DTU Wind
Department of Wind and Energy Systems

Proceedings of IEA Task 47 workshop
Held at DTU on November 29, 2024

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Preface

We present the proceedings with the presentations from the 2nd IEA Wind Task 47 workshop held on November 29, 2024 at DTU Campus Risø. The workshop is part of the dissemination activities in the Danish project supporting the participation of DTU in the IEA Vind Task 47, "Aerodynamic Experiments and Simulations on Wind Turbines in Turbulent Inflow", funded by EUDP. The presentations stand for themselves without comments.
The workshop was held in conjunction with the final project meeting with the participation of institutes from all countries participating in IEA Wind Task 47 coordinated by Gerard Schepers from TNO. The presentations are thus not only from DTU but also from other research institutes and industry.

Technical University of Denmark, March 2025

Helge Aagaard Madsen
Project coordinator

Contents

1 Introduction

The meeting was held as a hybrid meeting with participants both at Risø and online. Most of the presenters were attending in person, but some made the presentation online.
The agenda is shown in Section 1.1. After a welcome by the IEA task 47 coordinator Gerard Schepers from TNO he gave an introduction to the general IEA setup with the cooperation work organized tasks. Then followed the background for the present IEA task 47 and its contents.
The following two presentations were given by Koen Boorsma from TNO and Christian Grinderslev from DTU with a focus on the main activities in Task 47 within WP1, turbulent inflow using the experimental data from the DanAero project in the benchmarking and WP2, simulations on the 15MW reference turbine.
Full-scale experiments and how to conduct such an experiment have been part of the activities in WP1, and four presentations within this theme followed.
After the coffee break, three presentations on the specific outcome of IEA task 47 were given.
An outlook and research needs as seen from industry were presented after lunch by Torben Juul Larsen from Vestas and by Jesper Laursen from Siemens Gamesa Renewable Energy followed by two other industry presentations on more specific subjects.
The workshop concluded with an overview of the successor IEA task 47 II.

1.1 Agenda

Programme

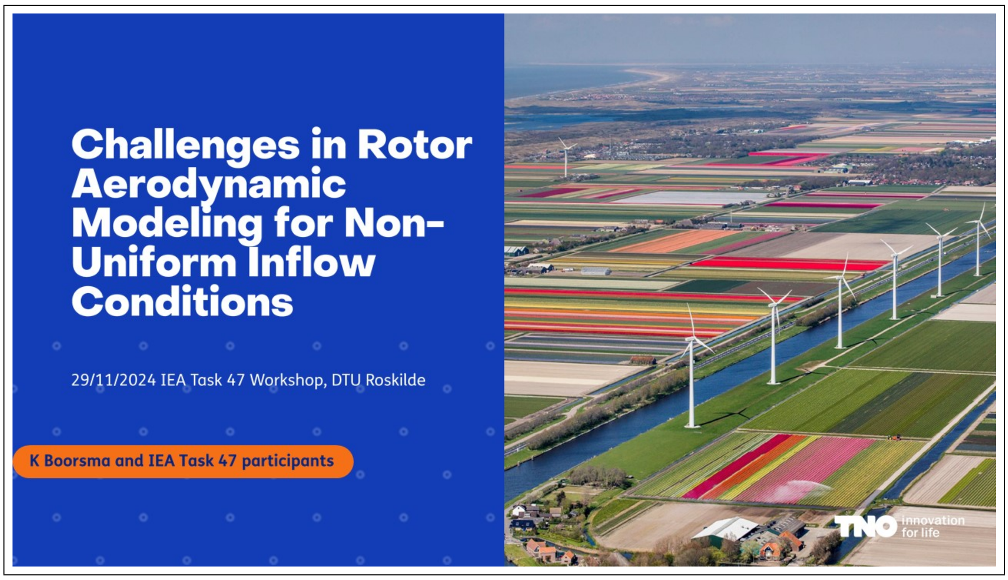
Workshop IEA Wind Task 47, Friday 29 November 2024

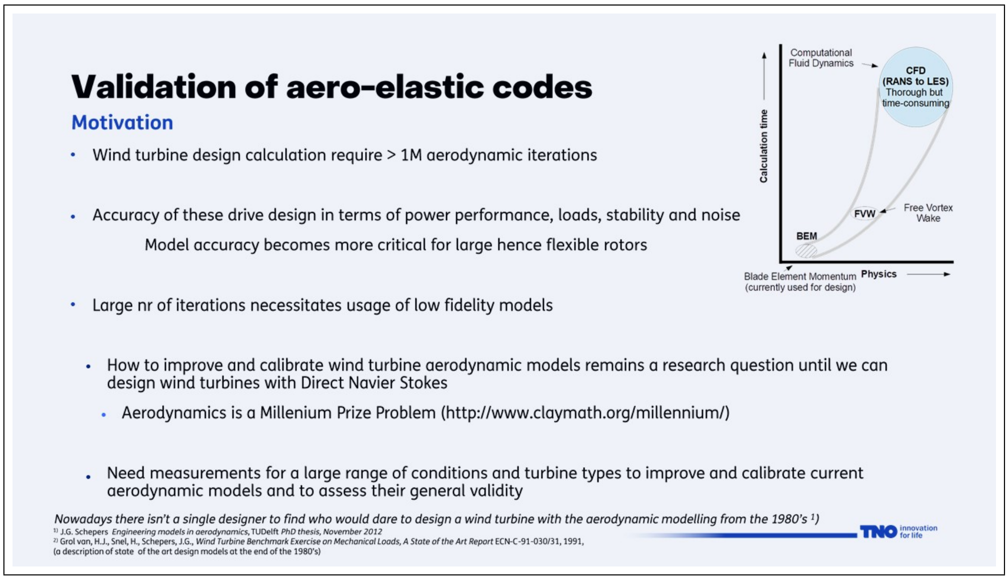
29 November 24

09:00 - 09:30	**Welcome and coffee for on-site participants**
09:30 - 09:50	**Overall overview of IEA Wind Task 47 and main outcomes, Gerard Schepers, TNO**
09:50 - 10:10	**Aerodynamic comparison rounds with DAN-AERO experiment, Koen Boorsma, TNO**
10:10 - 10:30	**CFD rotor computations on the IEA 15 MW turbine, Christian Grinderslev, DTU**
10:30 - 11:10	**Full scale aerodynamic experiments (4 10-minute presentations from Task 47 participants**
11:10 - 11:20	**Coffee break**
11:20 - 12:20	**Specific outcomes of Task 47 (4-6 presentations from Task 47 participants)**
12:20 - 13:00	**Lunchbreak**
13:00 - 15:00	**Presentations from industry: present and future research needs** Erik Mranda - Director, Next WTG Solutions, New Concepts & Power to X, Vestas Technology & Operations Jesper Lauersen, Principal key expert offshore blades - SGRE Carlos Rodrigues, Aerodynamic & Loads Specialist, Suzlon Galih Bangga, Aerodynamics expert, DNV
15:05 - 15:25	**Outlook for the next phase of IEA Wind Task 47**
15:25 - 15:30	**Closure of meeting**

Page 1 by 1 Workshop IEA Wind Task 47, Friday 29 November 2024

2 Overall overview of IEA Wind Task 47 and main outcomes - Gerard Schepers, TNO





Some explanation on IEA Wind Tasks

- IEA Wind Task (Annex):
  - IEA = International Energy Agency
  - IEA Wind Task = A cooperative (international) project organised under the auspices of the IEA Executive Commitee (ExCo) of the IEA TCP (Technology Colloboration Program) Wind.
  - The IEA ExCo consists of national representatives from the countries participating in the IEA TCP wind
    - These national representatives can be found on http://www.ieawind.org/contact_list/ExCoMembers.pdf
  - The cooperation in IEA Task makes 1 + 1 = 3!

10-3-2025 3

Table of content

- Background:
  - What is an IEA Wind Task
  - *History of IEA Tasks on Aerodynamics*
- IEA Task 47 TURBINIA?
  - Motivation, Objective, Workplan
- IEA Task 47 TURBINIA
  - Activities, Main outcomes

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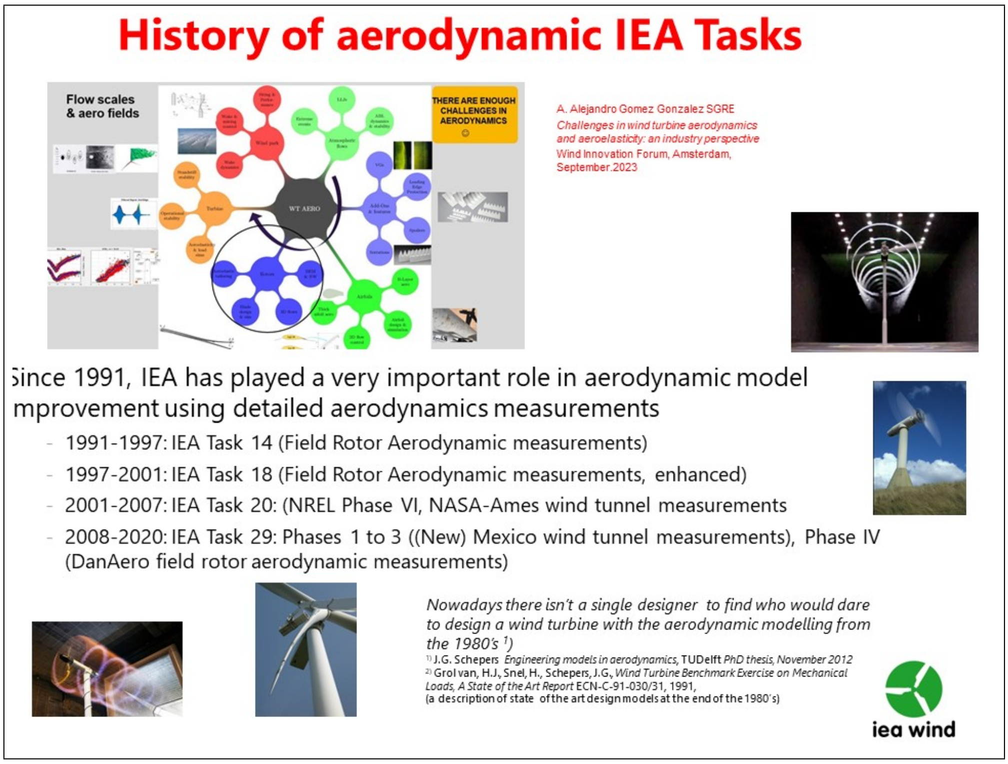
History of aerodynamic IEA Tasks
Flow scales & aero fields
WT AERO
THERE ARE ENOUGH CHALLENGES IN AERODYNAMICS
A. Alejandro Gomez Gonzalez SGRE
Challenges in wind turbine aerodynamics and aeroelasticity: an industry perspective
Wind Innovation Forum, Amsterdam, September 2023
Since 1991, IEA has played a very important role in aerodynamic model improvement using detailed aerodynamics measurements
- 1991-1997: IEA Task 14 (Field Rotor Aerodynamic measurements)
- 1997-2001: IEA Task 18 (Field Rotor Aerodynamic measurements, enhanced)
- 2001-2007: IEA Task 20: (NREL Phase VI, NASA-Ames wind tunnel measurements
- 2008-2020: IEA Task 29: Phases 1 to 3 ((New) Mexico wind tunnel measurements), Phase IV (DanAero field rotor aerodynamic measurements)
Nowadays there isn't a single designer to find who would dare to design a wind turbine with the aerodynamic modelling from the 1980's 1)
1) J.G. Schepers Engineering models in aerodynamics, TUDelft PhD thesis, November 2012
2) Grol van, H.J., Snel, H., Schepers, J.G., Wind Turbine Benchmark Exercise on Mechanical Loads, A State of the Art Report ECN-C-91-030/31, 1991,
(a description of state of the art design models at the end of the 1980's)
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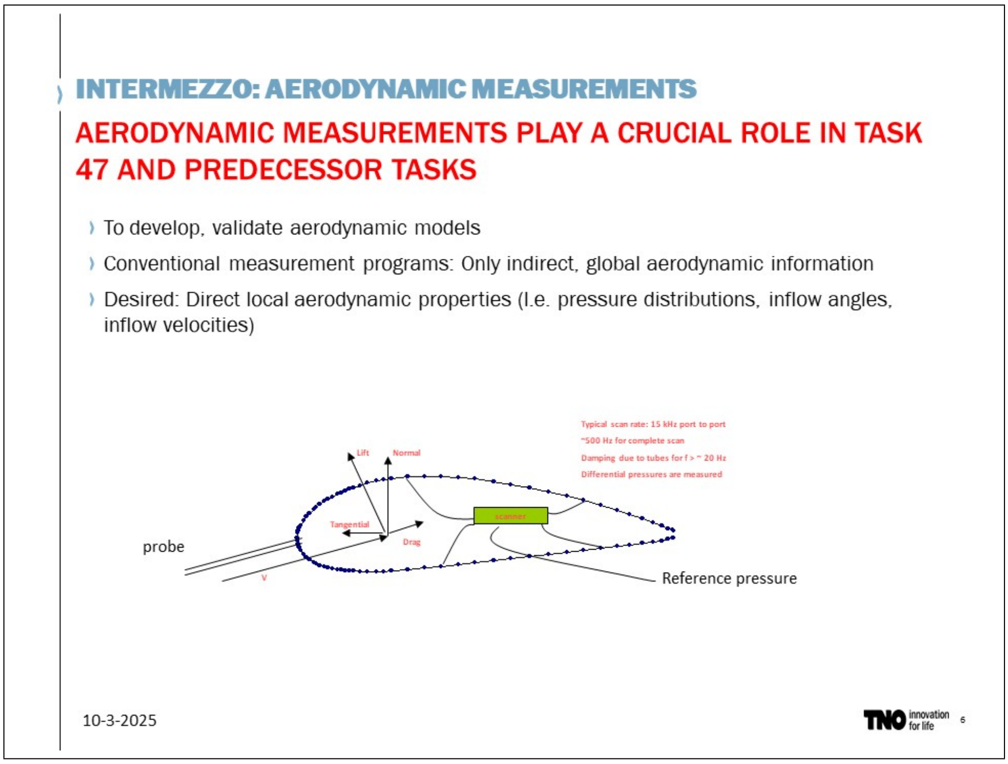
INTERMEZZO: AERODYNAMIC MEASUREMENTS
AERODYNAMIC MEASUREMENTS PLAY A CRUCIAL ROLE IN TASK 47 AND PREDECESSOR TASKS
To develop, validate aerodynamic models
Conventional measurement programs: Only indirect, global aerodynamic information
Desired: Direct local aerodynamic properties (I.e. pressure distributions, inflow angles, inflow velocities)
Typical scan rate: 15 kHz port to port
~500 Hz for complete scan
Damping due to tubes for f > ~ 20 Hz
Differential pressures are measured
Lift
Normal
Tangential
Drag
scanner
probe
V
Reference pressure
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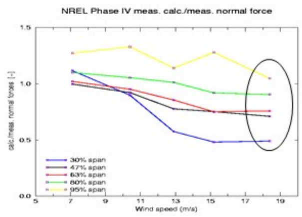
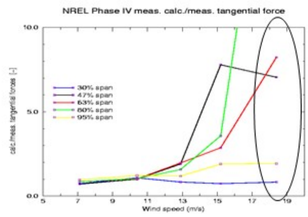
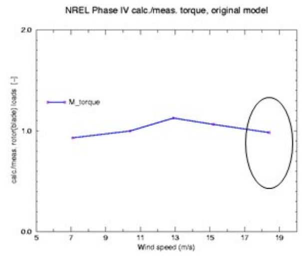
IEA TASKS 14/18 SHOWED THE NEED FOR DETAILED MEASUREMENTS







Ratio between ECN calculated and NREL measured normal and tangential forces at 5 radial positions (top) and rotorshaft moment (bottom) as function of wind speed

High wind speeds: Normal forces underpredicted, Tangential forces overpredicted:

Despite underpredicted normal forces and overpredicted tangential forces:
Excellent agreement in rotorshaft torque. **Compensating errors**

- Measurements of global loads **cannot** be used for improvement and validation of aerodynamic models

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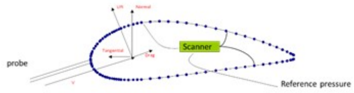
Why Task 47: Because many countries are doing aerodynamic field experiments

- Aerodynamic field experiments are now initiated at several countries (Denmark, France, Germany, Holland, Italy, Switzerland, USA). Experiments up to 8 MW
  - ✓Very **specialised** experiments, **cooperation** extremely useful



*) Some specific issues Drilling pressure holes non-intrusive in blades, choosing the right type of pressure transducers and data acquisition with the right measurement range and frequency response taking into account length of tubes, connecting sensors to the data acquisiton system, choosing the right locations for the sensors, powering the sensors, purging pressure tubes, protecting pressure tubes and sensors against rain, vibrations and centrifugal forces, calibration of pressure scanners, account for varying reference pressure, calibration of pitot tubes, definition of angle of attack and dynamic pressure, measurement uncertainties

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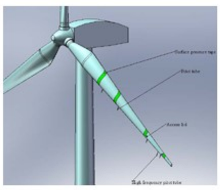
The DanAero field experiment is again included

DanAero Aerodynamic Field measurements

- Surface pressure and inflow measured at 4 radial stations
- the outboard station also instrumented with around 60 microphones for high frequency surface pressure measurements
- high frequency measurements of the inflow
- measurements from June to September 2009



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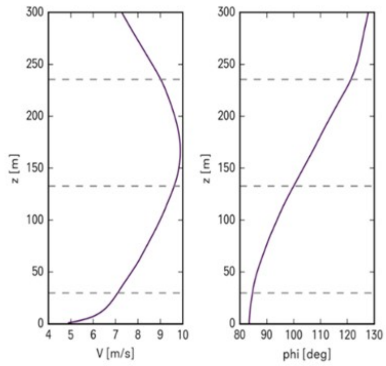
Why Task 47: Because wind turbine scales have growns to 10 MW+. Such rotor designs fall outside the validate range of aerodynamic design methods



Shear and extreme veer from year 2015 at met-mast IJmuiden
Dashed lines indicate hub height and limits of 10 MW rotor plane
Schepers, J.G.; van Dorp, P; Verzijlbergh, R.; Jonker, H (2020)
Aero-elastic loads on a 10 MW turbine exposed to extreme events selected from a year-long LES over the North Sea Wind Energy Science, https://doi.org/10.5194/wes-2020-1

- Shear and veer (wind direction as function of height) from Met-Mast IJmuiden
- The veer for a 10 MW turbine is almost 40 degrees!!!
- This violates all assumptions in industrial design codes

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Why Task 47:

Because the IEA 15 MW Reference Wind Turbine has become available as a public ‘testbed’ to investigate the modelling challenges for very large wind turbines

Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. 2020. *Definition of the IEA 15-Megawatt Offshore Reference Wind*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698. https://www.nrel.gov/docs/fy20osti/75698.pdf

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Task Objectives/Project period

Project period: January 1st 2021-December 31 2024

OBJECTIVES

- Establish a cooperation between experts on specialised innovative aerodynamic field measurements → steepen learning curve
- Validate and improve aerodynamic design codes for large scale wind turbines in turbulent inflow
  - `DanAero experiment
  - Cross-comparison of low, mid and high fidelity models for 15 MW RWT

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IEA Task 47: Participants

Table 1. Task 47 Participants in 2022

Member/Sponsor	Participating Organizations
Denmark	Technical University of Denmark (DTU), Siemens-Gamesa Renewable Energy
France	ECN, ONERA, IFP Energies Nouvelles
Germany	Forwind/Fraunhofer IWES, University of Stuttgart (IAG), Kiel University of Applied Sciences, WINDnovation, German Aerospace Center DLR, Enercon, UAS Emden/Leer
Italy	CNR-INM, PoliMi, University of Rome "La Sapienza" University of Rome "Roma Tre" - University of Florence, Politecnico di Bari
Netherlands	Netherlands Organisation for Applied Scientific Research (TNO), CWI, Delft University of Technology, Suzlon Blade Technology (SBT), Det Norske Veritas (DNV), LM, University of Twente,
Sweden	Uppsala University Campus Gotland
Switzerland	Eastern Switzerland University of Applied Sciences (OST)
United States	National Renewable Energy Laboratory (NREL)

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IEA Task 47: Main activities, measurements

Many interesting experimental data are generated

- No joint analysis and validation round was possible because machine data cannot be shared except DanAero
- Cooperation on the field of specialised aerodynamic experiments by sharing experiences and reporting it in a recommendation report

Recommendations for performing aerodynamic field measurements on wind turbine rotors

J.G Schepers, K. Boorsma, S. Barber, J. Deparday , C. Kelley, C. Braud, A.P. Schaffarczyk, A. Gomez Gonzalez.........

November 25, 2024

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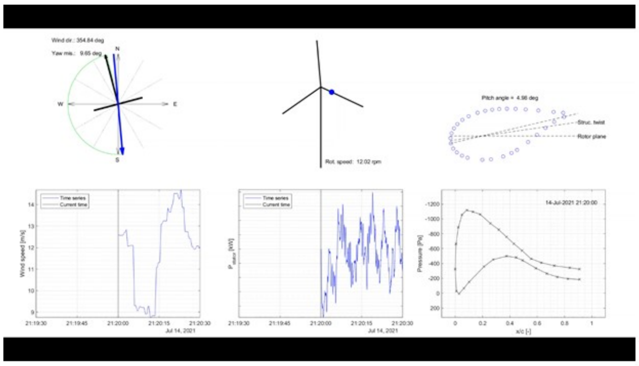
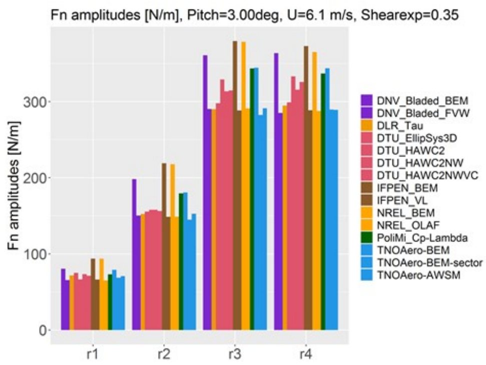
IEA Task 47: Main activities, measurements, ctd

Figure 1 Wake rake measurements



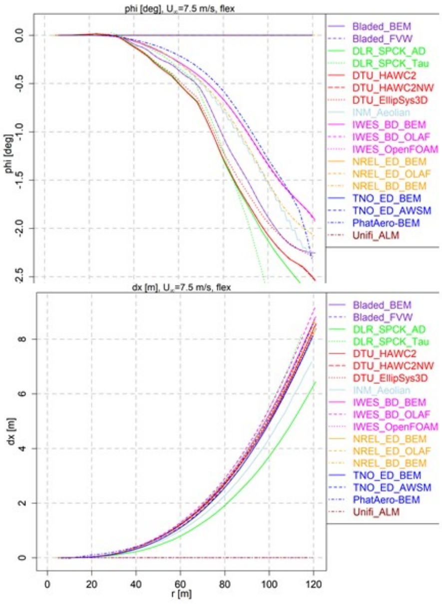
IEA Task 47: Main activities, DANAERO

- 3 Comparison rounds (flexible/rigid, constant/measured rpm) , focussed on a comparison between calculated and measured results under turbulent conditions. Some challenges:
  - Selection of cases
  - Generation of representative turbine wind input
  - Large differences in standard deviations of loads
- 2 Additional rounds for compariosn low and higher fidelity models to understand shear conditions
- High and moderate axial induction
- Mutual comparison of low and high fidelity results
- Overprediction of loads with lower fidelity



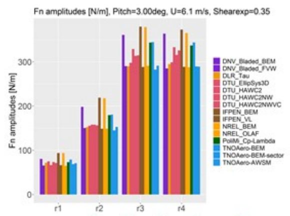
IEA Task 47: Main activities, 15 MW RWT

- 2 Initial comparison rounds (CAD file had to be generated) under rigid and flexible conditions
  - V = 7.5 m/s (a ~ 1/3) uniform steady conditions
  - Aero-elastic benchmark
- Turbulent round with many codes
  - Lifting line codes use empty box turbulent wind created by CFD
  - Still some differences in empty boxes (with impact!)
  - Fatigue loads seem overpredicted (again) with engineering methods



TO SUMMARIZE

- Task 47 is (Almost) Finished: Deliverables and milestones completed in time but final report after December 31
- Shortcomings detected in aerodynamic engineering methods at large wind turbines
- Many lessons learned and reported on the specialized field of detailed aerodynamic measurements, new measurement techniques on wind turbines
- Very many disseminations
  - Journal articles, presentations, workshops etc
  - Many students, now into industry
- Extremely inspiring cooperation in a very supportive atmosphere



Overpredicted loads at shear from engineering methods

Wake rakes measurements are used in the wind tunnel to measure drag but they had not been an accessible method for use on actual full scale wind turbines until experiments carried out within the VIAs project

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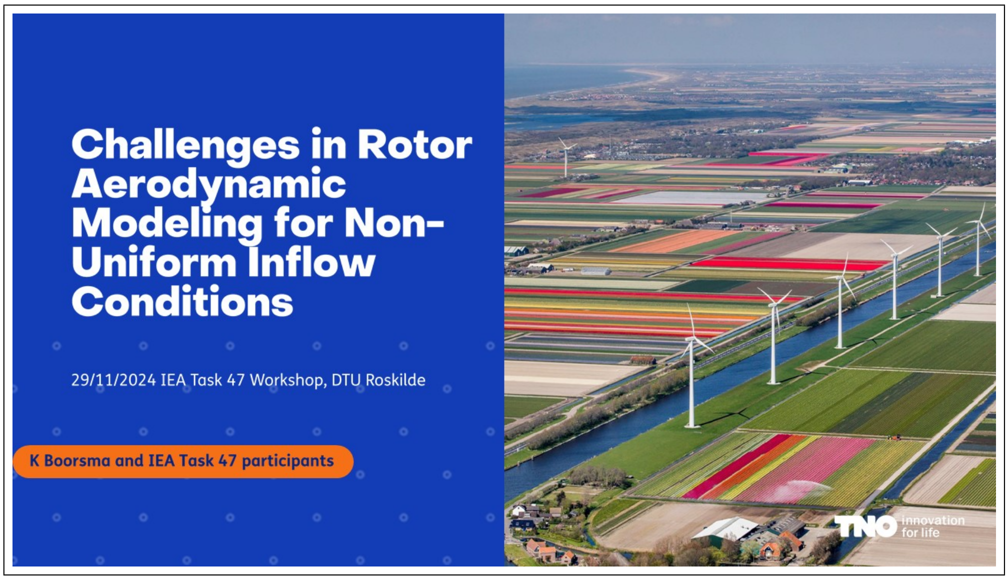
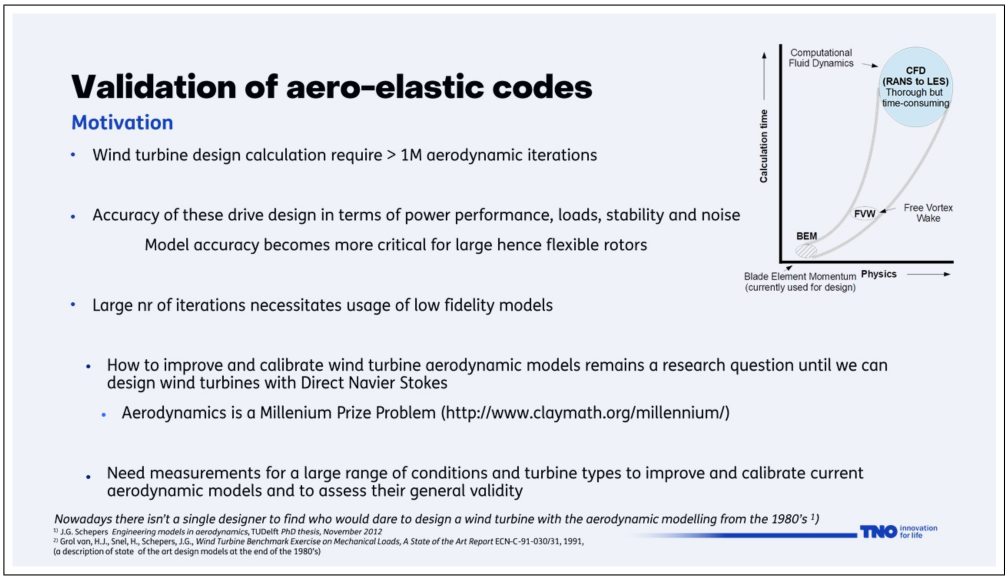
3 Challenges in Rotor Aerodynamic Modelling for Non-Uniform Inflow Conditions - Koen Boorsma, TNO





IEA Wind and aero-elastic model validation

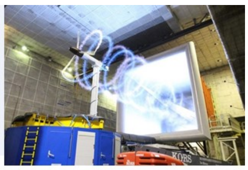
- Since 80s there have been joint efforts to validate and improve rotor aerodynamic models
  - Field experiments, wind tunnel test, benchmarking against high fidelity models (CFD)

Are we not be finished by now???

