AdVanced Aerodynamic Tools for lArge Rotors

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AVATAR project
Advanced Aerodynamic Tools for lArge Rotors

Gerard Schepers
January 20th, 2016

EERA Deepwind

Trondheim, Norway

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grand agreement No FP7-ENERGY-2013-1/n° 608396 .

List of Contents

- Introduction into the project
- Design of AVATAR Reference Wind Turbine [1])
- Aerodynamics at high Reynolds numbers
  - Results from a blind test on airfoil measurements taken in the pressurized DNW-HDG tunnel [2])
- Aero-elasticity of large turbines
  - BEM versus free wake aerodynamic modelling[3])

1) Acknowledgement G. Sieros, M. Stettner
2) Acknowledgement O. Ceyhan, O. Pires
3) Acknowledgement K. Boorsma, S. Voutsinas
And all other project partners!

EU FP7 Project initiated by EERA

1. Energy Research Centre of the Netherlands, ECN (Coordinator)
2. Delft University of Technology, TUDelft
3. Technical University of Denmark, DTU
4. Fraunhofer IWES
5. University of Oldenburg, Forwind
6. University of Stuttgart, USTUTT
7. National Renewable Energy Centre, CENER
8. University of Liverpool/University of Glasgow, ULIV/UoG
9. Centre for Renewable Energy Sources and Saving, CRES
10. National Technical University of Greece, NTUA
11. Politecnico di Milano, Polimi
12. GE Global Research, Zweigniederlassung der General Electric Deutschland Holding GmbH, GE
13. LM Wind Power, LM

Period

- Project period:

  November 1^{st} 2013- November 1^{st} 2017

Main motivation for AVATAR: Aerodynamics of large wind turbines (10-20MW

AdVanced Aerodynamic Tools for lArge Rotors

- We simply don't know if present aerodynamic models are good enough to design 10MW+ turbines
- 10MW+ rotors violate assumptions in current aerodynamic tools, e.g.:
  - Reynolds number effects,
  - Compressibility effects
  - Thick(er) airfoils
  - Flow transition and separation,
  - (More) flexible blades
  - Flow devices
- **Hence 10MW+ designs fall outside the validated range of current state of the art tools.**

Avatar: Main objective

To bring the aerodynamic and fluid-structure models to a next level and calibrate them for all relevant aspects of large (10MW+) wind turbines

Avatar: Work procedure

- **Problem:** No 10 MW turbines are on the market yet for validation
- Hence: Validate *submodels* against experiments
  - *Pressurized* HDG tunnel of German Dutch Wind Tunnel facilities (DNW)
    - Airfoil measurements at Reynolds numbers up to *RE = 15 M* and low Mach (< 0.2)
  - LM: Wind tunnel airfoil measurements also at dynamic conditions
  - Forwind: Wind tunnel airfoil measurements at *representative turbulence*
  - TUDelft: Wind tunnel experiments on airfoils with *vortex generators, flaps*
  - NTUA: Wind tunnel experiments on airfoils with/without *vortex generators*
  - DTU : Danaero: Aerodynamic *field* experiments on a *2.3 MW* turbine and supporting 2D wind tunnel measurements
  - Note: Several experiments are supplied *in-kind*

Avatar: Work procedure

Use the different models from partners in the project

- It is a ***cooperation*** project!
- In the project we have many models which range from computational efficient '*engineering*' tools to *high fidelity* but *computationally expensive* tools
- Engineering tools are needed in *industrial* design codes [1])
- *High fidelity* models (*and intermediate* models) feed information towards *engineering* models

[1]) J.G. Schepers '*Engineering models in wind energy aerodynamics,*', (2012). TUDelft PhD thesis **ISBN**: 9789461915078

Avatar: Work procedure

- Demonstrate the value of the improved tools on *10 MW reference rotors* with and without flow control devices
  1. INNWIND.EU reference rotor (more or less *conventional* design philosophy)
  2. AVATAR reference rotor which should be more *challenging* from an aerodynamic point of view (e.g. lower induction, longer, more slender blades, thicker airfoils, higher tip speed).
- Compare results from ‘old’ and improved models at the end of the project

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AVATAR RWT

	INNWIND.EU	AVATAR – AdVanced Aerodynamic Tools for lArge Rotors
Power:	10 MW	10 MW
Rotor diameter:	178.3m	205.8m
WTPD:	400 W/m^2	300 W/m^2
Axial induction:	0.3	0.24
RPM→Tip speed	9.8rpm→ 90m/s	9.8 →103.4 m/s
Hub height:	119m	132.7m

Classical Approach versus Low Induction

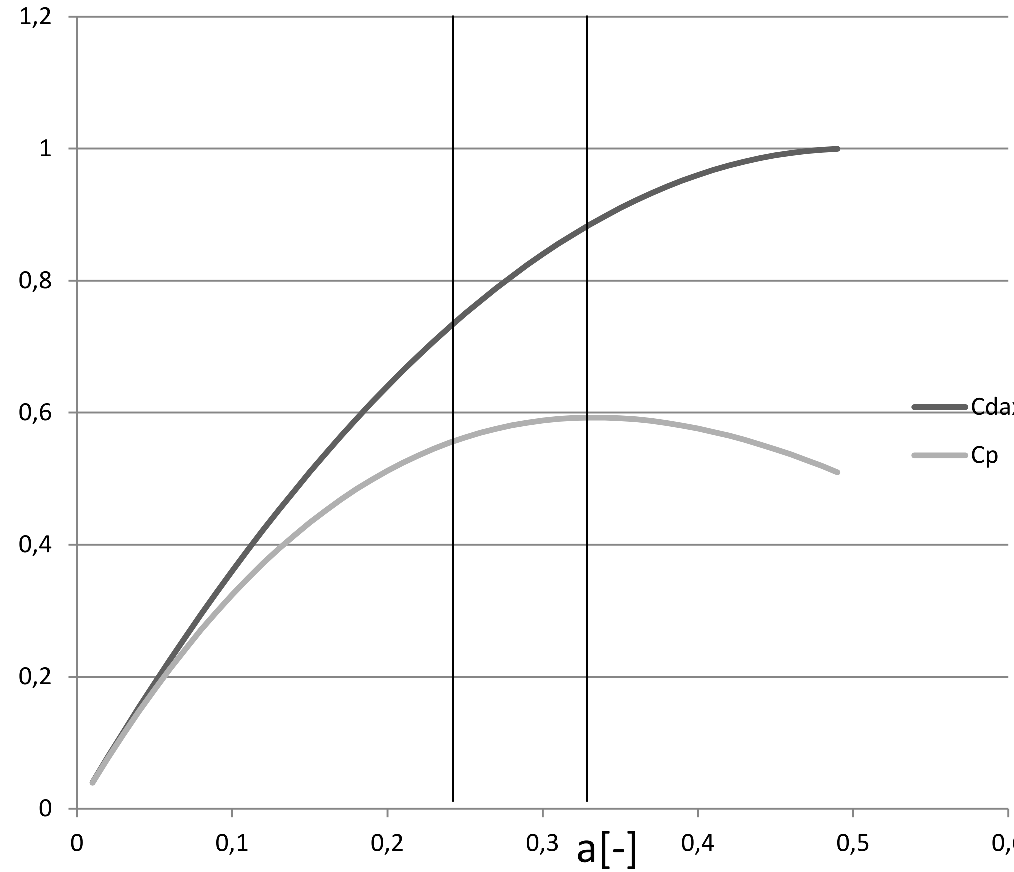
- Power Coefficient flat around Betz maximum (a = 1/3)

