Blade-resolved and actuator line CFD simulations of the flow through the NREL 5 MW wind turbine

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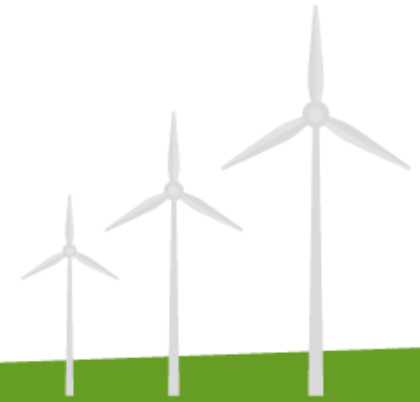
HPC WE

Agenda

- Blade-resolved simulations using OpenFOAM
  - Rotor simulations using URANS
  - Turbine simulations using URANS
- Actuator line simulations using WInc3D
  - Fixed TSR simulations of single turbine and two turbines side by side
  - Single controlled turbine simulations for different wind speeds
  - Moving turbine (prescribed motions) simulations

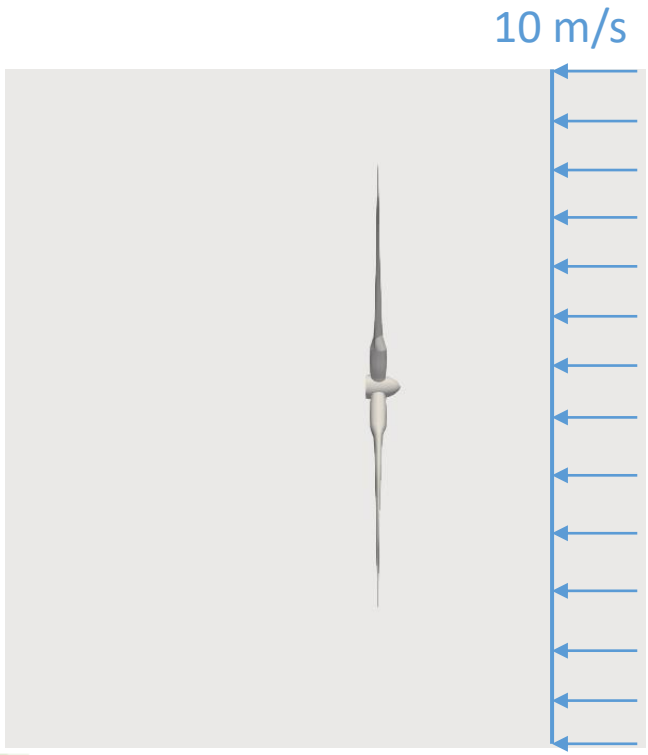


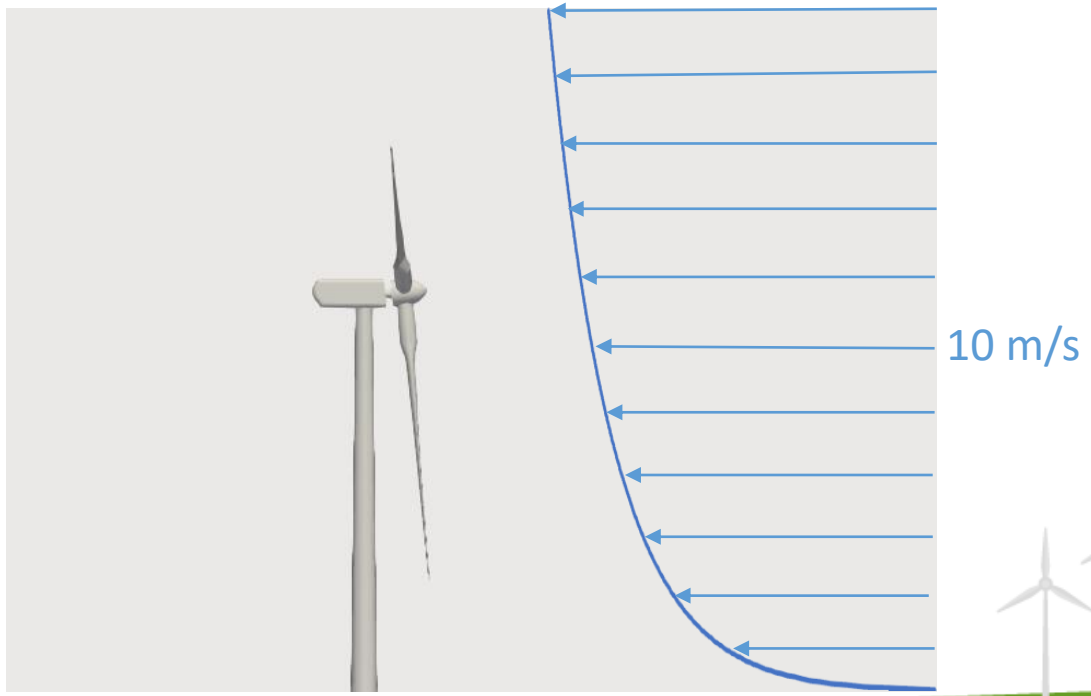
Blade-resolved simulations - OpenFOAM

- Open source CFD that uses finite volume method
- Used Solvers:
  - SIMPLE
    - Newtonian flows
    - Steady
    - Turbulent
    - Simulation initialization
    - OpenFOAM: simpleFoam
  - SIMPLE iterative
    - Newtonian flows
    - Unsteady
    - Turbulent
    - OpenFOAM: pimpleFOAM
  - Turbulence model
    - k–ω SST

Blade-resolved simulations performed

1. 5 MW NREL Rotor with uniform wind speed of 10 m/s
2. 5 MW NREL wind turbine with profile speed of 10 m/s at 80 m