Outline

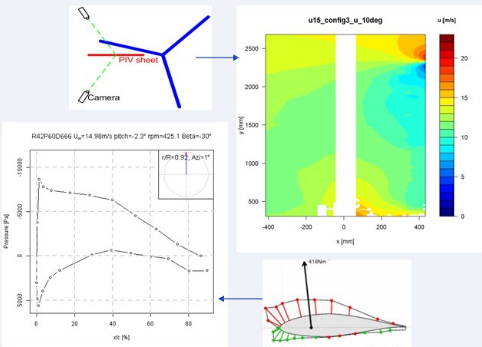
- Introduction
- Summary previous rounds
  - Wind tunnel to field
- DanAero
  - Turbulent inflow
  - Sheared inflow
- Conclusions and recommendations

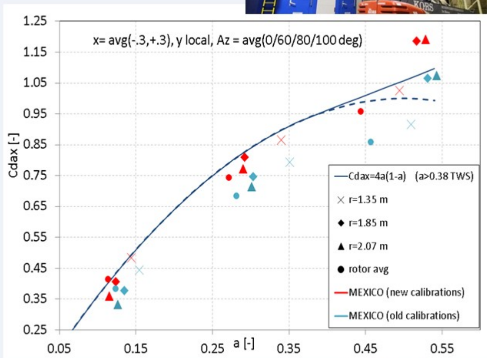
EU MEXICO and New MEXICO



Connecting loads and velocities: Momentum theory

- Induced velocity around rotor plane (PIV)
- Sectional and rotor axial force (integrated pressures)



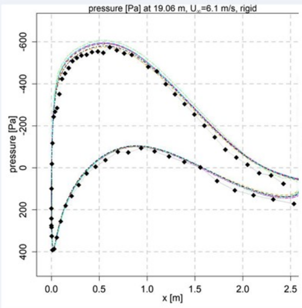


IEA Wind Task 29: From wind tunnel to field

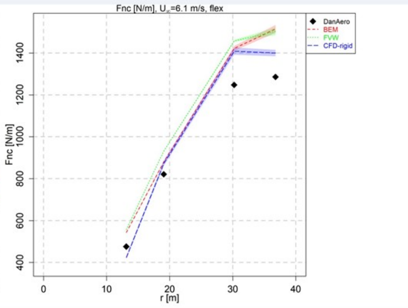
Code comparsion against DanAero field rotor aerodynamics (NM80 turbine)

- Axial, constant, uniform inflow (low TI)

DanAero test set-up (≈80m)



Pressure distribution at 19 m span



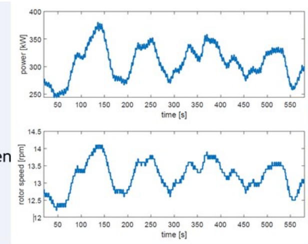
Comparison of integrated normal force as function of span

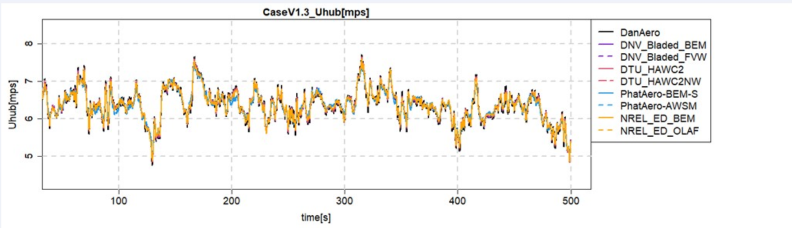
TNO innovation for life

IEA Wind Task 47

DanAero field rotor: Turbulent inflow case

- Sample in partial load with relatively constant conditions chosen
- Meteorological mast measurements as input to synthetic wind field generator, which is then fed to aero-elastic codes
  - Good alignment at measurement points like the hub



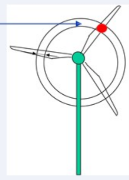


- But unknown wind at the remainder of the rotorplane…

TNO innovation for life

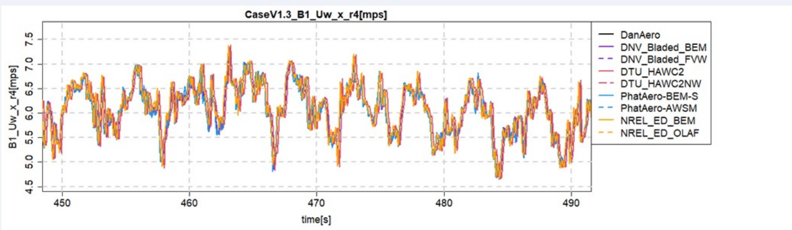
IEA Wind Task 47

Virtual probe sampling incoming wind field as seen by blade element



DanAero turbulent inflow: Alignment

- Alignment between codes can be checked using virtual velocity probes along the blades
  - Good alignment after some iterations, which is a prerequisite for valid comparison



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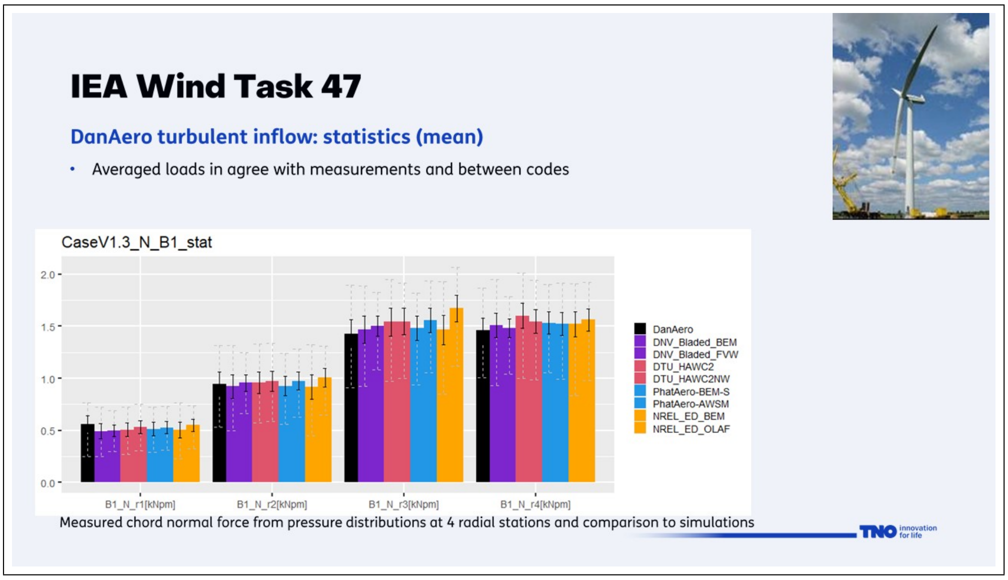
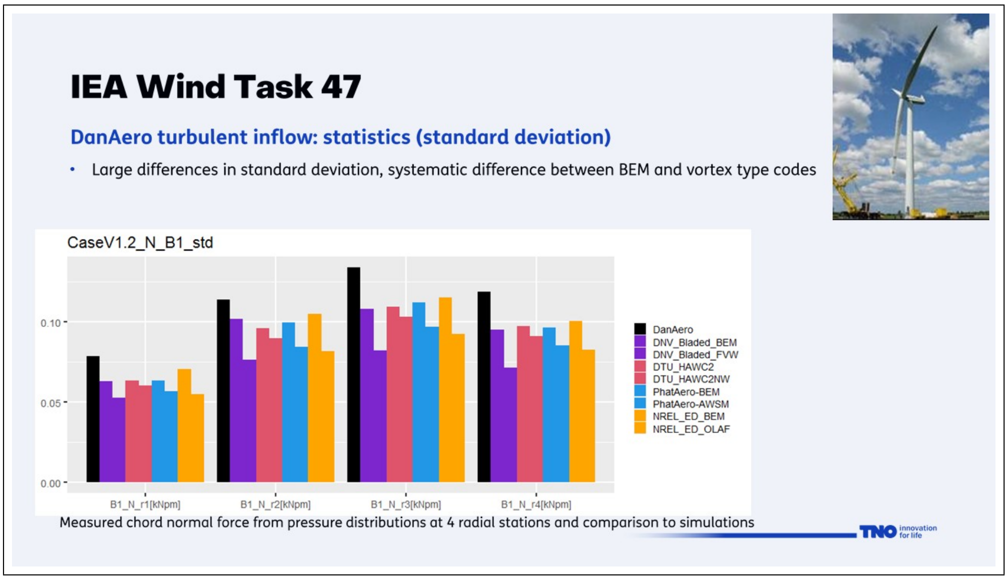
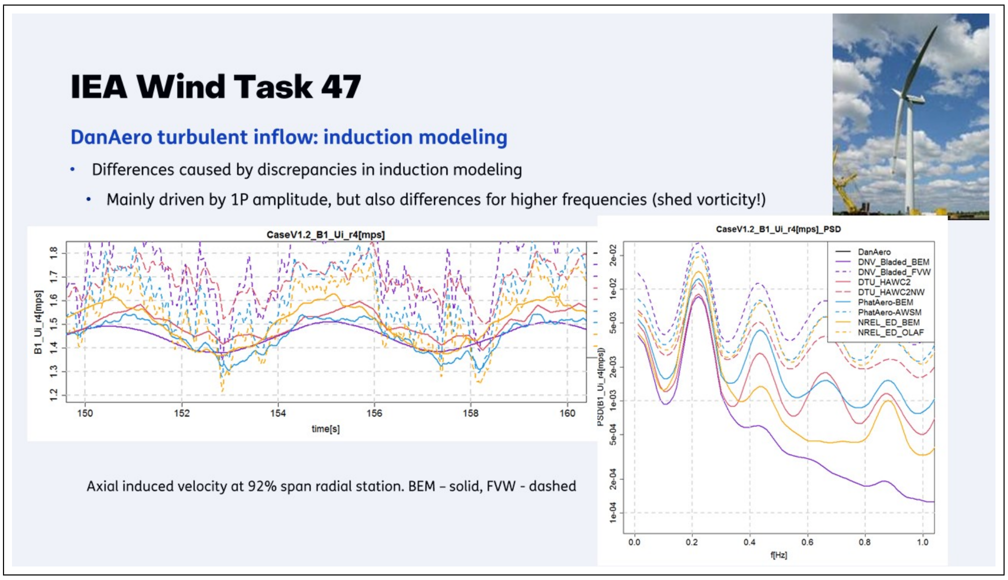
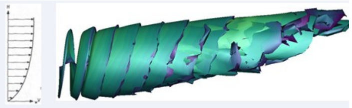

IEA Wind Task 47
DanAero turbulent inflow: statistics (mean)
• Averaged loads in agree with measurements and between codes
CaseV1.3_N_B1_stat
DanAero
DNV_Bladed_BEM
DNV_Bladed_FVW
DTU_HAWC2
DTU_HAWC2NW
PhatAero-BEM-S
PhatAero-AWSM
NREL_ED_BEM
NREL_ED_OLAF
B1_N_r1[kNpm]
B1_N_r2[kNpm]
B1_N_r3[kNpm]
B1_N_r4[kNpm]
Measured chord normal force from pressure distributions at 4 radial stations and comparison to simulations
TNO innovation for life


IEA Wind Task 47
DanAero turbulent inflow: statistics (standard deviation)
• Large differences in standard deviation, systematic difference between BEM and vortex type codes
CaseV1.2_N_B1_std
DanAero
DNV_Bladed_BEM
DNV_Bladed_FVW
DTU_HAWC2
DTU_HAWC2NW
PhatAero-BEM
PhatAero-AWSM
NREL_ED_BEM
NREL_ED_OLAF
B1_N_r1[kNpm]
B1_N_r2[kNpm]
B1_N_r3[kNpm]
B1_N_r4[kNpm]
Measured chord normal force from pressure distributions at 4 radial stations and comparison to simulations
TNO innovation for life

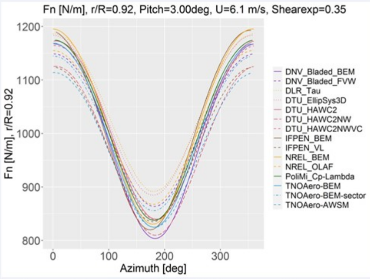

IEA Wind Task 47
DanAero turbulent inflow: induction modeling
• Differences caused by discrepancies in induction modeling
• Mainly driven by 1P amplitude, but also differences for higher frequencies (shed vorticity!)
CaseV1.2_B1_Ui_r4[mps]
B1_Ui_r4[mps]
time[s]
CaseV1.2_B1_Ui_r4[mps]_PSD
PSD(B1_Ui_r4[mps])
f[Hz]
DanAero
DNV_Bladed_BEM
DNV_Bladed_FVW
DTU_HAWC2
DTU_HAWC2NW
PhatAero-BEM
PhatAero-AWSM
NREL_ED_BEM
NREL_ED_OLAF
Axial induced velocity at 92% span radial station. BEM – solid, FVW - dashed

Modeling non-uniform conditions

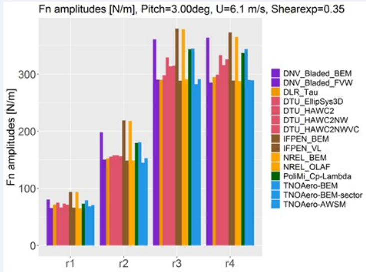


DanAero vertical wind shear case

- More systematic case to study modeling of non-uniformity in controlled manner
- No measurement data, but with CFD as 'numerical wind tunnel'



Chord normal force variation at 92% span radial station



Chord normal force amplitudes at 4 radial stations

- Apparent difference between BEM and vortex code types, where CFD agrees with the latter

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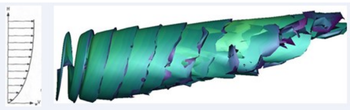
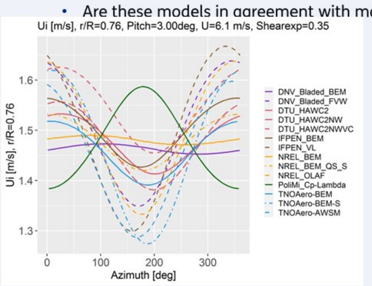
Modeling non-uniform conditions



DanAero vertical wind shear case: Induced velocities and momentum theory

- Large differences in underlying induced velocities
  - Are these models in agreement with momentum theory???



Axial induced velocity variation at 76% span radial station

Reprocess lifting line results and compare to $C_t = 4a(1-a)$

From forces to C_t:

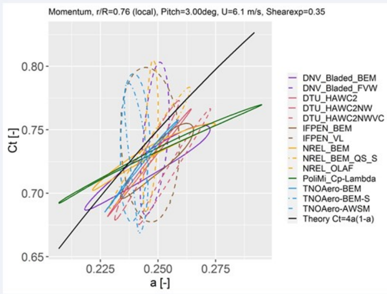
$C_t = F_{ax} / (0.5 \text{ rho } U_{ref}\text{^}2 \text{ A})$,
$F_{ax} = F_n\text{*}\cos(\text{phi}) - F_t\text{*}\sin(\text{phi})$,
phi = pitch + twist

From axial induced velocity to a-factor:

$U_i * F_{Prandtl} = a * U_{ref}$

Local BEM option:

$U_{ref} = U_{wind}(\text{azi})$, $U_i = U_i(\text{azi})$,
$F_{ax} = F_{ax}(\text{azi})$



Post-processed momentum curve (Thrust coefficient Ct versus axial induction factor a) at 76% span radial station

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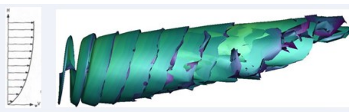
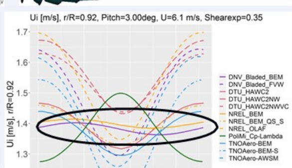
Modeling non-uniform conditions

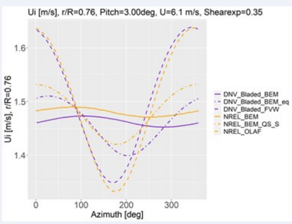


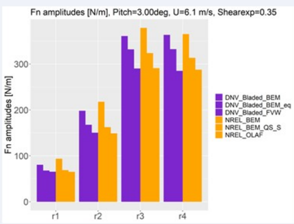
DanAero vertical wind shear case: Dynamic inflow modeling

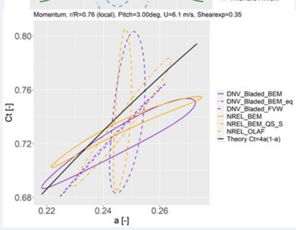
- Almost no U_i variation for some codes..
- Interaction with dynamic inflow model? $C_t = 4a\text{*}(1-a) + f\text{*}dUi_{onn}/dt$
  - Theoretically this model should act on inflow and wake changes

What happens when switching off this model (Eq/QS)?









- Is dynamic inflow term proportional to changes in local induced velocity (i.e. shear, tower, deformations, non-uniformities)??

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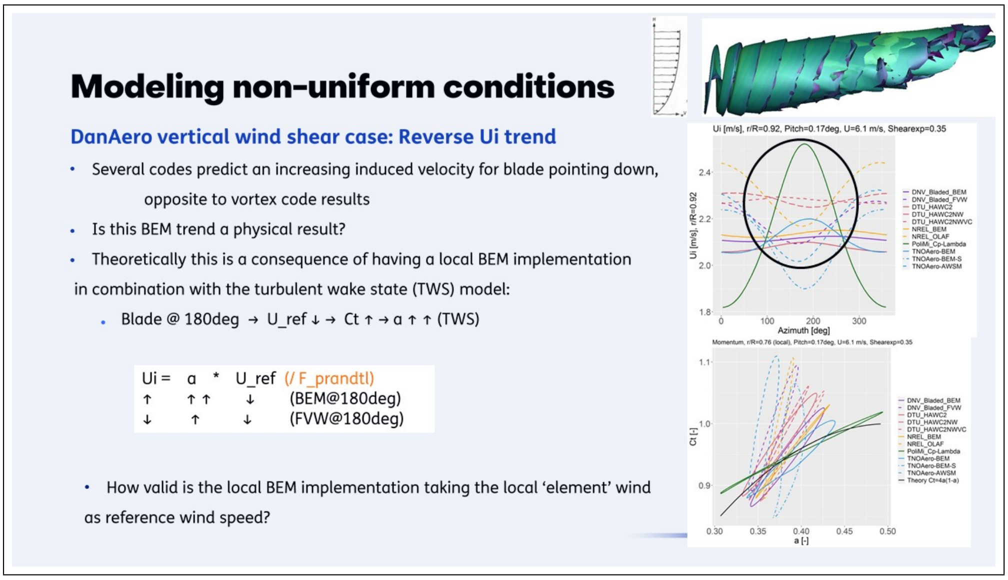
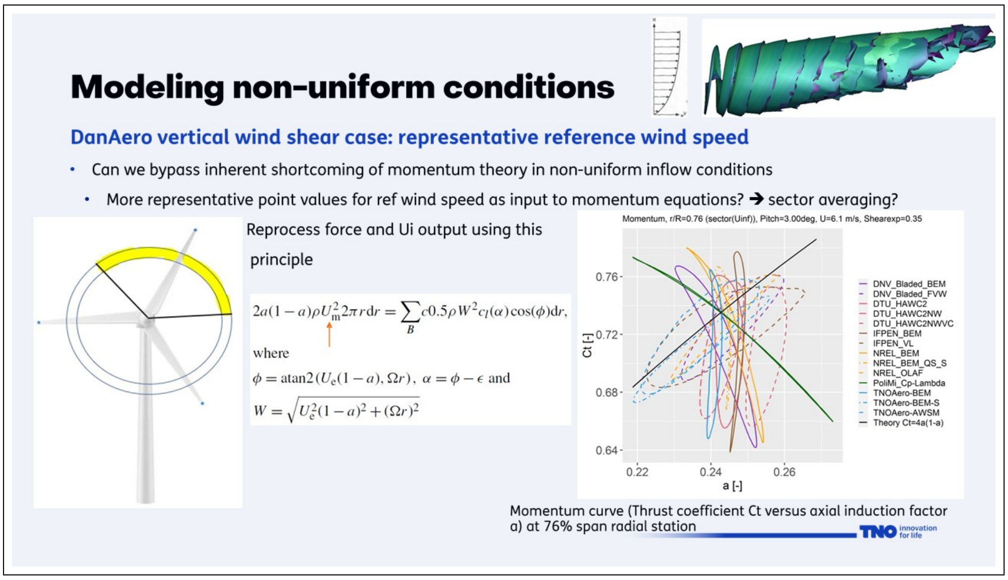
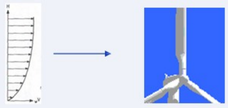

Modeling non-uniform conditions
DanAero vertical wind shear case: Reverse Ui trend
• Several codes predict an increasing induced velocity for blade pointing down, opposite to vortex code results
• Is this BEM trend a physical result?
• Theoretically this is a consequence of having a local BEM implementation in combination with the turbulent wake state (TWS) model:
• Blade @ 180deg → U_ref ↓ → Ct ↑ → a ↑ ↑ (TWS)
Ui = a * U_ref (/ F_prandtl)
↑ ↑ ↑ ↓ (BEM@180deg)
↓ ↑ ↓ (FVW@180deg)
• How valid is the local BEM implementation taking the local 'element' wind as reference wind speed?
Ui [m/s], r/R=0.92, Pitch=0.17deg, U=6.1 m/s, Shearexp=0.35
Ui [m/s], r/R=0.92
Azimuth [deg]
Momentum, r/R=0.76 (local), Pitch=0.17deg, U=6.1 m/s, Shearexp=0.35
Ct [-]
a [-]


Modeling non-uniform conditions
DanAero vertical wind shear case: representative reference wind speed
• Can we bypass inherent shortcoming of momentum theory in non-uniform inflow conditions
• More representative point values for ref wind speed as input to momentum equations? → sector averaging?
Reprocess force and Ui output using this principle
$2a(1-a)\rho U_m^2 2\pi r\,dr = \sum_B c\,0.5\rho W^2 c_l(\alpha)\cos(\phi)dr,$
where
$\phi = \mathrm{atan2}(U_e(1-a), \Omega r)$, $\alpha = \phi - \epsilon$ and
$W = \sqrt{U_e^2(1-a)^2 + (\Omega r)^2}$
Momentum, r/R=0.76 (sector(Uinf)), Pitch=3.00deg, U=6.1 m/s, Shearexp=0.35
Ct [-]
a [-]
DNV_Bladed_BEM
DNV_Bladed_FVW
DTU_HAWC2
DTU_HAWC2NW
DTU_HAWC2NWVC
IFPEN_BEM
IFPEN_VL
NREL_BEM
NREL_BEM_QS_S
NREL_OLAF
PoliMi_Cp-Lambda
TNOAero-BEM
TNOAero-BEM-S
TNOAero-AWSM
Theory Ct=4a(1-a)
Momentum curve (Thrust coefficient Ct versus axial induction factor a) at 76% span radial station

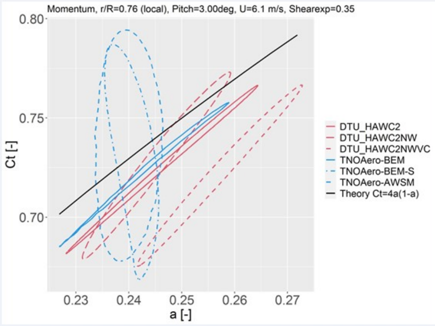

Modeling non-uniform conditions
DanAero: Load variation due to cyclic pitch
• What happens if we create a force variation similar to the shear case by means of harmonic pitch variation?
Fn [N/m], r/R=0.76, Pitch=3.00deg, U=6.1 m/s
Fn [N/m], r/R=0.76
Azimuth [deg]
DLR_Tau-IPC
DTU_EllipSys3D-IPC
DTU_HAWC2-IPC
DTU_HAWC2NW-IPC
DTU_HAWC2NWVC-IPC
TNOAero-BEM-IPC
TNOAero-BEM-S-IPC
TNOAero-AWSM-IPC
Fn amplitudes [N/m], Pitch=3.00deg, U=6.1 m/s
Fn amplitudes [N/m]
r1
r2
r3
r4

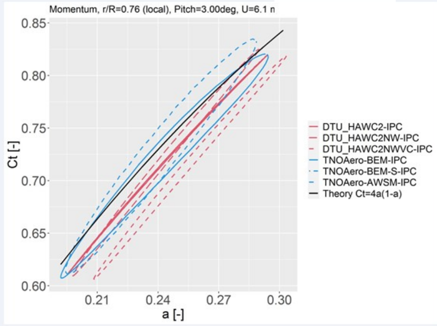
Modeling non-uniform conditions



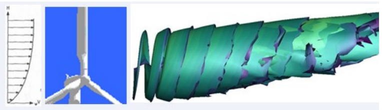
DanAero: Load variation due to cyclic pitch

- What happens if we create a force variation similar to the shear case by means of harmonic pitch variation?



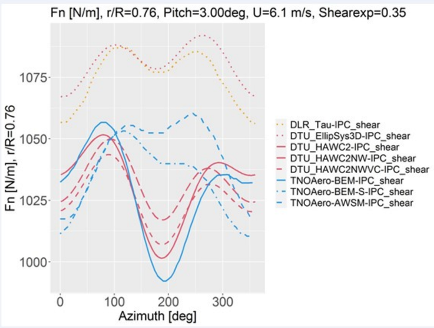


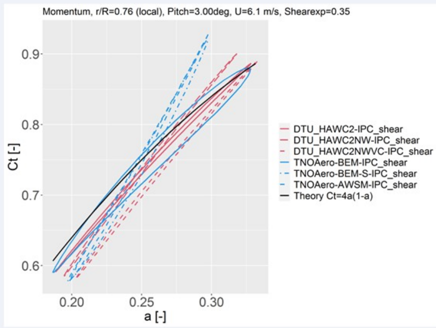
Modeling non-uniform conditions



DanAero: Load variation due to cyclic pitch and shear

- What happens if we create a similar force variation by means of harmonic pitch variation and try to balance out load variations due to shear by IPC





Summary

Current state of comparisons – *are we not finished yet??*

- Good agreement in axial, uniform inflow conditions, provided input and output is carefully selected
- Larger differences for more challenging unsteady conditions
    - Average load levels usually ok, but spread in unsteady character (dictating fatigue, stability etc.)
    - Non-uniform inflow (which is increasingly important for large rotors) problematic for BEM depending on implementation
    - Bechmarking against higher fidelity models exposes a systematic offset in predicted load variation
- The discrepancy between codes (as used by industry) is still enormous, which stresses the importance to continue with these comparison rounds (!!)

Computer says no..

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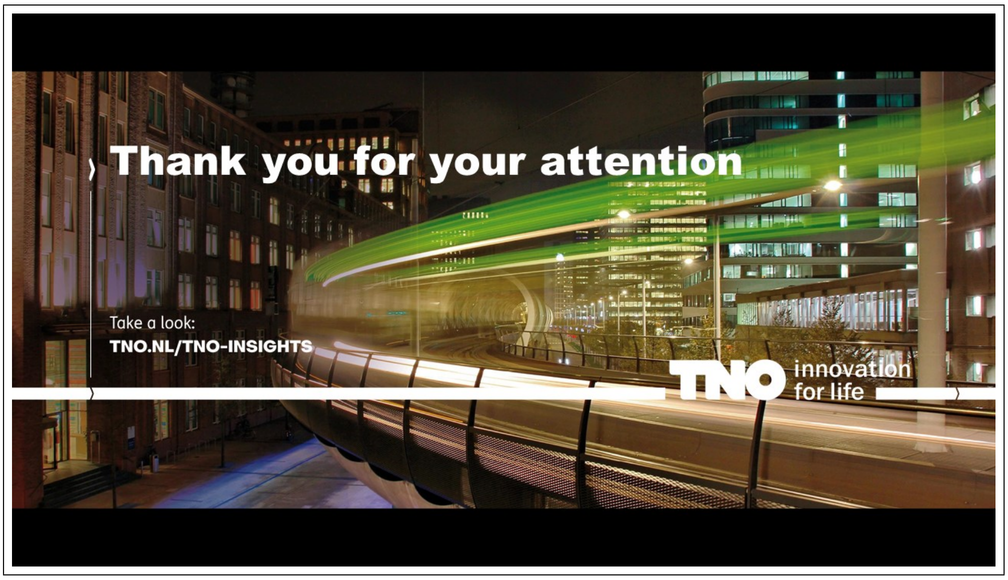
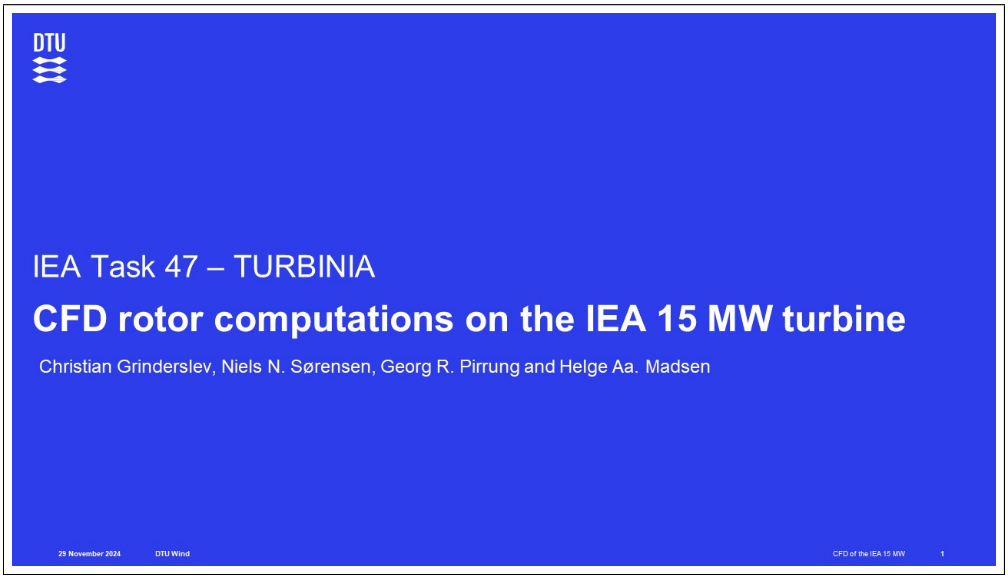
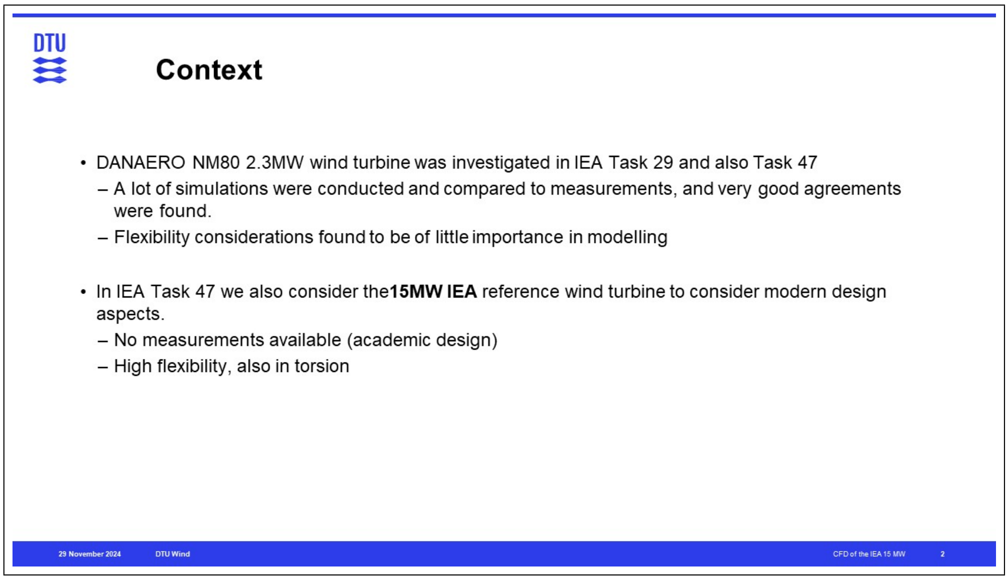

Thank you for your attention
Take a look:
TNO.NL/TNO-INSIGHTS
TNO innovation for life

4 CFD rotor computations on the IEA 15 MW turbine
- Christian Grinderslev et al., DTU

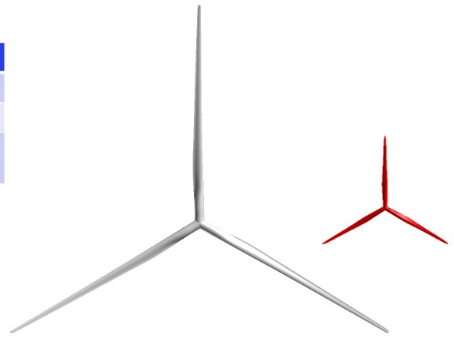




From NM80 to IEA15 MW

	NM80	IEA15MW
Rotor diameter	≈80m	≈240m
Hub height	≈57m	≈150m
Tip disp. at rated	≈2-3m (≈7.5% blade length)	≈13-14m (≈11.7% blade length)

- IEA15MW is much more flexible.
- Structural response bound to be more important than for NM80 rotor in CFD simulations.



