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

Numerische Untersuchung einer 10 MW Windenergieanlage mit elastischen Hinterkantenklappen

Universität Stuttgart

WINDFORS
Wind Energy
Research Cluster

INNWIND.EU

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Overview

Overview

Development in wind turbine size

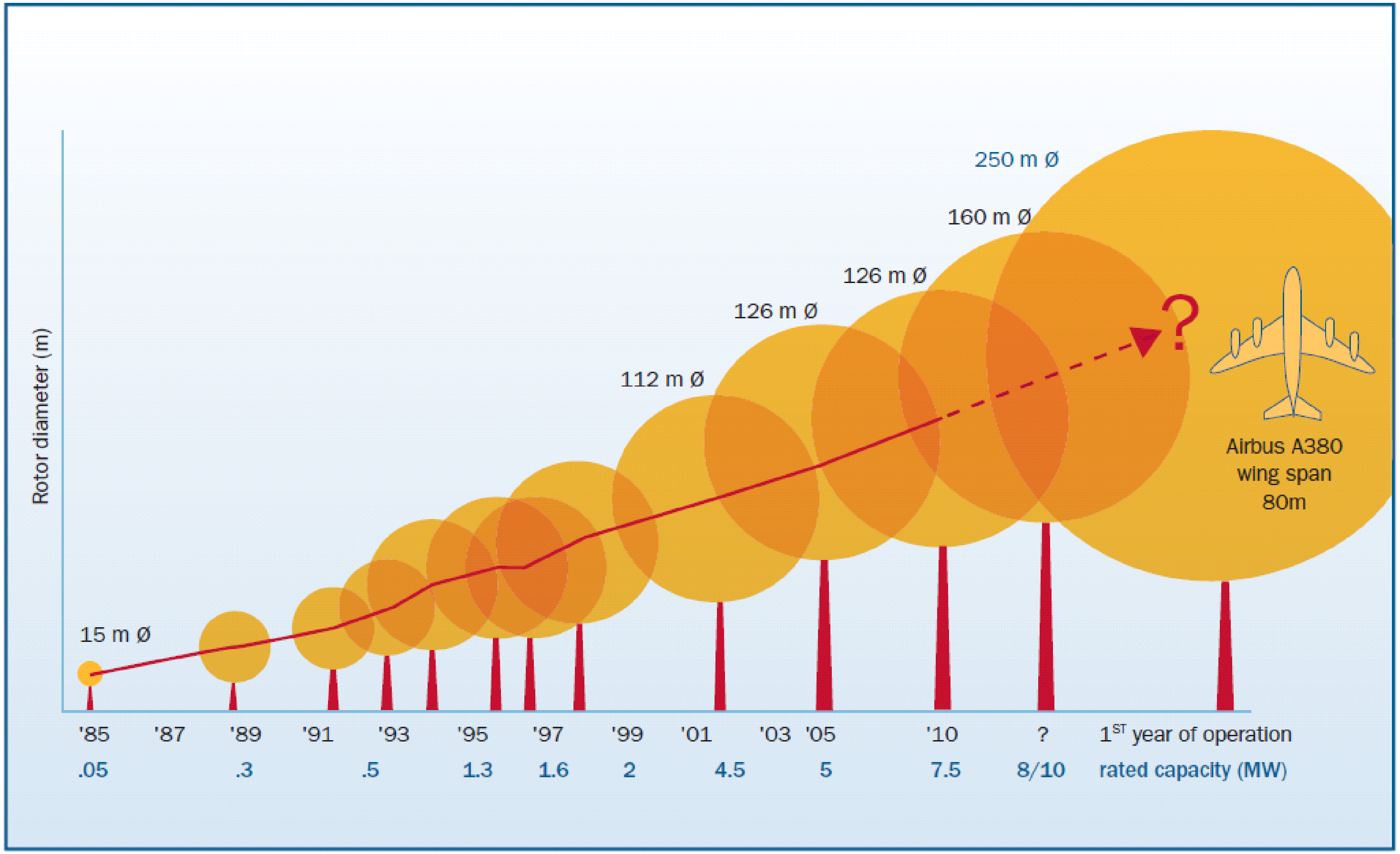


Figure: UpWind – Final report, March 2011, www.upwind.eu

Theory of similarity

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

Parameter	Proportionality
Power	$\sim R^2$
Thrust	$\sim R^2$
Rotor mass	$\sim R^3$

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

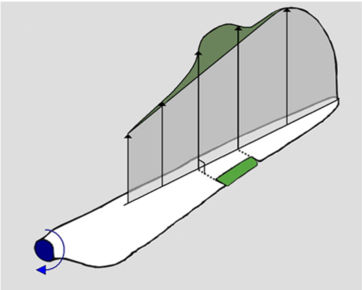
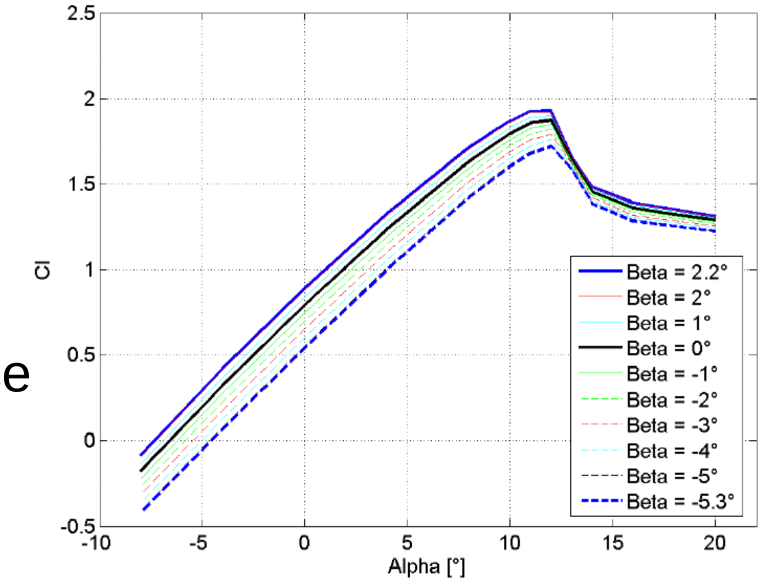


Figure bottom right: http://www.renewableenergyfocus.com/view/7457/wind-turbine-controllable-rubber-trailing-edge-flap-tested/

Active trailing edge flaps

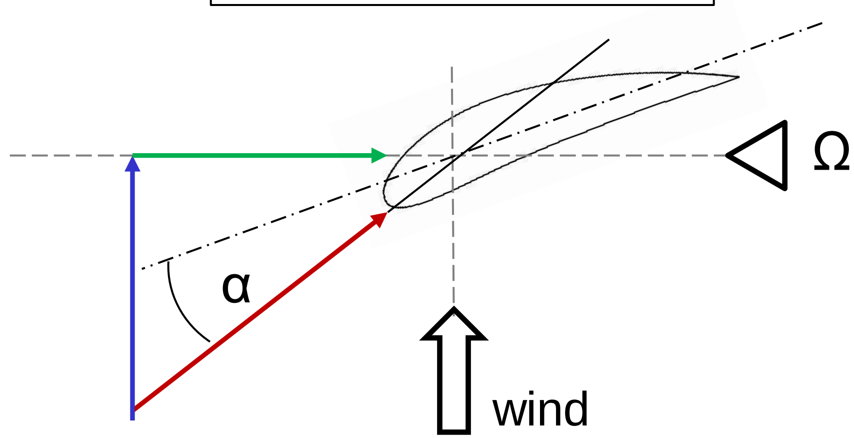


Reduction of dynamic load variations due to:

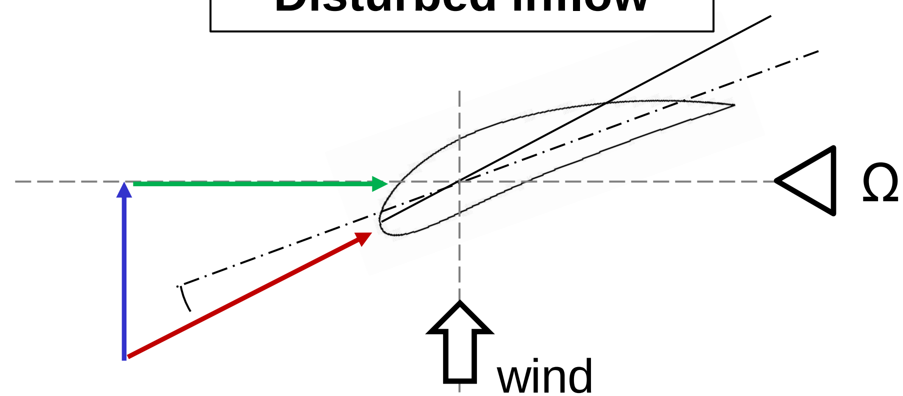
- Tower shadow
- Atmospheric boundary layer and turbulence
- Yawed inflow

Basic functioning:

Undisturbed inflow



Disturbed inflow



approach velocity c, wind velocity v, rotational velocity u=ωR

IAG
Institute of Aerodynamics and Gasdynamics

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

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 %[1]
  - Vortex method ~ 30 %[2]
- Difficulty: Modeling of unsteady and viscid 3D aerodynamics

Next step: CFD simulation as high fidelity method

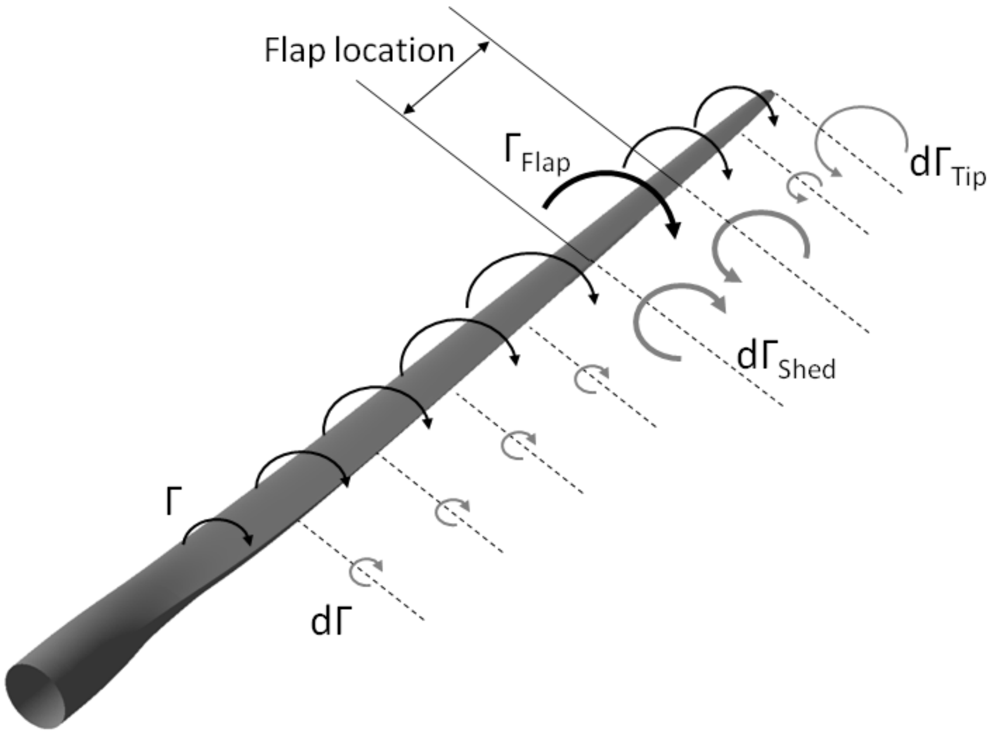
- validate the potential including 3D effects
- investigate unsteady and viscid effects in 2D and 3D

[1] S. Navalkar, J. van Wingerden, E. van Solingen, T. Oomen, E. Pasterkamp and G. van Kuik, „Subspace predictive control to mitigate periodic loads on large scale wind turbines,“ *Mechatronics* , vol. 24, pp. 916-925, February 2014.

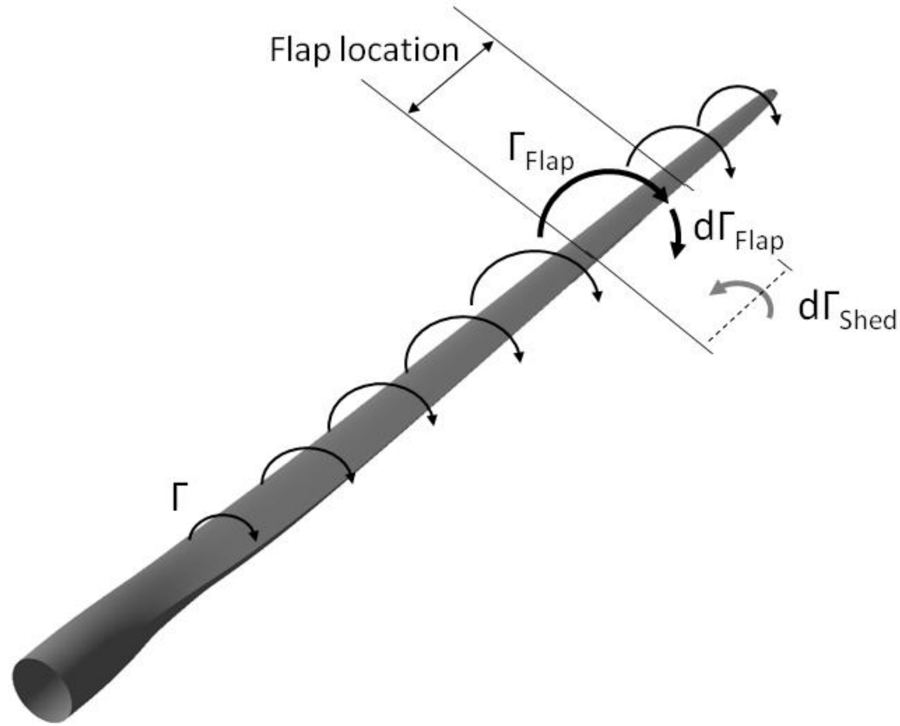
[2] V. Riziotis and S. Voutsinas, „Aero-elastic modelling of the active flap concept for load control,“ in *Proceedings of the EWEC*, Brussels, Belgium, 2008

3D aerodynamic effects

Spatial effects:



Temporal effects:



Overview

1. Background
2. Process chain
3. Wind turbine and validation
4. Simulations with trailing edge flap
    1. 120°-model of the pure rotor
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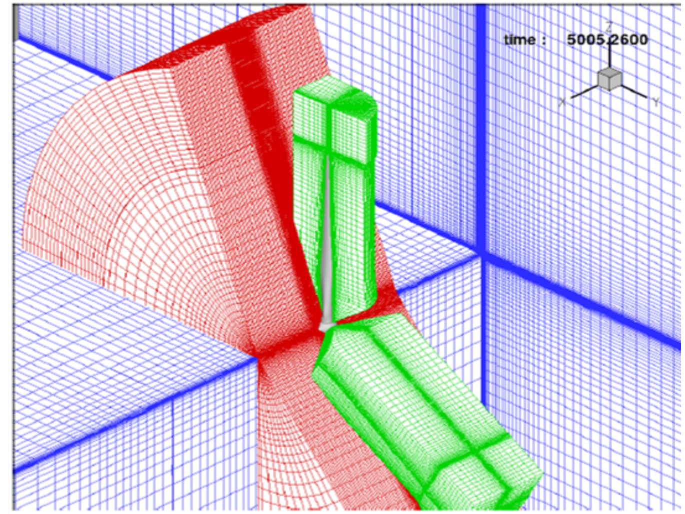
Simulation process chain