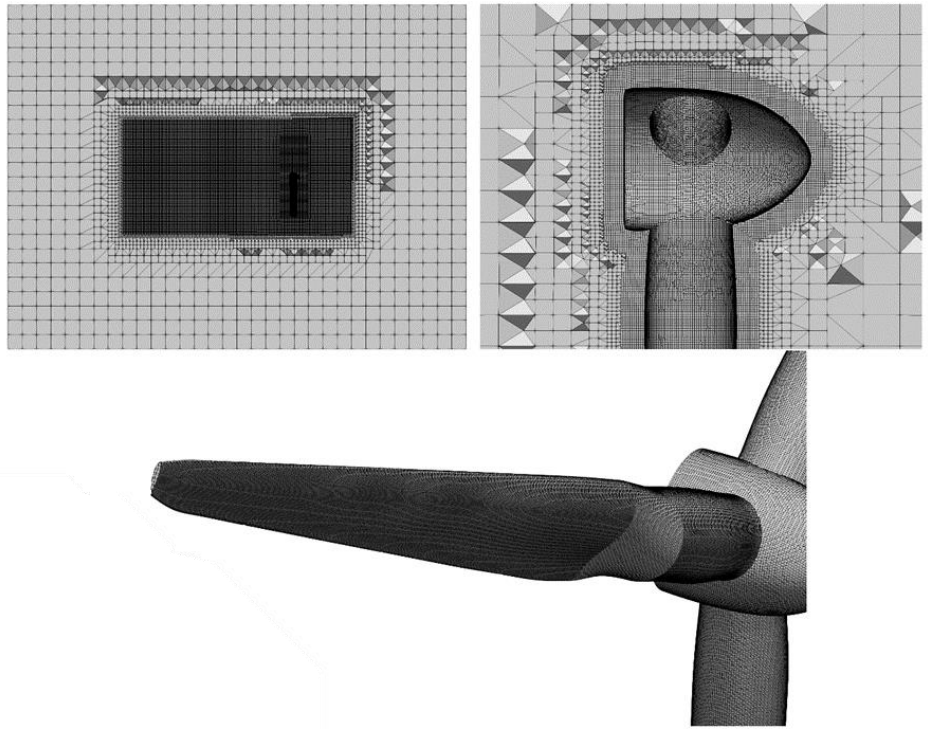


Calculations performed for the two simulations

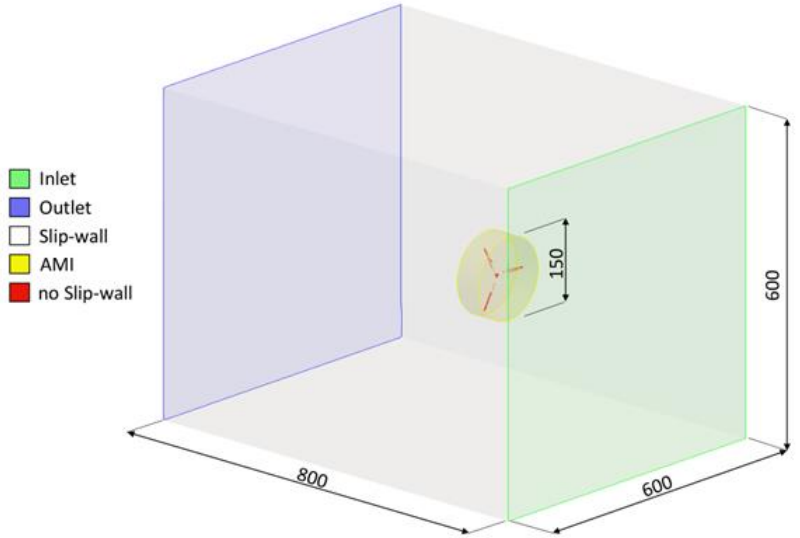
- Simulation Initialization
  - 10 Steps in PotentialFoam
  - 500 Iterations steady SimpleFoam
    - Velocity, pressure and turbulence parameters -> Tolerance of 10^{-7} per step
- Simulation running
  - Max. Courant Number: 0.94
  - Average Time-step: $2.7x10^{-4}$ s
  - Max. of 20 pimple iterations per time-step
    - Stops when velocity, pressure and turbulence parameters are lower than a tolerance of 10^{-6}
    - 1 velocity and pressure calculation per pimple iteration

Rotor mesh and domain

- NREL 5MW
- Rigid blade
- AMI (Arbitrary Mesh Interface) - Sliding Mesh
- 9,274,703 cells