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Initial benchmark case

- IEA15 MW rotor in stiff and flexible rotor configuration in axisymmetric flow case

	C2.1	C2.2	C2.3
Wind type	Uniform	Uniform	**Turbulent unsheared**
Rotor type	Rigid	**Flexible**	Rigid
Remaining structure	Rigid	Rigid	Rigid
Cone	4 deg	4 deg	4 deg
Wind speed	7.5m/s	7.5m/s	7.5m/s + fluctuations
Rotor speed	5.33 RPM	5.33 RPM	5.33 RPM
Pitch	0 deg	0 deg	0 deg
Yaw/Tilt	0 deg	0 deg	0 deg

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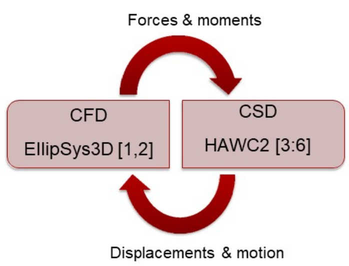
Framework

Fluid-structure interaction framework:

- Partitioned 2-way coupling between Ellipsys3D and HAWC2 structural model
- Loose coupling scheme

Engineering model framework:

- Pure HAWC2 including BEM aerodynamics



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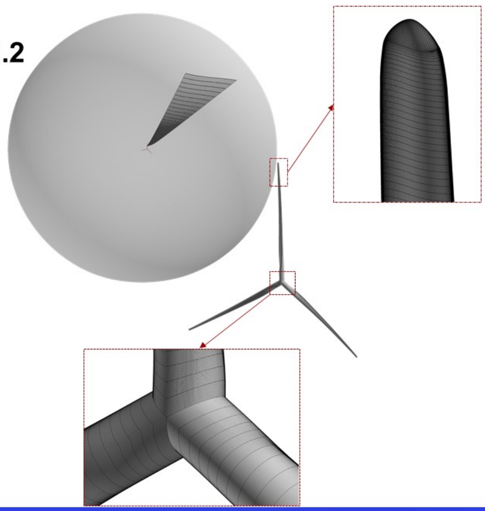
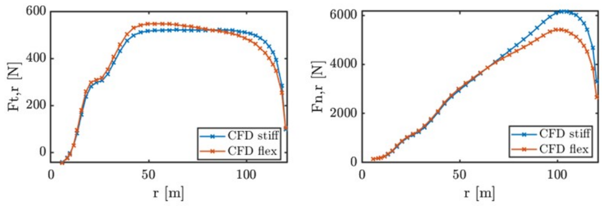
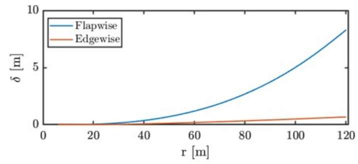
CFD setup C.2.1 and C.2.2

- Block-structured spherical domain grown hyperbolically from rotor surface.
- O-O mesh
- 192 cells spanwise per blade
- 256 cells chordwise
- 160 cells normal with $y^+ < 1$
- 25.6M cells total
- Domain radius ≈2000m
- K-ω SST URANS turbulence model
- QUICK convective scheme



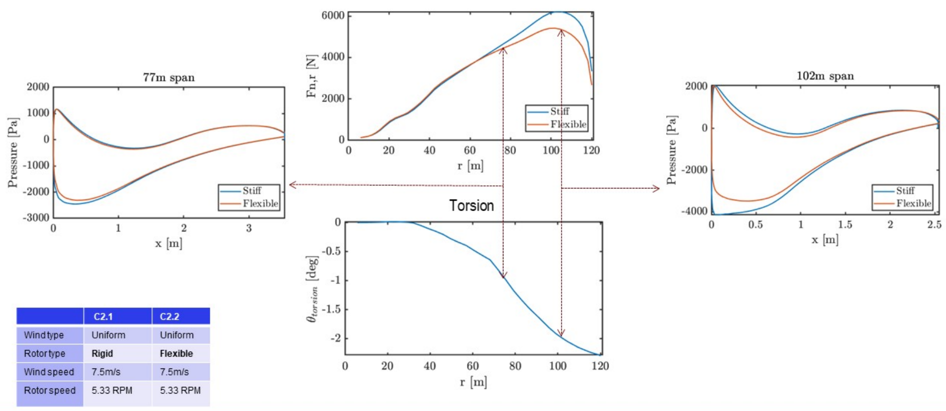
Results - Loads and deflection





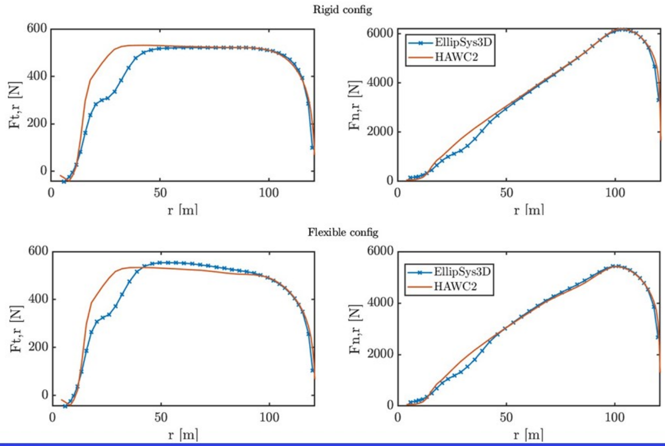
	C2.1	C2.2
Wind type	Uniform	Uniform
Rotor type	**Rigid**	**Flexible**
Wind speed	7.5m/s	7.5m/s
Rotor speed	5.33 RPM	5.33 RPM

Results - Torsion



	C2.1	C2.2
Wind type	Uniform	Uniform
Rotor type	**Rigid**	**Flexible**
Wind speed	7.5m/s	7.5m/s
Rotor speed	5.33 RPM	5.33 RPM

Results - Comparison to HAWC2



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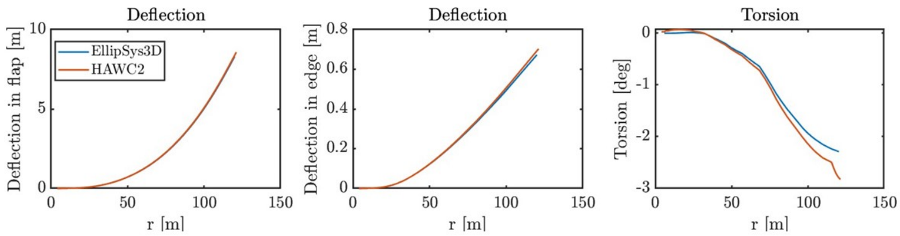
C2.2 – Uniform inflow, flexible rotor



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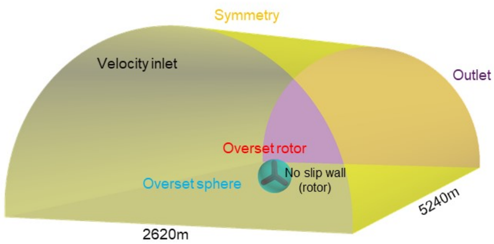
CFD setup C.2.3 (turbulent inflow)

- Overset grids → rotor mesh + rotating sphere + static background (semi-cylindrical)
- 192 cells spanwise per blade (same as for C.2.1/C.2.2)
- 256 cells chordwise (same as for C.2.1/C.2.2)
- ≈15.3M cells in rotor + ≈6.2M cells in sphere + ≈33M Cells in background
- ≈54.5M cells in total
- Domain size: 5240m × 2620m × 1368m
- IDDES K-ω SST turbulence model
- QUICK/CDS4 convective scheme



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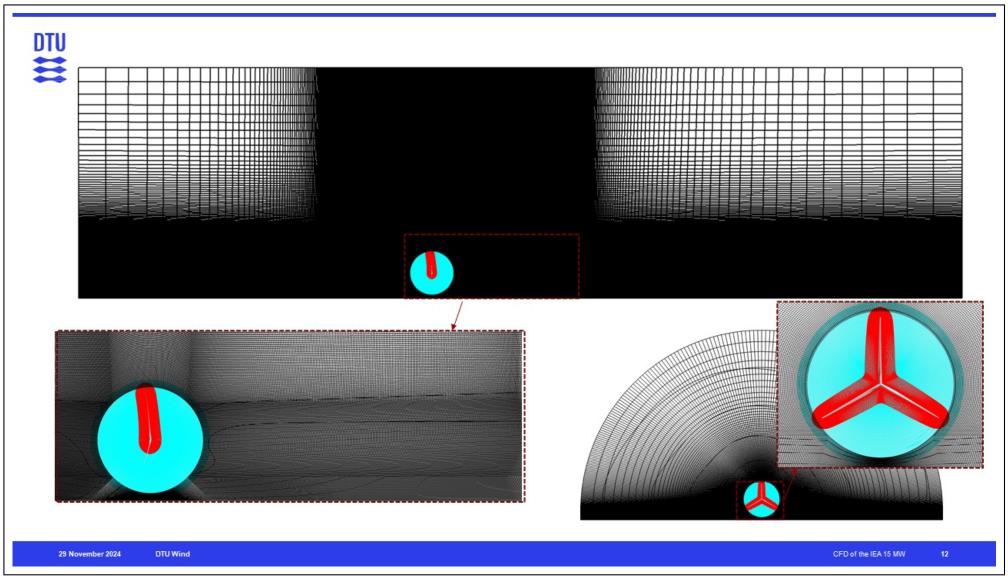
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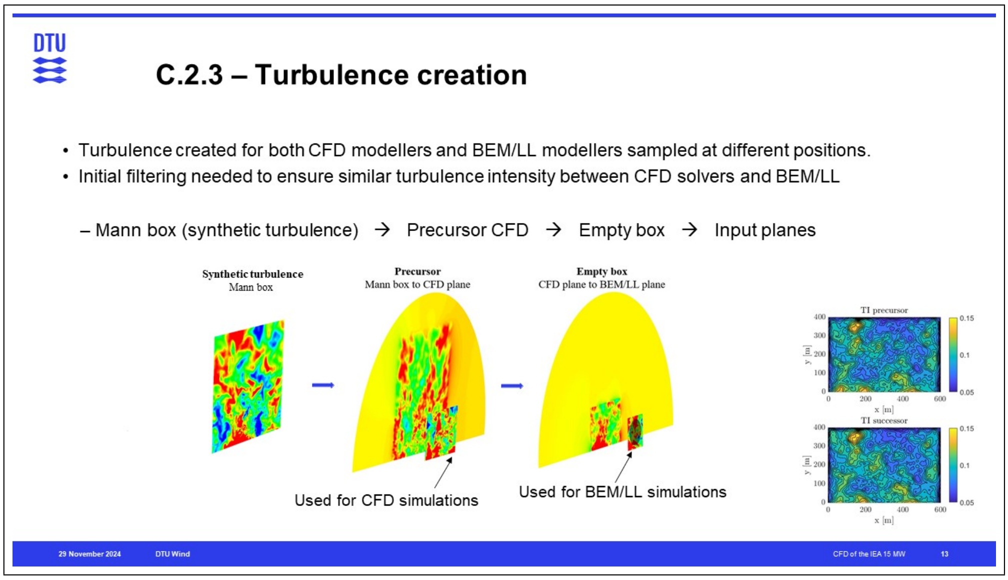
CFD of the IEA 15 MW
12


DTU
C.2.3 – Turbulence creation
• Turbulence created for both CFD modellers and BEM/LL modellers sampled at different positions.
• Initial filtering needed to ensure similar turbulence intensity between CFD solvers and BEM/LL
– Mann box (synthetic turbulence) → Precursor CFD → Empty box → Input planes
Synthetic turbulence
Mann box
Precursor
Mann box to CFD plane
Empty box
CFD plane to BEM/LL plane
Used for CFD simulations
Used for BEM/LL simulations
TI precursor
TI successor
y [m]
x [m]
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CFD of the IEA 15 MW
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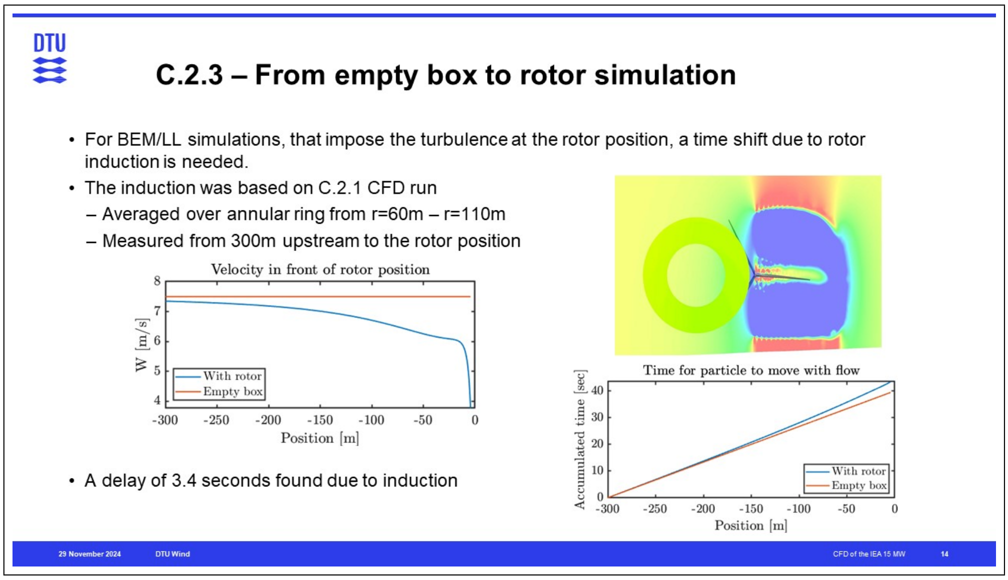
DTU
C.2.3 – From empty box to rotor simulation
• For BEM/LL simulations, that impose the turbulence at the rotor position, a time shift due to rotor induction is needed.
• The induction was based on C.2.1 CFD run
– Averaged over annular ring from r=60m – r=110m
– Measured from 300m upstream to the rotor position
Velocity in front of rotor position
W [m/s]
With rotor
Empty box
Position [m]
• A delay of 3.4 seconds found due to induction
Time for particle to move with flow
Accumulated time [sec]
With rotor
Empty box
Position [m]
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DTU Wind
CFD of the IEA 15 MW
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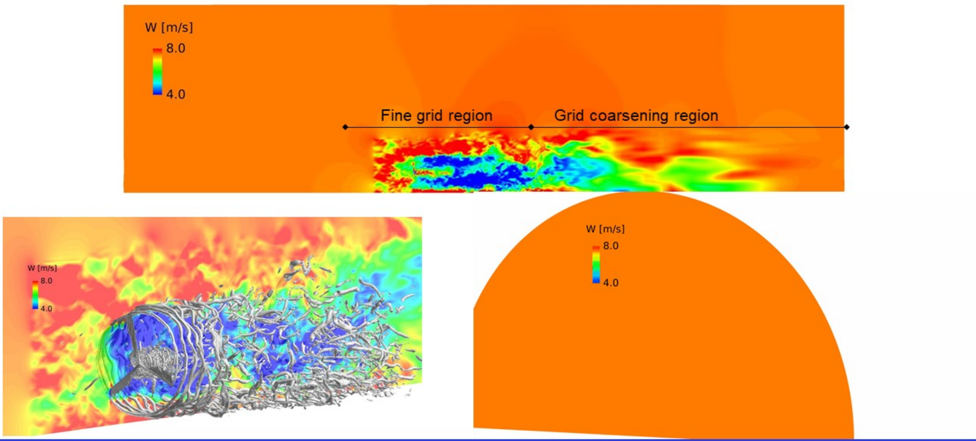
C.2.3 – Flow results



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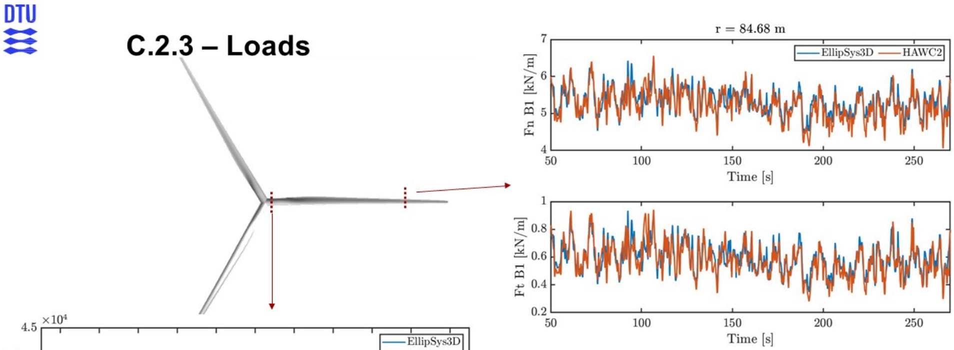
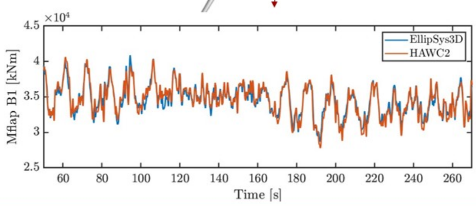
C.2.3 – Loads





M_{flap}	Ellipsys3D	HAWC2
Avg [kNm]	3.46 x 10^4	3.45 x 10^4
Std [kNm]	2.08 x 10^3	2.26 x 10^3

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Conclusions

- An excellent agreement found between CFD and HAWC2 results using various aerodynamic models for the IEA15MW.
- For this large rotor, flexibility of blades has large impact on resulting loads
- When imposing turbulence, sampling from empty box CFD at rotor position results in much better agreements than seen before.
  – Induction delay needs to be accounted for

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DTU

Thank you!
Any questions?

DTU

References

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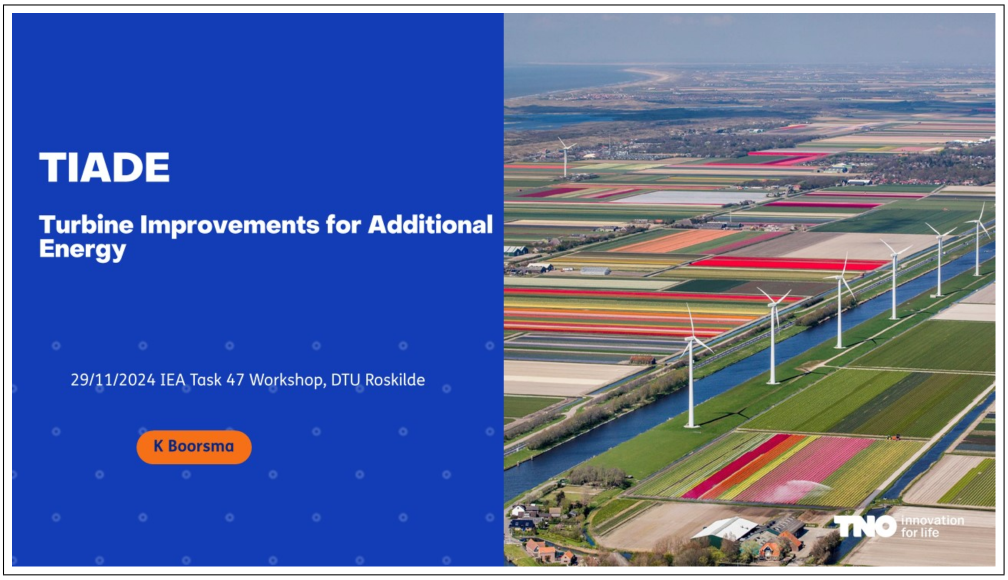
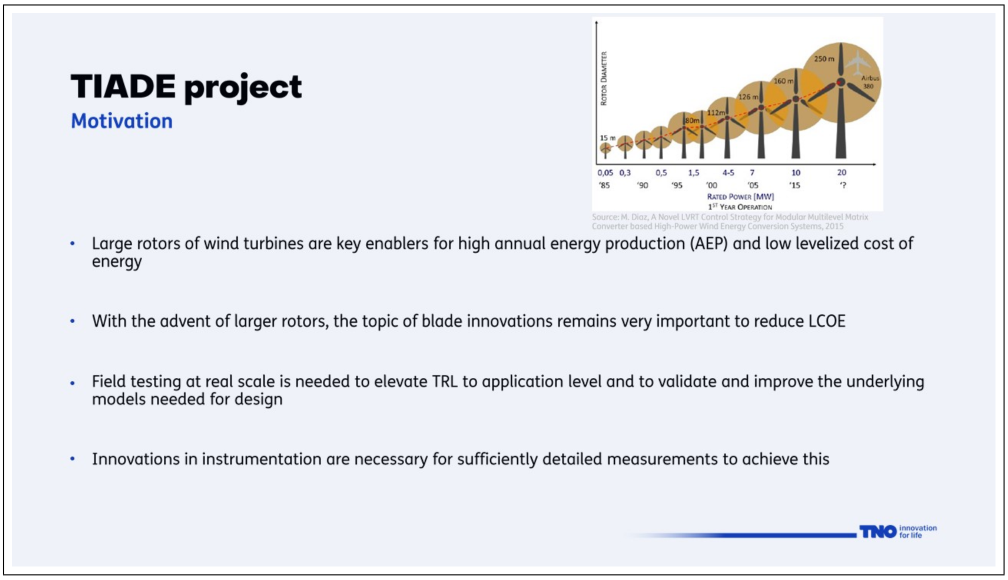
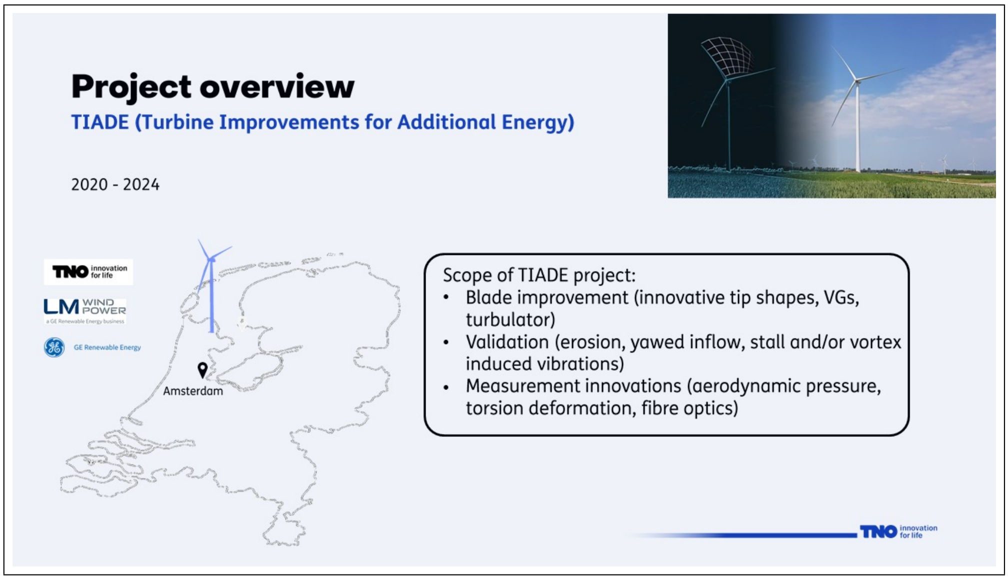
  - **[2]** Michelsen, J.: Basis3D – A Platform for Development of Multiblock PDE Solvers., Tech. rep., Risø National Laboratory, https://backend.orbit.dtu.dk/ws/portalfiles/portal/272917945/Michelsen_J_Basis3D.pdf (last access: 24 October 2023), 1992.
- **HAWC2**:
  - **[3]** Madsen, H. A., Larsen, T. J., Pirrung, G. R., Li, A., and Zahle, F.: Implementation of the blade element momentum model on a polar grid and its aeroelastic load impact, Wind Energ. Sci., 5, 1–27, https://doi.org/10.5194/wes-5-1-2020, 2020.
- **Near wake model**:
  - **[4]** Pirrung, G. R., Madsen, H. A., Kim, T., and Heinz, J. (2016) A coupled near and far wake model for wind turbine aerodynamics. Wind Energ., 19: 2053–2069. doi: 10.1002/we.1969.
  - **[5]** Li, A., Pirrung, G. R., Gaunaa, M., Madsen, H. A., and Horcas, S. G.: A computationally efficient engineering aerodynamic model for swept wind turbine blades, Wind Energ. Sci., 7, 129–160, https://doi.org/10.5194/wes-7-129-2022, 2022.
- **Vortex cylinder model**:
  - **[6]** Li, A., Gaunaa, M., Pirrung, G. R., and Horcas, S. G.: A computationally efficient engineering aerodynamic model for non-planar wind turbine rotors, Wind Energ. Sci., 7, 75–104, https://doi.org/10.5194/wes-7-75-2022, 2022.

5 Full scale experiments

5.1 TIADE - Turbine Improvements for Additional Energy - Koen Boorsma TNO






Project overview
TIADE (Turbine Improvements for Additional Energy)
2020 - 2024
TNO innovation for life
LM WIND POWER
GE Renewable Energy
Amsterdam
Scope of TIADE project:
• Blade improvement (innovative tip shapes, VGs, turbulator)
• Validation (erosion, yawed inflow, stall and/or vortex induced vibrations)
• Measurement innovations (aerodynamic pressure, torsion deformation, fibre optics)
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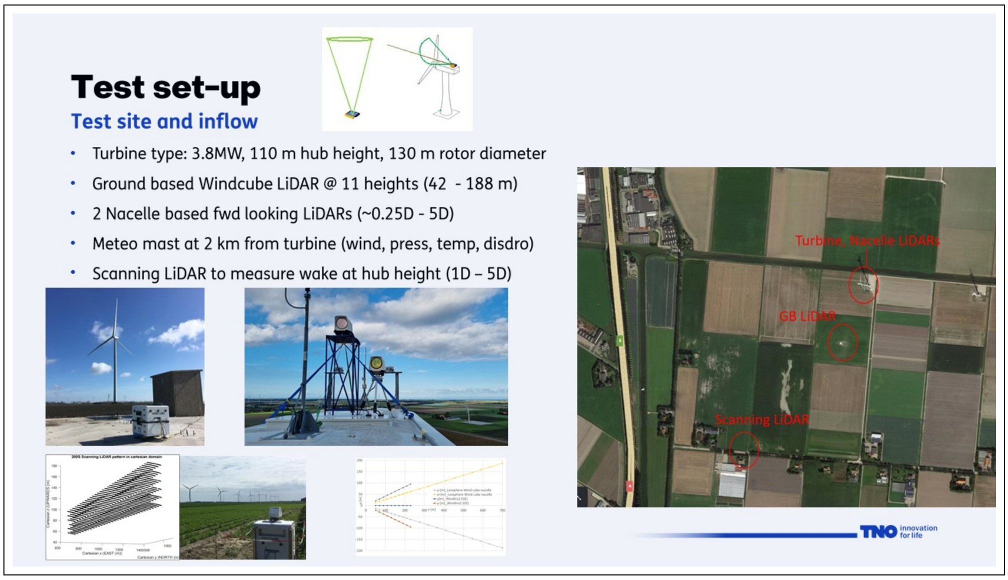
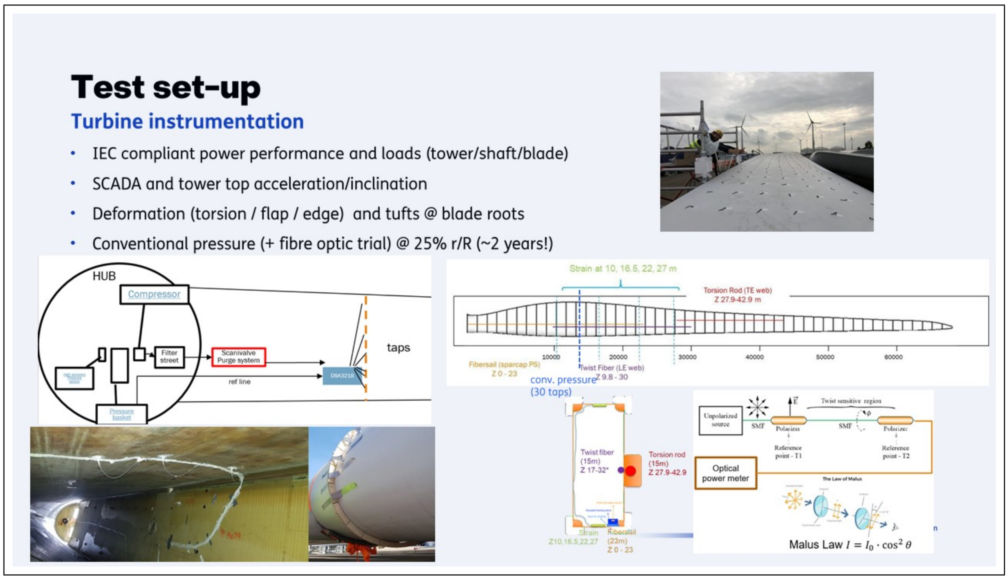
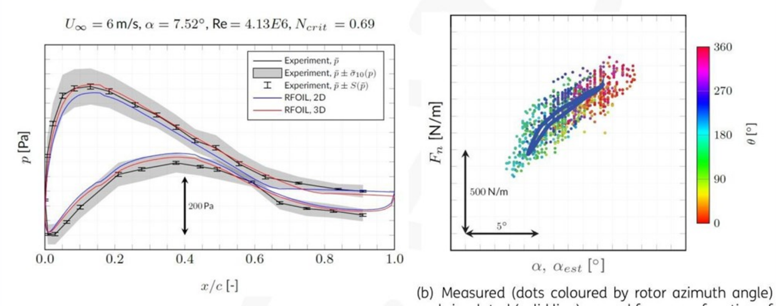

Test set-up
Test site and inflow
• Turbine type: 3.8MW, 110 m hub height, 130 m rotor diameter
• Ground based Windcube LiDAR @ 11 heights (42 - 188 m)
• 2 Nacelle based fwd looking LiDARs (~0.25D - 5D)
• Meteo mast at 2 km from turbine (wind, press, temp, disdro)
• Scanning LiDAR to measure wake at hub height (1D – 5D)
Turbine, Nacelle LiDARs
GB LiDAR
Scanning LiDAR
TNO innovation for life


Test set-up
Turbine instrumentation
• IEC compliant power performance and loads (tower/shaft/blade)
• SCADA and tower top acceleration/inclination
• Deformation (torsion / flap / edge) and tufts @ blade roots
• Conventional pressure (+ fibre optic trial) @ 25% r/R (~2 years!)
HUB
Compressor
Filter street
Scanvalve Purge system
ref line
taps
Strain at 10, 16.5, 22, 27 m
Torsion Rod (TE web) Z 27.9-42.9 m
Fibersail (sparcap PS) Z 0 - 23
Twist Fiber (LE web)
conv. pressure Z 9.8 - 30 (30 taps)
Twist fiber (15m) Z 17-32°
Torsion rod (15m) Z 27.9-42.9
Optical power meter
Malus Law $I = I_0 \cdot \cos^2 \theta$

Validation of models

Pressure measurements



(a) Pressure distribution measured in the field compared to simulation results

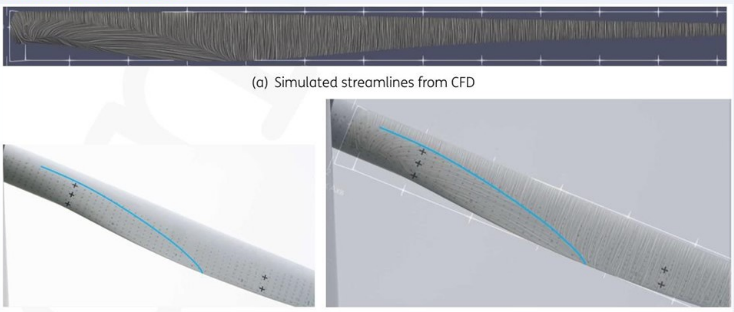
(b) Measured (dots coloured by rotor azimuth angle) and simulated (solid line) normal force as a function of the estimated or simulated angle of attack

Figure 3.10: Highlighted results from long term pressure measurements [12]

[12] E.K. Fritz et al. "Blade surface pressure measurements in the field and their usage for aerodynamic model validation." In: *Wind Energy* (), e2952. DOI: https://doi.org/10.1002/we.2952. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.2952. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/we.2952.

Validation of models

Tuft measurements



(a) Simulated streamlines from CFD

(b) Tuft visualization with separation line in blue

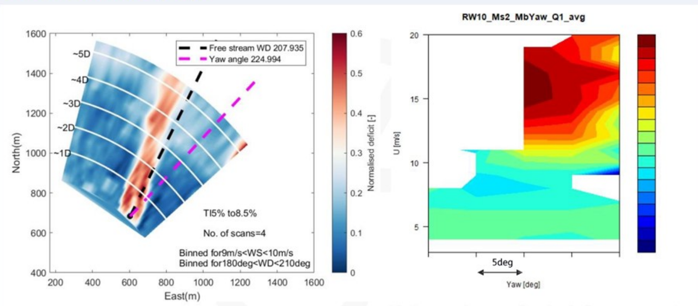
(c) Overlay of tuft and CFD results

Figure 3.11: Comparison between measured and predicted streamlines using tufts visualization and CFD simulations at 8 m/s [13]

[13] M. Caboni et al. *3D RANS-based CFD simulations on the LM637P blade*. Tech. rep. TNO 2024 M11257. TNO, Nov. 2024.

Validation of models

Yawed flow campaign



(a) Measured wake contours at hub height for yawed inflow conditions

(b) Measured mean of main shaft yaw moment as function of yaw angle and wind speed

Figure 3.12: Yawed flow campaign results

Validation of models

Wake modeling

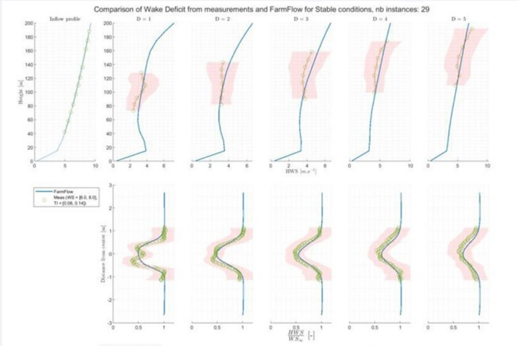


Figure 3.21: Comparison of wake deficits from measurements and FarmFlow (FF) for stable conditions. Vertical (top) and Horizontal (bottom) profiles of the wind flow downstream at 1, 2, 3, 4 and 5 diameters from the hub for measured wind speeds between 6 to 8 m/s and turbulence intensities between 9% and 13%. The red shaded area indicates the 95% (1.96*σ) confidence interval [31].

[32] M. Turrini et al. "Advancements in Wind Turbine Wake Modelling using 3D scanning LiDAR measurements from a test turbine campaign." In: *Wake Conference 2025*. June 2025.

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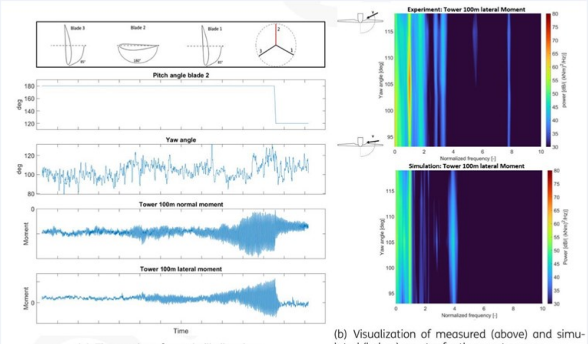
Validation of models

Standstill vibrations



(a) Time series of standstill vibrations

(b) Visualization of measured (above) and simulated (below) spectra for the yaw traverse

Figure 3.15: Vibrations as measured in the yaw traverse and comparison to simulations [17]

[16] J. Peeringa et al. "Field experiments of wind turbine vibrations in stand still conditions." In: *EERA DeepWind Conference 2025*. Jan. 2025.

