Application of Overset Grid Methods to Wind Turbine Rotors

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  - Scott Johnson
  - Henry Shiu

Et al.
Outline

- Wind Energy Overview
- Advanced Rotor Designs
  - BSDS blade
  - STAR blade
  - Active aerodynamic load control
  - Inboard flow separation mitigation
- Concluding Remarks
Why Wind Energy?

- Renewable
  - Guaranteed “fuel” availability
  - Large available resource in USA
  - No cost volatility
  - Does not rely on water

- Clean
  - Emission free operation
  - No waste generation

- Installation
  - Rapidly deployed

- Security
  - Non-centralized installation and operation
  - No imported fuel requirement

- Economics
  - Cost effective energy
  - Local economic benefits

Source: van Dam
Installed Wind Power Capacity

- In the 1980s, USA was the leader in installed wind-based electric power generation capacity.
- From the 1990s until recently, other countries outpaced the USA.
- Over the last few years, pace of installation in the USA has increased rapidly.

Reasons:
- Increase/uncertainty in fossil fuel prices
- PTC (Federal)
- RPS (States)
Global Installed Wind Energy Capacity

![Graph showing the growth of installed wind energy capacity from 2006 to 2010 for countries like USA, Germany, China, Spain, and India.]

![Pie chart showing the distribution of wind energy capacity in 2010 for countries like USA, China, Germany, Spain, and others.]

World Installed Capacity (159 GW) Start 2010
USA Installed Wind Energy Capacity

![Graph showing the increase in installed wind energy capacity from 2006 to 2010, with a line graph for each state, and a pie chart showing the top states: Texas (27.0%), Wyoming (11, 3.2%), North Dakota (10, 3.4%), California (3), and others.]

USA Installed Capacity (35 GW) Start 2010
Evolution of U.S. Utility-Scale Wind Turbine Technology

Source: NREL
Typical Wind Turbine Power Curve

- **I**: Wind Speed at Hub $V_{cut-in}$
- **II**: Normalized Power $V_{rated}$
- **III**: Sub-Rated Power
- **IV**: Rated Power $V_{cut-out}$
Basic Rotor Performance
(Momentum Theory)

Power in wind, \( P_w = \frac{1}{2} \rho V_w^3 A_d \)

Maximum rotor power, \( P = \frac{16}{27} P_w \)

Rotor efficiency, \( C_p = P / P_w \)

Betz limit, max \( C_p = \frac{16}{27} = 59.3\% \)
Efficiency of Various Rotor Designs
Butterfield (2008)

- $C_p = \frac{P_{\text{rotor}}}{(1/2 \rho V_w^3 A_d)}$
- Solidity = Blade Area / $A_d$
- TSR = Tip Speed / $V_w$
- High power efficiency for rotors with low solidity and high TSR
- Darrieus (VAWT) is less efficient than HAWT
- Current three-bladed rotors achieve high efficiency $C_p \Rightarrow 0.52$

Butterfield (2008)
Critical Performance Challenges to Meet Goal of 20% Wind by 2030

- Reduction in capital cost
  - Recently, turbine cost have increased sharply
- Increase in turbine capacity factor
  - Larger rotors for given rated power
- Reduced O&M cost
  - Rapid growth has resulted in reliability issues

Source: NREL
Increased Capacity Factor

- Larger rotors
  - Increased energy capture
  - Longer, lighter blades
  - Load alleviation (passive, active)
- Taller towers
  - Higher wind speeds
  - Innovative towers, erection methods
- Reduced losses
  - Improved drivetrains, power electronics
  - Wake losses
Innovations in Utility Scale Wind Turbines

Advanced Drive Trains

Advanced Blades

Advanced Tower Designs

Jack-up concept

Telescoping concept
## Utility Scale COE Reduction Potential

**Source:** Thresher, NREL

<table>
<thead>
<tr>
<th>Technology</th>
<th>Est. COE Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larger wind turbines (2-5 MW)</td>
<td>0% ± 5%</td>
</tr>
<tr>
<td>Advanced rotors and controls</td>
<td>-15% ± 7%</td>
</tr>
<tr>
<td>Advanced drive train concepts</td>
<td>-10% ± 7%</td>
</tr>
<tr>
<td>New tower concepts</td>
<td>-2% ± 5%</td>
</tr>
<tr>
<td>Improved availability and reduced losses</td>
<td>-5% ± 3%</td>
</tr>
<tr>
<td>Manufacturing improvements</td>
<td>-7% ± 3%</td>
</tr>
<tr>
<td>Region and site tailored designs</td>
<td>-5% ± 2%</td>
</tr>
</tbody>
</table>

