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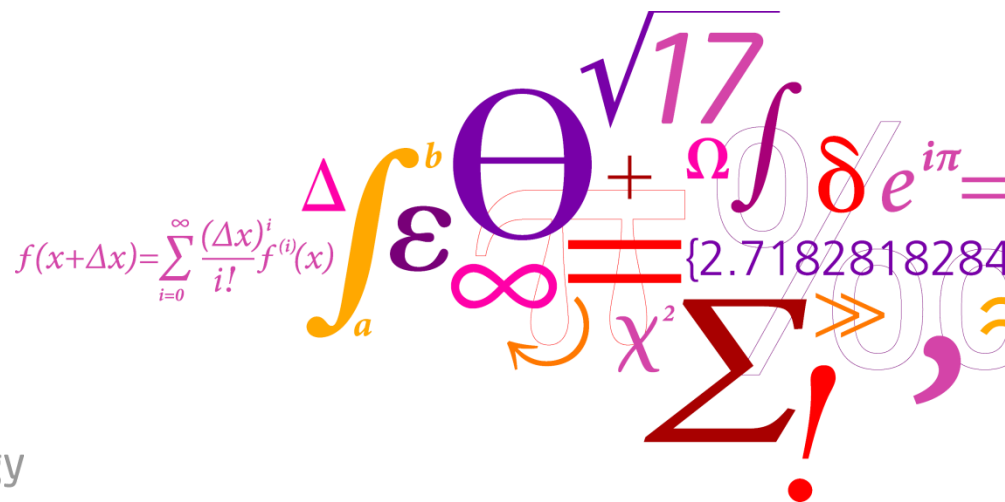
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# Comparison of wind turbine wake properties in non-uniform inflow predicted by different CFD rotor models

Niels Trolborg, Frederik Zahle, Niels N. Sørensen, Pierre-Elouan Réthoré

Wind Energy Department, DTU Wind Energy, DK-4000 Roskilde, Denmark



# Background

## Wind turbine models in CFD

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

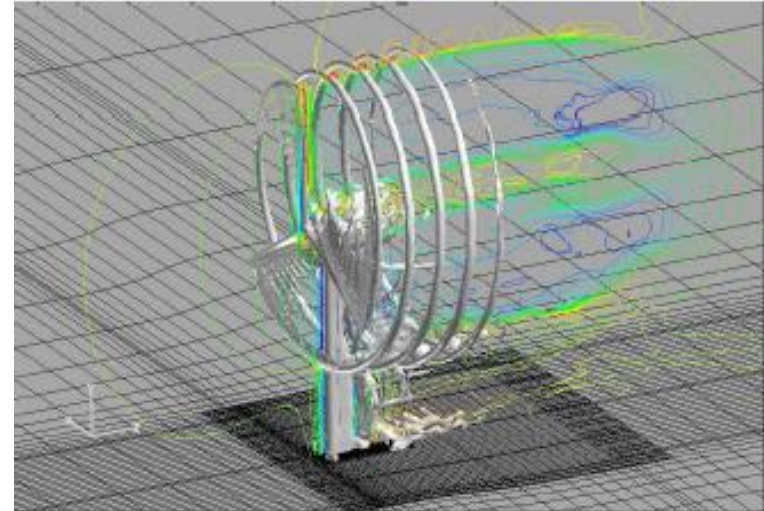
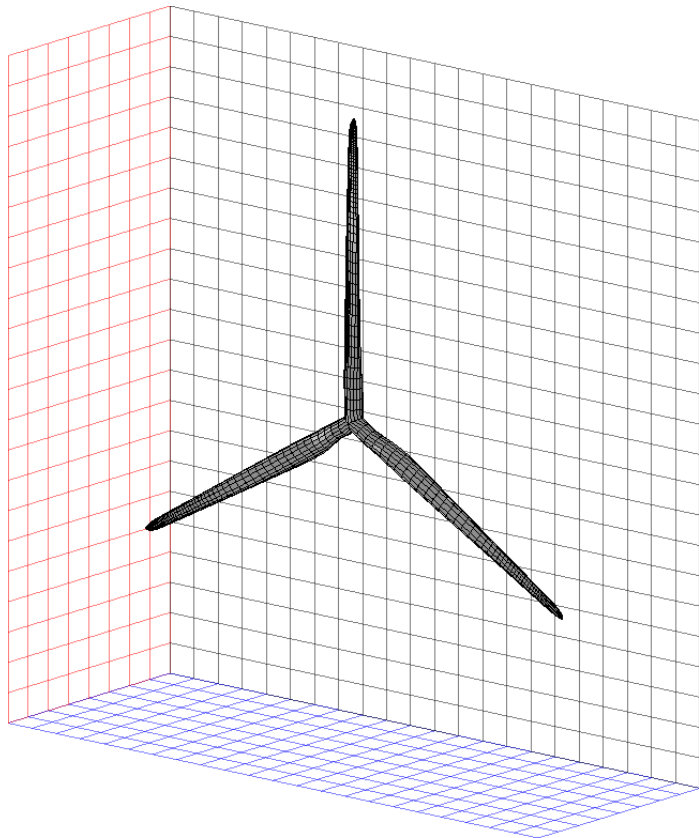


# Background

## Wind turbine models in CFD

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

- 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.

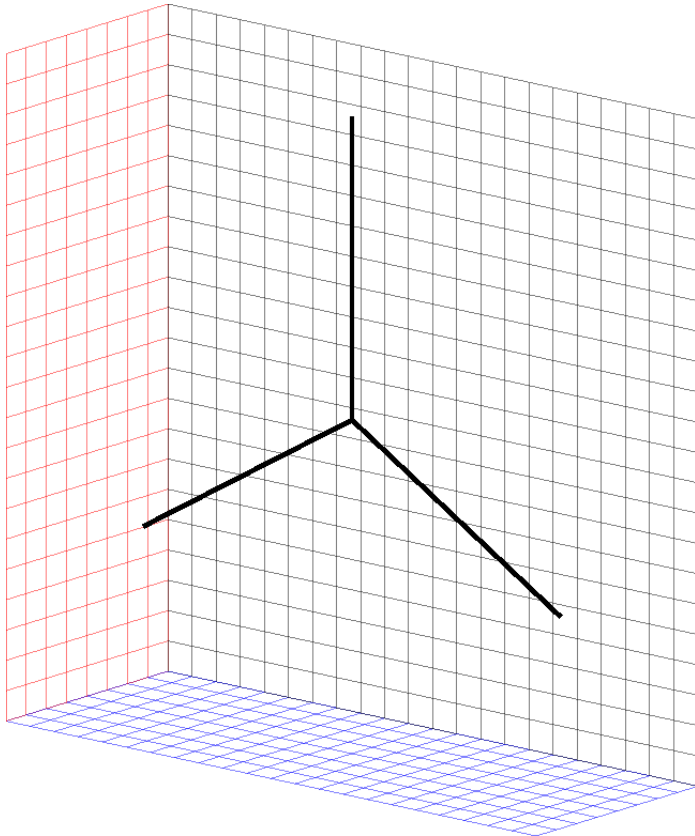


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## Wind turbine models in CFD

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➤ Blades represented as lines.