CFD code FLOWer:

- developed by DLR[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:

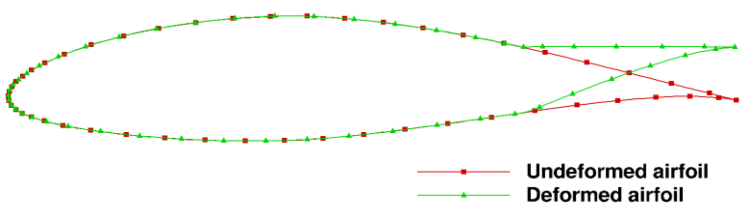
- Load computation
- Fast Fourier analysis

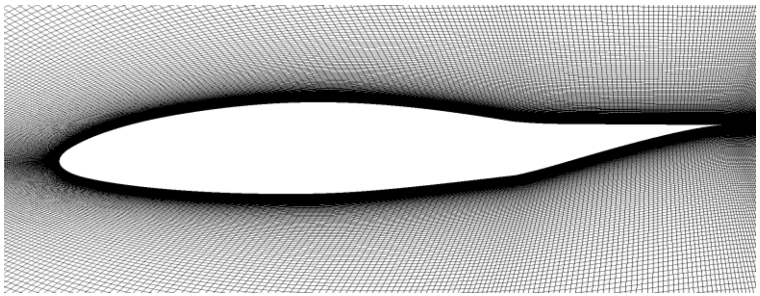
[1] N. Kroll and J. Fassbender, MEGAFLOW – Numerical Flow Simulation for Aircraft Design, Berlin/Heidelberg/New York: Springer Verlag, 2002.

Extension for trailing edge flaps

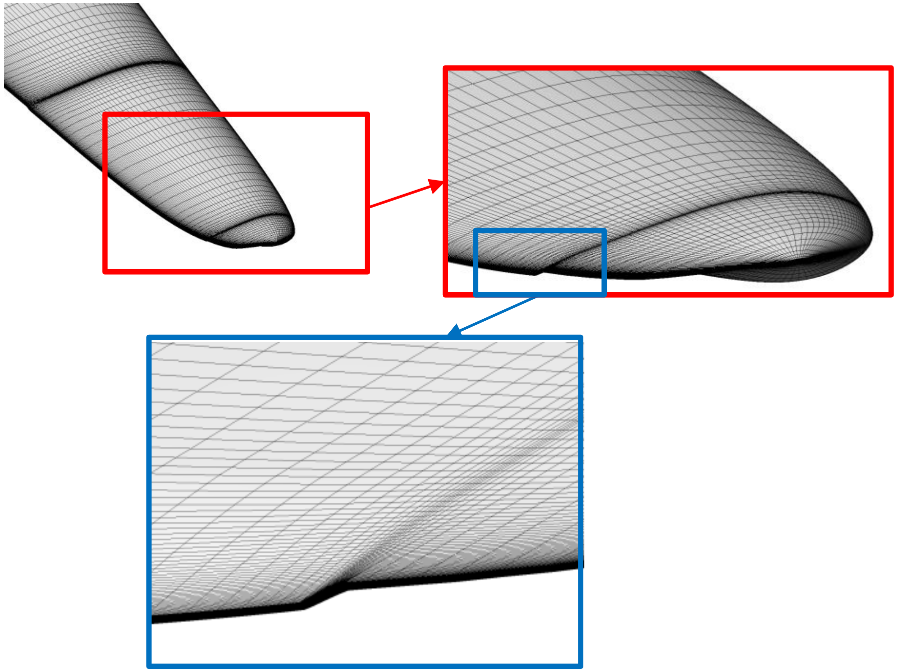
- Definition of un-deformed and deformed surface
- Mesh deformation based on radial basis functions[1]

2D simulation with flaps:





3D simulation with flaps:



[1] M. Schuff, P. Kranzinger, M. Keßler and E. Krämer, "Advanced CFD-CSD coupling: Generalized, high performant, radial basis function based volume mesh deformation algorithm for structured, unstructured and overlapping meshes," in *40th European Rotorcraft Forum*, Southhampton, 2014.

Morphing trailing edge flap

Rigid flap: Rotation of flap around defined hinge axis

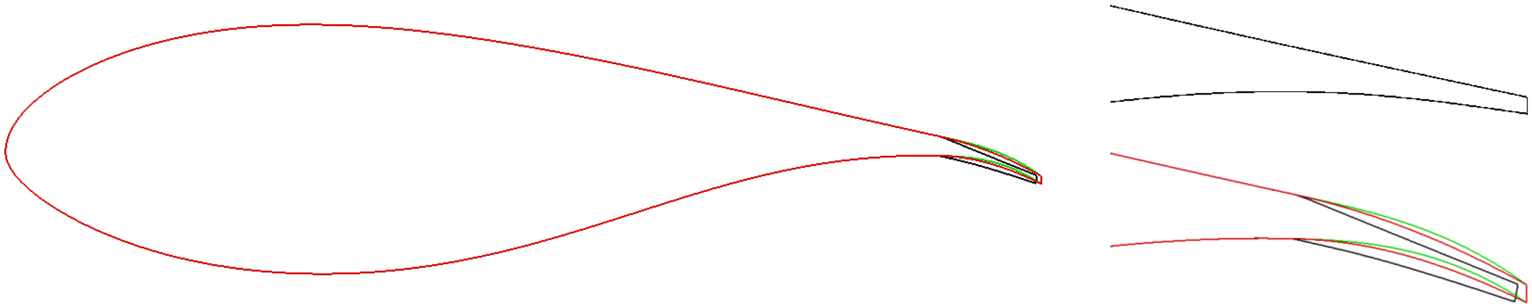
Morphing flap: Deflection based on defined function

$$w = \varphi(x)\beta \qquad \varphi(x) = \begin{cases} 0, & 0 \le x < c - b \\ \dfrac{(c - x - b)^2}{b}, & c - b \le x \le c \end{cases}$$