- Flexible, more slender, higher tip speed, hybrid carbon-glass, active control, etc.
- Hybrid drive trains with low-speed PM generators, reduced cost PE, etc.
- Taller, modular, field assembled, load feedback control
- Better controls, siting and improved availability
- New manufacturing methods, volume production and learning effects
- Tailoring of larger 100 MW wind plant turbine designs to unique sites
Impact of Advanced Rotors on COE

- Baseline turbine
  - 2.0 MW with 90 m rotor
  - Annual average wind speed at hub height = 6.5 m/s
  - Capacity Factor = 0.327
  - COE = $0.085 /kWh

- Turbine with advanced rotor (blade loads unchanged from baseline)
  - 2.0 MW with 100 m rotor
  - Annual average wind speed at hub height = 6.5 m/s
  - Capacity Factor = 0.370
  - Increased cost for advanced blades (passive and/or active load control)
  - COE = $0.077 - 0.080 /kWh

- Estimated improvement in COE = 6 - 9.5 %
Blade System Design Study (BSDS)
Blade System Design Study (B SDS)

- Multi-phase study with goal to investigate and evaluate design and manufacturing issues for wind turbine blades in the one to ten megawatt size range
- DOE WindPACT award to TPI Composites
- Phase I resulted in preliminary design of 50 m blade
- Phase II focus was to validate gains identified in Phase I preliminary design by:
  - Building, testing, and flying scaled (9 m) prototype blades
  - Conducting more detailed aerodynamic evaluation
Parametric Scaling Results - Blade Thickness

Section shapes at 25% span for 30m blade

Blade laminate mass as a function of rotor diameter

Blade Weight (kg)

Rotor Diameter (m)

Baseline = 0.0116*D^3.0144
Thicker = 0.0108*D^3.0059
Thickest = 0.011*D^2.9867
Effect of Leading Edge Roughness on Sectional Lift

DU97-300mod, t/c = 0.30, Freudenreich (2004)
Innovative Design Approaches

- Flatback airfoil development
  - Structural / aerodynamic optimization
- Structurally optimized design
  - Thick airfoils – constant spar cap width / thickness
- Blade material evaluation
  - E-glass
  - Carbon / E-glass hybrid
  - S-glass
  - Carbon / wood / E-glass hybrid (Zebrwood)
Blunt Trailing Edge or Flatback Airfoils

- Time-averaged pressure distributions of the TR-35 and TR-35-10 airfoils at $\alpha = 8^\circ$, $Re = 4.5$ million, free transition
- Blunt trailing edge reduces the adverse pressure gradient on the upper surface by utilizing the wake for off-surface pressure recovery
- The reduced pressure gradient mitigates flow separation thereby providing enhanced aerodynamic performance
- Note that airfoil is not truncated (this affects airfoil camber distributions) but thickness distribution is modified to provide blunt trailing edge
**BSDS Airfoils**

- FB Airfoil Series (FB-XXXX-YYYY)
  - Presented in BSDS Phase I final report
  - XXXX = % maximum thickness to chord ratio × 100, e.g. 3500 → 35% t/c
  - YYYY = % trailing edge thickness to chord ratio × 100, e.g. 0875 → 8.75% t_te/c
- Flatback generated by symmetrically adding thickness about the camber line
- Present study investigates FB-3500 airfoil series
  - FB-3500-0050 (nominally sharp trailing edge)
  - FB-3500-0875
  - FB-3500-1750
Experimental Results: FB-3500-0050

- Leading edge transition sensitivity clearly shown
- Free transition stall occurs near 19° with maximum $C_l$ near 1.5
- Fixed transition stall near 2°, lift continues to increase post stall but airfoil still stalled as shown by dramatic drag increase
- Minimal Reynolds number effects
Experimental Results: FB-3500-0875

