Comparison of wind turbine wake properties in non-uniform inflow predicted by different CFD rotor models

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Comparison of wind turbine wake properties in non-uniform inflow predicted by different CFD rotor models

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Risø DTU
National Laboratory for Sustainable Energy

Background

Wind turbine models in CFD

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

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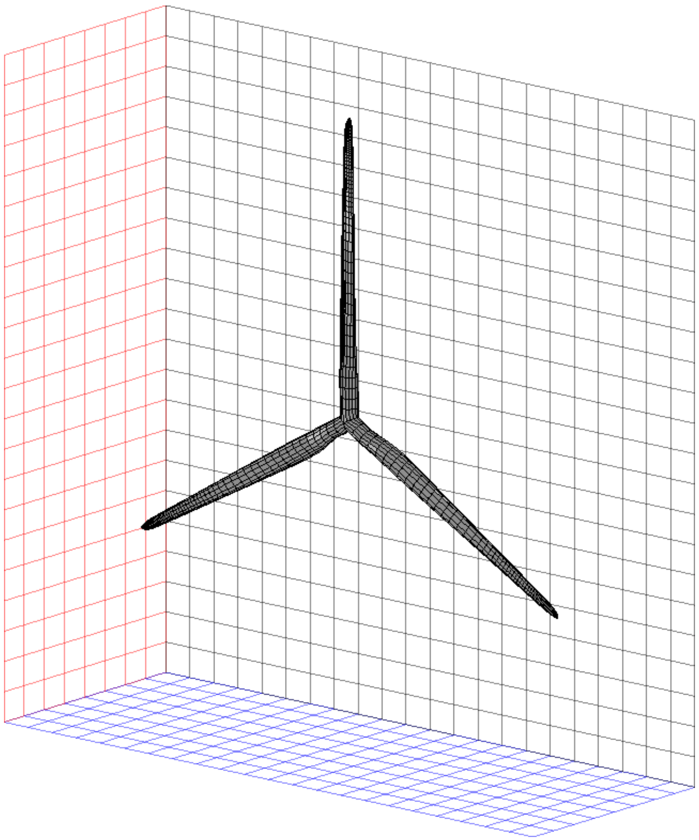
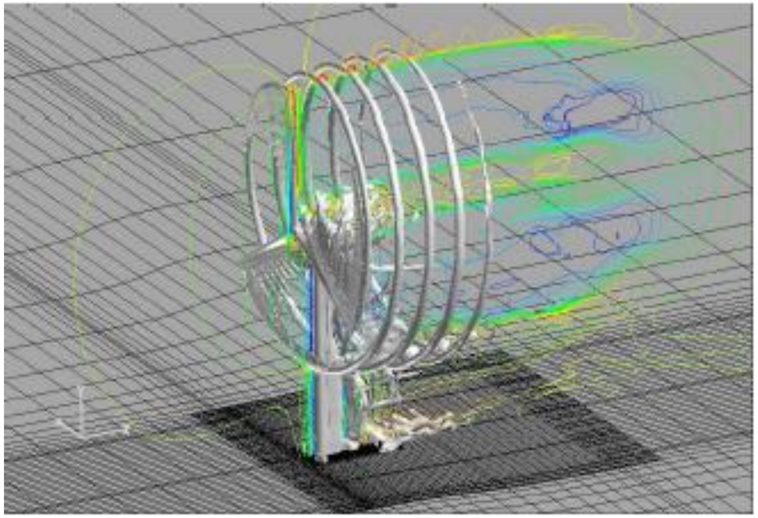


- The blade/airfoil boundary layer is resolved
- The required number of grid points for one rotor using RANS is $O(10^7)$
- Provides detailed insight about flow behaviour
- Usually used for accurately predict loads and power production
- Too computationally heavy for several wind turbines.



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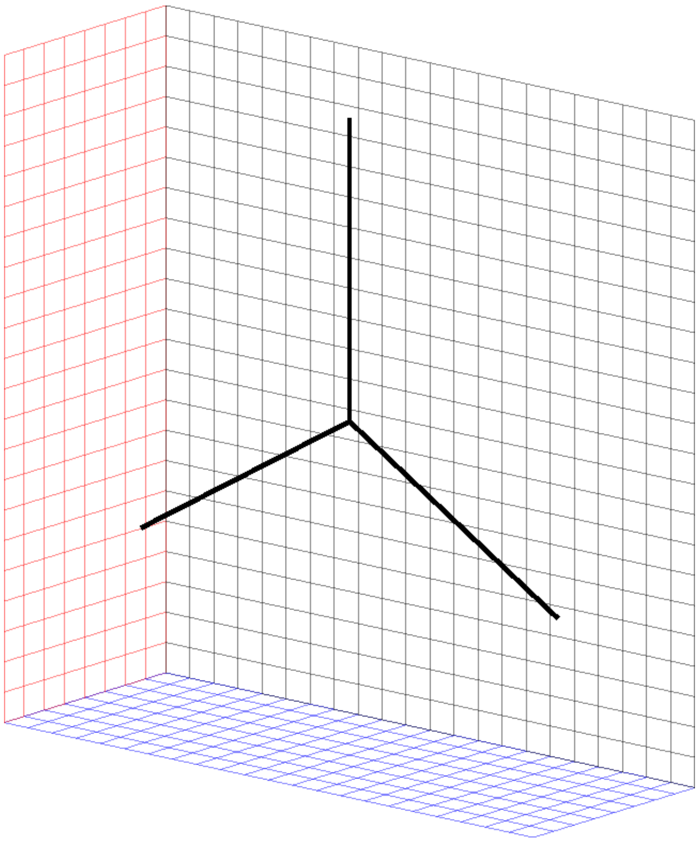

➢ Blades represented as lines.

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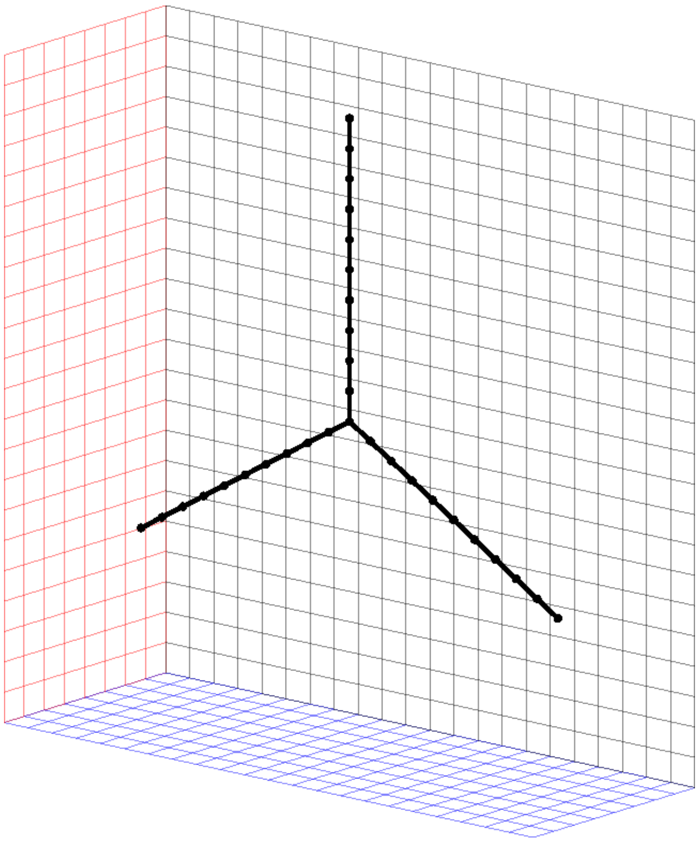

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- Aerodynamic blade forces determined from 2D airfoil data.

