Technical University of Denmark

The Problem of Multiple Scales in CFD Simulations of Wind Turbine Aerodynamics

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The Problem of Multiple Scales in CFD Simulations of Wind Turbine Aerodynamics

International Conference on Model Integration across Disparate Scales in Complex Turbulent Flow Simulations

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Aeroelastic Design Section, DTU Wind Energy

Penn State, 15-06-2015

Introduction
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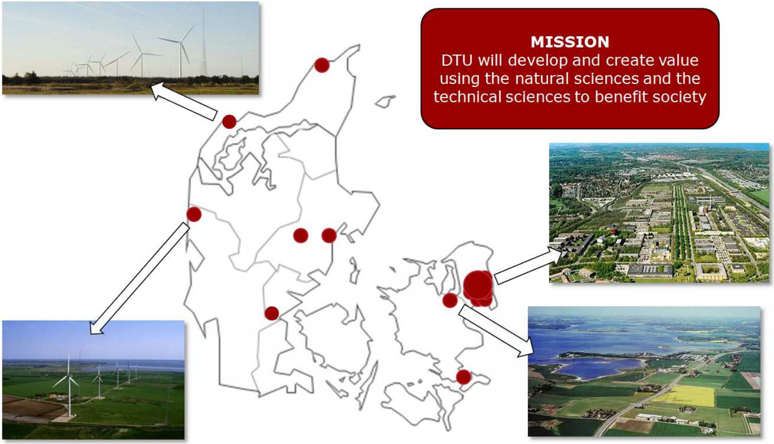

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Introduction
DTU Wind Energy

> 230 staff members
Including 150 academic staff members and 50 PhD students

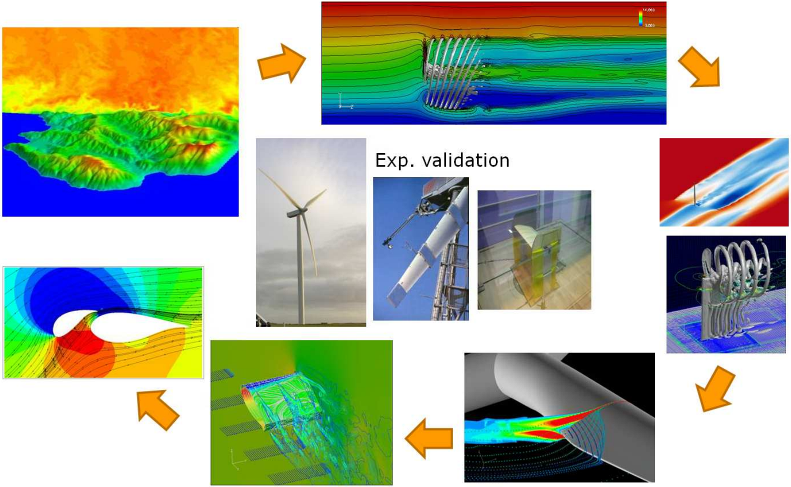
WIND ENERGY SYSTEMS
- Wind resources and siting
- Wind power integration and control
- Offshore wind energy
- Wind energy and society

WIND TURBINE TECHNOLOGY
- Aero-elastic design
- Structural design and safety
- Mechanical components
- Electro-technical components

WIND ENERGY BASICS
- Aero and hydro dynamics
- Boundary-layer meteorology and turbulence
- Light, strong materials
- Remote sensing and measurement technology

Introduction

Advanced Wind Turbine Aerodynamics -modeling and exp. validation



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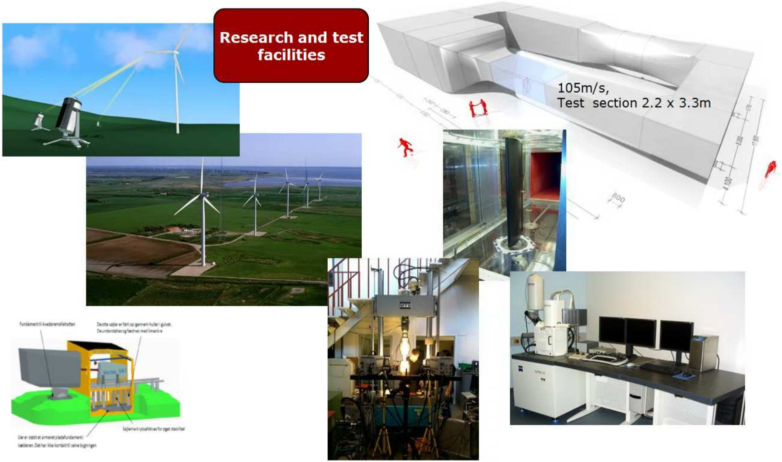
Experiments, Validation and Test



Model Integration over Disparate Scales

The overall goal is to be able to analyze and design wind turbines with respect to power production and loads in their natural environment

- Atmospheric Boundary Layer/Surface Layer
  - Yaw, Shear, Veering
  - Thermal effects
  - Turbulent inflow
- Park and Wake effects
- Rotor, Blade and Airfoil design
- Active and passive aerodynamic devices
- Laminar to turbulent transition of the blade boundary layer
- Aeroelatic effects

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Rough estimate of time scale of rotor simulations

Limiting our considerations to RANS/DES type simulations:

- RANS/DES resolution of an airfoil would require $N_{cells} \sim 200$ cells in chord-wise direction
- Typical tip chord dimension ~ 1 meter
- Typical tip speed $U_{tip} \sim 100$ [m/s]
- Typical time consumption of a single revolution 4-6 seconds
- Number of revolutions for wake build up 10-50

$$\Delta t = \frac{\frac{Chord}{0.5 \times N_{cells}}}{U_{tip}} \sim 1 \times 10^{-4} \text{seconds} .$$

Time-step	Time-steps per Rev.	Time-steps for full simulation
1×10^{-4} [s]	40.000-60.000	400.000-3.000.000

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Limiting the computational requirements for rotor simulations

We do the following assumptions to limit the computational requirements:

- Assume that the outer part of the blade is attached, allowing us to base time-step on the inboard part of the rotor (URANS and DES)
- Use steady-state approximation (RANS)
- Study specific phenomenas using 3D sectional approximations (Wind tunnel style)
- For some studies we go to 2D sectional considerations (RANS/URANS)

Typical RANS rotor grids are around 10-30 million grid points.