- Reduced in leading edge transition sensitivity
- Maximum $C_l$ approx. 1.65 and 0.9 for free and fixed, respectively
- Lift curve slopes similar for fixed and free transition
- For free transition, increased minimum drag compared to sharp trailing edge airfoil
Experimental Results : FB-3500-1750

- Further reduction of leading edge sensitivity
- Maximum $C_l$ near 2.2 (free) and 1.7 (fixed)
- Lift curve slope in excellent agreement
- Sharp stall behavior for fixed transition
- Nearly four-fold increase in minimum drag compared to free transition FB-3500-0050
Experimental Results: L/D Comparison

- Re = 666,000
- Free transition
  - FB-3500-0050 does well at low angles of attack, \((L/D)_{max} = 35.5\)
  - FB-3500-0875 produces \((L/D)_{max} = 44\)
- Fixed transition
  - Flatback airfoils outperform sharp trailing edge airfoil
  - FB-3500-0875 produces \((L/D)_{max} = 17.5\)
- Bluff-body drag reduction techniques could be used to further improve performance
## Blade Planform and Geometric Data

<table>
<thead>
<tr>
<th>Station Number</th>
<th>Radius Ratio (deg)</th>
<th>Twist (m)</th>
<th>Chord (mm)</th>
<th>Thickness (mm)</th>
<th>Thickness Ratio (%)</th>
<th>Airfoil Type</th>
<th>Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5%</td>
<td>29.5</td>
<td>2.798</td>
<td>2798</td>
<td>100.00%</td>
<td>Circle</td>
<td>2.00E+06</td>
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<tr>
<td>2</td>
<td>15%</td>
<td>19.5</td>
<td>4.191</td>
<td>2640</td>
<td>63.00%</td>
<td>FB 6300-1800</td>
<td>3.86E+06</td>
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<tr>
<td>3</td>
<td>25%</td>
<td>13.0</td>
<td>4.267</td>
<td>2341</td>
<td>54.87%</td>
<td>FB 5487-1216</td>
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<td>4</td>
<td>35%</td>
<td>8.8</td>
<td>4.097</td>
<td>1756</td>
<td>42.86%</td>
<td>FB 4286-0802</td>
<td>6.51E+06</td>
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<td>5</td>
<td>45%</td>
<td>6.2</td>
<td>3.518</td>
<td>1204</td>
<td>34.23%</td>
<td>FB 3423-0596</td>
<td>6.92E+06</td>
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<tr>
<td>6</td>
<td>55%</td>
<td>4.4</td>
<td>2.762</td>
<td>746</td>
<td>27.00%</td>
<td>FB 2700-0230</td>
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<td>7</td>
<td>65%</td>
<td>3.1</td>
<td>2.218</td>
<td>532</td>
<td>24.00%</td>
<td></td>
<td>6.50E+06</td>
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<tr>
<td>8</td>
<td>75%</td>
<td>1.9</td>
<td>1.675</td>
<td>352</td>
<td>21.00%</td>
<td>S830</td>
<td>5.28E+06</td>
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<tr>
<td>9</td>
<td>85%</td>
<td>0.8</td>
<td>1.232</td>
<td>234</td>
<td>19.00%</td>
<td>S831</td>
<td>4.57E+06</td>
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<tr>
<td>10</td>
<td>95%</td>
<td>0.0</td>
<td>0.789</td>
<td>142</td>
<td>18.00%</td>
<td>S831</td>
<td>3.12E+06</td>
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</tbody>
</table>
Comparative Weight and Strength
9m BSDS blade

<table>
<thead>
<tr>
<th>Property</th>
<th>CX-100</th>
<th>BSDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lb)</td>
<td>383</td>
<td>289</td>
</tr>
<tr>
<td>% of Design Load at Failure</td>
<td>115%</td>
<td>310%</td>
</tr>
<tr>
<td>Root Failure Moment (kN-m)</td>
<td>128.6</td>
<td>203.9</td>
</tr>
<tr>
<td>Max. Carbon Tensile Strain at Failure (%)</td>
<td>0.31%</td>
<td>0.81%</td>
</tr>
<tr>
<td>Max. Carbon Compressive Strain at Failure (%)</td>
<td>0.30%</td>
<td>0.87%</td>
</tr>
<tr>
<td>Maximum Tip Displacement (m)</td>
<td>1.05</td>
<td>2.79</td>
</tr>
</tbody>
</table>