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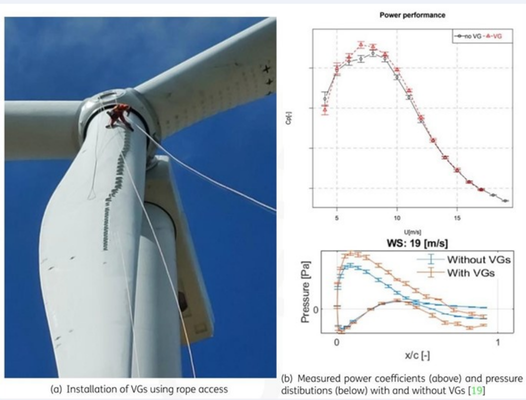
Blade improvements

Vortex generators



(a) Installation of VGs using rope access

(b) Measured power coefficients (above) and pressure distibutions (below) with and without VGs [19]

[18] K. Vimalakanthan. *Vortex generator layout design for TIADE blade section at 15m blade span*. Tech. rep. TNO 2024 R12151. TNO, 2024.
[19] G. Vanino. *Vortex Generators applied to large-scale Wind Turbines*. Tech. rep. TNO 2023 M12095. TNO, 2023.

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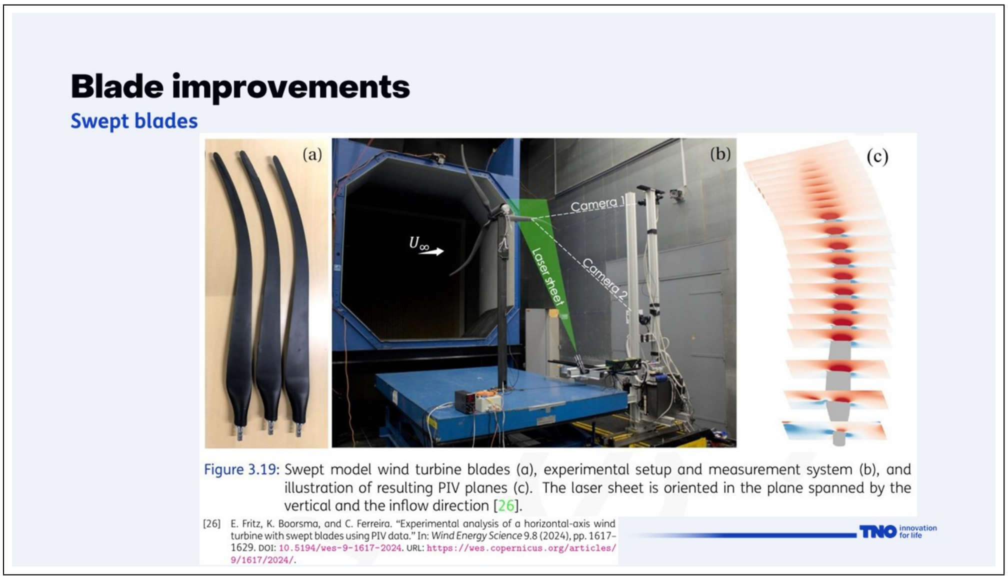
Blade improvements
Swept blades
(a)
(b)
(c)
Camera 1
Camera 2
Laser sheet
Figure 3.19: Swept model wind turbine blades (a), experimental setup and measurement system (b), and illustration of resulting PIV planes (c). The laser sheet is oriented in the plane spanned by the vertical and the inflow direction [26].
[26] E. Fritz, K. Boorsma, and C. Ferreira. "Experimental analysis of a horizontal-axis wind turbine with swept blades using PIV data." In: Wind Energy Science 9.8 (2024), pp. 1617–1629. DOI: 10.5194/wes-9-1617-2024. URL: https://wes.copernicus.org/articles/9/1617/2024/.
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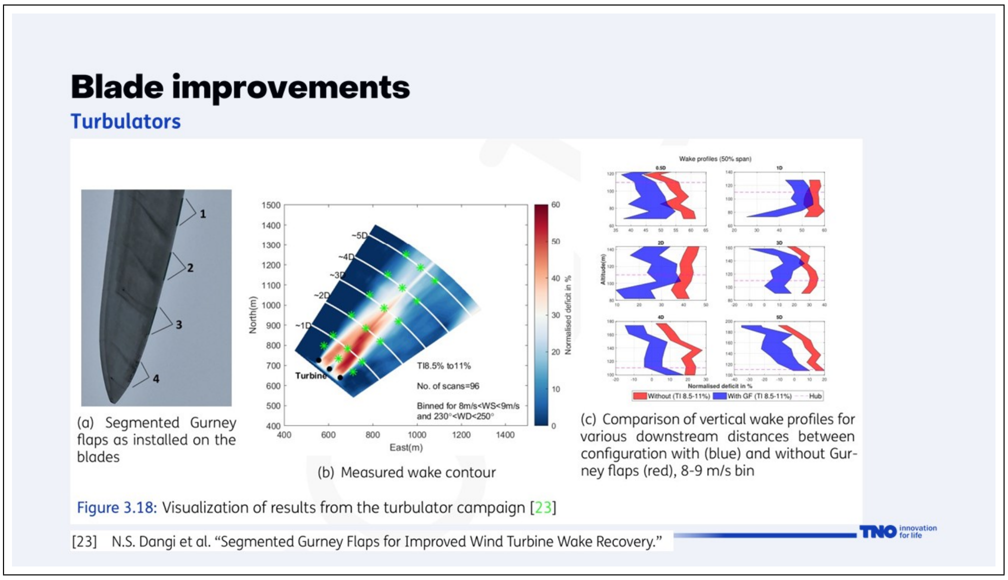
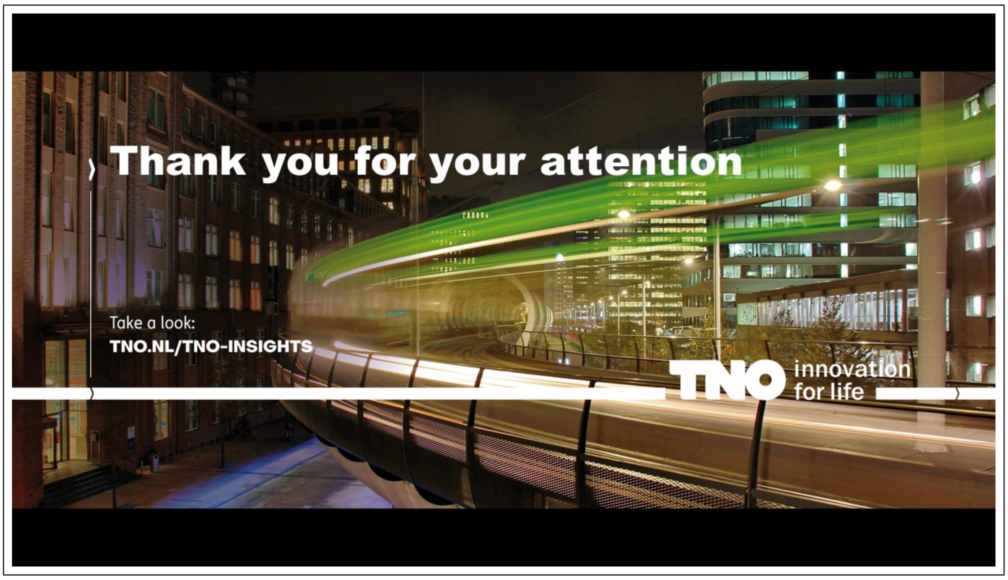
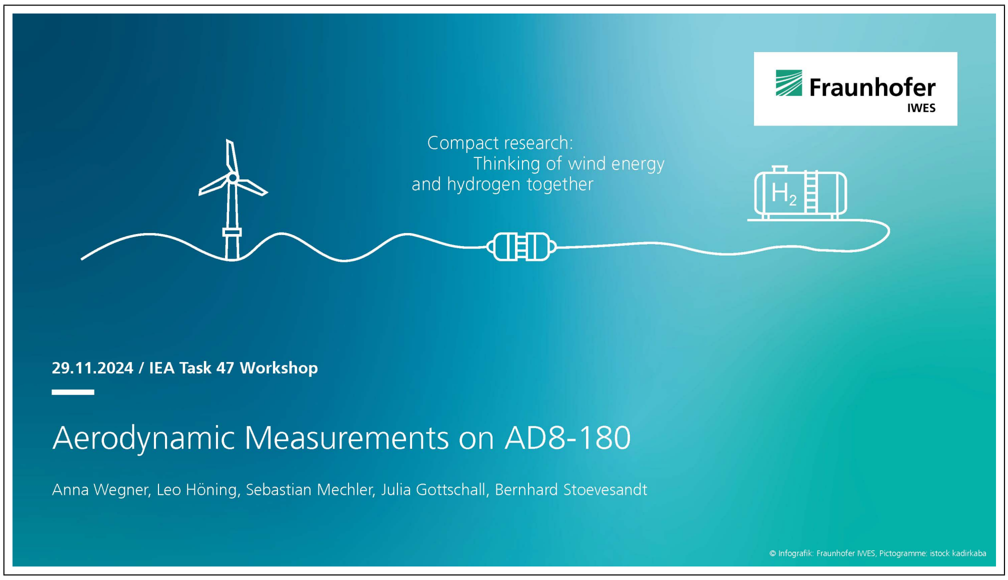

Blade improvements
Turbulators
(a) Segmented Gurney flaps as installed on the blades
(b) Measured wake contour
(c) Comparison of vertical wake profiles for various downstream distances between configuration with (blue) and without Gurney flaps (red), 8-9 m/s bin
Figure 3.18: Visualization of results from the turbulator campaign [23]
[23] N.S. Dangi et al. "Segmented Gurney Flaps for Improved Wind Turbine Wake Recovery."
TNO innovation for life


Thank you for your attention
Take a look:
TNO.NL/TNO-INSIGHTS
TNO innovation for life

5.2 Aerodynamic measurements on AD8-180 -Anna Wegner et al., Frauenhofer



Motivation & Background
HighRe

Validating low- and high-fidelity tool chains against field measurements of an 8 MW wind turbine

- Low fidelity models based on smaller wind turbines
- No data available on large multi-MW rotors
- Adwen 8MW (AD8) (offshore) wind turbine as research infrastructure by Fraunhofer IWES in Bremerhaven (2018-2022)
- Large turbine measurement campaign conducted within the **HighRe** project:
  - Inflow and wake measurements using a met mast, ground lidars, nacelle lidars
  - Turbine data available for BEM and CFD purposes within project (electric power, root bending moments, pitch, azimuth, blade data …)
  - Development of an aerodynamic measurement device (aerodynamic glove) that was attached on one blade
- Aiming at validation of in-house toolchains and investigate measurements for high Reynolds number effects (HighRe)
- Approach: getting setup as close as possible to real conditions, while targeting the scopes of the different tools (BEM, CFD)

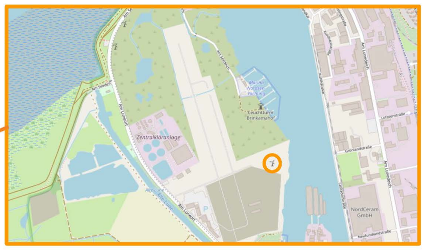
➢ Unique measurement campaign with this turbine size

Slide 3 12/4/2024 © Fraunhofer IWES Fraunhofer IWES

Measurements
Testsite

Turbine specifications

- Former airport in the harbor of Bremerhaven, Germany
- Surrounded by field, water and a few buildings
- Main wind direction South/Southwest
- Adwen 8MW turbine:
  - 8 MW rated power
  - 180m rotor diameter
  - 115m hub height
  - Prototype turbine



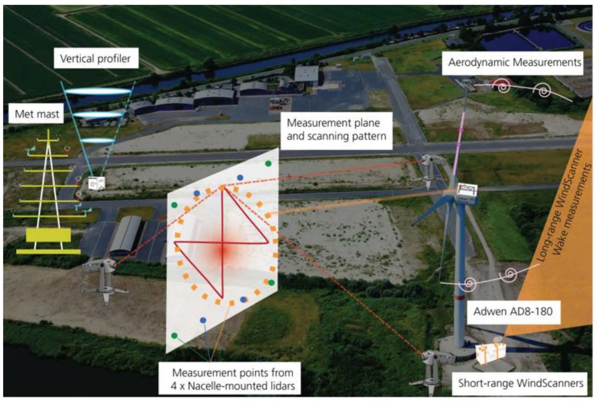
Slide 5 12/4/2024 © Fraunhofer IWES Fraunhofer IWES

Wind Measurements

Measurements on the AD8 turbine in Bremerhaven

Setup for wind field measurements

- Met mast located southwest of the turbine (main wind direction)
- Vertical profiler, short range wind scanner and nacelle mounted lidars for inflow measurements
- Long-range wind scanners for wake measurements



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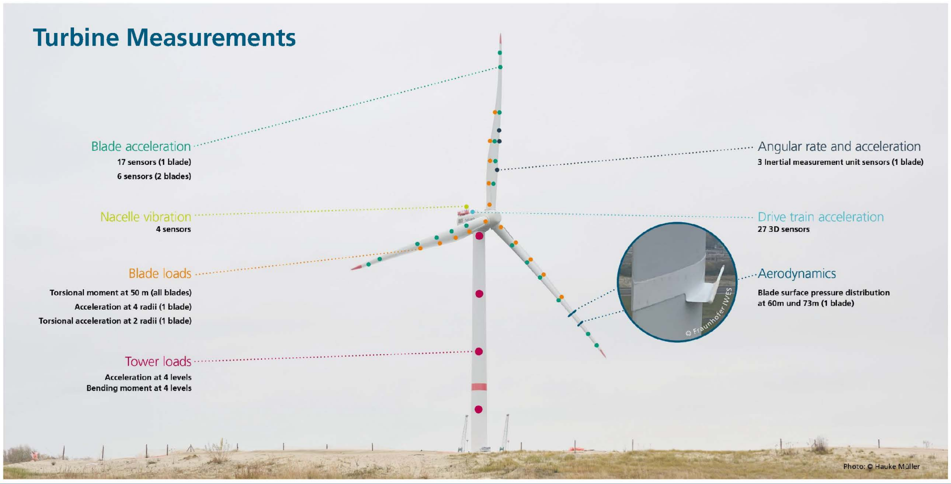

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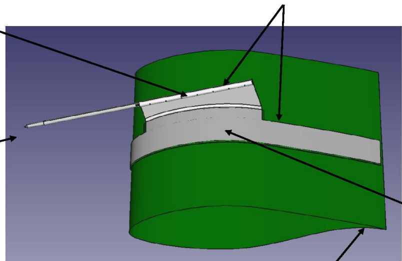
Turbine Measurements

Aerodynamic Measurements

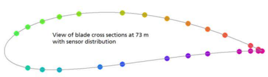
Blade inaccessible from inside
- ➢ 5-hole probe attachment on the outside

Probe tip optimized for minimal influence from blade

No influence of the sensors by the construction
- ➢ edge of construction with enough distance from sensors (model result)
- ➢ probe holder at outer radius



No influence of the sensors by each other
- ➢ staggered positioning
- ➢ surface roughness of shell similar to blade



No feedthrough of cables possible at outer radii
- ➢ cable guiding close to trailing edge to avoid an influence on aerodynamics

Fraunhofer IWES


Design of the Measurement system
Construction and Installation
Embedded pressure sensors
36 sensors at each radius
Installation process
Molds for pressure shells in the Fraunhofer IWES demo center, milled from foam blocks with epoxy coating.
Installation completed
November 2021: shell/probe @73 m
March 2022: shell/probe @ 60 m
De-Installation July 2022
Slide 9
12/4/2024
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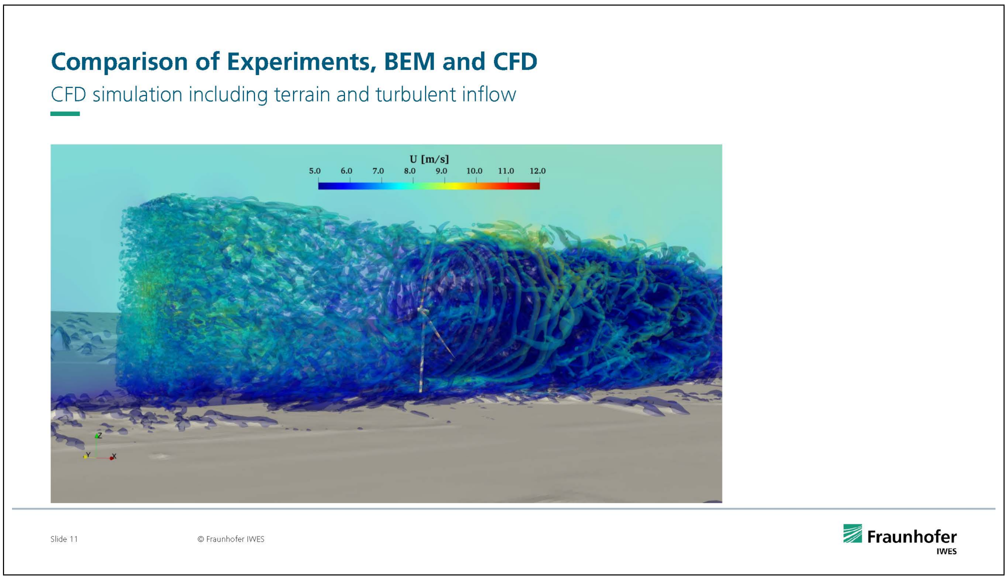
Results
© Brazhyk - stock.adobe.com


Comparison of Experiments, BEM and CFD
CFD simulation including terrain and turbulent inflow
U [m/s]
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
Slide 11
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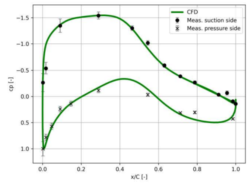
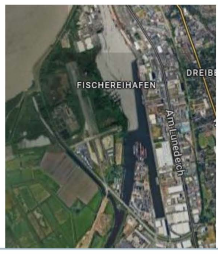
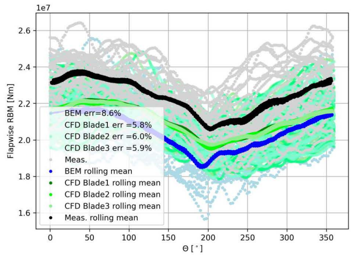
Comparison of Measurements, BEM and CFD

Simulations in comparison towards glove measurements

Turbulent wind field constrained by measured data
Injected by source terms upstream of turbine
15° yaw misalignment







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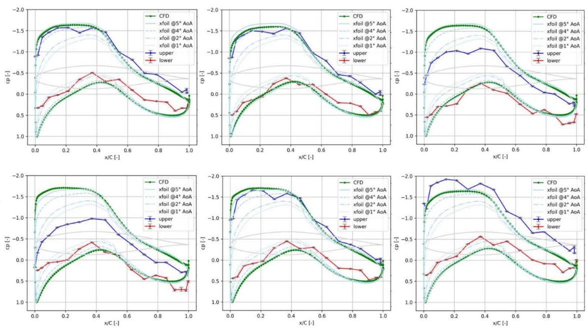
Comparison of Measurements and CFD

Simulations in comparison towards glove measurements

- CFD simulations performed with clean blades
- Measurements corrected for:
  - Height differences
  - Drifting effects
  - Temporal offset
- Fluctuations in measurements larger than in simulations
- Overall good agreement
- Huge amount of data available in BEM, CFD and field measurements → comparisons to be done to understand deviations in aerodynamic



Tower passage

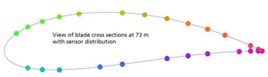
Fraunhofer IWES

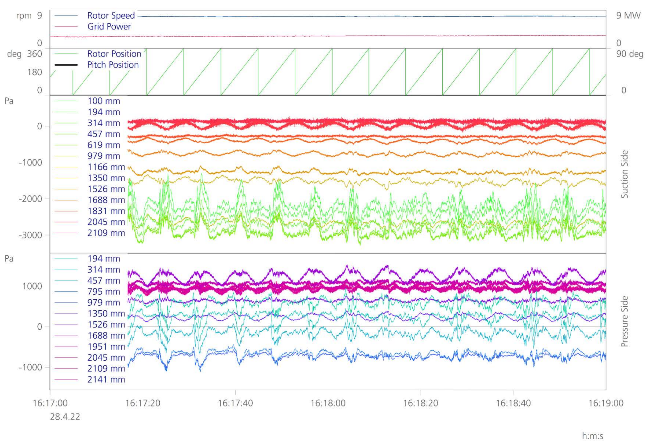
Results

Time series

Rotor rotation

- 73 m rotor radius
- Measurements corrected for:
  - Height differences
  - Drifting effects
  - Temporal offset
- Turbine conditions:
  - Below rated conditions
  - 7.7m/s inflow
  - El. Power 2.9 MW
  - Pitch 0°





 12/4/2024

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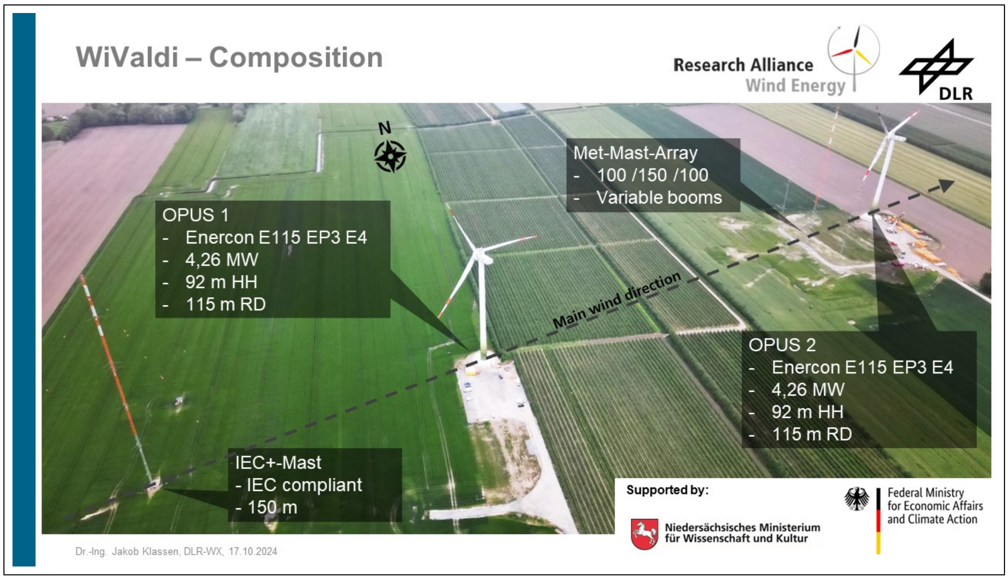
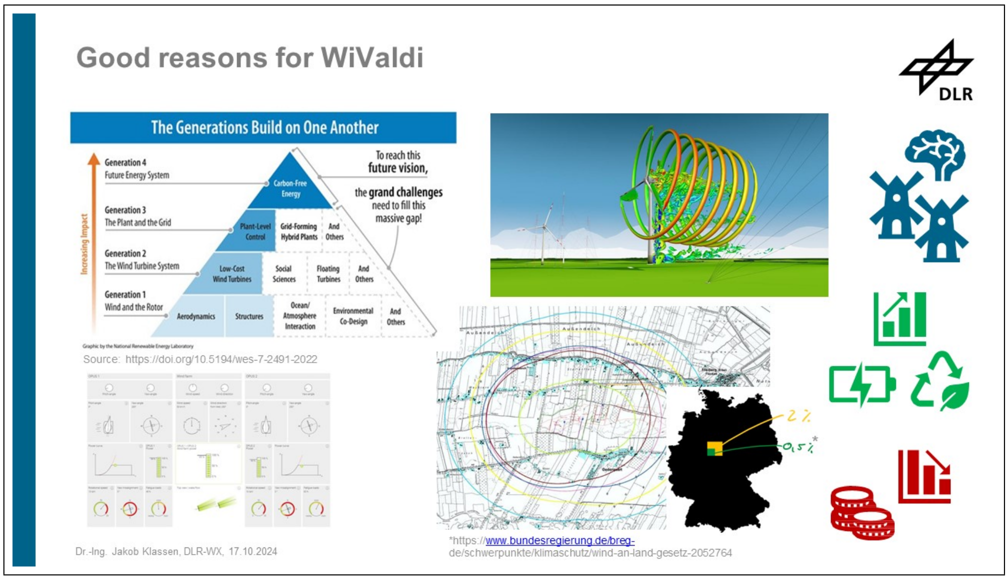
5.3 Forschungspark Windenergie WIVALDI - Jakob Klassen and Jan Tessmer, DLR





- Das **Labor im Originalmaßstab** bietet einzigartige Möglichkeiten der Forschung **mit und an** den Windenergieanlagen
- Ca. **250 Sensoren im Feld und auf den meteorologischen Messmasten** erfassen lokale Wetterbedingungen und Schallimmissionen
- Ca. **2.000 elektrische und faseroptische Sensoren in den Windkraftanlagen** für Dehnungs-, Temperatur- und Beschleunigungsmessungen
- **Zeitlich synchronisierte 24/7-Messdatenerfassung** bietet einmalige Referenz für die Validierung von Berechnungsmethoden und -modellen
- Datenbereitstellung für **industrielle und akademische Forschung** und Entwicklung
- Untersuchung von **Betriebsführungskonzepten im Windparkkontext** zur Steigerung der Wertschöpfung

Beteiligte Institutionen und Zuwendungsempfänger:

DLR
- Institut für Aeroelastik (AE)
- Institut für Aerodynamik und Strömungstechnik (AS)
- Institut für Antriebstechnik (AT)
- Institut für Faserverbundleichtbau und Adaptronik (FA)
- Institut für Flugsystemtechnik (FT)
- Institut für Physik der Atmosphäre (PA)
- Einrichtung für Windenergieexperimente (WX)

Universität Oldenburg
- Institut für Physik, AG Energiemeteorologie (EnMet)
- Institut für Physik, AG Turbulenz, Windenergie und Stochastik (TWiSt)
- Institut für Physik, AG Windenergiesysteme (WESys)

Universität Hannover
- Institut für Statik und Dynamik (ISD)
- Institut für Stahlbau (IfS)
- Institut für Baustoffe (IfB)
- Institut für Geotechnik (IGtH)
- Institut für Turbomaschinen und Fluiddynamik (TFD)
- Institut für Grundlagen der Elektrotechnik und Messtechnik (GEM)

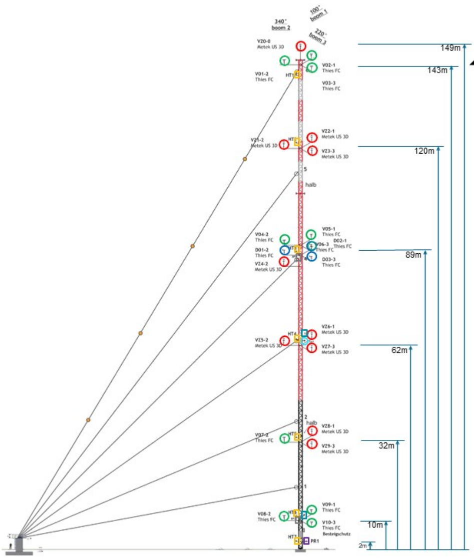
Universität Bremen
- Institut für integrierte Produktentwicklung (BIK)
- Institut für elektrische Antriebe, Leistungselektronik und Bauelemente (IALB)

Wobben Research & Development – WRD GmbH

Dr.-Ing. Jakob Klassen, DLR-WX, 17.10.2024

IEC Mast (IECM)

- 3D Ultrasonic anemometer
- Cup anemoeter
- Wind Vane
- Gas Analyser
- Temp/Humidity sensor
- Barometer
- Precipitation Sensor
- Temp Difference Sensor



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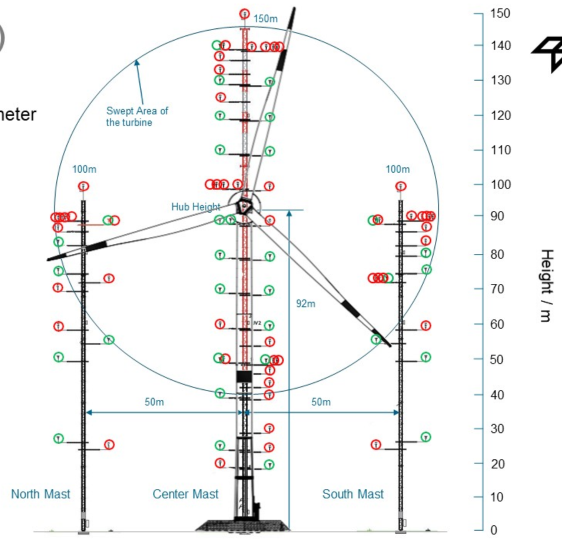
Met Mast Array (MMA)

- 51 x 3D Ultrasonic anemometer
- 32 x Cup anemometer



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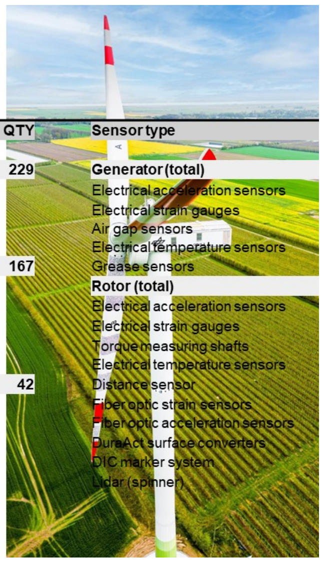
OPUS 1 & 2

(total installed sensors OPUS 1: 1225 / OPUS 2: 689)

Sensor type	QTY	Sensor type
Foundation (total)	**229**	**Generator (total)**
Inclinometer		Electrical acceleration sensors
Electrical strain gauges		Electrical strain gauges
Electrical displacement sensors		Air gap sensors
Fiber optic strain and temperature		Electrical temperature sensors
Tower (total)	**167**	Grease sensors
Electrical acceleration sensors		**Rotor (total)**
Electrical strain sensors		Electrical acceleration sensors
Electric strain gauges		Electrical strain gauges
Electrical temperature sensors		Torque measuring shafts
Pressure measuring belt		Electrical temperature sensors
Nacelle & azimuth (total)	**42**	Distance sensor
Electrical acceleration sensors		Fiber optic strain sensors
Electrical strain gauges		Fiber optic acceleration sensors
Power meter		DuraAct surface converters
Rotary encoder		DIC marker system
Electrical temperature sensors		Lidar (spinner)
Current clamp meters		



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OPUS 1 & 2
Rotor blades

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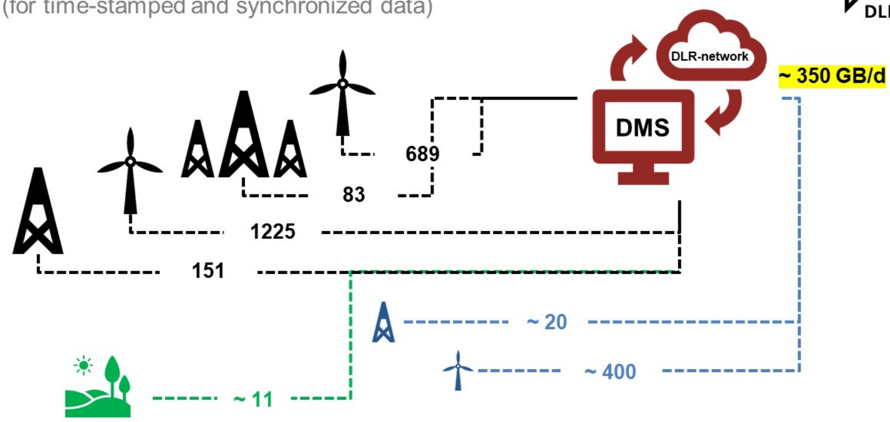
WiValdi – Data acquisition and processing system
(for time-stamped and synchronized data)



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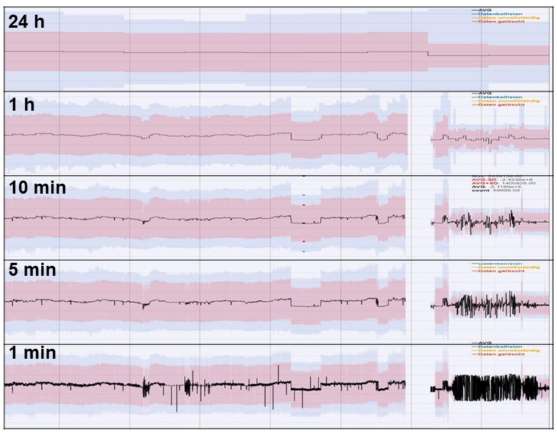
Data acquisition and processing system
Example

- one rotor blade of OPUS 1
- blade root bending moment
- edgewise
- 9 random consecutive days
- different aggregation



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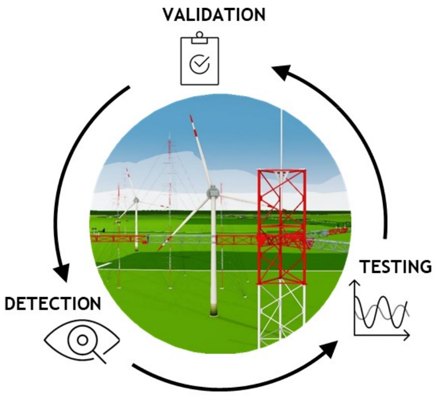
WiValdi – Providing a unique research infrastructure
(for you?)

