Comparison of the Wake of Different Kinds of Wind Turbine CFD Models

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Risø DTU
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Background

Wind turbine models in CFD
• Fully resolved rotor (FR)
• Actuator line model (AL)
• Actuator disc model (AD)

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- Fully resolved rotor (FR)
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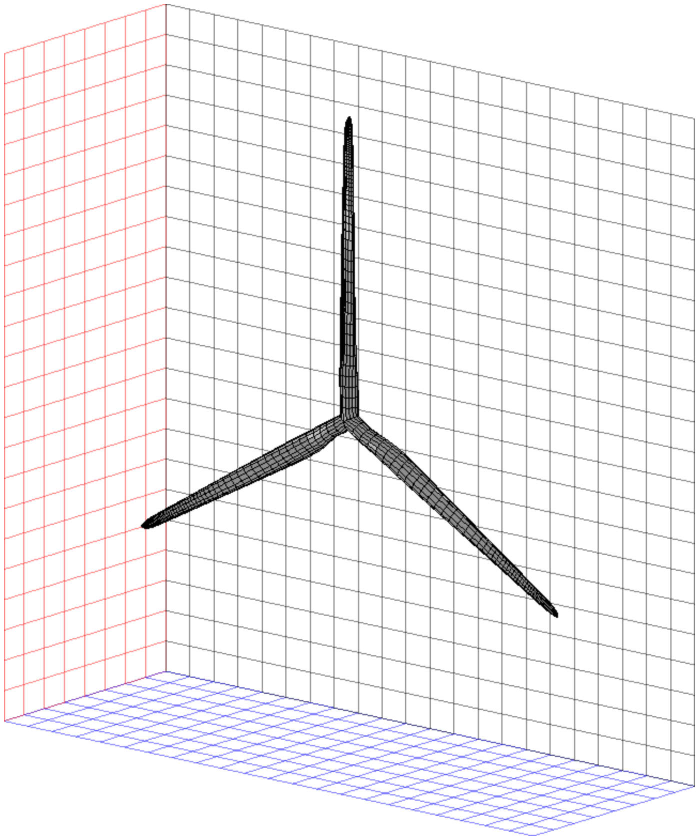
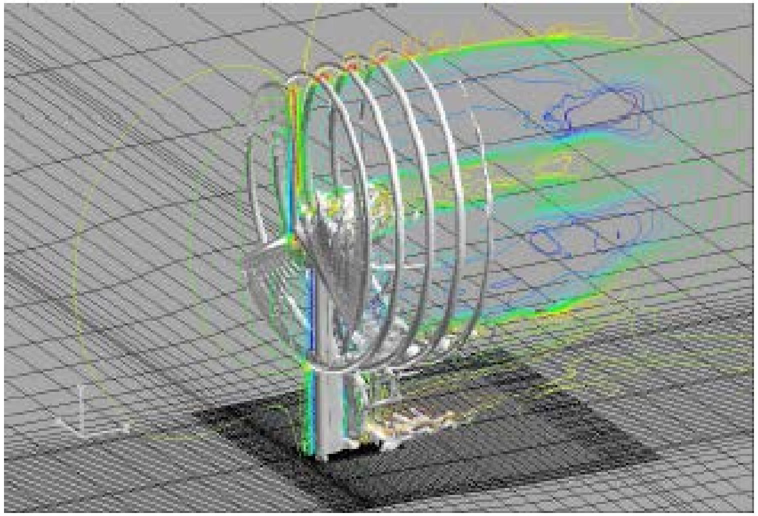


- The blade/airfoil boundary layer is resolved
- The required number of grid points for one rotor using RANS is $O(10^7)$
- Provides detailed insight about flow behaviour
- Usually used for accurately predict loads and power production
- Too computationally heavy for several wind turbines.



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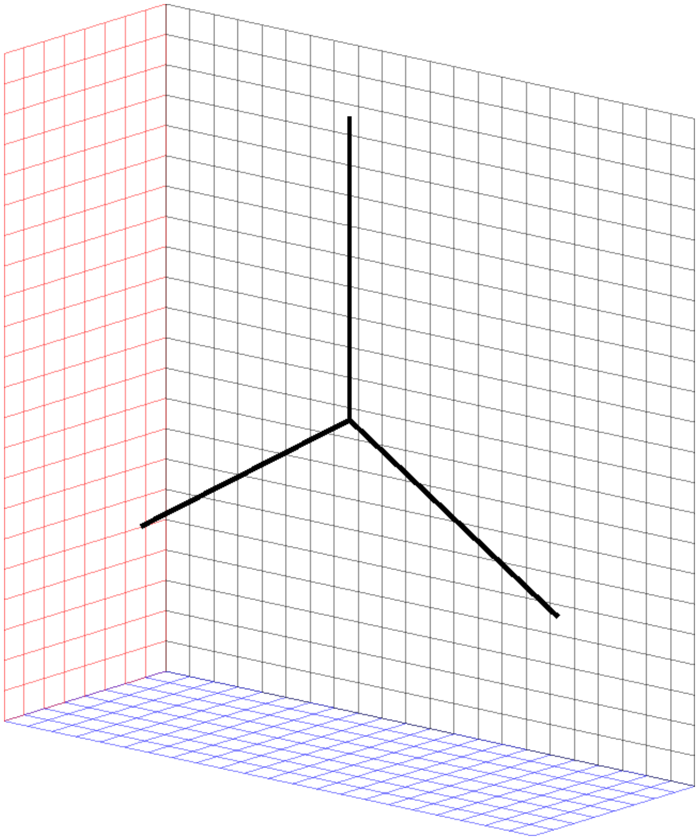

➢ Blades represented as lines.

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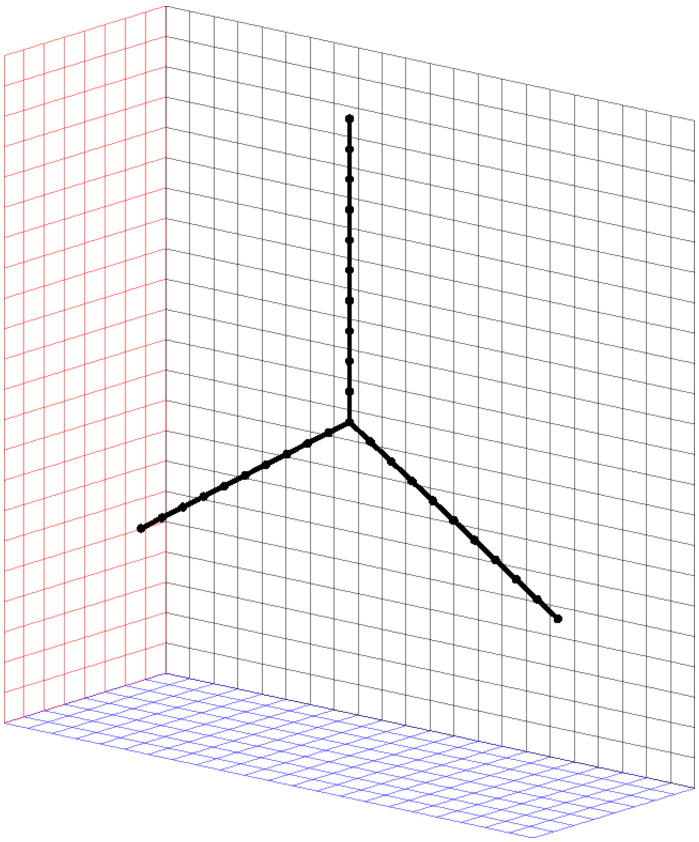

- Blades represented as lines.
- Aerodynamic blade forces determined from 2D airfoil data.

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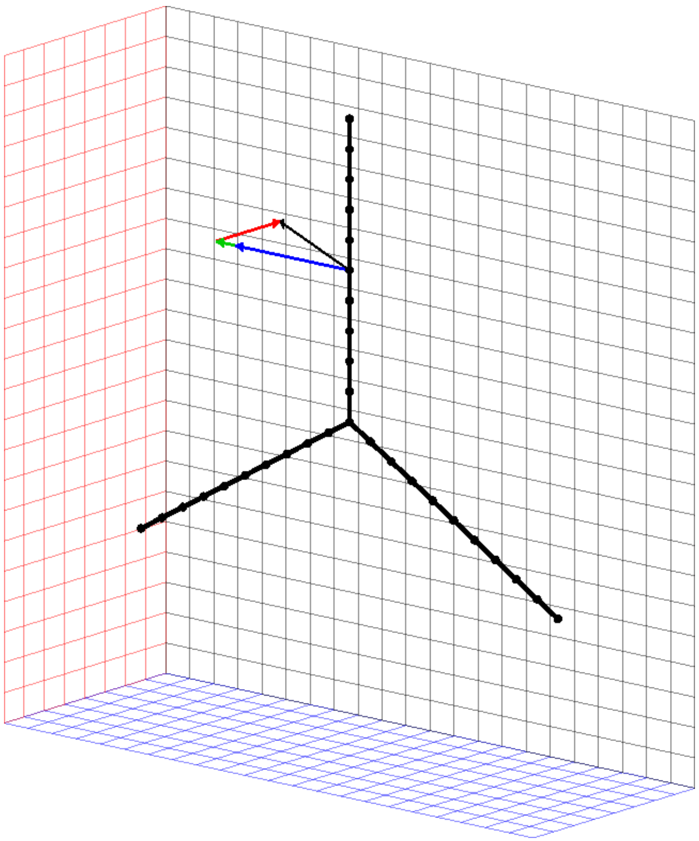
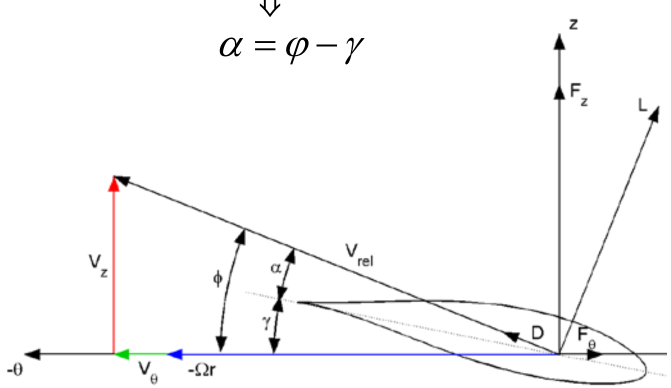