Historical Comparison of 9 m Blade Weights and Strengths

Source: Paquette & Veers, SNL
Issues Encountered in BSDS Study

- Transition has a dominant effect on flow characteristics of thick lifting surfaces but transition model missing in most CFD methods
- Blunt trailing edge airfoils have high levels of base drag negatively affecting their lift-to-drag ratios
Database e^N Transition Model

\[ \frac{A}{A_0} = \exp \left[ \int_{x_i}^{x_{tr}} (-\alpha_i) \, dx \right] \approx e^{N_{crit}} \]

- \( \alpha_i \) is a function of \( M_e, Re_{\delta*}, H_k \) and \( F \)
- LASTRAC was used to generate a database of \( \alpha_i \) values over a wide range of input values
  - Near-similarity attached velocity profiles
  - Non-similar separated velocity profiles
- \( \alpha_i \) values retrieved from database at run time using multidimensional interpolation
- Database characterizes the stability solver (high computational cost) with interpolation (low cost)
Database Storage

- Normalized structured topology is most efficient for storage and interpolation
- Interpolation / extrapolation is accomplished with $n^{th}$-order Lagrangian interpolating polynomials
FB-3500-0050 Performance

- Lift is very sensitive to surface soiling
- Premature boundary layer separation causes large drag forces

\[ \text{Re}_c = 666,000 \]
\[ M = 0.3, 0.13 \text{ (ARC2D, Exp.)} \]
\[ (x/c)_{\text{trip,upper}} = 0.02 \]
\[ (x/c)_{\text{trip,upper}} = 0.05 \]
FB-3500-0875 Performance

- Reduced sensitivity to surface soiling
- Only a modest drag penalty compared to the FB-3500-0050
FB-3500-1750 Performance

- Sensitivity to surface soiling greatly reduced
- Large (3x) drag penalty due to base drag
  - Baker is studying methods for drag reduction

\[ \text{Re}_c = 666,000 \]
\[ M = 0.3, 0.13 \text{ (ARC2D, Exp.)} \]
\[ (x/c)_{\text{trip, upper}} = 0.02 \]
\[ (x/c)_{\text{trip, upper}} = 0.05 \]
Blunt Trailing Edge Airfoil Drag Reduction

- **Baseline**
  - Large vortical wake structure
  - Vortex street
  - Computations may overpredict vortex strength due to 2D flow restriction

- **Splitter**
  - Twin, stable vortical structures surround plate
Simple Splitter Plate

- Nearfield
  - Splitter plate
  - O-grid topology
  - Note grid shock

- Farfield
Splitter Plate Length

- Best L/D max: 75% $t_{TE}$ length
Offset Trailing Edge Cavity

- Nearfield
  - O-grid topology near airfoil
  - Grid cell self-intersection required overset approach

- Farfield
  - Automatically generated “bricks”, cartesian offbody grids
Offset Cavity

- Loss in lift caused by reduced suction peak, compared to baseline
- Offset cavity resulted in steady flow for all angles prior to stall
- Multiple standing vortices surrounding plates
- Nearly stagnant flow in cavity
Offset Cavity

- Improved drag performance of offset cavity overcomes lift reduction for L/D
BSDS Blade

- Increased structural efficiency without loss of aerodynamic performance resulting in a much more cost effective blade
- Concept now adapted by major turbine manufacturers
- Blunt trailing edge airfoil (flatback) concept to improve lift characteristics of thick airfoils was studied and optimized using CFD
- Drag reduction concepts studied using CFD and now validated through wind tunnel and field testing
Sweep-Twist Adaptive Rotor (STAR)
Sweep Twist Adaptive Rotor (STAR)

- 2004 DOE award to Blade Division of Knight & Carver to design, build, and demonstrate a rotor based on the sweep-twist concept
- Rotor designed for testing on a Zond Z48 turbine with 750 kW rating
- Goal to increase annual energy capture of baseline turbine by 5%-10% without exceeding baseline rotor loads
- To achieve this rotor radius was increased from 24 m to 27 m
- Rotor test conducted in 2008
- Program results published in SAND2009-8037
Sweep Twist Passive Load Control Concept

Load Control through passive means utilizing blade geometry
Structured Grid System
Total number of grid points = 3.5 million

