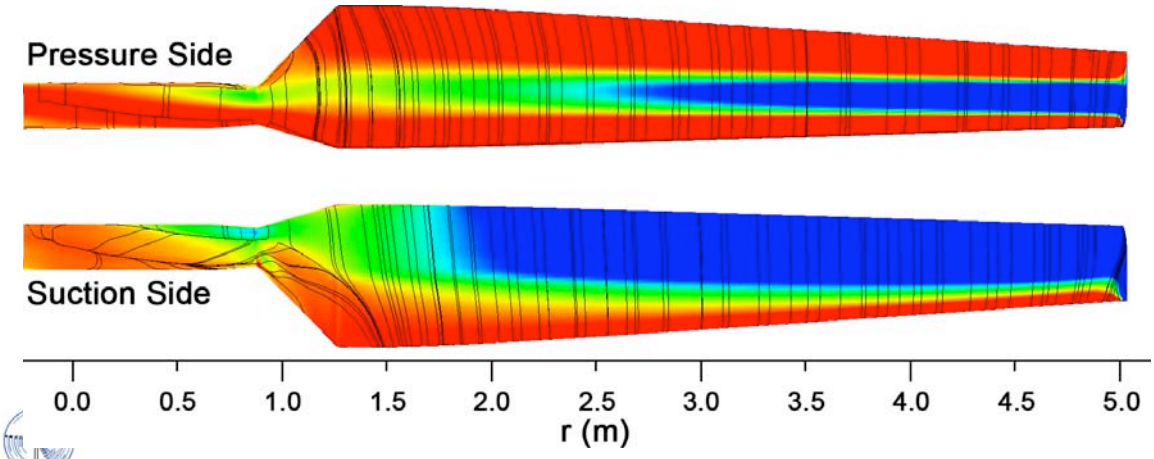
- OVERFLOW-2
  - Unsteady RANS solver
  - Structured, Chimera, overset grids
  - Central difference Euler
  - Beam-Warming pentadiagonal scheme
  - Matrix dissipation
  - Menter's SST k-ω turbulence model
  - Dual sub-iteration time marching
    - 2nd-order time accurate
    - 2 orders of sub-iteration convergence to ensure time accuracy
  - Rotational Source Term
    - Coriolis and centrifugal acceleration terms added to momentum

Validation: Phase VI at U_∞ = 5 m/s



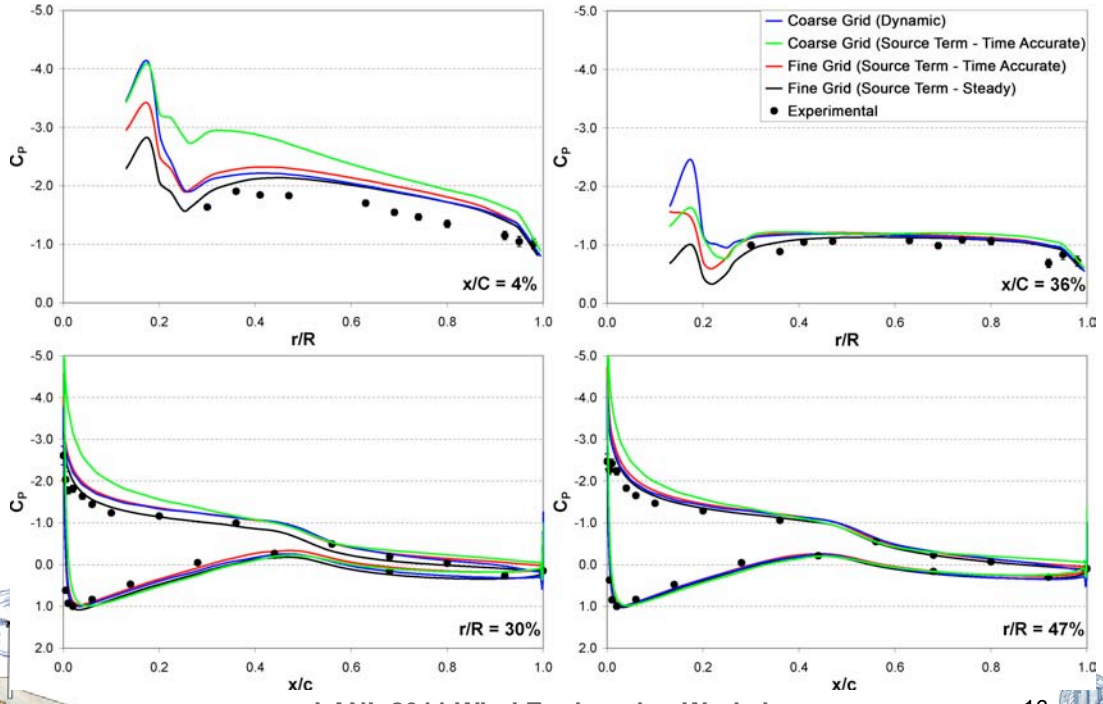
Validation: Phase VI at U_∞ = 5 m/s

- Surface pressure contours
- Instantaneous surface streaklines

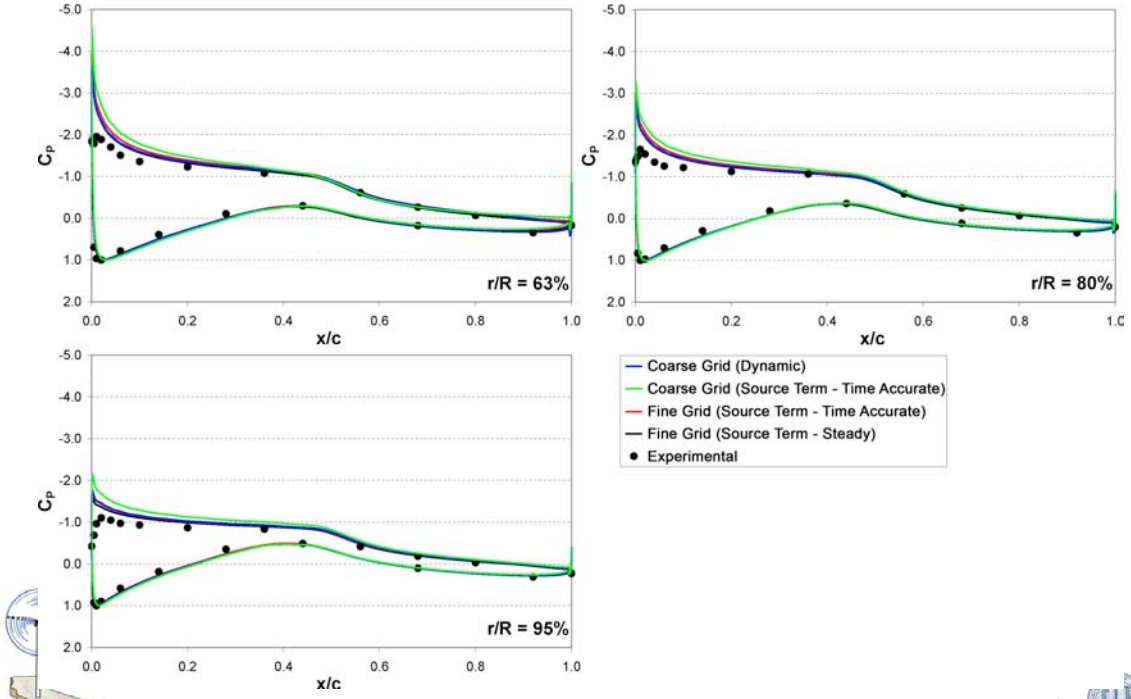


Fine grid – Source Term (Unsteady)

