Aerodynamics and Aeroacoustics of a Wind Turbine Airfoil using Wall Modeled Large Eddy Simulation

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Introduction

- Noise generated by a turbulent boundary layer that encounters the trailing edge of an airfoil

Fig: Wolf et al., 2012
Motivation

Google Images

Oerlemans et al., 2007
Motivation

- Trailing edge noise dominates modern wind turbine noise
- Semi-empirical wind turbine noise prediction methods not robust enough
- RANS not reliable for predicting stall
- Aerodynamics and acoustics from first principles – a pacing item and a challenge

• Why Wall Modeled LES (WMLES)?
• WMLES of canonical turbulent flows
• WMLES of flow past a wind turbine airfoil
• Conclusions and ongoing work
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LES of a wall bounded turbulent flow – The challenge of high Reynolds number

- Scale disparity between production and dissipation exists only away from the wall
- Wall Resolved LES grid needs to be very fine close to a wall
- Consequence - Number of grid points \( N_g \propto \text{Re}_x^{13/7} \)
- Wall Resolved LES is prohibitively expensive at large Reynolds numbers

Filled contours – co-spectra of tangential Reynolds stress (production), Line contours – Spectra of vorticity magnitude (surrogate for dissipation). Results from DNS of turbulent channel flow at a friction Reynolds number of 2000

Jimenez, 2012  Choi and Moin, 2012
### Implication for wind turbine noise predictions

<table>
<thead>
<tr>
<th>Contributors</th>
<th>Year</th>
<th>Configuration</th>
<th>Number of grid points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wang and Moin (LES)</td>
<td>2000</td>
<td>Hydrofoil ( \text{Re}_c = 2.15 \times 10^6 )</td>
<td>~7 Million</td>
</tr>
<tr>
<td>Wang et al. (LES)</td>
<td>2009</td>
<td>CD airfoil ( \text{Re}_c = 1.5 \times 10^5 )</td>
<td>~5 Million</td>
</tr>
<tr>
<td>Moon et al. (LES)</td>
<td>2010</td>
<td>Flat Plate ( \text{Re}_c = 1.3 \times 10^5 )</td>
<td>~3 Million</td>
</tr>
<tr>
<td>Winkler et al. (LES)</td>
<td>2012</td>
<td>NACA 6512-63 ( \text{Re}_c = 1.9 \times 10^5 )</td>
<td>~3 Million</td>
</tr>
<tr>
<td>Wolf et al. (LES)</td>
<td>2012</td>
<td>NACA 0012 ( \text{Re}_c = 4.08 \times 10^5 )</td>
<td>~54 Million</td>
</tr>
<tr>
<td>Jones and Sandberg (DNS)</td>
<td>2012</td>
<td>NACA 0012 with serrated TE ( \text{Re}_c = 5 \times 10^4 )</td>
<td>~170 Million</td>
</tr>
<tr>
<td>GE-Stanford Project</td>
<td>2012</td>
<td>DU96 ( \text{Re}_c = 1.5 \times 10^6 )</td>
<td>~127 – 180 Million</td>
</tr>
</tbody>
</table>

- WRLES of airfoil trailing edge noise restricted to low Reynolds numbers
- NREL 5MW offshore wind turbine – \( R = 63\text{m}, V = 9\text{m/s}, \omega = 1.08\text{rad/s}, \ r = 7.55, \ \text{Re}(r = 3/4R) = 12 \times 10^6 \)

\( R \) – rotor radius
\( V \) – wind speed
\( \omega \) – rotation rate
\( r \) – tip speed ratio

Bazilevs et al., 2010
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WMLES of turbulent channel flow, $Re_\tau \sim 590$, DNS $\sim 25M$ points, WMLES $\sim 1M$ points
WMLES of turbulent channel flow, $\text{Re}_{\tau} \sim 1440$, DNS $\sim 500\text{M points}$, WMLES $\sim 1\text{M points}$

WM matching location
WMLES of turbulent boundary layer over a flat plate, $Re_\theta \sim 4060$, DNS $\sim 3B$ points, WMLES $\sim 7M$ points
WMLES of turbulent boundary layer over a flat plate, $Re_\theta \sim 5160$, DNS $\sim 64B$ points, WMLES $\sim 7M$ points.
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WMLES of turbulent flow past a DU96 airfoil

- Configuration – DU96 airfoil at an angle of attack of 6.2 degrees, chord based Reynolds number of 1.5M
- Comparisons made with WRLES from GE