- Swept rotor
- Unswept blade
- Swept blade

Section shape in tip region
Conditions

- Rotor RPM = 26.6
- Zero yaw
- Full turbulent flow (SST turbulence model) over blades
- Freestream velocities:
  - 10 m/s
- Solution techniques:
  - Steady - source terms with low-Mach preconditioning, actual velocity and rpm
CFD vs. BEM Blade Spanwise Loads

Swept blade, $V_{\text{wind}} = 10 \text{ m/s}$, RPM = 26.6
Effect of Blade Sweep on Spanwise Loads

CFD, $V_{\text{wind}} = 10$ m/s, RPM = 26.6
## Comparison of Power and Thrust Predictions

\( V_{\text{wind}} = 10 \text{ m/s} \), \( \text{RPM} = 26.6 \)

<table>
<thead>
<tr>
<th></th>
<th>Unswept Blades</th>
<th></th>
<th>Swept Blades</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CFD</td>
<td>BEM</td>
<td>CFD</td>
<td>BEM</td>
</tr>
<tr>
<td><strong>Power [kW]</strong></td>
<td>734</td>
<td>733</td>
<td>729</td>
<td>725</td>
</tr>
<tr>
<td><strong>Thrust [kN]</strong></td>
<td>114.6</td>
<td>114.2</td>
<td>113.4</td>
<td>112.5</td>
</tr>
</tbody>
</table>

- Good agreement between BEM and CFD predictions
- Currently no experimental data available to compare against
Effect of Blade Sweep on Blade Pressure

CFD, $r/R = 0.99$

![Graph showing the effect of blade sweep on blade pressure. The graph compares Unswept and Swept conditions with $x/c$ on the x-axis and CP (blade pressure) on the y-axis. The graph highlights the differences in pressure distribution between the two conditions.](image)
Oil Flow Simulations

$V_{\text{wind}} = 10 \text{ m/s}, \text{ RPM } = 26.6, \text{ Blade suction side}$
Field Testing

Source: K. Jackson
Field Test Site
Tehachapi Wind Resource Area
Power Comparison
Measured Power Curves

The graph shows the relationship between nacelle wind speed (m/s) and power output (kW) for different models and rotor types. The data points represent measured power outputs at various wind speeds, with distinct markers for STAR Rotor, Group 2 Best, Model 54 m, and Model 48 m.
## Energy Comparison

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Energy (kWh)</th>
<th>Compare</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group 1</strong></td>
<td></td>
<td></td>
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<tr>
<td>RP-01</td>
<td>243009</td>
<td>101%</td>
</tr>
<tr>
<td>RP-02</td>
<td>236301</td>
<td>99%</td>
</tr>
<tr>
<td>RP-04</td>
<td>237148</td>
<td>99%</td>
</tr>
<tr>
<td>RP-08</td>
<td>242496</td>
<td>101%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>239738</td>
<td>100%</td>
</tr>
<tr>
<td><strong>STAR</strong></td>
<td>268711</td>
<td>112%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Energy (kWh)</th>
<th>Compare</th>
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</thead>
<tbody>
<tr>
<td><strong>Group 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RP-05</td>
<td>144456</td>
<td>99%</td>
</tr>
<tr>
<td>RP-06</td>
<td>145654</td>
<td>100%</td>
</tr>
<tr>
<td>RP-07</td>
<td>146298</td>
<td>101%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>145469</td>
<td>100%</td>
</tr>
<tr>
<td><strong>STAR</strong></td>
<td>197147</td>
<td>136%</td>
</tr>
</tbody>
</table>
Flatwise Blade Root Moment Comparison

- STAR rotor loads compared to Z48 data collected at Lake Benton site
Rank Ordered Blade Flatwise Load Maxima

Z48 DESIGN MAXIMUM OPERATING LOAD

STAR 54 MEASURED MAXIMUM OPERATING LOAD

Max. Flatwise (kNm @ RCL)

Rank Ordered Load Maxima
(10 minute records / 50 Hz data / 2439 records)
STAR Blade