Validation: Phase VI at U_∞ = 7 m/s

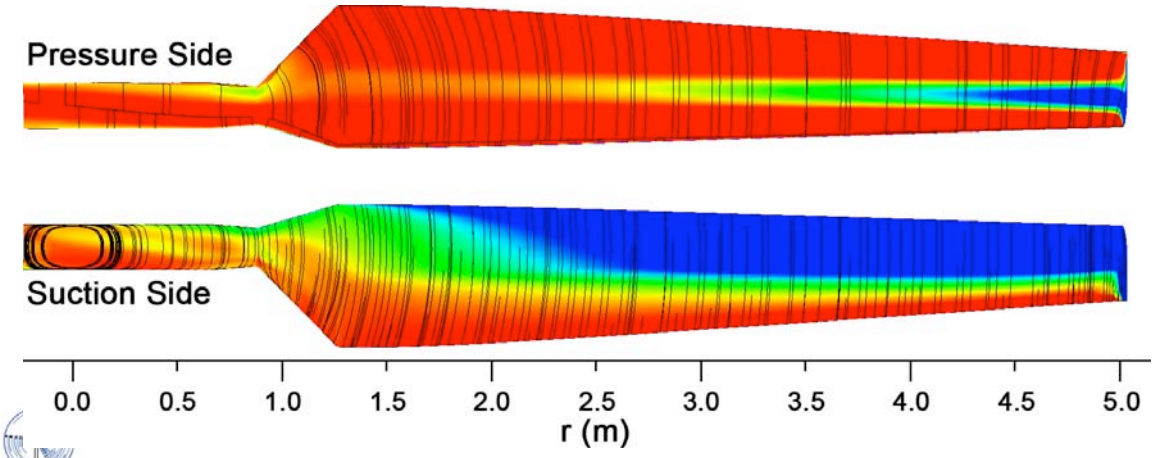


Validation: Phase VI at U_∞ = 7 m/s



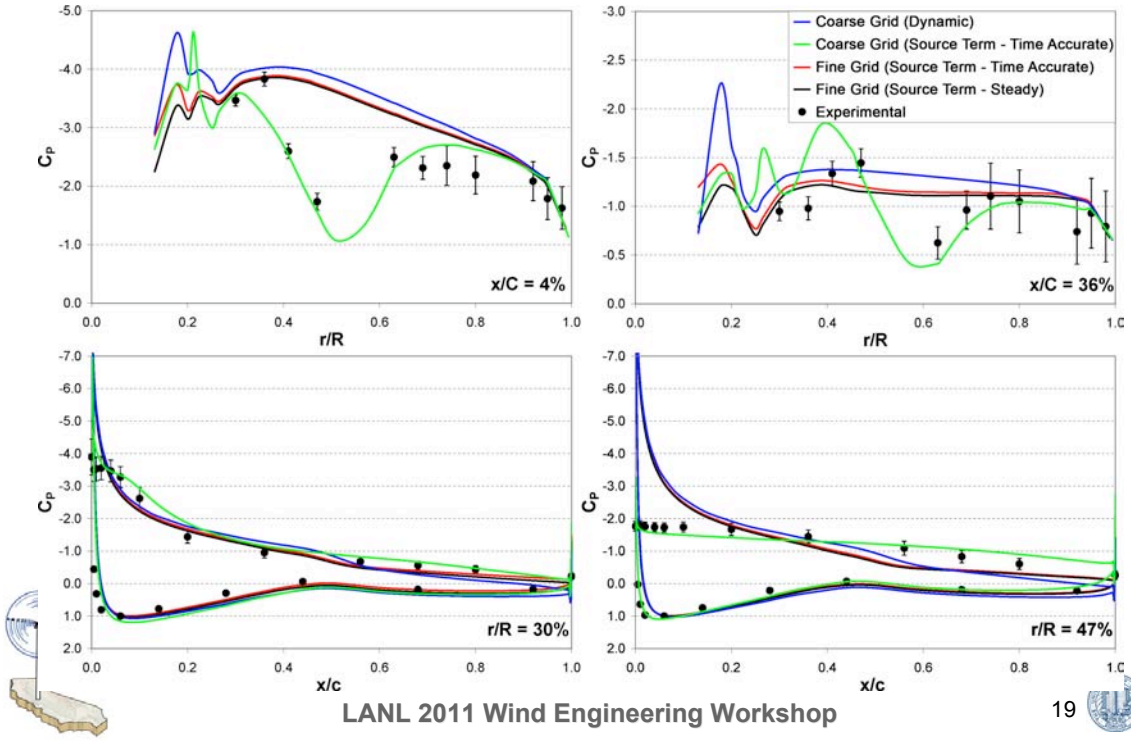
Validation: Phase VI at U_∞ = 7 m/s

- Surface pressure contours
- Instantaneous surface streaklines

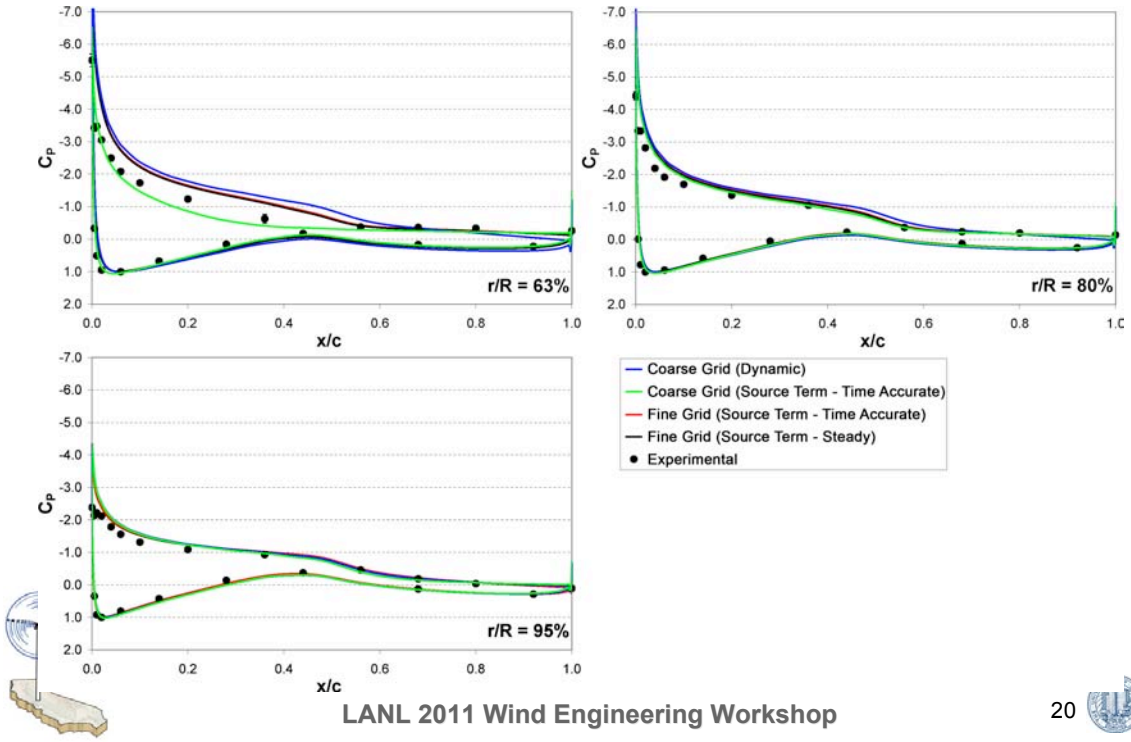


Fine grid – Source Term (Unsteady)

Validation: Phase VI at U_∞ = 10 m/s

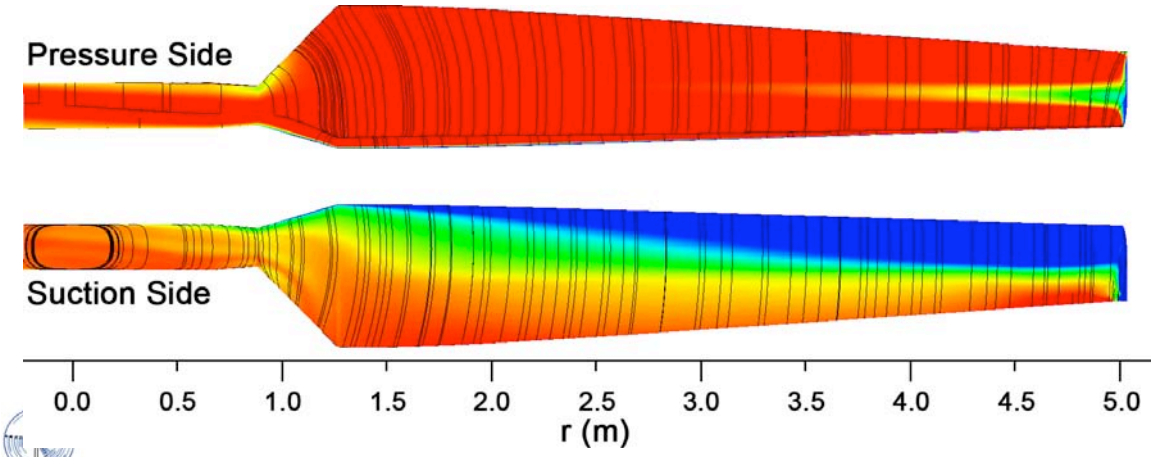


Validation: Phase VI at U_∞ = 10 m/s



Validation: Phase VI at U_∞= 10 m/s

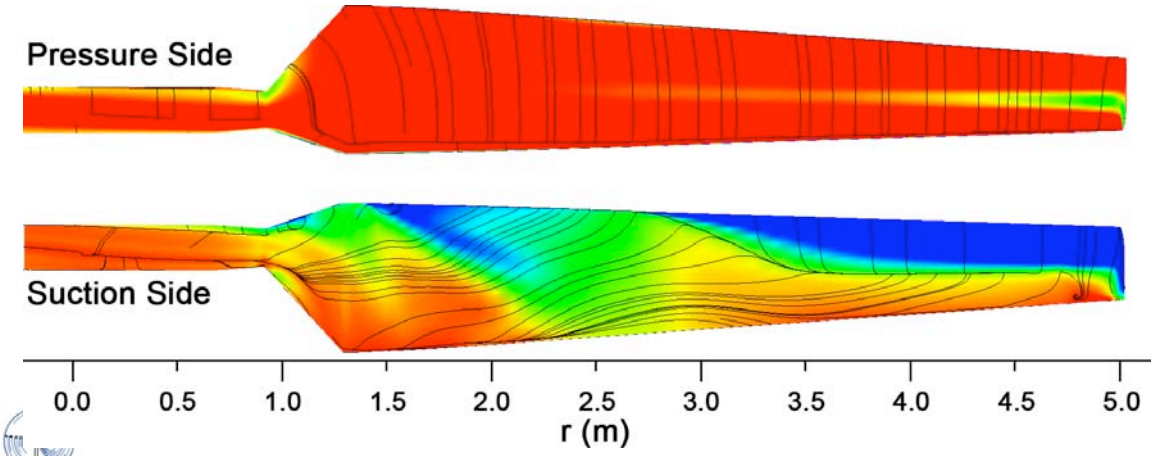
- Surface pressure contours
- Instantaneous surface streaklines



Fine grid – Source Term (Unsteady)

Validation: Phase VI at U_∞= 10 m/s

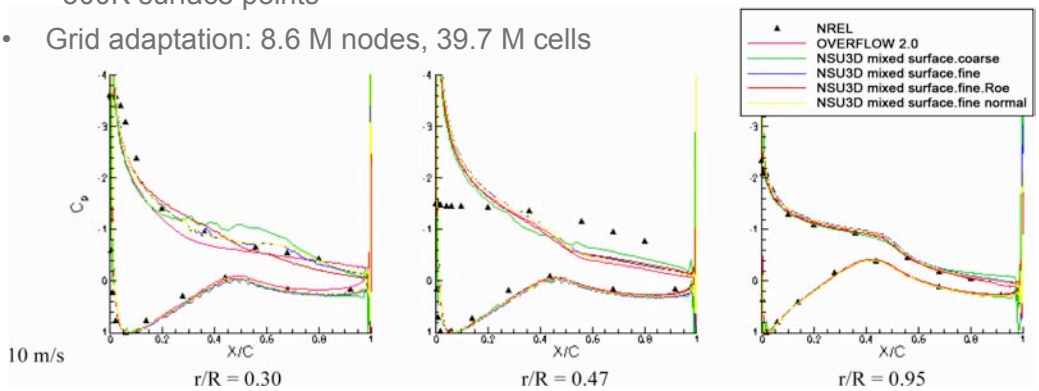
- Surface pressure contours
- Instantaneous surface streaklines



Coarse Grid – Source Term (Unsteady)

Phase VI at 10 m/s

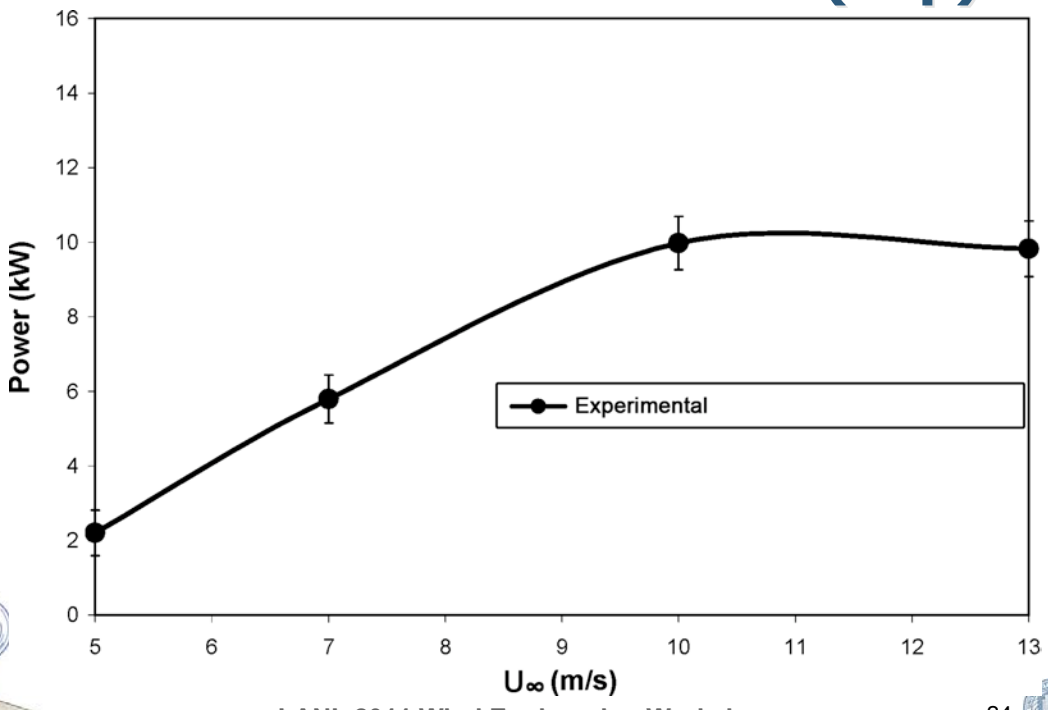
- NSU3D – unstructured RANS solver
- ~500K surface points
- Grid adaptation: 8.6 M nodes, 39.7 M cells



