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
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

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

US-Egypt Workshop on Wind Energy Development
Cairo, Egypt, March 22-24, 2010
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, $M = 0.2$
- $Re = 3 \times 10^6$
- $\alpha = 10^\circ$
- $\Delta t = 0.005$, ~500 steps/cycle
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

SST

HRLES
### Mean forces and Strouhal number

<table>
<thead>
<tr>
<th>Grid</th>
<th>Model</th>
<th>Code</th>
<th>Mean CL</th>
<th>Mean CD</th>
<th>Strouhal</th>
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<tbody>
<tr>
<td>-</td>
<td>Experiment</td>
<td>-</td>
<td>1.57 ± 0.13</td>
<td>0.055 ± 0.005</td>
<td>0.24 ± 0.01</td>
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<tr>
<td>Prismatic with walls</td>
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<td>FUN</td>
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<td>0.0740</td>
<td>0.088, 0.15</td>
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<td>Hex overset, farfield</td>
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<td>0.061</td>
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</table>
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

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Code</th>
<th>Turb. model</th>
<th>Root flap bending moment (N-m)</th>
<th>Torque (N-m)</th>
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<tbody>
<tr>
<td>15</td>
<td>Exp. S</td>
<td></td>
<td>2750 ± 260</td>
<td>1172 ± 95</td>
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<tr>
<td></td>
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<td>3067</td>
<td>922</td>
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<tr>
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<td>646</td>
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<tr>
<td></td>
<td>OF</td>
<td>SST</td>
<td>2789</td>
<td>988</td>
</tr>
</tbody>
</table>

- 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 at 0 degrees azimuth

<table>
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<tr>
<th>30% span</th>
<th>47% span</th>
<th>63% span</th>
<th>80% span</th>
<th>95% span</th>
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</table>

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Rotor near wake: Q criterion

k-w SST

HRLES

Q = 1 \times 10^{-4} iso-surfaces, colored by vorticity magnitude, after 5 revs
Blade Pressure Distributions

• 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

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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