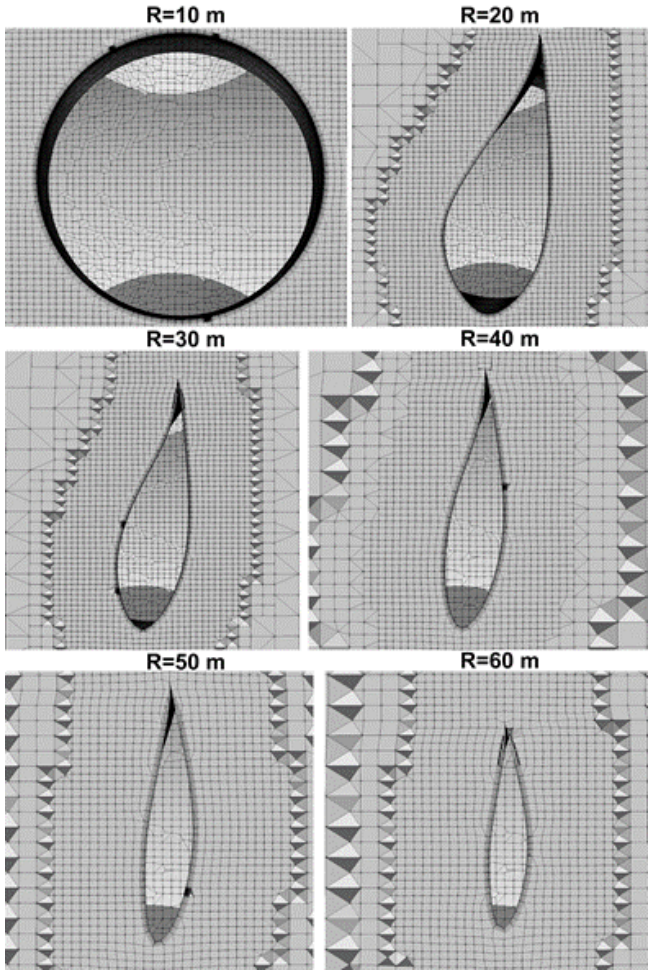
Mesh Cells



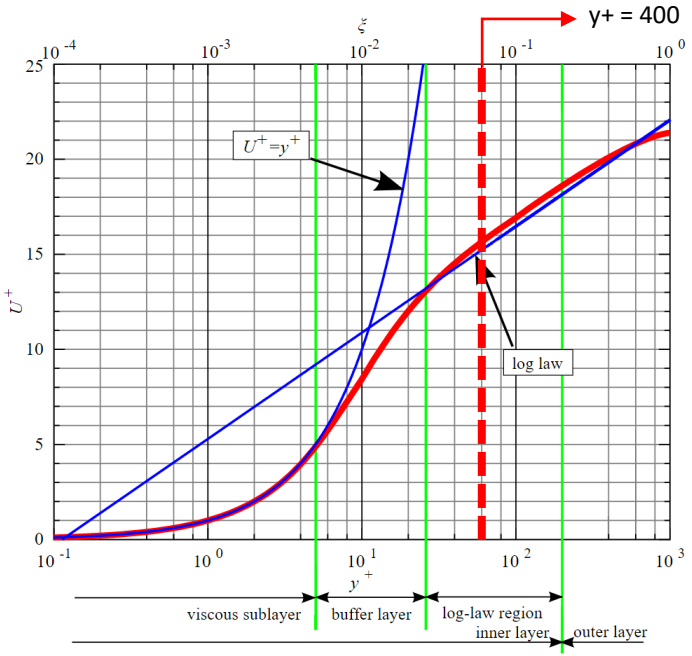
Mesh Domain

Mesh details

- SnappyHexMesh
- First cell length 2x10^{-3} m
- Grow rate 1.2
- 6 layers
- Tip Y+ 400
  - Logarithm region
  - Wall-Function
- Max. Aspect Ratio: 83

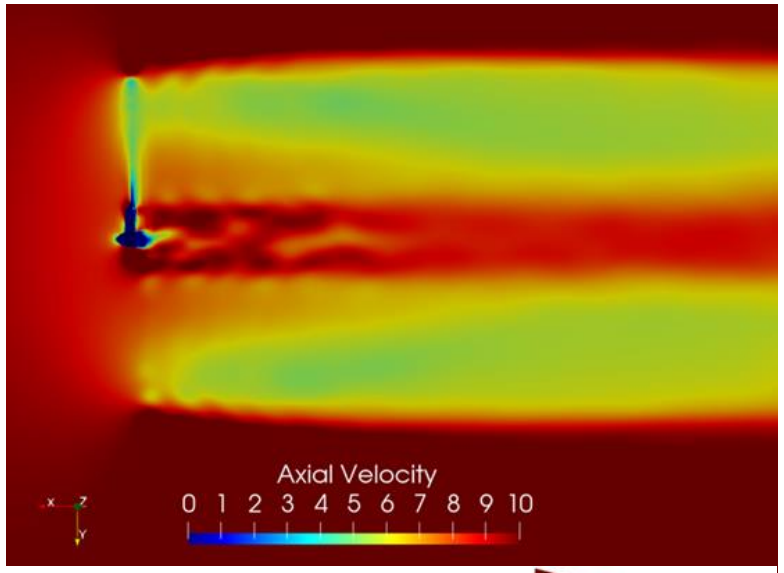


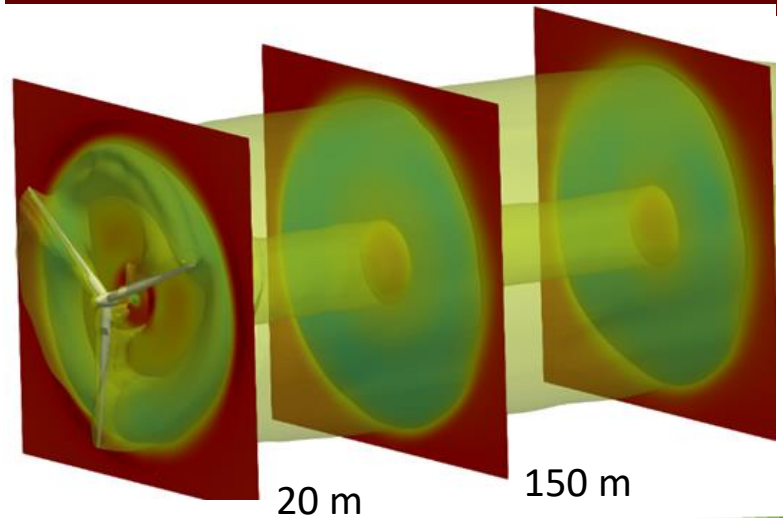
Airfoils Cells



Rotor simulation results

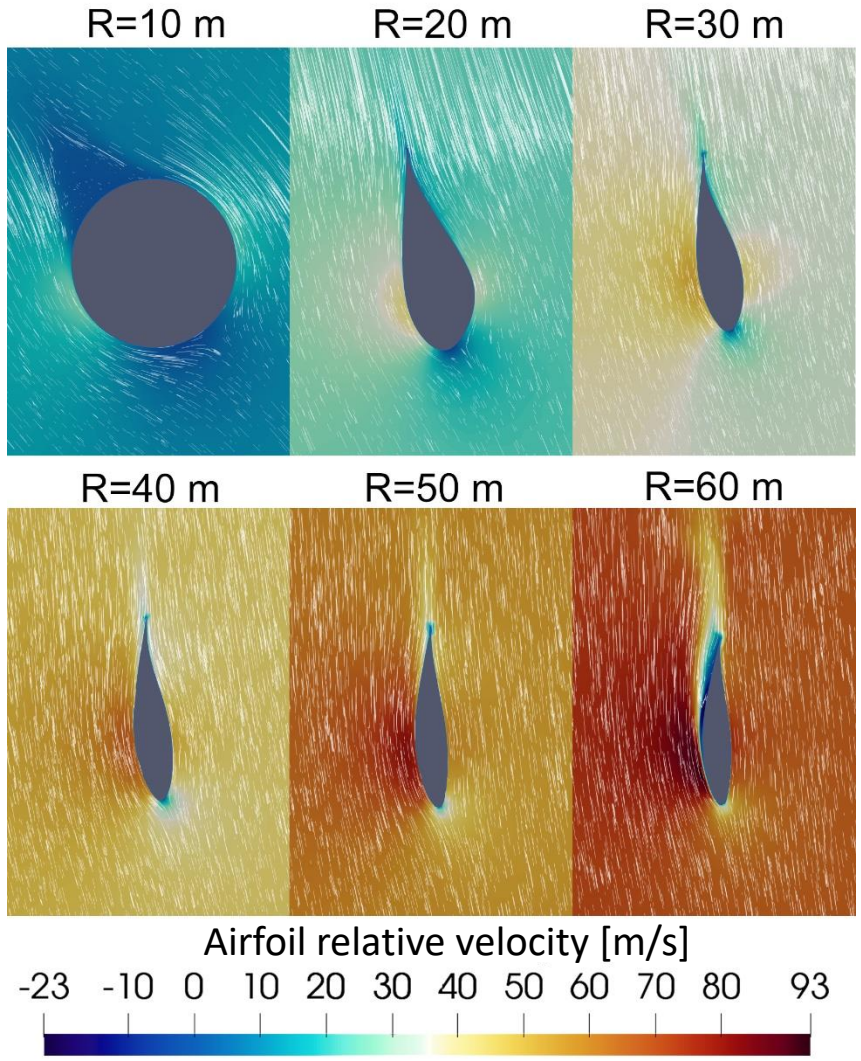
- Wind velocity: Uniform 10 m/s
- 50 seconds simulated
- Performance
  - 240 processors in 10 nodes
  - 35 days of simulation
- Wake formation
  - Speed decreases from 10 m/s to 5 m/s
  - 300 m downstream from the rotor the wake is still strong