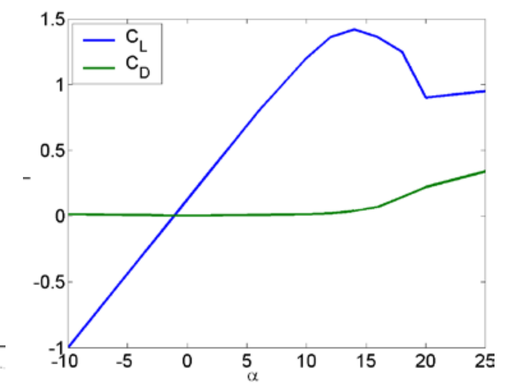
$$\varphi = \tan^{-1}\left(\frac{V_z}{\Omega r - V_\theta}\right)$$

$$\Downarrow$$

$$\alpha = \varphi - \gamma$$

$$\mathbf{f} = \begin{pmatrix} L \\ D \end{pmatrix} = \tfrac{1}{2}\rho V_{rel}^2 c \begin{pmatrix} C_L(\alpha)\mathbf{e}_L \\ C_D(\alpha)\mathbf{e}_D \end{pmatrix}$$





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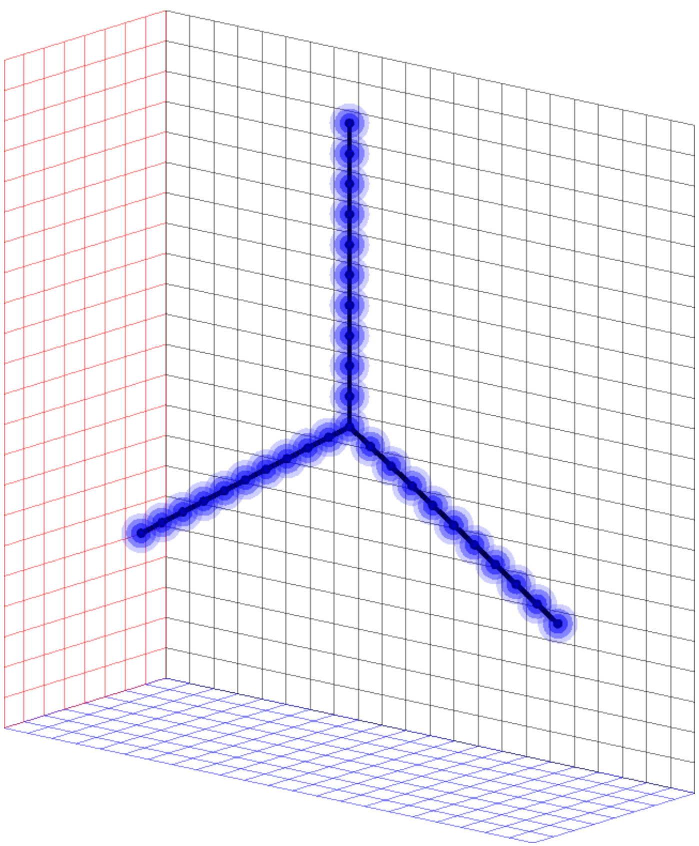

- Blades represented as lines.
- Aerodynamic blade forces determined from 2D airfoil data.
- Blade forces smeared to avoid singular behaviour.

$$\mathbf{f}_\varepsilon = \mathbf{f} \otimes \eta_\varepsilon, \quad \eta_\varepsilon = \frac{1}{\varepsilon^3 \pi^{3/2}} \exp\left[-\frac{d^2}{\varepsilon^2} \right]$$

$$\varphi = \tan^{-1}\left(\frac{V_z}{\Omega r - V_\theta}\right)$$

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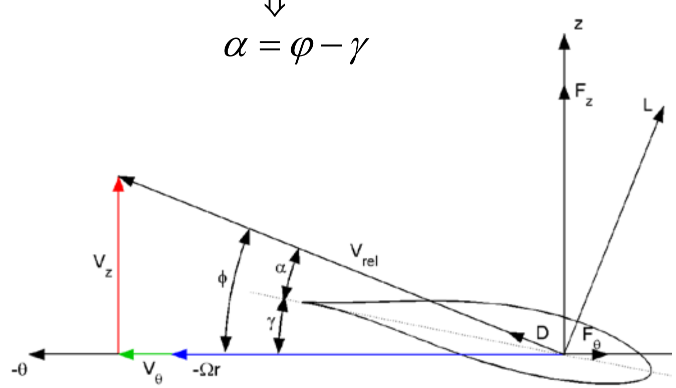
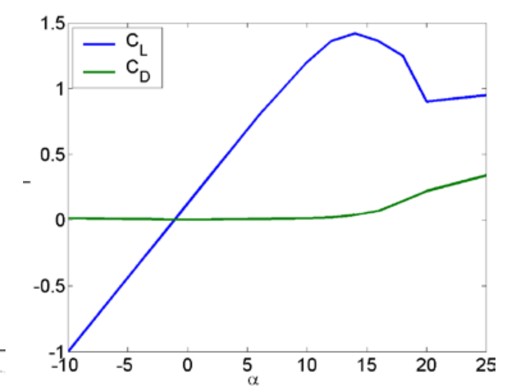
$$\mathbf{f} = \begin{pmatrix} L \\ D \end{pmatrix} = \tfrac{1}{2} \rho V_{rel}^2 c \begin{pmatrix} C_L(\alpha)\mathbf{e}_L \\ C_D(\alpha)\mathbf{e}_D \end{pmatrix}$$





Background

Wind turbine models in CFD

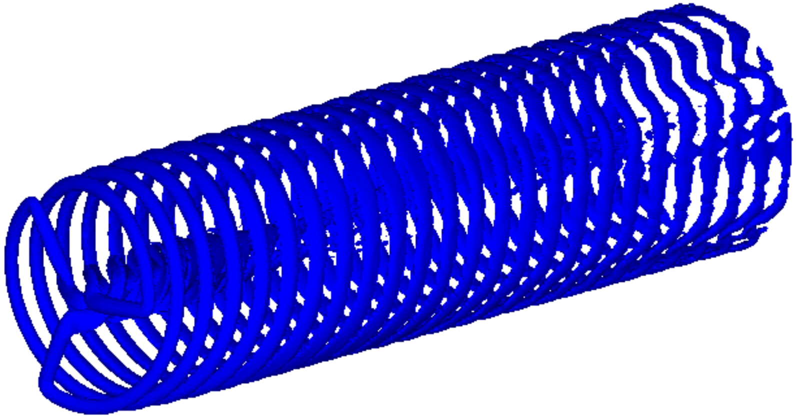
- Fully resolved rotor (FR)
- Actuator line model (AL)
- Actuator disc model (AD)

Advantages:

- Low number of grid points $O(10^6)$ needed compared to full rotor CFD.
- Applicable with simple grid geometries.
- Captures the most important features of the wake including tip/root vortices.
- Well suited for LES simulations (no boundary layers need to be resolved)

Disadvantages:

- Relies on airfoil data



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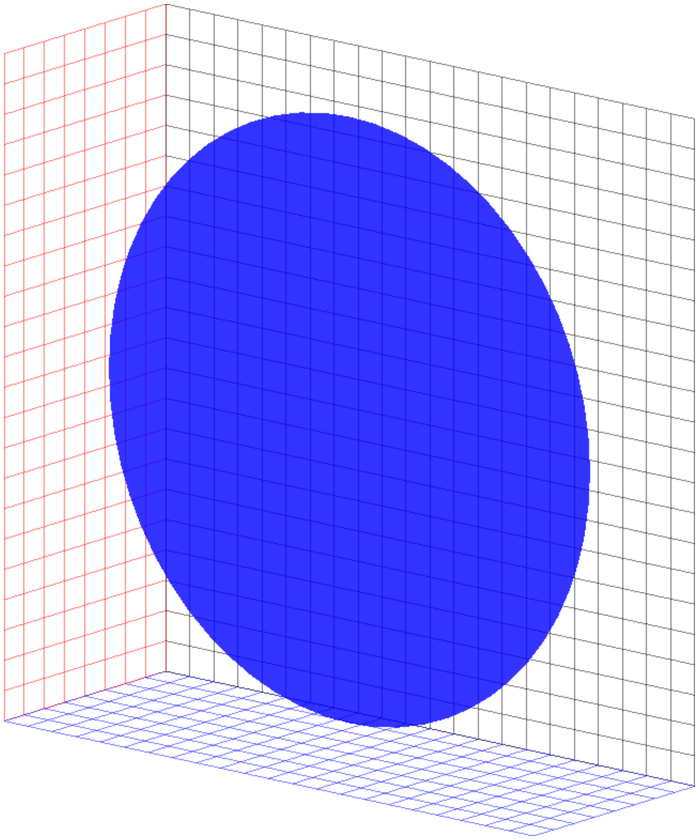

➢ Rotor represented by forces distributed on permeable disc.

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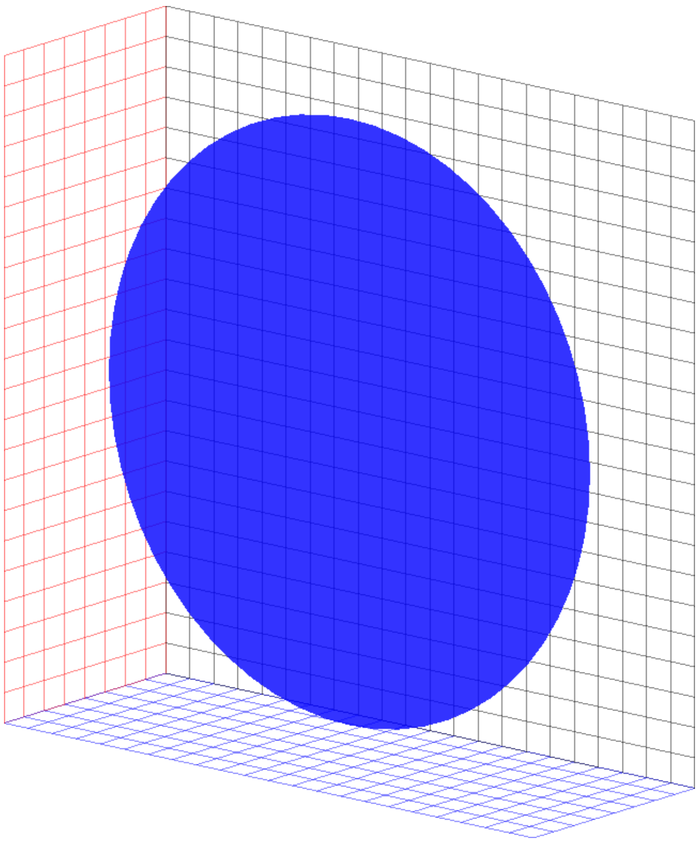


➢ Rotor represented by forces distributed on permeable disc.

