Numerical studies of a 10 MW wind turbine with morphing trailing edge flaps

Numerische Untersuchung einer 10 MW Windenergieanlage mit elastischen Hinterkantenklappen

17. STAB-Workshop, 10. November 2015, Göttingen
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Overview

1. Background
2. Process chain
3. Wind turbine and validation
4. Simulations with trailing edge flap
   1. 120°-model of the pure rotor
   2. Full turbine model with prescribed flap motion
5. Conclusion
Overview

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Development in wind turbine size

Figure: UpWind – Final report, March 2011, www.upwind.eu
Theory of similarity

Empirical scaling rules for wind turbines based on a similar turbine layout (tip speed ratio, profile selection, etc.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proportionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>( \sim R^2 )</td>
</tr>
<tr>
<td>Thrust</td>
<td>( \sim R^2 )</td>
</tr>
<tr>
<td>Rotor mass</td>
<td>( \sim R^3 )</td>
</tr>
</tbody>
</table>

**Problem:** Realisation of 10 to 20 MW turbines is hardly possible based on simple scaling

Demand of new technologies to reduce loads, load variations and mass:
- Structure
- Control
- Aerodynamics

Active trailing edge flaps

Active trailing edge flaps

Reduction of dynamic load variations due to:

- Tower shadow
- Atmospheric boundary layer and turbulence
- Yawed inflow

Basic functioning:

\[ \alpha, \omega R \]

Undisturbed inflow

\[ \Omega \]

Disturbed inflow

\[ \Omega \]

Figure top right: Joachim Heinz; “Investigation of Piezoelectric Flaps for Load Alleviation using CFD”; M.Sc. Thesis; Riso DTU; 2009

approach velocity \( c \), wind velocity \( v \), rotational velocity \( u = \omega R \)
Previous work and objectives

- Prove of concept based on blade element momentum (BEM) and vortex methods
- Fatigue load reduction of blade root bending moment
  - BEM method ~ 18 %
  - Vortex method ~ 30 %
- Difficulty: Modeling of unsteady and viscid 3D aerodynamics

Next step: CFD simulation as high fidelity method
- validate the potential including 3D effects
- investigate unsteady and viscid effects in 2D and 3D

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3D aerodynamic effects

Spatial effects:

Temporal effects:
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Simulation process chain

CFD code FLOWer:
• developed by DLR\textsuperscript{1}
• Compressible block structured finite-volume solver
• Moving/overlapping meshes (CHIMERA)
• Extensions with regard to wind turbine application
  • Dirichlet boundary condition for turbulent inflow
  • Grid deformation based on radial basis functions (FSI coupling)
  • Load integration during runtime

Mesh generation:
• Gridgen/Pointwise
• Automesh: Automatic parameterized blade meshing

Post-processing:
• Load computation
• Fast Fourier analysis

Extension for trailing edge flaps

- Definition of un-deformed and deformed surface
- Mesh deformation based on radial basis functions

2D simulation with flaps:

3D simulation with flaps:

Morphing trailing edge flap

**Rigid flap:** Rotation of flap around defined hinge axis

**Morphing flap:** Deflection based on defined function

\[
\begin{align*}
w &= \varphi(x) \beta \\
\varphi(x) &= \begin{cases} 
0, & 0 \leq x < c - b \\
\frac{(c - x - b)^2}{b}, & c - b \leq x \leq c
\end{cases}
\end{align*}
\]

\(w\) : change  \(y\) - coordinate  
\(\beta\) : flap angle  \(c\) : chord 
\(b\) : flap length  \(n\) : order

Internal flap structure described by Madsen et al\(^1\).

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DTU 10 MW reference wind turbine

<table>
<thead>
<tr>
<th>Class</th>
<th>IEC 1A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-in wind speed</td>
<td>4 m/s</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>11.4 m/s</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>178.3 m</td>
</tr>
<tr>
<td>Hub height</td>
<td>119 m</td>
</tr>
<tr>
<td>Max. RPM</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Code-to-code validation without trailing edge flaps - Simulation setup

- Code-to-code validation within FP7 project AVATAR
- 120 degree model with periodic boundary conditions
- 4 different grids: blade, spinner, nacelle and background
- Turbulence model: Menter SST, fully turbulent boundary layer
- Grid independency study performed for blade and background grid
- Total amount of grid cells: ~ 20 mio. Cells
- Comparison of integral power and thrust, sectional forces and $c_p/c_f$-distributions
Validation without trailing edge flaps

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Simulations cases with flap

Flap configuration:
- Local chord length: 10%
- Radial dimensions: 70 to 80%
- Morphing flap based on 2nd order polynomial

Simulation cases:
- Pure rotor model with harmonic flap oscillations
  - 1p, 2p, 3p and 6p frequency
- Full turbine model with prescribed flap motion
  - Comparison to simulation without flap
- Separate study regarding temporal resolution and grid independency
Overview

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Comparison of different flap frequencies
- Integral power and thrust

Flap deflection function:
\[ \beta(t) = 10^\circ \cdot \cos(2\pi \omega_i t) \]
Comparison of different flap frequencies
- Sectional forces 75 % blade cut

![Graphs showing comparison of different flap frequencies with sectional forces for 75% blade cut.](image-url)
Blade wake with oscillating flap
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Full turbine model - Simulation setup

- Full turbine model including tower and nacelle
- Computational domain: [(-540,996),(-608,608),(0,768)]
- Cell size around turbine: 1 m³
- Total amount of grid cells: ~ 60 Mio.
- Use of hanging grid nodes

- 19 m/s, steady atmospheric boundary layer based on power law
- Flap signal as function of azimuth provided by TU Delft (S.T. Navalkar, BEM-model in GH Bladed, PI control)
- minor modifications for lower gradient in flap angle
Full turbine model
- Integral power and thrust

- Evaluation of 11th and 12th revolution
- General reduction of power and thrust of the turbine
- No reduction of the load variations
Full turbine model
- Power and thrust on blade level

► Blade root bending moment: reduction of 40% of absolute mean value
Full turbine model
- Sectional force distributions

Without flaps

With flaps
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Conclusion

- Unsteady effects play an important role on trailing edge flaps, comparison to steady polars showed:
  - Phase shift in lift and drag
  - Reduced magnitude in lift variation, Highly increased magnitude of drag variation
- 3D effects reduce the flap effectiveness (flap edge downwash)
- Simulation of the full turbine model with prescribed flap motion
  - Decreased integral power and thrust
  - Reduction of load fluctuations on blade level
  - High load gradients along the blade span (► FSI coupling needed)

Outlook

- Further study of unsteady effects (more wind speeds, etc.)
- Use of controller, FSI coupling
Thank you for your attention.
Questions?

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