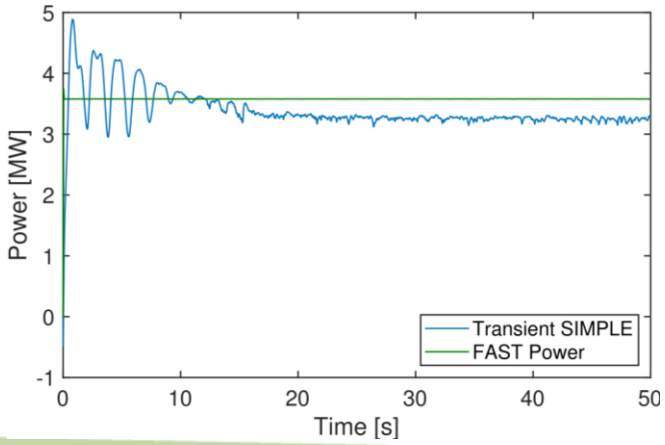
Rotor simulations results details

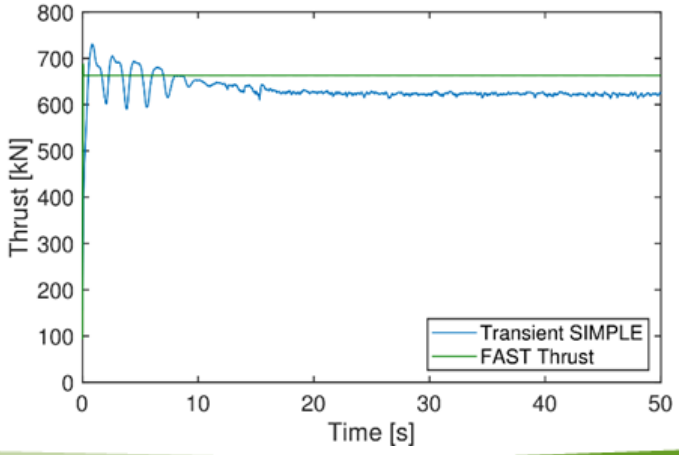
- It is possible to see how each blade part has different relative velocity
- The flow starts to detach from the airfoil located at *R* = 60 m

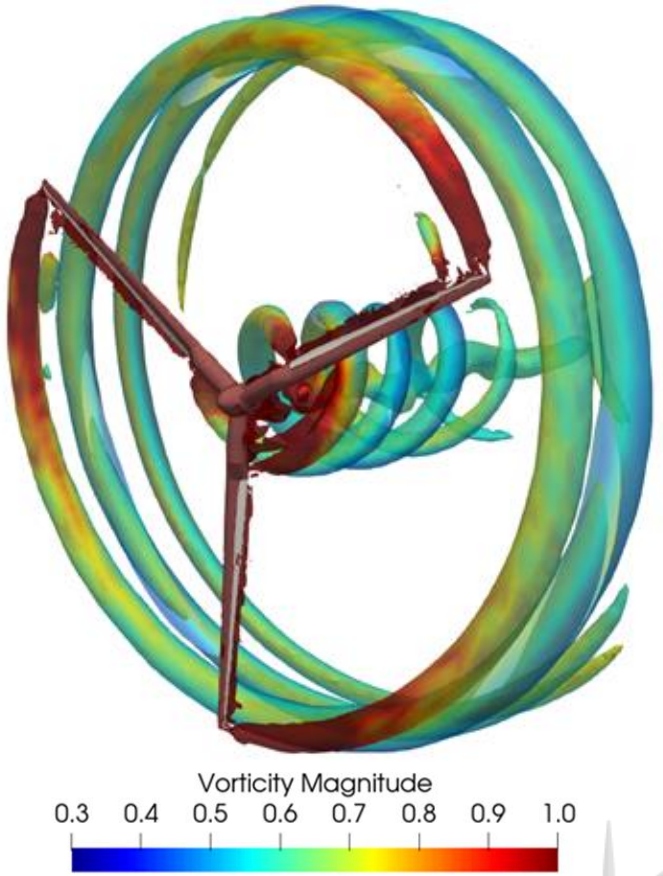


Rotor simulation results

- Power: 3.27 MW – FAST: 3.57 MW
- Thrust: 624.2 kN – FAST: 663.1 kN
- Vorticity plot: show vortices in the blade tips and some points in the middle of the blade → energy loss