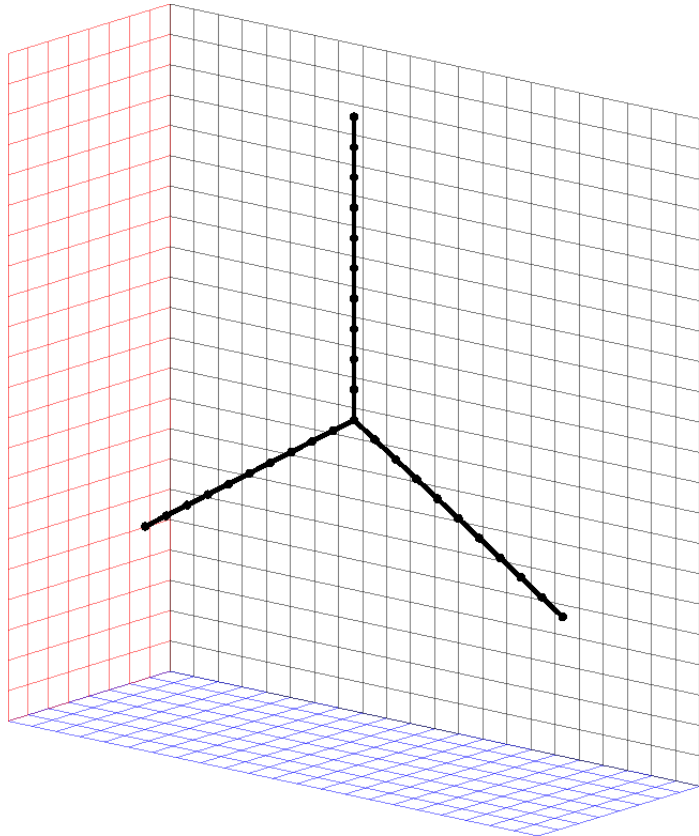


# Background

## Wind turbine models in CFD

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

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

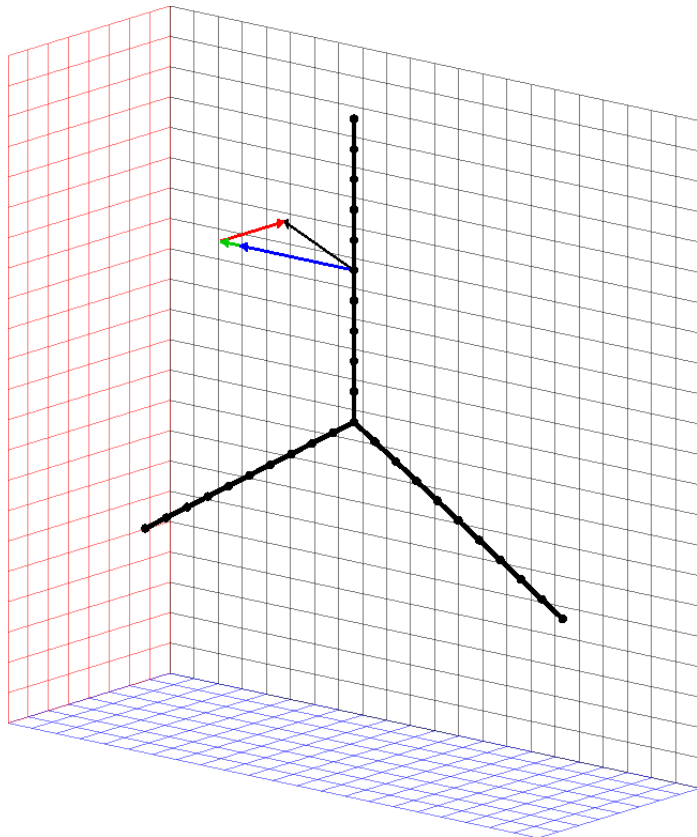


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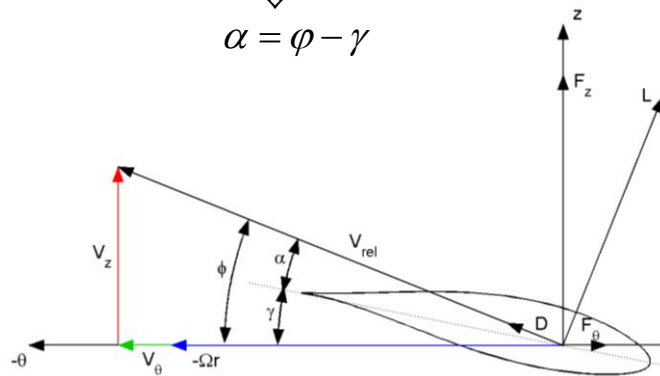
- Blades represented as lines.
- Aerodynamic blade forces determined from 2D airfoil data.



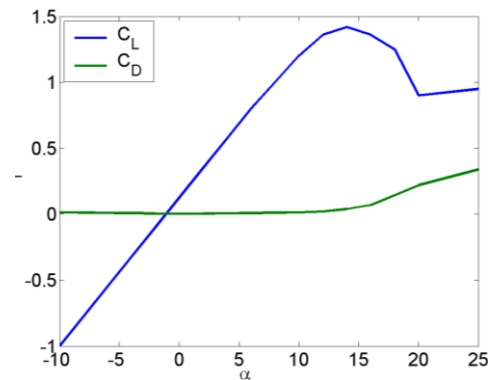
$$\varphi = \tan^{-1}\left(\frac{V_z}{\Omega r - V_\theta}\right)$$

$$\Downarrow$$

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



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



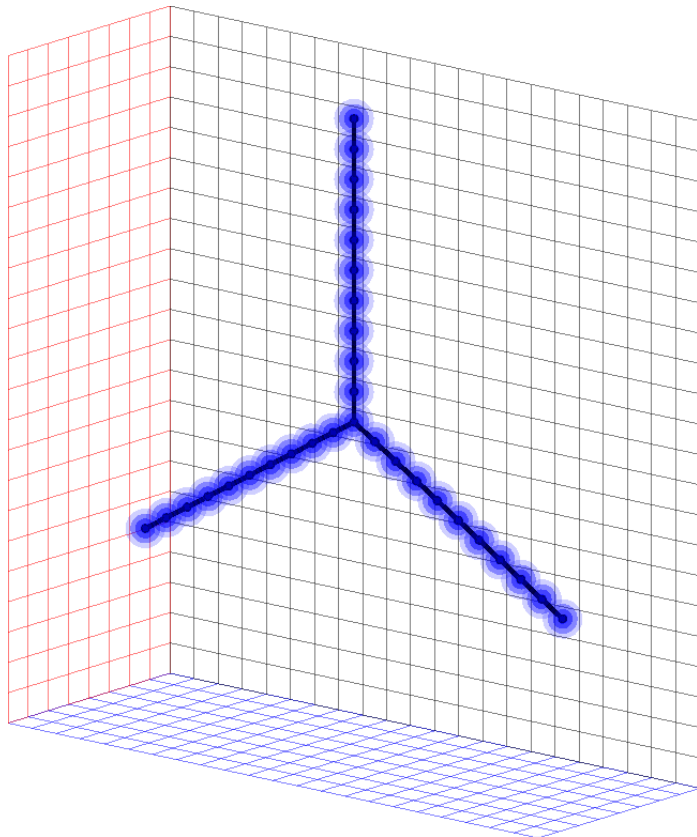
# Background

## Wind turbine models in CFD

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

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

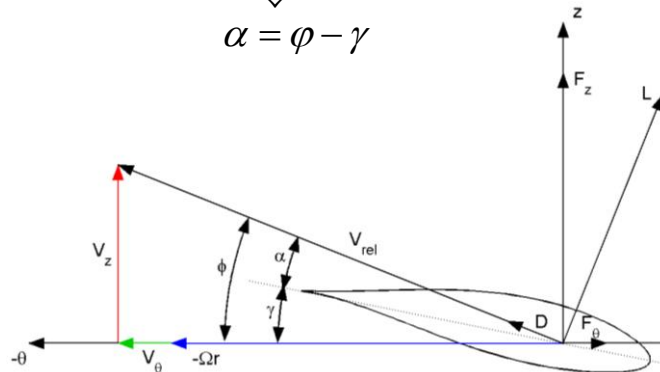
$$\mathbf{f}_\varepsilon = \mathbf{f} \otimes \eta_\varepsilon, \quad \eta_\varepsilon = \frac{1}{\varepsilon^3 \pi^{3/2}} \exp\left[-\frac{d^2}{\varepsilon^2}\right]$$