Scale considerations
Rotors in atmospheric flows

When studying rotor in atmospheric flows we try to limit the scales involved by dividing the problem:

- Fully resolved rotor geometries, steady inflow (yaw/shear)
  - Power Curve determination, airfoil data
  - Laminar turbulent transition
  - Studies of devices and rotor details (winglets, spoilers)
  - Aeroelastic studies
- Unsteady turbulent inflow, rotor is resolved by actuator forces
  - Wake studies
  - Park effects

The switch from fully resolved geometry to actuator forces brings the time step requirement down by a factor of 50 and severely limits the spatial requirements.

Mexico Experiment

Model EX periment In Controlled cOnditions, MEXICO

How to simulate a large scale European wind tunnel experiment of a wind turbine model:

Figure 2.4: Model turbine on balance

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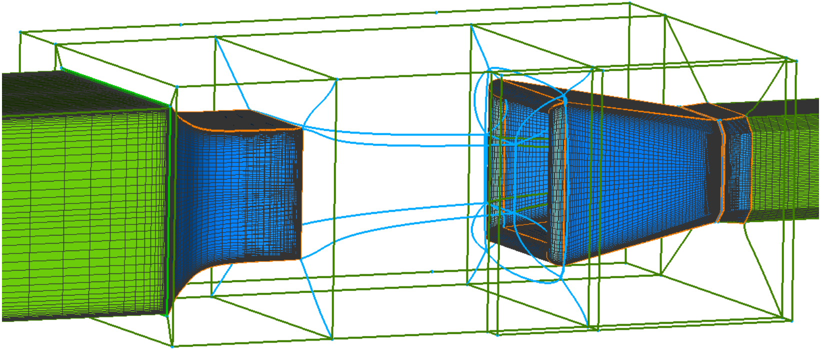
Mexico Experiment
Modeling it all



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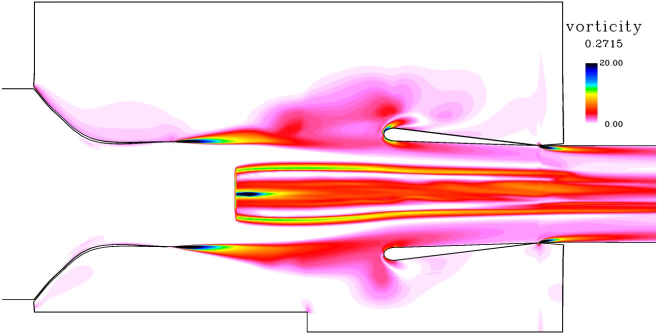
Mexico Experiment
Vorticity contours



- Instability region at the jet interface.
- Rapid contraction of the wake width due to the collector.

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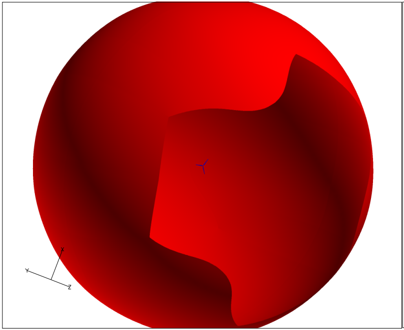
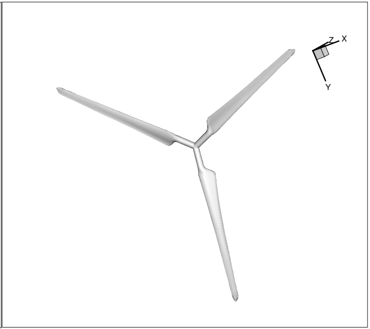
Mexico Experiment
Yawed Flow Case, Modeling only the essentials





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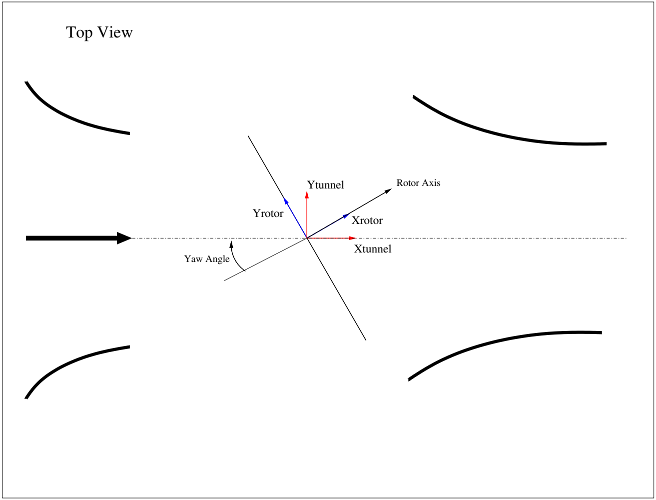
Mexico Experiment
Transects for deficit extraction



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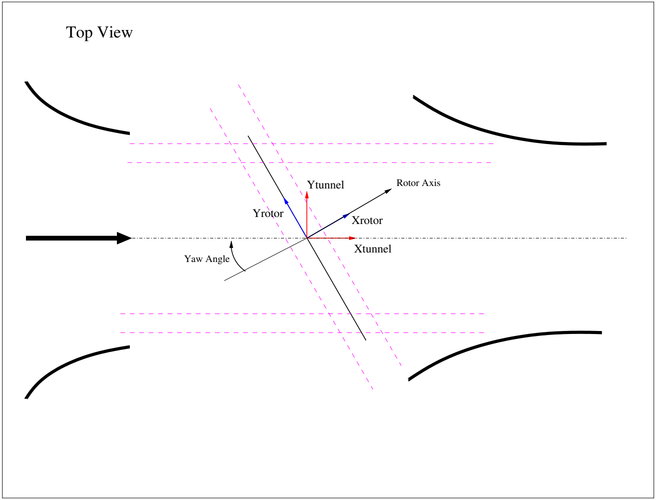

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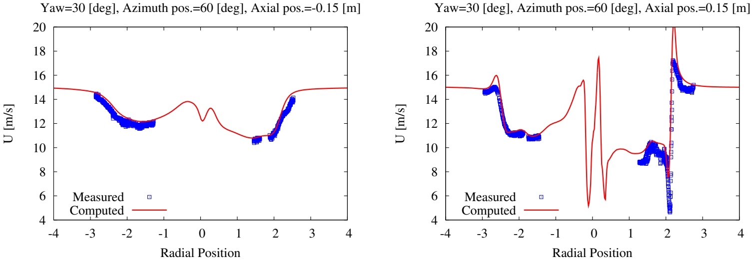
Yawed Flow Case, yaw angle 30 degrees, 15 m/s

Up and downstream radial traverses in the horizontal plane
Rotor azimuth position=60 deg.



