Unstructured CFD for Wind Turbine Analysis

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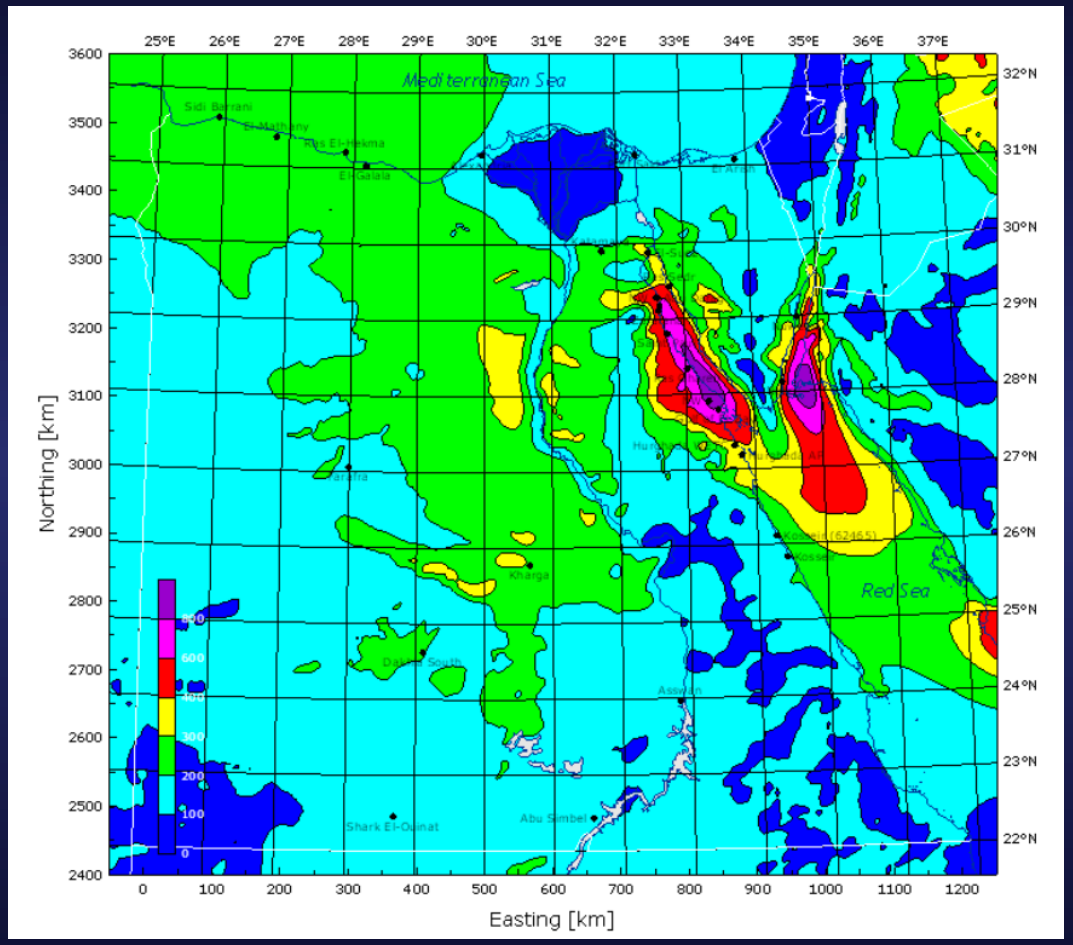
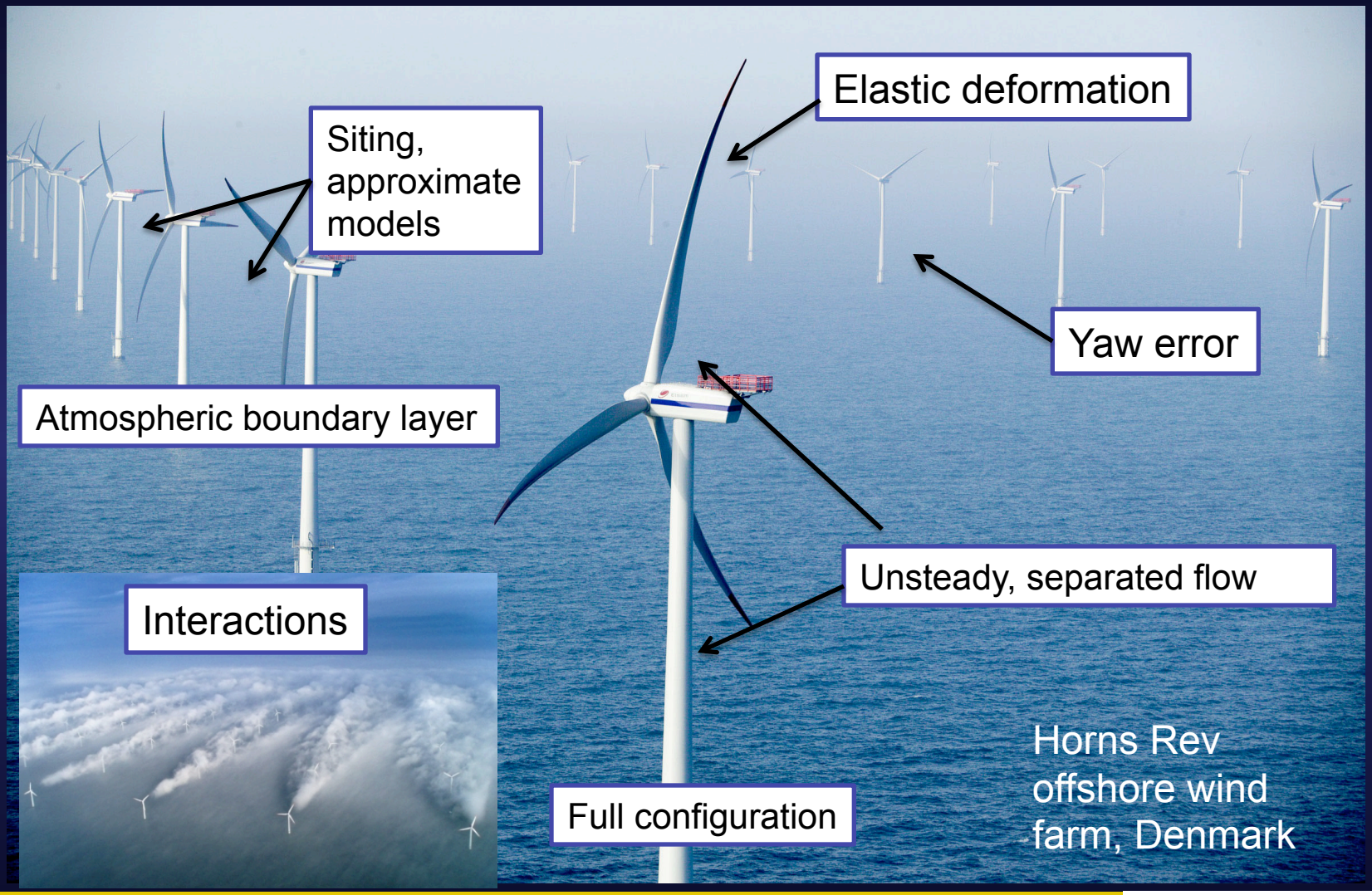
Wind availability: Egypt