$$C_P = \frac{P}{\frac{1}{2}\rho A U_\infty^{\;3}} = 4a(1-a)^2$$

- Aerodynamic load coefficient strongly dependant on a

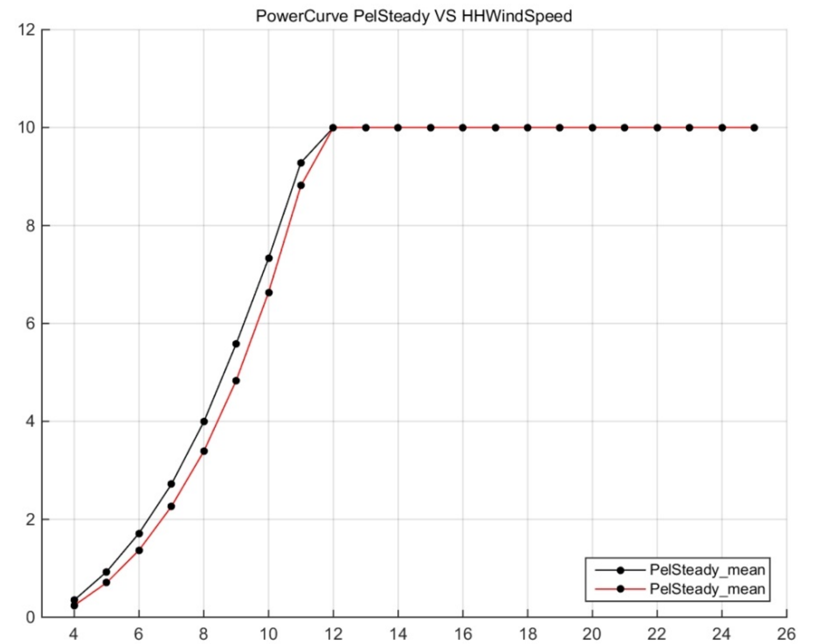
$$C_{D.ax} = \frac{D.ax}{\frac{1}{2}\rho A U_\infty^{\;2}} = 4a(1-a)$$

- Increase diameter→ maintain aerodynamic loads→ increase power



Design of AVATAR RWT

- 5% Increase in energy production due to larger diameter
- Key rotor load levels are maintained
- Non-rotor loads exceeded→ Redesign of AVATAR rotor at end of project
- Note: LCOE of AVATAR turbine assessed in [1]) taking into account additional advantage of lower wake effects



[1]) R. Quinn, B. Bulder, J.G. Schepers
A parametric investigation into the effect of low induction rotor (LIR) wind turbines on the LCoE of a 1GW offshore wind farm in a North Sea wind climate, EERA-Deepwind 2016

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Design of AVATAR RWT

- The operational conditions

Section Thickness	Re (rated)	Ma (rated)	Re (Min)	Ma (Min)
60.0%	**7.0×106**	**0.05**	4.4×106	0.03
40.1%	**11.0×106**	**0.07**	7.0×106	0.05
35.0%	**14.0×106**	**0.09**	9.0×106	0.06
30.0%	**17.0×106**	**0.12**	10.0×106	0.07
24.0%	**20.0×106**	**0.16**	12.0×106	0.10
24.0%	**16.0×106**	**0.25**	11.0×106	0.15
24.0%	**13.0×106**	**0.30**	8.0×106	0.18
21.0%	**20.0×106**	**0.16**	12.0×106	0.10
21.0%	**16.0×106**	**0.25**	11.0×106	0.15
21.0%	**13.0×106**	**0.30**	8.0×106	0.18

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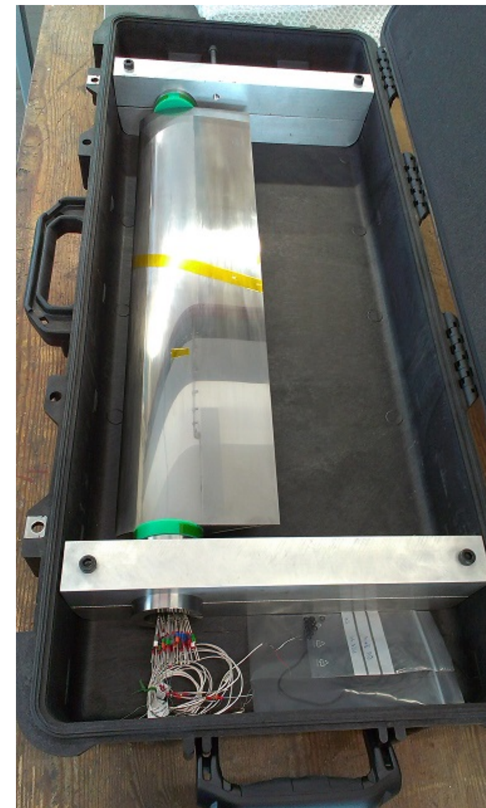
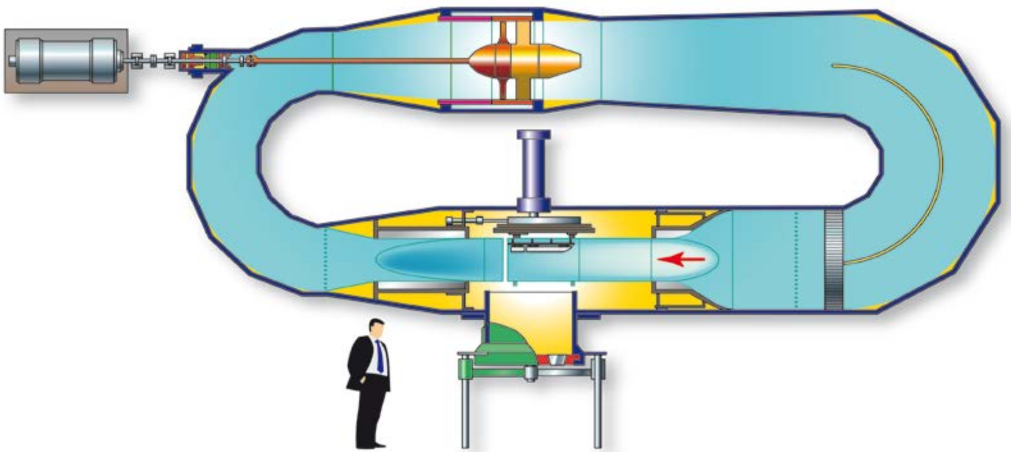
Measurements in DNW-HDG pressurized tunnel