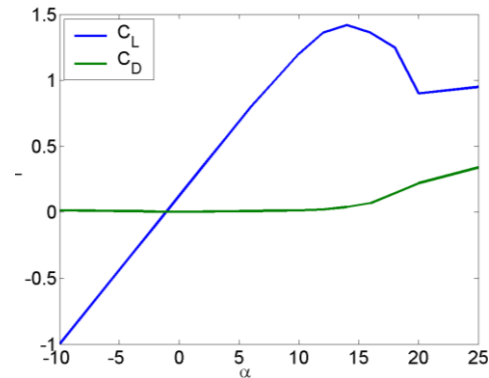
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## Wind turbine models in CFD

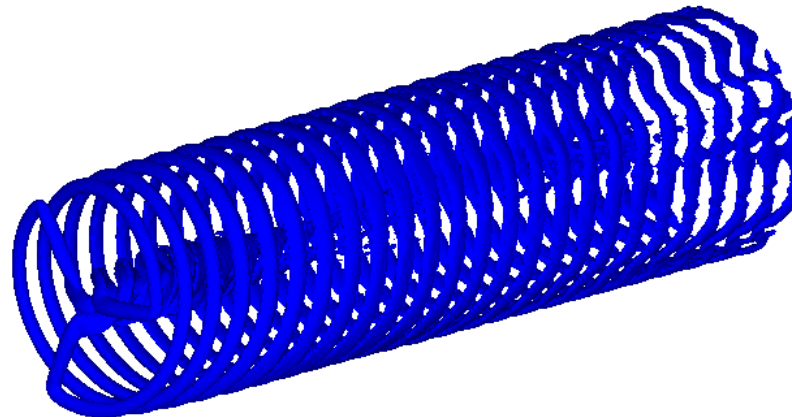
- Fully resolved rotor (FR)
- Actuator line model (AL)
- Actuator disc model (AD)

### 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

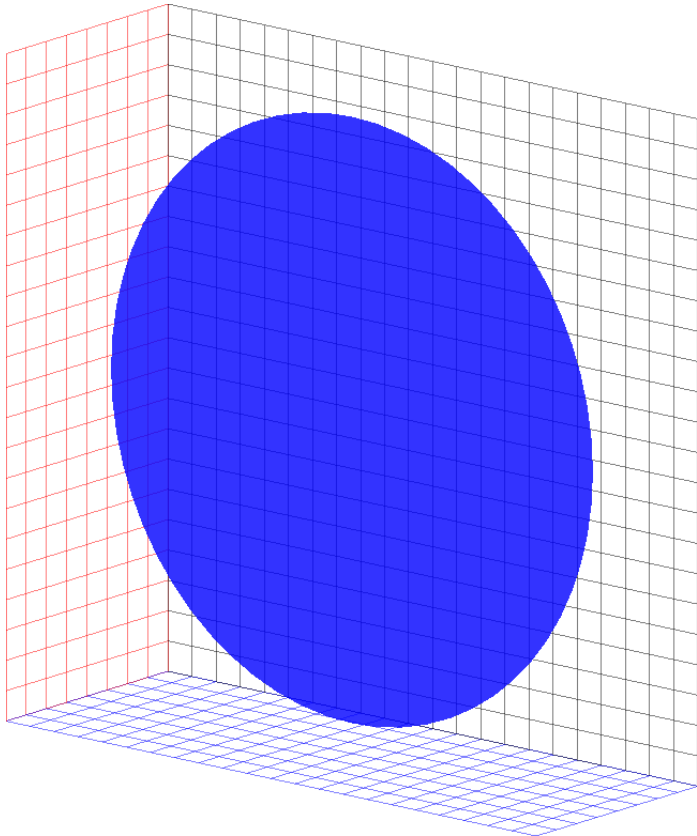


# Background

## Wind turbine models in CFD

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- Actuator disc model (AD)

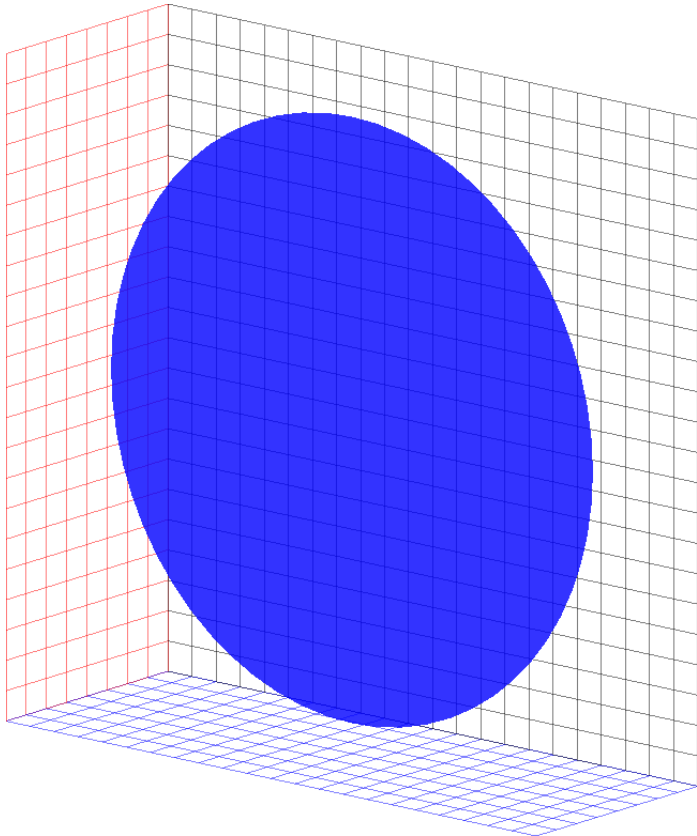
➤ Rotor represented by forces distributed on permeable disc.



## Wind turbine models in CFD

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

- 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



## Wind turbine models in CFD

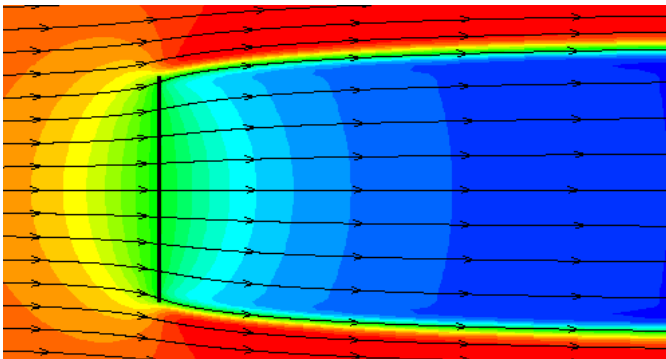
- Fully resolved rotor (FR)
- Actuator line model (AL)
- Actuator disc model (AD)