w : *change y – coordinate*

β : *flap angle* , c : *chord*

b : *flaplength* , n : *order*

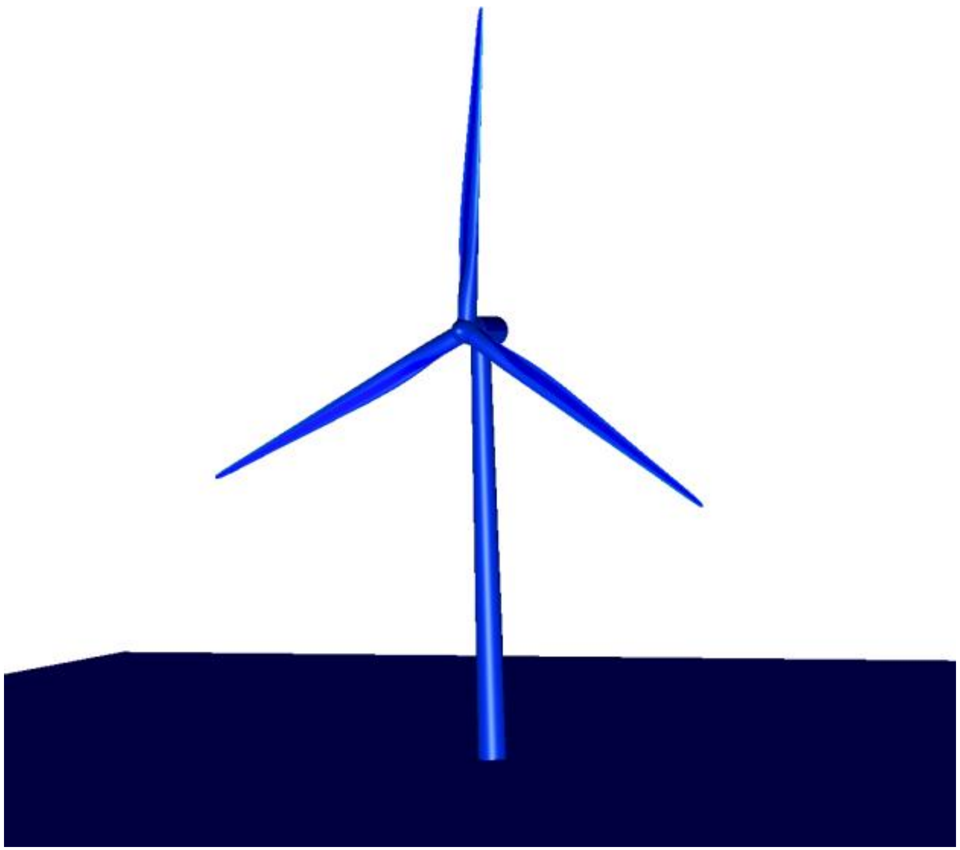


Internal flap structure described by Madsen et al[1].

[1]H. A. Madsen, P. B. Andersen, T. L. Andersen, C. Bak and T. Buhl, "The potentials of the controllable rubber trailing edge flap (CRTEF)," in *Proceedings of EWEC*, 2010.

Overview

DTU 10 MW reference wind turbine[1]

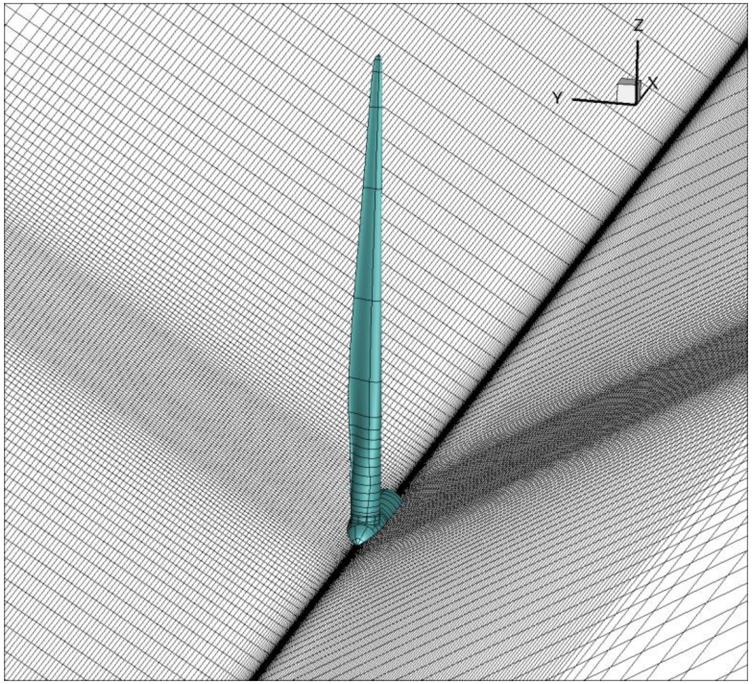


Class	IEC 1A
Cut-in wind speed	4 m/s
Cut-out wind speed	25 m/s
Rated wind speed	11.4 m/s
Rotor diameter	178.3 m
Hub height	119 m
Max. RPM	9.6

[1]C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. Henriksen, P. Andersen, A. Natarajan and M. Hansen, „Design and performance of a 10 MW turbine,“dtu-10mw-rwt.vindenergi.dtu.dk.

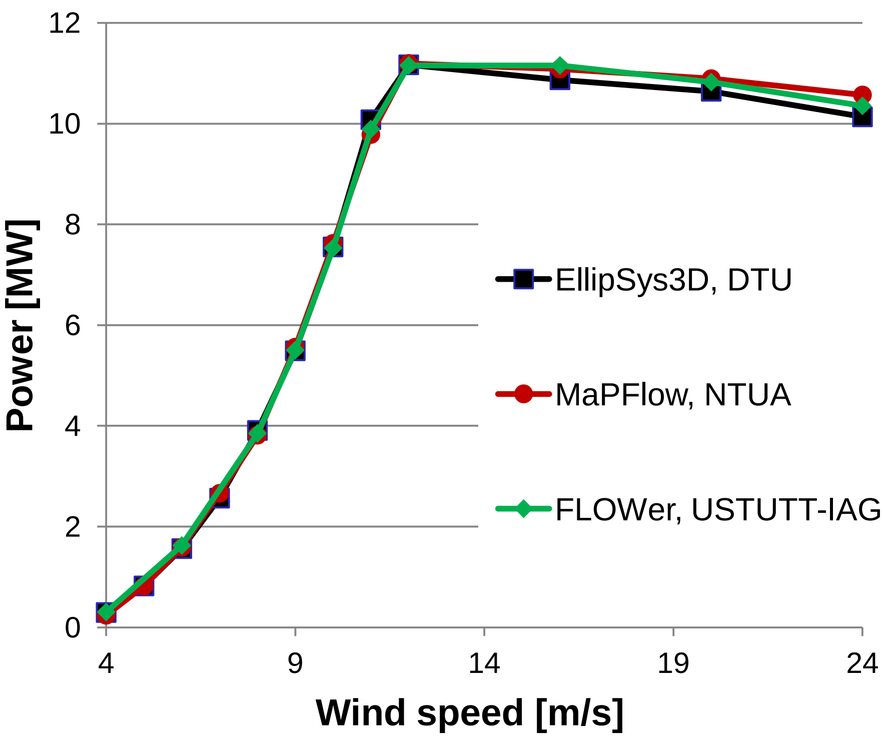
Code-to-code validation without trailing edge flaps - Simulation setup

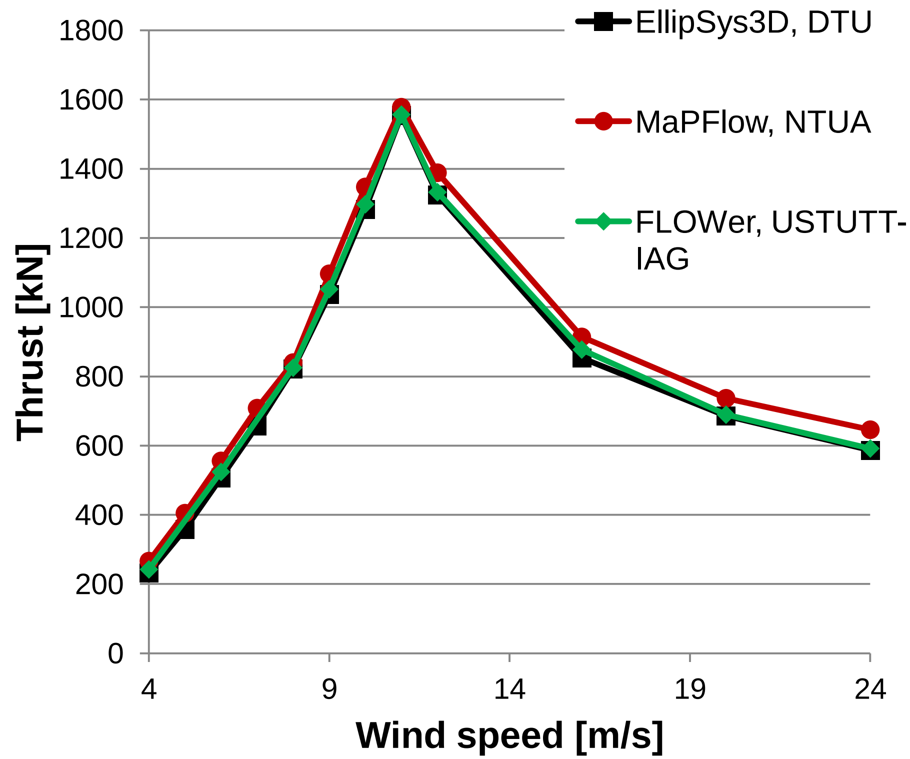
- Code-to-code validation within FP7 project AVATAR
- 120 degree model with periodic boundary conditions
- 4 different grids: blade, spinner, nacelle and background
- Turbulence model: Menter SST, fully turbulent boundary layer
- Grid indepency study performed for blade and background grid
- Total amount of grid cells: ~ 20 mio. Cells