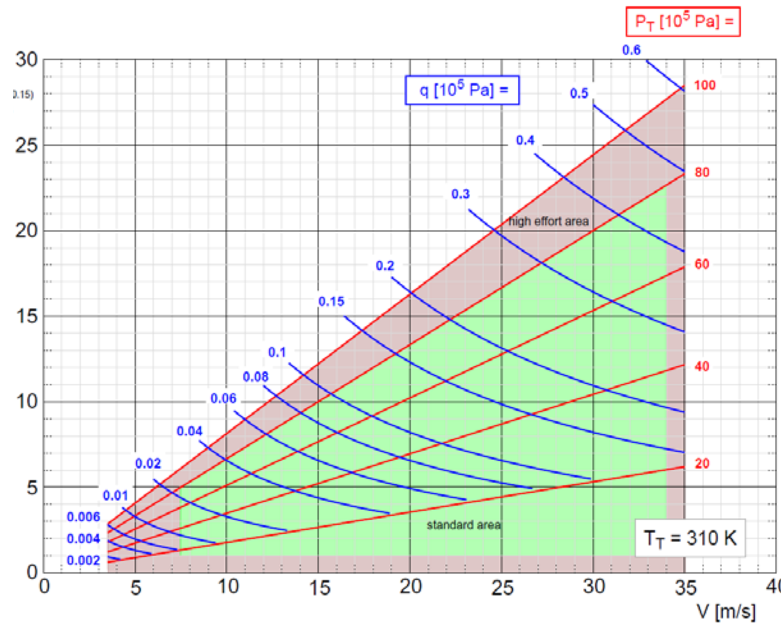
DNW-HDG model, c=15 cm



- Airfoil: DU00-W-212
  - Measurements up to Re = 15M
  - DU00-W-212 is also measured by LM up to RE=6M and by Forwind at controlled turbulent conditions up to 1M
- Results are brought into a 'blind test'
  - including participants outside project

DNW-HDG Wind Tunnel





General Tunnel Characteristics

Test section : 60cmx60cm
Fan Rpm : 200 – 820 Fan blade angle fixed
Tunnel Pres. : 1 – 100 × 10^5 Pa
Tunnel Temp. : ambient to 45° C

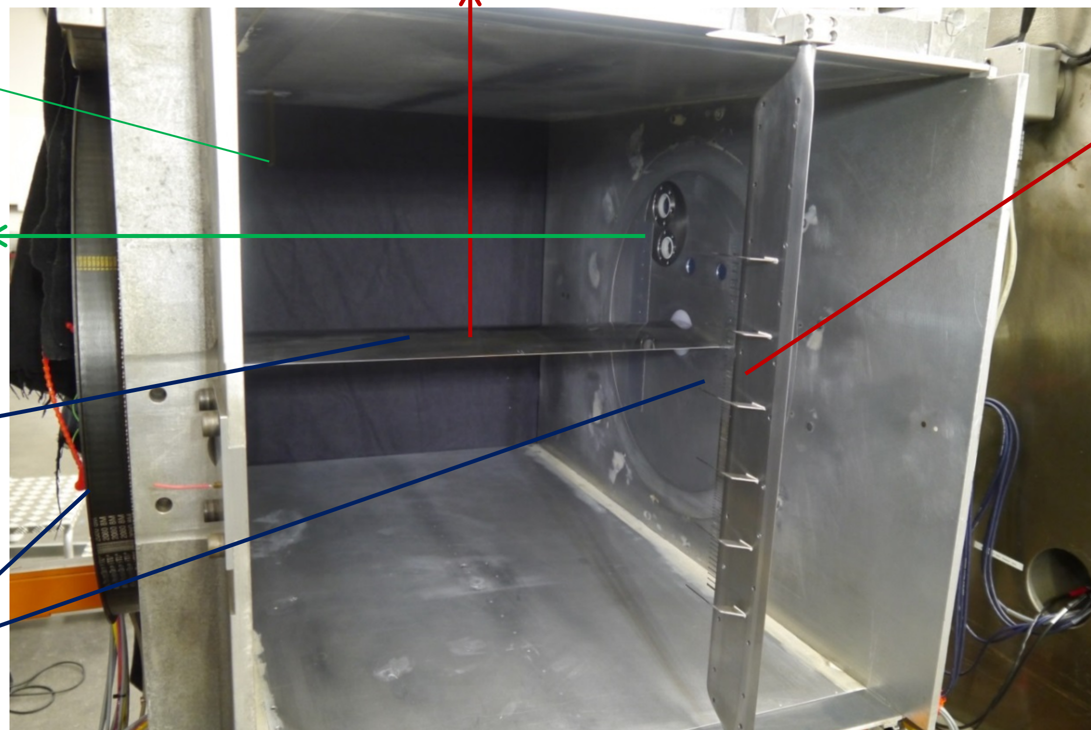
Test Section

Probe holder for hot wire

Sensicam & UV LED's Flow visualization

90 PTs at half span

Wake rake
118 pitot tubes
6 pressure taps



Kulites
4 pressure side
1 suction side

3-component Balance

Participants/Codes

			Test 1. Re=3mil	Test 2. Re=6mil-1	Test 3. Re=6mil-2	Test 4. Re=9mil-1	Test 5. Re=9mil-2	Test 6. Re=12mil	Test 7. Re=15mil
		P_t [bars]	12	34	67	34	67	67	60
		V_{tunnel} [m/s]	25.6	19	10	28.6	15	20	28.4
Full CFD	**DTU/EllipSys**	Fully turbulent							
		Transition	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	KIEL/TAU	Fully turbulent							
		Transition	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	NTUA/Mapflow	Fully turbulent							
		Transition	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	UoG/HMB	Fully turbulent	Yes						Yes
		Transition	Yes		Yes				
	Forwind-IWES/OpenFOAM	Fully turbulent	Yes	Yes	Yes	Yes	Yes	Yes	Yes
		Transition							
Panel Methods	**USTUTT/XFOILvUSTUTT**	Fully turbulent							
		Transition	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	ORE Catapult/XFOILv6.96	Fully turbulent							
		Transition	Yes	Yes	Yes	Yes	Yes	Yes	Yes