DLR



- BYO equipment for test and validation
- access sensor data
- access WTG data
- test WTG and system modifications
- not limited to wind energy research
- real digital twin

Dr.-Ing. Jakob Klassen, DLR-WX, 17.10.2024

Tailored opportunities for collaboration

DLR

Project goals

- Simply use measured data for own res.
- Validate your equippment (e.g. new generation sensors)
- Test operation modes
- etc.

Basic tasks

- Operate in "normal mode"
- Use 24/7 gathered data
- Measuring with new sensors / technologies
- Operation in off-design spaces
- (ex)change (major) components

Cooperation models

- Funded project (BMWK, DFG, EU)
- Direct commissioning / contract research

favoured: „effective cooperation"

Costs

- charge rates for WiValdi depend on the cooperation model
- Support services provided by the operating staff (time and material basis)

Dr.-Ing. Jakob Klassen, DLR-WX, 17.10.2024

Ongoing research @WiValdi
A selection of current projects with a potentially high impact on the wind industry

DLR

Project	Reference number*
DFWind Phase 2 German Research Platform for Wind Energy; - Structural dynamics, monitoring and validation - Wind physics, control engineering and extended plant characterization - Research-technical upgrading and overall integration with basic systems, instrumentation and data management - Implementation of manufacturer-specific research and technology topics at the research platform - Instrumentation of the power electronics, the main, azimuth and three blade flange bearings for a condition assessment and reliability evaluation	0325936
OPUS 3 Construction of an experimental turbine	03EE2045
DataWind Efficient data management, processing and advanced analysis for wind turbines	03EE3113
A2Monitor Aerodynamic & Aeroacoustic Condition Monitoring on the Rotor Blade of a Wind Turbine; - System integration and evaluation of measured data - Measurement of aerodynamic surface pressure distributions on the rotor blade of a wind turbine using MEMS sensors and reconstruction of operating conditions of these wind turbines	03EE3108

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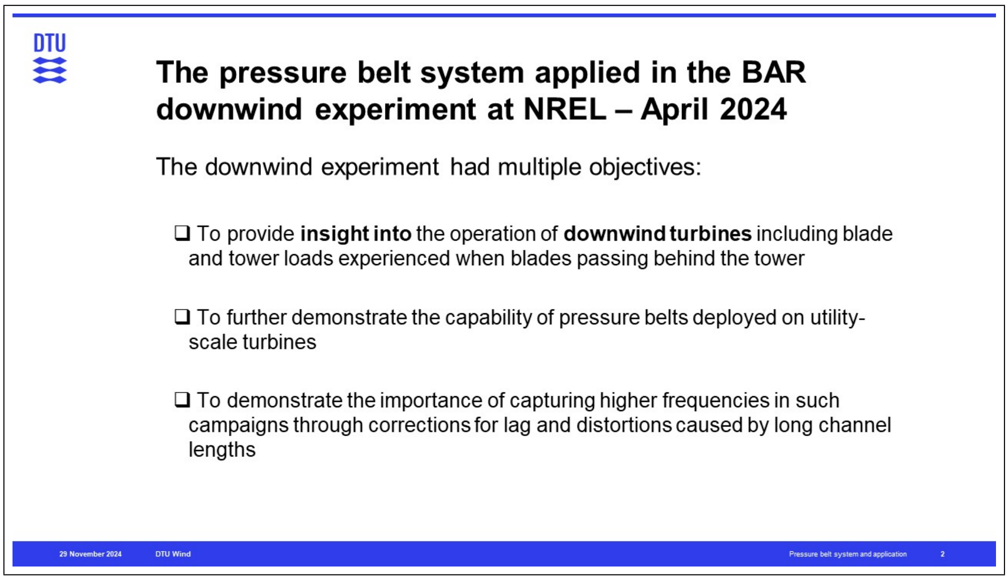
* www.enargus.de

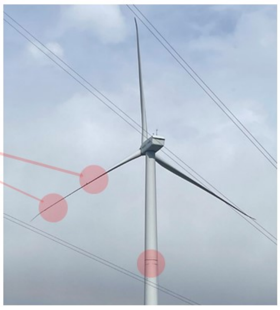
5.4 The pressure belt system applied in the NREL downwind experiment
- Helge Aagaard Madsen et al., DTU



DTU

Installation on site in April 2024

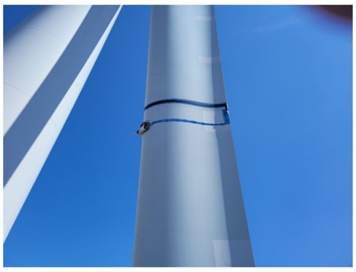
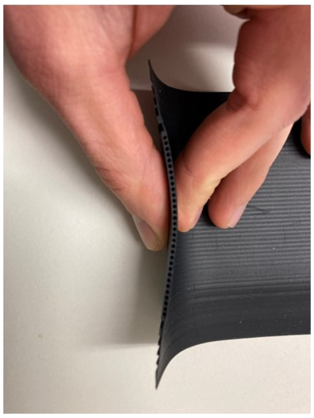
- NREL's Flatirons campus, **GE 1.5MW** operated in a downwind configuration
- blade: **2 pressure belts** with 2 'flyboards' (32 taps, 5-hole-probes, data acquisition)
- tower: **1 pressure belt** (64 taps, data acquisition)


DTU

Pressure Belt, Pressure Scanners, and Flyboard

- Extruded pressure belt (new)
  - Thirty-two 0.8mm channels
  - maximum height of 1.8mm
  - 100mm wide
- Pressure Scanners
  - Two 16 channel mini pressure scanners per belt
  - Belt channels connected to scanners via printed fittings connecting the tubes
- Flyboards
  - Data acquisition (100 Hz)
  - Data transmission and storage
  - Communications (WiFi)
  - Five hole pitot tube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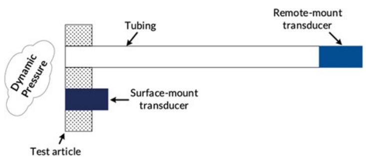
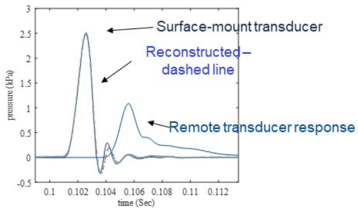
Pressure correction applied by Resono

Signal distortions associated with attenuation, lag and amplification of the pneumatic signals can result in significant error in the acquired measurements





However, unsteady **content** can be recovered effectively using the **Wiener Filtered Inverse System Response Model (WFiSRM)**

Two step process:

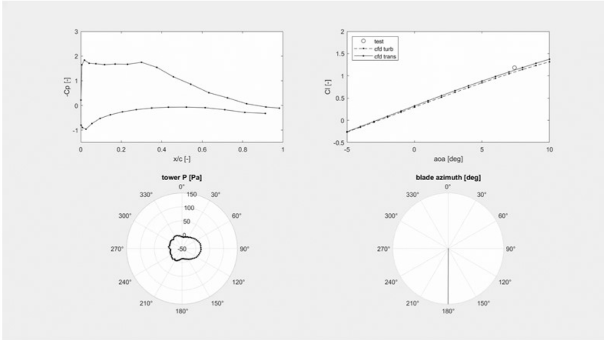
- In-situ characterization of the tubing system – **identify tubing system parameters**
- Reconstruction of the test data – **use the characterized tubing system parameters**

Results – Animation of Raw 100Hz Data

Raw data from April 29th where the tower pressure belt had been mounted

Pressure distribution on outboard blade section

Pressure distribution on the tower section



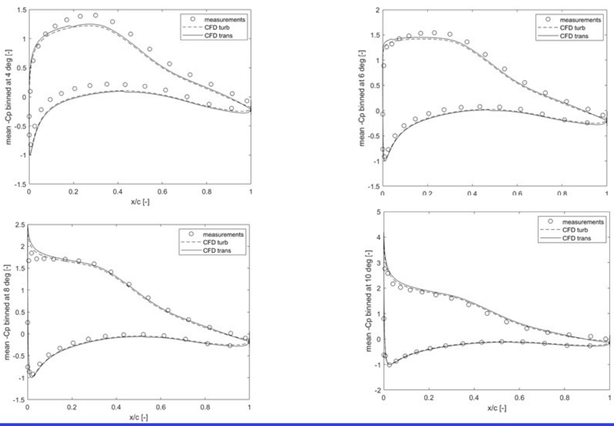
Blade pressure distributions – outboard section

AoA 4 deg

AoA 6 deg

AoA 8 deg

AoA 10 deg



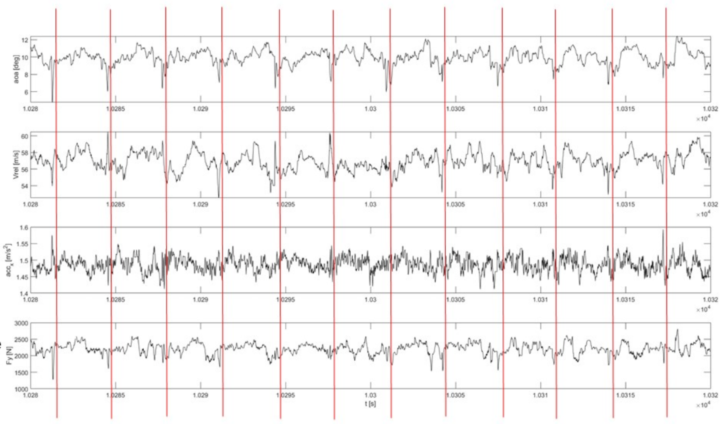
Blade/tower interaction

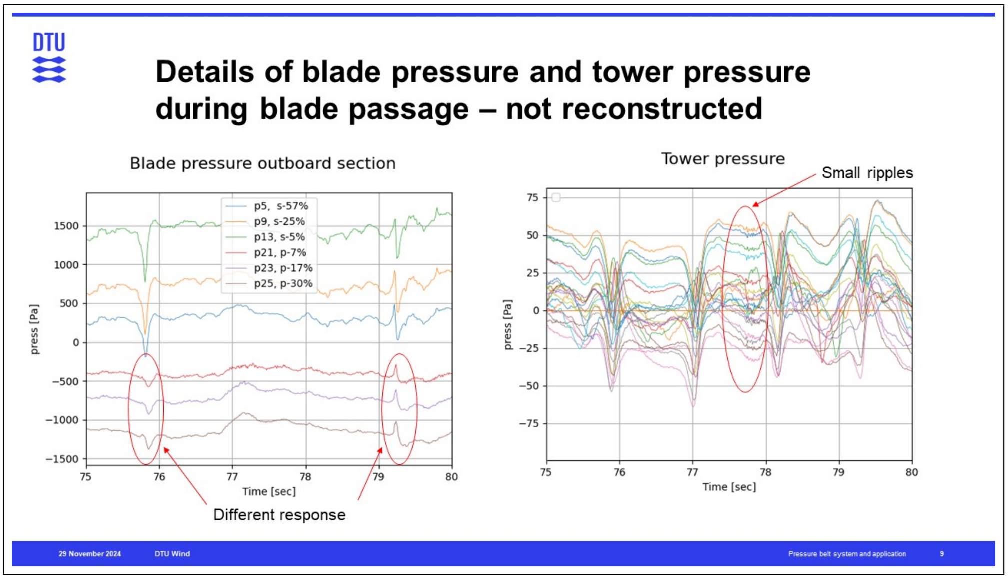
AoA

Vrel

Acc flapwise

Fy at blade section




DTU
Details of blade pressure and tower pressure during blade passage – not reconstructed
Blade pressure outboard section
p5, s-57%
p9, s-25%
p13, s-5%
p21, p-7%
p23, p-17%
p25, p-30%
press [Pa]
Time [sec]
Different response
Tower pressure
Small ripples
press [Pa]
Time [sec]
29 November 2024
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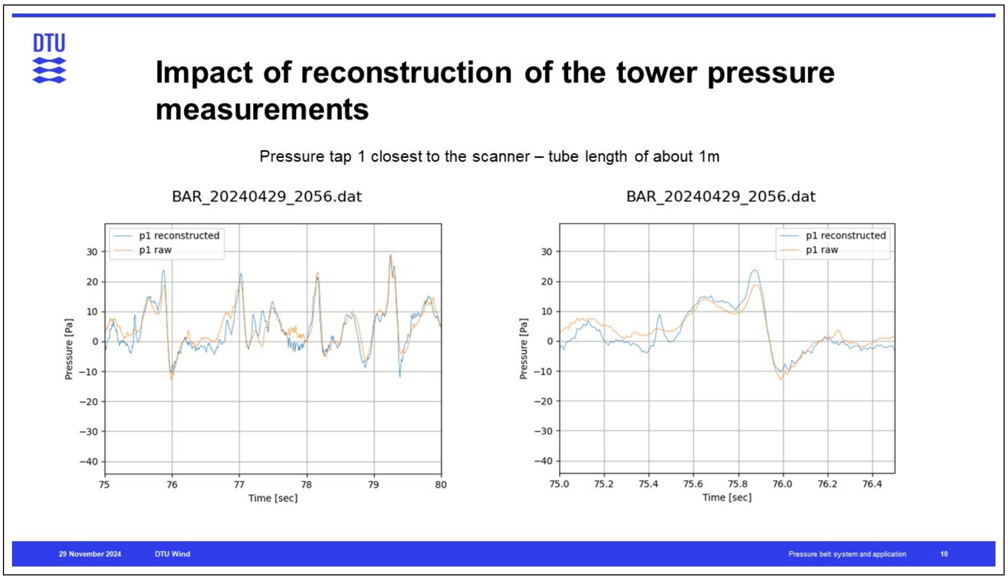
DTU
Impact of reconstruction of the tower pressure measurements
Pressure tap 1 closest to the scanner – tube length of about 1m
BAR_20240429_2056.dat
p1 reconstructed
p1 raw
Pressure [Pa]
Time [sec]
BAR_20240429_2056.dat
p1 reconstructed
p1 raw
Pressure [Pa]
Time [sec]
29 November 2024
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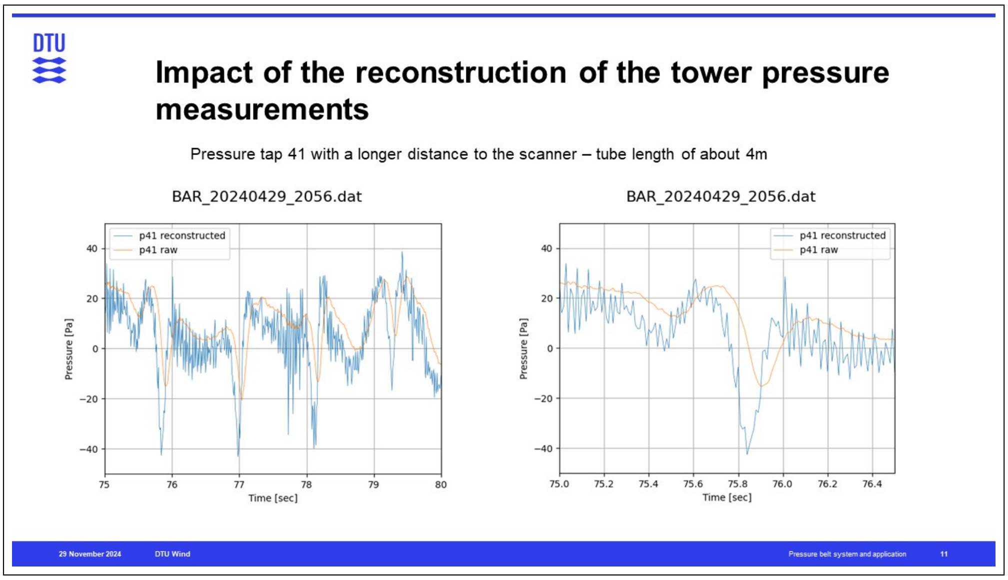
DTU
Impact of the reconstruction of the tower pressure measurements
Pressure tap 41 with a longer distance to the scanner – tube length of about 4m
BAR_20240429_2056.dat
p41 reconstructed
p41 raw
Pressure [Pa]
Time [sec]
BAR_20240429_2056.dat
p41 reconstructed
p41 raw
Pressure [Pa]
Time [sec]
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Outlook

- Ruggedizing system for operation in inclement weather conditions
  - Purging
  - On board powering
- Using the system in longer campaigns to catch severe load events
- Use the system in different campaigns in the Danish **Flow Adaptive Rotor (FAR)** project over the next 2½ years (project partners SGRE and DTU with funding from EUDP)
- Deploying the system on turbines in wind farms with complex inflow

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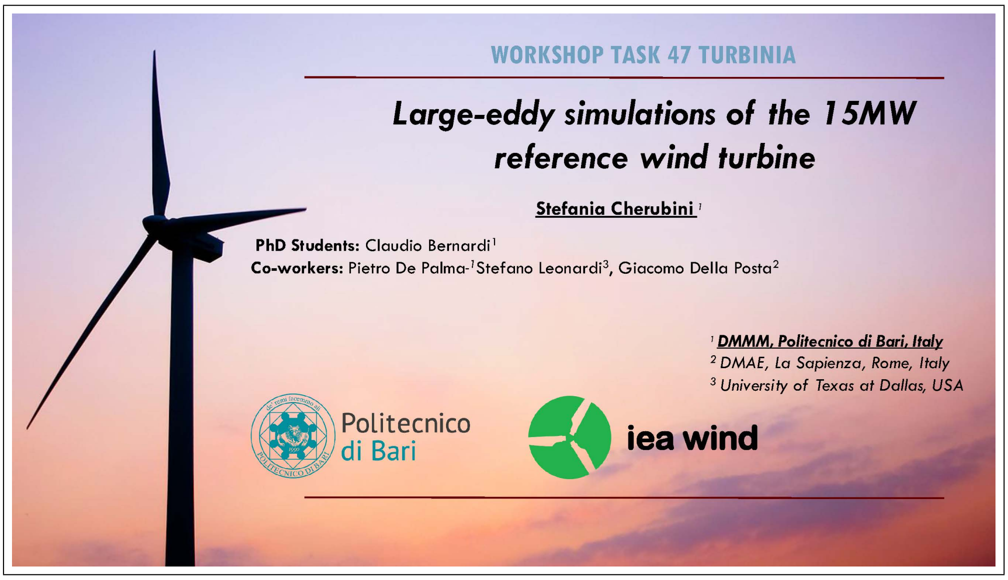
DTU

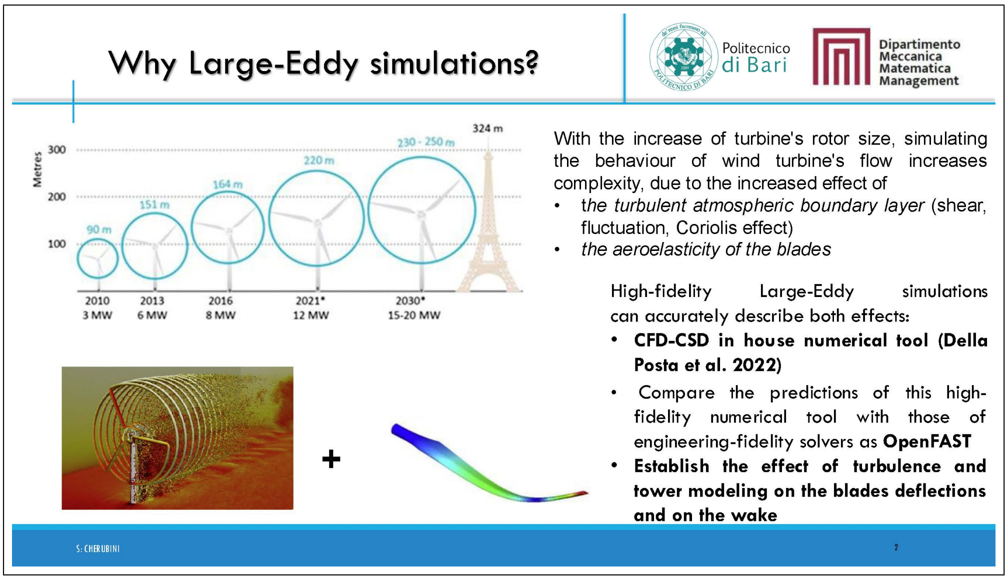
Thank you

29 November 2024 DTU Wind Pressure belt system and application 13

6 Specific outcomes of Task 47

6.1 Large-eddy simulations of the 15MW reference wind turbine - Stefania Cherubini et al., Politecnico di Bari





LES equations

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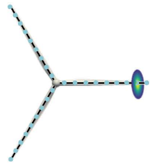
$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} + \overline{F}_i,$$

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0.$$

F_i = *forcing term representing the aerodynamics forces relative to the Actuator Line Model*

τ_{ij} = *residual stresses which are modeled using* ***the Smagorinsky model***



Rotor blades are simulated by using the Actuator Line Model (ALM), as proposed by Sørensen and Shen [3]

$$\tilde{\boldsymbol{f}} = -\boldsymbol{f}^{aero}\frac{1}{\epsilon^2 \pi} exp\left[-\left(\frac{r_\eta}{\epsilon}\right)^2\right] \qquad \boldsymbol{f}^{aero} \to F_d = \frac{1}{2}\rho U_{rel}^2 C_d(\alpha) c F, \quad F_l = \frac{1}{2}\rho U_{rel}^2 C_l(\alpha) c F$$

Tower and nacelle are modelled using the Immersed Boundary Method (IBM), using an approach similar to the one proposed by Orlandi et al. [2]

NREL-5MW tower and nacelle

S. Cherubini 3

CSD Methodology (Della Posta et al.)

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The elastic generalized displacement **d**, which includes **translational** and **rotational** degrees of freedom is decomposed through a modal approach:

$$\boldsymbol{d}(X_1, t) = \sum_{m=1}^{M} q_m(t)\, \boldsymbol{\psi}^m(X_1)$$

Using the virtual work principle leads to the following system of elastic equations:

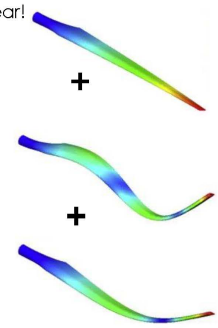
$$\mathbf{M}\ddot{q} + \left[\mathbf{D} + \mathbf{D}^{Co}(\Omega)\right]\dot{q} + \left[\mathbf{K} + \mathbf{K}^{c}(\Omega) + \mathbf{K}^{Eu}(\dot{\Omega})\right] q = e + e^{c} + e^{Eu}$$

where **M** , **D** and **K** are the modal structural mass, damping, and stiffness matrices, Ω is the rotor angular velocity vector, **e** represents the external loads in modal basis

Finite element model of the blade with 6 degrees of freedom :

- Euler–Bernoulli for bending in the streamwise/azimuthal directions
- linear shape functions for axial and torsional deformations

Modal method: Reduced number of variables.. but linear!



S. CHERUBINI 4

CFD - CSD Coupling

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- **Six DoF** system in each node solved using the **generalized α-method**

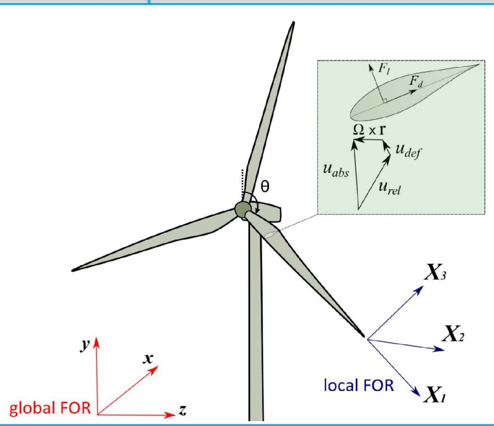
Two-way coupling aeroelastic approach:

- the relative velocity and angle of attack at each blade section modified according to the velocity field, the angular rotor velocity and the elastic state computed by the structural solver

$$\vec{u}_{\epsilon}^{AL} = \vec{u}_{e}^{AL} - \vec{u}_{def} - \vec{\Omega} \times \vec{r}$$

relative velocity | absolute velocity | deformation velocity | rotational velocity

Loose coupling algorithm: CFD-CSD communications only at the beginning of each RK substep to reduce the computational cost



S. CHERUBINI 5

Comparison with BEM solver: OPENFAST

Aerodynamic model
AeroDyn module based on the BEM theory with a Prandtl loss model for tip/root effects

Structural model
- *BeamDyn module:* geometrically exact beam theory, suitable for non-linear, large deflections
- *ElastoDyn module:* based on modal approach and suitable for blades deformation dominated by bending

Aerodynamic-Structural coupling

Local angle of attack determined taking into account the local deformation velocities.

	CFD-CSD solver	OpenFAST	
		ElastoDyn	*BeamDyn*
Blade modeling	*LES+ALM*	*BEM*	*BEM*
Structural nodes N	80	20	20
Structural modes M	15	3	-
DoF × node	6	2	6
CPUs used	200	1	1
Physical time [s]	200	200	200
Number of revolutions	40	40	40
CPU time [h]	72	0.02	0.20

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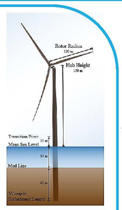
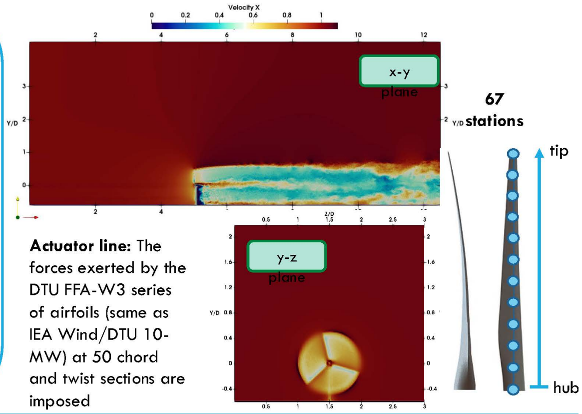
Simulation setup

NREL 15MW turbine
Design TSR = 9 **(ω=7.58 RPM)**
Rotor diameter D = 240m
Hub height h= 150 m
Tower base diameter Dt=10m
Nacelle diameter Dn=7.94m
Nacelle overhang Ln=11.35m
Wind velocity U=10.58m/s
CFD
Domain dimensions: 12.5D x 5D x 3D
2048 x 512 x 512 gridpoints
INLET: laminar/turbulent with $U_\infty = 10.6\ m/s$
OUTLET: radiative boundary conditions
BOTTOM WALL: no-slip
TOP WALL: free-slip
LATERAL BOUNDARIES: periodic
Reynolds number $Re = 1.72 * 10^8$



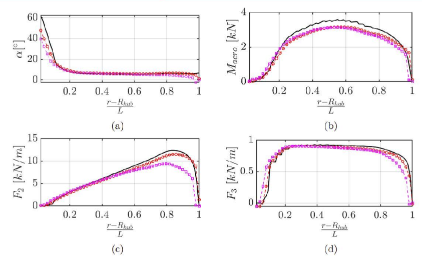


Actuator line: The forces exerted by the DTU FFA-W3 series of airfoils (same as IEA Wind/DTU 10-MW) at 50 chord and twist sections are imposed

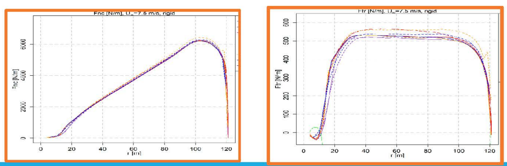
S. CHERUBINI 7

Comparison with OpenFast

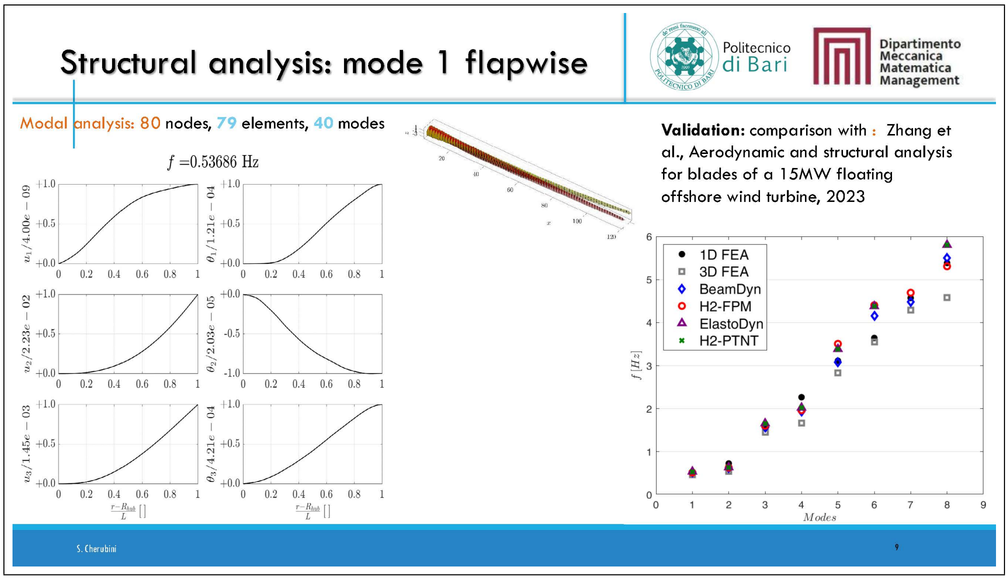
Time average of the aerodynamic quantities along the blade for **LES (black),** ElastoDyn (o), BeamDyn (□):
(a) Angle of attack;
(b) Pitching moment per unit length;
(c) Streamwise force per unit length;
(d) Edgewise force per unit length



Validation with rigid case
ref: IEA Wind TCP Task 47 – Definition of first round (Case V2.1)
Flow setting:
- ω_{rot} **fixed** at 7.56 RPM
- $V_{wind} = 10.59\ m/s$
- Shear, but no turbulence yet



S. CHERUBINI 8


Structural analysis: mode 1 flapwise
Politecnico di Bari
Dipartimento Meccanica Matematica Management
Modal analysis: 80 nodes, 79 elements, 40 modes
f =0.53686 Hz
Validation: comparison with : Zhang et al., Aerodynamic and structural analysis for blades of a 15MW floating offshore wind turbine, 2023
1D FEA
3D FEA
BeamDyn
H2-FPM
ElastoDyn
H2-PTNT
Modes
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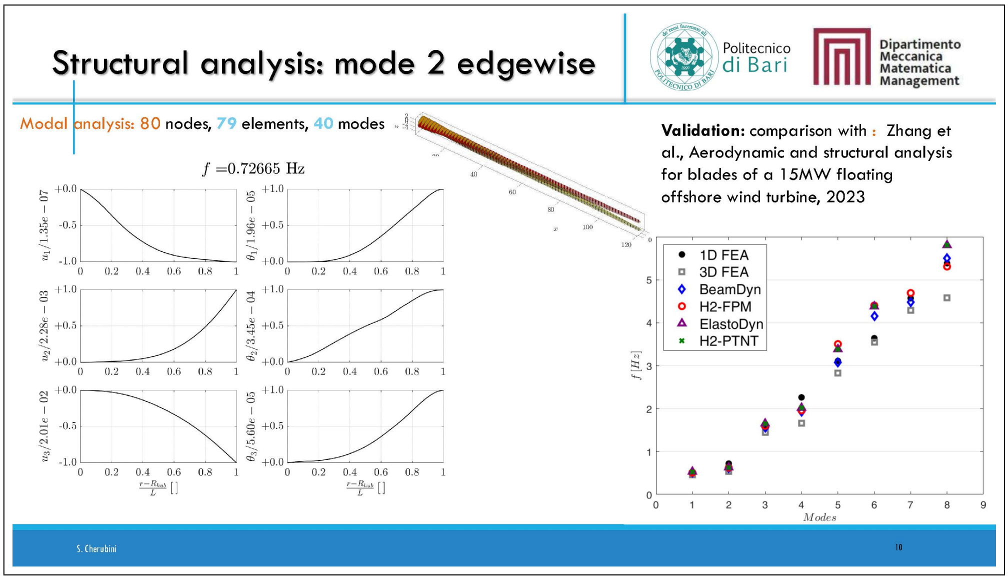
Structural analysis: mode 2 edgewise
Politecnico di Bari
Dipartimento Meccanica Matematica Management
Modal analysis: 80 nodes, 79 elements, 40 modes
f =0.72665 Hz
Validation: comparison with : Zhang et al., Aerodynamic and structural analysis for blades of a 15MW floating offshore wind turbine, 2023
1D FEA
3D FEA
BeamDyn
H2-FPM
ElastoDyn
H2-PTNT
Modes
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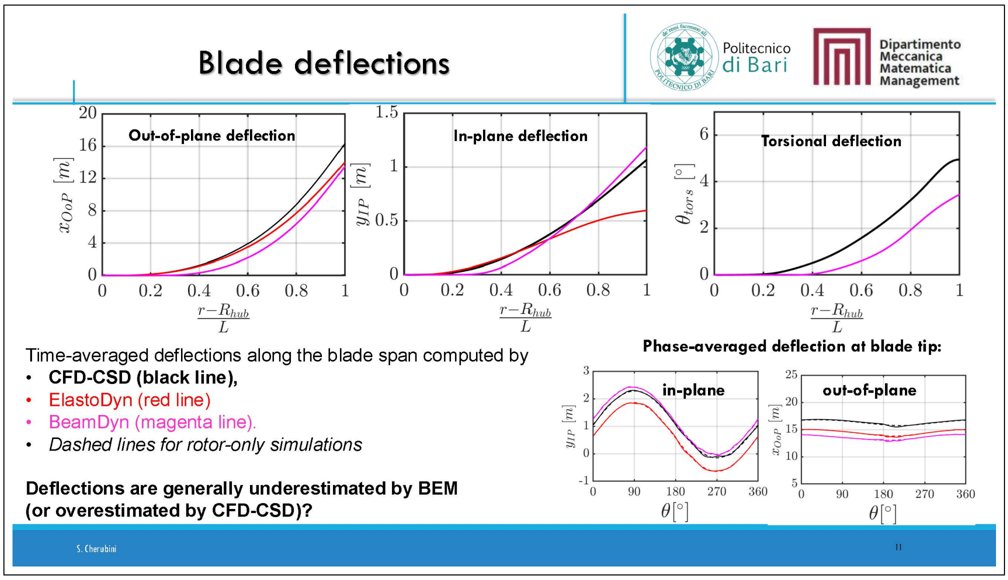
Blade deflections
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Out-of-plane deflection
In-plane deflection
Torsional deflection
Time-averaged deflections along the blade span computed by
CFD-CSD (black line),
ElastoDyn (red line)
BeamDyn (magenta line).
Dashed lines for rotor-only simulations
Deflections are generally underestimated by BEM (or overestimated by CFD-CSD)?
Phase-averaged deflection at blade tip:
in-plane
out-of-plane
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CFD vs BEM

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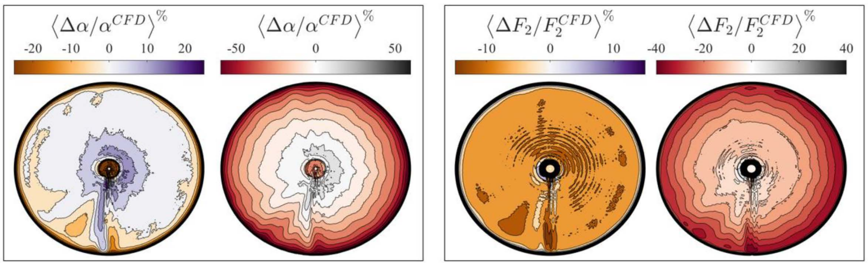

Phase-averaged contours of the **percentual differences in incidence angle** between the CFD code and: ElastoDyn (left); BeamDyn (right).