➢ The disc loading is either prescribed or determined from airfoil data.

➢ Modified Rhie-Chow algorithm to avoid pressure velocity decoupling with body forces

Background

Wind turbine models in CFD

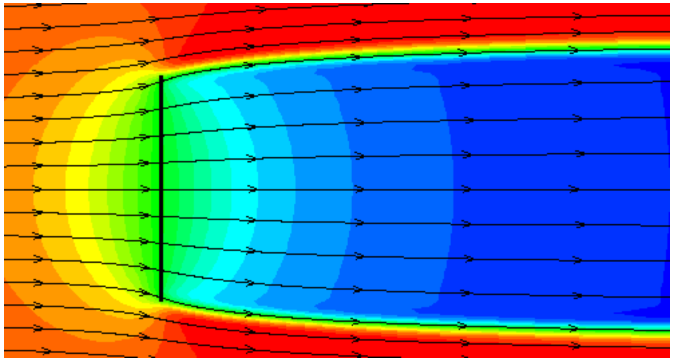
- Fully resolved rotor (FR)
- Actuator line model (AL)
- Actuator disc model (AD)

Advantages:

- Low number of grid points
- Applicable with simple grid geometries
- Well suited for LES simulations
- Large time steps can be used
- Can run in steady state

Disadvantages:

- Relies on airfoil data
- Does not capture influence of individual blades
- May be questionable in non-uniform inflow



Axial velocity contours and streamlines for a uniformly loaded disc at C_T*=0.89*

Background & Objectives

Summary:

- AL/AD typically used for wake studies
- Details of rotor geometry assumed unimportant in far wake

Objectives:

- Study importance of wind turbine model on wake characteristics
  - How much details are lost due to the simpler models?

- Conduct a consistent comparison of the three models
  - Simulate wake of the NREL 5MW Reference turbine
  - Same numerical setup for all models

Approach – Flow solver

EllipSys3D:

- In-house CFD code
- Incompressible Navier-Stokes equations
- Finite volume discretization
- Structured curvelinear grids
- Pressure/Velocity formulation
- Multigrid
- Multiblock
- Grid sequencing
- MPI

Solver parameters:

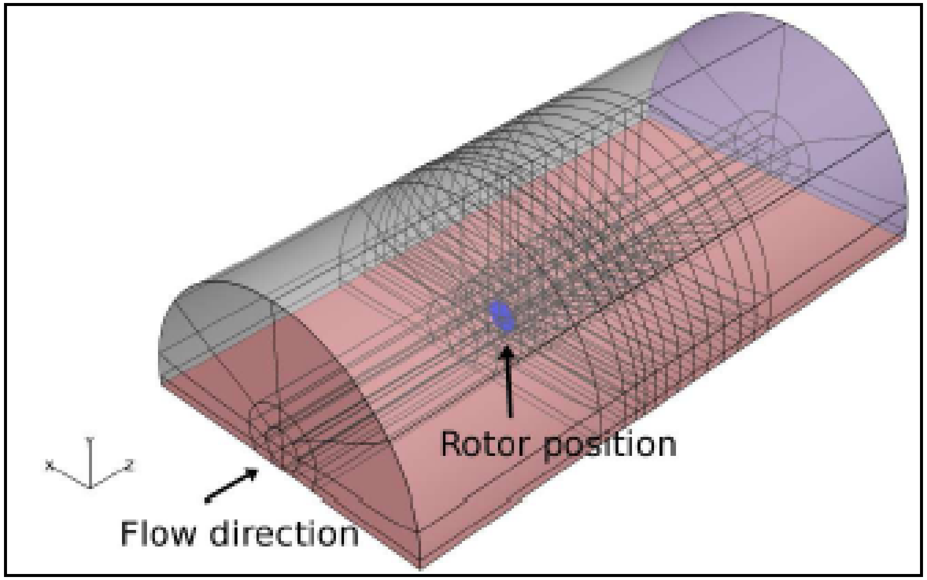
- QUICK/QUICK_CDS4
- SIMPLE

Approach - Numerical setup

Background mesh:

- Same background mesh for all simulations
- Half cylinder with radius 10R
- 308 blocks of 32^3 ($10.1 \cdot 10^6$ cells)
- High resolution of the first 5D of the wake

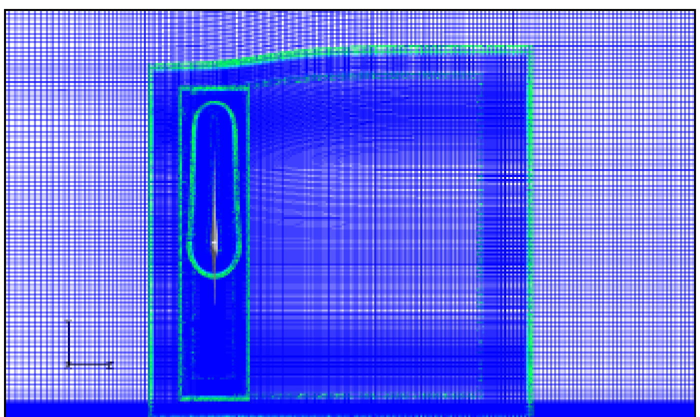
(80 cells per rotor diameter)

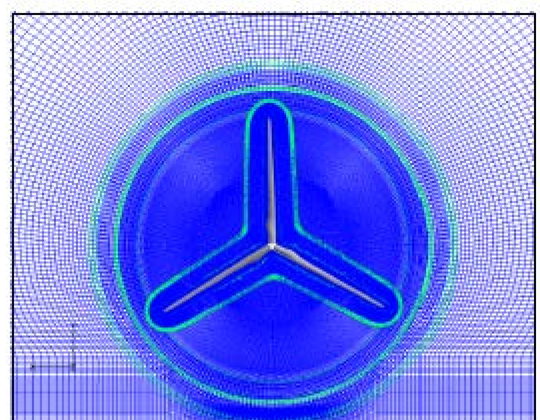


Approach - Numerical setup

Full rotor with overset grid:

- Four overlapping mesh groups
- Rotor mesh generated using HypGrid3D to form an O-O topology
- Total number of grid points is $23 \cdot 10^6$
- Rotor surface with a non-slip boundary condition
- First cell height $y=1.0 \cdot 10^6$ ($y^+ < 2$)





Approach - Numerical setup

Actuator line simulations:

- Same background mesh as the full rotor simulation ($10.1 \cdot 10^6$ cells)
- Force smearing using 3D convolution
- 33 force elements along each line

Approach - Numerical setup

Actuator disc simulations:

- Same background mesh as the full rotor simulation ($10.1 \cdot 10^6$ cells)
- 33 radial force elements
- Modified Rhie-Chow algorithm to avoid pressure velocity decoupling with body forces

Results

Test cases
• Uniform inflow (RANS)
• Uniform inflow (DES)
• Turbulent inflow (DES)

Results

Test cases

- Uniform inflow (RANS)
- Uniform inflow (DES)
- Turbulent inflow (DES)

- V_∞ = 8 m/s
- Time step Δt = 0.00435s, 0.0244s and 0.0600s in FR, AL and AD, respectively (1500, 267 and 109 time steps per rev.)
- Forces from FR simulation applied directly in the AL and AD simulations
- Computing expenses:
  - $T_{FR} \approx 21T_{AL} \approx 45T_{AD}$

Results

Test cases

- Uniform inflow (RANS)
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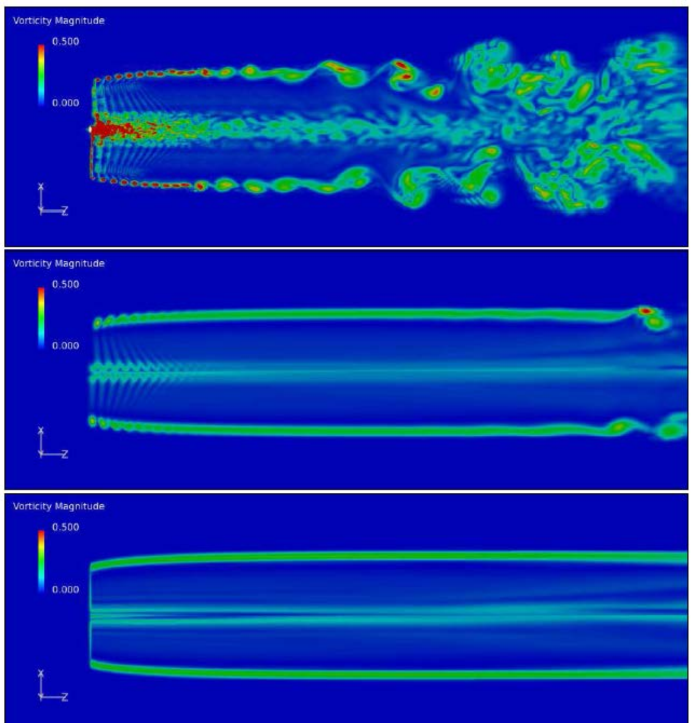

Snapshot of vorticity magnitude contours in horizontal cross-section through rotor center.