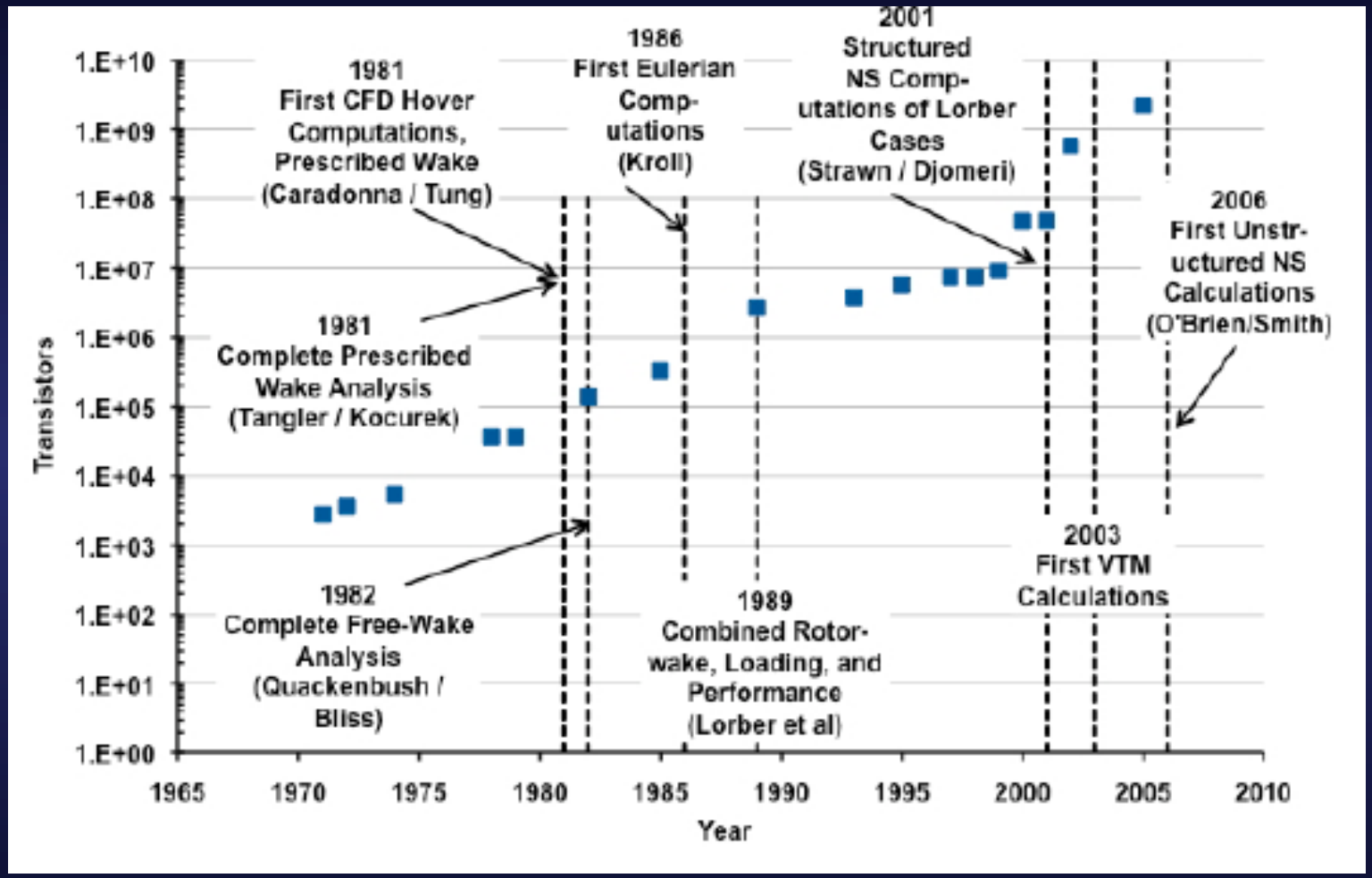


- Extremely high wind availability on Red Sea coast
- Good to moderate wind availability in other portions

Wind Turbine Aeromechanics



Numerical Advances



Euler/Navier-Stokes Formulations

- Major goal of Euler/Navier-Stokes methods was ability to capture nonlinear effects without resorting to lower-fidelity methods that need empirical models
- Formulations include structured and unstructured, overset, chimera, etc., most typically finite-volume or finite-difference
- Dissipation of the wake vorticity remains biggest issue in long-age wake problems
  - Grids too large for engineering applications
  - Restrictive computational requirements
- Other research areas:
  - Turbulence modeling
  - Transition from laminar to turbulent flows

Emerging Technologies

- Reduced Unsteady Blade Models
- "Intelligent" Algorithms for CFD Spatial and Temporal Multi-scales
- Improved Hybrid Methods to Resolve the Far Wake:
  - Cartesian CFD with Grid Adaptation/Refinement
  - Vorticity Transport Methods
  - Vorticity Confinement Methods
  - Vortex Element Methods

CFD Methods

- National Research Codes
  - e.g., OVERFLOW, FUN3D
  - Pro: CS supported, many features, source code, no cost
  - Con: Access by US citizens only
- Commercial Codes
  - e.g., FLUENT, CFD++
  - Pro: Access by everyone, CS supported, many features
  - Con: Executables only, pay to use, highly dissipative to improve code robustness
- International Research Code
  - OpenFOAM
  - Pro: Access by everyone, many developers support, no cost
  - Con: Not as many features as other two categories

Prior CFD Efforts

- Hybrid RANS-VE method for single blade (Sankar *et al.*)
- Incompressible, non-inertial (Sorensen *et al*. 2002)
- Pinpointing of separation as source of unsteadiness (Le Pape and Lecanu 2004)
- Structured overset (Duque 1999)
- Comparison of structured overset with comprehensive analysis (Duque 2003)
- Time-accurate overset incompressible with tower (Zahle 2004, 2007)
- Unstructured non-inertial with grid adaptation (Potsdam, 2009)