Phase-averaged contours of the **percentual differences in flapwise aerodynamic force** between the CFD code and: ElastoDyn (left); BeamDyn (right).

Largest differences in correspondence with the tower

S. Cherubini 12

Aerodynamics is important!

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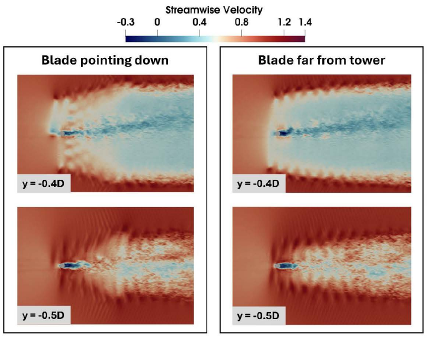
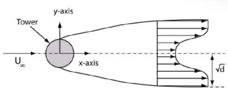
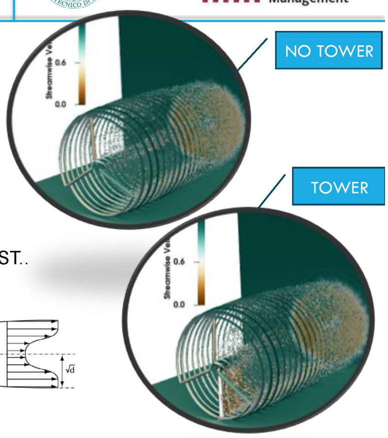
CFD aerodynamic modeling of the tower:

- LES results



- while OpenFAST..





S. CHERUBINI 13

Rotor only vs Tower & Nacelle

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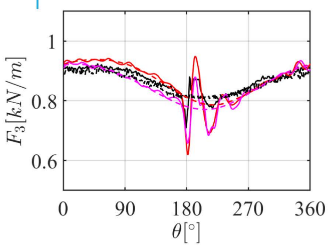
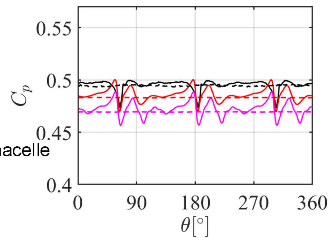


Phase-averaged **edgewise aerodynamic force** at the 80% of the blade

- **CFD-CSD (black line)**
- ElastoDyn (red line)
- BeamDyn (magenta line)

- *Solid lines:* with tower & nacelle
- *Dashed lines:* rotor-only



Phase-averaged **power coefficient** at 80% of the blade

The oscillations due to the tower are overestimated by OpenFAST (or underestimated by CFD-CSD)
➡ *we observed the opposite for the 5MW reference turbine! (see Bernardi et al. Journal of Physics: Conference Series - Wake Conference 2023*

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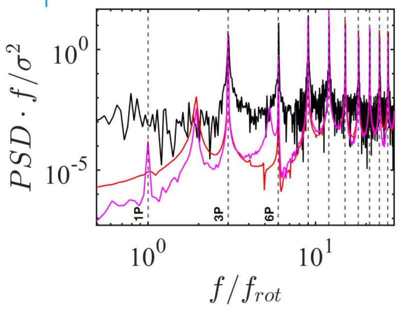
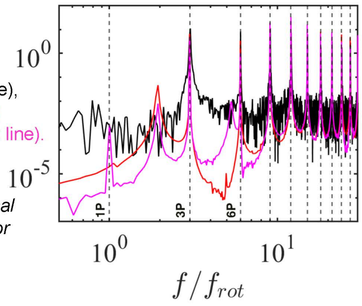
Power spectral densities: CFD vs BEM



Power Spectral Density (PSD) of the power coefficient

- CFD-CSD (black line),
- ElastoDyn (red line)
- BeamDyn (magenta line).

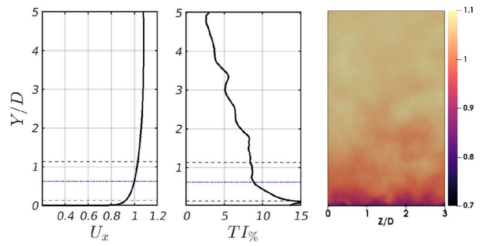
The vertical lines highlight the rotational frequency of the rotor and its multiples

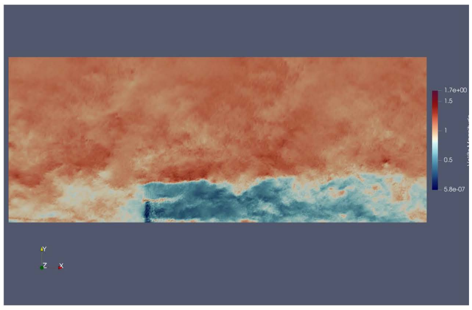


Power Spectral Density (PSD) of the thrust coefficient

CFD-CSD have a much broader spectrum, especially in the low frequency range → possible cause of larger deflections

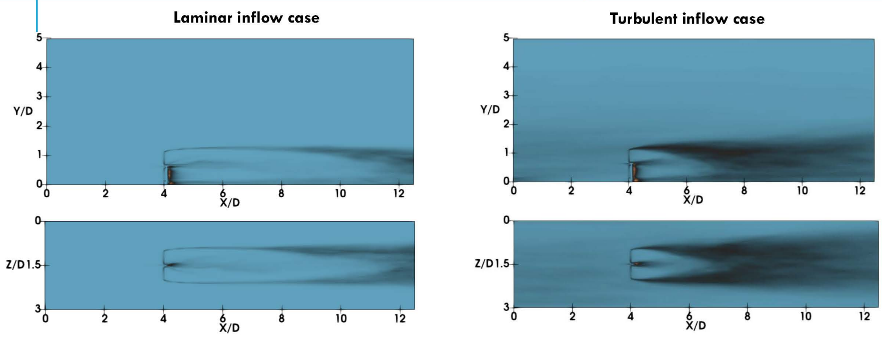
Turbulent inflow: precursor simulation





- Turbulence induced with a precursor simulation (Re = 10^8)
- Boundary layer described by a power law
- Turbulence intensity around 8% at turbine hub height

Flow field: turbulent kinetic energy



- *Turbulent kinetic energy increases strongly in the near wake*
- *More mixing, meaning earlier wake recovery!*
- *The wake spreads after a few diameters in the turbulent case*

Blade deflections: laminar vs turbulent

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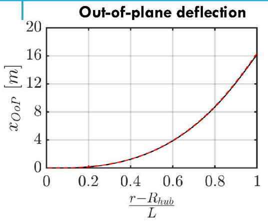
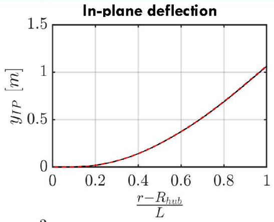
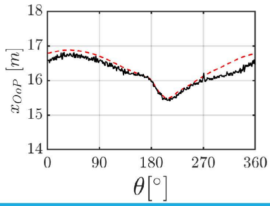


Results of CFD-CSD:

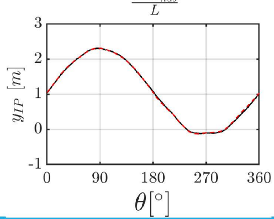
Time-averaged deflections along the blade span





Phase-averaged deflections at blade tip

- **Turbulent inflow (black),**
- Laminar inflow (red dashed)



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The effect of turbulence

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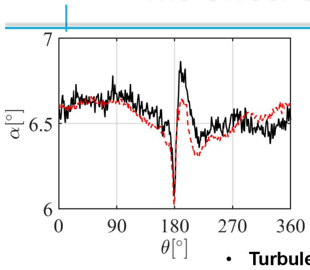

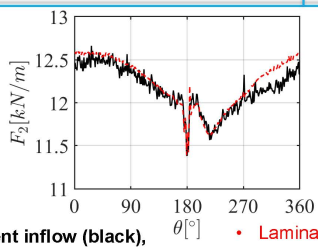

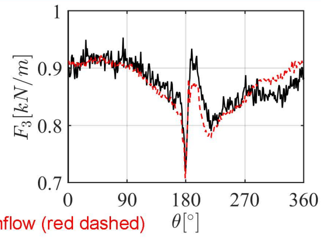

- **Turbulent inflow (black),**
- Laminar inflow (red dashed)

Phase-averaged **local incidence angle** at 80% of the blade

Phase-averaged **flapwise aerodynamic force** at 80% of the blade

Phase-averaged **tangential aerodynamic force** at 80% of the blade

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Conclusions

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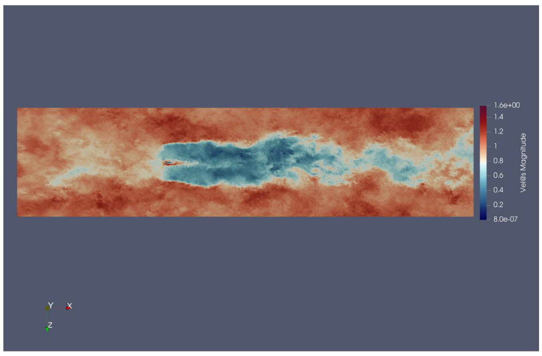
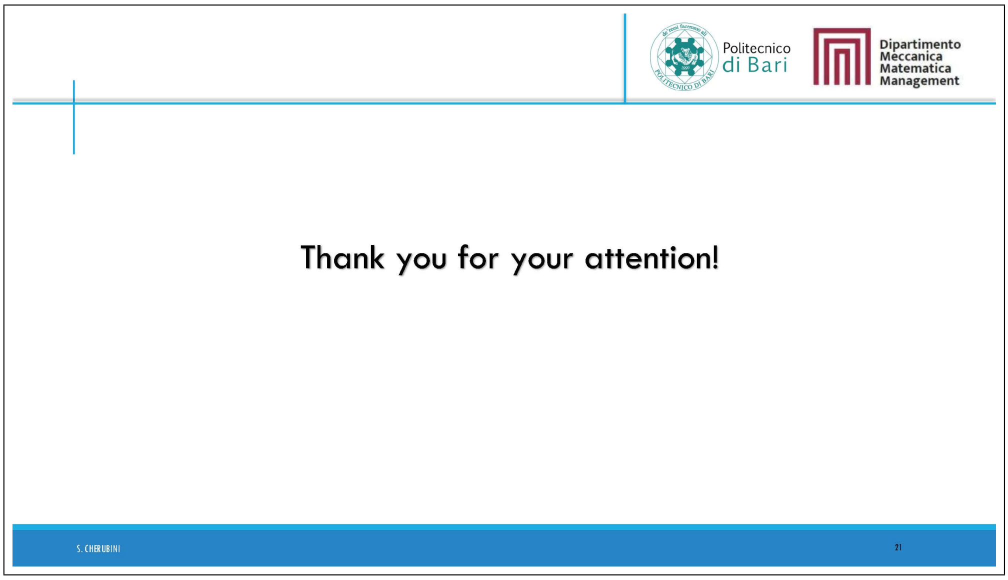
- **Large blade deflections**, generally underestimated by engineering-fidelity codes



- Taking into account the **tower's shedding** is crucial for accurately predict the turbine's dynamics and power production!
- The **complexity of the atmospheric boundary layer** considerably affects the wake (not much the deflections)

S. CHERUBINI 20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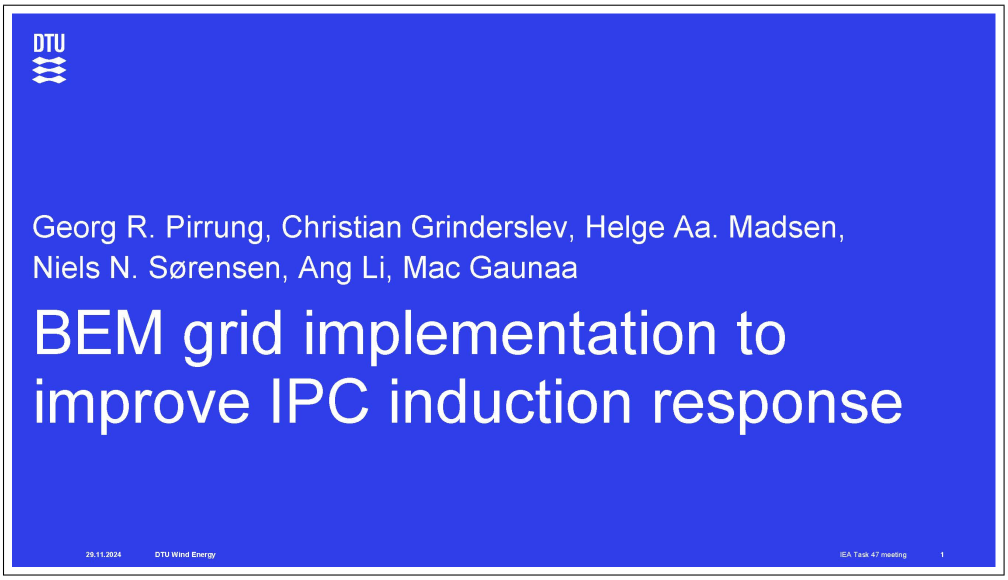
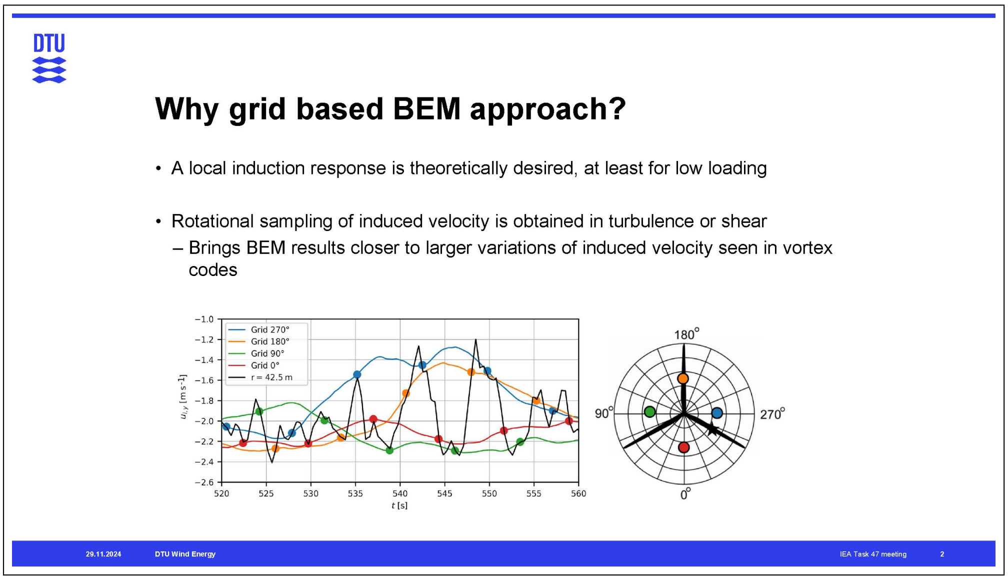
Matematica
Management
Thank you for your attention!
S. CHERUBINI
21

6.2 BEM grid implementation to improve IPC induction response - Georg Pirrung et al., DTU



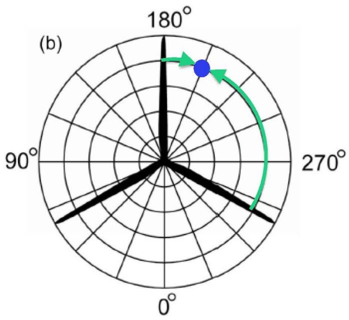


DTU

Original BEM approach

1) Compute induced velocity on grid points
   – Interpolate between 2 CT values
     • Using **local** wind speed
     • Using rotated **orientation and relative velocity of 2 closest blades**
   – Compute a=f(CT)

2) Apply dynamic stall at blade sections to compute blade forces



DTU

Some pros and cons of original grid BEM

• Shear cases generally computed very well
   – But induction not fully local with respect to aerodynamic forces – unsteady airfoil aerodynamics not coupled to induction computation

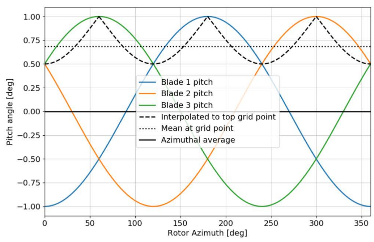
• Dynamic inflow acting on each grid point => dynamic inflow modelling only active in time-varying inflow, not in constant shear

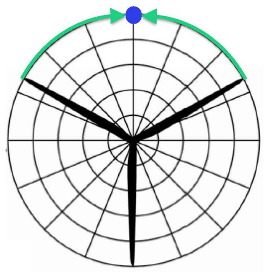
• Not optimal to account for blade orientation variations due to
   – azimuth-varying torsion (gravity)
   – pitch (cyclic/individual pitch control)

DTU

Some pros and cons of original grid BEM

• Example: Sinusoidal pitching, 1 degree amplitude
   – Pitch of a blade pointing up is always 1
   – Average pitch interpolated to point is only 0.68

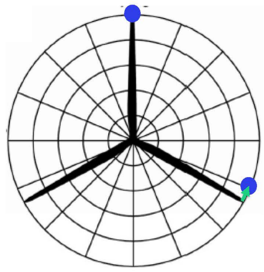




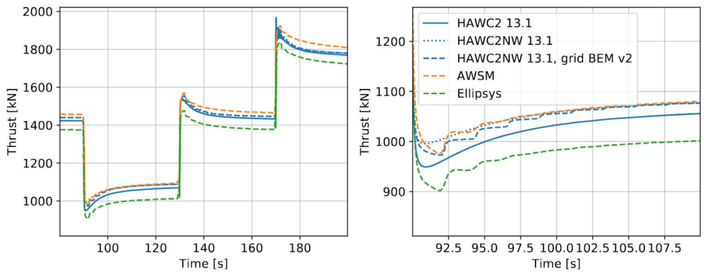
Proposed new approach (to be used with NW!)

Swap order of computation of forces and computation of induced velocity

- 1) Compute force and CT, CQ on blade section based on local wind speed and induction
  - Including dynamic stall model
- 2) Compute induced velocity on grid
  - Find out if a new blade *b* has passed during the last time step – if so interpolate between time steps
  - Apply dynamic inflow (on new or old quasi steady induced velocity)



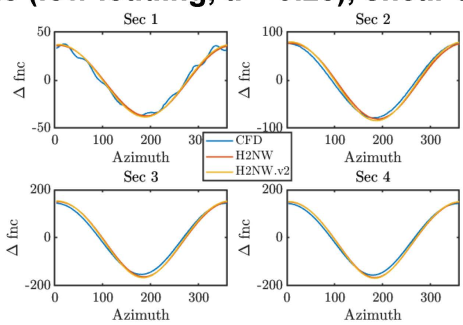
(not Task 47: AVATAR turbine pitch step case)



- In the original HAWC2 code, activating the NW model leads to reduced overshoots (also seen previously in many other cases)
- With the new BEM implementation, the staircase pattern shows up

=> Implementation works as intended

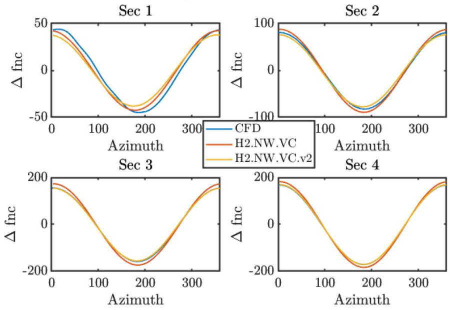
Case 1.5 (low loading, a ~ 0.25), shear exponent 0.35



- Generally excellent agreement with CFD
- The new BEM implementation matches the phases a tiny bit better
- Overall changes due to BEM implementation are very small

DTU

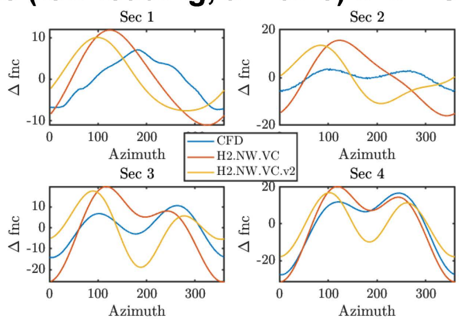
Case 1.5 (low loading, a ~ 0.25) IPC (1.25 deg amp)



- Excellent agreement as well
- The new BEM implementation matches the amplitudes and phases better (except most inboard)
- The hypothesis that the original implementation predicted too small induction amplitude is confirmed

DTU

Case 1.5 (low loading, a ~ 0.25) IPC + shear



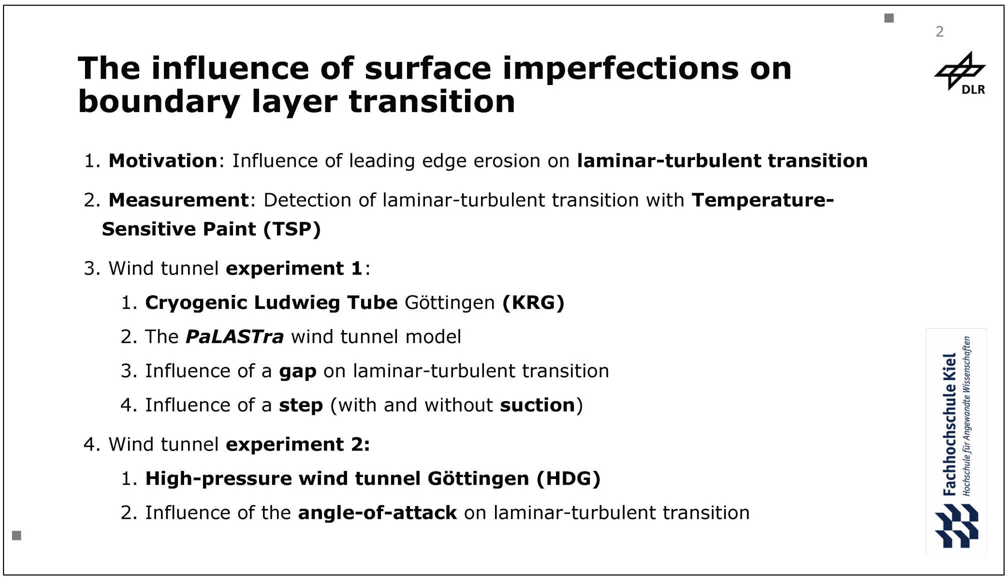
- All codes predict that the IPC almost perfectly counteracts the shear
- Remaining variations are only a few % of mean load
- No clear improvement from new BEM implementation can be seen for combined case

DTU

Conclusions

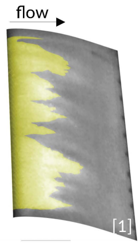
- New BEM implementation seems to work as intended
  – Needs to be used with the near wake model to provide fast induction response
- Differences to the previous implementation are expected for azimuth-dependent pitch or torsion
- More development and testing is needed
- Generally better agreement on the IPC cases than on the shear cases
  – The same was found to be true in the bigger comparison rounds in the task

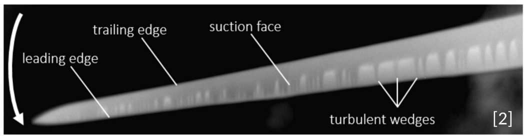
6.3 The influence of surface imperfections on boundary layer transition - Steffen Risius et al., University of Applied Sciences, FH Kiel



Influence of leading edge erosion on laminar-turbulent boundary-layer transition

- **Leading edge erosion** and **contamination** has become an important issue for wind industry, especially **offshore**
- **Surface imperfections** lead to **earlier laminar-turbulent transition** of the boundary layer
- Earlier laminar-turbulent transition **reduces the aerodynamic performance** of the rotor blades





[1] Reichstein, T., Schaffarczyk, A.P., Dollinger, C., Balaresque, N., Schülein, E., Jauch, C., & Fischer, A. (2019). Investigation of Laminar–Turbulent Transition on a Rotating Wind-Turbine Blade of Multimegawatt Class with Thermography and Microphone Array. Energies.

[2] Traphan, D., Meinlschmidt, P., Schlüter, F., Lutz, O., Peinke, J., & Gülker, G. (2015). High-speed measurements of different laminar-turbulent transition phenomena on rotor blades by means of infrared thermography and stereoscopic PIV.

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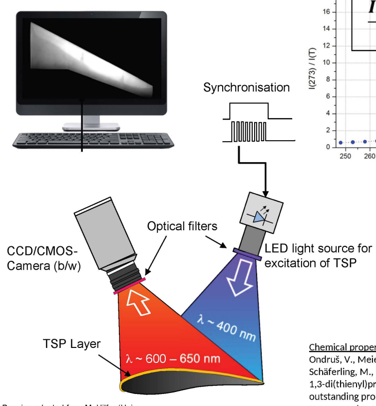
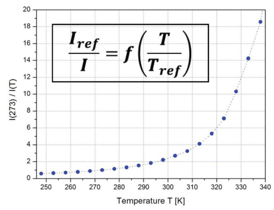
Detection of laminar-turbulent transition: Temperature-Sensitive Paint (TSP)

- **Non-invasive** method for **temperature** measurement on surfaces
- **Excitation** of TSP with light of **short-wavelengths** (UV)
- **Emitted light** (fluorescence) with longer wave length is **temperature dependent**
- Calibration curve: **relative inverse intensity** of the luminescence is plotted as a **function of temperature**



Drawing adapted from M. Hilfer (Univ. Braunschweig) and U. Fey (DLR)



Chemical properties of the TSP:
Ondruš, V., Meier, R.J., Klein, C., Henne, U., Schäferling, M., & Beifuss, U. (2015). Europium 1,3-di(thienyl)propane-1,3-diones with outstanding properties for temperature sensing. Sensors and Actuators A-physical, 233, 434-441.

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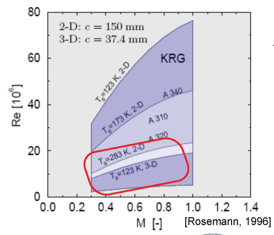
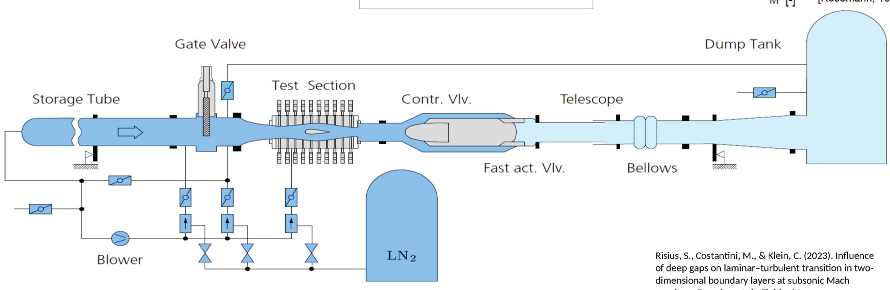
Cryogenic Ludwieg Tube Göttingen (KRG)

- **Independent variation of**:
  - **Reynolds** number
  - **Mach** number
  - **Pressure gradient**

➡ Investigation of their **influence on laminar-turbulent transition**





Risius, S., Costantini, M., & Klein, C. (2023). Influence of deep gaps on laminar–turbulent transition in two-dimensional boundary layers at subsonic Mach numbers. Experiments in Fluids, 64.

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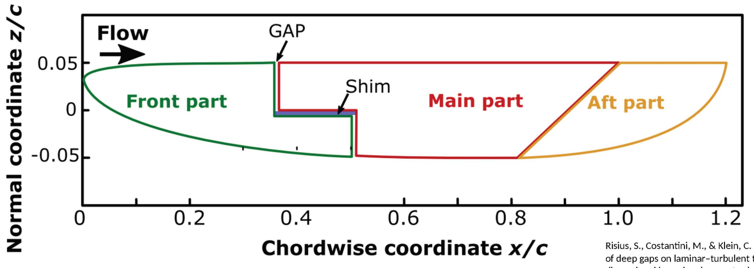
6

Measurement inside KRG: 2D wind tunnel model (*PaLASTra*)

- Original **flat-plate configuration** (*c* = 200 mm) with an **additional aft part** to reduce separation-induced pressure fluctuations
- **2D gaps** and **steps** (spanwise-invariant) can be installed at ***x/c* = 35%**
- Design appropriate for **sharp (rectangular) gaps** (with depth *d* = 9 mm)



Risius, S., Costantini, M., & Klein, C. (2023). Influence of deep gaps on laminar-turbulent transition in two-dimensional boundary layers at subsonic Mach numbers. Experiments in Fluids, 64.