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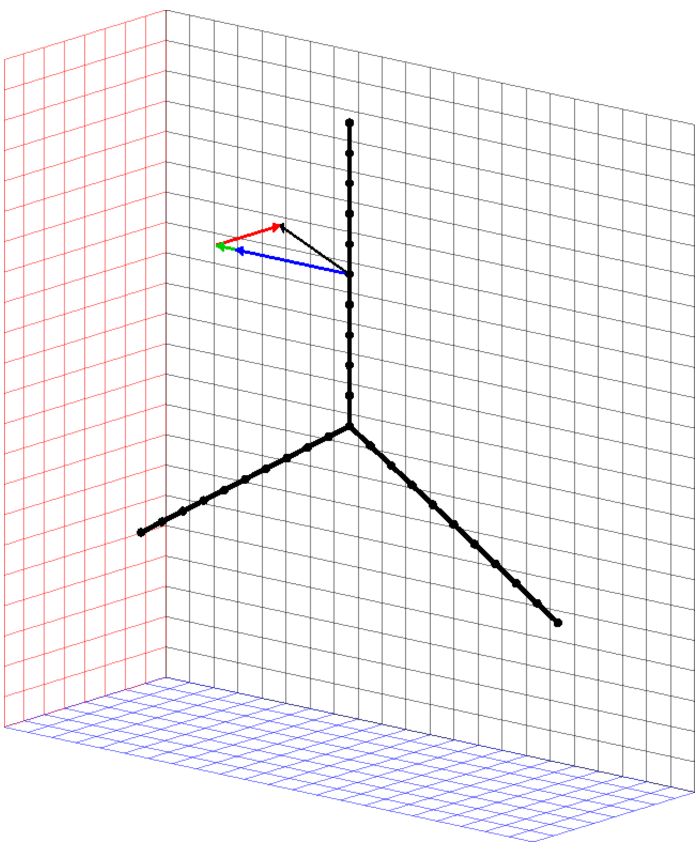
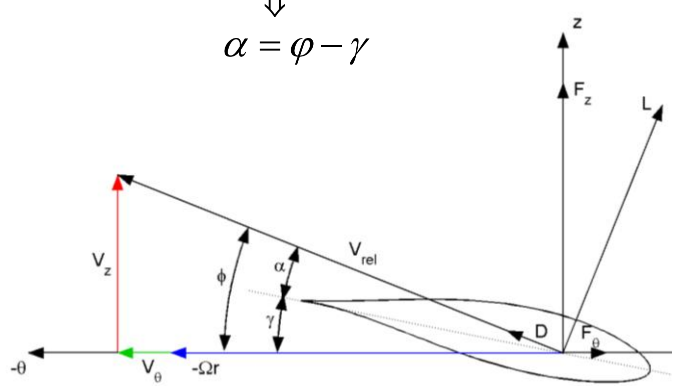
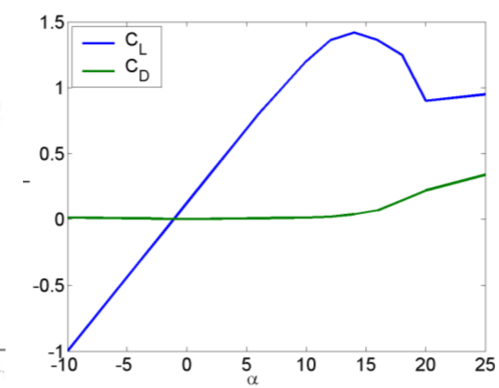


$$\varphi = \tan^{-1}\left(\frac{V_z}{\Omega r - V_\theta}\right)$$
$$\Downarrow$$
$$\alpha = \varphi - \gamma$$

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





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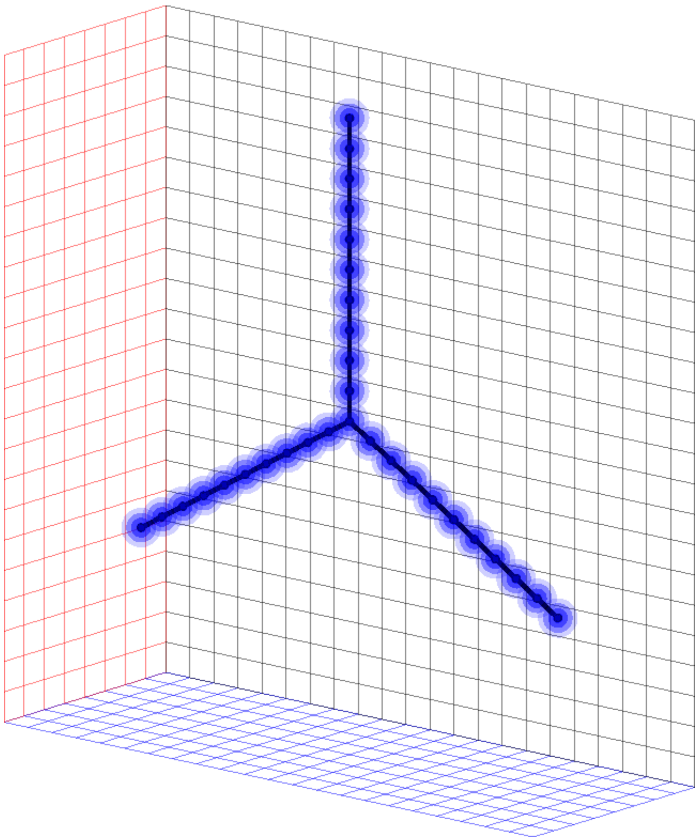

- Blades represented as lines.
- Aerodynamic blade forces determined from 2D airfoil data.
- Blade forces smeared to avoid singular behaviour.

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

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

$$\Downarrow$$

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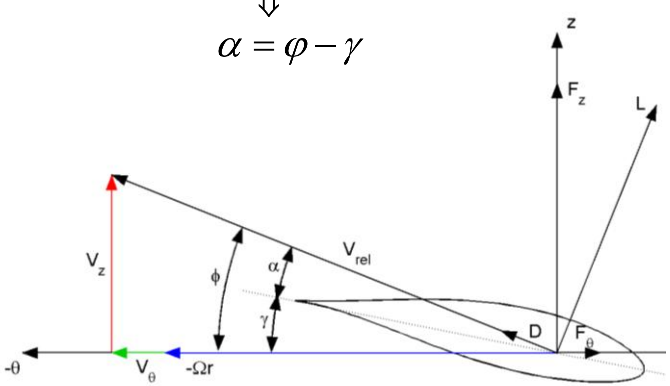
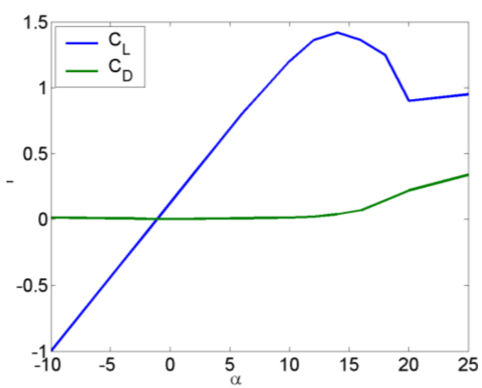




Background

Wind turbine models in CFD

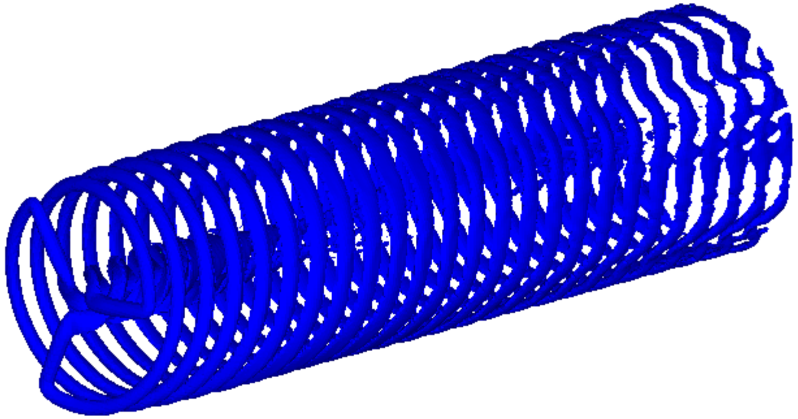
- Fully resolved rotor (FR)
- Actuator line model (AL)
- Actuator disc model (AD)