- Vorticity from tip vortices much stronger in FR than in AL and AD.
- Wake of FR becomes unstable and breaks up.
- Similar vorticity contours for AL and AD (except for instabilty in the far wake of AL)
- Reasons for more unstable wake of FR:
  - Higher grid resolution
  - Fluctuating loads (e.g. stall effets near root)

Results

Test cases
• Uniform inflow (RANS)
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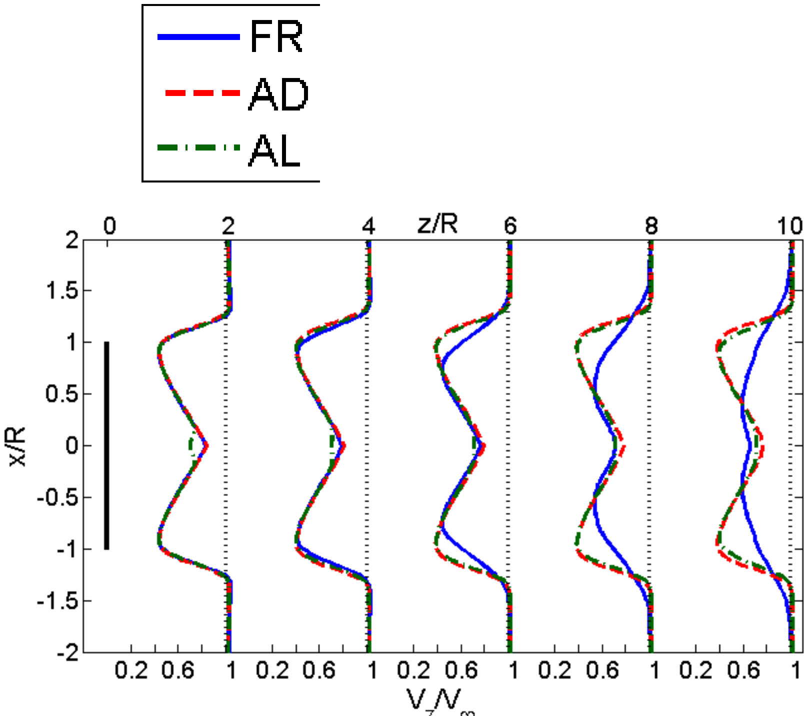
- Good agreement in predicted near wake deficit
- AL and AD in close agreement
- Wake of FR develops faster into a bell shaped form than the AL and AD.



Axial velocity

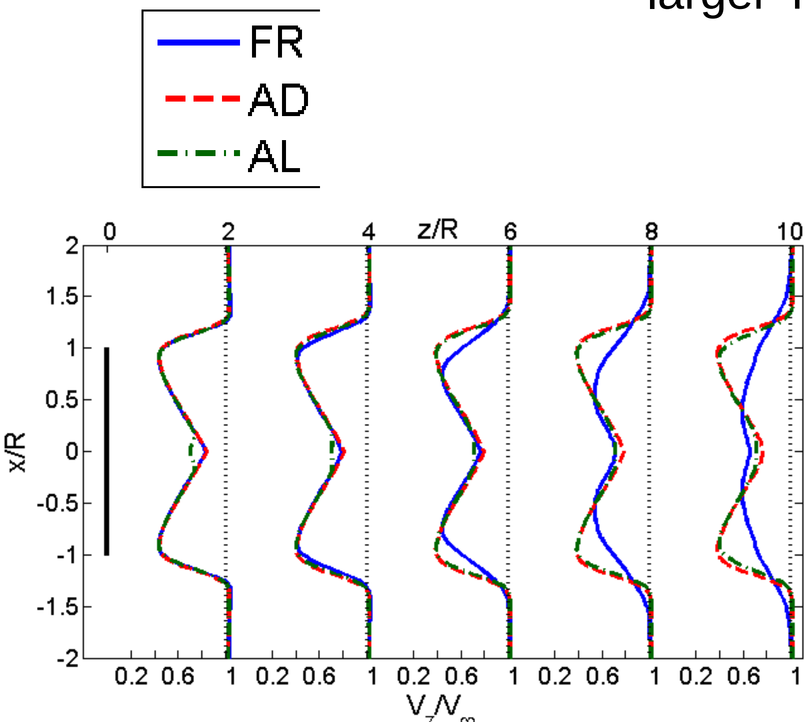
Turbulent kinetic energy

Results

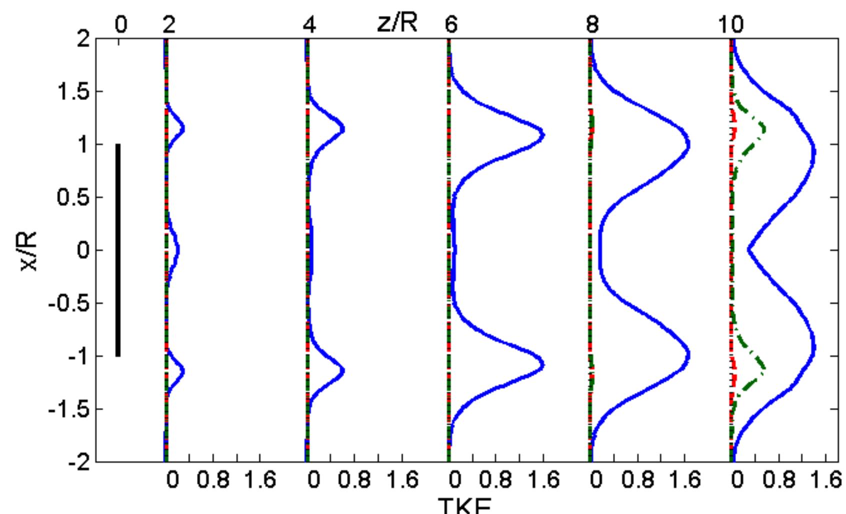
Test cases

- Uniform inflow (RANS)
- Uniform inflow (DES)
- Turbulent inflow (DES)

- ➢ Good agreement in predicted near wake deficit
- ➢ AL and AD in close agreement
- ➢ Wake of FR develops faster into a bell shaped form than the AL and AD.
- ➢ Faster spreading of wake is caused by much larger TKE in the FR simulation.



Axial velocity



Turbulent kinetic energy

Results

Test cases
• Uniform inflow (RANS)
• Uniform inflow (DES)
• Turbulent inflow (DES)

- V_∞ = 8 m/s
- No shear
- Time step Δt = 0.00435s and 0.0244s in FR and AL, respectively.
- Blade loads in AL simulations determined from airfoil data.

Results

Test cases

- Uniform inflow (RANS)
- Uniform inflow (DES)
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➢ V_∞ = 8 m/s

➢ No shear

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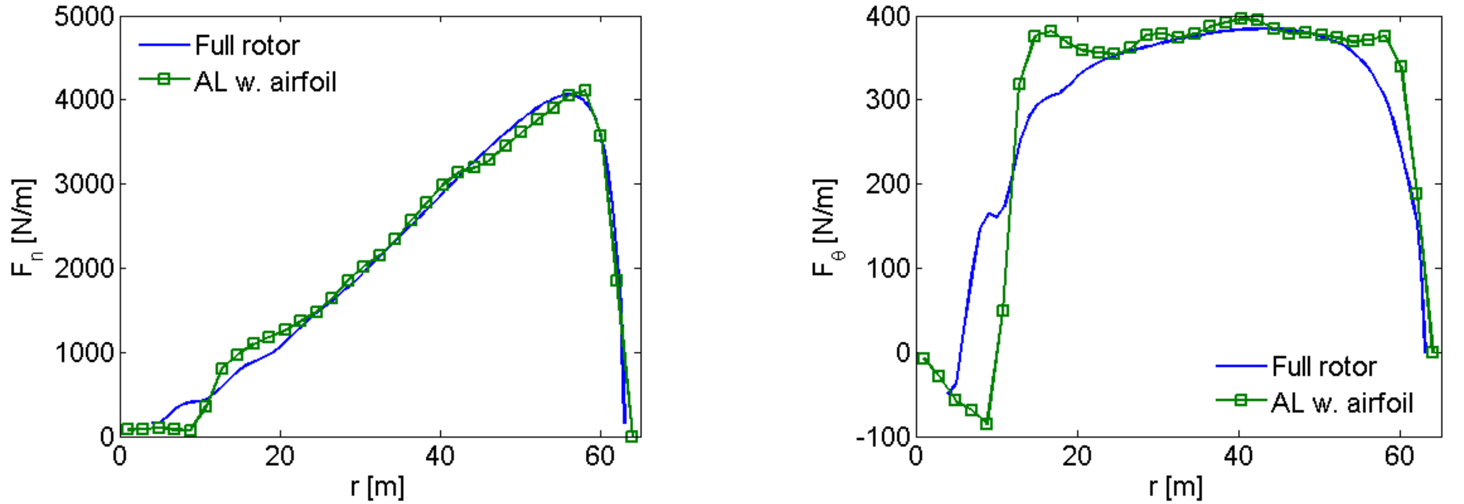

Spanwise distribution of normal and tangential loads on the blades

Results

Test cases
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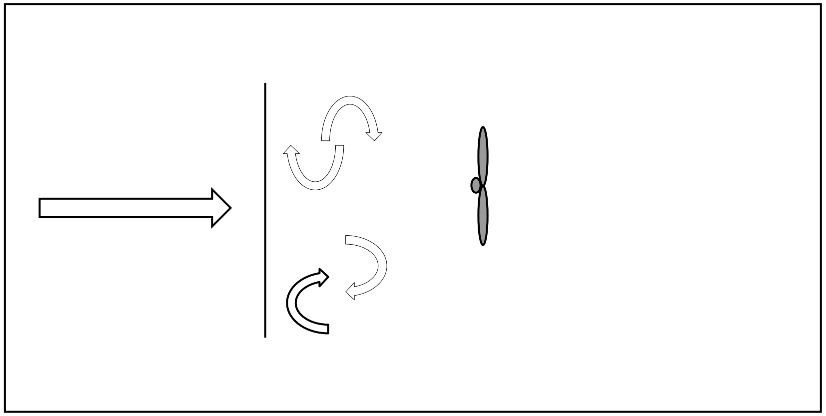
• Uniform inflow (DES)
• Turbulent inflow (DES)

- V_∞ = 8 m/s
- No shear
- Time step Δt = 0.00435s and 0.0244s in FR and AL, respectively.
- Blade loads in AL simulations determined from airfoil data.
- Synthetic atmospheric turbulence inserted in a cross-section 3R upstream of the rotor.
- Turbulence generated using algorithm of Mann.
- Turbulence intensities TI = 0.015, 0.03 and 0.06