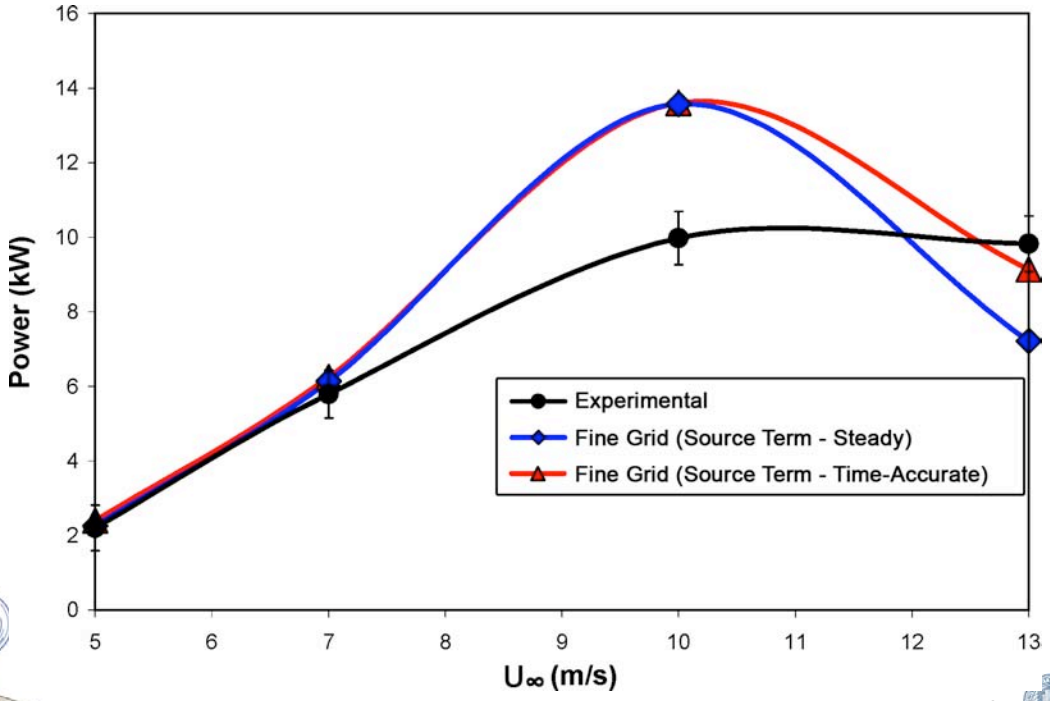
Mark Potsdam and Dimitri Mavriplis

"Unstructured Mesh CFD Aerodynamic Analysis of the NREL Phase VI Rotor" - AIAA 2009-1221

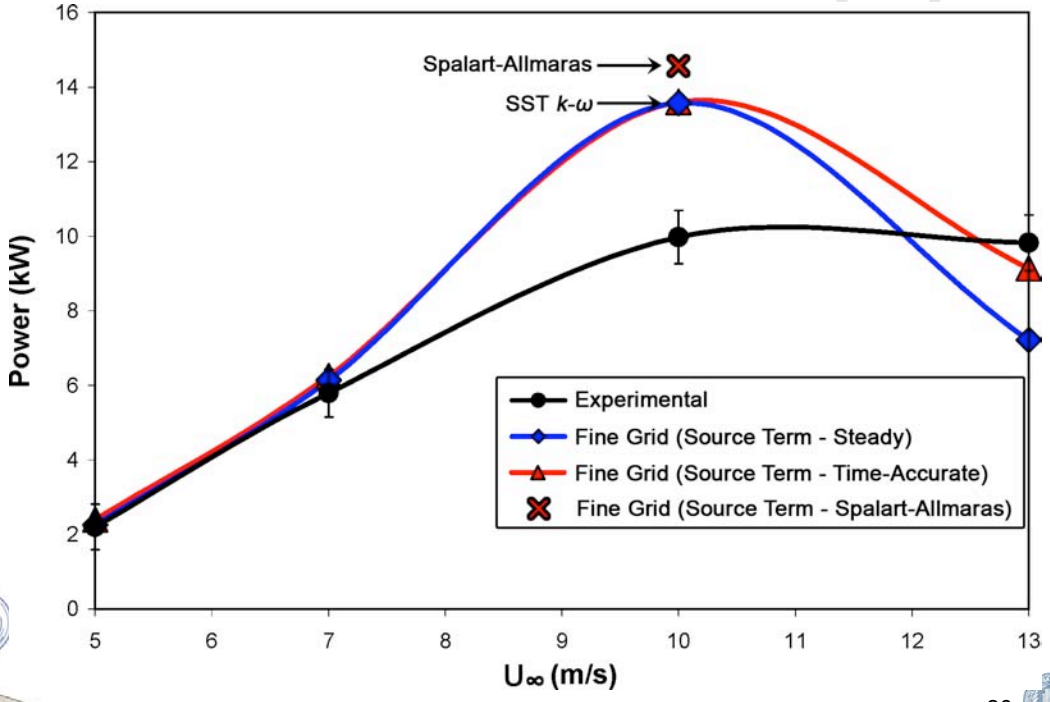
Validation: Phase VI Power (Exp)



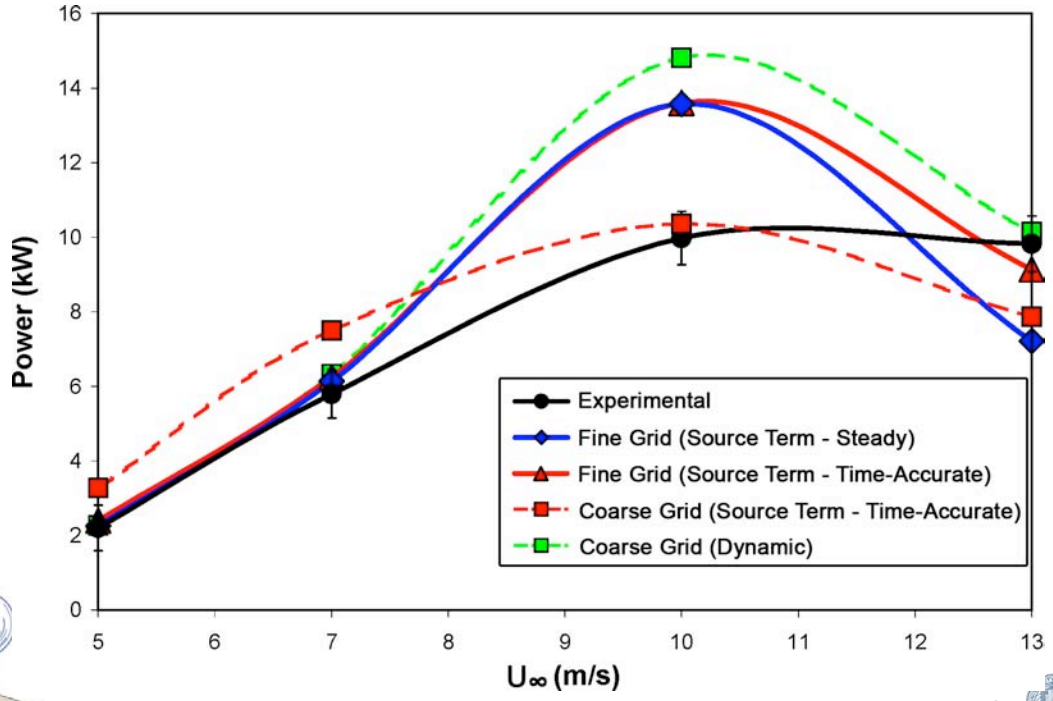
Validation: Phase VI Power



Validation: Phase VI Power (SA)



Validation: Phase VI Power



NREL Phase VI Conclusions

- Phase VI at 5, 7, 13 m/s accurately predicted
  - Inboard separation (5 m/s), fully attached (7 m/s), separation (13 m/s)
- Time-accurate solutions are definitely required to capture unsteady separated flow
- Full dynamic simulations may not be necessary to achieve required aerodynamic accuracy
- Time-step ~2×10^{-3}DT with 20 sub-iterations
  - ~2000-5,000 time-steps per rev
- Grid resolution ~10+ million

Validation: NREL Phase VI

- Benchmark two-bladed rotor dataset
- Well documented and supported by NREL
- Observations:
  - Blade geometry (inboard of max chord, tip shape) not well defined
  - Two-bladed stall-controlled rotor with low $C_{l,max}$ airfoil section
  - Rotor tip speed rather low (38 m/s) $\Rightarrow$ relatively low TSR
  - Only qualitative wake data

Validation Study:

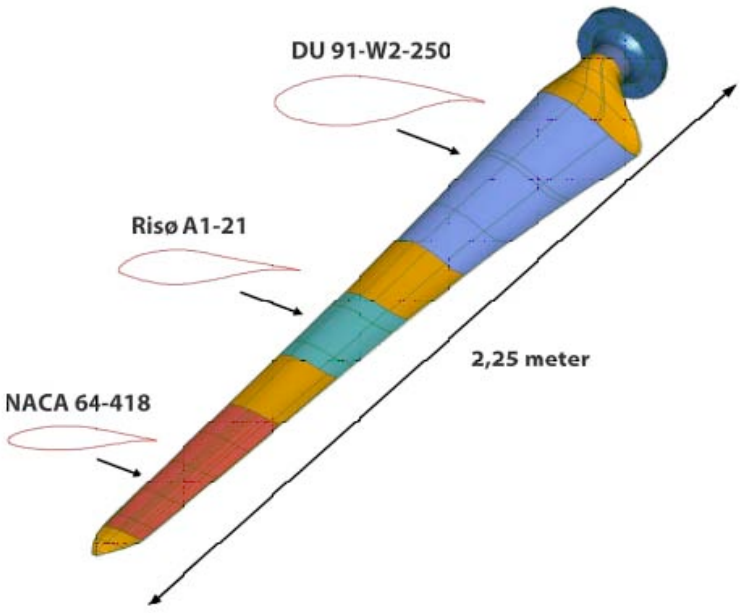
Mexico Experiment

Validation: EU Mexico Project

- EU project involving 10 institutes from 6 countries
- Tested in 9.5 m x 9.5 m open section of DNW LLF
- 3-blade upwind rotor
- 4.5 m diameter
- 324.5 or 424.5 RPM
- Boundary layer trips
- Speeds from 10 to 30 m/s
- Design TSR = 6.67 @ 15 m/s and 424.5 RPM

Source: ECN

Mexico Experiment Rotor Blade



Source: ECN

Validation: Mexico Experiment

- Benchmark three-bladed rotor dataset
- Well documented and supported by ECN et al.
- Focus on rotor wake ⇒ extensive wake data
- Observations:
  - Blade geometry (transitions between major airfoils) not well defined
  - Rather small rotor ⇒ low Reynolds number
  - Experiment conduced in open-jet wind tunnel

Validation Study:

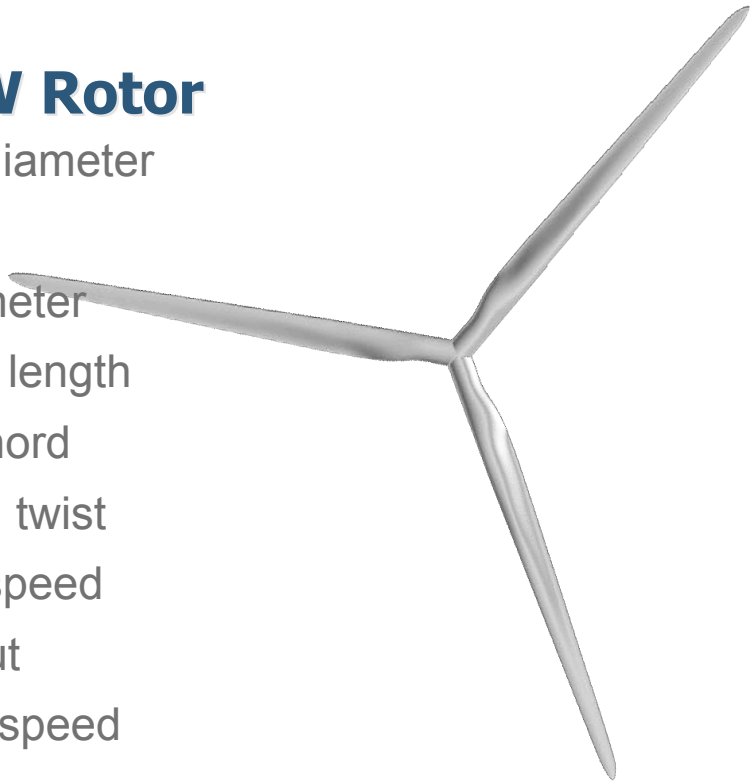
NREL 5-MW Rotor

NREL 5-MW Rotor

- Geometry based on 6-MW DOWEC rotor
  - Conceptual off-shore turbine design
  - ECN (Energy Research Centre of the Netherlands)
- Rotor diameter truncated and hub diameter reduced

NREL 5-MW Rotor

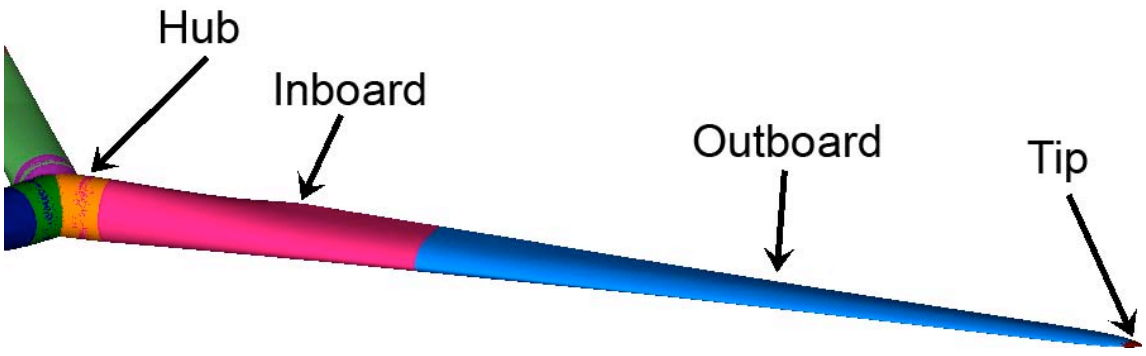
- 126 m rotor diameter
- 12.1 RPM
- 3 m hub diameter
- 61.5 m blade length
- 4.7 m max chord
- 13.3° inboard twist
- 3 m/s cut-in speed
- 25 m/s cut-out
- 12 m/s rated speed



Methodology

- OVERFLOW-2
  - Reynolds-averaged Navier-Stokes solver (RANS)
    - Fully viscous, ⅓ y^+ near wall spacing
    - 2-equation, k-ω SST turbulence model
    - 2-order spatial in viscous, near-body region
    - 4-order inviscid off-body grids (pseudo-DES method)
    - 2-order time-accurate
      - Dual-time stepping
    - Rotational source term applied to NS equations to model rotation
  - Chimera/overset grid topology

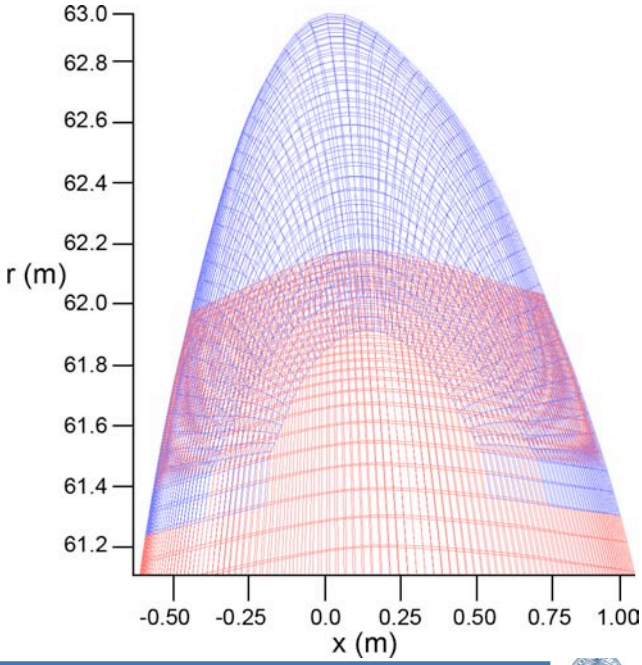
NREL 5-MW – Grid Topology



- Grid system designed to take advantage of overset/Chimera topology
- Modifications limited to inboard region

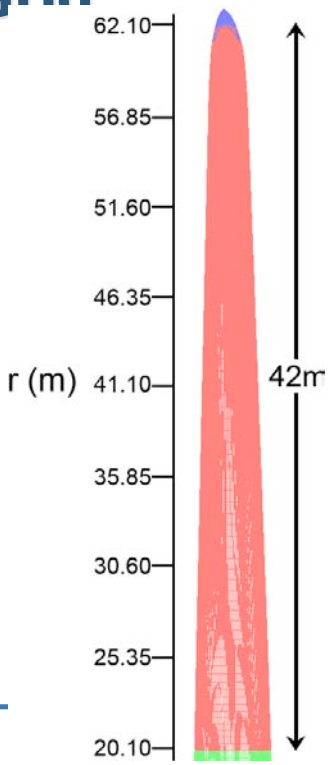
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81



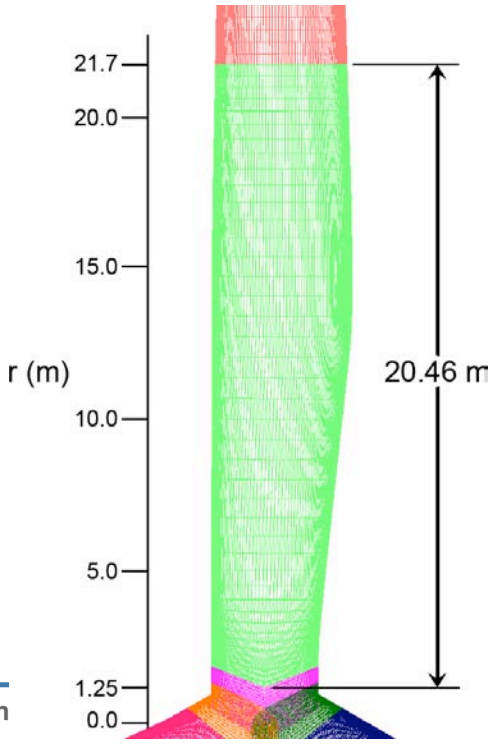
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81
- Outboard: 201×116×81



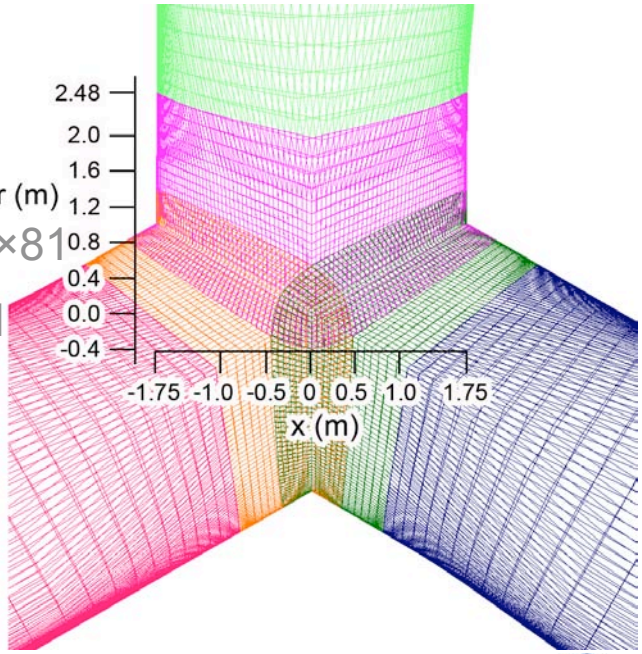
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81
- Outboard: 201×116×81
- Inboard: 201×43×81



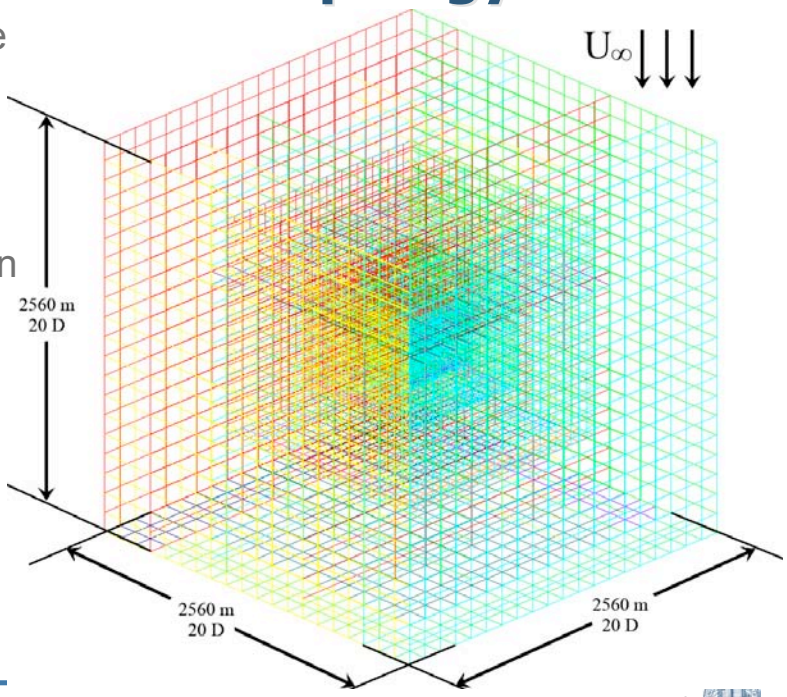
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81
- Outboard: 201×116×81
- Inboard: 201×43×81
- Hub: 201×26×81



