Computational Modelling of Solidity Effects on Blade Elements with an Airfoil Profile for Wind Turbines

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§ Overview
§ Solidity effect
§ Analysis of cascade forces
§ Review of the Mesh
§ Fluent settings
§ Current results
§ Future work
Objective: to investigate the aerodynamic performances of NACA 4415, especially solidity effect, including isolated airfoil and cascade blades

Motivation: Standard Blade Element Theory (BET) for wind turbines assumes zero solidity, however, it is NOT zero for wind turbines in reality

Obstacle: It would be very hard to perform accurate wind tunnel tests at low solidity

Method: CFD simulation

Tool: ICEM and FLUENT 15.0
What is solidity?

Global Solidity can be defined as:

$$\sigma = \frac{\text{Blade area}}{\text{Swept area}} = \frac{A_{\text{blade}}}{\pi R^2} / n = n \cdot \frac{A_{\text{blade}}}{\pi R^2}$$

Typical range for 3-blade HAWT:

0.021 (at the tip) - 0.11 (at the hub)

Low solidity (<0.1): High speed, Low torque
Example: wind turbine

High solidity (>1.0): Low speed, High torque
Example: wind mill, propeller
Solidity can also be defined that blades are symmetrically placed along one direction where solidity equals the chord length divided by the distance, noted as $S$.

Local solidity:

$$\sigma = n \cdot \frac{c}{2\pi r} = \frac{c}{s}$$

c=chord length
s=distance between blades
Solidity Effect:
- If the solidity is adequately high, the lift and drag coefficient would be impacted as well as lift-to-drag ratio
- Delay the stall partially
- Mean angle of attack would be altered → correlation of Lift and Drag

**Questions:**
- How the solidity would influence the coefficients?
- What is the sufficient solidity to cause the change of lift and drag coefficient?
Analysis of Cascade Forces

Data acquired from Fluent: $F_{↓x}, F_{↓y}, U_{↓x}, U_{↓y}$

Results reduction:

Mean angle of attack: $\tan \alpha_{↓m} = \frac{1}{2} \left( \tan \alpha + \frac{U_{↓y}}{U_{↓x}} \right)$

Mean velocity: $U_{↓m} = \frac{U_{↓x}}{\cos \alpha_{↓m}}$

Lift: $L = \frac{F_{↓y}}{\cos \alpha_{↓m}} - F_{↓x}$

Drag: $D = \frac{F_{↓y}}{\cos \alpha_{↓m}} + F_{↓x}$

Lift coefficient: $C_{↓l} = \frac{L}{1/2 \rho U_{↓m}^2}$

Drag coefficient: $C_{↓d} = \frac{D}{1/2 \rho U_{↓m}^2}$
Pitch angle $\theta_{\Downarrow p}$: the angle between the plane of rotation and the blade’s chord line

Pitch angle is usually fixed for small wind turbines and can be adjusted for large wind turbines with a controller.

Pitch angle near hub: around 20°

Pitch angle near tip: around 0°
Review of the Mesh

- Tool: ANSYS ICEM 15.0
- Mesh size: 150182 elements
- Elements type: Hexahedra
- Max Y plus value: 1.5
- Domain type: H-grid
- Domain size: 10×30m

Zoom-in views of the airfoil mesh
Pitch angle = 20 °
## Boundary Conditions

<table>
<thead>
<tr>
<th>Constants &amp; Boundary conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number: Re</td>
<td>$1.01 \times 10^6$</td>
</tr>
<tr>
<td>Chord length: L</td>
<td>1m</td>
</tr>
<tr>
<td>Temperature: T</td>
<td>0°C</td>
</tr>
<tr>
<td>Air density: $\rho$</td>
<td>1.2933 $kg/m^3$</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$1.7231 \times 10^{-5} \ Ns/m^2$</td>
</tr>
<tr>
<td>Intermittency</td>
<td>1</td>
</tr>
<tr>
<td>Turbulence viscosity ratio</td>
<td>10</td>
</tr>
<tr>
<td>Turbulent intensity: $Tu$</td>
<td>0.1%</td>
</tr>
<tr>
<td>Inlet velocity: $U$</td>
<td>13.457 m/s</td>
</tr>
</tbody>
</table>

- The Reynolds number was calculated according to the Ohio State University’s experimental data
- $Re=\rho UL/\mu$
Turbulence Model

- **Transition SST 4-Eqn Model**
  - Based on the SST k-w transport equation with two other two transport equations

  Intermittency: \( \gamma \) (gamma)

  \( \gamma = 0 \): laminar; \( \gamma = 1 \): turbulent

  Momentum-thickness Reynolds number: \( Re_{\theta t} \)

  \[ Re_{\theta t} = \frac{\rho U \theta t}{\mu} \]