Importance of Turbulence modeling

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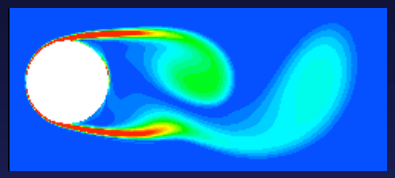
Eddies with Energy

Inertial Subrange

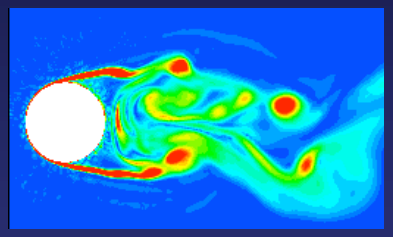
η

Viscous Range

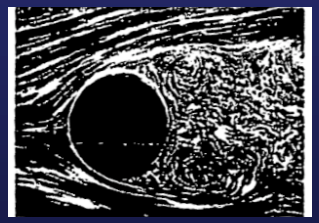
Turbulence Scales



RANS



Hybrid RANS-LES



Experiment[1]

RANS

VLES

LES

DNS

100%

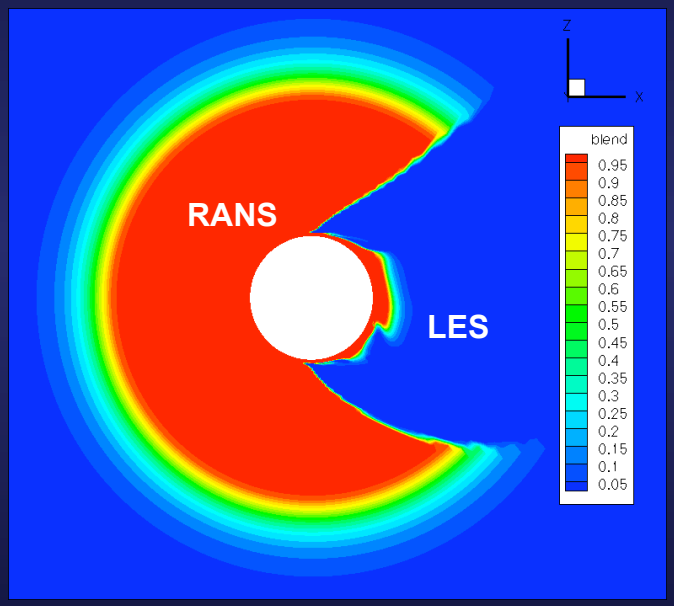
0%

Statistical Modeling of Turbulence

[1]Wilcox, D. C., Turbulence Modeling for CFD, DCW Ind., 2004

Hybrid RANS/LES

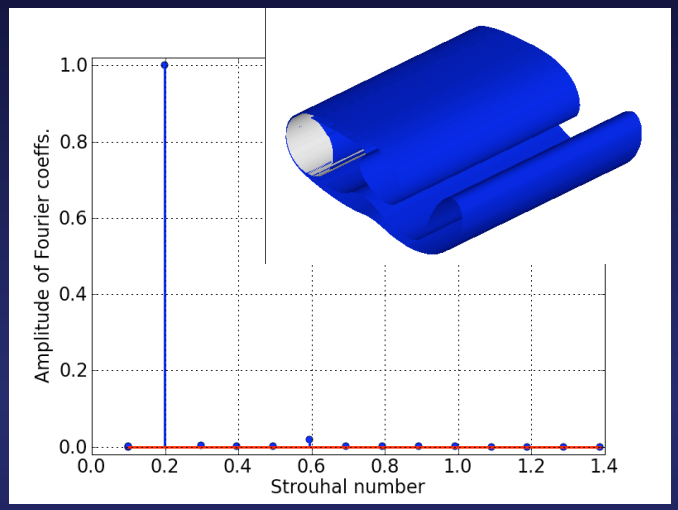
- Use RANS near the wall where finest grids are required
- Use LES away from wall to model largest turbulent eddies
- Detached Eddy Simulation (DES) is a common form of hybrid model
- Georgia Tech HRLES-sgs model:
  - RANS based on Menter's k-ω SST, solving for turbulent kinetic energy and dissipation
  - LES based on Menon and Kim constant coefficient k-Δ model
  - Two sets of equations are linearly blended using a blending function



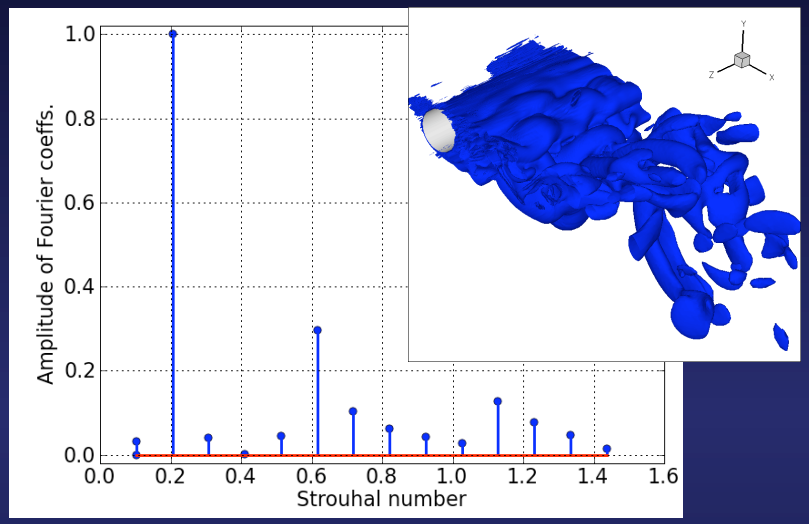
- HRLES-sgs shown to capture more physics and provide better performance predictions even on RANS mesh sizes