### 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  $C_T=0.89$*

## Summary:

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

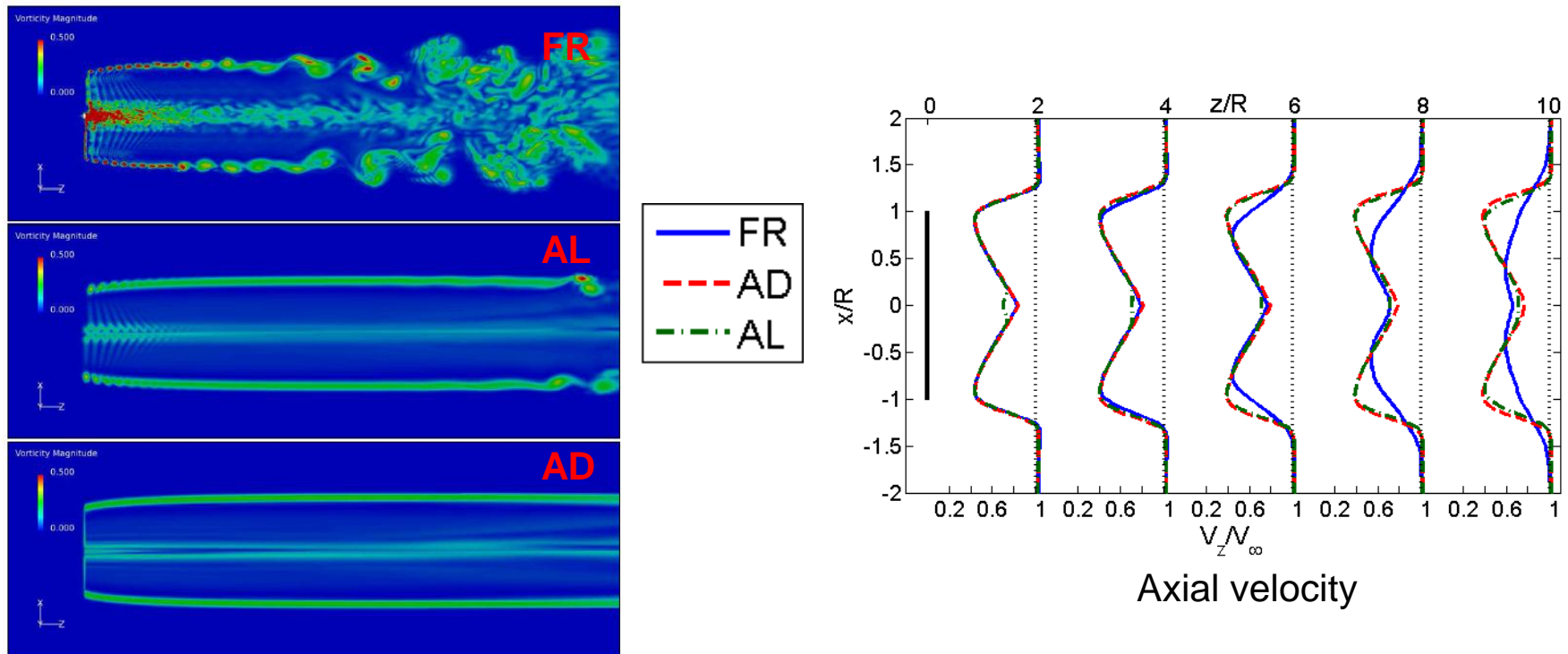
## Objectives:

- 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



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

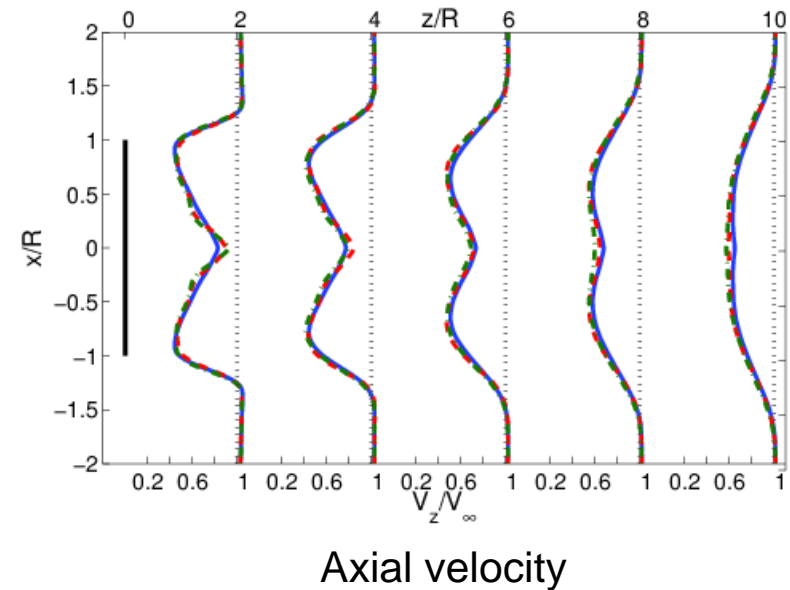
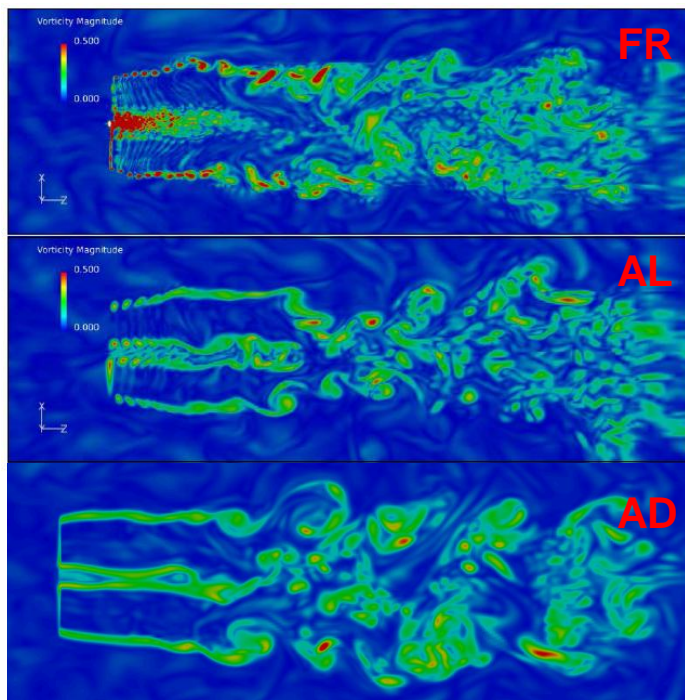
- Wake of FR develops faster into a bell shaped form than the AL and AD.
- Faster spreading of wake is caused by larger TKE in the FR simulation.



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

# Previous work

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



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

## 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 curvilinear grids
- Pressure/Velocity formulation
- Multigrid
- Multiblock
- Grid sequencing
- MPI