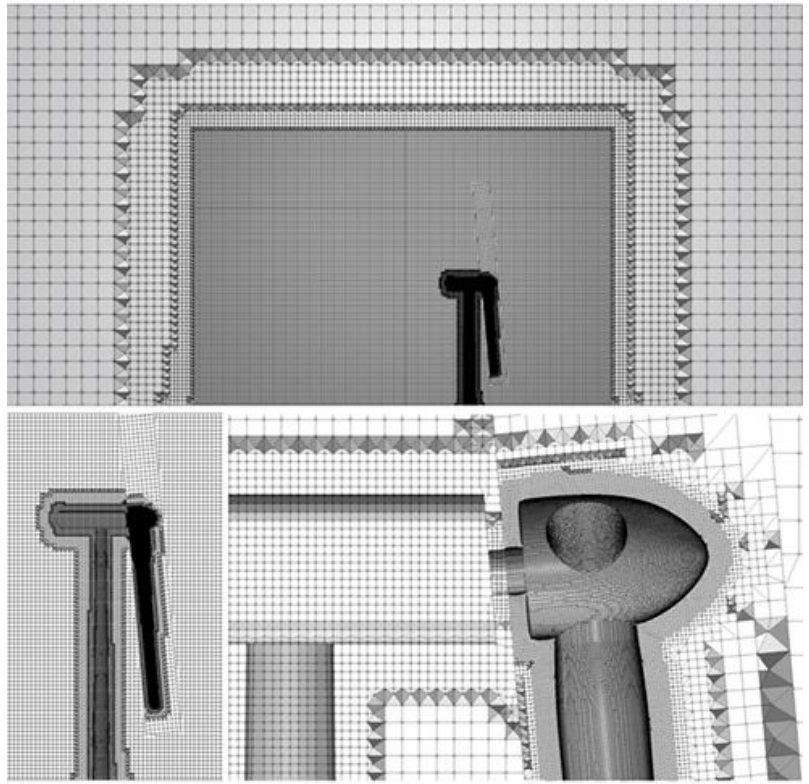


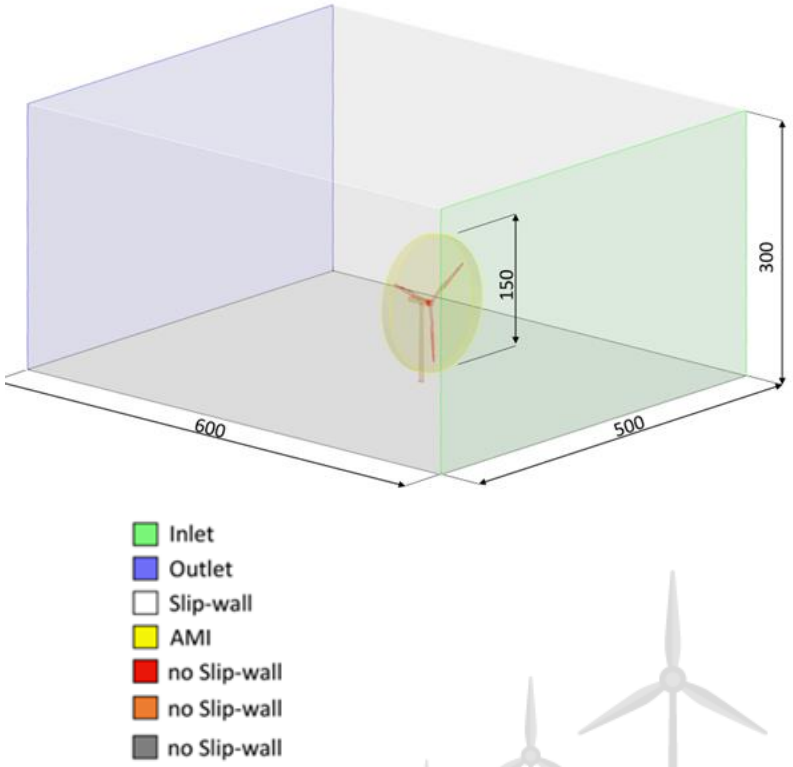




Turbine simulations – mesh and domain

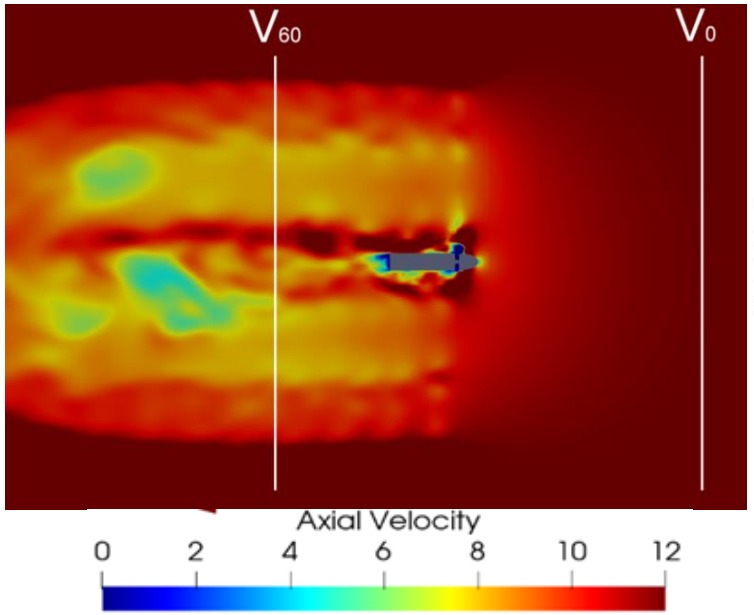
- Ground, tower and nacelle modelled
- Rigid blade
- AMI Sliding Mesh
- 12,008,991 cells
- Same characteristics of rotor mesh next to the blade