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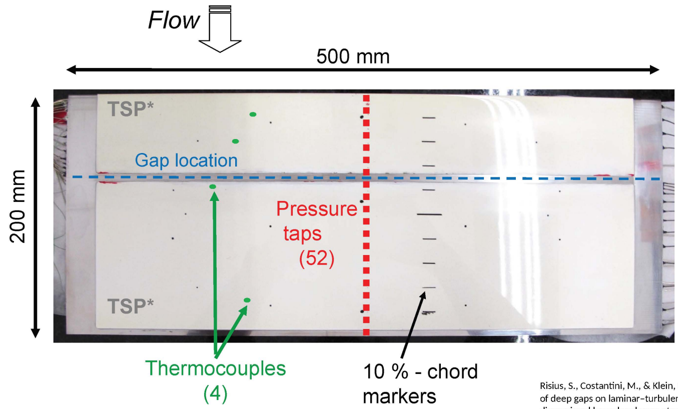
7

Test model and instrumentation of 2D wind tunnel model (*PaLASTra*)



Risius, S., Costantini, M., & Klein, C. (2023). Influence of deep gaps on laminar-turbulent transition in two-dimensional boundary layers at subsonic Mach numbers. Experiments in Fluids, 64.

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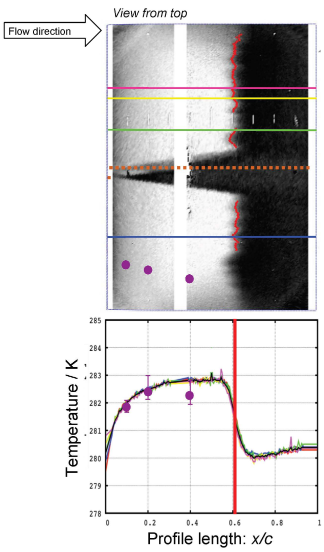
8

Temperature and transition measurement

- **Pressure taps** in the center of the model
- **TSP temperature distribution** comparable with **measurement by thermocouples**
- **Maximum temperature gradient** is the location of laminar-turbulent transition
- Exact determination of **temperature and transition locations** allows systematic investigation of **aerodynamic effects**



Risius, S., Costantini, M., Koch, S., Hein, S., & Klein, C. (2018). Unit Reynolds number, Mach number and pressure gradient effects on laminar–turbulent transition in two-dimensional boundary layers. Experiments in Fluids, 59, 1-29.

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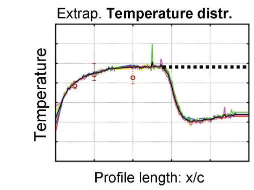
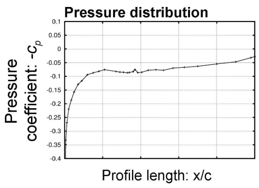
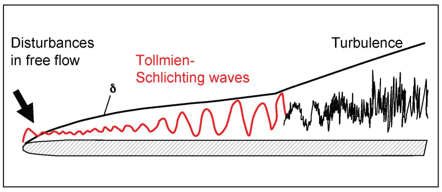
9

Boundary layer calculation and linear stability theory

Starting parameters







Calculation of laminar boundary layer and Tollmien-Schlichting (T-S) waves with:

- **Boundary layer solver** *(Software: COCO)*
- Linear local **stability calculation** *(Software: LILO)*

Calculation of:

1. Boundary layer thickness (δ) and **shape factors (H_{12})**
2. Frequency and **amplitudes** of Tollmien-Schlichting (T-S) waves: ***N*-factor distribution**

Risius, S., Costantini, M., Koch, S., Hein, S., & Klein, C. (2018). Unit Reynolds number, Mach number and pressure gradient effects on laminar–turbulent transition in two-dimensional boundary layers. Experiments in Fluids, 59, 1-29.

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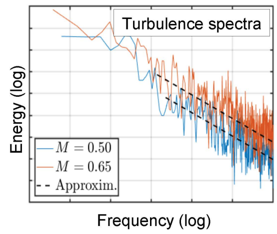
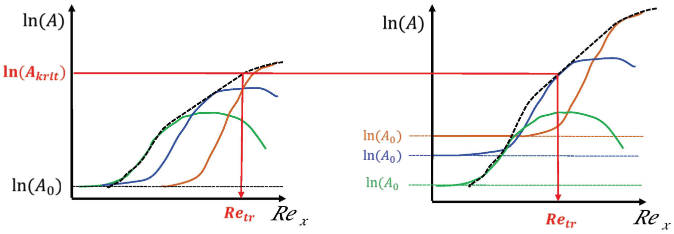
10

Frequency dependent correction of the starting amplitude

- **Energy of the total pressure fluctuations** decreases with increasing frequency
- **Starting amplitude** of the T-S wave decreases with increasing frequency
- Starting amplitudes have to be **corrected depending on their frequency** to improve transition predictions





Risius, S., Costantini, M., Koch, S., Hein, S., & Klein, C. (2018). Unit Reynolds number, Mach number and pressure gradient effects on laminar–turbulent transition in two-dimensional boundary layers. Experiments in Fluids, 59, 1-29.

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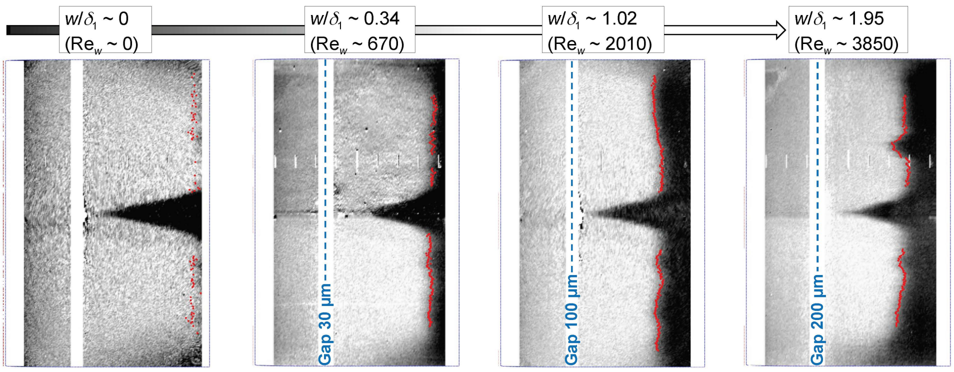
11

Influence of GAP: $M = 0.35$, $Re_1 = 17.5 \times 10^6\ m^{-1}$, $H_{12} = 2.6$



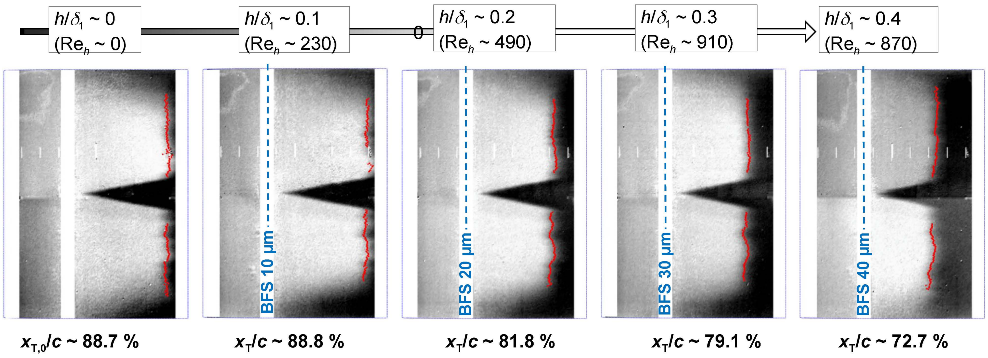
$x_{T,0}/c \sim 92\ \%$ | $x_T/c \sim 87\ \%$ | $x_T/c \sim 77\ \%$ | $x_T/c \sim 77\ \%$

- **Flow direction** is from the **left to right**
- **Transition location** marked by the **red dots**

Risius, S., Costantini, M., & Klein, C. (2023). Influence of deep gaps on laminar–turbulent transition in two-dimensional boundary layers at subsonic Mach numbers. Experiments in Fluids, 64.

12

Influence of a backward-facing step (BFS): M = 0.50, Re_1 = 22.5 × 10⁶ m⁻¹, H_{12} = 2.58



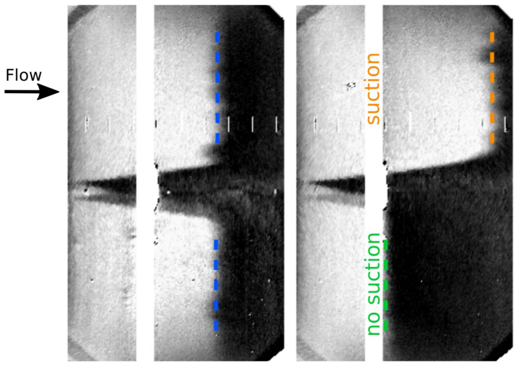
- **Flow direction** is from the **left to right**
- **Transition location** marked by the **red dots**

Risius, S., Costantini, M.:. Influence of backwards facing steps on laminar–turbulent transition in two-dimensional boundary layers at subsonic Mach numbers. (Under Review 2024)

13

Surface imperfections and suction of the boundary layer

- Investigation of a **2D step**
- Surface imperfections **reduce the laminar flow-length** (bottom)
- The influence of surface imperfections can be **compensated by suction of the boundary layer** (top)



(a) smooth ($Re_h \sim 0$)   (b) step-2 ($Re_h \sim 2400$)

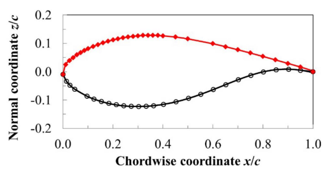
Dimond, B., Costantini, M., Risius, S., Fuchs, C., Klein, C.: "*Experimental analysis of suction on step-induced boundary-layer transition.*" Experimental Thermal and Fluid Science, vol 109 (109842), 2019

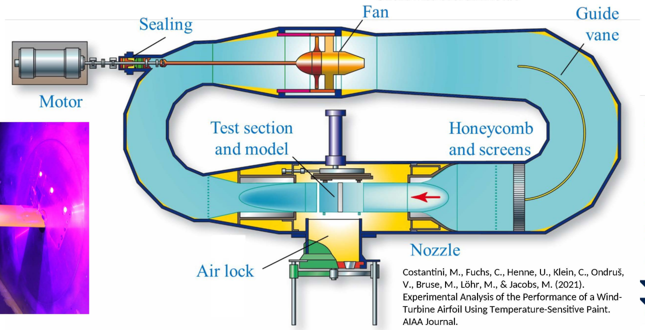
14

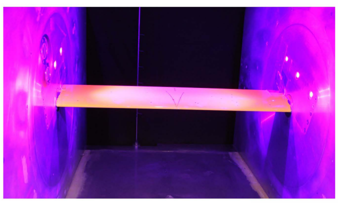
High-Pressure Wind Tunnel Göttingen (HDG): *DU 91-W2-250* airfoil

Examined test conditions
- p_0 = 4.6 to 7.0 MPa
- Re = 3 to 12 · 10⁶
- -14° ≤ AoA ≤ 20°

HDG test envelope
- p_0: up to 10 MPa
- U_∞: up to 35 m/s
- Re: up to 20 · 10⁶







Costantini, M., Fuchs, C., Henne, U., Klein, C., Ondruš, V., Bruse, M., Löhr, M., & Jacobs, M. (2021). Experimental Analysis of the Performance of a Wind-Turbine Airfoil Using Temperature-Sensitive Paint. AIAA Journal.

Effect of the angle-of-attack (AoA)
TSP results (suction side) at Re = $3 \cdot 10^6$

M. Costantini, U. Henne, C. Klein, M. Bruse, Boundary-Layer Evolution over the Lower Surface of a Wind-Turbine Airfoil, AIAA Journal, 2024, in press.

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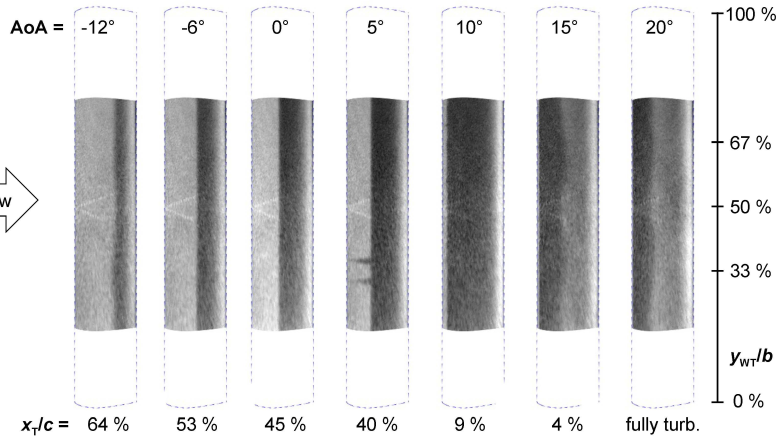

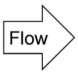

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Outlook and thank you!

DLR

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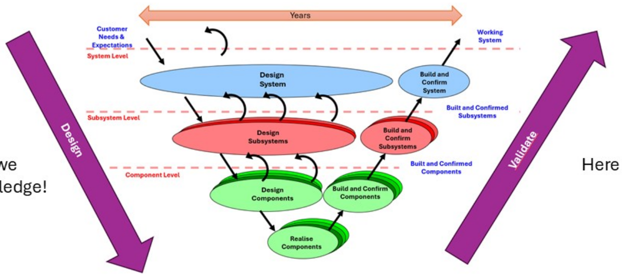
7 Presentations from industry: present and future research needs

7.1 Input on the Need for Research in Denmark - Erik Miranda and Torben Juul Larsen , Vestas

Handle risk early

Here is where we need the knowledge!



Here is where we get it...

- Any risk comes with a high penalty if issues are discovered late in the process
- Possible mitigations and workaround of potential issues are important to have as reserve option.
- Sometimes solutions of one issue causes other unforeseen issues. Avoid: *Unexpected emergent behaviour on a system level*
- Late in the process only the controller is a usable handle

| 22 April 2025

Vestas

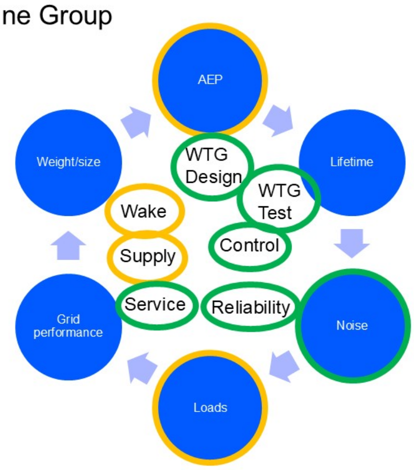
Priorities from DAFREs Wind Turbine Group

First priorities:

- Noise
- Design for O&M and reliability design tools
- Testing and model validation

Second priorities:

- Instabilities
- Wind Farm performance
- Supply chain scalability

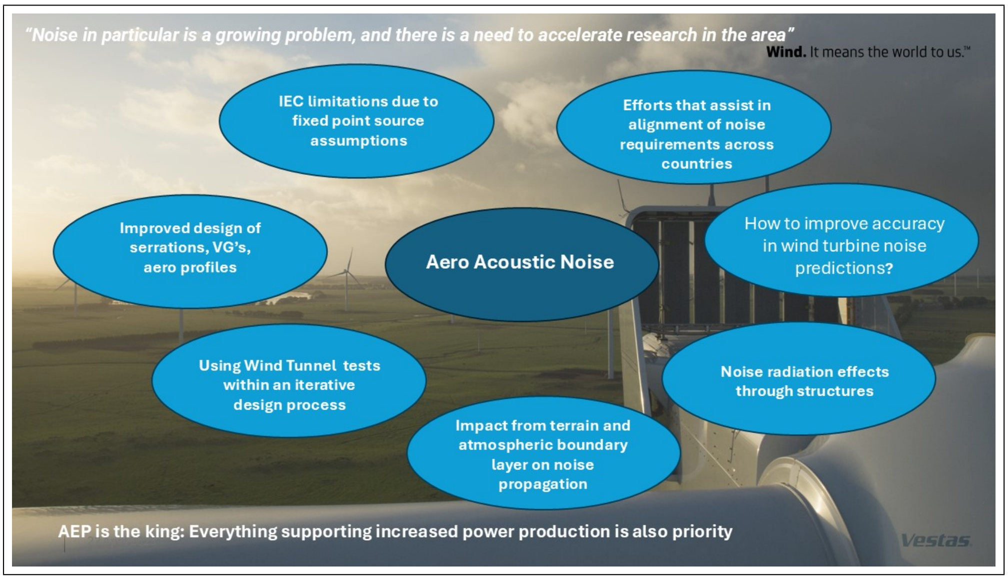


22 April 2025

4 |

Classification: Confidential

Vestas



Aeroelastic stability/vibrations

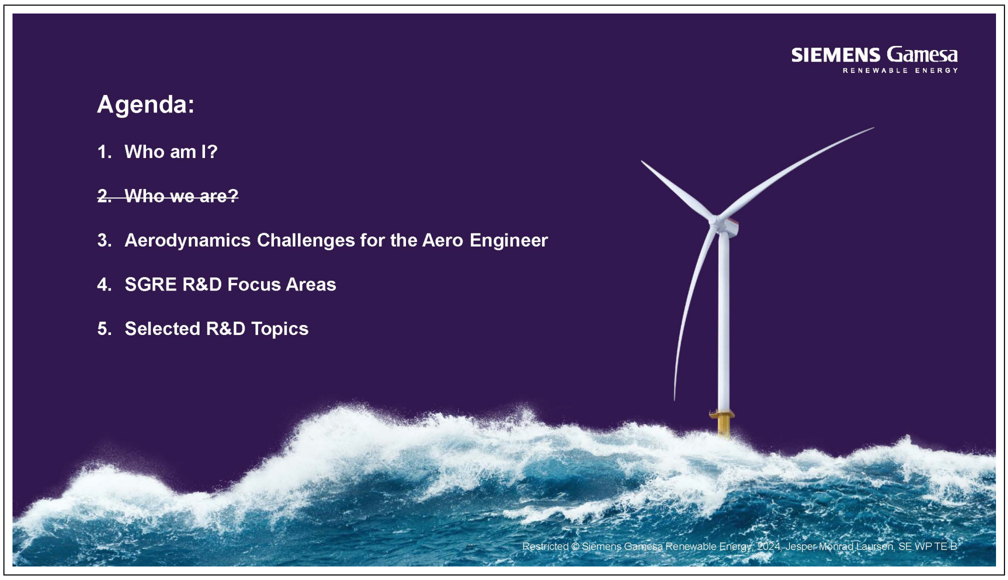
We want to be able to calculate instability in standstill as well as in operation and make physical design changes to the turbine or changes in the operational strategy, so that we can mitigate the problem with a high degree of certainty *already in the early design phase long before prototype testing.*

- Vortex Induced Vibration (VIV): Understand the physics and build the foundation for accurate and fast engineering tools that can predict the phenomenon primarily for turbines at standstill
- Aeroelastic stability tools able to map the real risk of classic stall induced vibrations (especially during standstill/service combined with high wind speeds)
- Operational conditions including effects of controller and non-isotropic inflow conditions (eg high yaw error).
- Furthermore, stability on non-standard designs are also important. Eg cable-stayed towers, cable stayed rotors, multi-rotors etc.

22 April 2025

6 | Classification: Confidential Vestas

7.2 Present and Future Research Needs - Jesper Laursen, SGRE



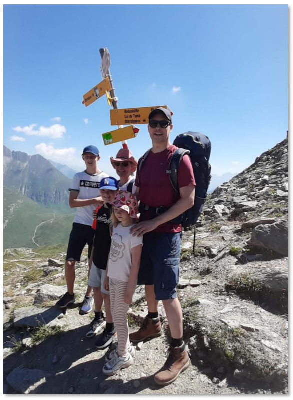
Who am I?

SIEMENS Gamesa RENEWABLE ENERGY

Personal Details:
Name: Jesper Monrad Laursen
Age: 49 years old
Married with 3 kids (10, 13 and 16 years old)
Hobbies: Likes doing family stuff, dining, running, mountain biking, paddle tennis, fitness training, hiking (with dog), listen to music

Professional Career:
M.Sc. And Ph.D. in Civil Engineering from Aalborg University

Joined Siemens Wind Power in 2005
- Started as CFD specialist/expert, implementing CFD tools for airfoils, blades, siting
- Worked on several design projects (applied CFD). Designed first flatback airfoils, etc.
- Became teamlead for aerodynamics/rotor performance
- Started Module Chief Engineer (2013 – today)
- Today's focus broader than core aerodynamics
  - Conceptual design
  - Aerodynamic design
  - Technology development



 3

Aerodynamics in Industri

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Performance:
Single turbine Cp
Farm AEP

Loads:
Aerodynamic loads (directly)
Gravitational loads (indirectly)

How can aerodynamics impact our products?

Cost:
Blade mass
Manufacturability

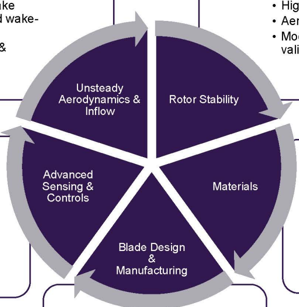
Stability:
Flutter
Vortex induced vibrations
Stall induced vibrations

Robustness:
Predictability
Deliver as promised

SGRE R&D Focus Areas

- Background polars
- Dynamic stall
- Atmosphere-wake interactions and wake-dynamics
- Modeling tools & validation
- Real-life conditions

- Standstill vibrations
- Operational resonance
- High-speed flutter
- Aeroelastic damping
- Modeling tools & validation



- Monitoring of aerodynamics state and loads
- New sensors (lidar, wakes, wind environment)
- New control devices (active aero), robust operation
- Wake-control
- Floating
- Machine learning farm data

- Efficient geometry, enabling lightweight blade structure (building height, low loads planform, etc.)

- Advanced design and validation methods
- Design for Manufacturing:
  - Drapability of beams based on pultrusions
  - Geometry that doesn't induce stress hotspots, wrinkles in laminates, etc.

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Unsteady Aerodynamics & Inflow

Unsteady Aerodynamics & Inflow

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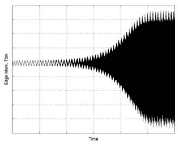
Aerodynamics in high-speed flutter events

Rationale: Although there are no known issues in fleet with rotors experiencing flutter, we acknowledge that current models are far from perfect

Experiments:
- Full-scale turbine campaign to measure CL and CD dynamic behavior at selected spanwise positions during high-rpm flutter events => insight into what rotor modes are exited and the nature of underlying aerodynamics

Modelling:
- What is the appropriate dynamic stall-model?
- What can be learned from advanced FSI?



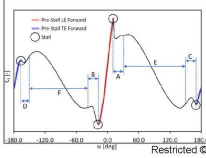
Thick Airfoil Experiment in Deep-Stall

Rationale: Deep-stall aerodynamics of thick airfoils impacts loads and stability of large-scale modern wind turbines

Experiments:
- Conventional approach: "Small-scale" wind tunnel for conducting deep-stall experiments on thick airfoils (forward and reverse flows)
- Unconventional approach: Large chord WT test facility or field test? Or other ideas?

Outcome: Improved background polars for more accurate loads and stability modelling

Modelling opportunity:
- Leverage data to improve CFD computational methodology



The 'red' part of the curve illustrates typical operational AoA range, whereas this proposal addresses deep-stall regions

Computational Aerodynamics of Large Offshore Blades in Deep Stall

Rationale: Large offshore blades can be driven by standstill and idling loads

Modelling:
- Develop 3D virtual wind tunnel for wind turbine blade modeling at 360 deg. inflow angles => extract airfoil coefficient from simulations
  - Meshing, turbulence modelling, solver setup, convergence criteria, etc.
- Both SGRE blades and open-source blade geometries could be included

Outcome:
- Improved 360 deg. background polars for aeroelastic simulations
- Contribute to more accurate modelling in "off-design" load cases

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Unsteady Aerodynamics & Inflow

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High Re Number Experiments & Validation

Rationale: Current high Re data is insufficient:
- WT capability fall severely short of full-scale wind turbines
- Limited "thick" airfoil data
- VG's, LEP or other add-ons rarely included

High Re number flow with nonlinear effects:
- BL thinning due to high flow speeds
- BL thickening from transition dynamics

Experiments:
- Define most "optimal" test facility (does it exist, or can it be built?)
- Design test models and specify instrumentation
  - Measure surface pressures and wake momentum
  - Measure BL structure and turbulence state

Outcome:
- Improved accuracy of loads calculations from aero-elastic tools on large-scale wind turbines
- Improved accuracy of performance predictions of large-scale wind turbines

Floating Turbine Wake Modelling and Validation

Rationale:
- Wind turbine wakes in wind farms interact with downstream turbines, generating additional load
- Floating wind turbines comes with additional complexity due to increased static tilt and larger oscillatory motion of entire system

Modeling:
- Improve current low- (e.g. FLORIS) and mid fidelity (e.g. DWM) floating wind turbine wake models

Validation:
- Validate wake model with high fidelity CFD
- Validate wake models with tests on wind farms


Hywind Scotland, Equinor


The TetraSpar Demonstrator Project ApS.

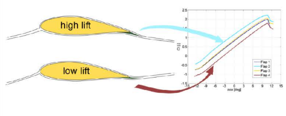
Active Blade Add-ons Demonstration

Rationale:
- Active add-ons can be used to modify rotor performance
- Active add-ons can be enable larger rotors by loads alleviation

Experiments:
- Testing technology on wind farm in agreement with wind farm operator

Modelling
- Further comparison and tuning of misc. fidelity models (aero-elastic tools, CFD)

Outcome:
- Demonstration of capabilities
- Reduce risk on full value chain



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Rotor Stability

Rotor Stability

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Aerodynamics for Stand-still Vibrations

Rationale:

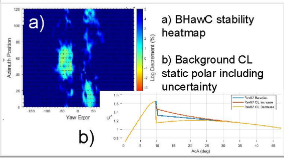
- Many remaining uncertainties in e.g. aero-elastic models
- Small variations in aerodynamic model input can change conclusions relating to rotor stability

Experiments:

- 360 degree polar validation
- Full-scale rotor campaigns in locked and yawed conditions

Modelling:

- Uncertainty analysis of aerodynamic inputs on rotor stability
- Determine appropriate aerodynamic input to various sub models



a) BHawC stability heatmap

b) Background CL static polar including uncertainty

Idling Stability of Floating Wind Turbines

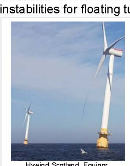
Rationale:

- Very little research focusing specifically on floating wind turbines has been conducted, especially in idling conditions

Modeling:

- Use/further develop a "heat-map" methodology to perform fleet studies and identify stability zones by various parameters
  - Turbine idling state
  - Wind- and wave conditions
  - Water depth

Outcome: Understand- and reduce risk of rotor instabilities for floating turbines



Hywind Scotland, Equinor

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Miscellaneous Topics

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Miscellaneous Topics

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Hurricane Wind Condition Modelling

Rationale:
- Current IEC definition for T-class is very simple:
  - Higher Vref for 1yr and 5yr extremes
- Limited knowledge about wind conditions that wind turbines are experiencing during hurricane events
- Many new 'Hurricane' markets: USA, Japan, Taiwan, etc.

What to obtain:
- Better understanding of hurricane WC => may enable industry for better optimizing turbine, tower and foundation

How to obtain knowledge???
- Measurements in hurricane/extreme wind conditions?
- Modelling of hurricane/extreme wind conditions?

Wake Control, Modelling and Validation

Rationale:
- The effect of environmental conditions like e.g. wind shear, veer, ambient turbulence, etc. on wake characteristic is still connected with some uncertainty

Modeling:
- Validate wake models with high fidelity models (CFD)
- Develop surrogate wake models
- Develop models to assess farm wake impact on neighboring farms
- Develop wind farm control strategies

Experiments:
- Experiments on wind farms to validate wake models and control strategies

Outcome: With improved understanding of the wakes, better wind farm layout and operational strategies can be developed to improve wind farm performance and reliability

Aerodynamic Optimization

Rationale:
- Cost and manufacturability are some of the main drivers for blade design.
- The challenge is how to design blades that are lower cost (less material) and easier to manufacture, while maintaining current performance levels?
  - How to enable high performing blade sections in areas where geometry is constrained
  - How to enable robust design for high relative thickness design that goes beyond the boundaries of today's best practice?
  - How to best utilize add-ons and local geometry optimization to improve performance in local areas of the blade?