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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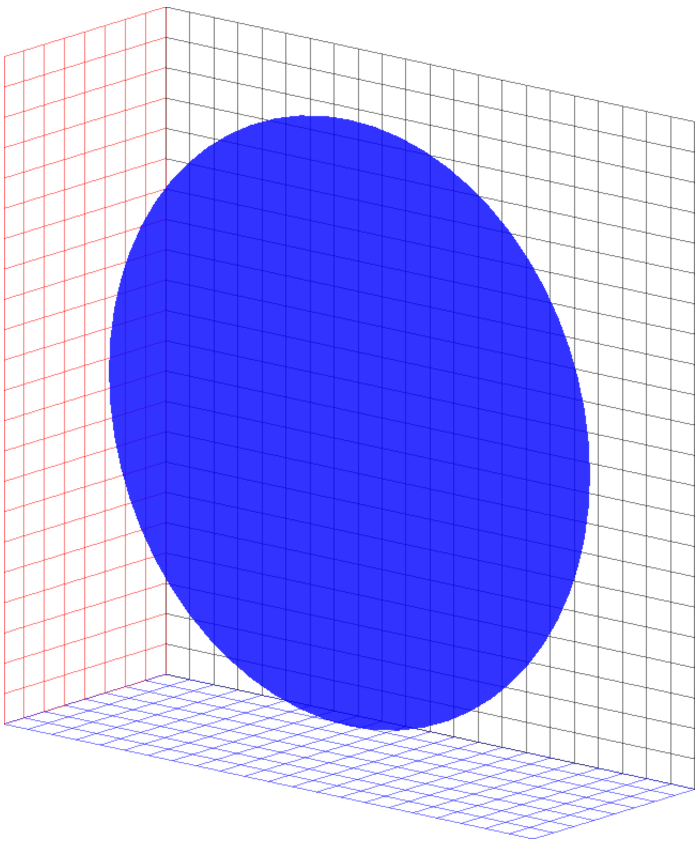

➢ Rotor represented by forces distributed on permeable disc.

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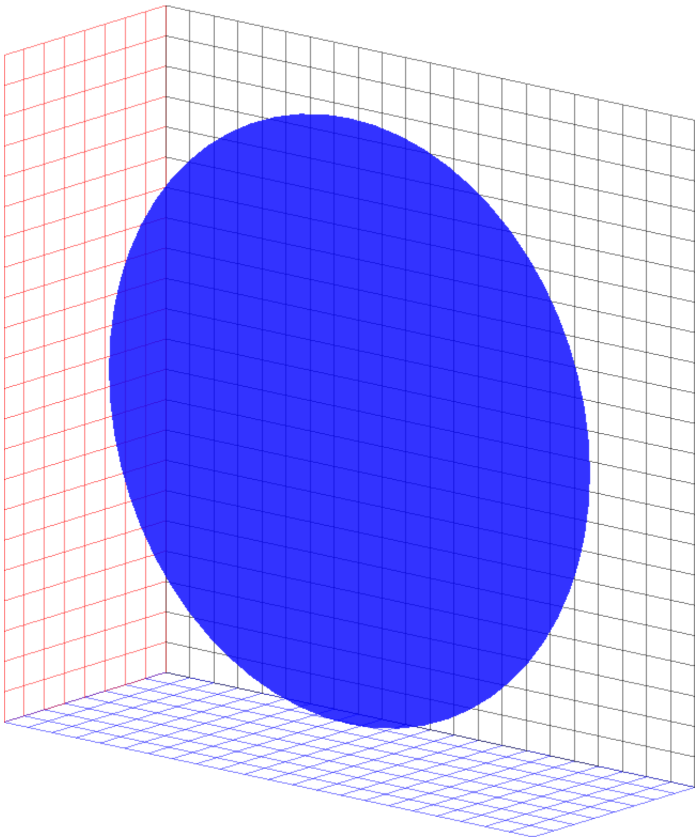


- Rotor represented by forces distributed on permeable disc.
- The disc loading is either prescribed or determined from airfoil data.
- Pressure velocity decoupling avoided using Gaussian force smearing or a modified Rhie-Chow algorithm

Background

Wind turbine models in CFD

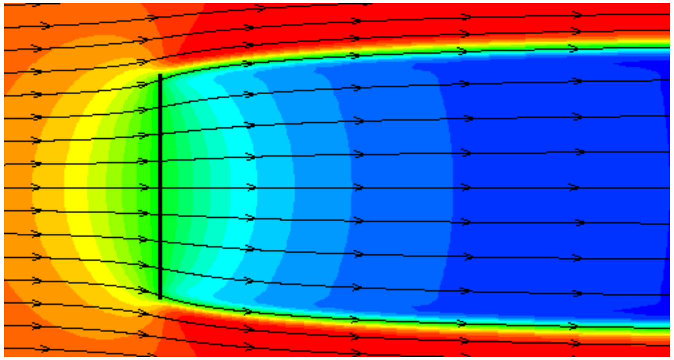
- Fully resolved rotor (FR)
- Actuator line model (AL)
- Actuator disc model (AD)

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

Summary:

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

Objectives:

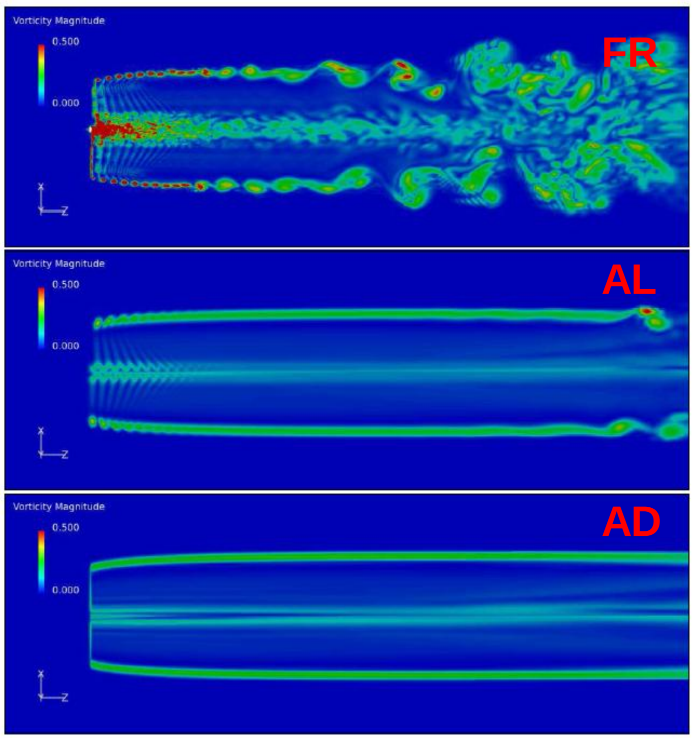
- Study importance of wind turbine model on wake characteristics
    - How much details are lost due to the simpler models?