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Mexico Experiment
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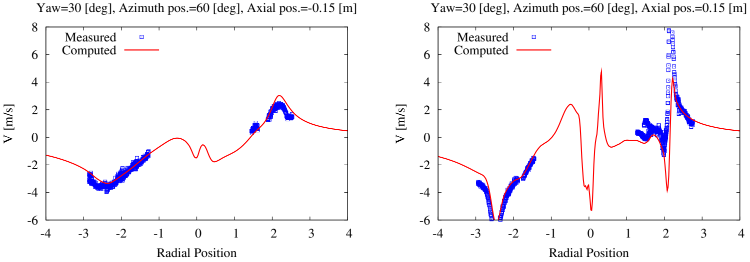

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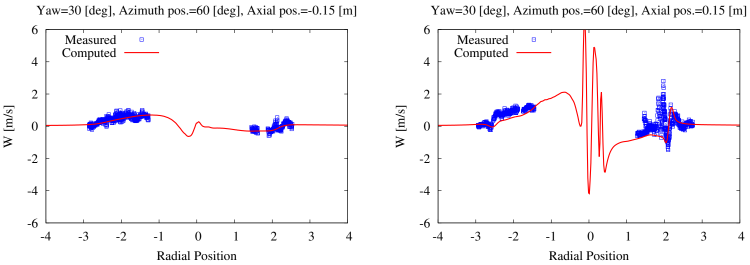

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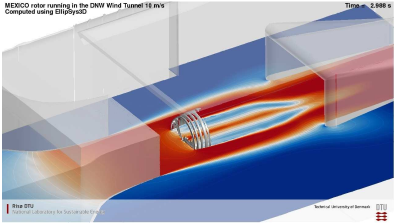
Mexico Experiment
Conclusion

Choosing the right scales to resolve with respect to the studied phenomenas is essential:

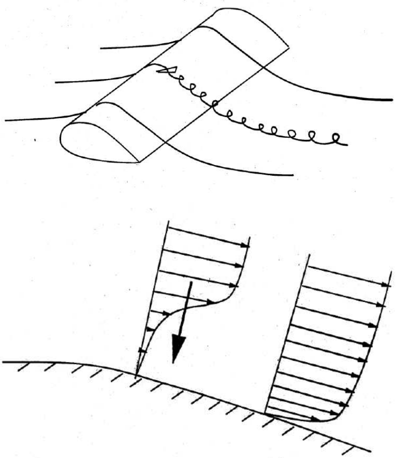
- For studying the turbine wake interaction, both the tunnel and the turbine are needed
- For studying the near wake behind the turbine, we can neglect the tunnel and the turbine tower
- Often we will need to evaluated the assumptions included



Simulations including Vortex Generators
Background

Vortex generators (VGs)

- Small passive devices mounted on the blade surface
- VGs generate longitudinal vortices ⇒ transfer of high momentum air into the bottom boundary layer ⇒ delay of separation and stall
- Can increase lift and reduce drag on airfoils at high angles of attack
- Used intensively on modern wind turbines



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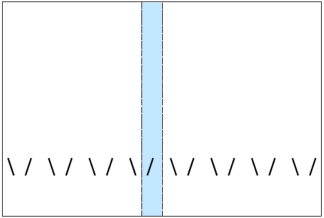
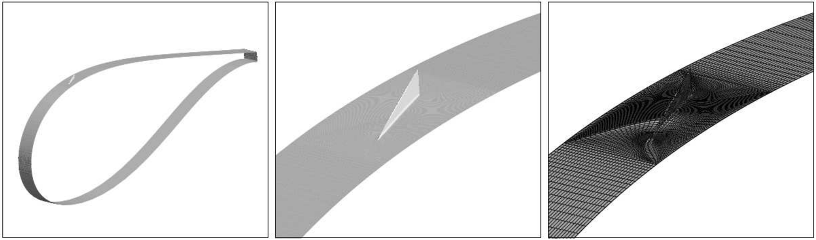
Simulations including Vortex Generators
Fully resolved VG

CFD simulations of FFA-W3-301 airfoil with VG at 20% chord

- Fully resolved VG
- Small span-wise section simulated
- Symmetry conditions used to simulate a row of VG pairs
- O-mesh grid configuration





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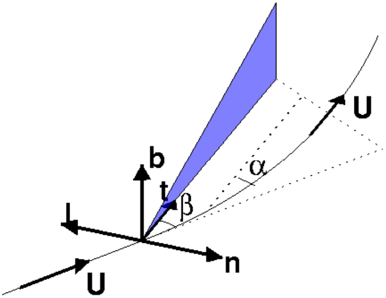
Simulations including Vortex Generators
Simplified VG model