<table>
<thead>
<tr>
<th>Grid</th>
<th>Domain size</th>
<th>Grid points</th>
<th>CPU hours/ chord FTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMLES</td>
<td>40Cx40Cx0.06C</td>
<td>~23.2M</td>
<td>~11500 (Certainty cluster, Stanford)</td>
</tr>
<tr>
<td>WRLES, GE</td>
<td>22Cx27Cx0.06C</td>
<td>~127.7M</td>
<td>~6.8x10⁵ (Blue Gene/P, BNL)</td>
</tr>
<tr>
<td>WRLES, Stanford</td>
<td>12.5Cx12Cx0.06C</td>
<td>~180M</td>
<td>~1.7x10⁵ (Red Sky cluster, Sandia)</td>
</tr>
</tbody>
</table>
Wall model in the laminar region

\[ \frac{d}{d\eta} \left( (\mu + \mu_{t,wm}) \frac{du_\parallel}{d\eta} \right) = -S_m(\eta), \]

\[ \frac{d}{d\eta} \left( (\mu + \mu_{t,wm}) u_\parallel \frac{du_\parallel}{d\eta} + (\lambda + \lambda_{t,wm}) \frac{dT}{d\eta} \right) = -S_e(\eta), \]

\[ \mu_{t,wm} = \kappa \eta \sqrt{\rho T_w} \left[ 1 - \exp \left( -\frac{\eta^+}{A^+} \right) \right]^2 \quad \text{with} \quad A^+ = 17, \ \kappa = 0.41 \]

Bodart and Larsson, 2011

- RANS equations are not justified in the laminar region
- If eddy viscosity is switched off locally, the wall model becomes a weak form implementation of no slip BC up to O(y_m)
- If the RANS-LES matching location y_m is close enough to the wall (y_m^+ \sim O(1)), the wall model automatically reverts to no slip BC (The eddy viscosity is inactive)
The need for transition treatment

- Wall model reverts to no slip BC if matching location is too close
- Unphysical transition if matching location is in inertial region of the trailing edge boundary layer
- Eddy viscosity gets switched on too early
- No slip BC needs to be explicitly enforced in the laminar region
Transition treatment

- Airfoil split into two ZONES – airfoil_noslip (top) and airfoil_wm (bottom) in a preprocessing step
- No slip BC in laminar region and stress BC in turbulent region
- Input from WRLES/Experiments on transition location
- *Law of the wall* does not hold in the transitional region
Comparison with WRLES results: $C_p$

WM matching location – 0.0025c, WM beyond $x/c = 0.5$ on SS and $x/c = 0.8$ on PS
Comparison with WRLES results: $C_f$

WM matching location – 0.0025c, WM beyond $x/c = 0.5$ on SS and $x/c = 0.8$ on PS
Improving transition prediction on pressure side using local grid refinement
WMLES of flow past a DU96 airfoil at an angle of attack of 10.3 degrees: Convergence of suction peak
Predicting wind turbine stall using WMLES

![Graph showing comparison between RANS, Rfoil, WMLES, and NREL experiment results.](image-url)
Preliminary noise prediction: DU96 airfoil, $Re_c = 1.13 \text{M}$, $M = 0.173$, $\alpha = 4.0^\circ$ (BANC workshop, category 1, problem 5)
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Conclusions and ongoing work

• Low order statistics from WMLES of canonical turbulent flows show excellent agreement with DNS results
• Predictions from WMLES of flow past a DU96 airfoil compare favorably with results from WRLES
• Predicted wind turbine stall from first principles using WMLES
• Far field noise prediction in progress
Acknowledgements

• Dr. F. Ham and Dr. G. Bres
• Carlo, Julian, Ivan and other developers of CharLESX
• Dr. R. Balakrishnan
• Present and past members of Lele group
Backup slides
Preliminary noise prediction: DU96 airfoil, $Re_c = 1.13 \times 10^6$, $M = 0.173$, $\alpha = 4.0^\circ$ (BANC workshop, category 1, problem 5): Assessment of statistical uncertainty
WM matching locations

- Channel flow calculations – H/10
- Boundary layer calculations - δ/10
- Airfoil – 0.0025c – δ_{t.e,s.s}/14.4, δ_{t.e,p.s}/6.8
- Airfoil – 0.00375c – δ_{t.e,s.s}/9.6, δ_{t.e,p.s}/4.5
- Airfoil – 0.00125c – δ_{t.e,s.s}/28.8, δ_{t.e,p.s}/13.6
- Airfoil – 0.0025c – 84u_{τ,t.e,s.s}/ν, 174u_{τ,t.e,p.s}/ν
- Airfoil – 0.00375c – 126u_{τ,t.e,s.s}/ν, 261u_{τ,t.e,p.s}/ν
- Airfoil – 0.00125c – 42u_{τ,t.e,s.s}/ν, 87u_{τ,t.e,p.s}/ν
Resolution close to trailing edge: G2