Sketch of computational domain with turbulence cross section upstream of the turbine

Results

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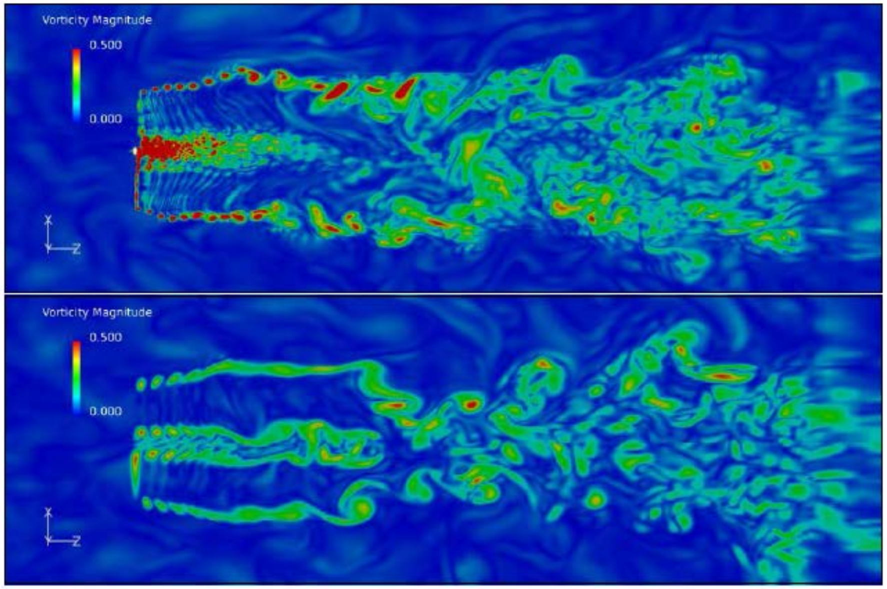
- Ambient turbulence causes wake to break down close to the rotor
- Similar wake behavior predicted by FR and AL



Snapshot of vorticity magnitude contours in horizontal cross-section through rotor center.

Results

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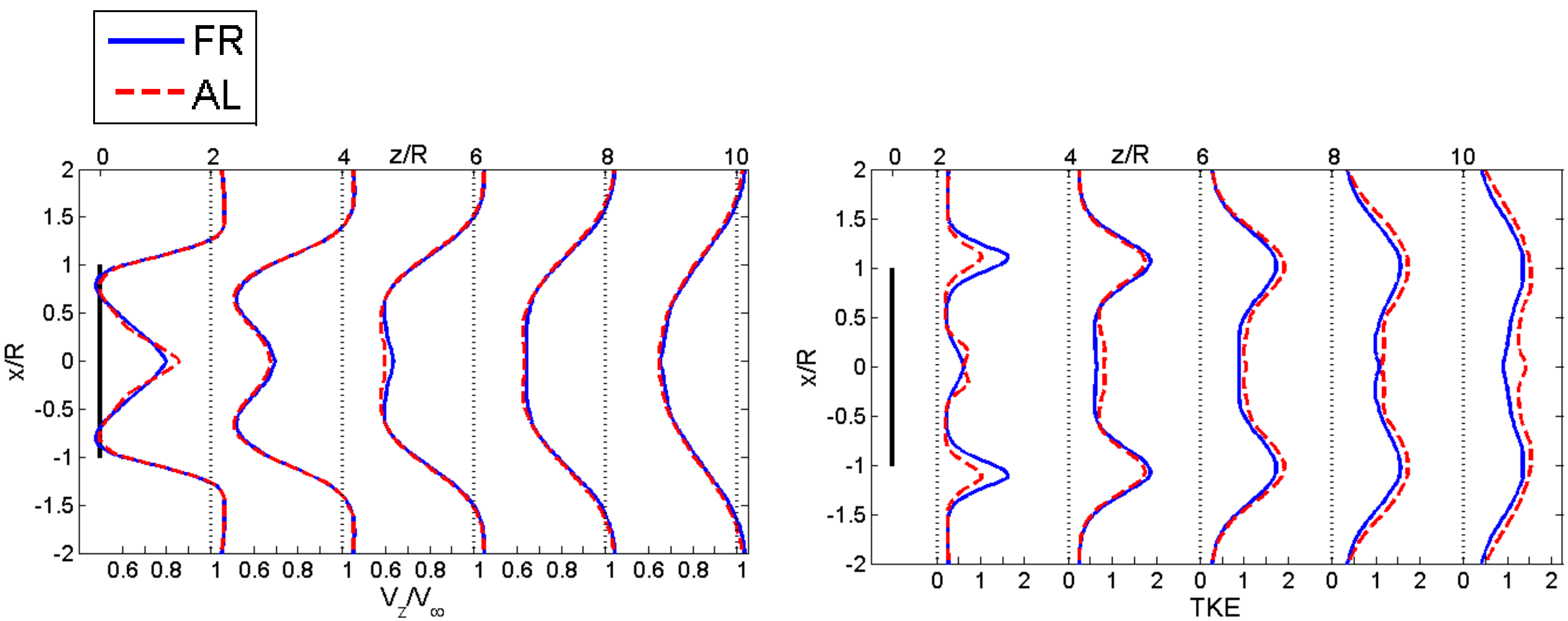
➢ Wake deficit and TKE predicted by AL in close resemblance with FR when TI = 0.06.



Axial velocity

Turbulent kinetic energy

Results

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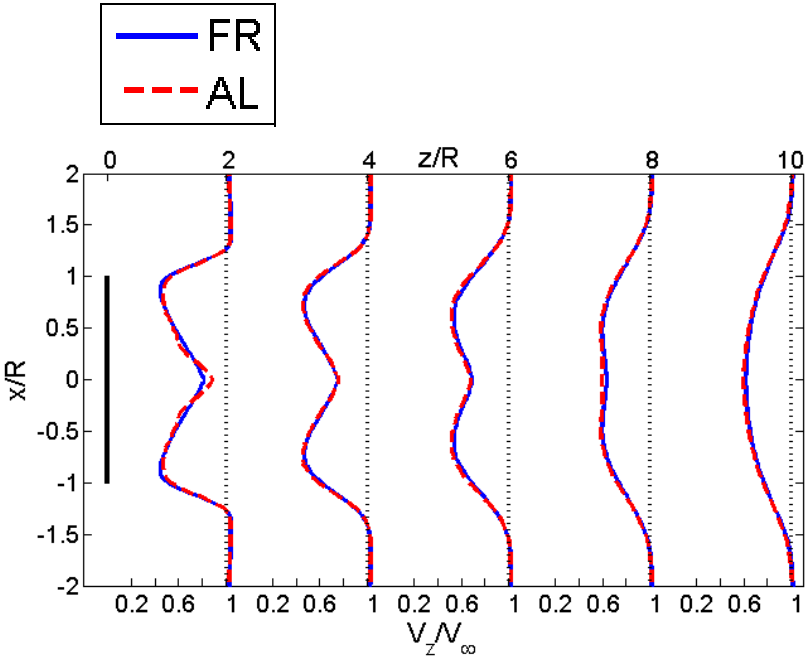
➢ Wake deficit and TKE predicted by AL in close resemblance with FR when TI = 0.06.

➢ and when TI = 0.03



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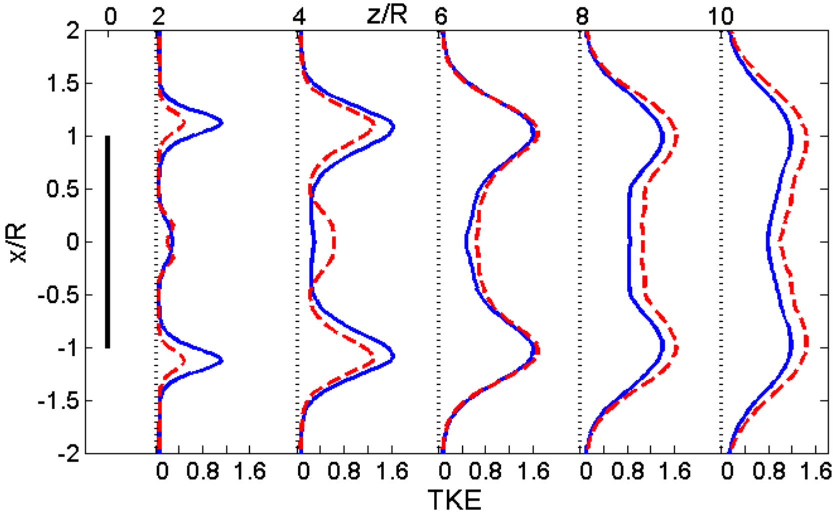

Turbulent kinetic energy

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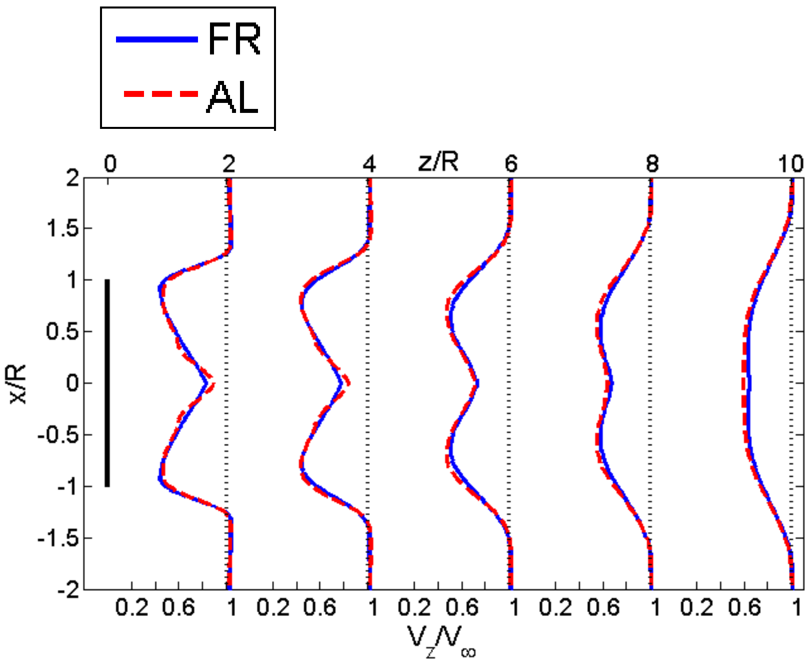
- ➢ Wake deficit and TKE predicted by AL in close resemblance with FR when TI = 0.06.
- ➢ and when TI = 0.03
- ➢ and when TI = 0.015