- Increased rotor energy capture through aeroelastically tailored blade design is feasible.
- STAR-54 captured 12% more energy over baseline Z48 turbines without increasing blade loads.
- Effectiveness of concept is demonstrated by fact that prototype STAR-54 is operating without any issues more than 2 years after installation and it remains the highest grossing “Z48” in Tehachapi.
- CFD was key to validate aerodynamic performance and loads of swept blade rotor
Active Aerodynamic Load Control (AALC)
Active Load Control

- With wind turbines blades getting larger and heavier, can the rotor weight be reduced by adding active devices?
- Can active control be used to reduce fatigue loads?
- Can energy capture in low wind conditions be improved?
- Goal is to understand the implications and benefits of embedded active blade control, used to alleviate high frequency dynamics
Blade Load Control Techniques

- Techniques to control blade loads and rotor performance:
  - Blade size (variable blade length)
  - Incidence angle (variable pitch, variable twist)
  - Airspeed (variable speed)
  - Section aerodynamic characteristics

- In future consider the control of all of these simultaneously

- Focus is on small fast-acting systems that change sectional aerodynamic characteristics to alleviate load spikes due to gusts and to reduce blade tip deflections during high load conditions

\[ L = \int_{r=0}^{R} C_L \frac{1}{2} \rho \left( V_{\text{wind}}^2 + (2\pi nr)^2 \right) c \, dr \]

\[ C_{L_{\text{min}}} \leq C_L = C_L\alpha (\alpha + \beta - \alpha_o) \leq C_{L_{\text{max}}} \]
Rotor Control Strategy Diagram

<table>
<thead>
<tr>
<th>MC</th>
<th>Master Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>Blade Control</td>
</tr>
<tr>
<td>D</td>
<td>Devices</td>
</tr>
<tr>
<td>S</td>
<td>Sensors</td>
</tr>
<tr>
<td>----</td>
<td>Communication</td>
</tr>
</tbody>
</table>
Microtab Concept

- Conceptualized in 1998
- Tabs that deploy (near-)normal to flow direction
- Forward of the trailing edge
  - Upper or lower surface
- Hinge-less device
  - Small actuation forces
- \( h_{\text{tab}} \sim \) boundary layer thickness
- Trailing-edge flow condition is altered
Microtab Grids

- Leading edge of the tab placed at 95.0%c of airfoil
Microtab Grids

- Leading edge of the tab placed at 95.0% c of airfoil
- An additional $183 \times 74$ refinement grid is added
- 40,626 grid points
Off-Body Grids

- 35 Cartesian off-body ‘Bricks’
- 8 Levels grid expansion
- Far-field ~50c away
- ~300,000 total grid points in domain
Microtab Deployment
Tab Aerodynamic Response
Tab Activation Details

NACA 0012, Re=1x10^6, Ma=0.25, T_{act}=1, \alpha=0, h_{tab} = 0.01c
Tab Deployment Details

NACA 0012, Re=1x10^6, Ma=0.25, T_{act}=1, \alpha=0, h_{tab} = 0.01c
$C_p$ Contours: $T = 0 \rightarrow 2 \frac{c}{U}$

Time = 0
$T_{deploy} = 1 \frac{Ut}{c}$
$C_p$ Contours: $T = 0 \rightarrow 2 ~\frac{c}{U}$

Time = 0.005

$T_{deploy} = 1 ~\frac{Ut}{c}$
Microjet Concept

- Pneumatic system may be preferred over mechanical system
- Simulation of actively controlled microjet simpler than microtab
- Is effect of physical tab similar to that of jet at same location?

NACA 0018, Re=6.6x10^5, M_∞=0.176, α=0
Jet Activation Details

NACA 0012, Re=1x10^6, Ma=0.25, \( T_{act} =1 \), \( \alpha=0 \), \( C_\mu =0.0029 \)
Jet Activation Details – $T=0.1$

NACA 0012, $Re=1 \times 10^6$, $Ma=0.25$, $T_{act}=1$, $\alpha=0$, $C_\mu=0.0029$
Jet Activation Details – T=0.5

NACA 0012, Re=1x10^6, Ma=0.25, T_{act}=1, α=0, C_μ=0.0029
Jet Activation Details – T=0.6

NACA 0012, Re=1x10^6, Ma=0.25, T_{act}=1, \alpha=0, C_\mu=0.0029
Jet Activation Details – T=1.0