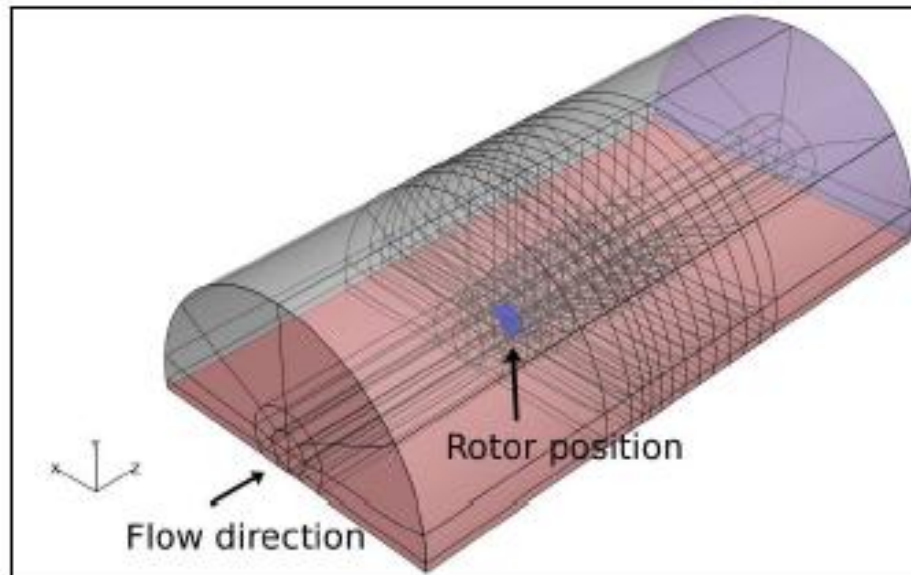
## **Solver parameters:**

- QUICK/QUICK\_CDS4
- SIMPLE
- DES

# Approach - Numerical setup

## Background mesh:

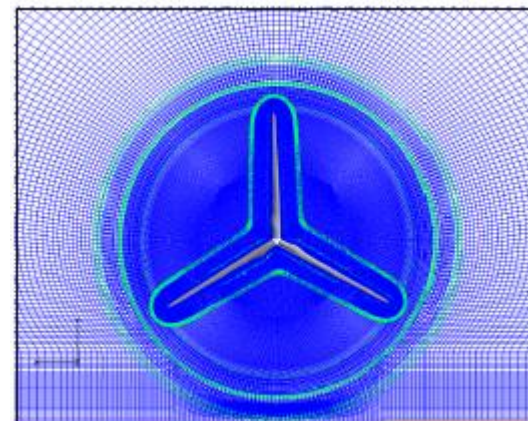
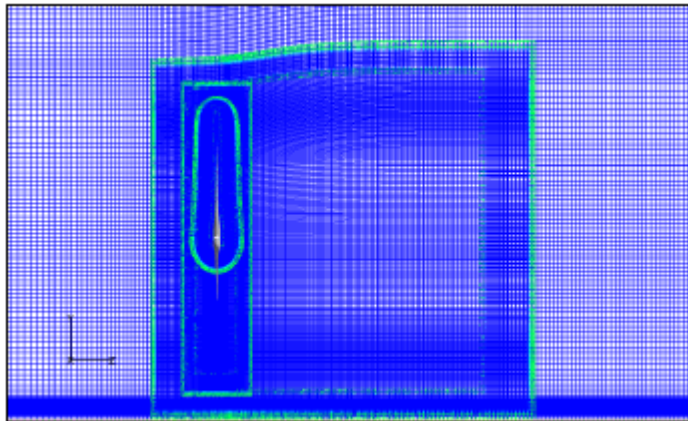
- Same background mesh for all simulations
- Half cylinder with radius  $8D$
- 308 blocks of  $32^3$  ( $10.1 \cdot 10^6$  cells)
- High resolution of the first  $5D$  of the wake (cell size  $1.3\text{m} \times 1.3\text{m} \times 0.8\text{m}$ )



# 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:

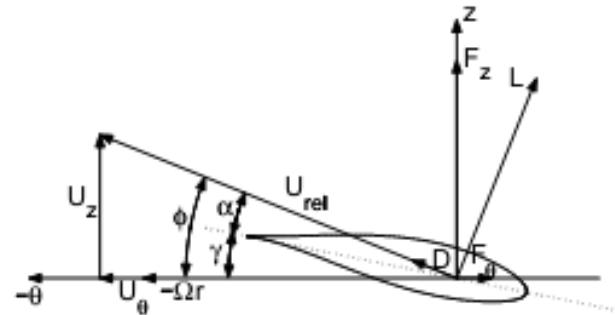
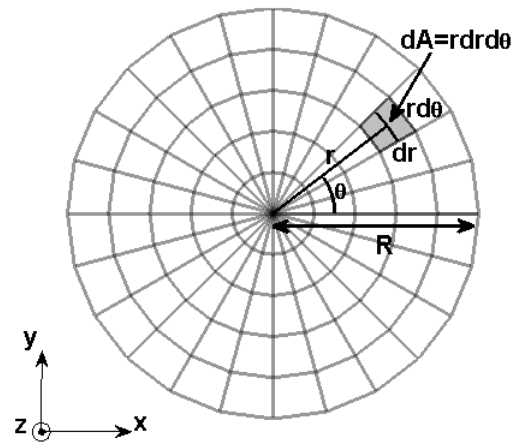
- Same background mesh as the full rotor simulation ( $10.1 \cdot 10^6$  cells)
- Force smearing using 3D convolution
- 33 force elements along each line



# 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  $dA=rdrd\theta$  is determined from local flow conditions and airfoil data.



# Results



## Test cases

- Sheared inflow
- Yawed inflow

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- Sheared inflow
- Yawed inflow

➤  $V_\infty = 8 \text{ m/s}$

➤ Power law inflow ( $\alpha = 0.55$ ):

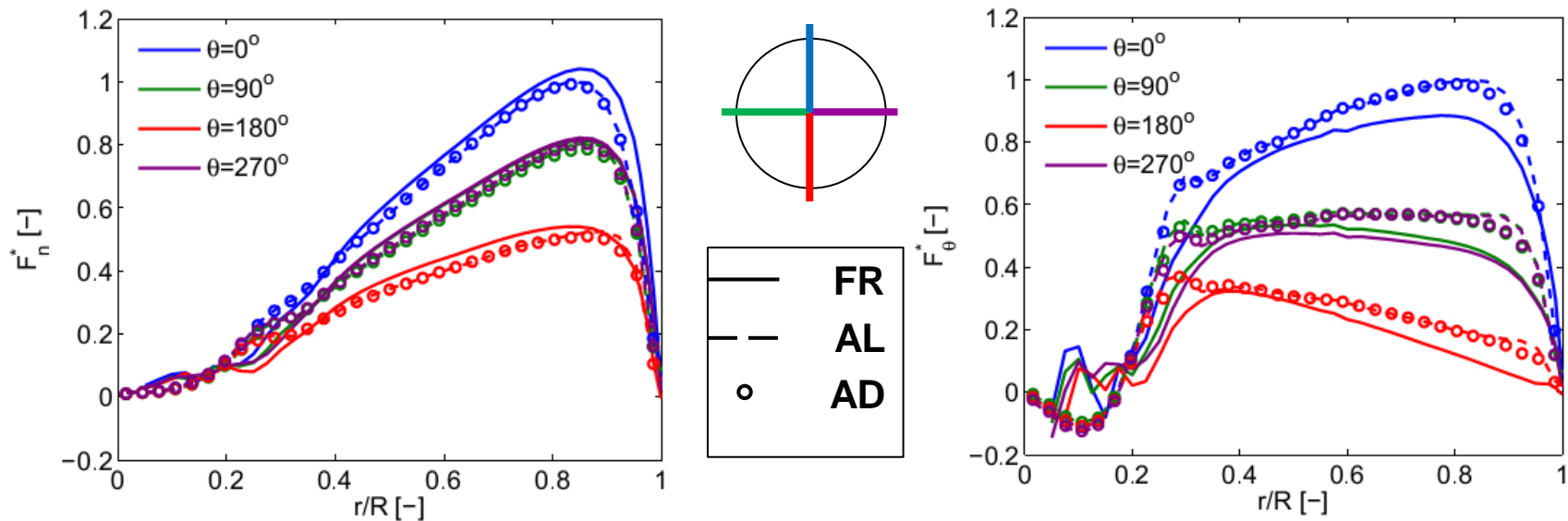
$$V_z = V_\infty \left( \frac{y}{H} \right)^\alpha$$

# 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

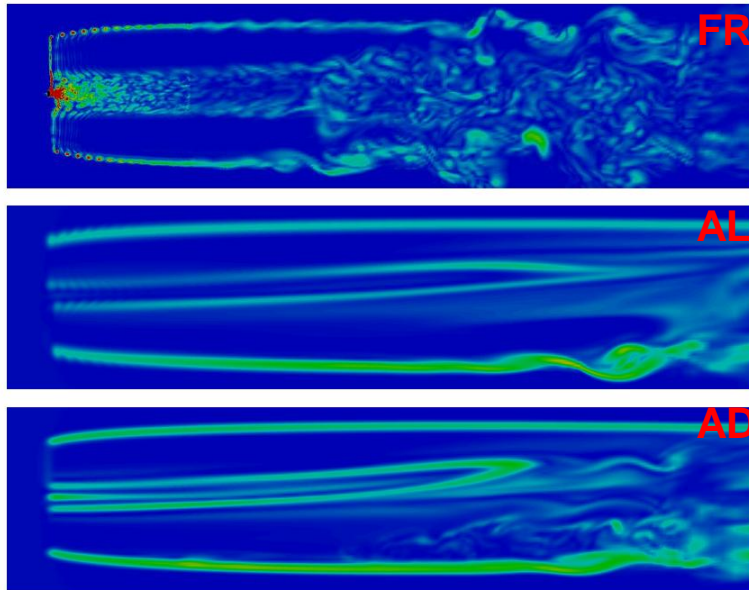


# Results

## 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 instability in the far wake)
- Reasons for more unstable wake of FR:
  - Higher grid resolution
  - Fluctuating loads (e.g. stall effects near root)