The BAY model

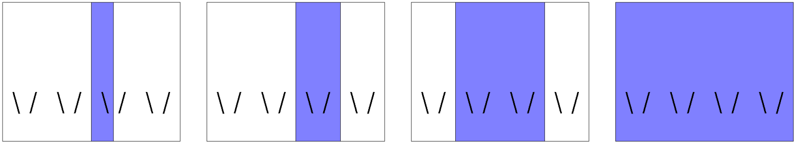
- VG represented as a body force perpendicular to the local flow
- Force introduced using the actuator shape model
- Force applied to cell *i* is determined using thin plate analogy:
  - $\mathbf{L}_i = c_{VG} \rho A_i |\mathbf{U}|^2 \alpha \mathbf{l}$
    - $\mathbf{l} = \frac{\mathbf{b} \times \mathbf{U}}{|\mathbf{U}|}$
    - $\alpha \approx \cos\alpha \sin\alpha = \frac{\mathbf{U} \cdot \mathbf{t}}{|\mathbf{U}|} \frac{\mathbf{U} \cdot \mathbf{n}}{|\mathbf{U}|}$
    - A_i: Area of intersection between cell *i* and VG
    - c_{VG}: Calibration coefficient
  - Large $c_{VG} \Rightarrow \alpha \rightarrow 0 \Rightarrow \mathbf{L}_i$ independent of c_{VG}



Simulations of FFA-W3-301 airfoil with VGs

Mesh sensitivity study

Name	n_{chord}	n_{norm}	n_{span}	$\frac{L_{span}}{chord}$	n_{VG}
G0:	448	128	64	0.045	1
G1:	256	128	32	0.045	1
G2:	256	128	32	0.090	2
G3:	256	128	32	0.180	4
G4:	256	128	32	0.360	8

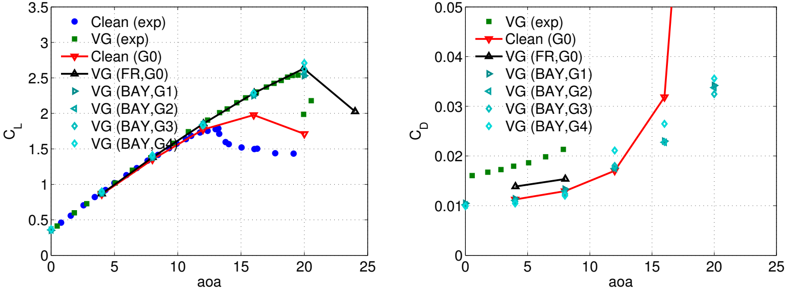


G0-G1 G2 G3 G4

Simulations of FFA-W3-301 airfoil with VGs

Overall findings

- The BAY model performs well on all grid levels
- The drag is under estimated using both types of modeling



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Simulations including Vortex Generators
CFD simulations of MW wind turbine with VGs

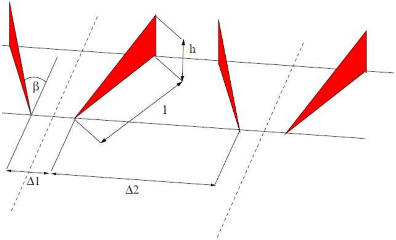
The DTU 10 MW reference wind turbine

- Open source research turbine designed at DTU
- Based on the FFA-W3 airfoil series along the entire blade
- $R = 89.166\ m$

CFD simulations of MW wind turbine with VGs

VG set-up

- $\beta = 16^o$
- $h = 0.01c_{max} = 0.062\ m$
- $l = 4h = 0.248\ m$
- $\Delta_1 = 0.045c_{max} = 0.279\ m$
- $\Delta_2 = 0.055c_{max} = 0.341\ m$
- VG LE along a line from $0.5c$ at $r = 5\ m$ to $0.21c$ at $r = 30\ m$.
  - 40 VG pairs on each blade



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Simulations including Vortex Generators
CFD simulations of MW wind turbine with VGs

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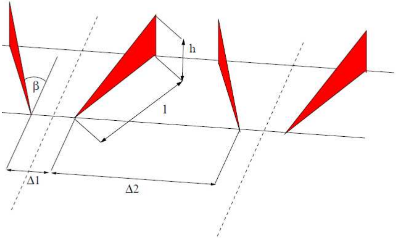

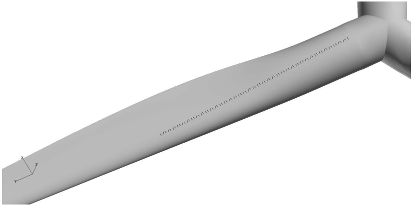

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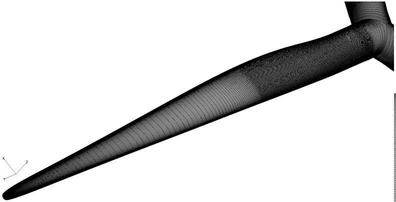
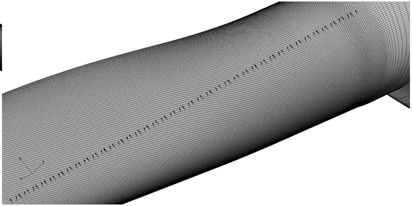
CFD simulations of MW wind turbine with VGs

Computational mesh

- Total number of grid cells: $48.8 \cdot 10^6$
  - Chord-wise: 256; Normal: 128; Span-wise: 480; Tip cap: 64×64
- Span-wise cell length at inner part of the rotor corresponds to 8 cells per VG pair





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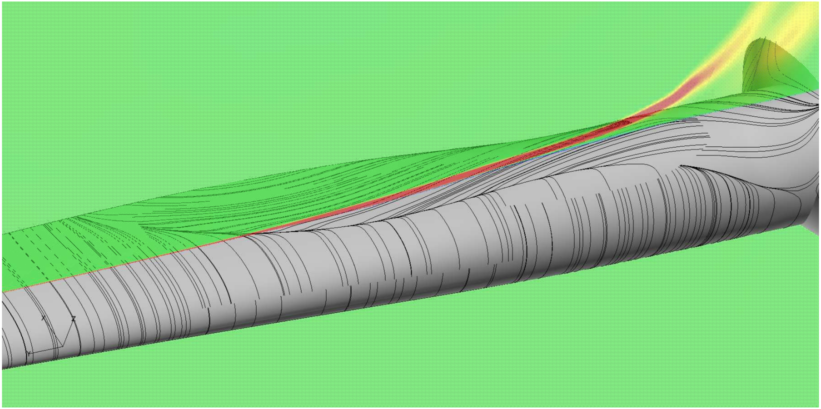
CFD simulations of MW wind turbine with VGs