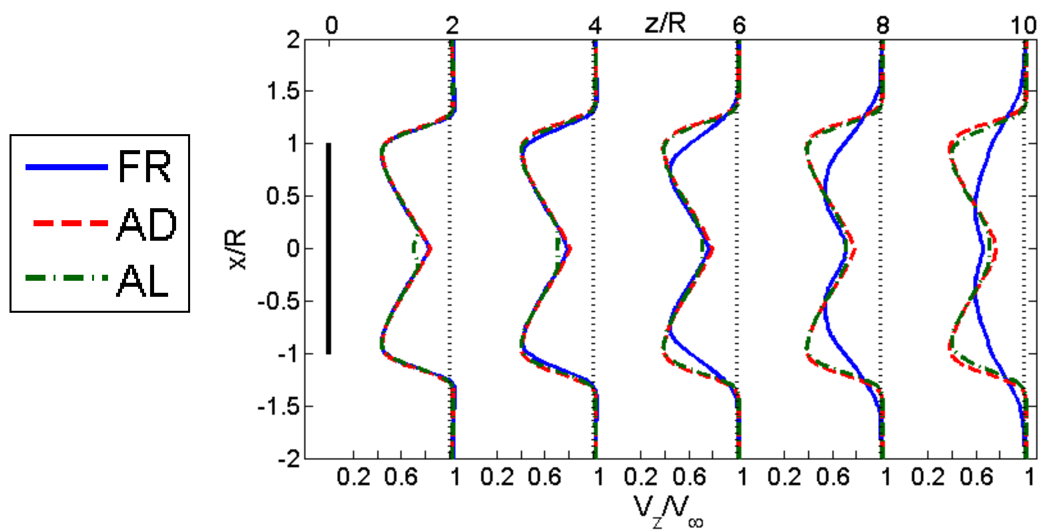
- Conduct a consistent comparison of the three models
    - Same numerical setup for all models

Previous work

Simulations of NREL 5MW reference turbine in non-sheared laminar inflow

- Wake of FR develops faster into a bell shaped form than the AL and AD.
- Faster spreading of wake is caused by larger TKE in the FR simulation.

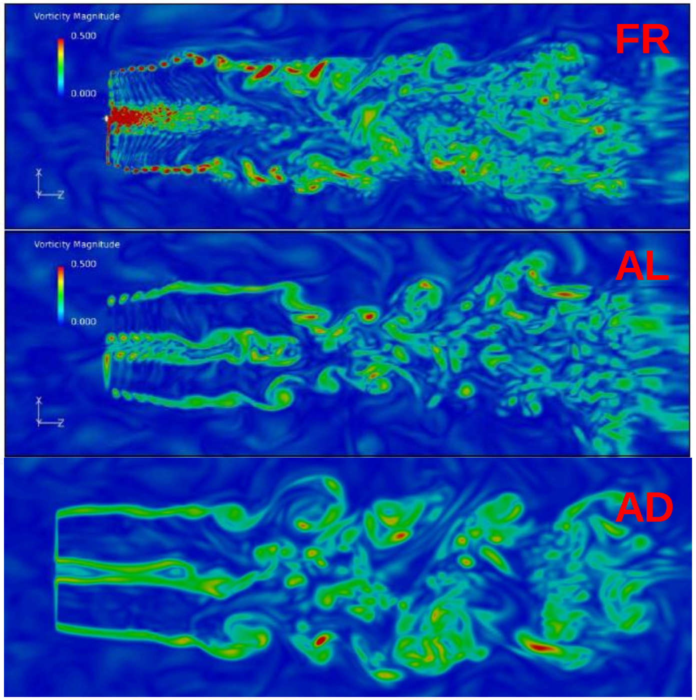


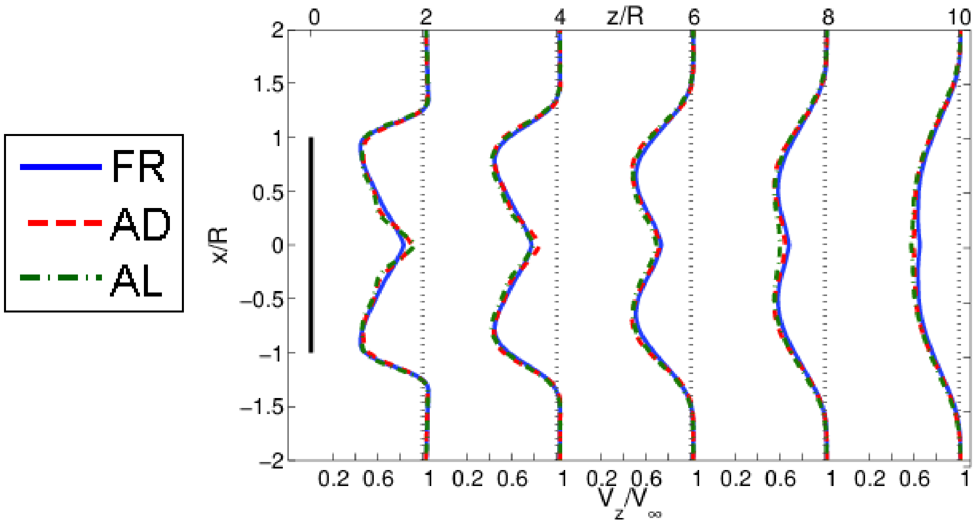


Axial velocity

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

Simulations of NREL 5MW reference turbine in non-sheared turbulent inflow





Axial velocity

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

Present work

Objectives:

➢Study importance of wind turbine model on wake characteristics in non-uniform inflow:

- ➢ Sheared inflow
- ➢ Yawed inflow

➢ Simulating the 2MW NM80 turbine using similar numerical setup

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

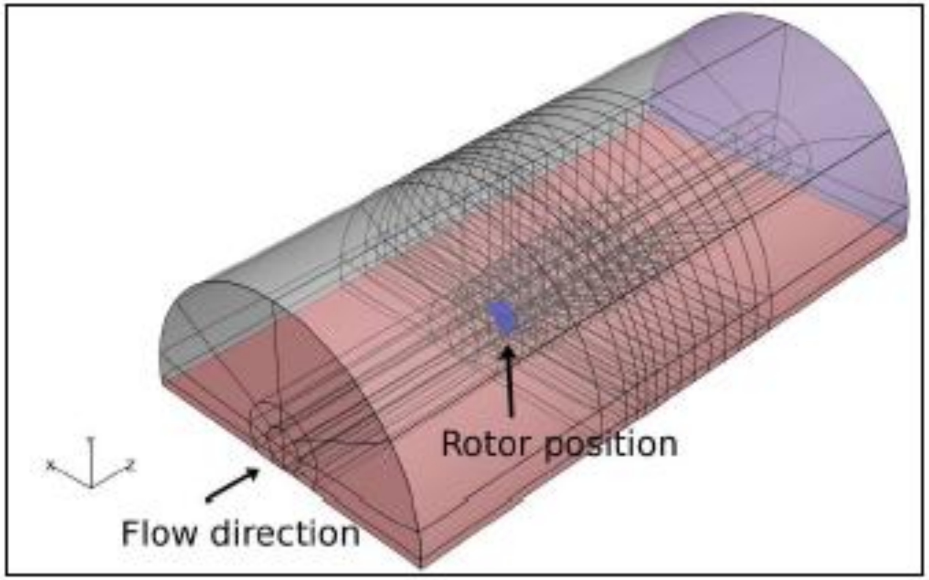
Solver parameters:

- QUICK/QUICK_CDS4
- SIMPLE
- DES

Approach - Numerical setup

Background mesh:

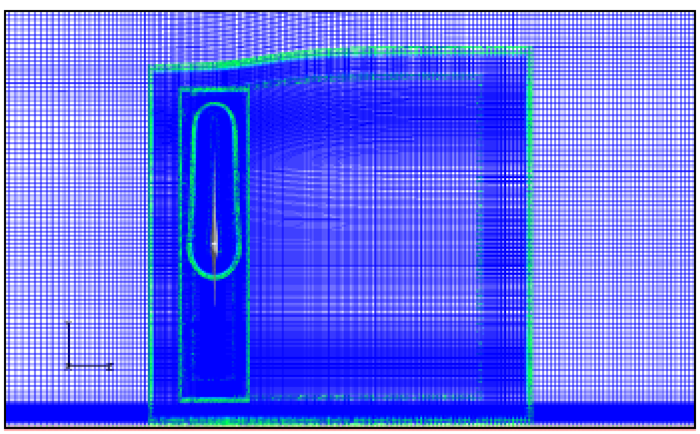
- Same background mesh for all simulations
- Half cylinder with radius 8D
- 308 blocks of 32^3 ($10.1 \cdot 10^6$ cells)
- High resolution of the first 5D of the wake
(cell size 1.3m x 1.3m x 0.8m)