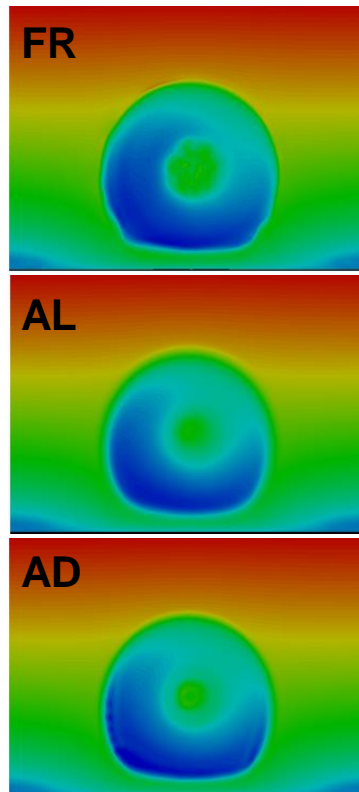
Snapshot of vorticity magnitude contours in horizontal cross-section through rotor center.

# Results

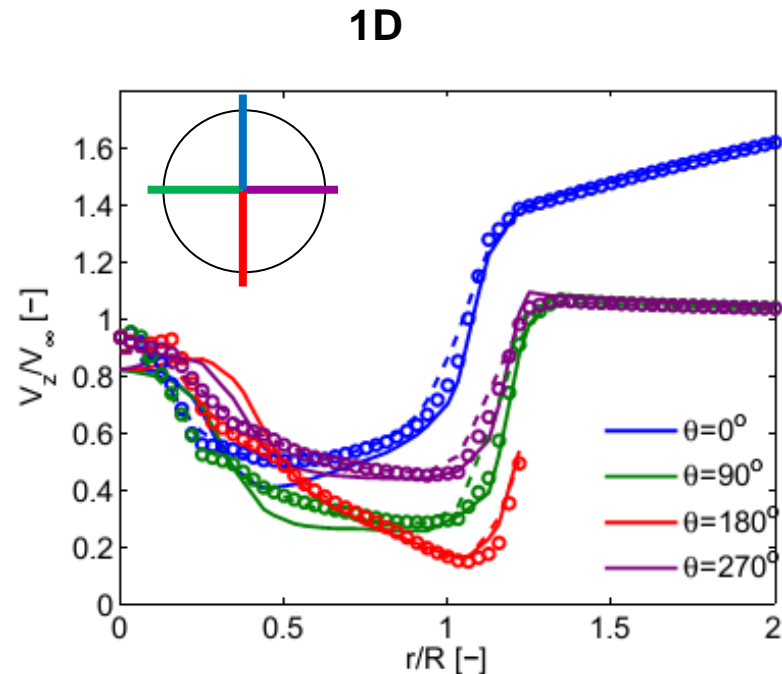
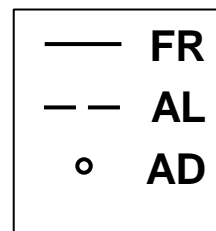
## Test cases

- Sheared inflow
- Yawed inflow

- 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.



Streamwise velocity contours in cross-section 1D downstream.



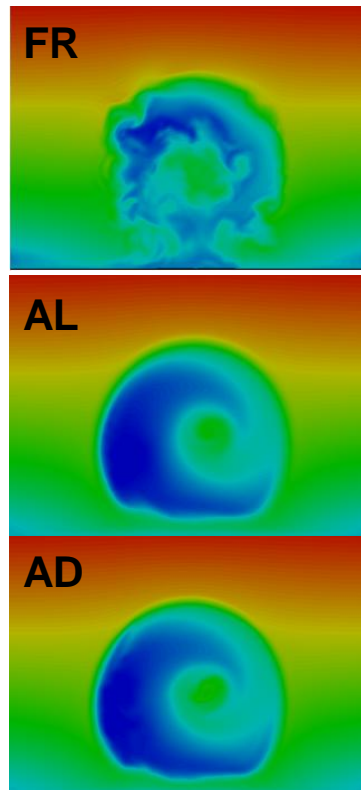
Mean streamwise velocity 1D downstream for various azimuth positions

# Results

## Test cases

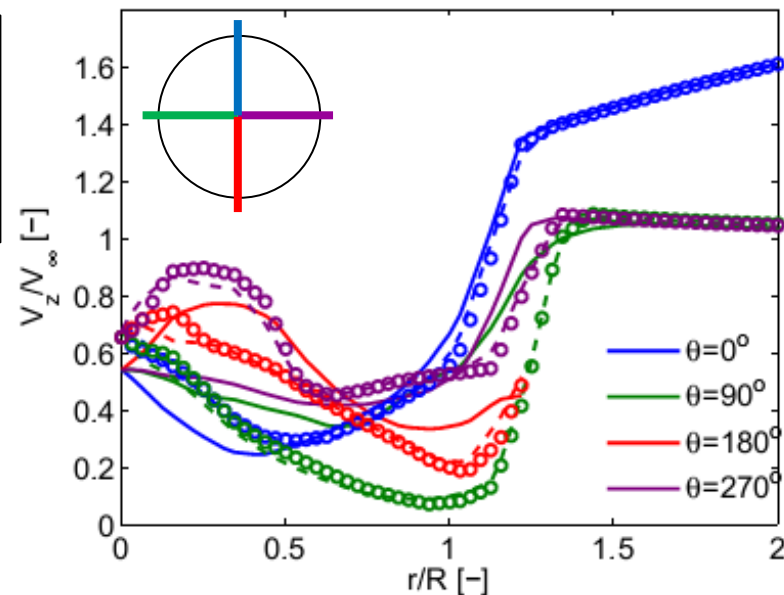
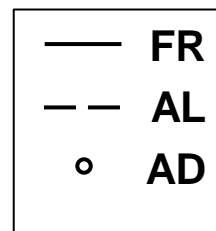
- Sheared inflow
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- Good agreement in predicted near wake deficit
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Streamwise velocity contours in cross-section 3D downstream.

## 3D



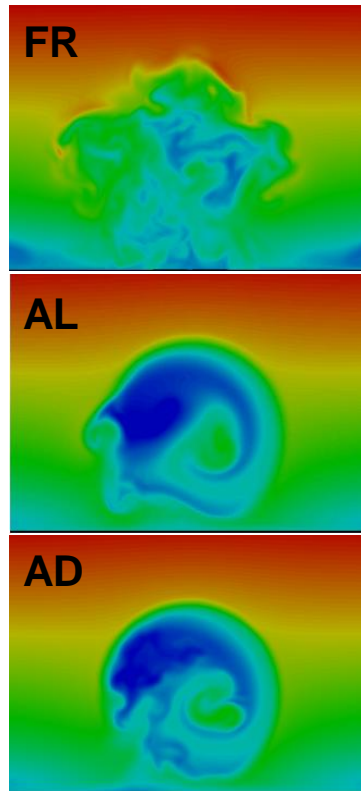
Mean streamwise velocity 3D downstream for various azimuth positions