Flow characteristics at 10 m/s

- The flow at the inner part of the blade separates and there is a strong radial flow when there is no VGs



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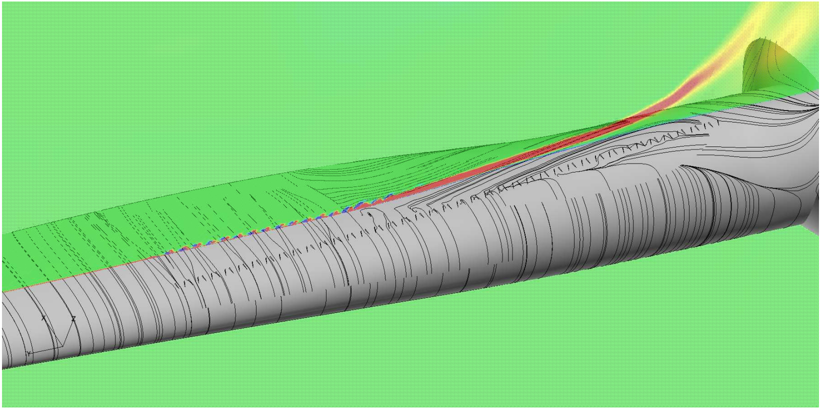
CFD simulations of MW wind turbine with VGs

Flow characteristics at 10 m/s

- The counter rotating vortices induced by the VGs effectively suppress separation but further inboard the VGs have no effect.



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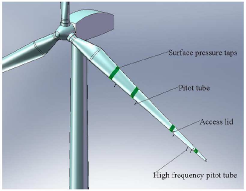
Conclusions

- The resolved modeling can be used to validate the actuator type modeling for simple cases
- The BAY/actuator modeling requires less computations resources
- The BAY/actuator modeling facilitates easy variation of the VG layout
- The BAY/actuator modeling facilitates fully resolved rotor simulations
- The BAY/actuator modeling approach can be used to provide airfoil data for even simpler rotor descriptions (AC Line/Disk or BEM)

DanAero Setup

DanAero experimental setup:

- The DanAero experiment features a 3 bladed modern wind turbine in the ABL
- Pressure measurements at four stations are available [13, 19, 30, 37] meter
- Pitot tubes, strain gauges, microphones, met mast inflow measurements, LIDAR measurements



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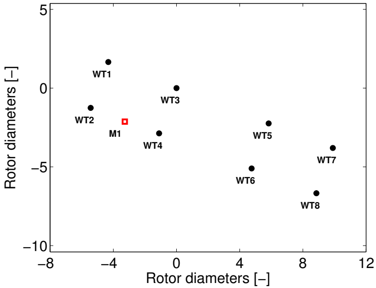
DanAero Yaw Simulations
Park Setup

Location and park configuration:

- The experimental turbine (WT3) is part of a small park
- The park is located closely to the coast



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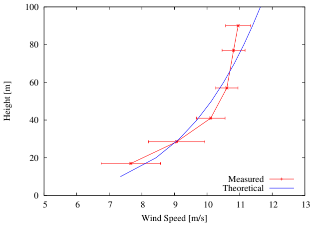
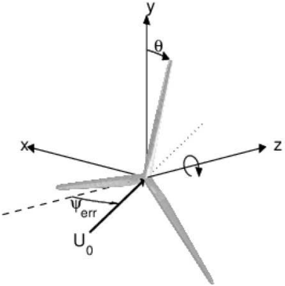
DanAero Yaw Simulations
Selected Case

Selected yaw case

- Wind from South South-East ($\sim 155^\circ$)
- Weak shear $\sim U_\infty \left(\frac{z}{H}\right)^{0.2}$, with $U\infty = 10.3[\mathrm{m/s}]$ and $H = 57[\mathrm{m}]$
- Negative yaw error of 17.1 degrees defined according to the drawing below
- The RPM is 16.2





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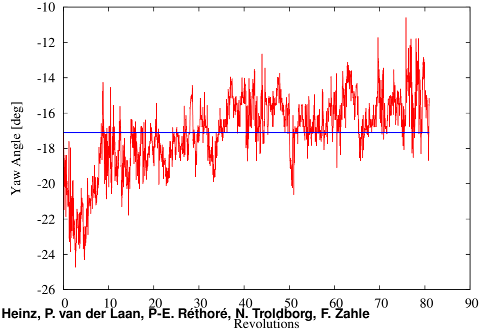
The Atmospheric Inflow

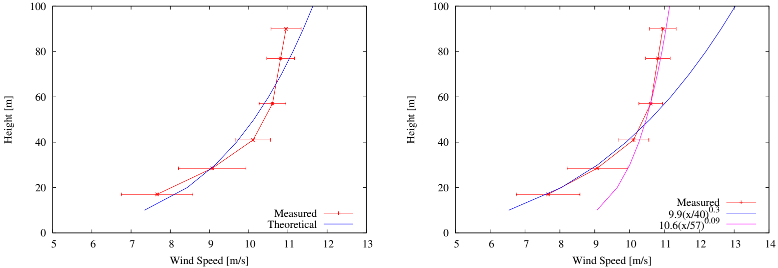
Some of the issues of ASL experiments

- The theoretical velocity profile do not fit the measured profile well at all heights
- We suspect that the actual profile has an growing internal boundary layer due to the close-by shore
- Due to the unsteady nature of the ASL, the yaw error is not constant.



Mean Shear Approximation

Modeling the shear using one or two power law approximations:



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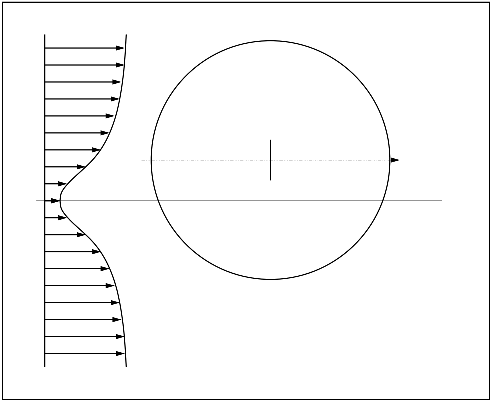
DanAero Yaw Simulations
In-house flow solver, EllipSys3D.