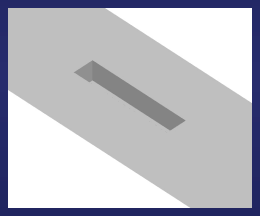
HRLES-sgs versus RANS

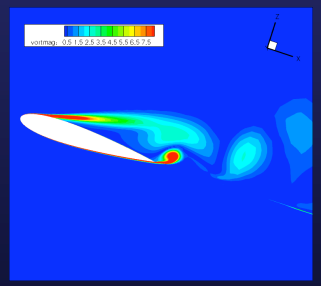
SST

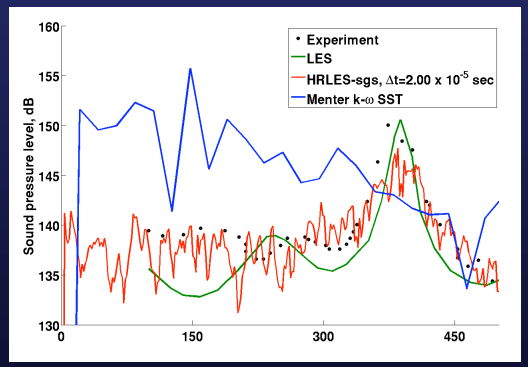


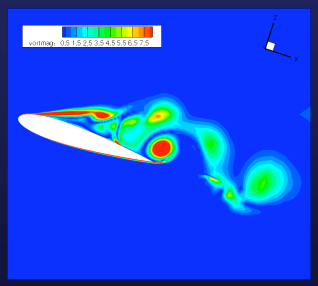
HRLES









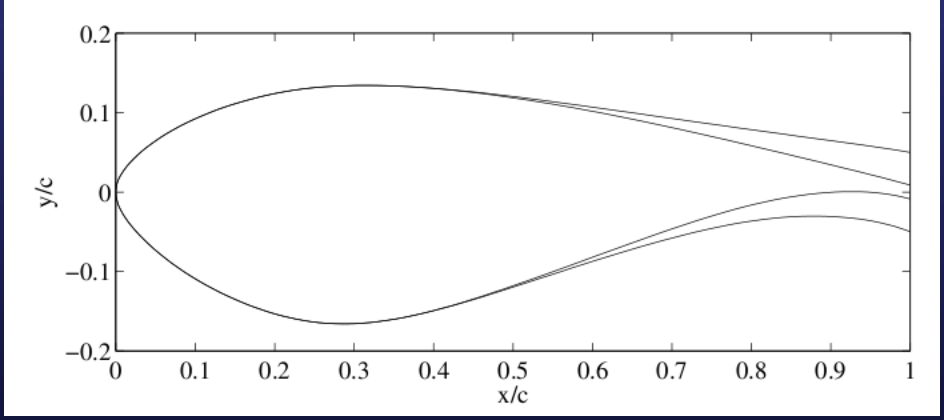


Flatback airfoil test case

- Attempt to emulate wind tunnel tests of Berg and Zayas (2008)
- DU97 flatback airfoil with 10% thick trailing edge
- Wind tunnel wall porous effects not known

- Compressible, M = 0.2
- Re = 3×10^6
- $\alpha = 10^o$
- $\Delta t = 0.005$,

~ 500 steps/cycle

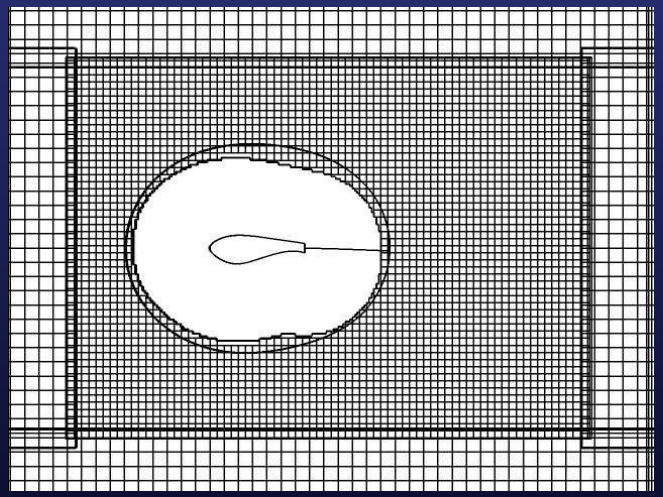


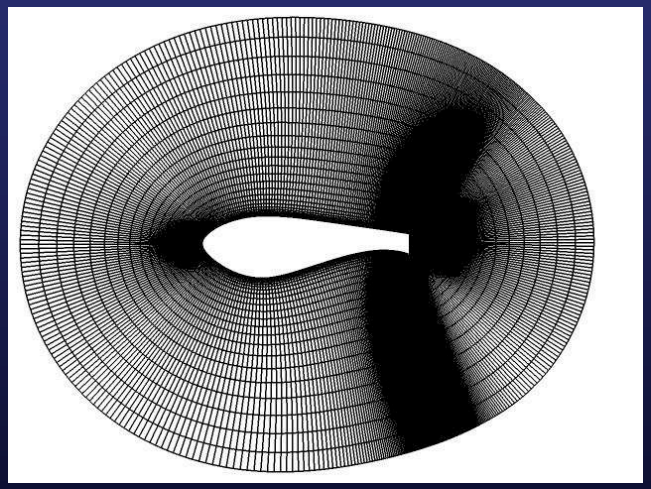
Computational Grids

Results vary significantly with grid topology/resolution:

1. Prismatic with tunnel walls, 5h/33, 108k nodes per plane, periodic BC

2. Hex overset with farfield boundaries, 5h/33, 7.2M nodes

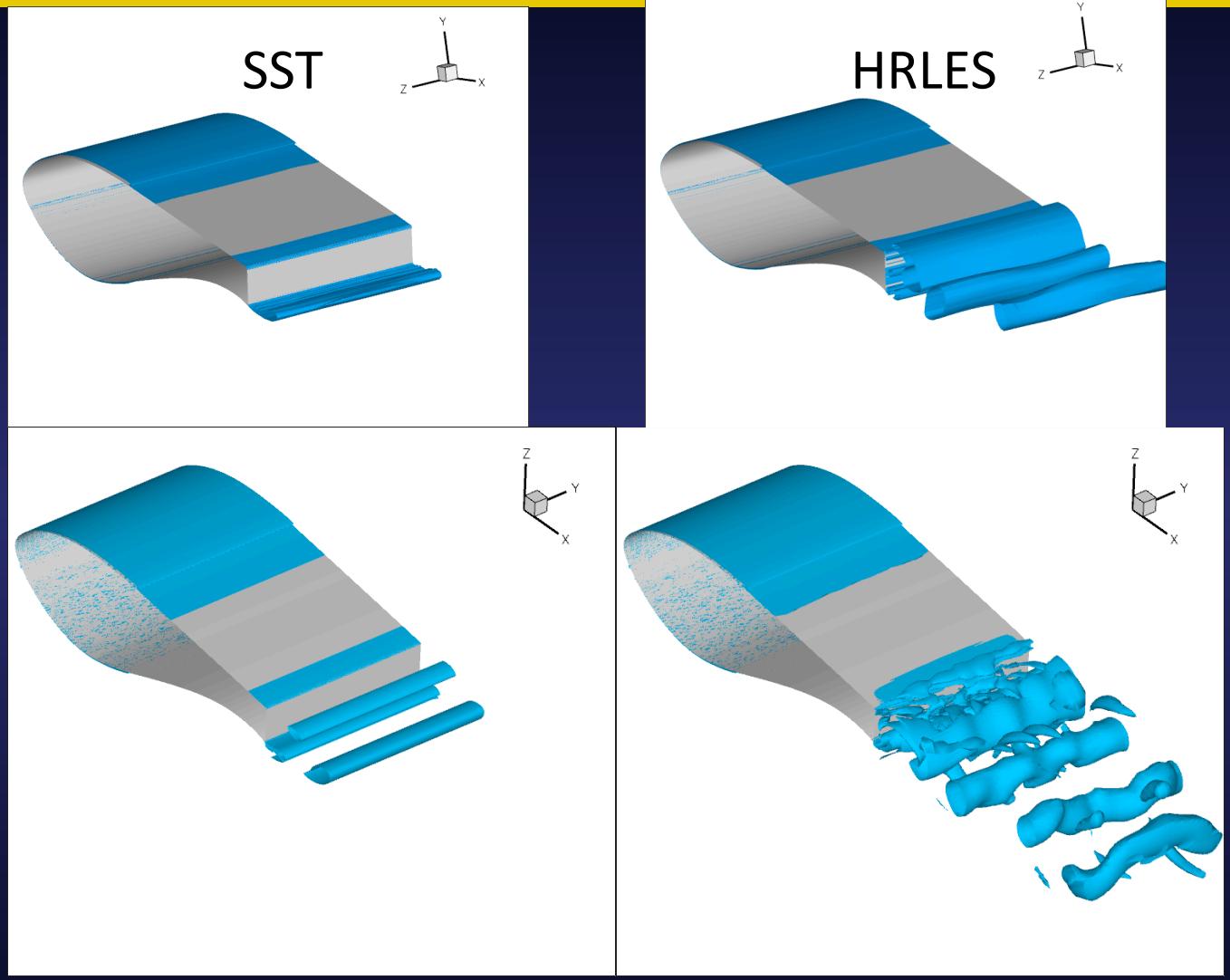




Vortex shedding: Q criterion

Prismatic, w/ tunnel walls, periodic BC in spanwise dir.

Hex grid, overset, farfield BCs



Mean forces and Strouhal number

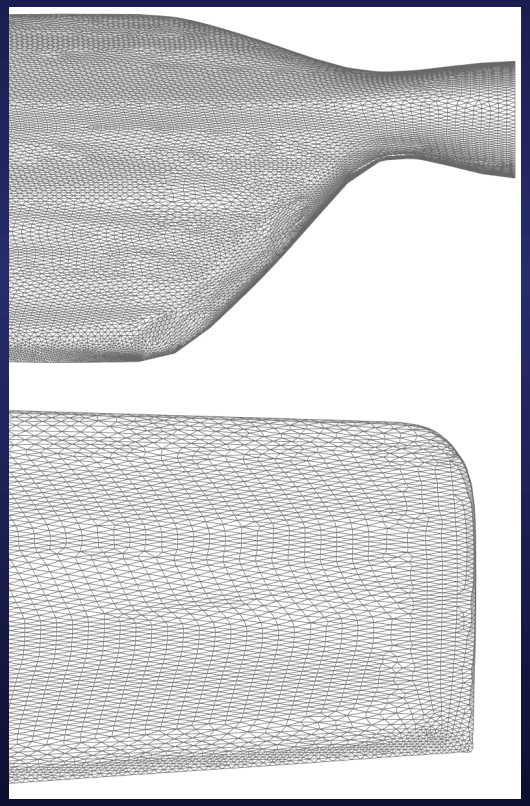
Grid	Model	Code	Mean CL	Mean CD	Strouhal
-	Experiment	-	1.57 ± 0.13	0.055 ± 0.005	0.24 ± 0.01
Prismatic with walls	SST	FUN	1.87	0.0493	0.088
"	HRLES	FUN	1.88	0.0740	0.088, 0.15
Hex overset, farfield	SST	FUN	1.615	0.039	0.177
"	HRLES	FUN	1.647	0.061	0.182

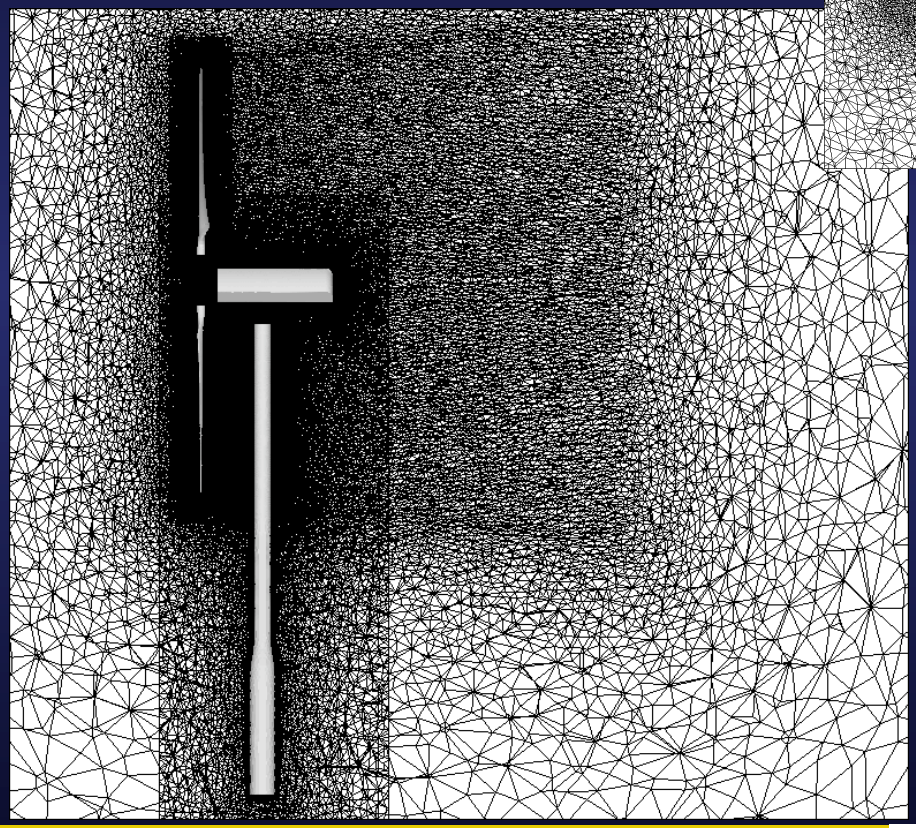
NREL Phase VI cases

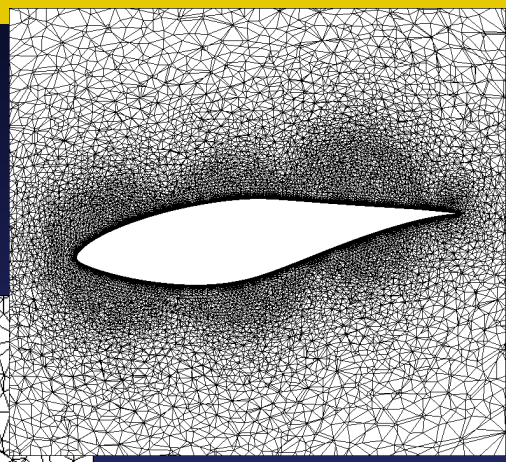
- 7, 13, and 15 m/s upwind baseline cases at zero yaw
- Compared against Sequence S (no probes, free transition) and Sequence M (no probes, tripped)
- Found very few transitional effects, so only untripped results shown here