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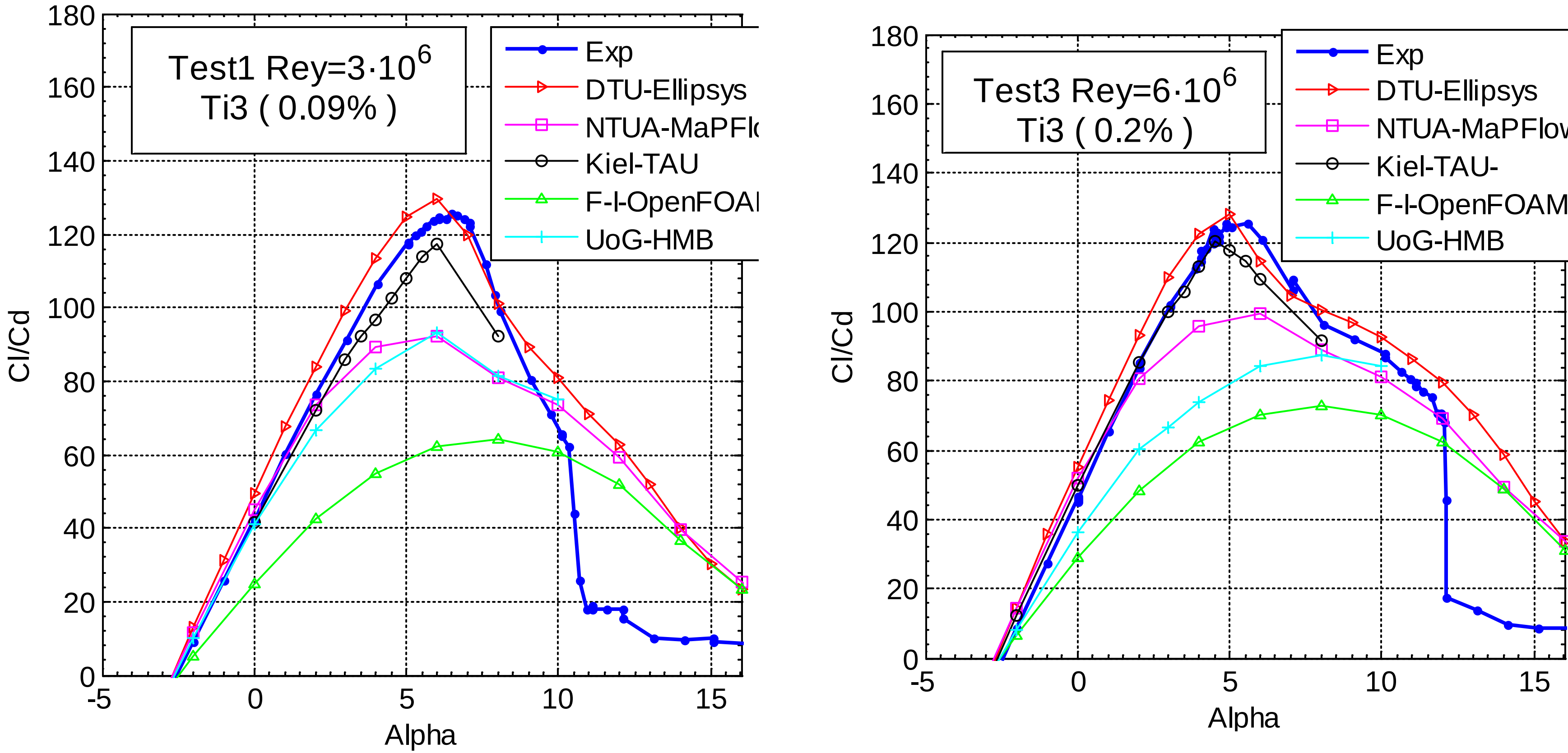
DNW-HDG Full CFD calculations vs measurements
Effect in Blade Design parameter: Cl/Cd