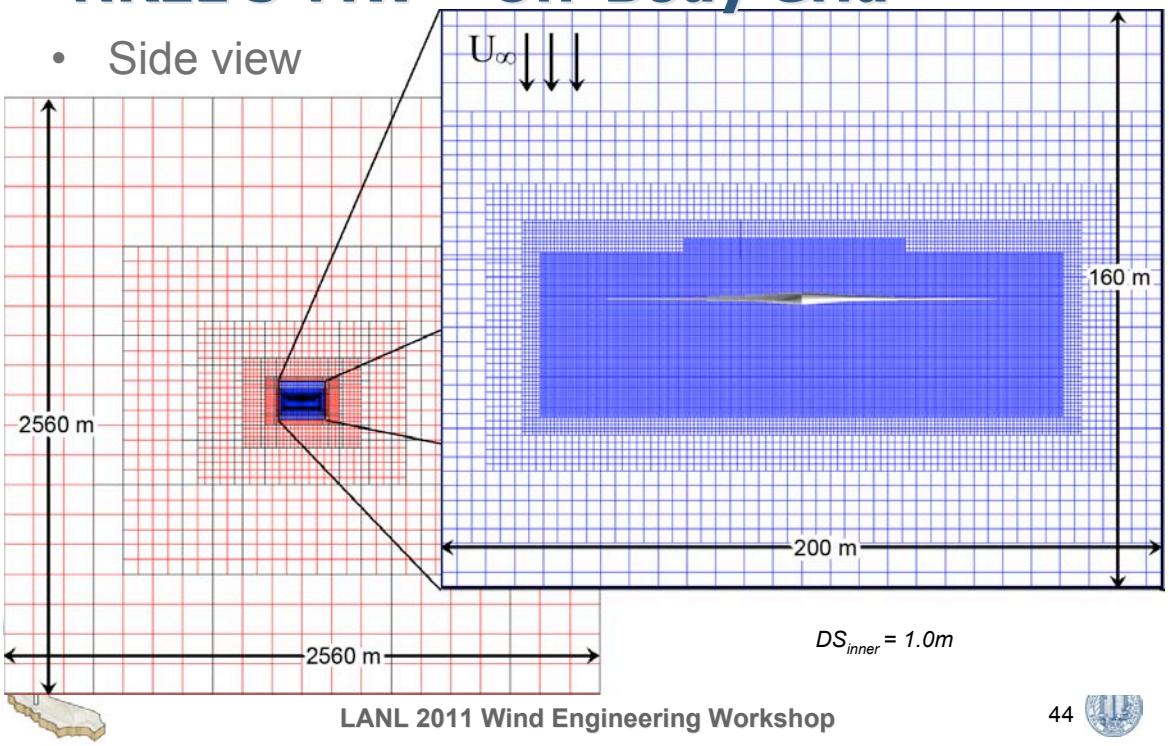
NREL 5-MW – Grid Topology

- Representative of a ~10D far-field distance
- BRICKS allow for rapid and efficient domain construction
- Improved load balancing