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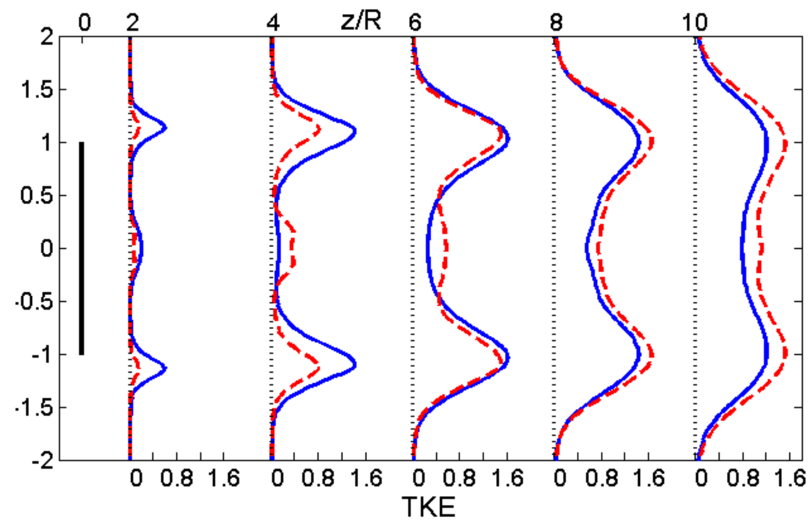


Turbulent kinetic energy

Conclusions

- Uniform and laminar inflow
  - Three models show good agreement in axial velocity up to 2D downstream of the turbine.
  - Further downstream the FR simulation predicts a faster smearing of the mean gradients
  - Much higher TKE in the FR simulation
  - Generally good agreement between AL and AD for all downstream position.

- Turbulent inflow
  - Good resemblance between wake behavior predicted using FR and AL at all TI.

Future works

- AD in turbulent inflow

- Non-uniform inflow
  - Shear
  - Yaw
  - Wake

- Grid dependency study

Turbulent inflow

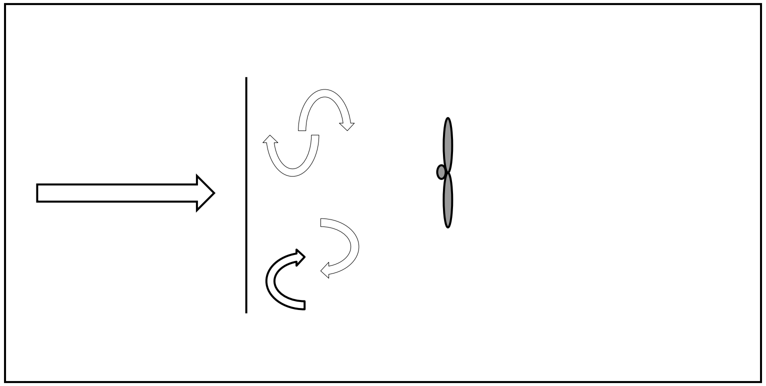
Atmospheric turbulence model:

- Synthetic turbulent fluctuations introduced in a cross section upstream of the turbine.
- Turbulence field generated using the method of Mann.
- Fluctuations introduced through unsteady body forces, **f**, in the cross section (corresponding to unsteady actuator disc).

$$\mathbf{f} = \dot{m}\mathbf{u}$$

- Forces smeared in the direction normal to the cross section to avoid singular behaviour.

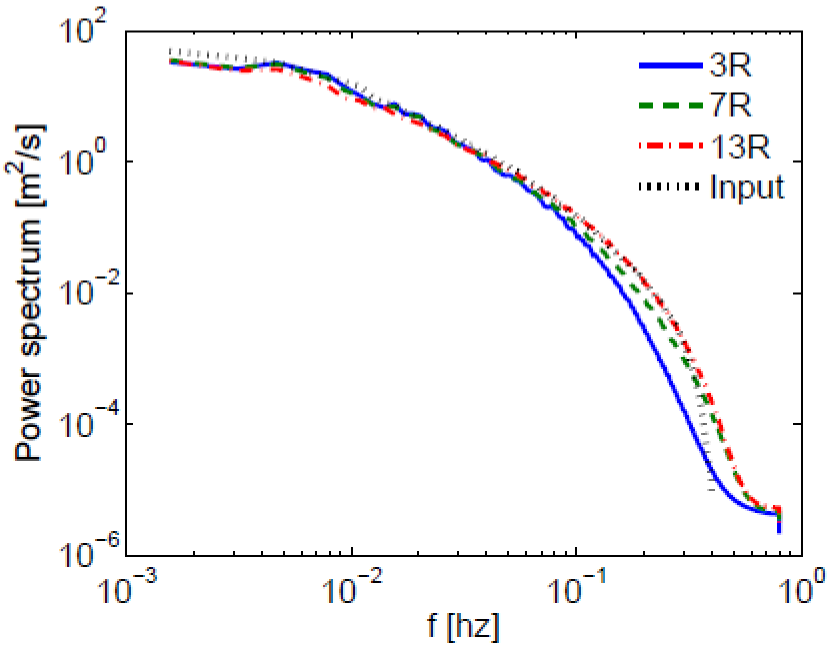
$$\mathbf{f}_\varepsilon = \mathbf{f} \otimes \eta_\varepsilon, \quad \eta_\varepsilon = \frac{1}{\varepsilon \pi^{1/2}} \exp\left[-\frac{d^2}{\varepsilon^2}\right]$$



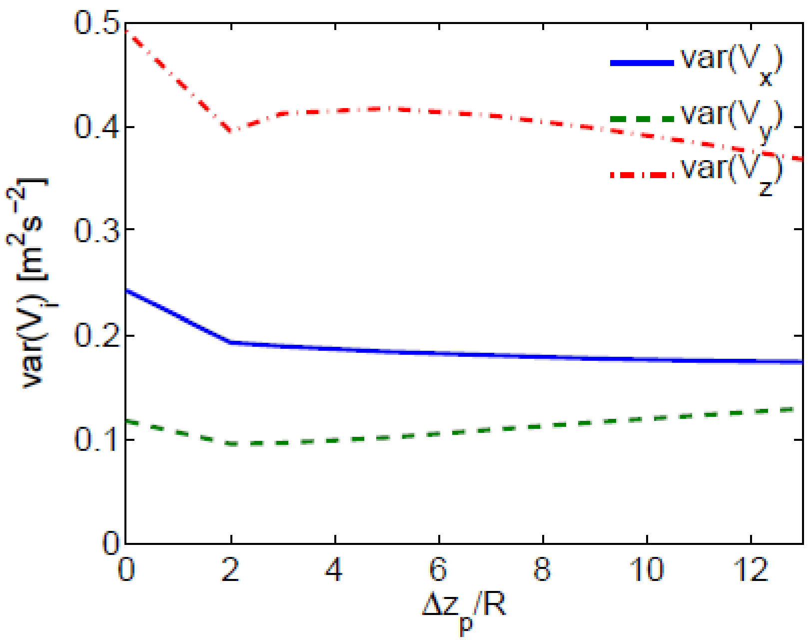
Turbulent inflow

Decay of inserted turbulence:

- Turbulence decays (no production to balance dissipation)
- Decay of energy is in the order of 80% in the region of interest



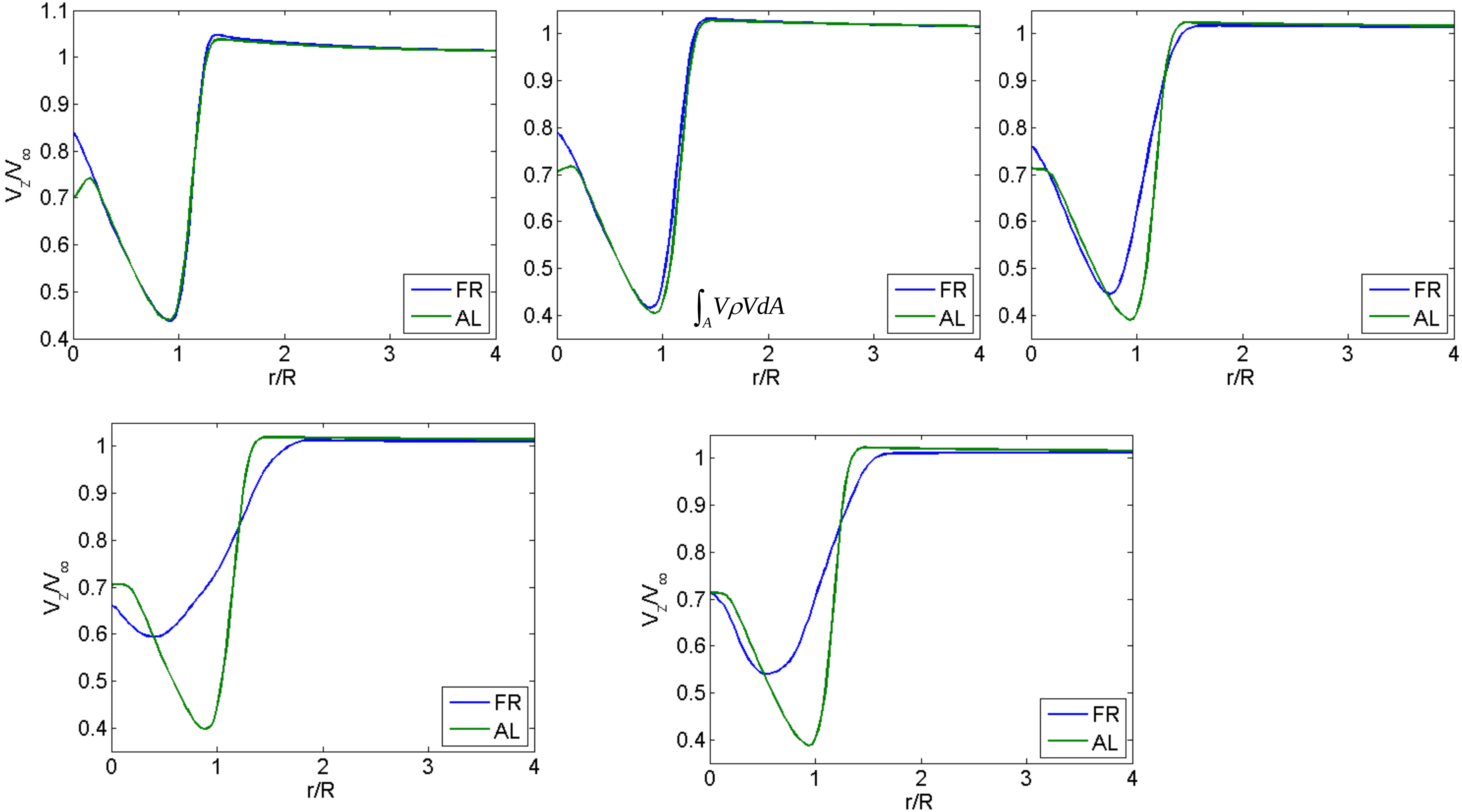
Spectra of axial velocity downstream of cross-section