Modelling:
- Optimization and detailed analysis with high-fidelity tools

Experiments:
- Testing of extreme designs => allowing to fail and know boundaries and limitations

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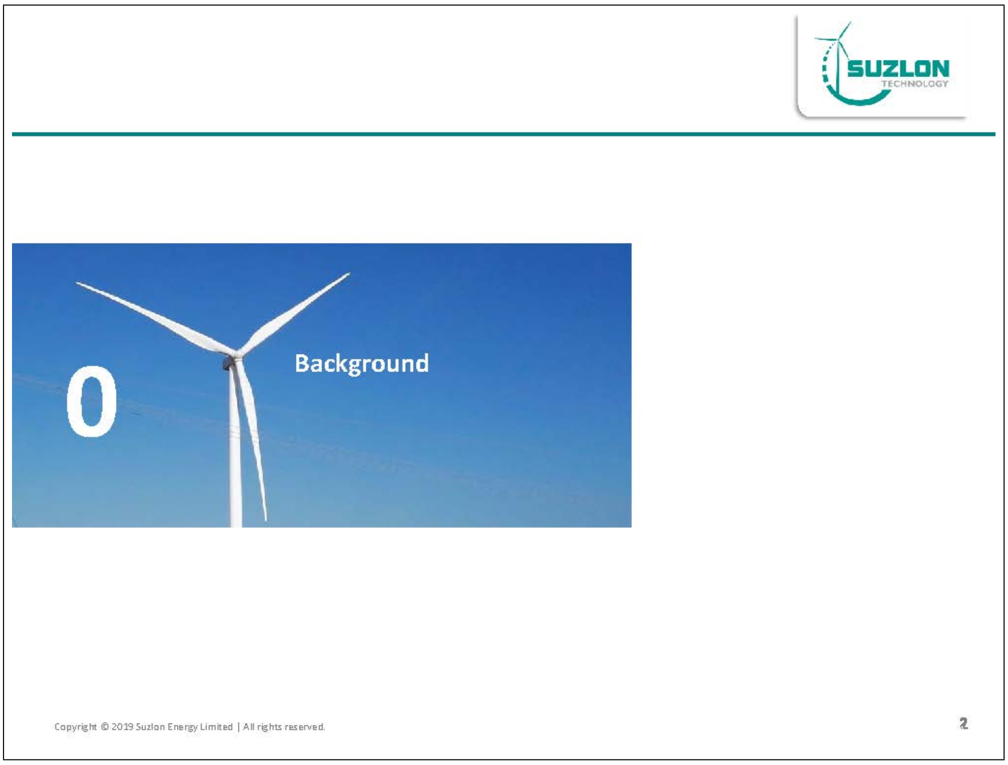
7.3 Hawc2 implementation in a Flex5 environment - Carlos Rodriguez , Suzlon



Background
Context and goals

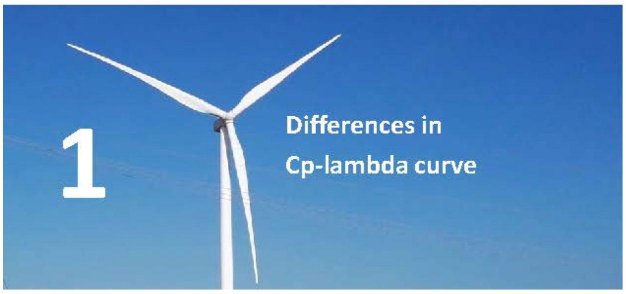
- Hawc2 should be implemented to capture torsional deflections more precisely
- Ultimate goal: fatigue loads calculated with Flex5 and HAWC2 within 5% tolerance

Background
Previous steps

To make this implementation run smoothly, first we needed to facilitate these three steps:

- Use of Flex5 original controller: implemented
- Use of Flex5 original wind files: implemented
- Use of Flex5 original postprocessing tools: implemented


Problems encountered
and
solutions implemented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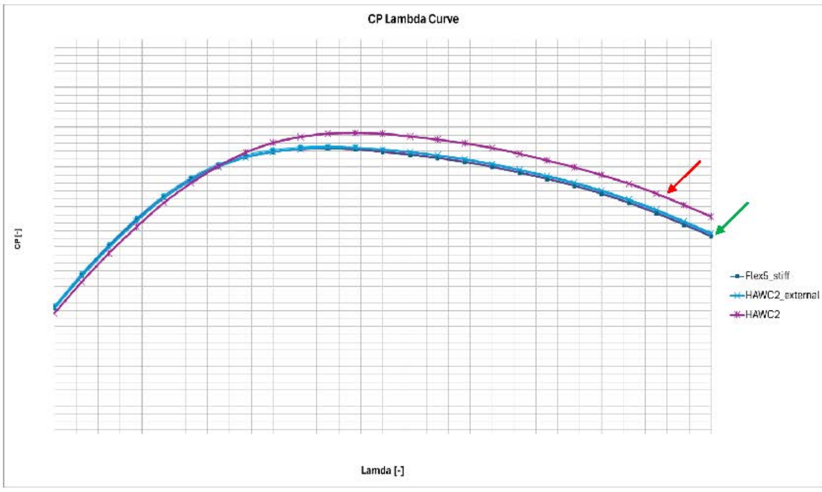
Differences in
Cp-lambda curve

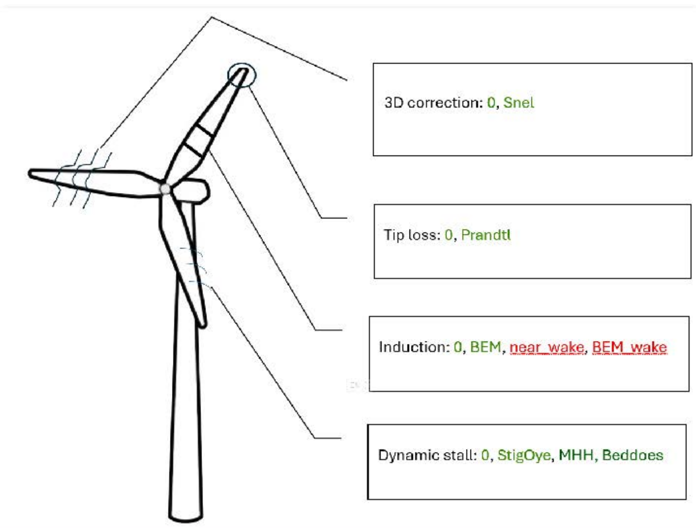
Differences in Cp-lambda curve



Hawc2 needed to be fed with an a-Ct look up table to override its induction model

7

Differences in Cp-lambda curve

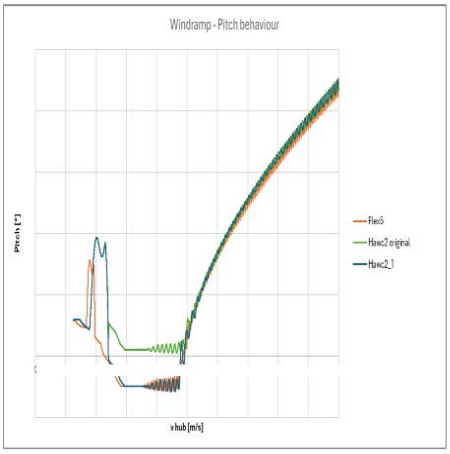


Aerodynamic models shared and Hawc2 exclusive

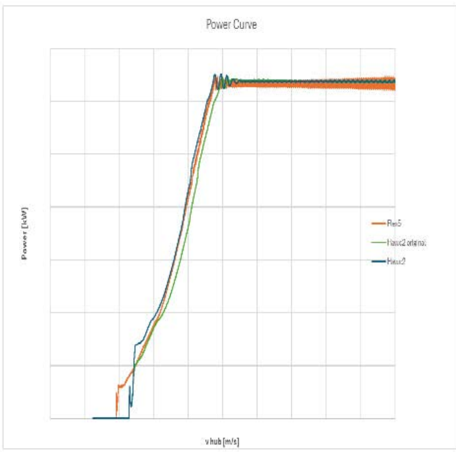
8

Differences in Wind ramp and Power curve

Windramp



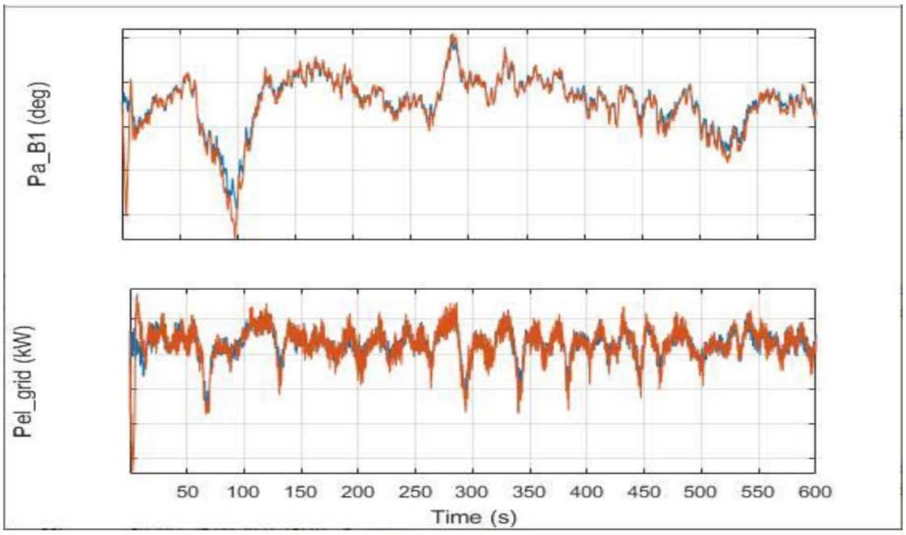
Power curve



After correcting some controller parameters, both curves match

11

Current status



Very good match overall for turbulent simulations

12

Current status

Fatigue loads comparison

Variant : k=2.0, Nref=1e6		Stiff blade	Soft blade
Sensor Name	Sensor Description	Comparison Hawc2/Flex5	Comparison Hawc2/Flex5
SKTbMy	Tower Bottom Fore-aft	[illegible]	[illegible]
SKTbMz	Tower Bottom Side-side	[illegible]	[illegible]
SKTbMx	Tower Bottom Torsion	[illegible]	[illegible]
SKTtMy	Tower Top Fore-aft	[illegible]	[illegible]
SKTtMz	Tower Top Side-side	[illegible]	[illegible]
SKTtMx	Tower Top Torsion	[illegible]	[illegible]
MYK2	Yaw bearing tilt	[illegible]	[illegible]
MZK2	Yaw bearing roll	[illegible]	[illegible]
MXK2	Yaw bearing yaw	[illegible]	[illegible]
MYR1	Main bearing rotating R1 tilt	[illegible]	[illegible]
MXR1	Main bearing rotating R1 yaw	[illegible]	[illegible]
MZR1	Main bearing rotating R1 roll	[illegible]	[illegible]
MYN	Main bearing standstill tilt	[illegible]	[illegible]
MXN	Main bearing standstill yaw	[illegible]	[illegible]
MZN	Main bearing standstill roll	[illegible]	[illegible]
MYR2	Hub rotating yaw/tilt 2	[illegible]	[illegible]
MXR2	Hub rotating yaw/tilt 1	[illegible]	[illegible]
MZR2	Hub rotating yaw torque	[illegible]	[illegible]
MYN2	Hub standstill yaw/tilt 2	[illegible]	[illegible]
MXN2	Hub standstill yaw/tilt 1	[illegible]	[illegible]
MZN2	Hub standstill yaw torque	[illegible]	[illegible]
MYF1	Flap moment flange 1	[illegible]	[illegible]
MZF1	Edge moment flange 1	[illegible]	[illegible]
MXF1	Pitch moment flange 1	[illegible]	[illegible]

< ± 5%
> ± 5%

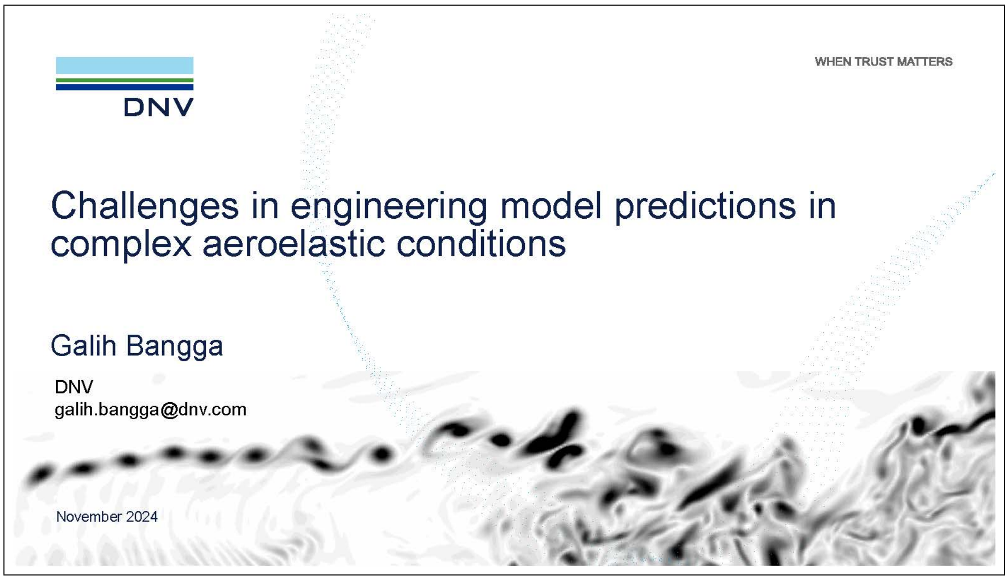
 13

High winds

Q&A

 14

7.4 Challenges in engineering model predictions in complex aeroelastic conditions - Galih Bangga, DNV



Challenges we all are aware of

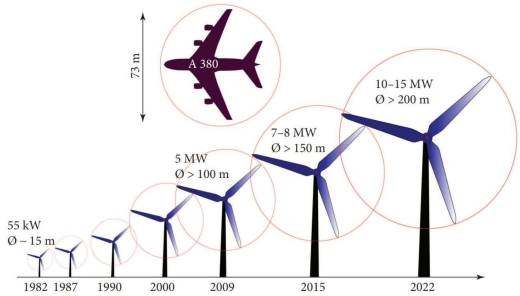
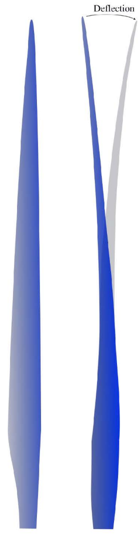
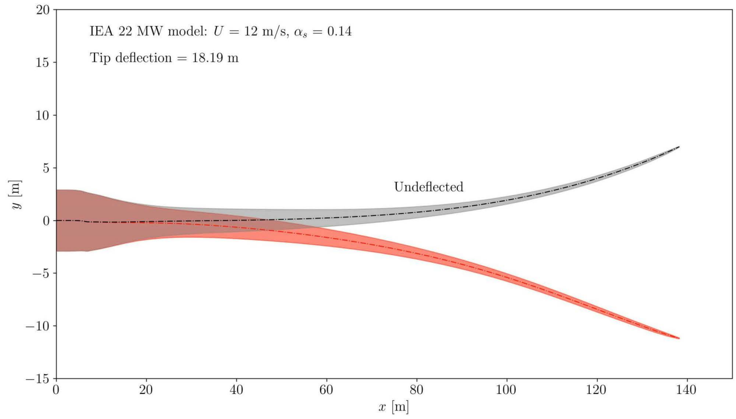


FIG. 1.5
Wind turbine growth over the time.

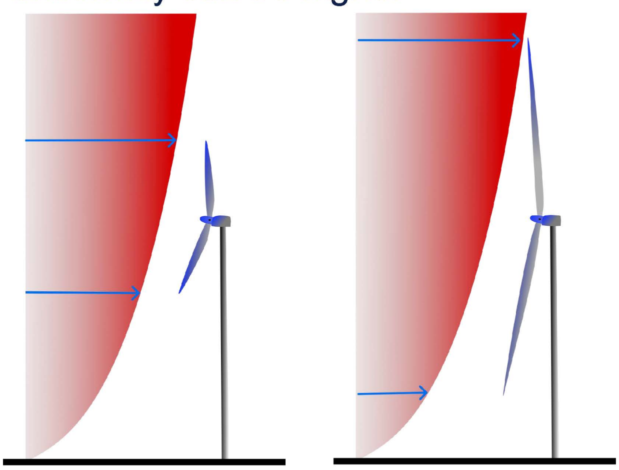
Bangga, Wind Turbine Aerodynamics Modeling Using CFD Approaches, 2022, https://doi.org/10.1063/9780735424111



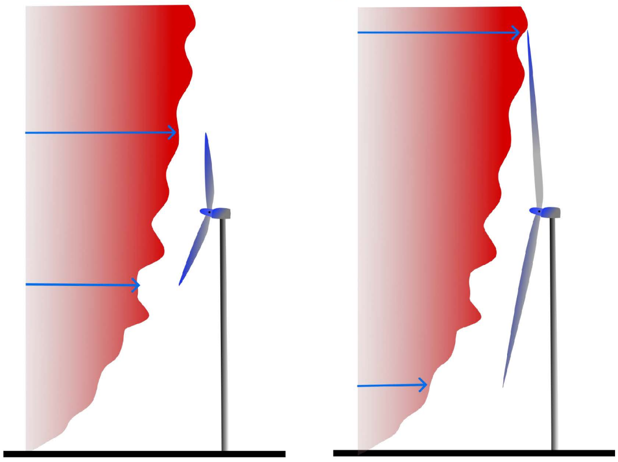
Challenges we all are aware of



Flow non-uniformity can be higher

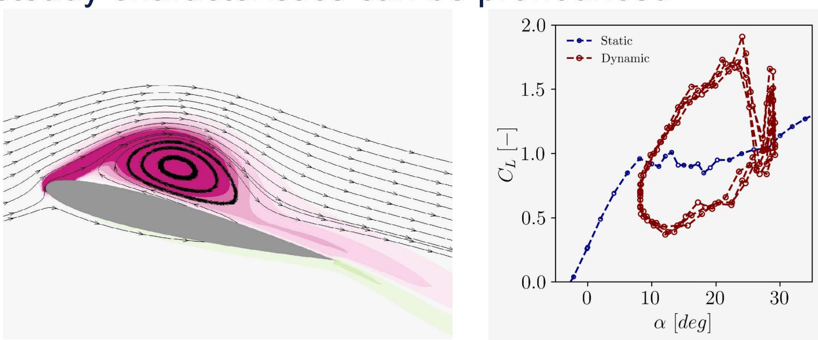


Flow non-uniformity can be higher



DNV

Unsteady characteristics can be pronounced

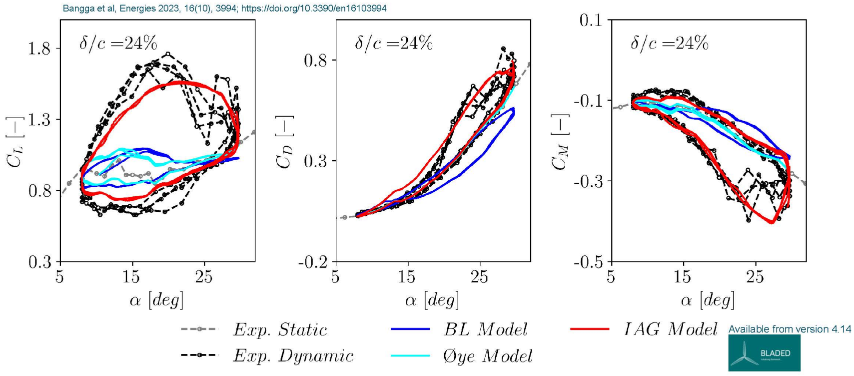


Standstill conditions are connected to uncertainty in *aerodynamic damping* since the blade section undergoes dynamic stall

DNV

Accurate dynamic stall predictions become important

Bangga et al, Energies 2023, 16(10), 3994; https://doi.org/10.3390/en16103994



Available from version 4.14

BLADED

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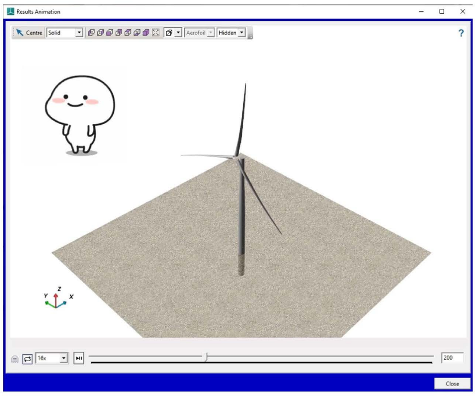
Potential stand-still instability increases

a dancing wind turbine



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Vortex wake approach

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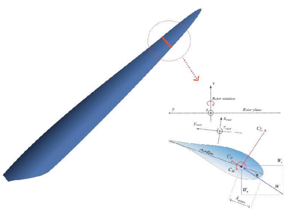
Vortex wake approach

Blade Element Theory

Momentum Theory

BEM



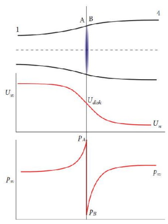


FIG. 3.1
Development of velocity and static pressure along the stream tube due to the presence of the actuator disk shown as blue colored area.

Bangga, AIP Publishing, 2022

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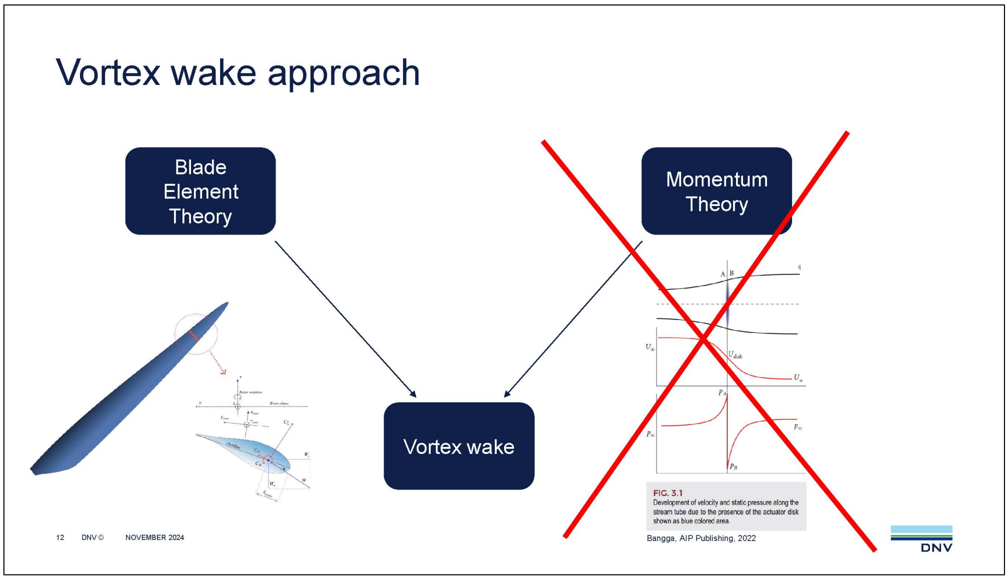
Vortex wake approach
Blade Element Theory
Momentum Theory
Vortex wake
FIG. 3.1
Development of velocity and static pressure along the stream tube due to the presence of the actuator disk shown as blue colored area.
Bangga, AIP Publishing, 2022
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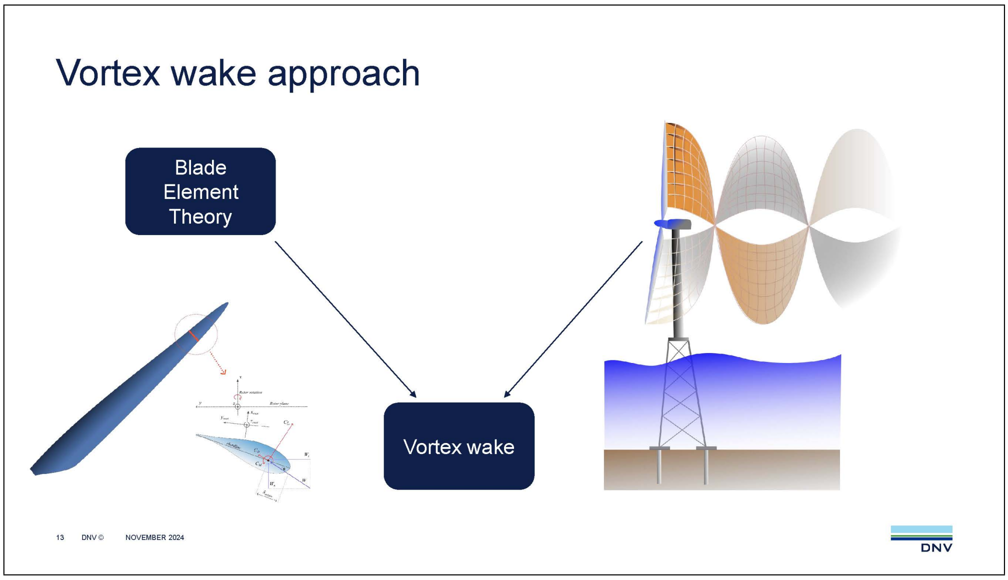
Vortex wake approach
Blade Element Theory
Vortex wake
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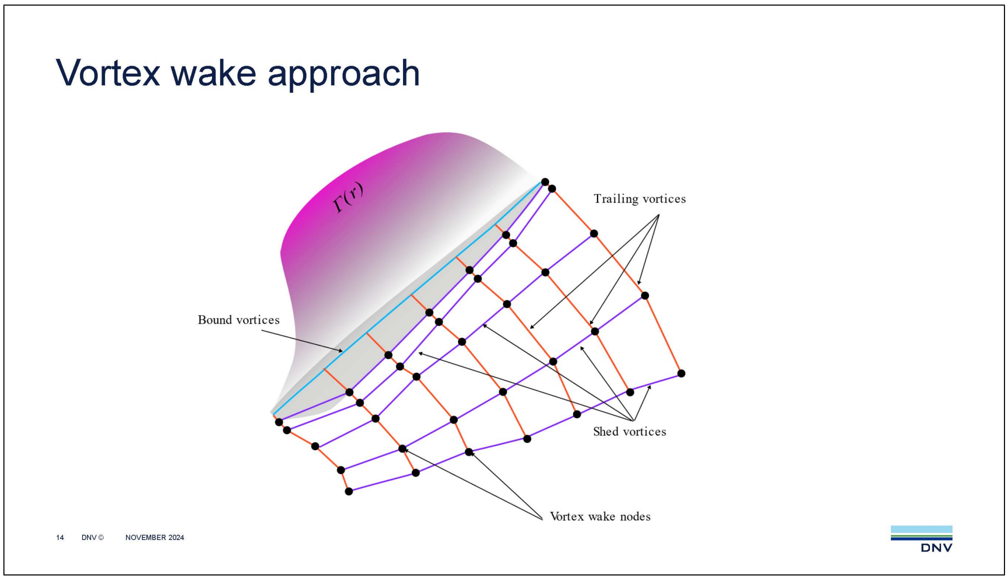
Vortex wake approach
Γ(r)
Trailing vortices
Bound vortices
Shed vortices
Vortex wake nodes
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Adopting vortex wake approach in wind turbine projects

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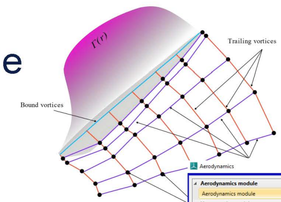
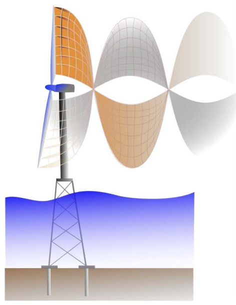
Bladed Vortex wake module

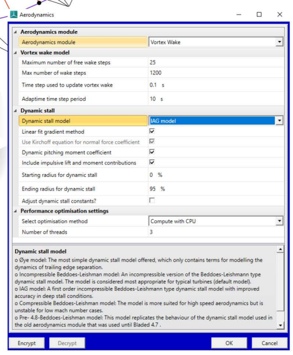


Soon to be officially released....

Vortex wake module

in Bladed 4.17





Powered by:

CPU and GPU parallelization

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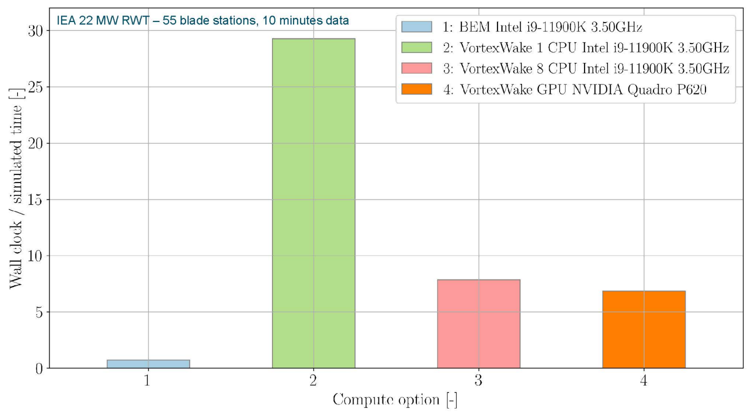
Computational effort of vortex wake



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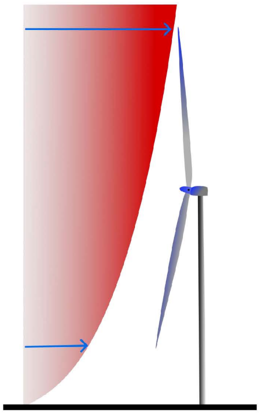
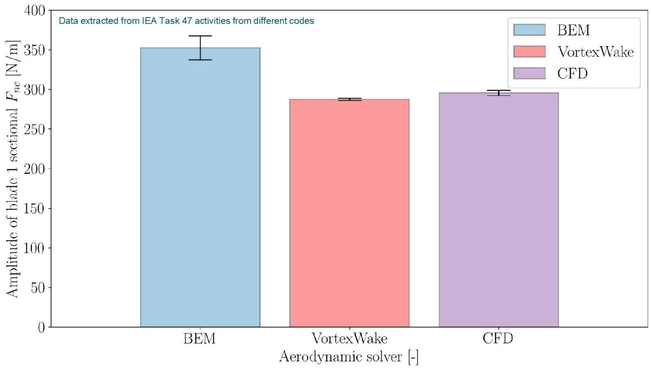
A constant wind shear over a turbine





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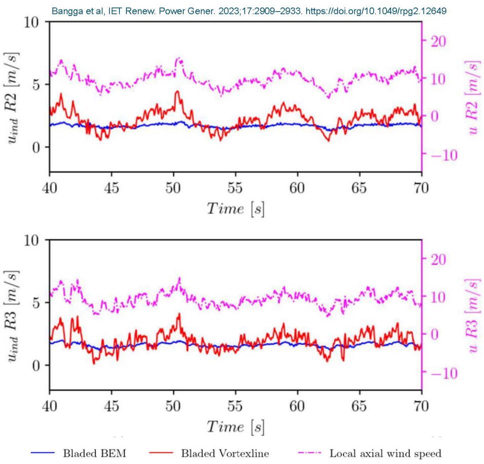
Induced velocity variations in turbulent flow

- Induced velocity response of different models are presented
- Vortex wake induced velocities follow the wind fluctuations well



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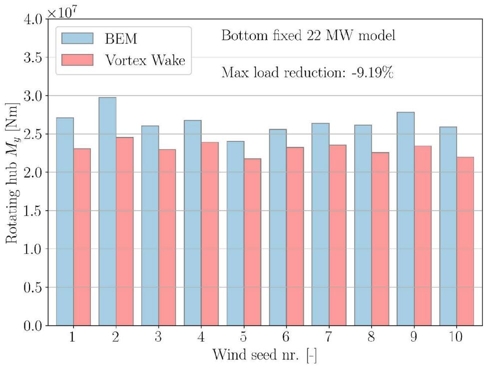
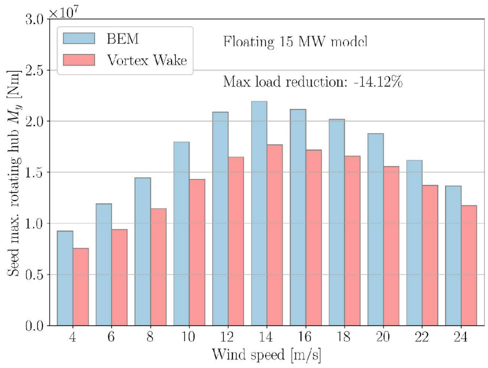
Fatigue loads on large wind turbines





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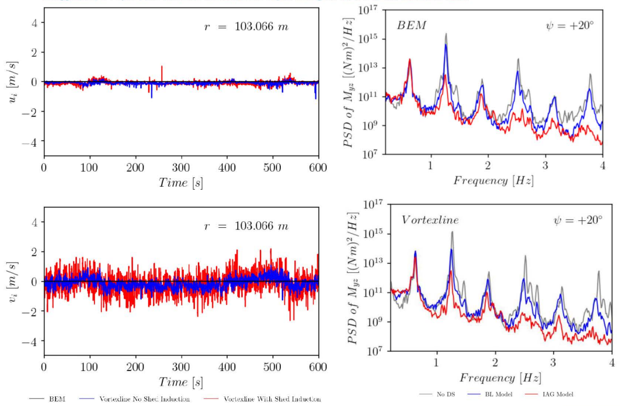
Wind turbine in extreme loads environment

- Tangential inductions are severely affected in idling for vortex wake predictions, while it is negligible for BEM
- Combining vortex wake approach and IAG dynamic stall generates lower loads amplitude in idling conditions

Bangga et al, J. Phys.: Conf. Ser. 2626 012026, 2023. https://doi.org/10.1088/1742-6596/2626/1/012026

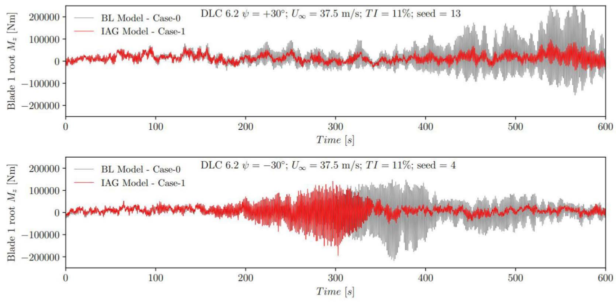


DNV

Wind turbine in extreme loads environment

- Tangential inductions are severely affected in idling for vortex wake predictions, while it is negligible for BEM
- Combining vortex wake approach and IAG dynamic stall generates lower loads amplitude in idling conditions
- Vibration characteristics are different under stall induced vibration case when using BL model against the IAG model

Bangga and Yu, J. Phys.: Conf. Ser. 2767 022007, 2024. https://doi.org/10.1088/1742-6596/2767/2/022007



DNV

Summary of the challenges and remarks

DNV

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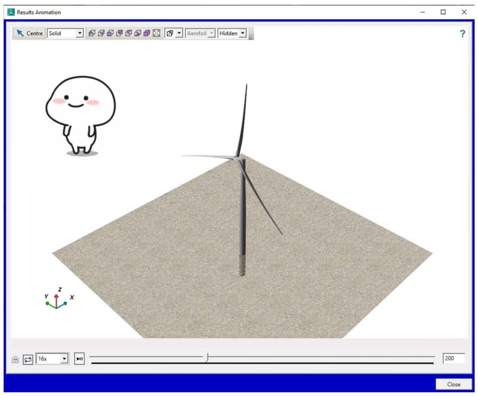
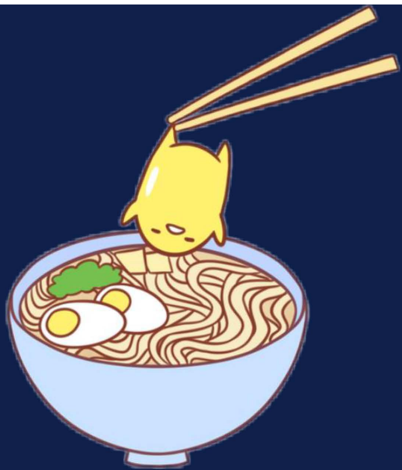
- Large wind turbine size poses real aerodynamic challenges
- Vortex wake approach provides a more realistic induction calculations and brings benefit in wind turbine design load cases
- Combining vortex wake approach and the IAG dynamic stall model enhances the prediction in standstill conditions
- Last but most important:
  Lack of dedicated joint cooperation between universities, manufacturers, software developers, operators, regulatory, etc
  EU Call? Country specific call? JIP?
  Let's get the discussion rolled!



WHEN TRUST MATTERS

Thank you!

*now time for ~~snacks~~ questions



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