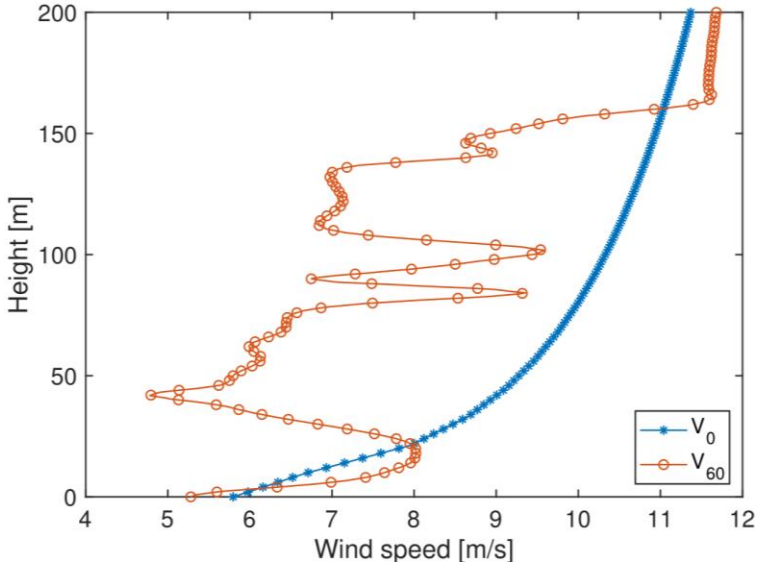




Turbine simulation results

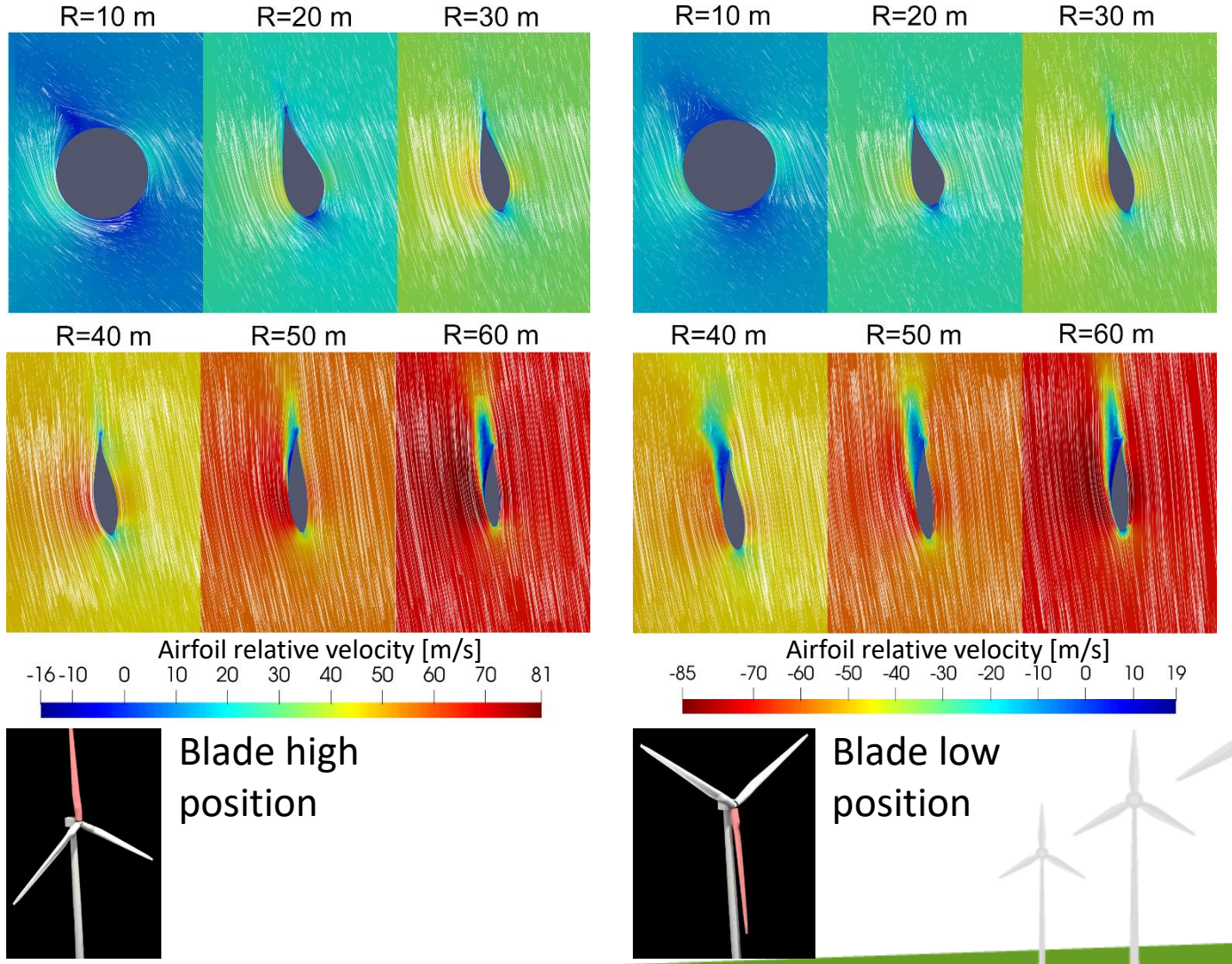
- Wind velocity: 10 m/s at 80 m
  - $v(h) = v(80).\frac{\log\left(\frac{h}{r}\right)}{\log\left(\frac{80}{r}\right)}$
  - Ground roughness (r): 0.01 m
- 20 seconds simulated
- Performance
  - 240 processors in 10 nodes
  - 20 days of simulation
- Wake formation and wind profile





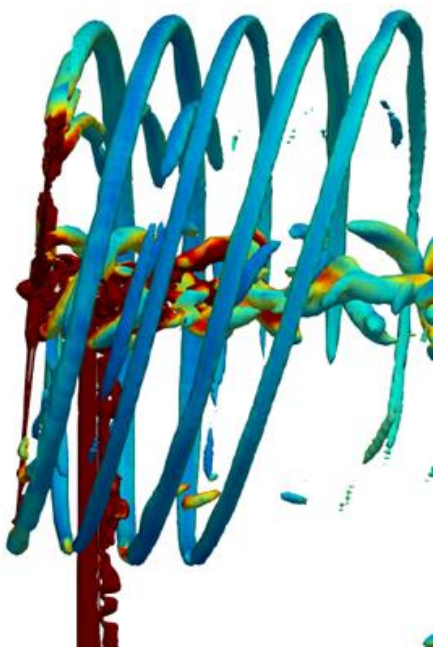
Turbine simulation results details

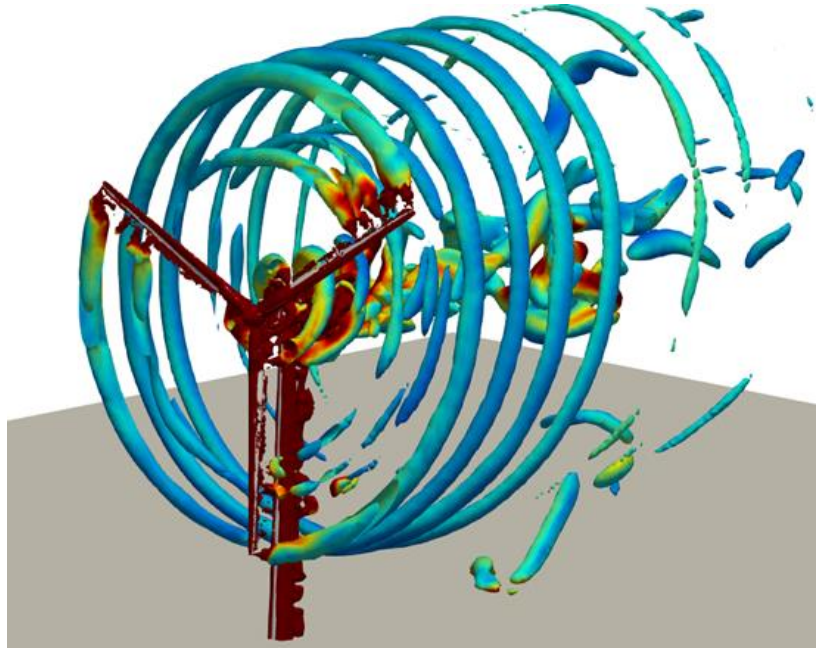
- Figures show the blade at two different critical locations
  - High position → higher wind velocity
  - Low position → lower wind velocity and tower interference
- High position
  - *R* = 50 and 60 m → stall
- Low position
  - *R* = 40, 50 and 60 m → stall