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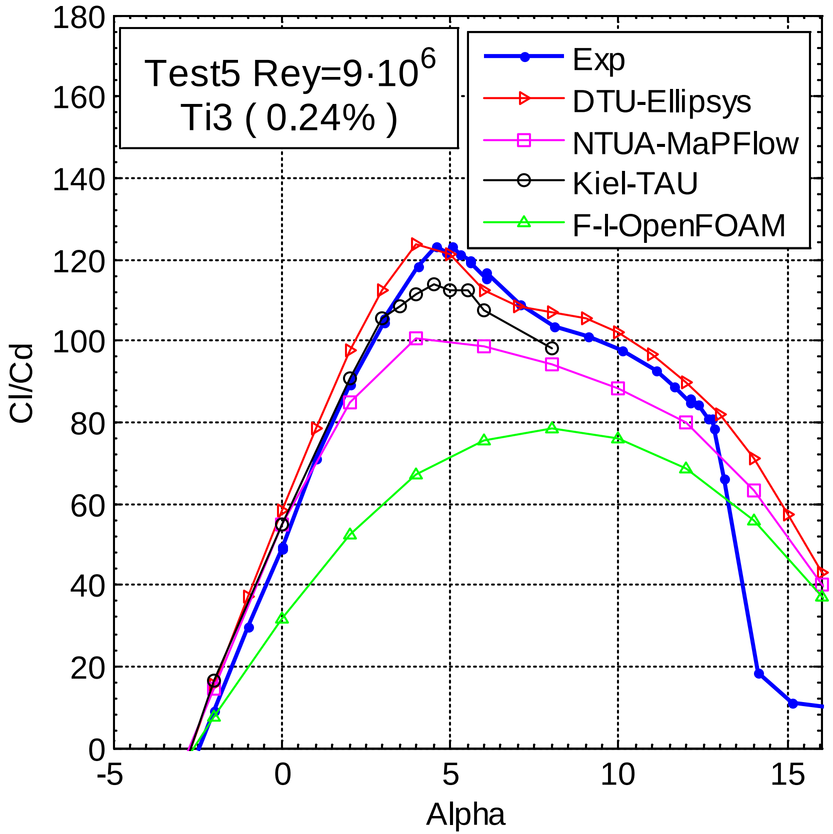
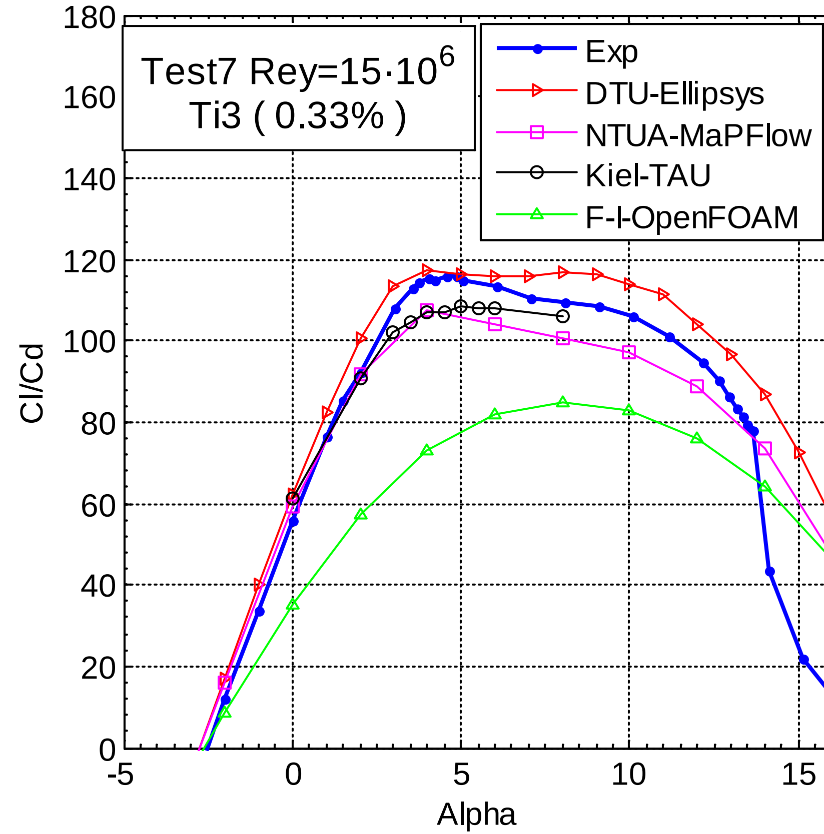
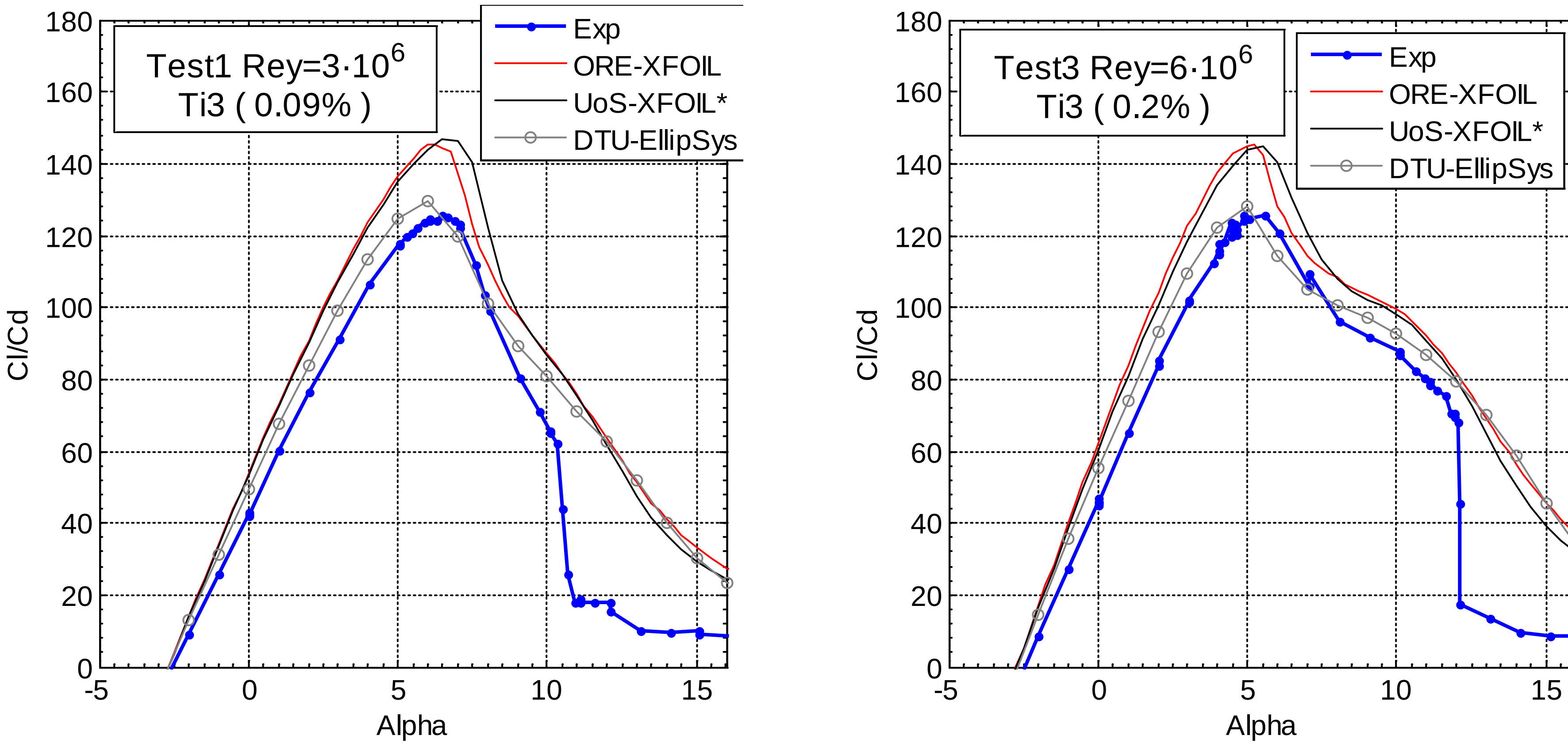
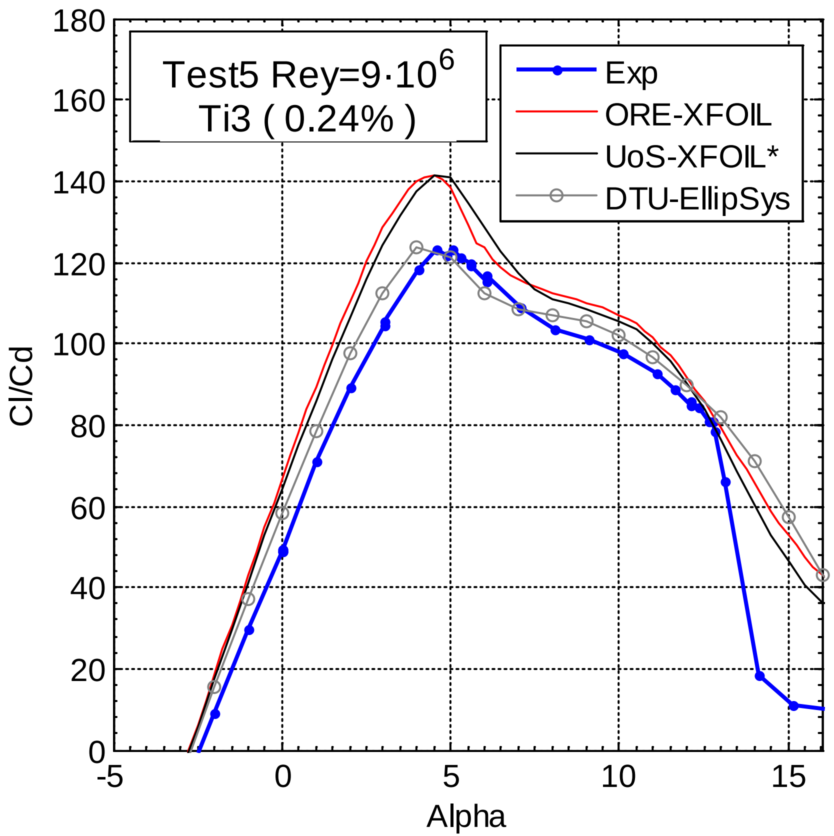