- Comparison of integral power and thrust, sectional forces and c_p/c_f-distirbutions

Validation without trailing edge flaps





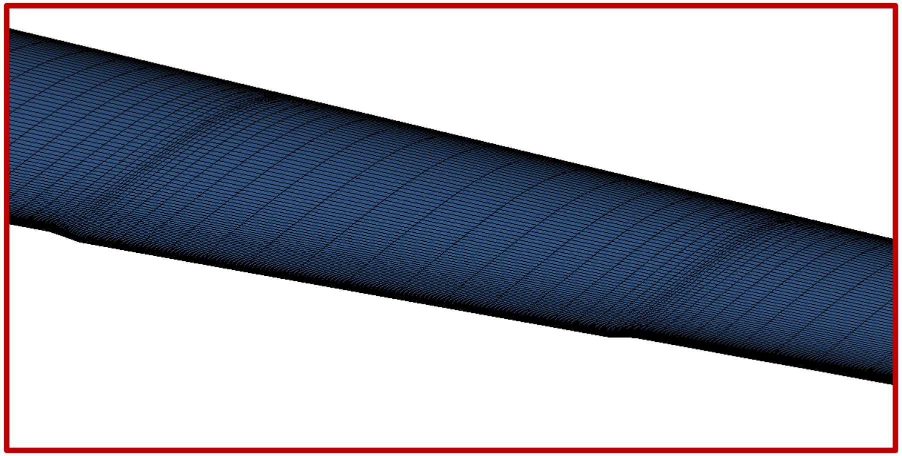
Plots modified from: N. Sorensen, M. Hansen, N. Garcia, L. Florentie, K. Boorsma, S. Gomez-Iradi, J. Prospathopoulus, G. Barakos, Y. Wang, E. Jost and T. Lutz, “AVATAR Deliverable 2.3: Power Curve Predictions,” 1 June 2015. [Online]. Available: http://www.eera-avatar.eu/fileadmin/mexnext/user/report-d2p3.pdf.

Overview

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

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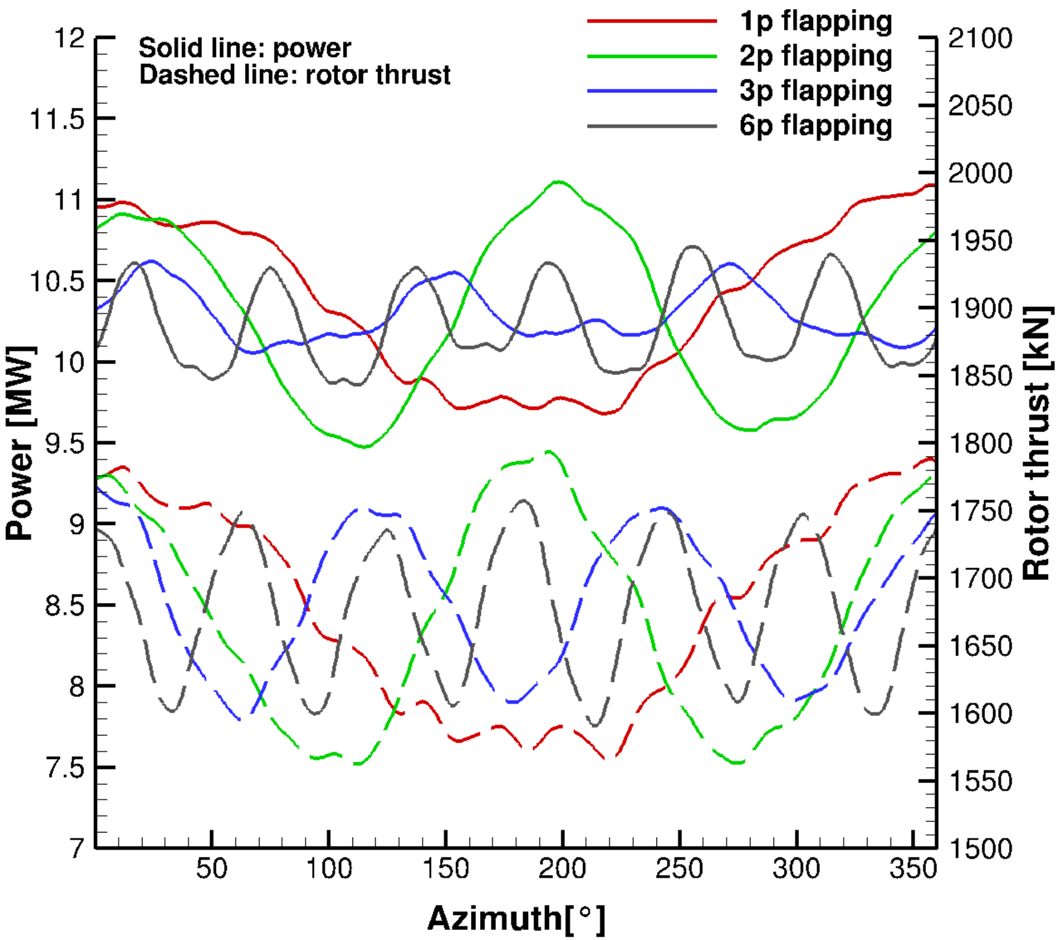
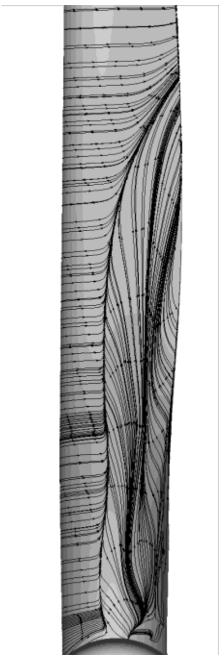
Comparison of different flap frequencies - Integral power and thrust