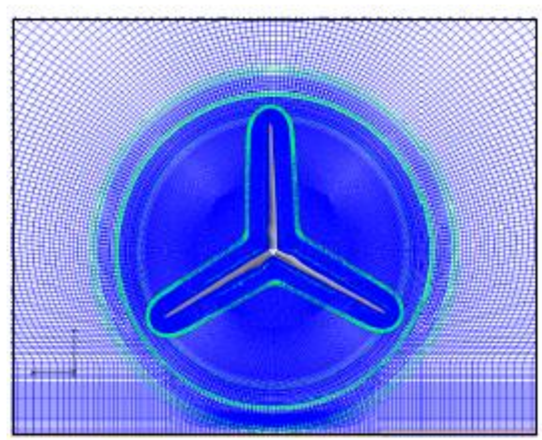


Approach - Numerical setup

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 $26.7 \cdot 10^6$
- Rotor surface with a non-slip boundary condition
- First cell height $y=1.0 \cdot 10^6$ ($y^+ < 2$)





Approach - Numerical setup

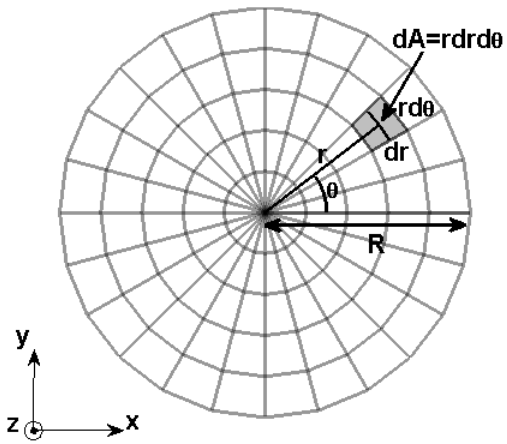
Actuator line simulations:

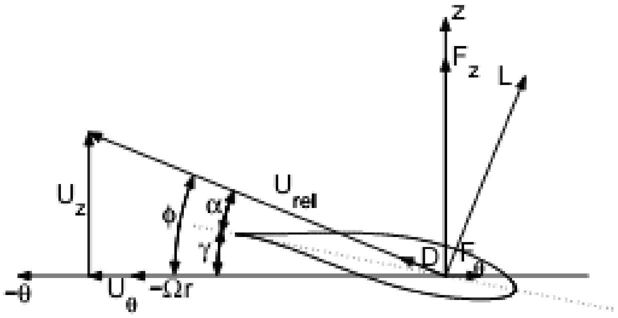
- Same background mesh as the full rotor simulation ($10.1 \cdot 10^6$ cells)
- Force smearing using 3D convolution
- 33 force elements along each line

Approach - Numerical setup

Actuator disc simulations:

- Same background mesh as the full rotor simulation ($10.1 \cdot 10^6$ cells)
- 33 radial force elements
- Force smearing using 1D convolution in normal and radial direction
- Forces on each differential area dA=rdrdθ is determined from local flow conditions and airfoil data.





Results

Test cases
• Sheared inflow
• Yawed inflow

Results

Test cases
• Sheared inflow
• Yawed inflow

- V_∞ = 8 m/s
- Power law inflow (α = 0.55):

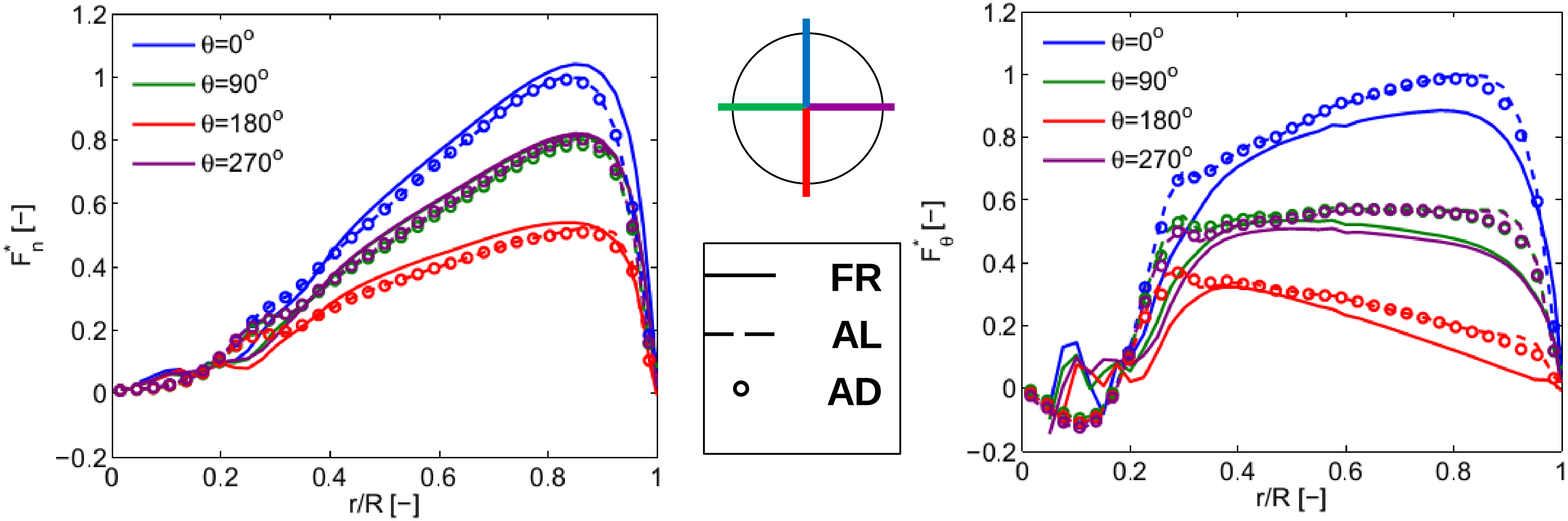
$$V_Z = V_\infty \left(\frac{y}{H} \right)^\alpha$$

Results

Test cases

- Sheared inflow
- Yawed inflow

- Normal loads in good agreement
- Tangential loads less in FR than in AL and AD



Spanwise distribution of normal and tangential loads at various azimuth positions

Results

Test cases
• Sheared inflow
• Yawed inflow

➢ Vorticity from tip vortices much stronger in FR than in AL and AD.

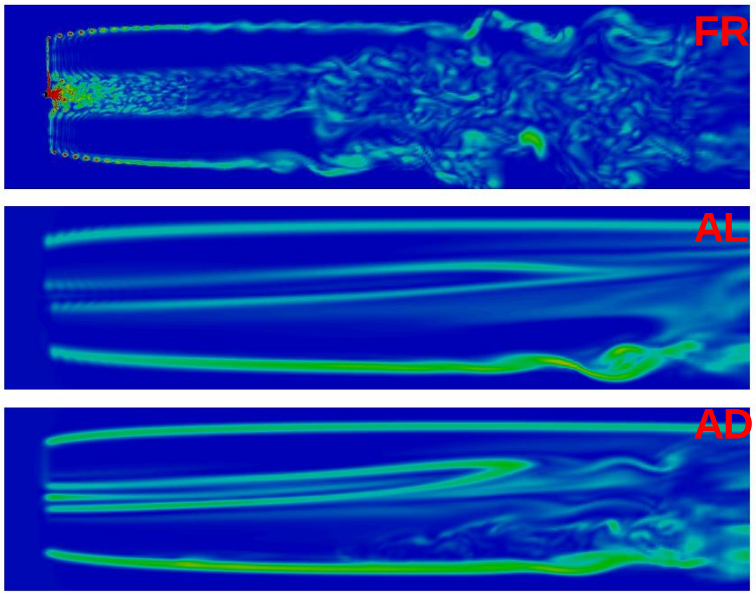
➢ Wake of FR more unstable

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

➢ Reasons for more unstable wake of FR:

  ➢ Higher grid resolution

  ➢ Fluctuating loads (e.g. stall effets near root)