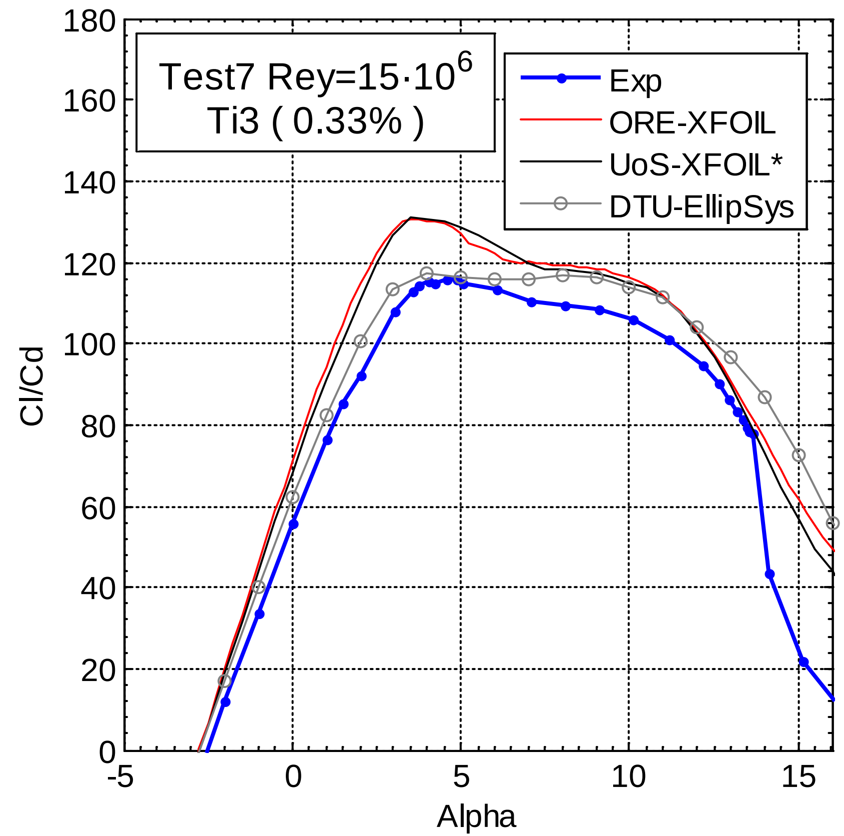


DNW-HDG Panel code calculations vs measurements
Effect in Blade Design parameter: Cl/Cd

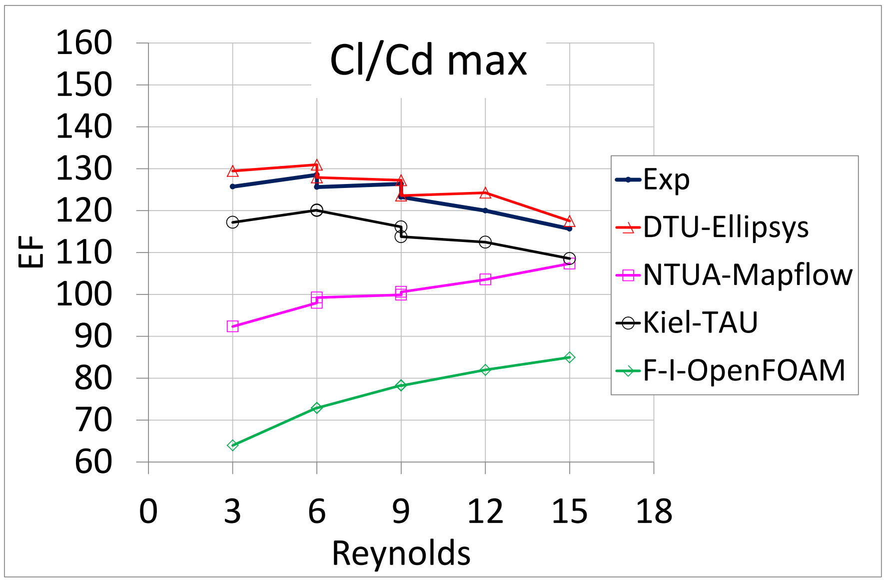


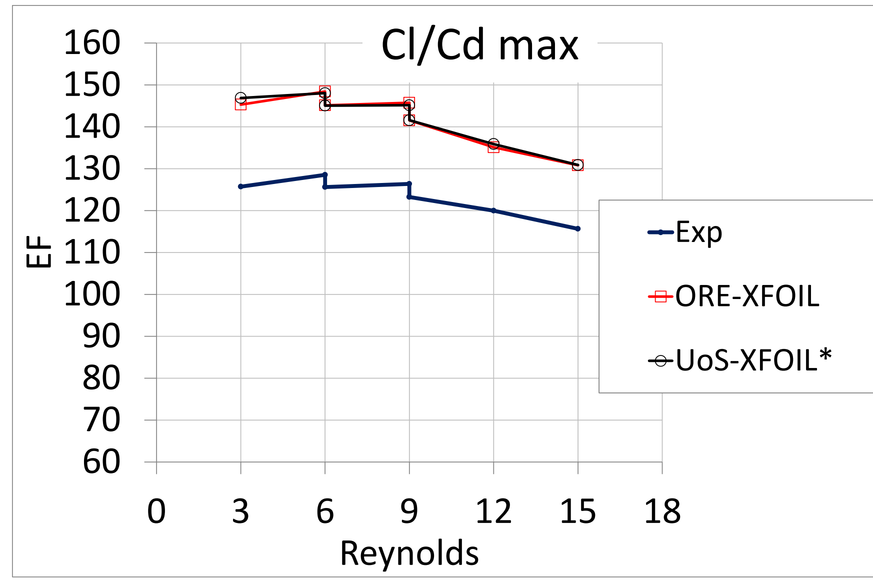
DNW-HDG Panel code calculations vs measurements
Effect in Blade Design parameter: Cl/Cd





Results
Re effects in Cl/Cd trends





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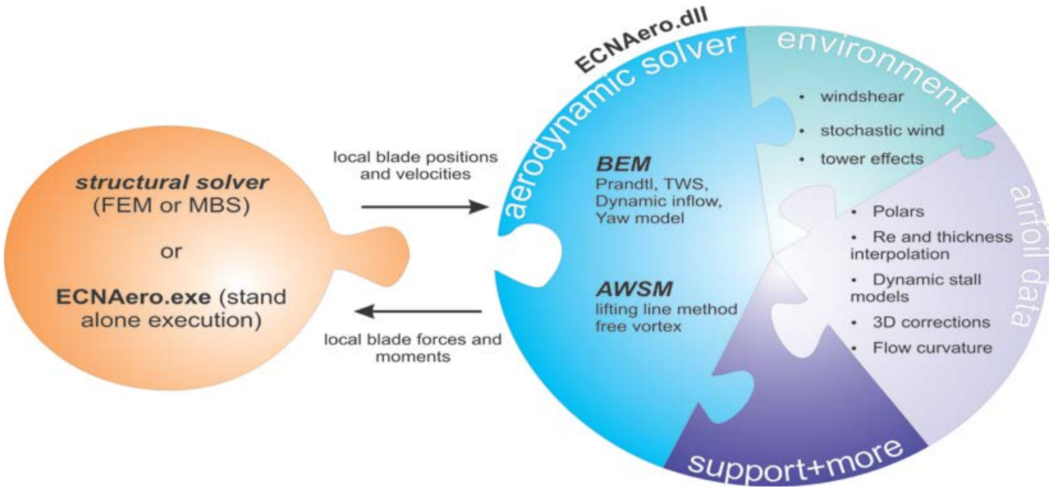
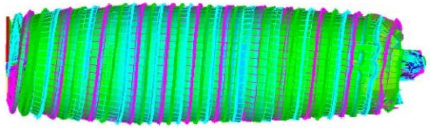
ECN Aero-module