NACA 0012, Re=1x10^6, Ma=0.25, T_{act}=1, \alpha=0, C_\mu=0.0029
Active Aerodynamic Load Control

- CFD was key technology to design and analyze effectiveness of active aerodynamic load control for wind turbine blades.
- Systems must:
  - Be small and scalable
  - Have fast activation speed
  - Have low activation force and power requirements
  - Should be reliable and dependable
- Blade manufacturing and maintenance should be considered when embedding AALC systems
- Driving factor is economics ⇒ successful system must reduce COE
- AALC (include tab-based system) is currently being field tested on wind turbines in Europe and USA
Inboard Flow Separation Mitigation
NREL 5-MW Rotor

- Geometry based on 6MW 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
- \( \text{TSR}_{\text{Design}} = 8 \)
- 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
NREL 5-MW – Grid Topology

- Grid system designed to take advantage of overset/Chimera topology
- Modifications limited to inboard region
NREL 5-MW – Grid Topology

- Inboard (r < 20 m) blade grid can be modified and replaced
- Surface and volume grids of the outboard and tip regions can be reused
- Geometric modifications can be kept consistent and isolated to inboard region
- Hub geometry can also be examined without affecting remaining grid system
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: $61 \times 61 \times 81$
- Outboard: $201 \times 116 \times 81$
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 – Baseline Grid Domain

- Top view of domain
- 9 layers of BRICKS
- Each layer doubles cell dimension, i.e:
  - $D_{S_{\text{inner}}} = 0.5 \text{ m}$
  - $D_{S_{\text{outer}}} = 128 \text{ m}$
NREL 5-MW – Initial Off-Body Grid

- Side view
NREL 5-MW – Grid Topology

- Baseline ~10D far-field distance
- BRICKS allow for rapid and efficient domain construction
- Improved load balancing
NREL 5-MW – $U_\infty = 11\text{m/s}$

- Surface pressure with streaklines
Ring Fence Geometry

- Uniform height
  - $h_{fence} = 0.05c_{max}$
  - $h_{fence} \approx 0.23$ m

- Centered at max chord
  - $r = 13.7$ m
  - $r/R = 21.7\%$

- Overset grid
  - $201 \times 47 \times 81$ points
  - ~5M additional points
  - Point-matched overlap on blade surface
  - Existing blade region IBLANKED
Suction Side Streaklines – 8 m/s

Clean Blade

Fenced Blade
Suction Side Streaklines – 11 m/s

Clean Blade

Fenced Blade
## Ring Fence Effect on Rotor Power

<table>
<thead>
<tr>
<th>Solver Mode</th>
<th>$U_\infty$</th>
<th>RPM</th>
<th>$P_{\text{baseline}}$ (kW)</th>
<th>$P_{\text{fenced}}$ (kW)</th>
<th>$\Delta P$ (kW)</th>
<th>% Gain</th>
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<tbody>
<tr>
<td>Steady</td>
<td>8</td>
<td>9.16</td>
<td>1718</td>
<td>1733</td>
<td>15.3</td>
<td>0.889%</td>
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<tr>
<td>Time-Acc</td>
<td>8</td>
<td>9.16</td>
<td>1719</td>
<td>1735</td>
<td>15.3</td>
<td>0.888%</td>
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<tr>
<td>Steady</td>
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<td>11.89</td>
<td>4650</td>
<td>4679</td>
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<tr>
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<td>11.89</td>
<td>4654</td>
<td>4681</td>
<td>27.1</td>
<td>0.583%</td>
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</tbody>
</table>
Inboard Flow Separation Mitigation

- Extensive grid independence and external validation were performed to ensure baseline solution accuracy
- Existence of inboard flow separation was verified
- A framework for detailed study of inboard rotor flows has been established
- A simple fence geometry to limit spanwise flow successfully increased power capture by nearly 1% in Region II
Departing Thoughts

- Wind power can and will continue to play a significant role in the global energy portfolio because it is:
  - Clean, renewable, emission-free
  - A mature and reliable technology
  - Economically viable

- Rotor RD&D is continuing to further reduce wind COE through
  - Further improvements in $C_p$
  - Reductions in blade loads and mass for given energy capture
  - Improvements in rotor energy capture for given loads and mass

- Overset Grid methodology has been key to the development of technologies and concepts that lead to further reductions in COE