  \( \theta t \): momentum thickness

  - Laminar to turbulent can be predicted
  - User-defined correlations (UDF) can be used to control the transition onset and transition length

- **Correlations are proposed by Malan (2009), Sorenson (2009), and Suluska (2009).**

  - \( Re_{\theta c} \): critical Reynolds number where the intermittency first starts to increase in the boundary layer
### Wind Tunnel Comparison

<table>
<thead>
<tr>
<th></th>
<th>Ohio State University</th>
<th>NACA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Year</td>
<td>1996</td>
<td>1945</td>
</tr>
<tr>
<td>Wind tunnel</td>
<td>OSU</td>
<td>NACA LTT</td>
</tr>
<tr>
<td>Turbulence level</td>
<td>0.1%</td>
<td>0.03% (unbelievable!)</td>
</tr>
<tr>
<td>Re range</td>
<td>0.75-1.5 million</td>
<td>0.7-1.5 million</td>
</tr>
<tr>
<td>Surface</td>
<td>Smooth</td>
<td>Smooth</td>
</tr>
<tr>
<td>Model aspect ratio</td>
<td>3</td>
<td>3.8</td>
</tr>
<tr>
<td>Data</td>
<td>Cl, Cd, Cp</td>
<td>Cl, Cd</td>
</tr>
</tbody>
</table>
Results of Isolated Airfoil

<table>
<thead>
<tr>
<th></th>
<th>Max Cl</th>
<th>Max Cl/Cd ratio</th>
<th>Stall angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSU</td>
<td>1.354</td>
<td>106.5</td>
<td>14.3</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>1.36</td>
<td>105.4</td>
<td>13.5</td>
</tr>
<tr>
<td>Xfoil</td>
<td>1.64</td>
<td>127.8</td>
<td>16.2</td>
</tr>
<tr>
<td>Menter</td>
<td>1.59</td>
<td>108.1</td>
<td>15.3</td>
</tr>
<tr>
<td>Sorenson</td>
<td>1.65</td>
<td>111.0</td>
<td>14.3</td>
</tr>
</tbody>
</table>
Results of Cascaded Blades

Lift Coefficient

@11.2

<table>
<thead>
<tr>
<th>S</th>
<th>Cl</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>S=0</td>
<td>1.5136</td>
<td>-</td>
</tr>
<tr>
<td>S=0.1</td>
<td>1.5016</td>
<td>-0.79%</td>
</tr>
<tr>
<td>S=0.2</td>
<td>1.4745</td>
<td>-2.58%</td>
</tr>
<tr>
<td>S=0.3</td>
<td>1.4430</td>
<td>-4.66%</td>
</tr>
</tbody>
</table>

Angle of Attack

Cl

-2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Results of Cascaded Blades

Drag Coefficient

<table>
<thead>
<tr>
<th>@11.2</th>
<th>Cd</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>S=0</td>
<td>0.01977</td>
<td>-</td>
</tr>
<tr>
<td>S=0.1</td>
<td>0.01716</td>
<td>-13.2%</td>
</tr>
<tr>
<td>S=0.2</td>
<td>0.01698</td>
<td>-14.1%</td>
</tr>
<tr>
<td>S=0.3</td>
<td>0.01625</td>
<td>-17.8%</td>
</tr>
</tbody>
</table>
Results of Cascaded Blades

Lift to Drag ratio

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>S=0</th>
<th>S=0.1</th>
<th>S=0.2</th>
<th>S=0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Cl/Cd</td>
<td>111</td>
<td>121</td>
<td>123</td>
<td>119</td>
</tr>
<tr>
<td>AOA</td>
<td>6.2</td>
<td>6.5</td>
<td>6.9</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Results of Cascaded Blades

Pressure coefficient @ 11.2

Pressure side

Suction side
Conclusion and Outlook

- **Validation:**
  Lift has not good agreement at high angle of attack. Drag has good agreement with experimental data
  
  Sorenson’s correlation was used because it has the same stall angle as the experimental results

- **Solidity Effect**
  - It can reduce both of lift and drag
  - But it rises the lift to drag ratio and delay the stall
  - Solidity of 0.1 could have significant impact on aerodynamic performances of the blade, especially on drag

- **Future work:**
  - Improve the accuracy of lift at high angles
  - Simulate the case of pitch angle=0 with solidity varying from 0.1 to 0.3 and pitch angle=20 with solidity varying from 0.1 to 0.3
- C. Bak, “The DTU 10-MW Reference Wind Turbine”, Danish Wind Power Research, 2013
- I. H. Abbott, A. E. Von Doenhoff, Theory of Wing Sections, Dover, 1958
Thank you for the attention!

Any questions?

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