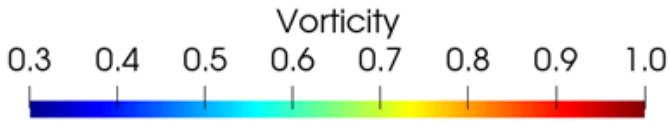


Turbine simulation results

- Power: 1.67 MW
- Thrust: 505.2 kN
- Vorticity plot: vortices in the blade tips and in points in the middle of the blade even more than in the Rotor simulation → energy loss
- Presence of stall in the blade next to the tip

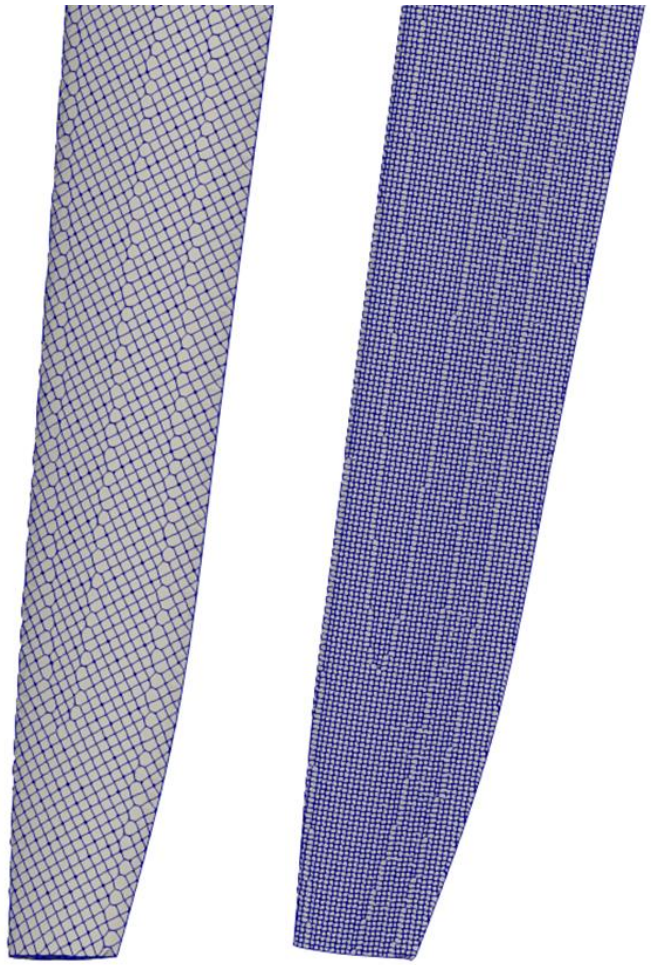


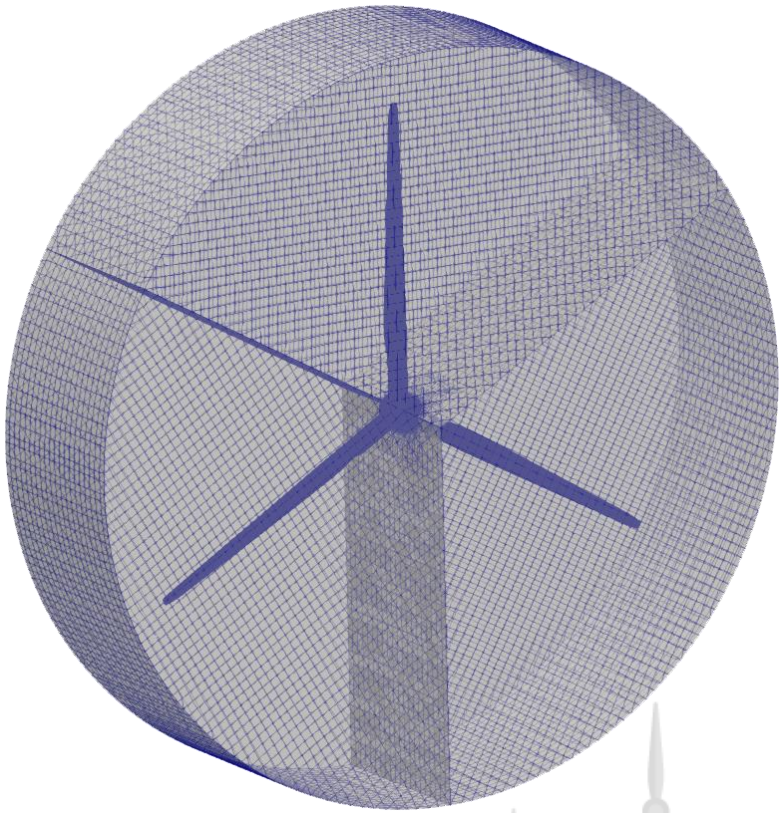




Mesh improvements - rotor

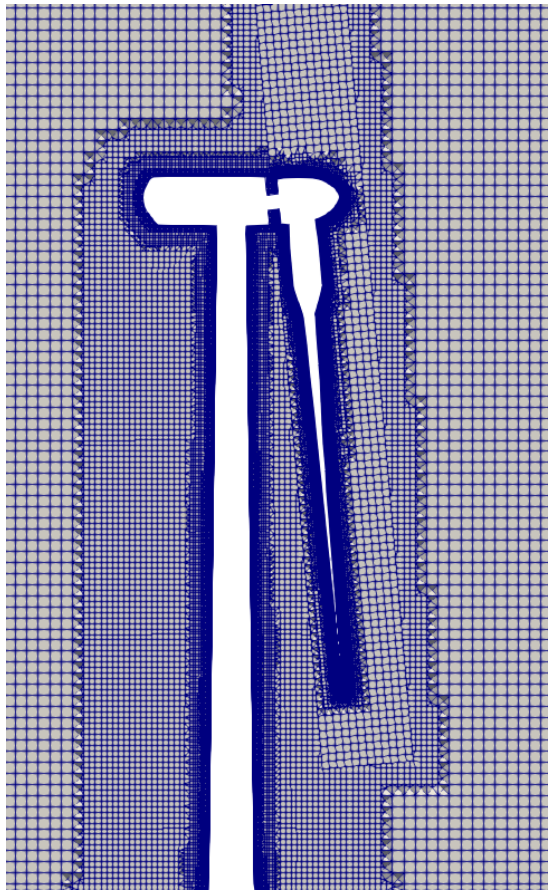
- Ongoing work
- Finer mesh
- Tip Y+ = 180
- 10 layers
- Fix of non-parallel cells in relation to the blade chord
- Mirroring of the blades
- AMIs to pass the information between the mirrored blades

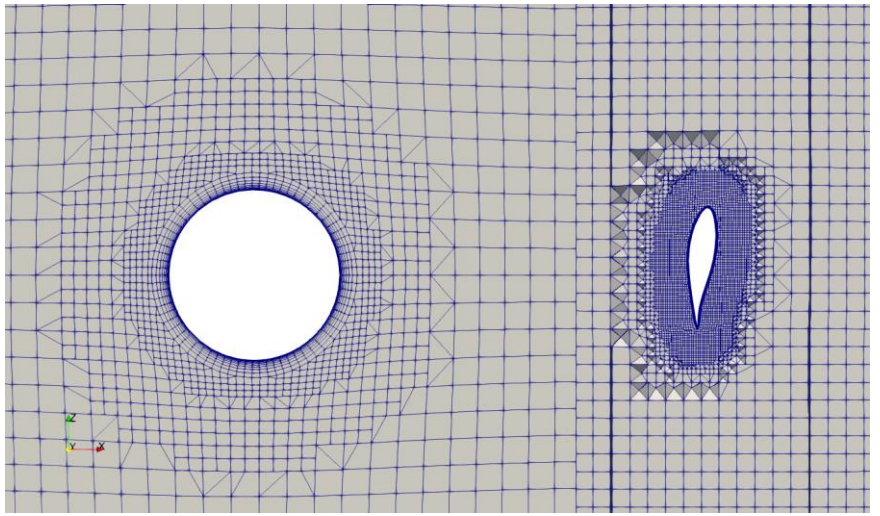




Mesh improvements - turbine

- Ongoing work
- More elements between the tower and blade sliding interface