- \( \Delta x_w \sim \delta_{t.e,s.s}/30, \ \Delta y_w \sim \delta_{t.e,s.s}/100, \ \Delta z_w \sim \delta_{t.e,s.s}/15 \)
- \( \Delta x_w^* \sim 40, \ \Delta y_w^* \sim 12, \ \Delta z_w^* \sim 80 \) (Wall units based on suction side boundary layer close to the trailing edge)
Addressing the challenge of high Reynolds number

- The scale disparity between outer and inner scales responsible for $N_g \propto Re_x^{13/7}$

- Remedy - inner scales not resolved

- Effect on outer scales modeled using a stress boundary condition

- Outer eddies scale with the local boundary layer thickness – weak dependence on $Re_x$

Consequence - Number of grid points ($N_g$) $\propto Re_x$

Instantaneous streamwise velocity field from DNS of a turbulent boundary layer at $y^+ = 15$. Friction Reynolds numbers (top to bottom) - 251, 497, 1116

Pirozzoli and Bernardini, 2011  Choi and Moin, 2012
Modeling the effect of *inner* scales

- *Detached* eddies feel the no slip BC *indirectly* through the mean shear
- The inertial layer is in equilibrium – Production balances dissipation
- If the right mean shear is generated through a stress BC, the *detached* eddies can be simulated accurately
- *Law of the wall* generates a sufficiently accurate mean shear for equilibrium flows

The ratio of turbulent kinetic energy production to dissipation as a function of wall normal distance. Results from DNS of turbulent channel flow.

Solid surface FWH predictions validated against porous surface FWH predictions (Effect of end cap averaging): DU96 airfoil, $Re_c = 1.13M$, $M = 0.2$, $\alpha = 4.4^\circ$
Solid surface FWH predictions validated against porous surface FWH predictions (Effect of FWH surface location) : DU96 airfoil, Re$_c = 1.13M$, M = 0.2, $\alpha = 4.4^\circ$
WMLES methodology (CharLES)

- Compressible Navier-Stokes equations with constant coefficient Vreman sub-grid scale model on the LES grid
- Time-independent ODEs in wall normal direction based on the equilibrium assumption and an algebraic eddy viscosity model with wall damping for turbulence on the RANS grid

Bodart and Larsson, 2011
Wall model equations

\[
\frac{d}{d\eta} \left( (\mu + \mu_{t,wm}) \frac{du_{\parallel}}{d\eta} \right) = -S_m(\eta),
\]

\[
\frac{d}{d\eta} \left( (\mu + \mu_{t,wm}) u_{\parallel} \frac{du_{\parallel}}{d\eta} + (\lambda + \lambda_{t,wm}) \frac{dT}{d\eta} \right) = -S_e(\eta),
\]

\[
\mu_{t,wm} = \kappa \eta \sqrt{\rho \tau_w} \left[ 1 - \exp \left( -\frac{\eta^+}{A^+} \right) \right]^2 \quad \text{with} \quad A^+ = 17, \quad \kappa = 0.41
\]

\[
\lambda_{t,wm} = \mu_{t,wm} c_p / Pr_{t,wm} \quad Pr_{t,wm} = 0.9
\]

• No slip is the ‘correct’ BC everywhere
• Stress BC becomes necessary because near wall gradients are too steep to be resolved on the LES grid
• The wall-model matching location is in the inertial layer where the flow is well-resolved
• Matching location moved away from the first off-wall cell to avoid log-layer mismatch

Kawai and Larsson, 2011  Bodart and Larsson, 2011
WMLES of turbulent channel flow

- Domain size – 6H x 2H x 3H (x, y, z)

- Resolution - $\Delta x \sim H/16$, $\Delta y \sim H/260 - H/11$ ($\Delta y_{\text{avg}} \sim H/64$), $\Delta z \sim H/27$ (~ 1M points)

- Resolution not constrained in wall units

- Number of grid points required for WMLES of a turbulent boundary layer at a local $Re_\delta$ is independent of $Re_\delta$

- Results validated by comparison with DNS data

- Friction Reynolds numbers – 590, 1440
WMLES of turbulent boundary layer over a flat plate

- Domain size – $42\delta \times 6\delta \times 2.5\delta$ (x, y, z)

- Resolution – $\Delta x \sim \delta/17$, $\Delta y \sim \delta/646 - \delta/5$ (BL resolved by approximately 100 points), $\Delta z \sim \delta/26$ (~ 7M points)

- Synthetic turbulence at the inflow using digital filtering

- Numerical sponge with moving average target at the outflow

- Results validated by comparison with DNS data

- Approximate Momentum thickness Reynolds numbers – 4060, 5160
Improving suction peak prediction using local grid refinement