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

Results

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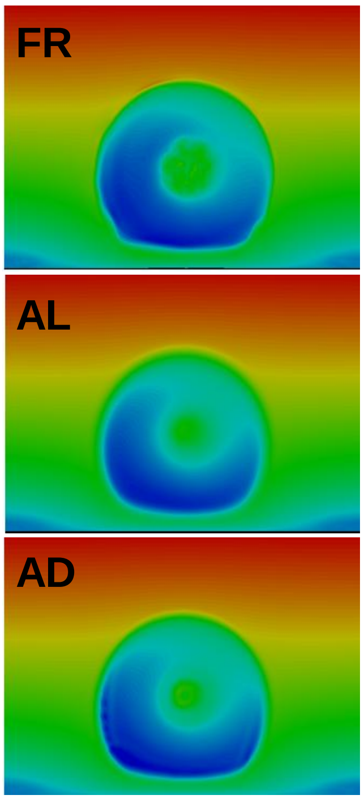
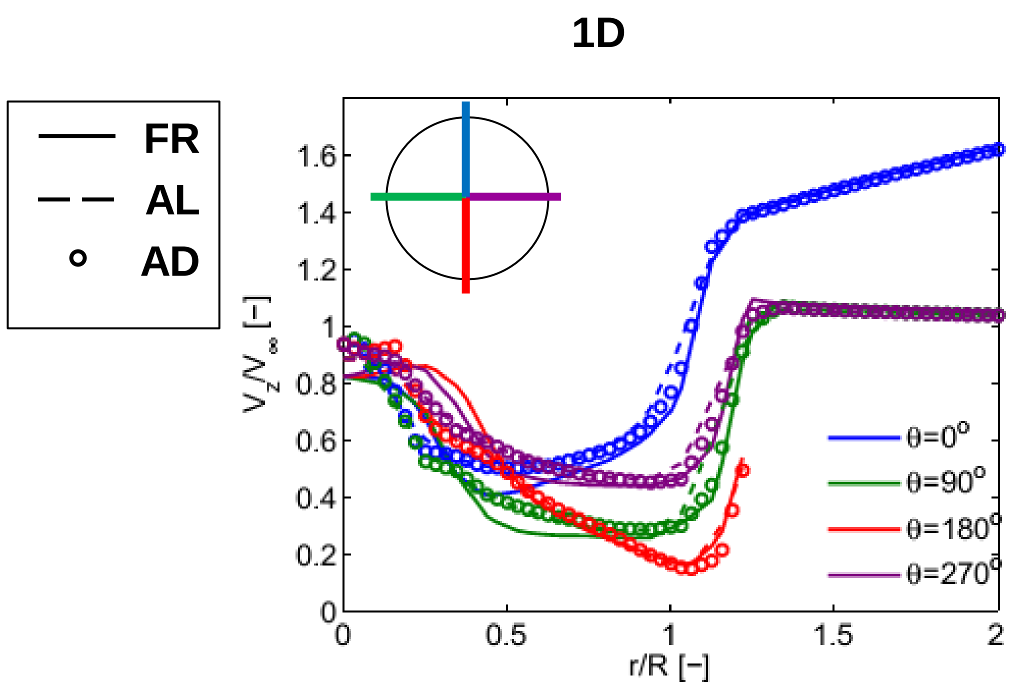


Streamwise velocity contours in cross-section 1D downstream.

- 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.



Mean streamwise velocity 1D downstream for various azimuth positions

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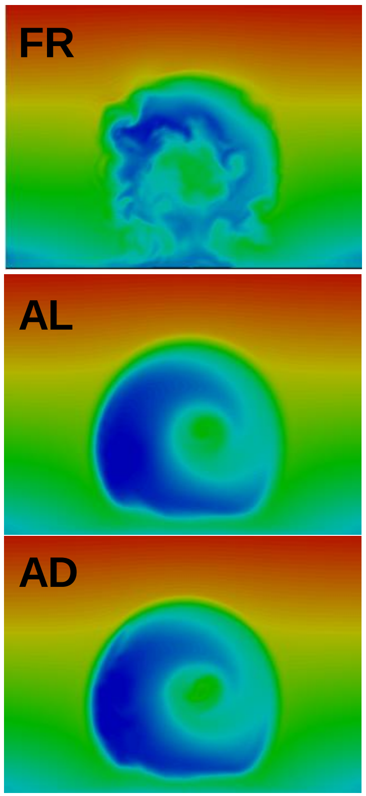
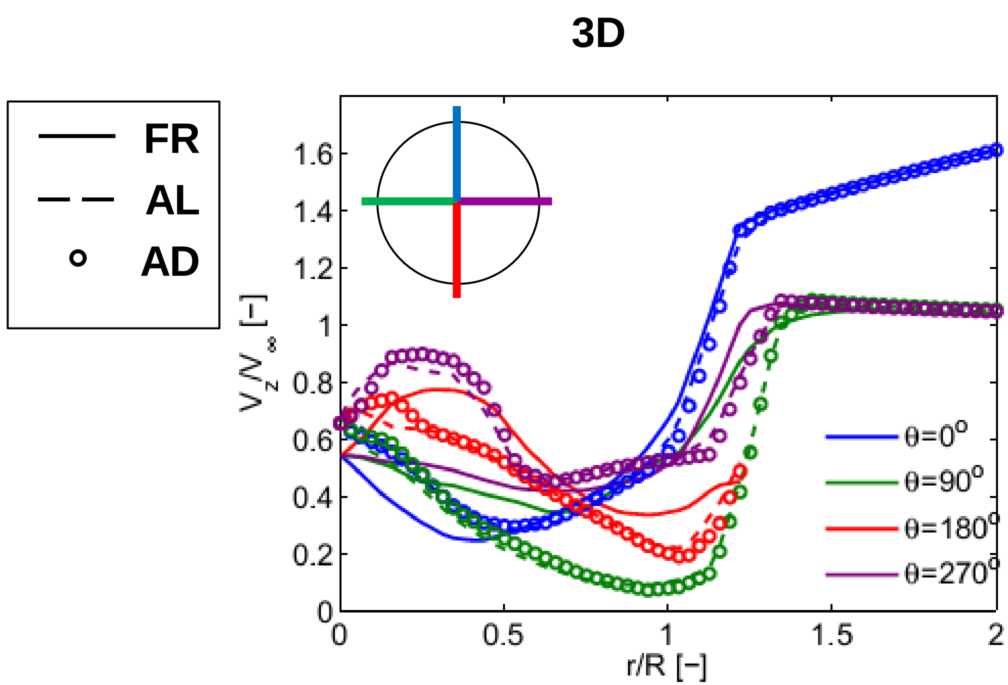


Streamwise velocity contours in cross-section 3D downstream.