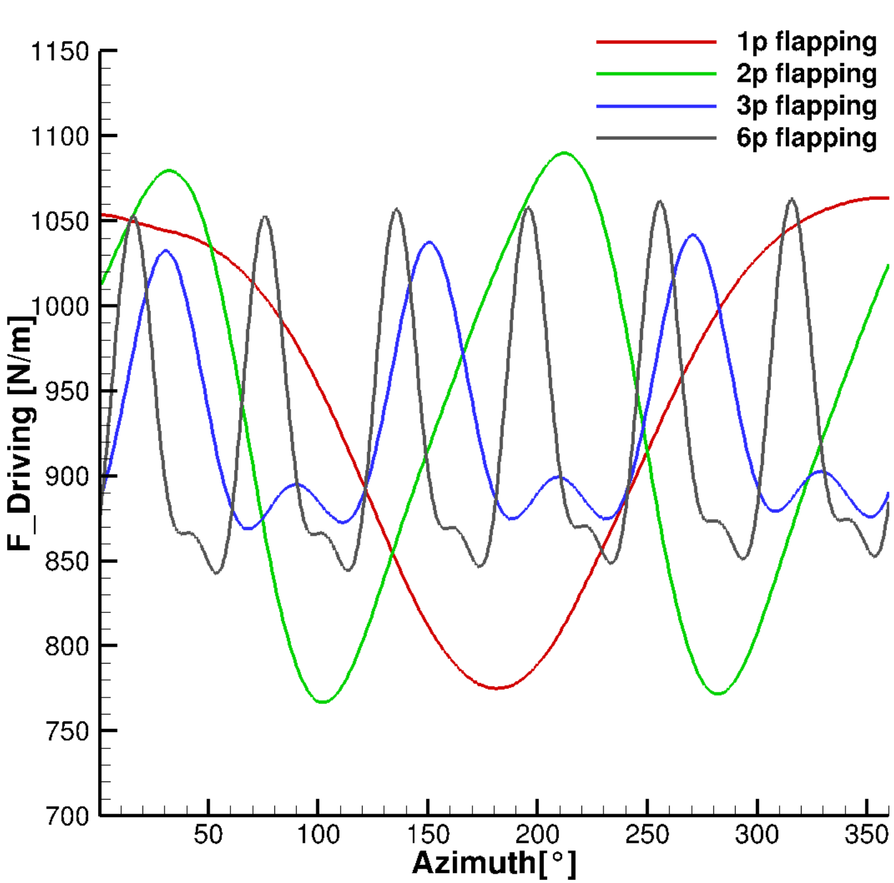


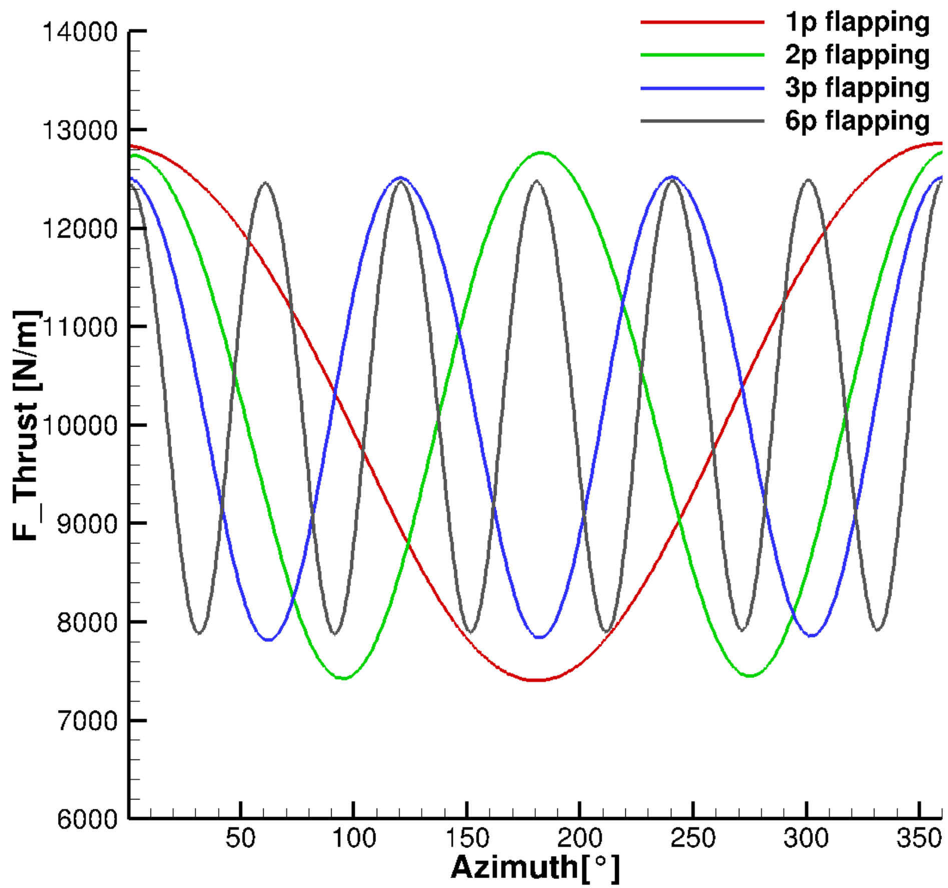
Flap deflection function:

$$\beta(t) = 10^{\circ} \cdot \cos(2\pi\omega_i t)$$

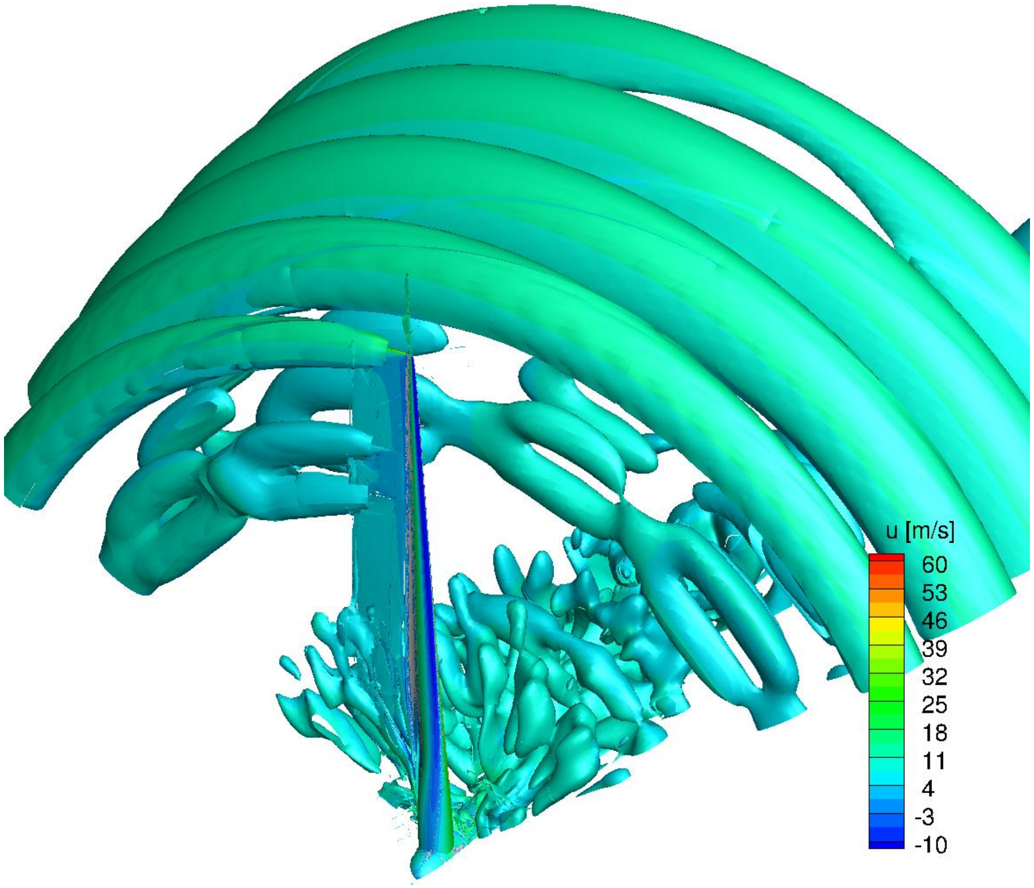


Comparison of different flap frequencies - Sectional forces 75 % blade cut





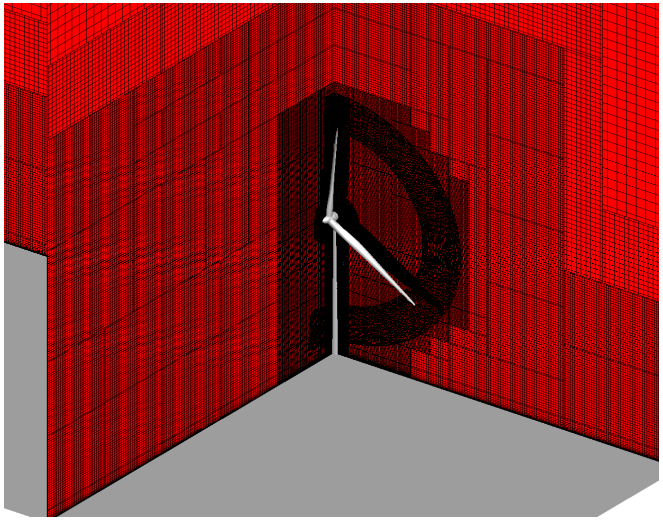
Blade wake with oscillating flap



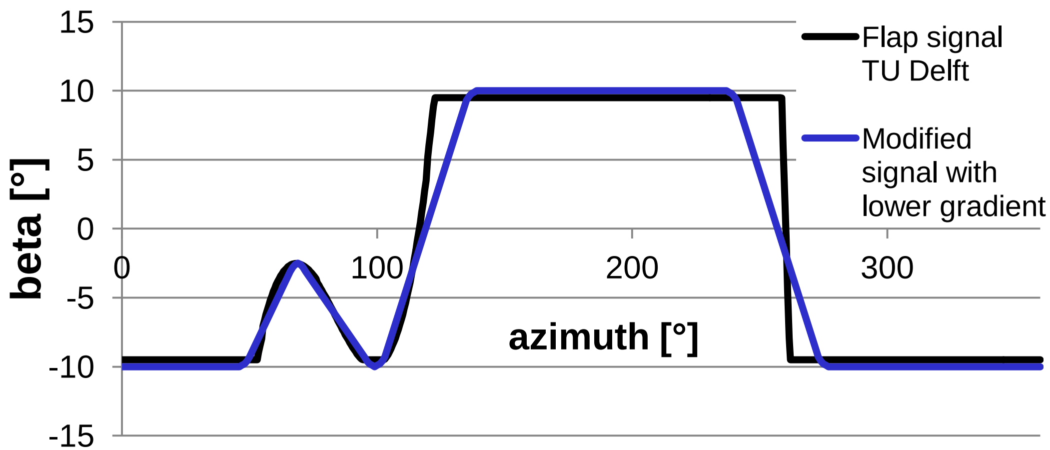
Overview

Full turbine model
- Simulation setup

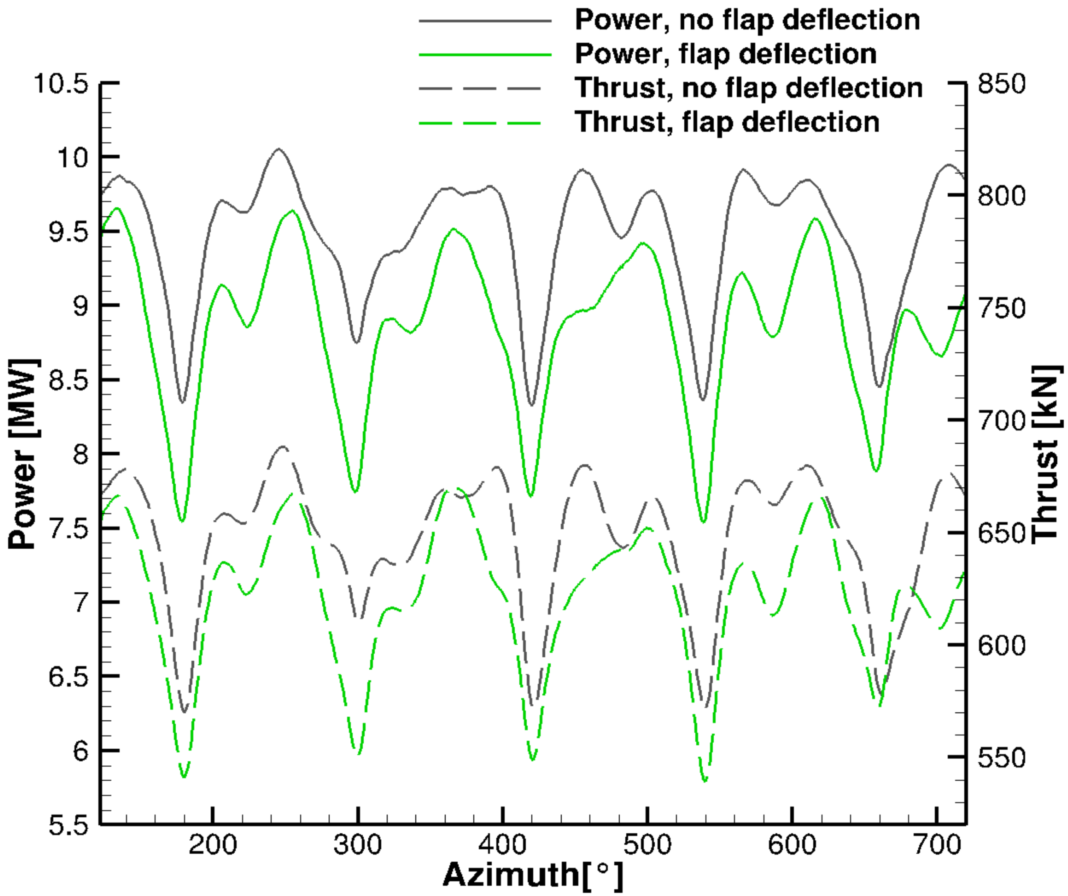
- Full turbine model including tower and nacelle
- Computational domain: [(-540,996),(-608,608),(0,768)]
- Cell size around turbine: 1 m^3
- Total amount of grid cells: ~ 60 Mio.
- Use of hanging grid nodes