Variance of each velocity component downstream of cross-section

Velocity profiles

- Integration of momentum over circular cross-section with r=2R gives



Numerical investigations

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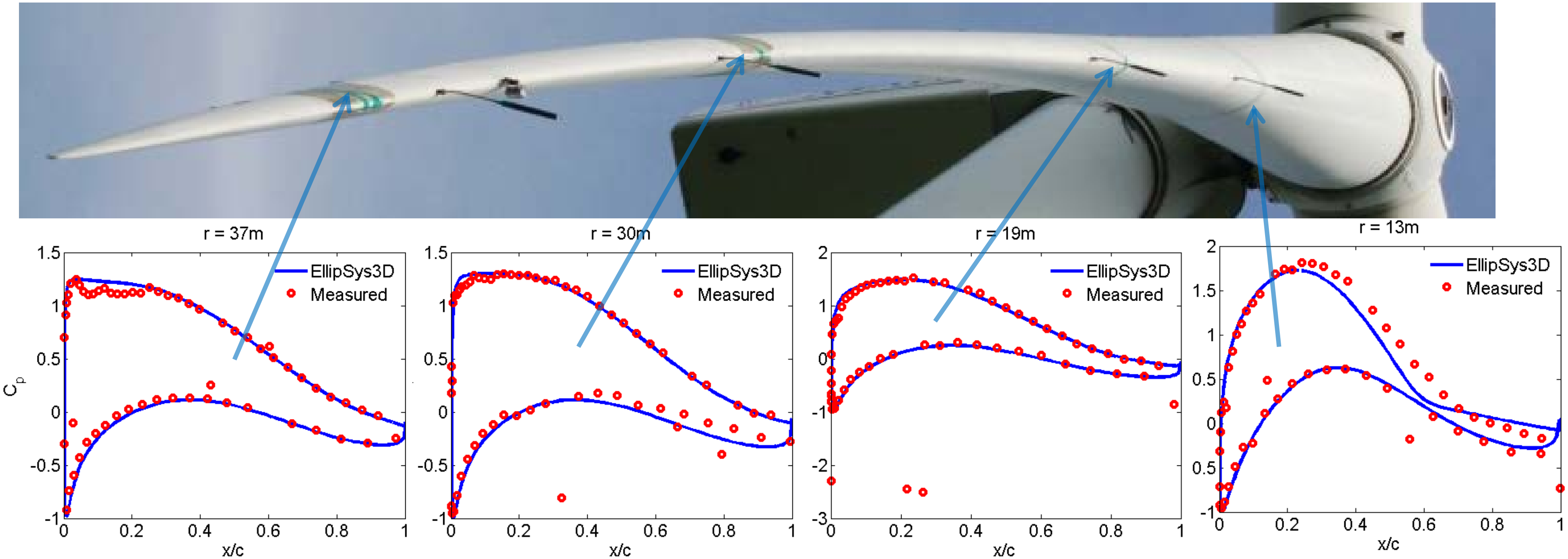

Comparison of computed and measured pressure distributions obtained during the DAN-AERO project

Results

Test cases
• Uniform inflow (RANS)
• Uniform inflow (DES)
• Turbulent inflow (DES)

- $V_\infty = 8$ m/s
- Closure using k-ω SST turbulence model
- Steady state AD simulation
- $\Delta t = 0.00435$s and 0.0244s for FR and AL, respectively (1500 and 267 time steps per rev.)
- Forces from FR simulation applied directly in the AL and AD simulations
- Computing expenses:
  - $T_{FR} \approx 21T_{AL} \approx 105T_{AD}$

Results

Test cases

- Uniform inflow (RANS)
- Uniform inflow (DES)
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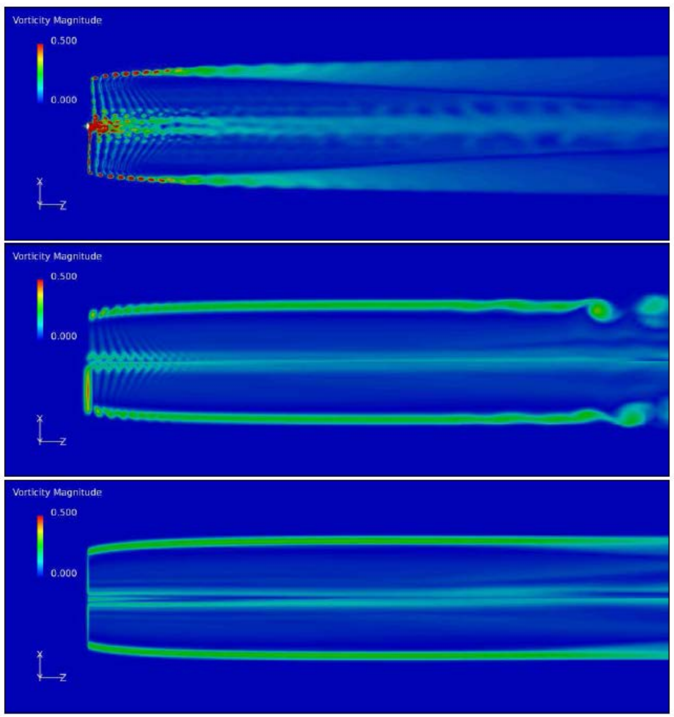
➢ Vorticity from tip vortices much stronger in FR than in AL and AD.

➢ Larger spreading of vorticity in FR

➢ Similar vorticity contours for AL and AD (except for instabilty in the far wake)



Snapshot of vorticity magnitude contours in horizontal cross-section through rotor center.

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- Good agreement in predicted near wake deficit
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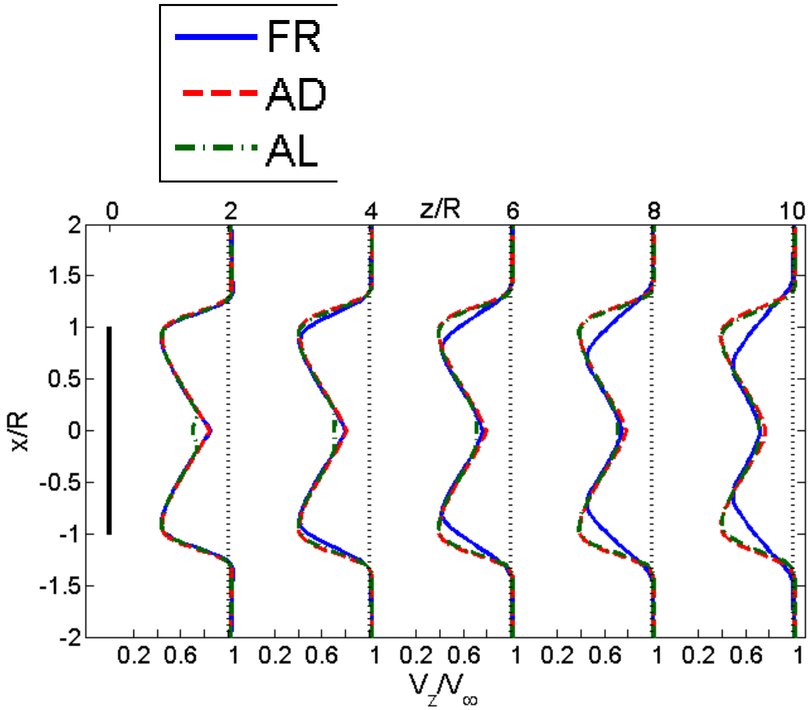