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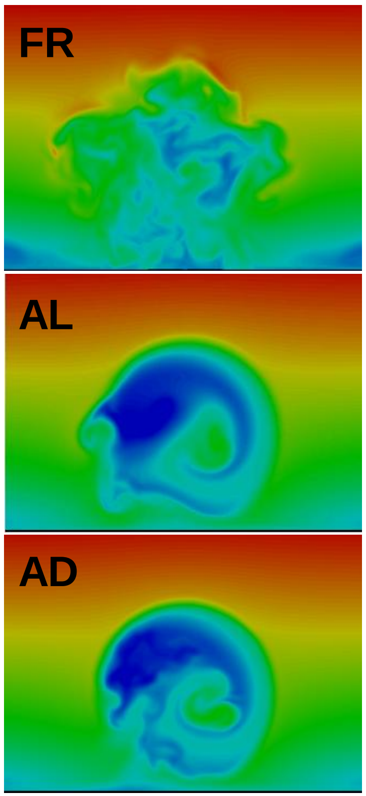
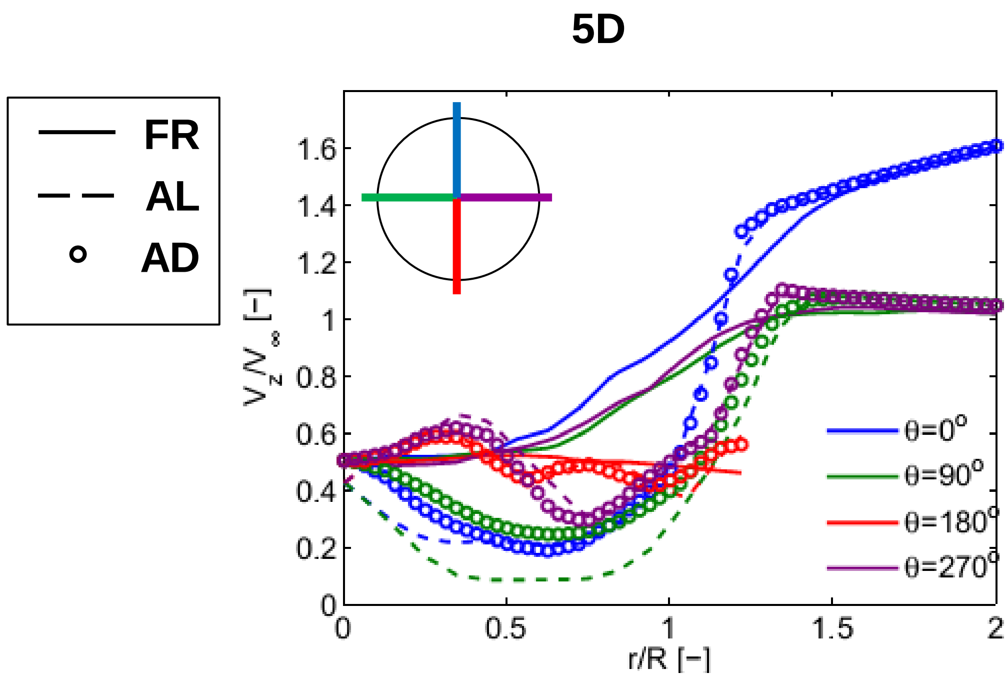


Streamwise velocity contours in cross-section 5D downstream.



Mean streamwise velocity 5D downstream for various azimuth positions

Results

Test cases
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• Yawed inflow

- V_∞ = 8 m/s
- Yaw error of 20°

Results

Test cases
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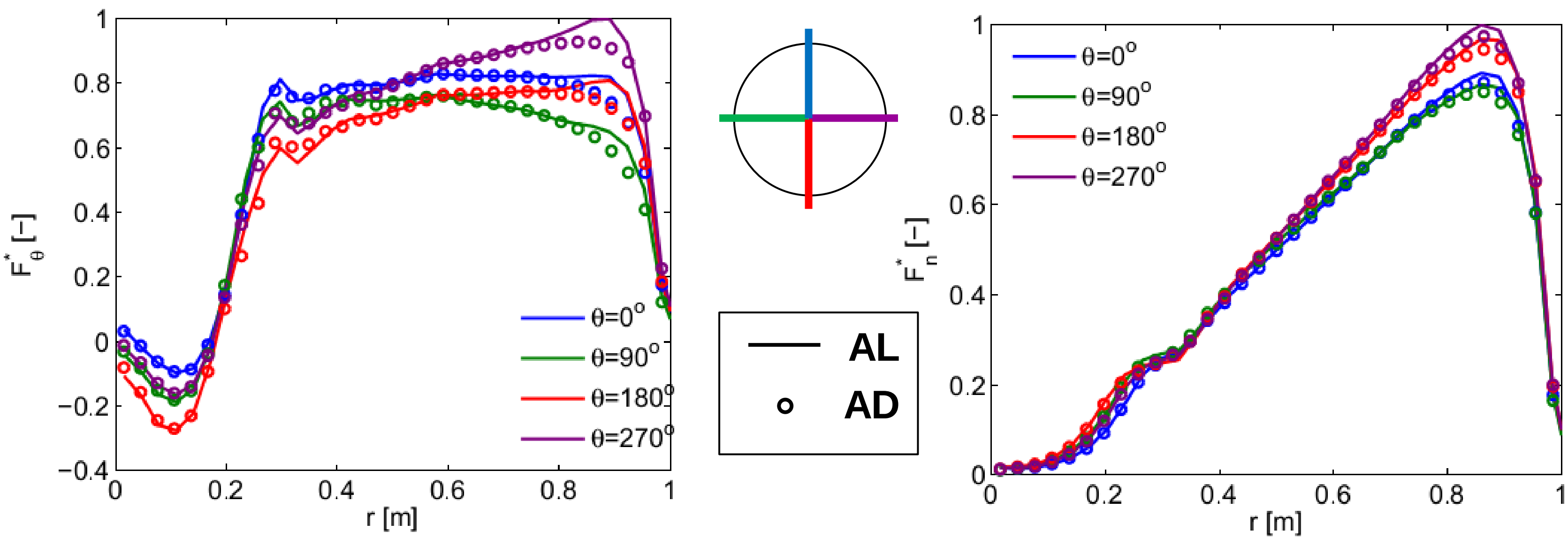
• Yawed inflow

- Load predictions in good agreement



Spanwise distribution of normal and tangential loads at various azimuth positions

Results

Test cases
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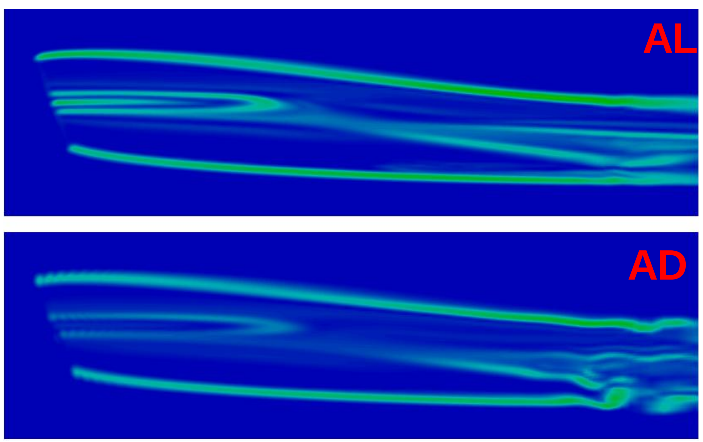
➢ Similar vorticity contours



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

Results

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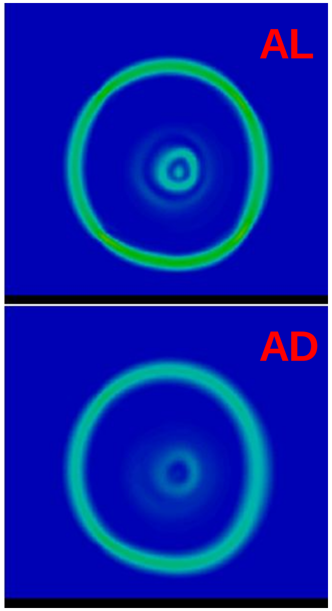
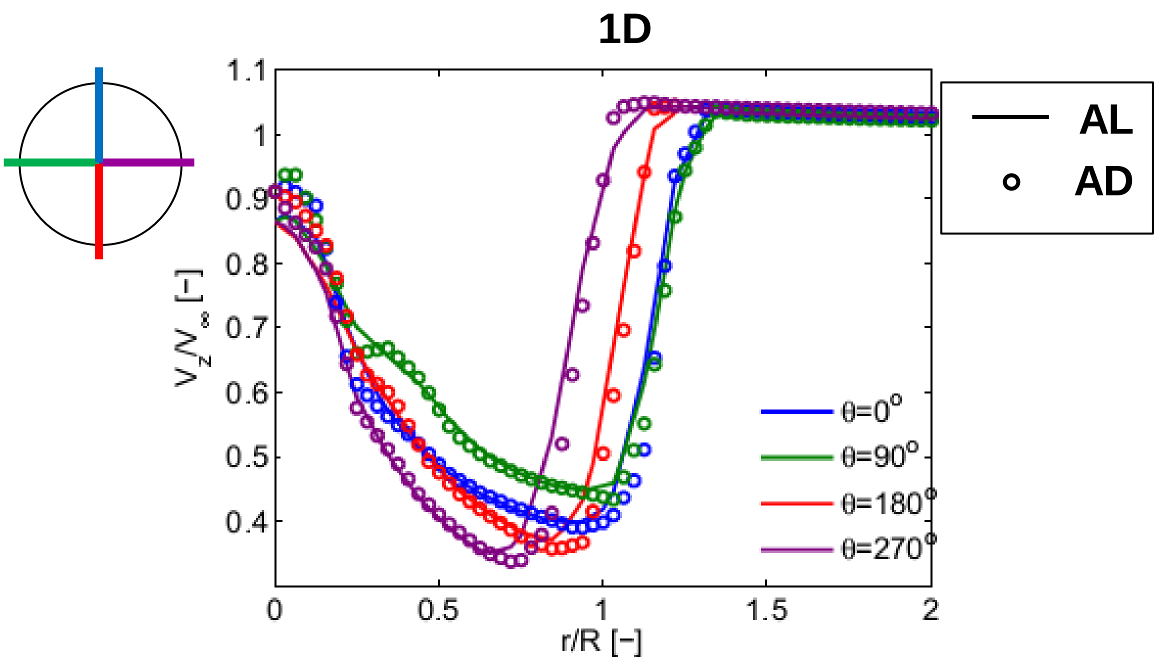
➢ Good agreement in predicted wake deficit and wake structure