- 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

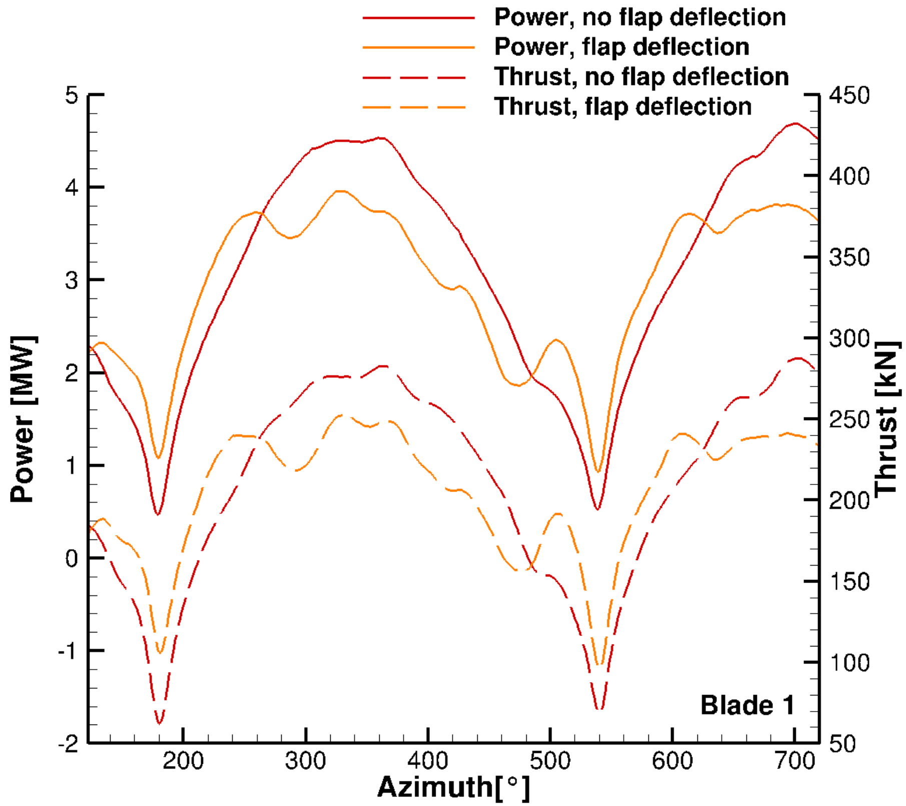


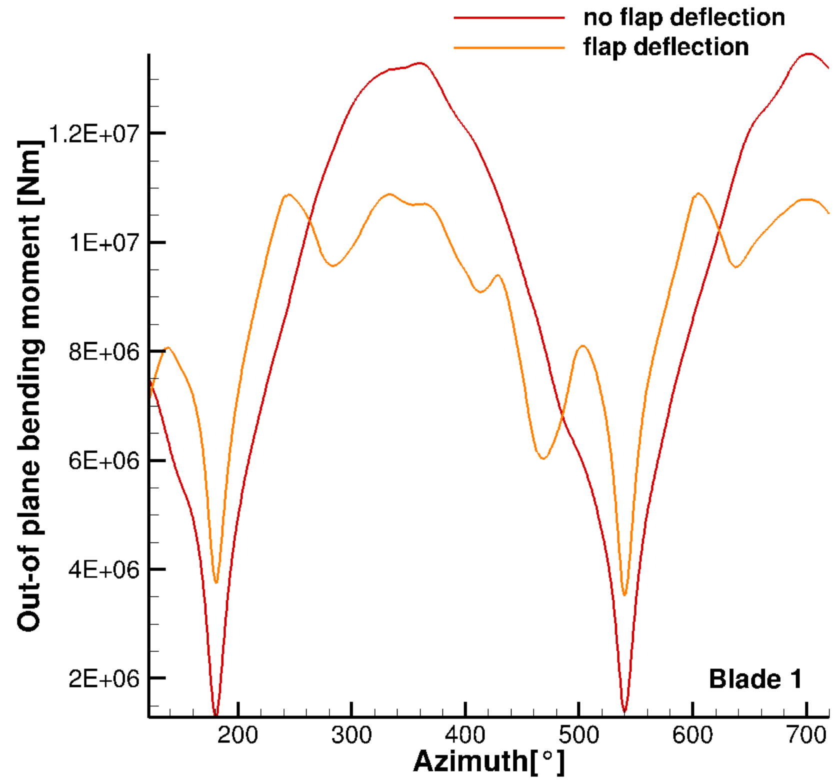
Full turbine model
- Integral power and thrust



- 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

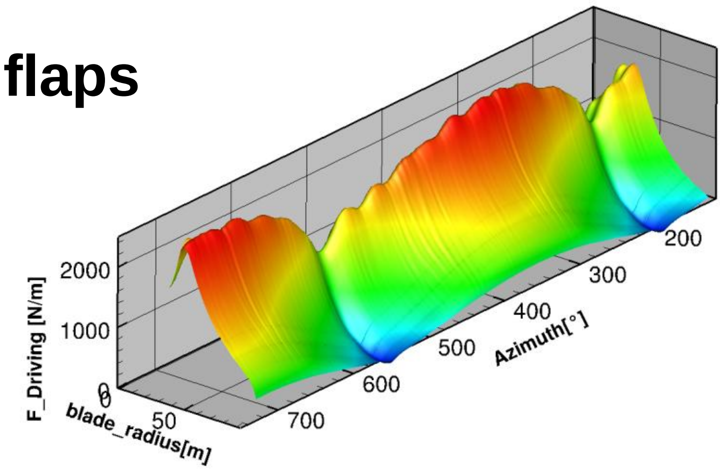


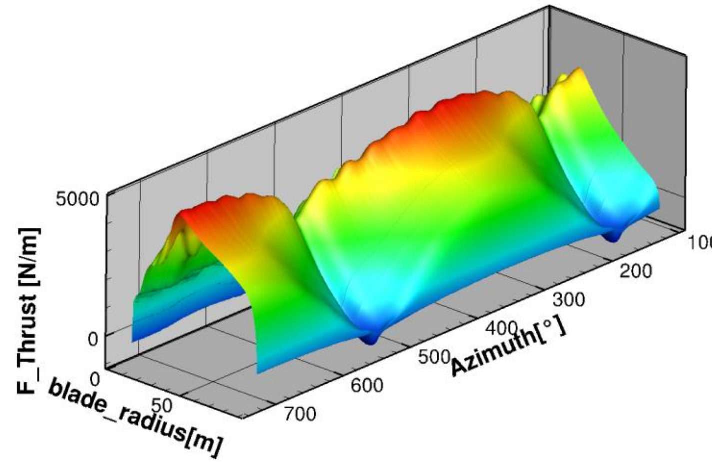


► Blade root bending moment: reduction of 40% of absolute mean value

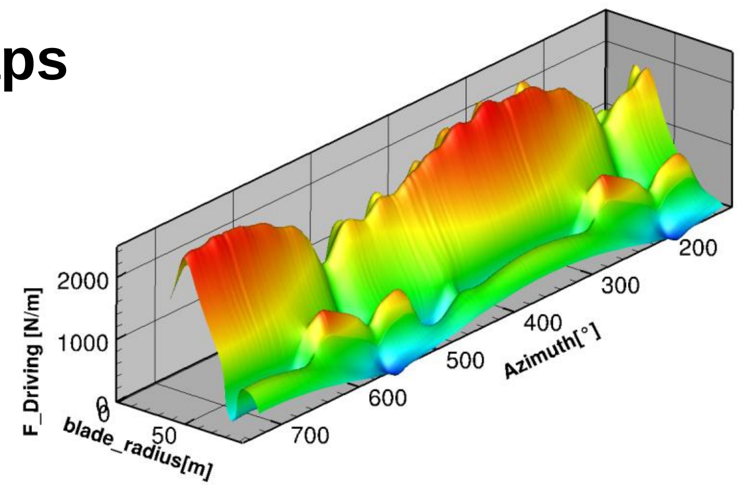
Full turbine model
- Sectional force distributions

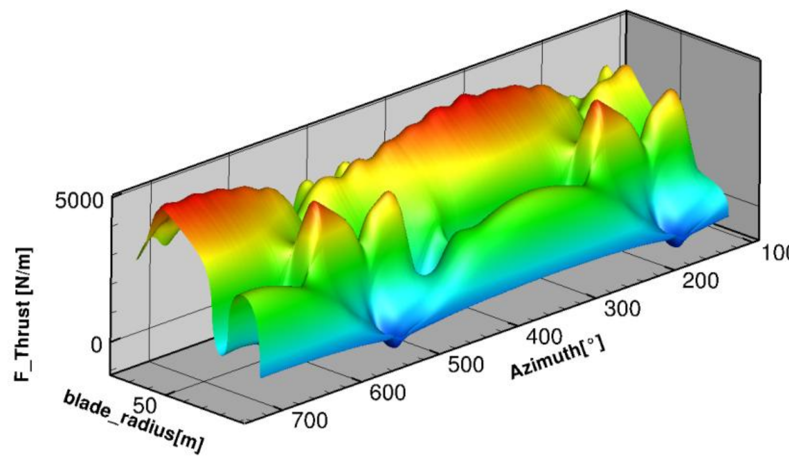
Without flaps





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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