Full Wind Turbine Grids

- 2.6M nodes per blade volume grid
- 129k surface triangles per blade
- 7.2M total







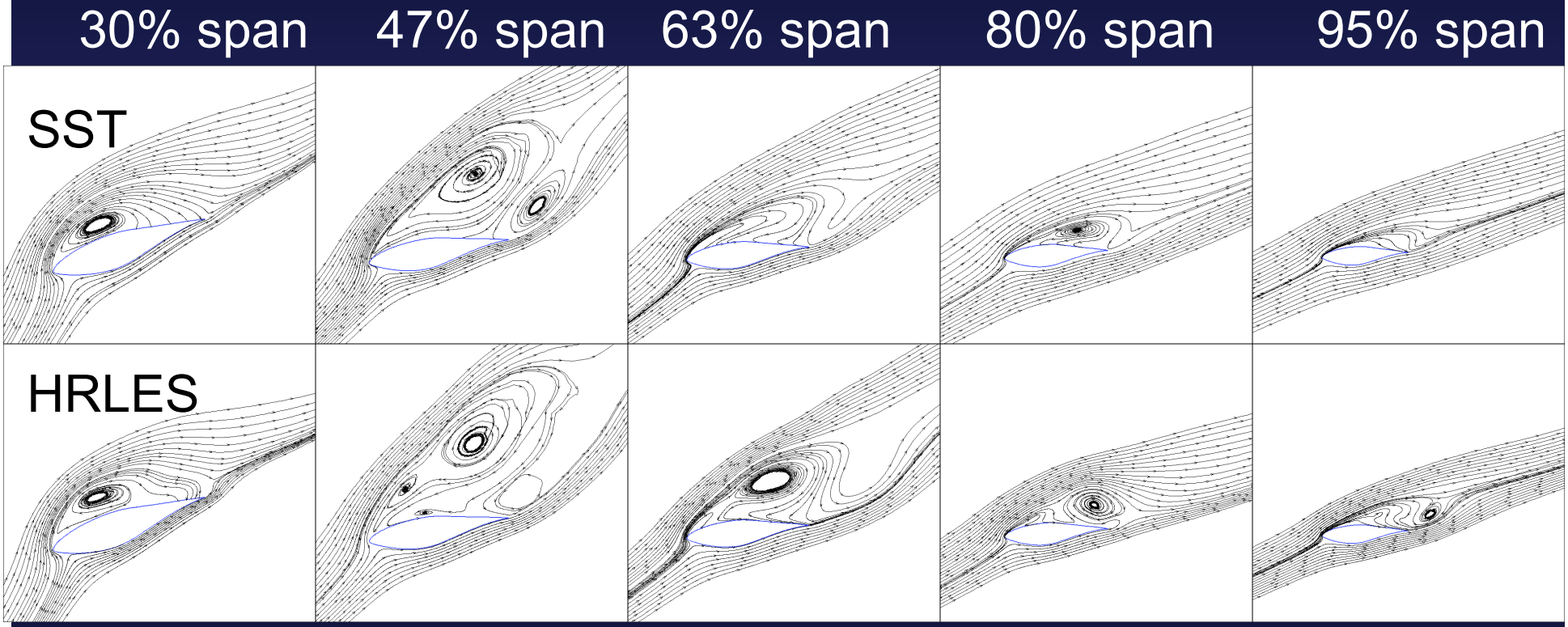
Integrated loads

Wind speed (m/s)	Code	Turb. model	Root flap bending moment (N-m)	Torque (N-m)
15	Exp. S		2750 ± 260	1172 ± 95
	FUN3D	SST	3067	922
	FUN3D	HRLES	2898	646
	OF	SST	2789	988

- Unstructured method captures root bending moment within experimental limits
- Low torque predictions common to structured mesh as well
- Blade tip modeling inconsistencies were observed.