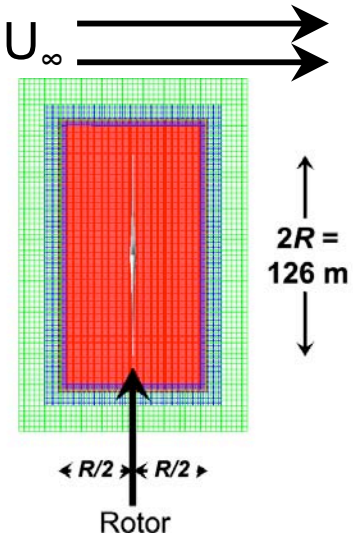
NREL 5-MW – Off-Body Grid

- Side view



DS_{inner} = 1.0m

NREL 5-MW – Near-Wake Size

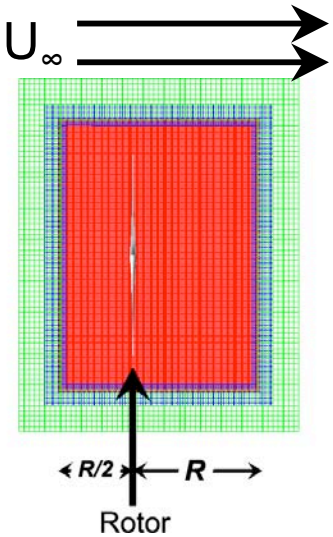


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

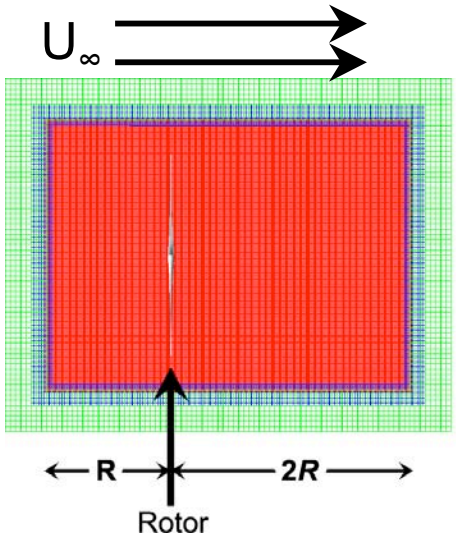


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

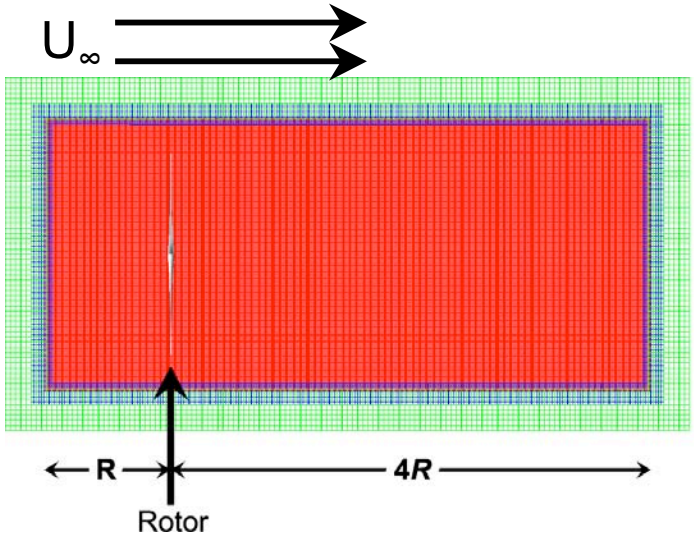


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

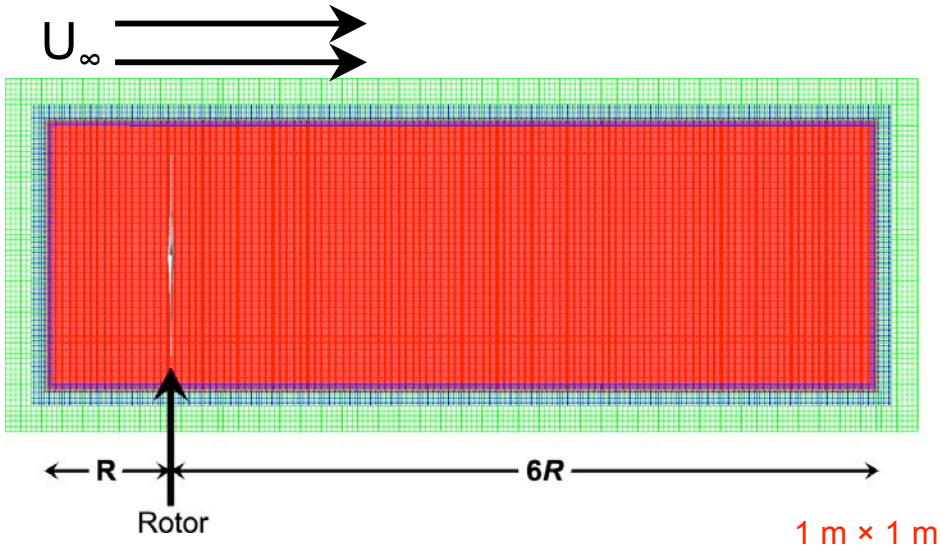


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

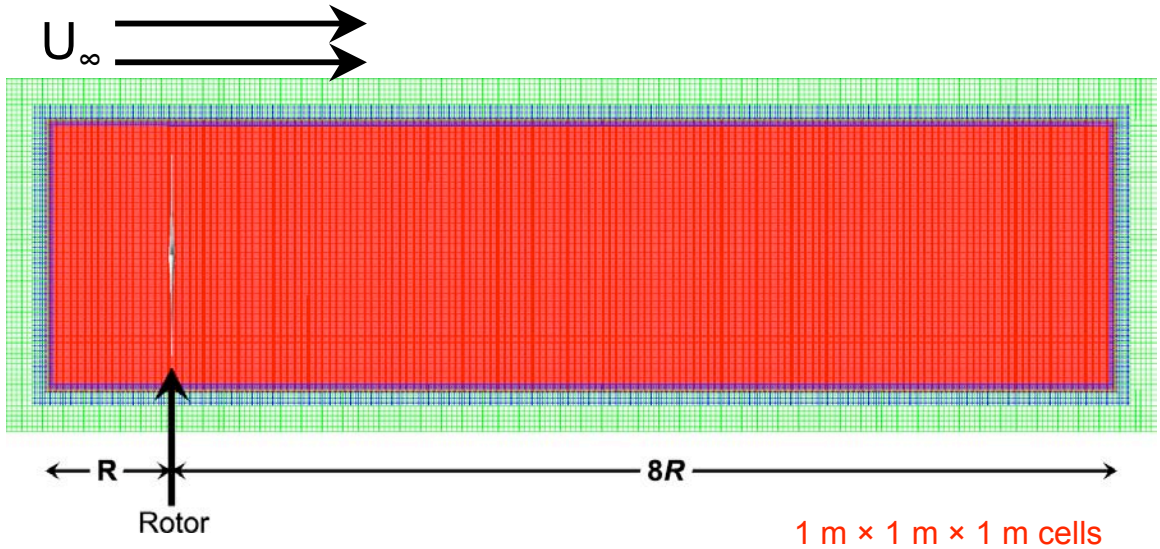


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

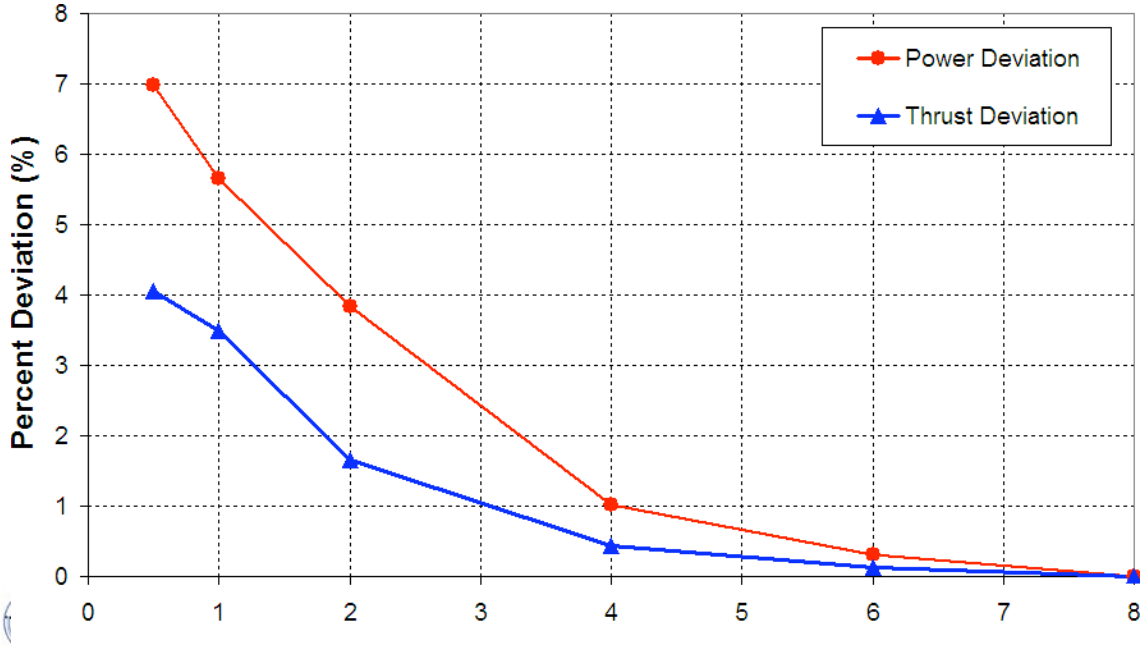


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

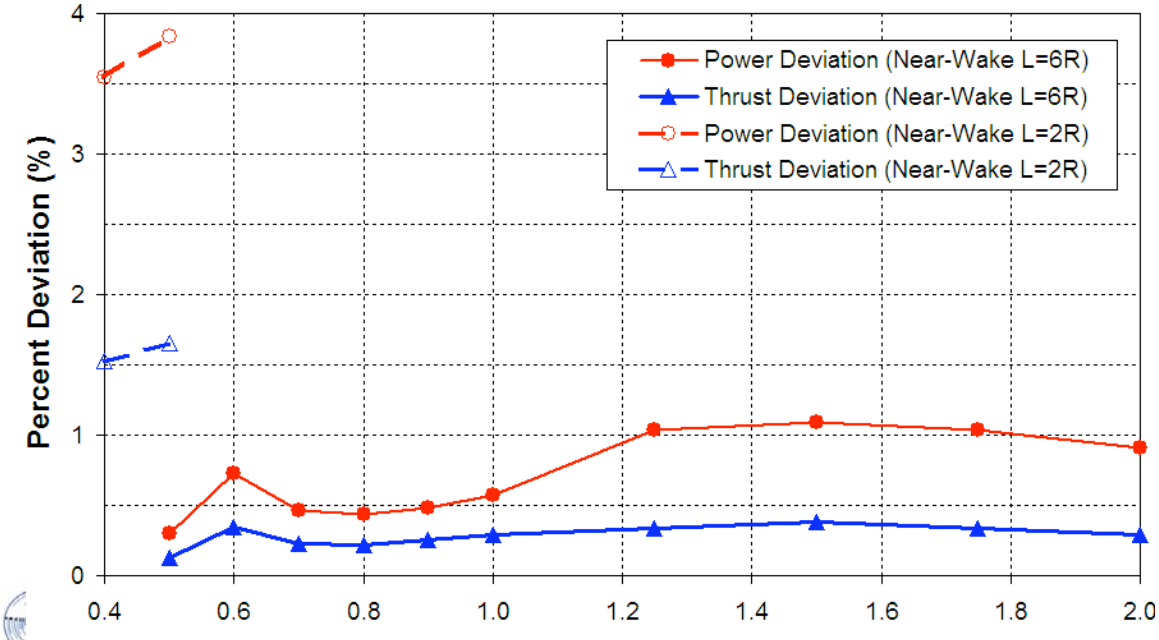
4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size



DS = 0.5 m

NREL 5-MW – Near-Wake Cell Size

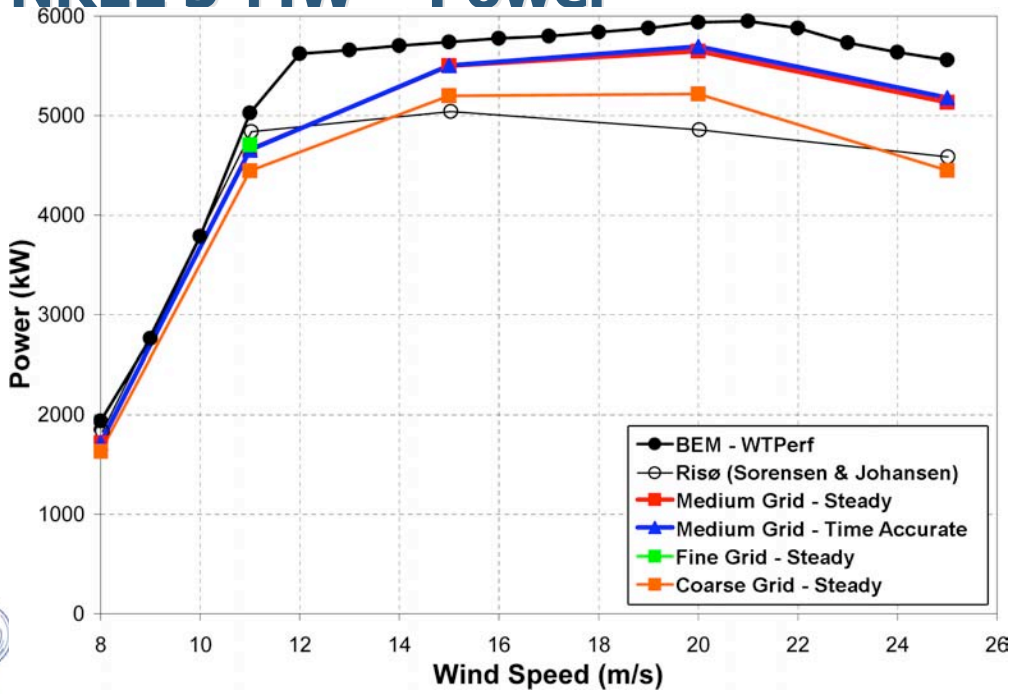


Baseline:
DS = 0.5 m, L = 8R

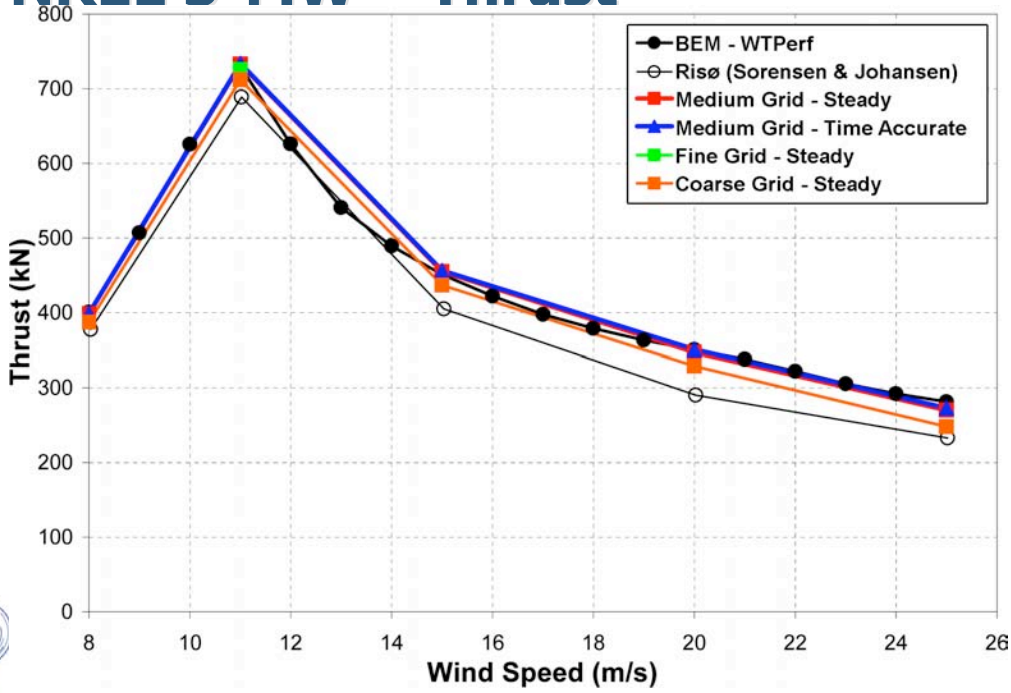
NREL 5-MW – Final Wake Grid Size

- Near-wake
  - Length = 6*R* = 3*D* = 378 m
  - Width = 140 × 140 m
  - Spacing DS = 1 m
- Far-field
  - 40*D (5040* m*)* to inlet, N,S,E,W boundaries
    - Characteristic freestream boundary conditions
  - 80*D* downstream exit boundary
    - 1st order inflow/outflow
- Total of ~28 million points
  - ~18M near-body grids points
  - ~10M off-body grid points