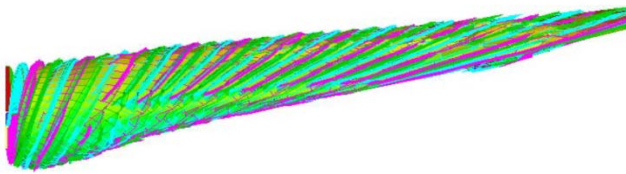
- ECN Aero Module: One code with aero-models of different degrees of fidelity (BEM and free/prescribed vortex wake) coupled to same structural solver (PHATAS/FOCUS)
  - Straightforward comparison of different aerodynamic models

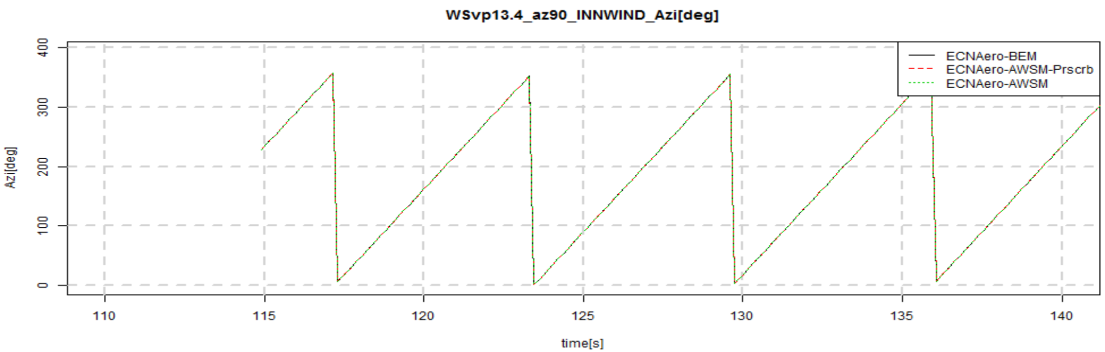


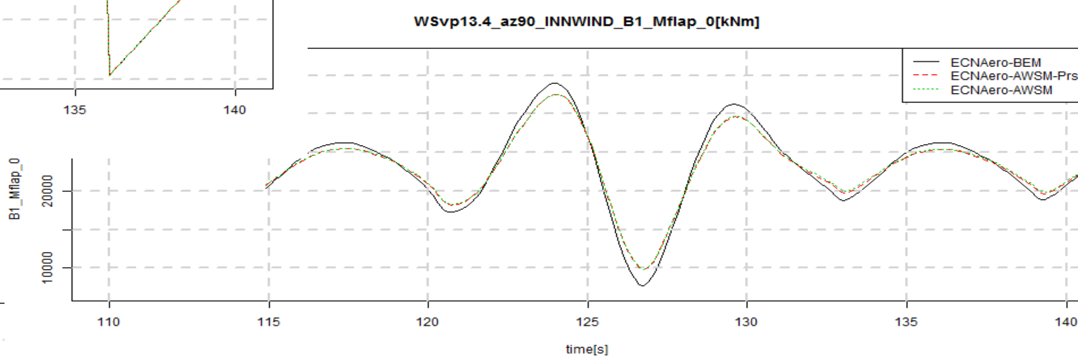
Results: Extreme transient shear

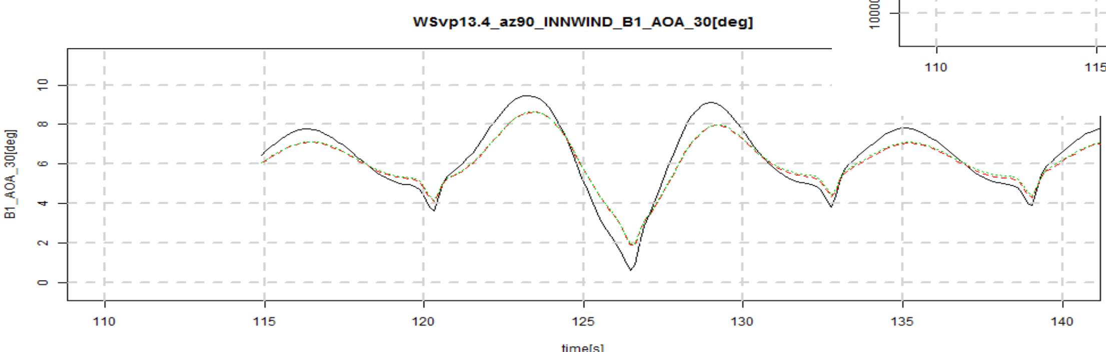
- INNWIND, rated power





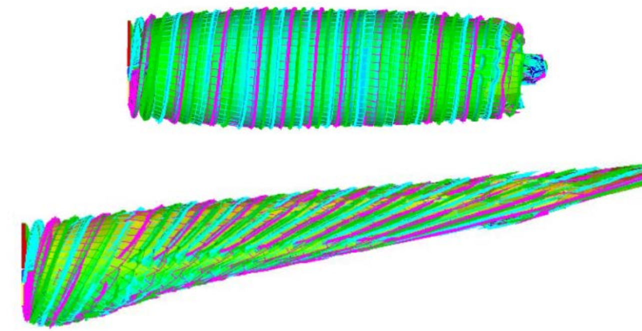


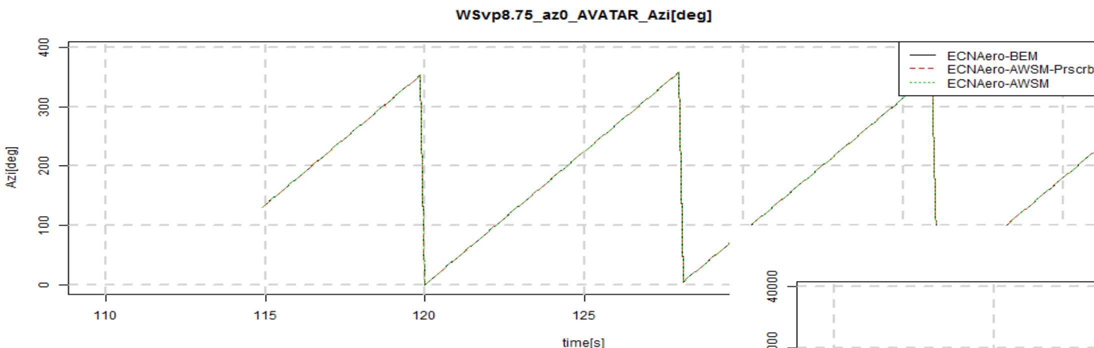


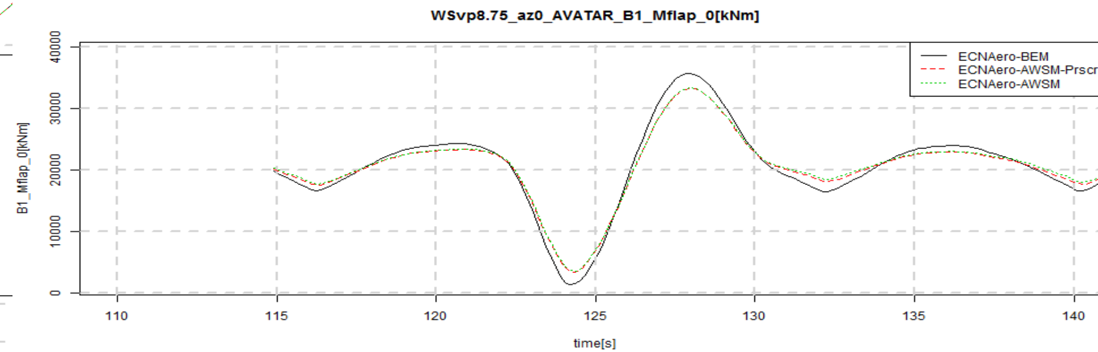


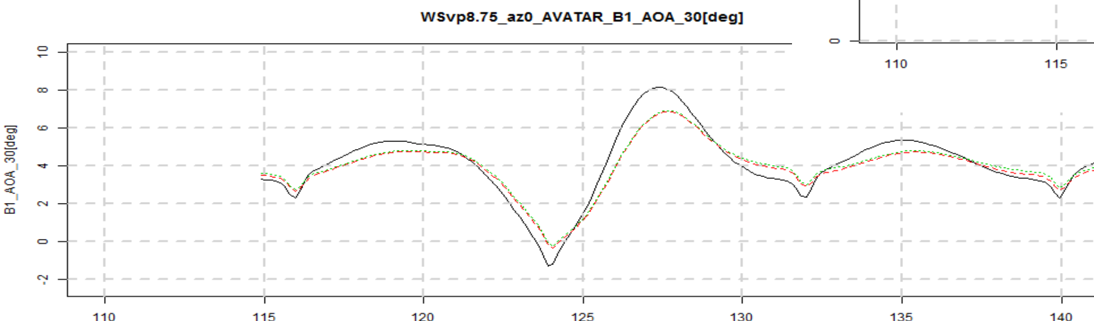
Results: Extreme transient shear

- AVATAR, partial load



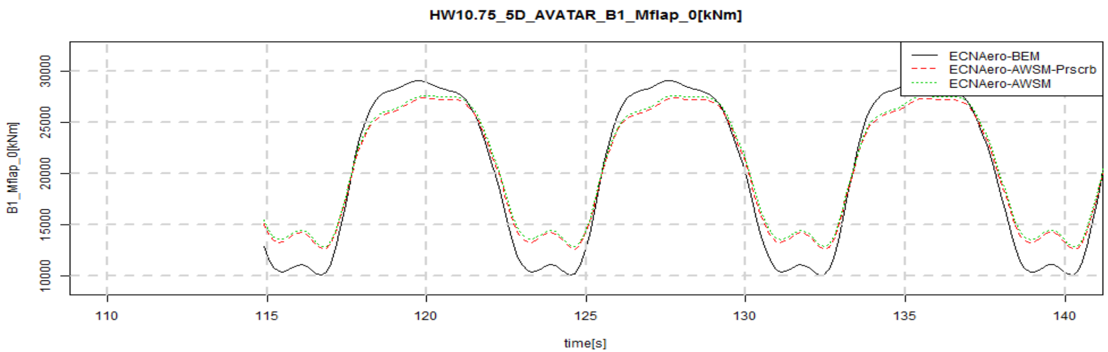


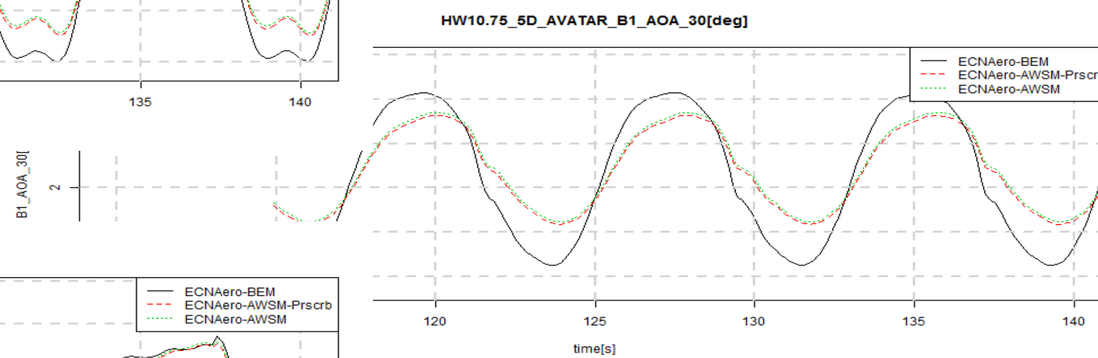


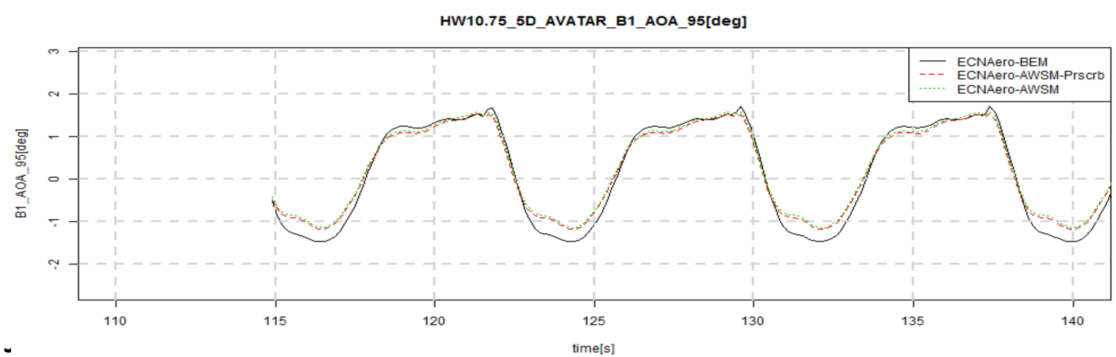


Results: Half wake

- AVATAR, rated conditions







AdVanced Aerodynamic Tools for lArge Rotors

Summary

- AVATAR is an EU FP7 projects which aims to validate, improve and calibrate aerodynamic models for 10MW+ turbines with and without flow devices and with and without aero-elastic effects
- Several (wind tunnel) measurements have been taken which have helped to validate and improve (sub) models relevant for 10MW+ turbines
  - Correlation based transition models shown to be deficient at high Reynolds numbers
- Models of different degrees of fidelity are evaluated on two 10 MW reference wind turbines:
  - AVATAR low induction turbine with special aerodynamic challenges
  - INNWIND.EU conventional induction turbine
  - Engineering prediction of load fluctuations at transients/wake operation overestimated
- The amount of results is far too much to present in 20 minutes
  - All technical deliverables are public: http://www.eera-avatar.eu/publications-results-and-links/

Consortium

Coordinator:

ECN

Partners in alphabetical order:

CENER – Centro Nacional de Energías Renovables – National Renewable Energy Centre

ΚΑΠΕ CRES – Centre for Renewable Energy Sources and Saving

DTU

ForWind – Center for Wind Energy Research – Bremen Hannover Oldenburg

Fraunhofer IWES

GE

LM Wind Power

National Technical University of Athens

Politecnico di Milano

TU Delft – Delft University of Technology

University of Liverpool

University of Stuttgart Germany

Thank you for your attention

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