OVERFLOW results courtesy of Dr. Chris Stone, *Computational Science, LLC*

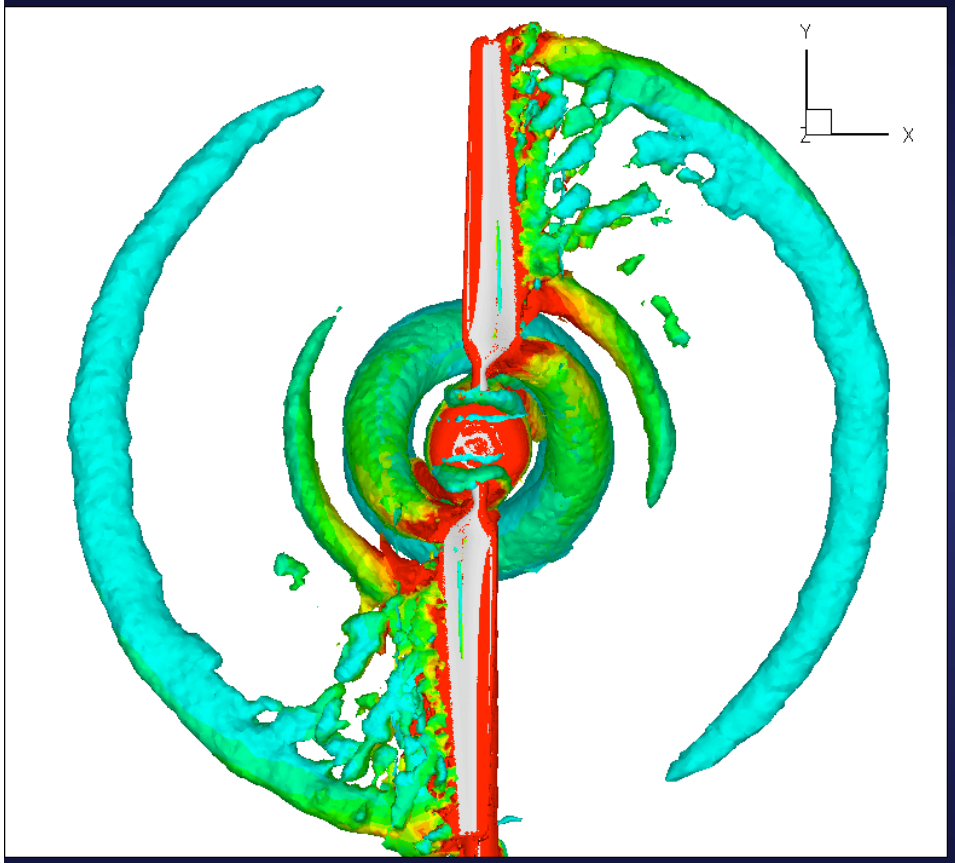
Instantaneous streamlines



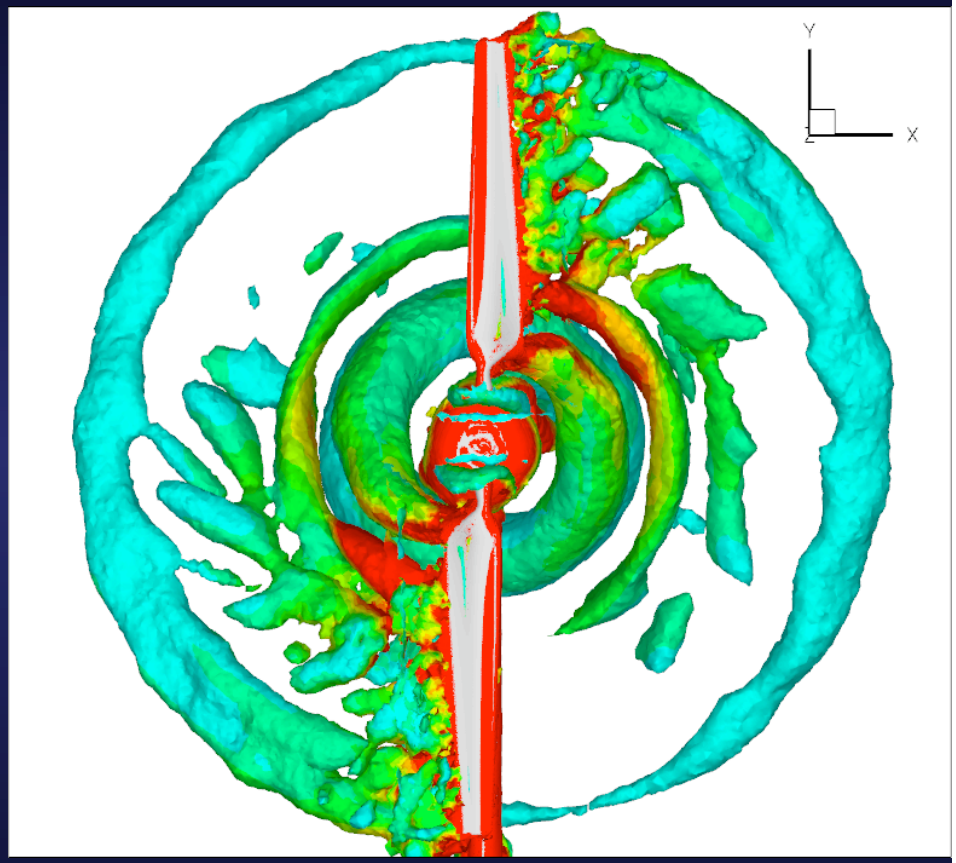
Instantaneous streamlines at 0 degrees azimuth

Rotor near wake: Q criterion

k-w SST



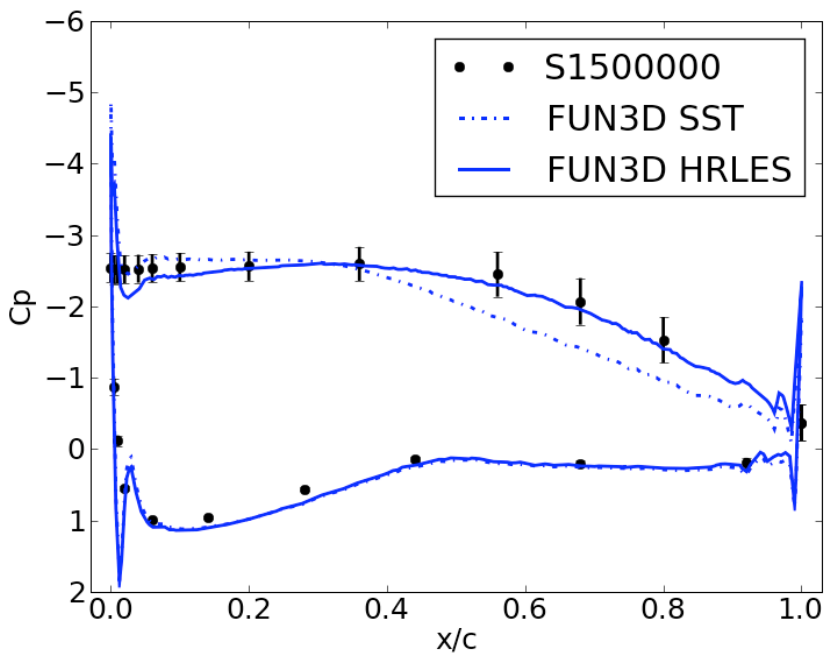
HRLES



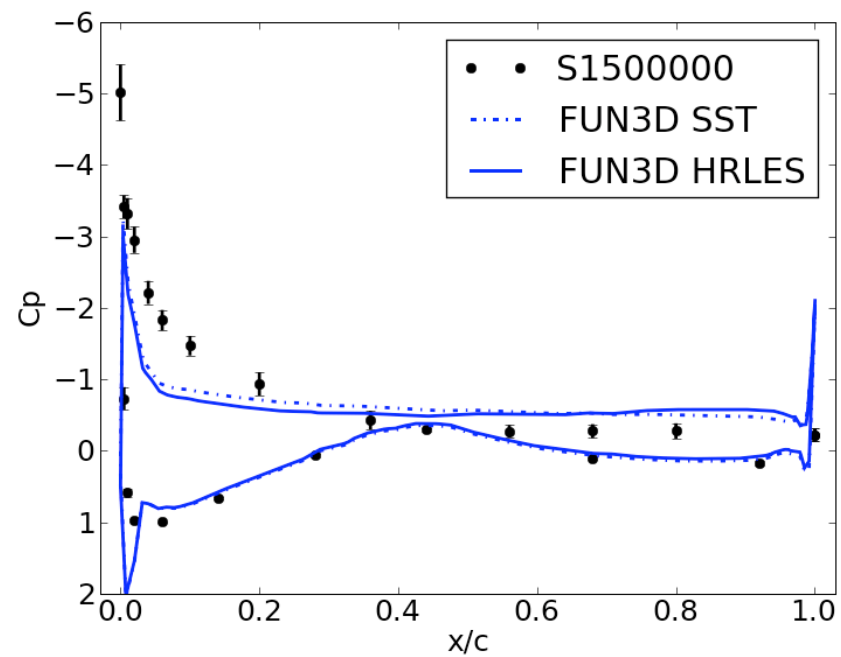
Q = 1 x 10^{-4} iso-surfaces, colored by vorticity magnitude, after 5 revs