Axial velocity

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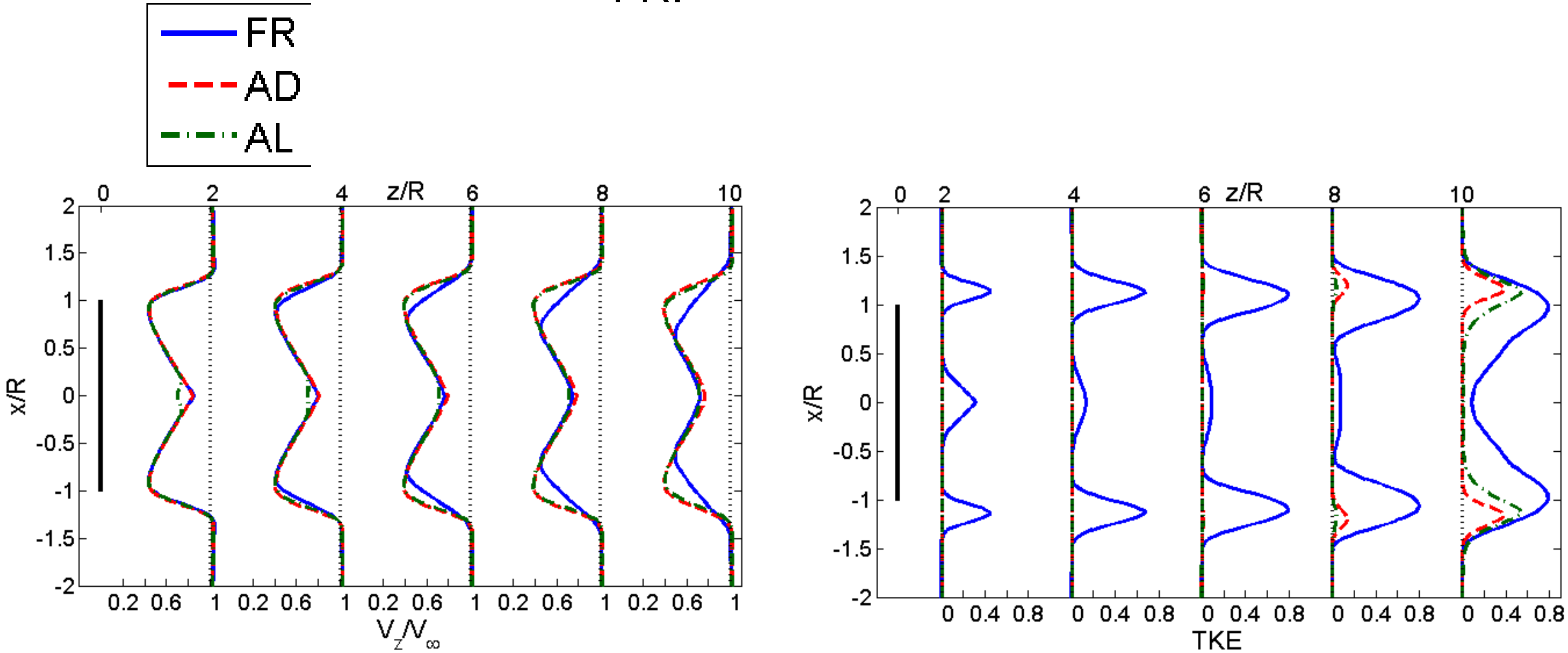
- Faster spreading of wake deficit with FR than with AL and AD.
- Faster spreading caused by much larger TKE in FR.



Axial velocity

Turbulent kinetic energy

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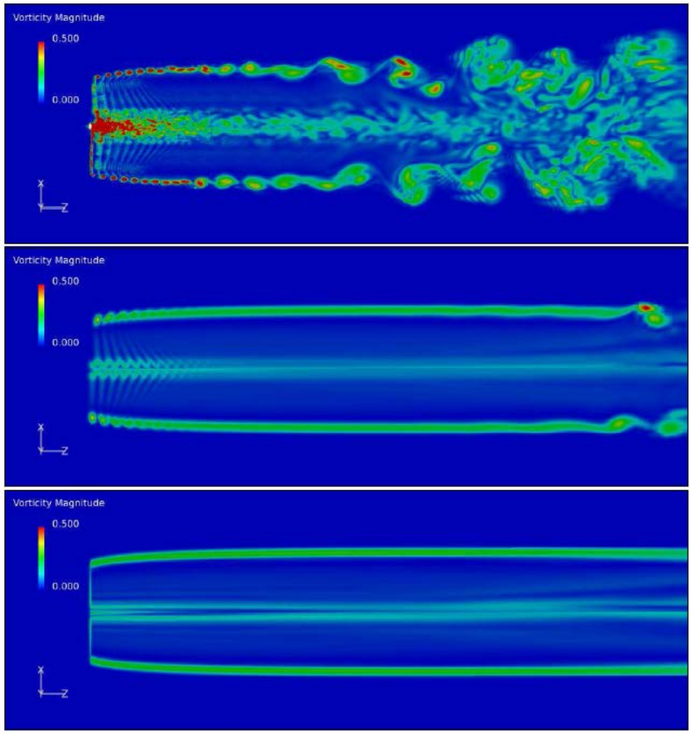


Snapshot of vorticity magnitude contours in horizontal cross-section through rotor center.

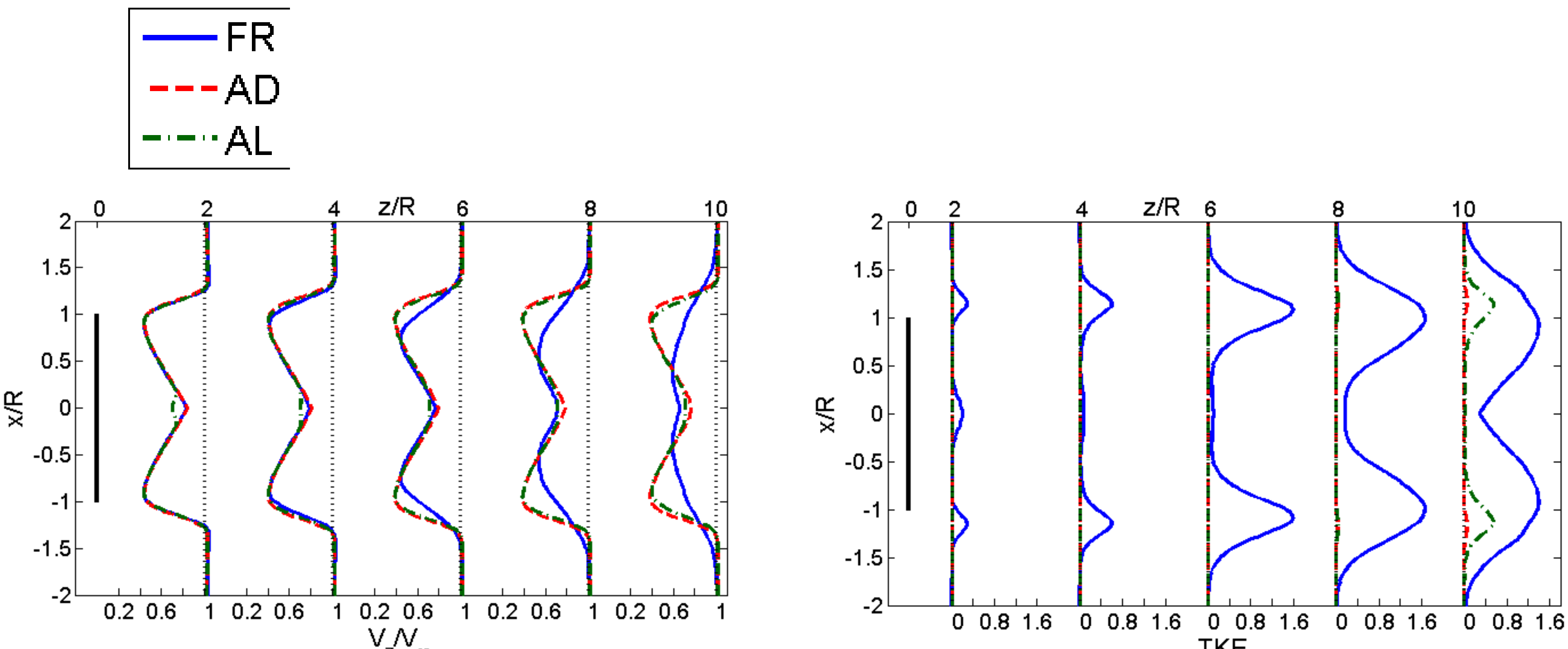
- Wake of FR becomes unstable and breaks up.
- Switching to DES has limited effect on AL and AD simulations.
- Reasons for more unstable wake of FR:
  - Higher grid resolution
  - Fluctuating loads (e.g. stall effets near root)

Results

Test cases

- Uniform inflow (RANS)
- Uniform inflow (DES)
- Turbulent inflow (DES)

- Wake of FR develops faster into a bell shaped form than the AL and AD.
- AL and AD again in close agreement
- Switching to DES causes increased levels of TKE in the FR simulation



Axial velocity

Turbulent kinetic energy

Objectives

- Conduct a consistent comparison of the three models
  - Simulate wake of the NREL 5MW Reference turbine
  - Same numerical setup for all models
- Study the strength and limitations of the models
- Establish guidelines for when and how to use the models

Results

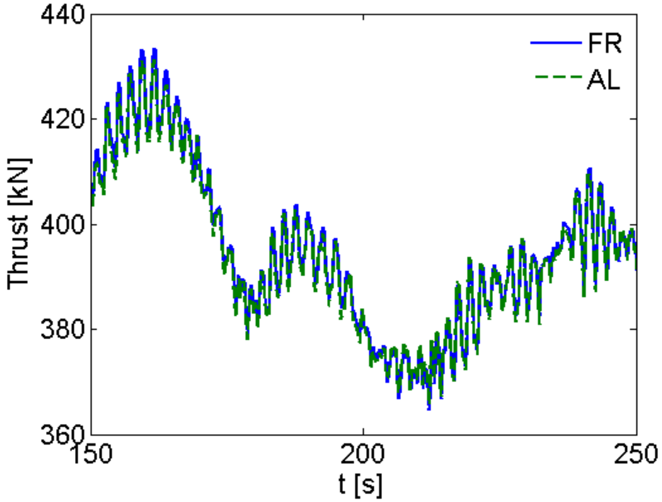
Test cases

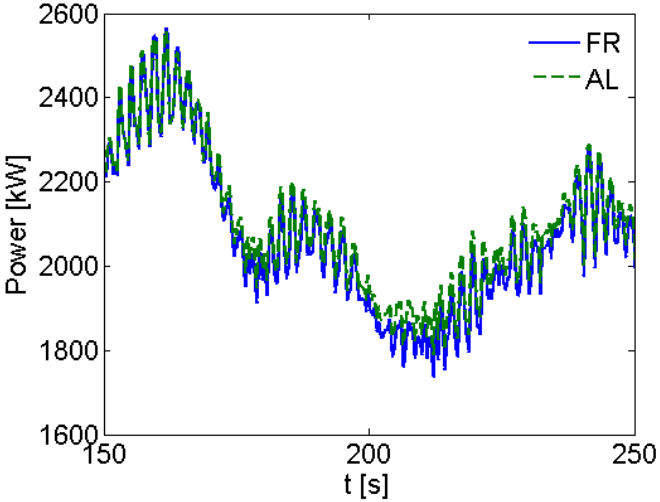
- Uniform inflow (RANS)
- Uniform inflow (DES)
- Turbulent inflow (DES)

➢ V_∞ = 8 m/s

➢ Time step Δt = 0.00435s and 0.0244s in FR and AL, respectively.

➢ Blade loads in AL simulations determined from airfoil data.





Temporal variation of integrated thrust and power with FR and AL, respectively