- Incompressible Reynolds Averaged Navier-Stokes equations
- Rotation enforced through a moving grid option
- Turbulence is modeled by $k - \omega$ SST model
- Fully turbulent simulations
- Second order accurate in times
- Convective terms is modeled by QUICK
- Time-step 1600 per revolution, with 4 sub-iterations
- The computations are accelerated by using a three level grid sequence [1, 4, 8 $\sim$ 10] revolutions

Modeling the Shear

The ASL effects are modeled through the mean flow:

$$U(z) = U_\infty \left(\frac{|x+57| \tanh((\frac{x+57}{10})^4) + 4(1-\tanh((\frac{x+57}{10})^4))}{57} \right)^{0.2}$$



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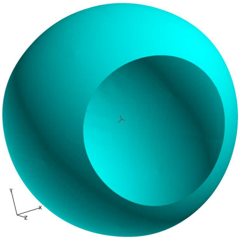
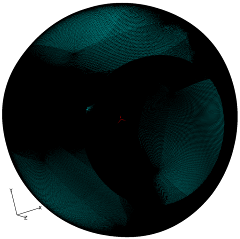
DanAero Yaw Simulations
Computational Grid

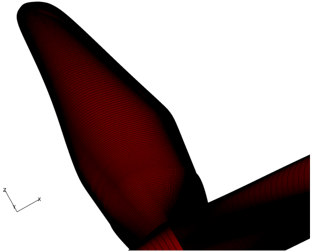
- The domain is $\sim$ 20 rotor diameters in diameter
- O-O-Topology of 432 blocks of 64^3 $\sim$ 113 Million points

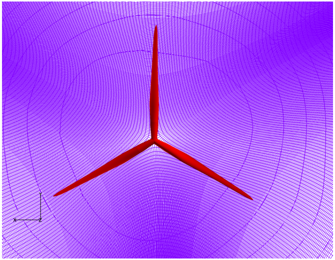




DanAero Yaw Simulations
Computational Grid

- Chord-wise 512, Span-wise 256, Normal 256
- The wall normal y^+ is less than two on the blade surface





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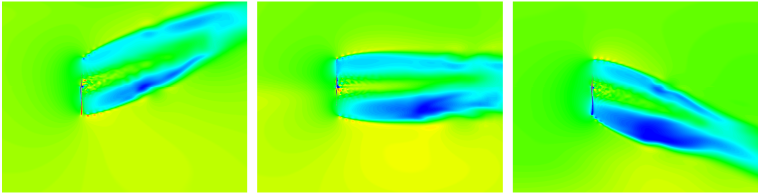
Wake geometry

The three most relevant cases (The actual case is the Shear-Yaw):

Shear +Yaw | Pure Shear | Shear -Yaw



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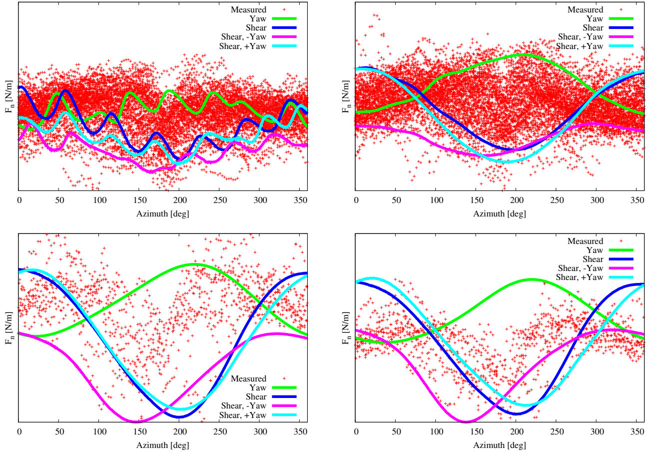
DanAero Yaw Simulations
Normal Forces

The Azimuth variation of the normal forces

r=13 [m]

r=19 [m]



r=30 [m]

r=37 [m]

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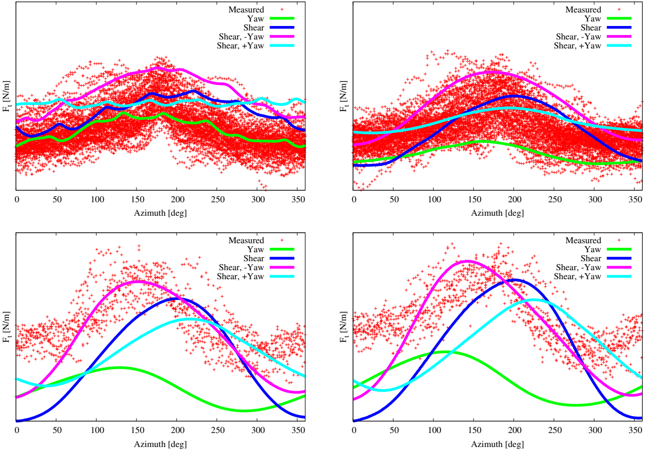
DanAero Yaw Simulations
Tangential Forces

The Azimuth variation of the Tangential forces

r=13 [m]

r=19 [m]



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r=37 [m]

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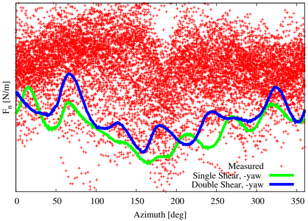
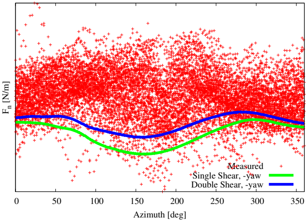
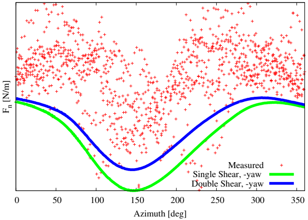


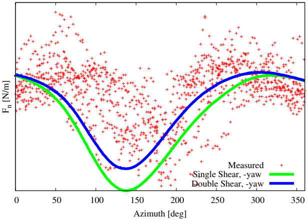
r=19 [m]



r=30 [m]



r=37 [m]