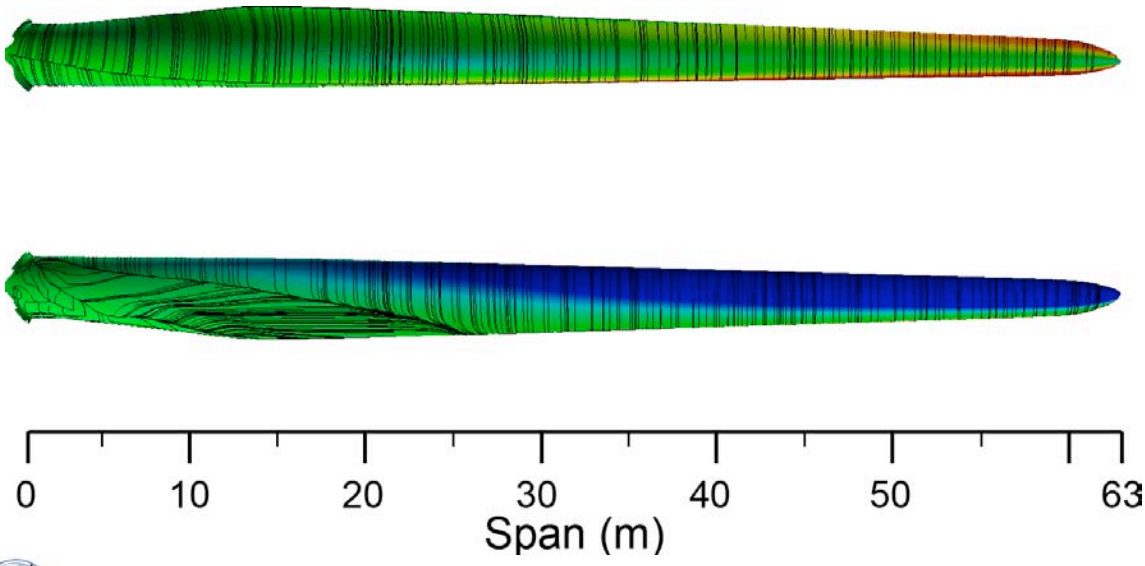
NREL 5-MW – Power



NREL 5-MW – Thrust

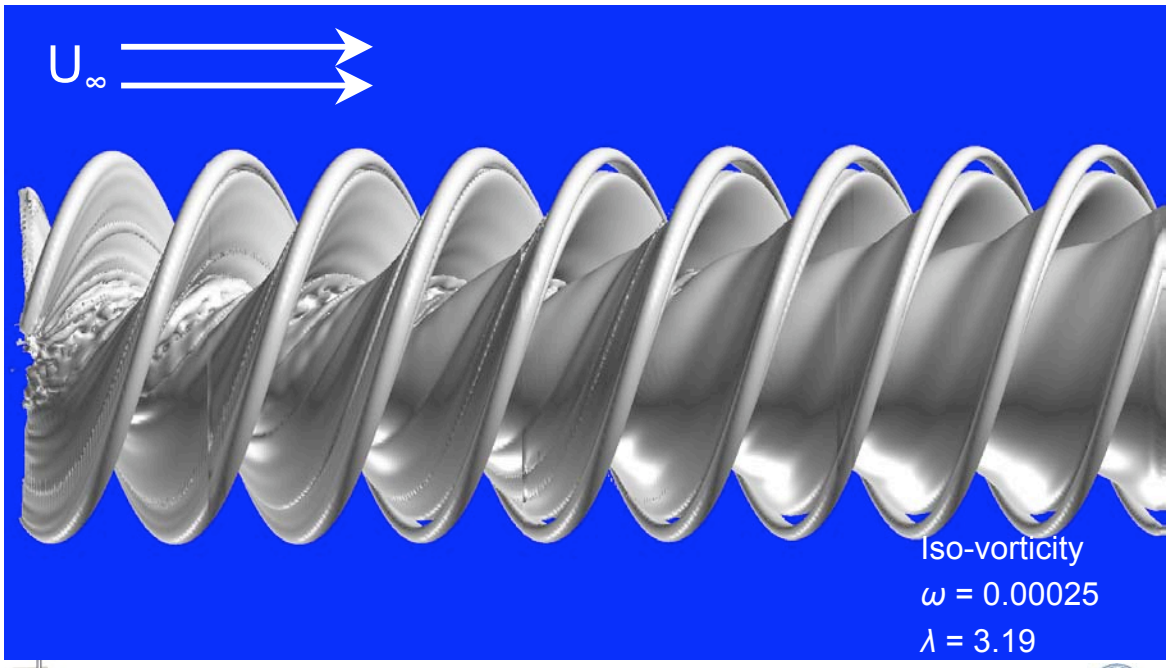


NREL 5-MW – U_∞ = 11m/s

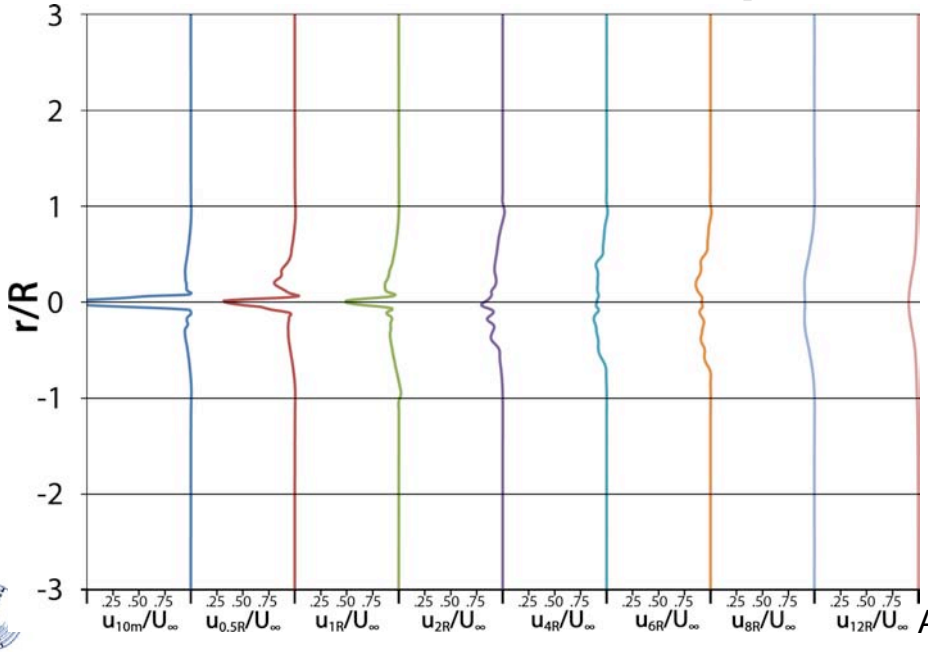


- Surface pressure with streaklines
- Medium Grid

NREL 5-MW – U_∞ = 25 m/s



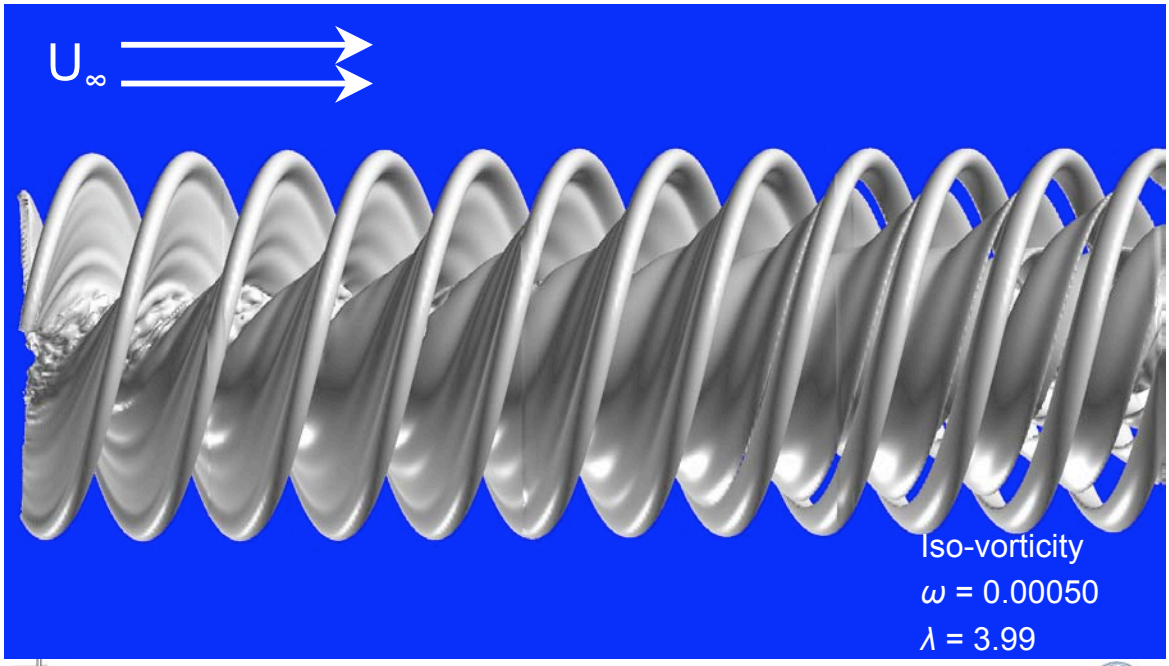
NREL 5-MW – U_∞ = 25 m/s



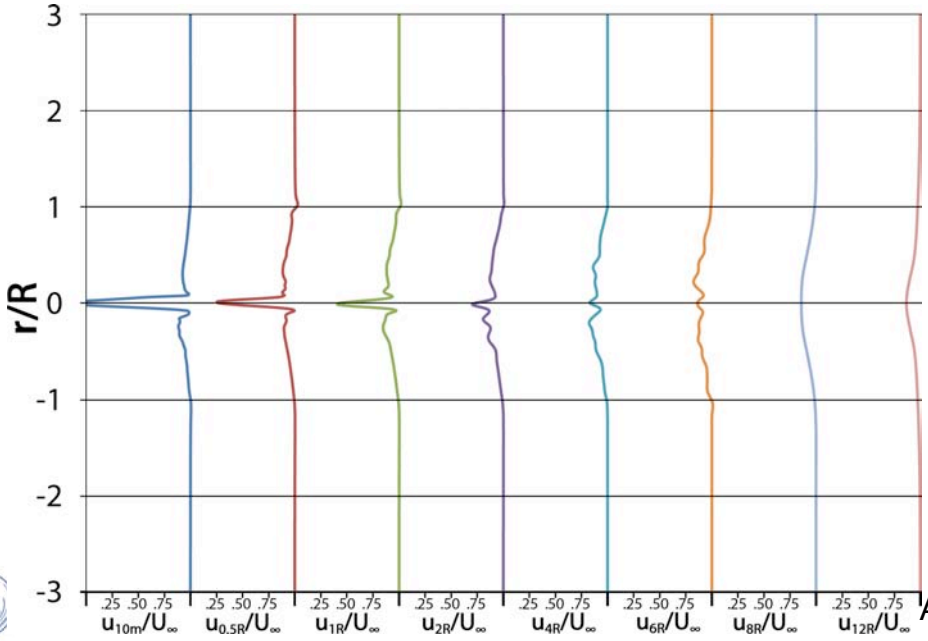
Axial velocity

λ = 3.19

NREL 5-MW – U_∞ = 20 m/s

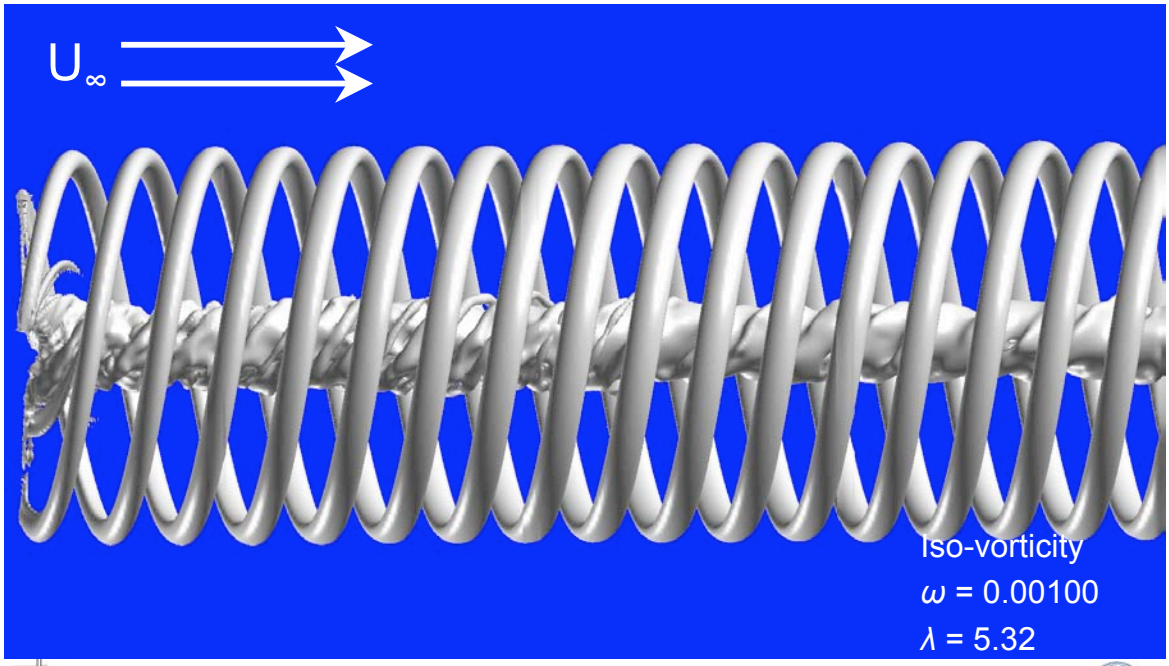


NREL 5-MW – U_∞ = 20 m/s

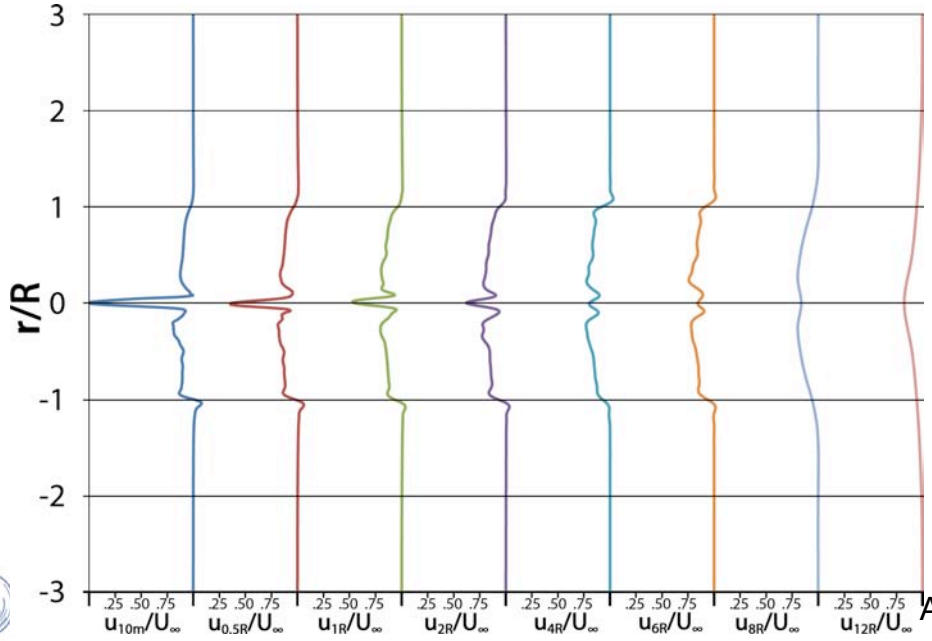


Axial velocity
λ = 3.99

NREL 5-MW – U_∞ = 15 m/s

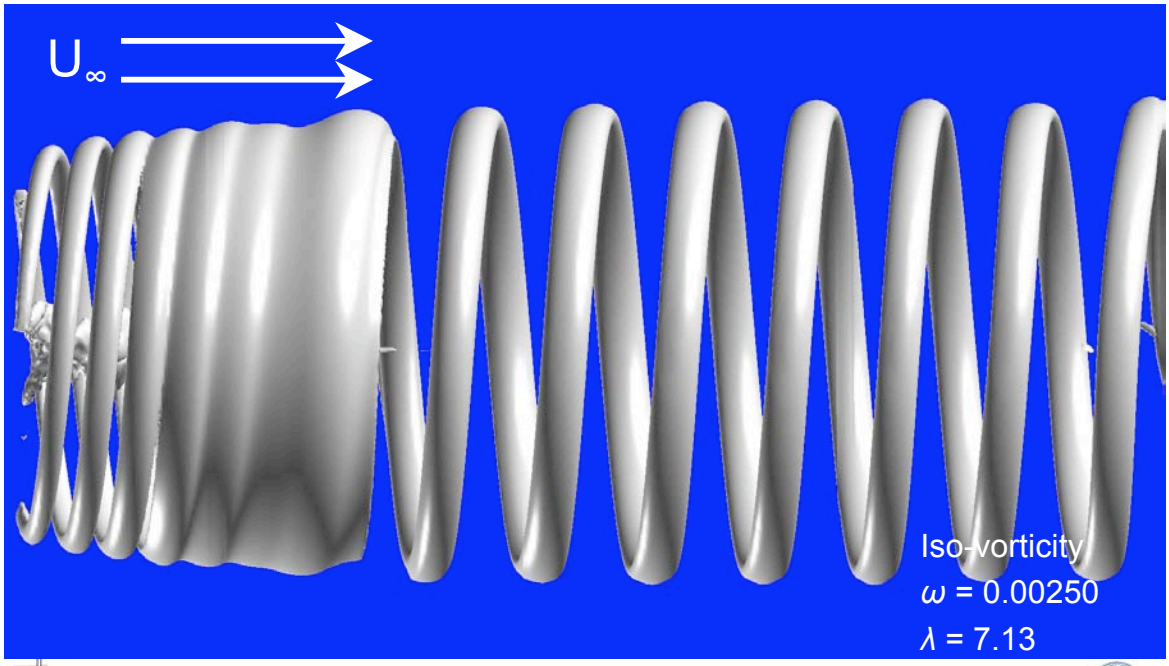


NREL 5-MW – U_∞ = 15 m/s

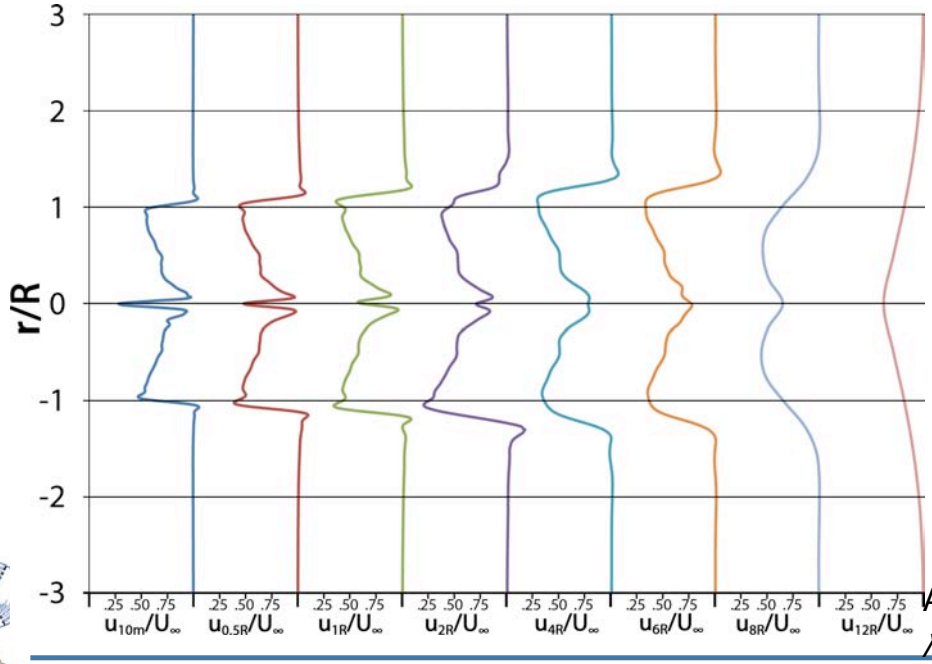


Axial velocity
λ = 5.32

NREL 5-MW – U_∞ = 11 m/s

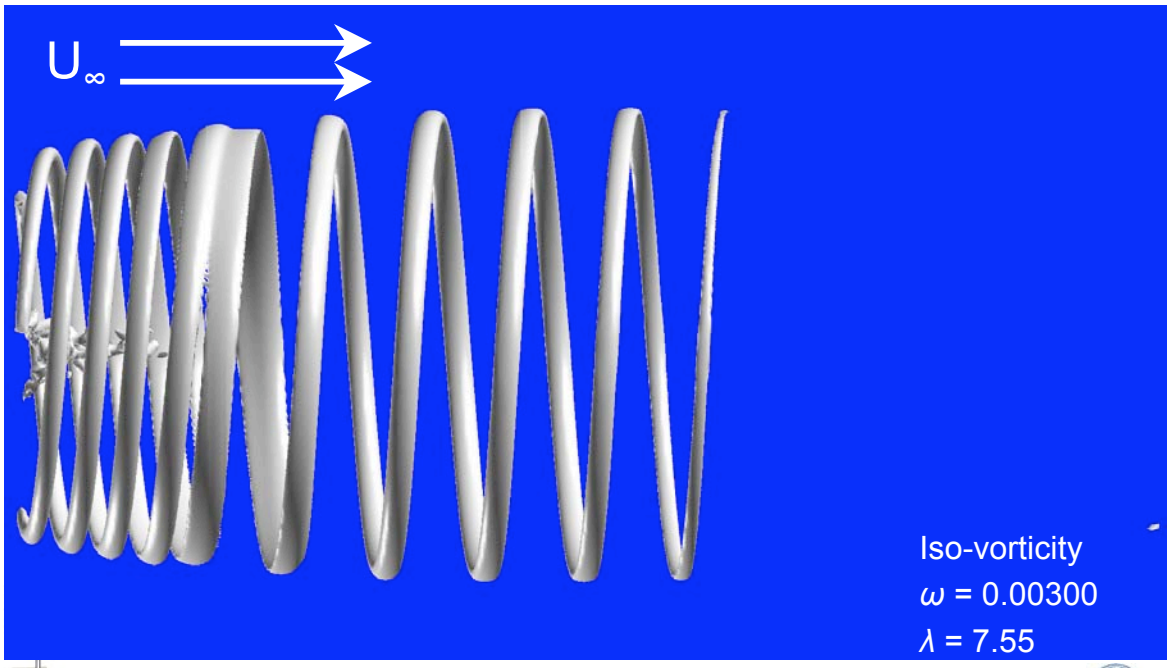


NREL 5-MW – U_∞ = 11 m/s

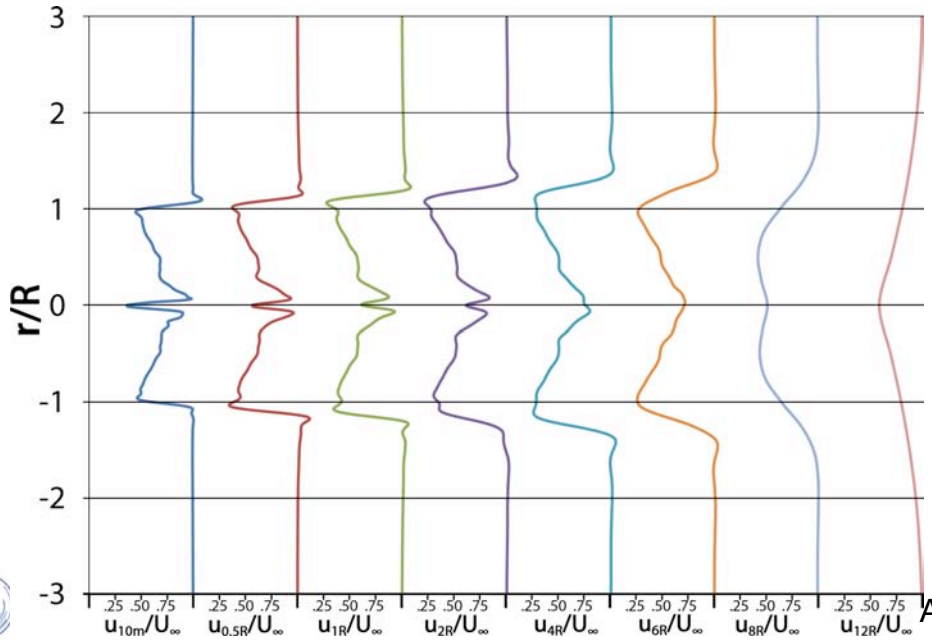


Axial velocity
λ = 7.13

NREL 5-MW – U_∞ = 8 m/s



NREL 5-MW – U_∞ = 8 m/s



Axial velocity
λ = 7.55

NREL 5-MW Conclusions

- Extensive grid independence and external validation were performed to ensure baseline solution accuracy
- Existence of extensive inboard flow separation was verified
- Inboard blade geometry modifications as well as nacelle effect are being studied

Validation: NREL 5-MW Rotor

- State-of-the-art rotor configuration
  - Pitch-to-feather
  - High performance airfoil sections
  - High Reynolds number
- Extensively studied in EU UpWind Project
- Observations:
  - Blade geometry not uniquely defined
  - No experimental results available
  - Code-to-code comparisons only

Final Observations

- Simulations of wake development critically affected by grid
- Wake development significantly affected by rotor TSR and aerodynamic loading
- Experimental results to validate rotor simulations in terms of aerodynamic loading, performance, and wake development for state-of-the-art turbines at full-scale conditions are sorely lacking