# Results

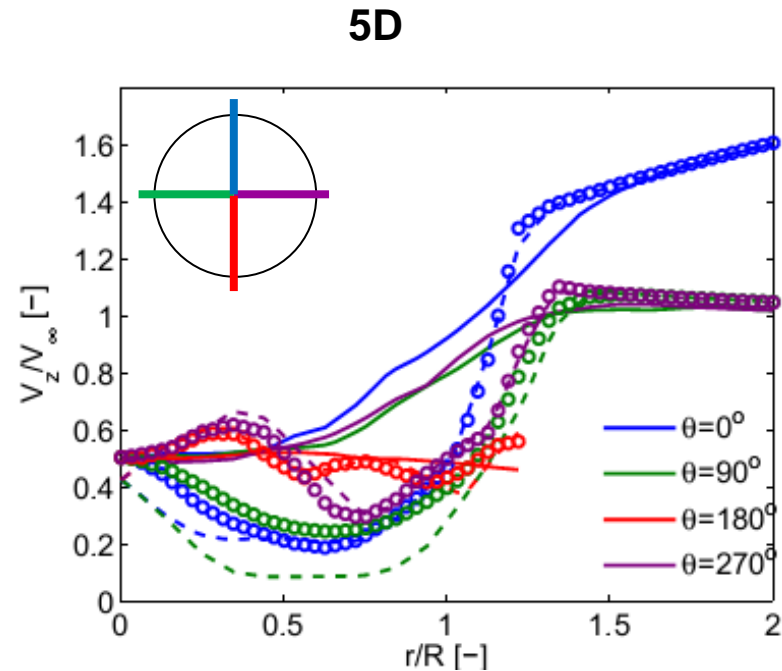
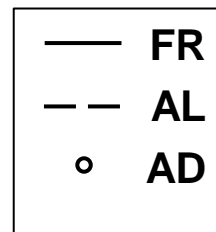
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Streamwise velocity contours in cross-section 5D downstream.



Mean streamwise velocity 5D downstream for various azimuth positions

# Results

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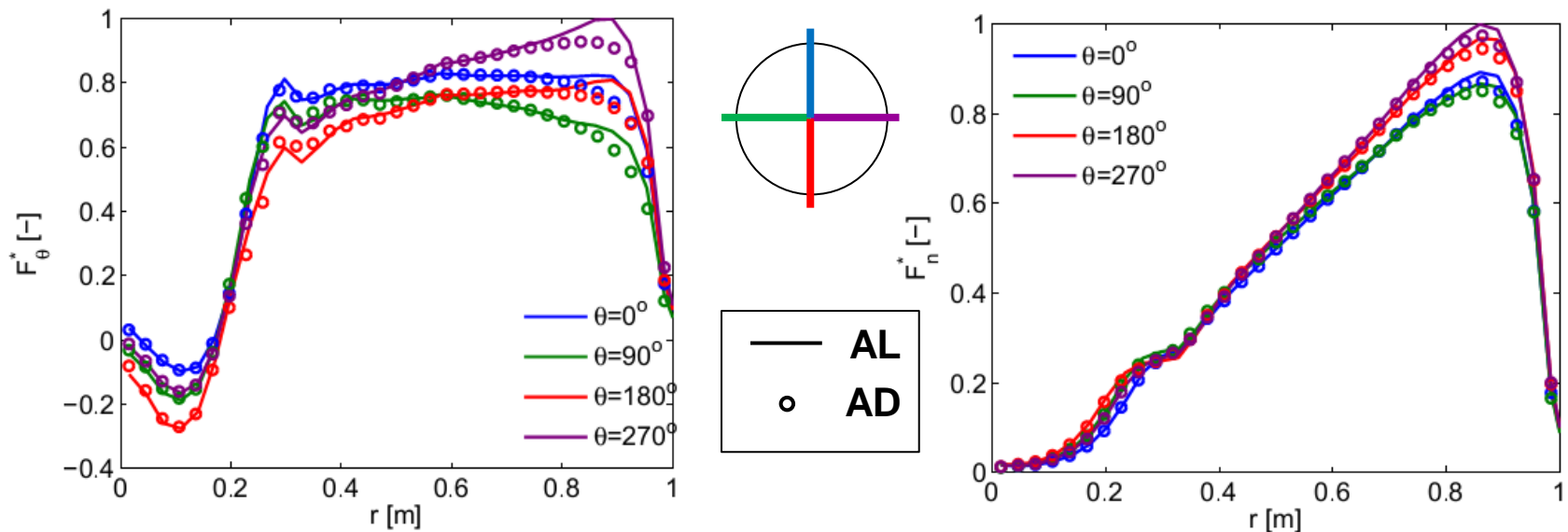
- $V_{\infty} = 8 \text{ m/s}$
- Yaw error of  $20^{\circ}$

# Results

## Test cases

- Sheared inflow
- Yawed inflow

➤ Load predictions in good agreement



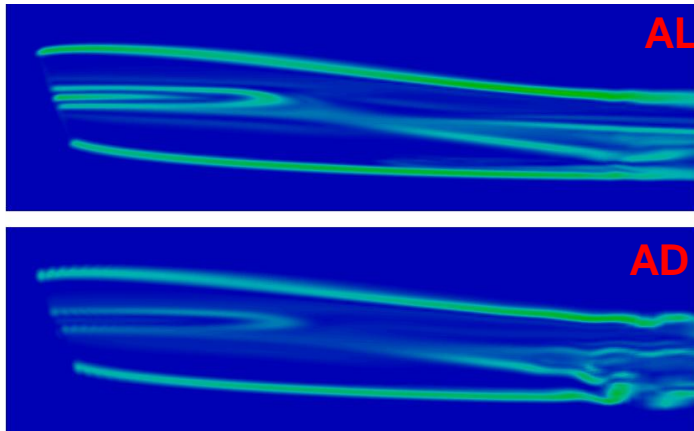
Spanwise distribution of normal and tangential loads at various azimuth positions

# Results

## Test cases

- Sheared inflow
- Yawed inflow

➤ Similar vorticity contours



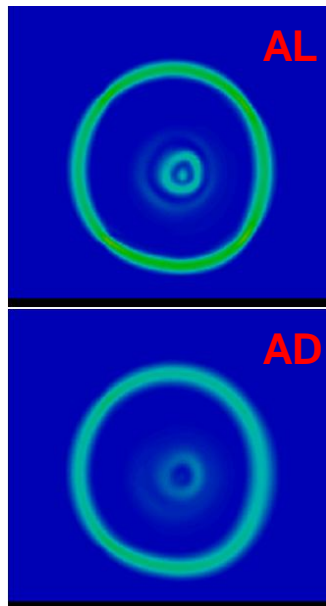
Snapshot of vorticity magnitude contours in horizontal cross-section through rotor center.

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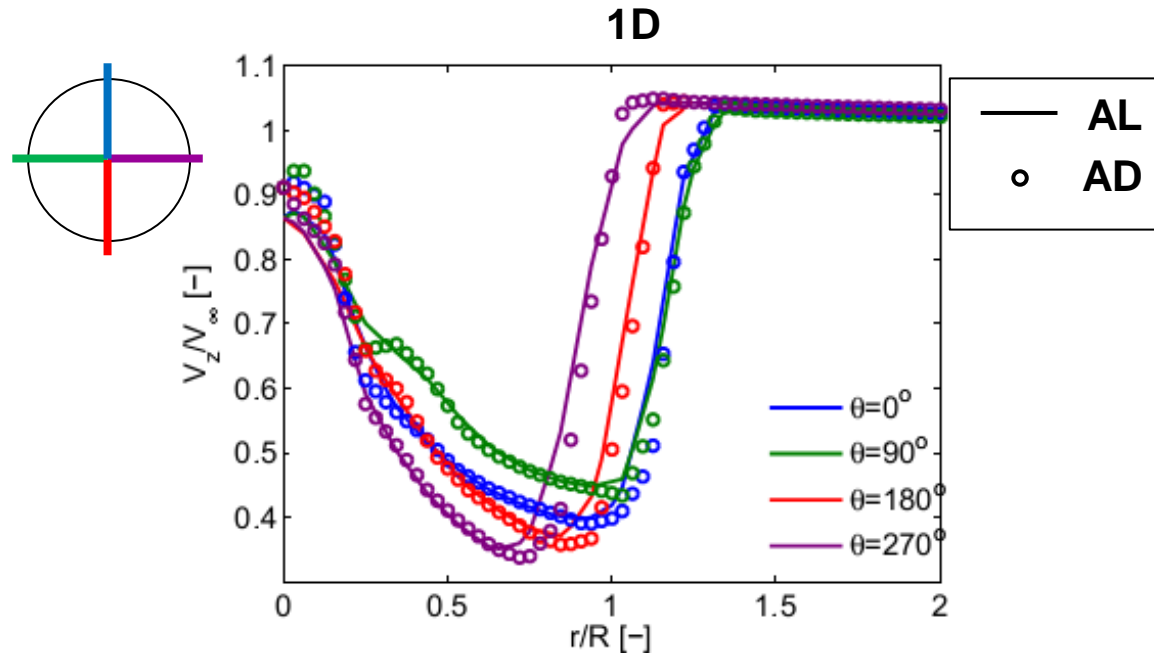
## Test cases