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DanAero Yaw Simulations
Tangential Forces

The Azimuth variation of the Tangential forces

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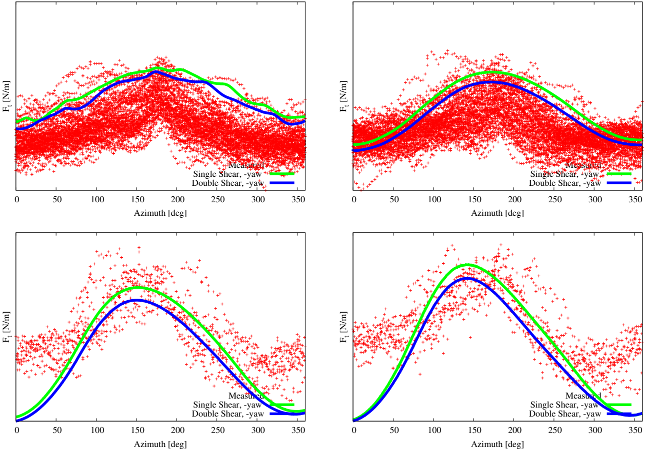

r=30 [m]

r=37 [m]

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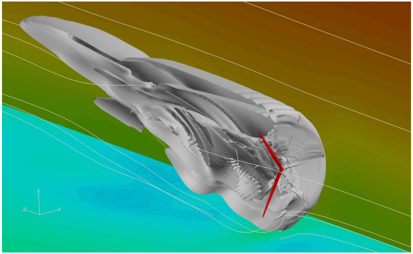
Conclusion and outlook

- Generally the azimuthal variation in the measurements are captured
- For the low yaw angle in the present case, shear is the dominant effect
- The improvement by including the double shear is minor
- The effect of the neglected tilt angle needs to be evaluated
- In the future we plan to look at higher yaw angles



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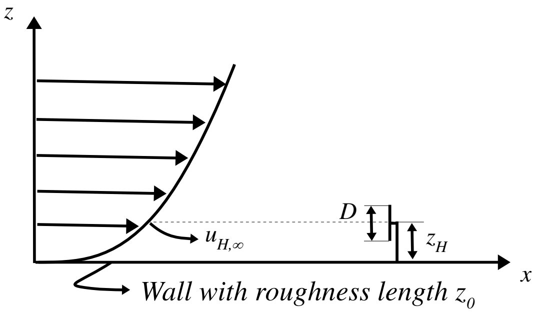
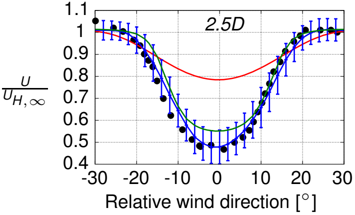
Wake Modeling
Approach



- The rotor forces are modeled with an actuator disk.
- The flow is resolved with EllipSys3D.
- The flow is driven by turbulence since $Re \sim 10^7$.

Single wake

Velocity deficit



- (•) Field measurements of Nibe wind turbine (D = 40 m).
- Resolve large scale turbulence using (—) Large-eddy simulation (LES).
- Model all turbulence using Reynolds-averaged Navier-Stokes (RANS):
  - (—) standard k-ϵ model.
  - (—) k-ϵ-f_P model

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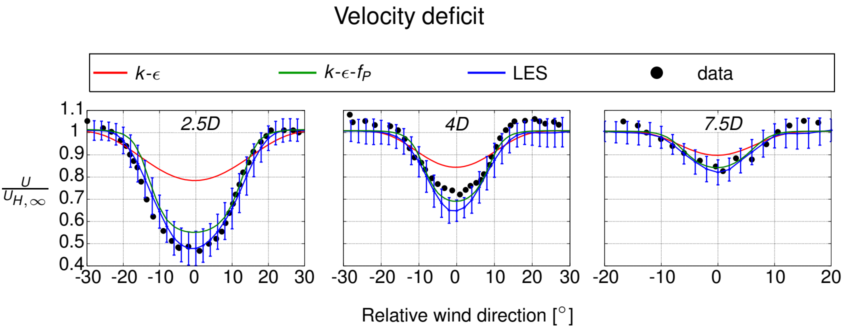
Wake Modeling
Single wake



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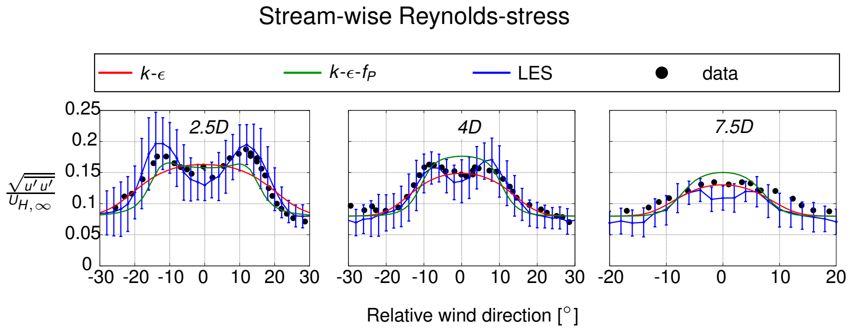
Wake Modeling
Single wake



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Wake Modeling
Lillgrund off-shore wind farm

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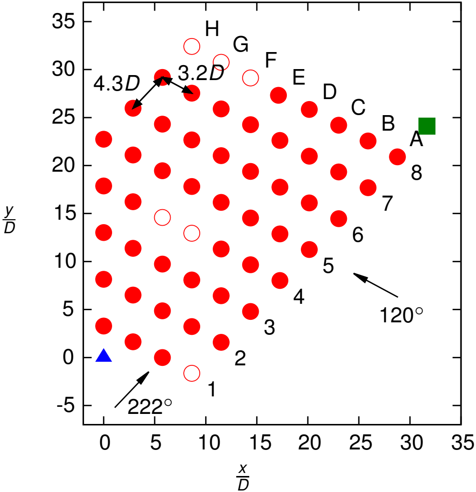
Wake Modeling
Lillgrund: layout.