Vorticity magnitude contours in cross-section 1D downstream.



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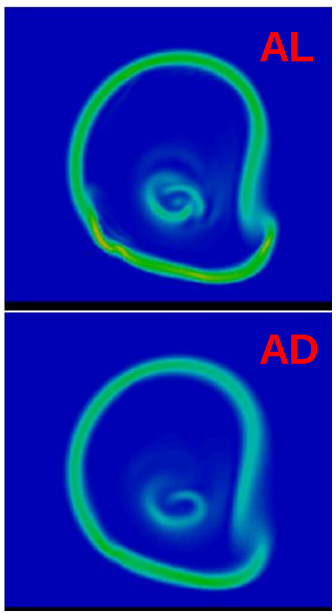

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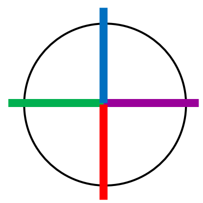

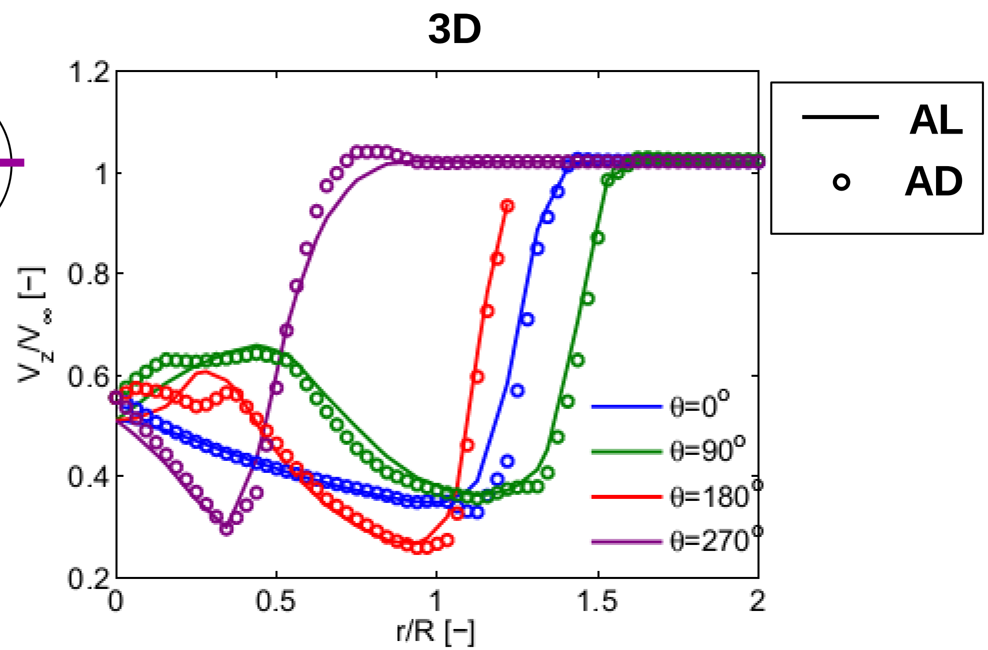

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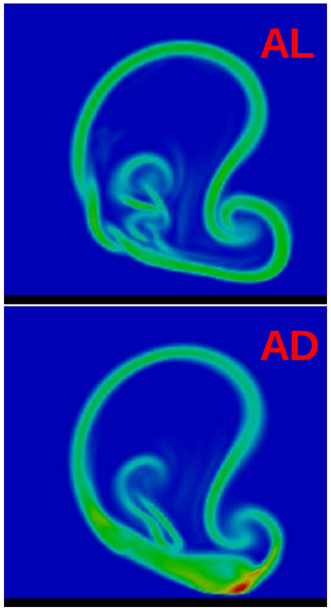

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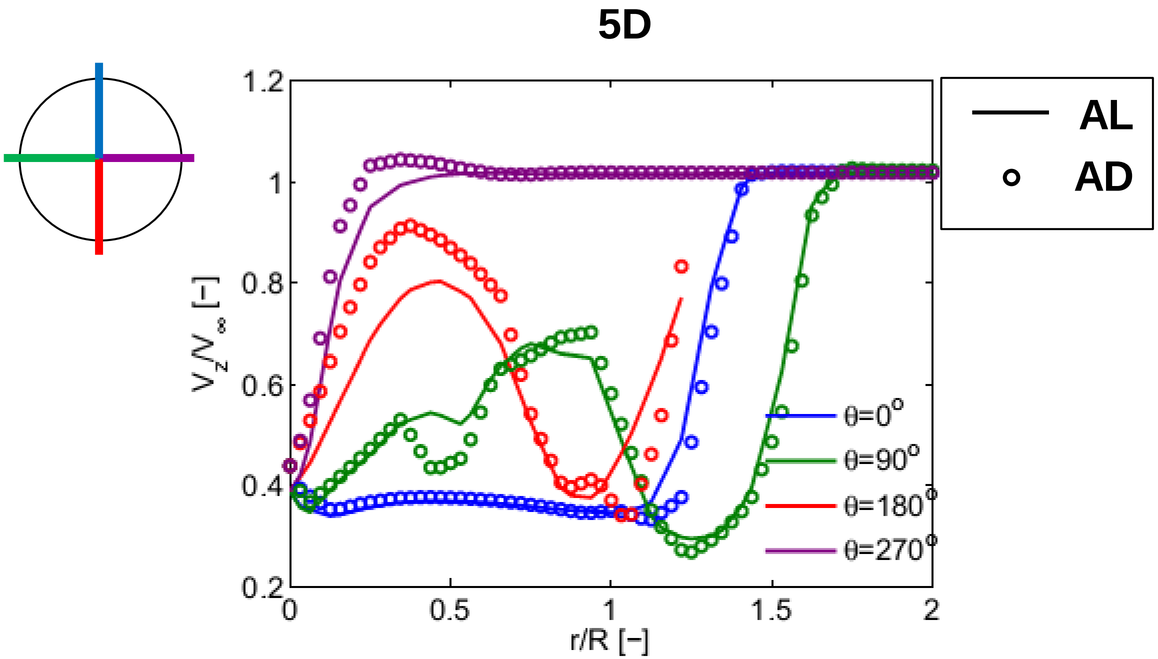

Mean streamwise velocity 5D downstream for various azimuth positions

Conclusions

- Sheared 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 turbulence in the FR simulation
  - Generally good agreement between AL and AD for all downstream position.
- Yawed inflow
  - Good resemblance between wake behavior predicted using AL and AD.
  - AD representation as accurate as AL even in non-uniform inflow.