- Sheared inflow
- Yawed inflow

➤ Good agreement in predicted wake deficit and wake structure



Vorticity magnitude contours in cross-section 1D downstream.



Mean streamwise velocity 1D downstream for various azimuth positions

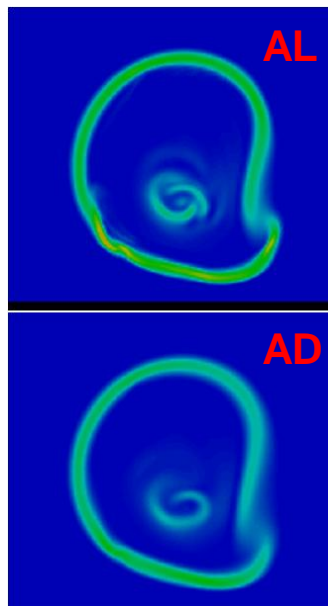


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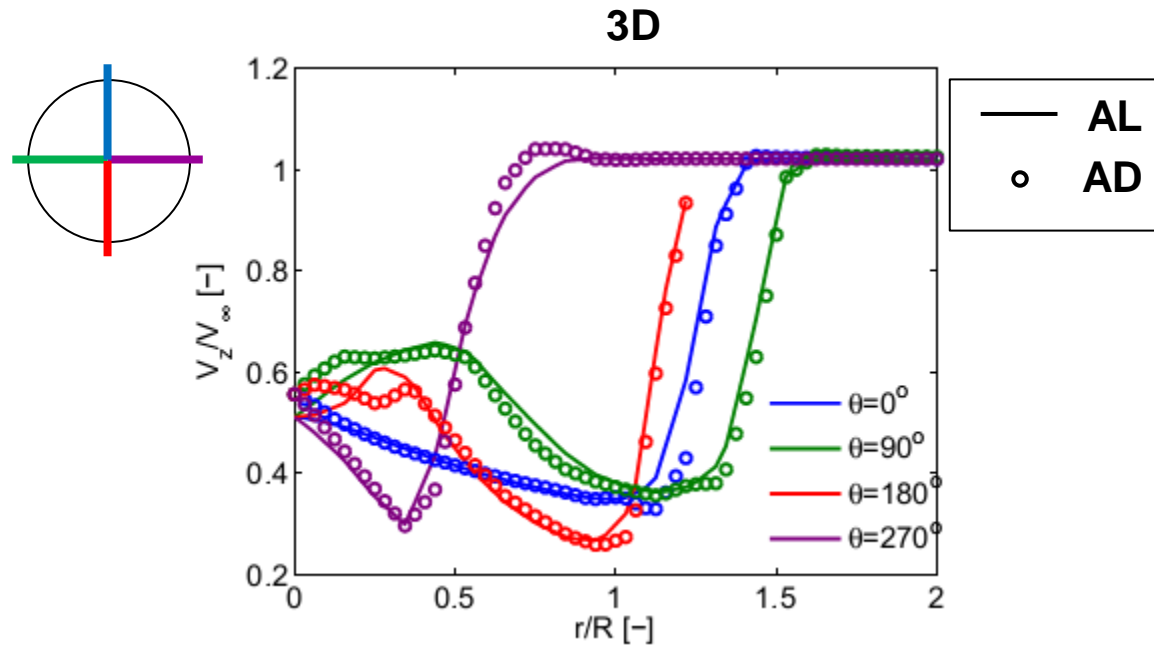
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Vorticity magnitude contours in cross-section 3D downstream.



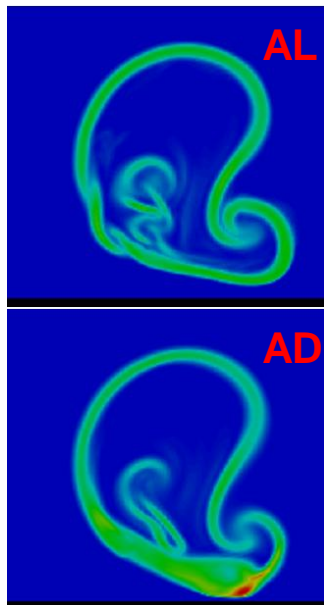
Mean streamwise velocity 3D downstream for various azimuth positions

# Results

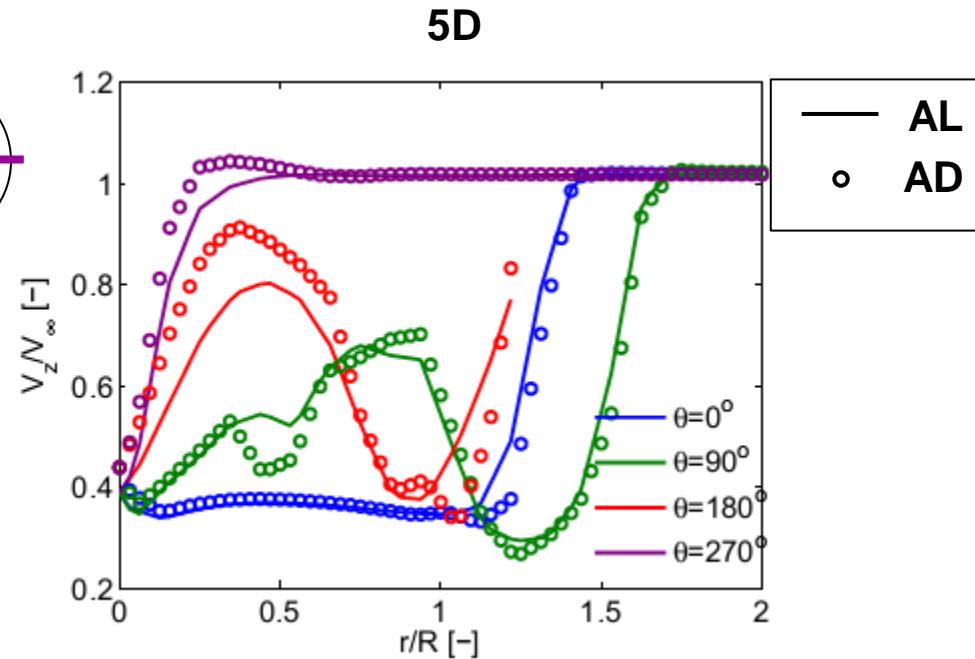
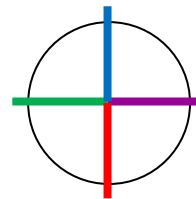
## Test cases

- Sheared inflow
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➤ Good agreement in predicted wake deficit and wake structure



Vorticity magnitude contours in cross-section 5D downstream.



Mean streamwise velocity 5D downstream for various azimuth positions

- 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.