- 48 Turbines
- Siemens 2.3 MW
- Empty positions



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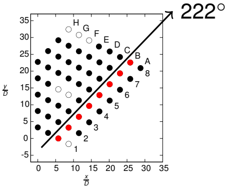
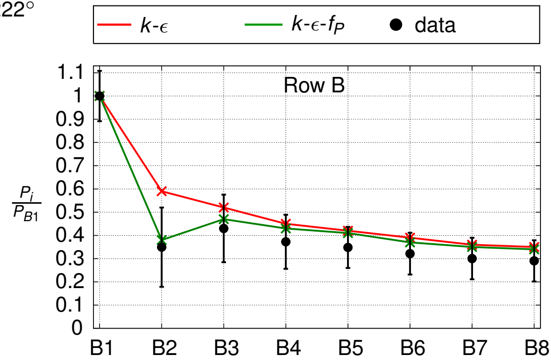
Lillgrund: power deficit.[?]

Results includes Gaussian averaging with a standard deviation of 3.3°.





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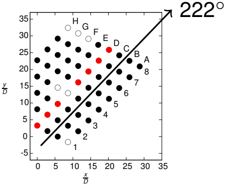
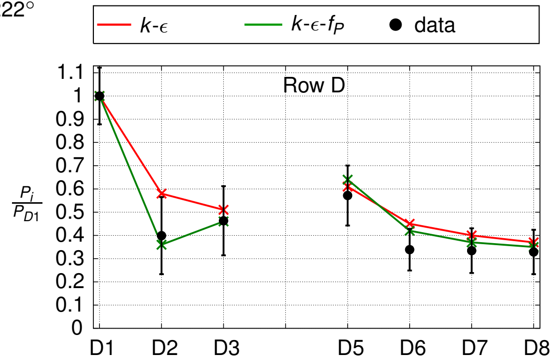
Lillgrund: power deficit.

Results includes Gaussian averaging with a standard deviation of 3.3°.





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Wake Modeling
Lillgrund: power deficit.

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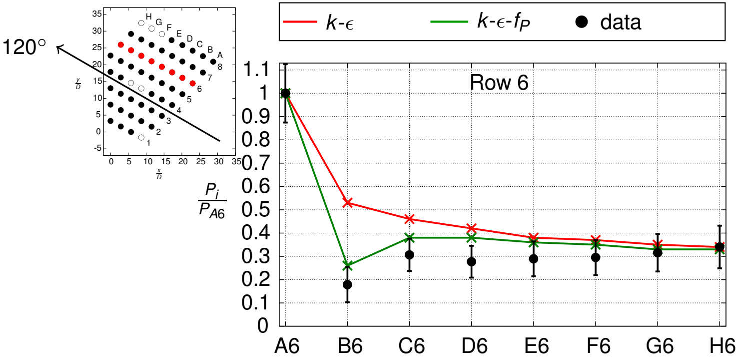

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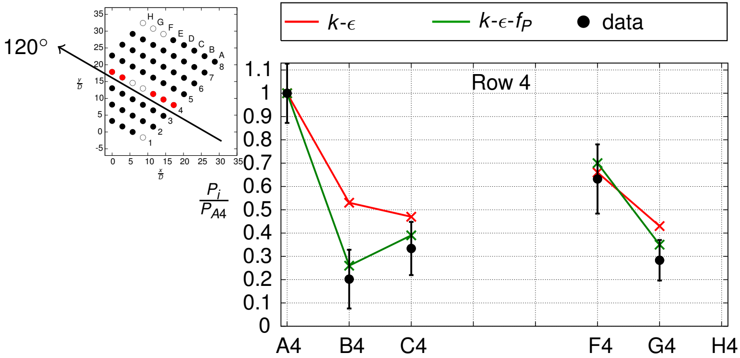

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Lillgrund: efficiency

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Wake Modeling
Lillgrund: efficiency

Overal efficiency for a wind speed of 9 m/s
(assuming a uniformly distributed wind direction):

Data	k-ϵ model	k-ϵ-f_P model
0.65$\pm$0.035	0.66	0.64

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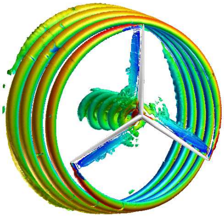
Fluid Structure Modelling
Including CFD into FSI Modelling

Potentials of high-fidelity CFD:

- Detailed modeling of the flow around the wind turbine
- Exact modeling of the 3D wind turbine geometry
- Capturing viscous effects
- Capturing dynamic effects and 3D effects
- Very reliable results

Using CFD instead of BEM to:

- Validate the BEM based FSI models
- Simulate load cases which lie outside the limits of BEM theory
- Better understand the complex flows around a flexible wind turbine structure



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Partitioned FSI Coupling using CFD (HAWC2CFD)

Idea at DTU Wind Energy:

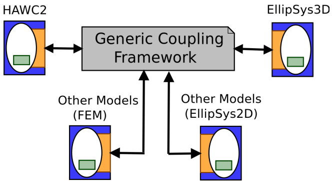
- Couple the BEM based FSI code **HAWC2** with the finite volume CFD code **EllipSys3D**

  ⇒ Compute the structural response with HAWC2
  ⇒ Compute the aerodynamic forces with EllipSys3D

Partitioned Coupling:

- Develop a **Generic Coupling Framework** to connect the independent stand-alone solvers

  ⇒ Solvers are kept as independent entities
  ⇒ Models can be easily exchanged or added



Vortex-Induced Vibrations

Standstill with inflow conditions $V = 18\,\text{m/s}$ and $\Psi = 15^\circ$

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Conclusions

We have seen a series of examples where we use CFD ....

- We can't resolve all relevant scales
- We need to resolve the most important scales
- Often the deliberate decision to resolve specific scales while neglecting others can provide new insight
- Often simpler models can be calibrated on subset problem using more advanced model
  - Airfoil Data for AC Line/Disk or BEM
  - Park modeling with AC Line/Disk
  - BAY VG Model
  - The calibrated model can be applied to the actual problem
- We can use CFD to analyze complicated aeroelastic phenomenas, but we often need to simplify the problem