Blade Pressure Distributions

Cp at 30% span



Cp at 95% span



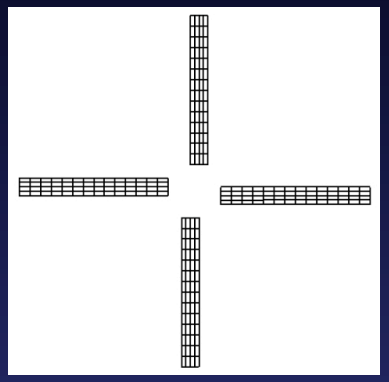
- Well within experimental error bars near root.
- Less so at tip where grid problems are most pronounced

Actuator Methods

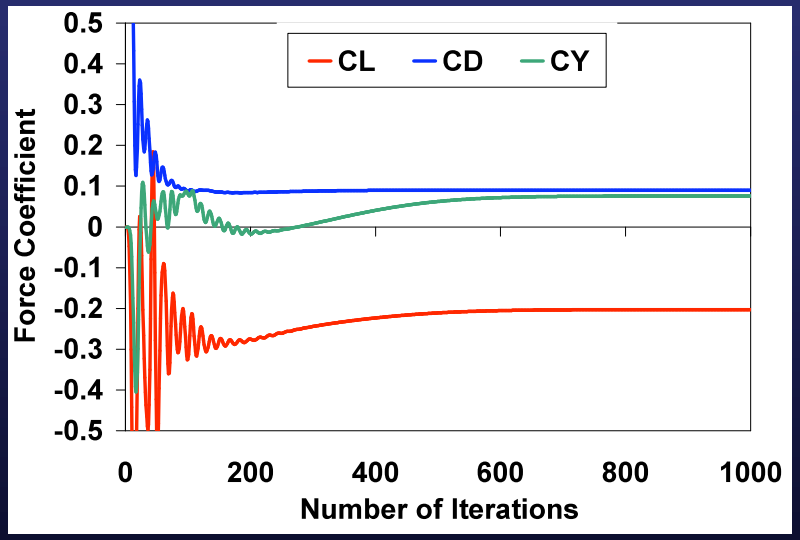
- A compromise between full rotor CFD and lower fidelity methods
- Based on momentum theory
- Remove the rotor and model its influence on the flow field
- Can be implemented as a pressure discontinuity BC or as body forces (source terms) in interior
- Efficient because need not model blade geometry or boundary layers

Actuator blades/lines

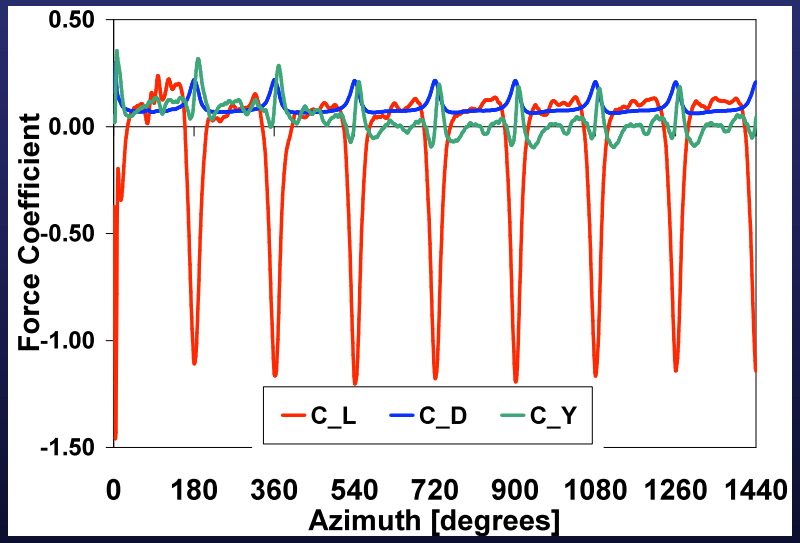
- Locate sources along lines or moving surfaces
- Source strength comes from BEM or comprehensive methods



Actuator disc

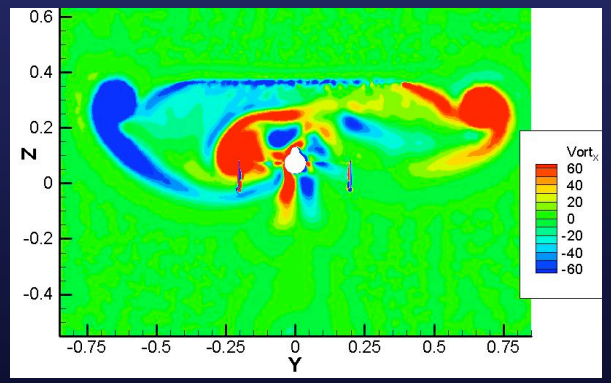


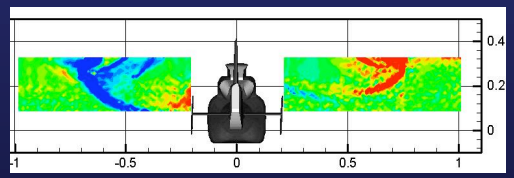
Actuator blades



Actuator blade improvements

- Sources must be associated with a grid node, entailing a search at each time step – recent work increases search speed by 20%
- Coupling with DYMORE to use its finite-state aerodynamics model to determine source strengths with azimuth





T. Renaud, M. Potsdam, D. M. O'Brien, Jr., and M. J. Smith, "Evaluation of Isolated Fuselage and Rotor-Fuselage Interaction Using CFD," 60th AHS Annual Forum, Baltimore, MD, June 2004.

Current & Future work

- Improve quality of surface definition
- Evaluate sensitivity to grid quality and spacing
- Transition model for critical speed (10m/s)
- Yawed cases to better demonstrate advantages of full configuration CFD
- Use incompressible method to avoid low Mach converge and accuracy problems
- CFD-CSD coupling to capture blade flexibility
- Addition of atmospheric boundary layer model

Conclusions

- Hybrid turbulence models improve sectional loads and surface pressures in separated regions
- With HRLES, more of the unsteady wake physics is observed in the rotor wake
- Grids cannot be readily used from their structured counterparts as they can result in poor unstructured meshes
- Actuator blades hold promise to model wind farms by capturing individual rotor wakes

Acknowledgments

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- Thanks to Scott Schreck for the NREL Phase VI datasets