- Total cells: 20 M
- Utilization of PISO iterative for the unsteady solution
- Simulations are currently running



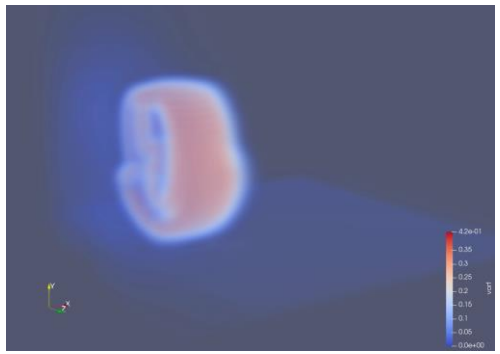
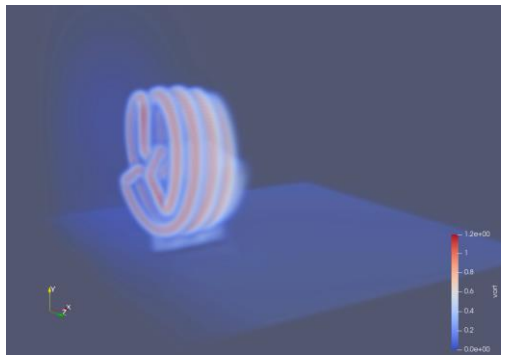
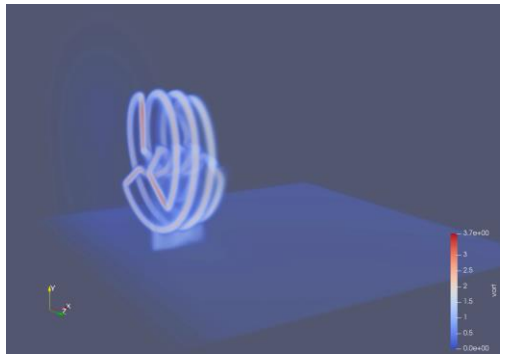


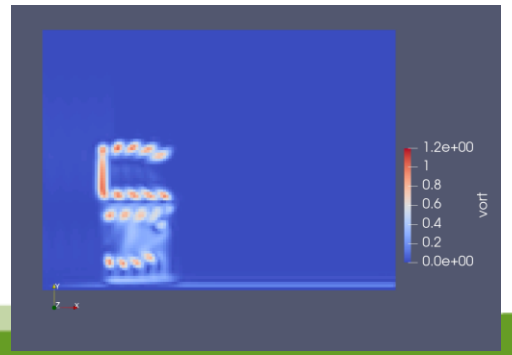
Actuator line simulations with WInc3D

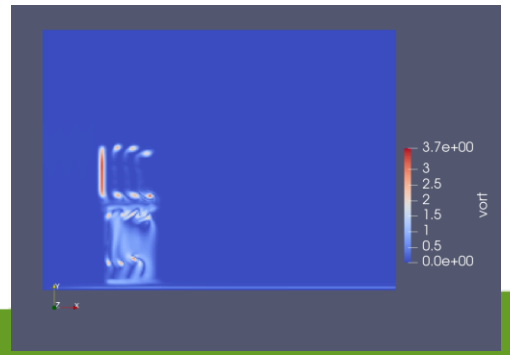
- WInc3D: Extension from Incompact3D for wind energy applications
- High-order finite diferences
- Cartesian, structured mesh
- Great scalability
- Simulations of NREL 5 MW turbine:
  - Fixed TSR simulations of single turbine and two turbines side by side
  - Single controlled turbine simulations for different wind speeds
  - Moving turbine (prescribed motions) simulations

Mesh refinement studies

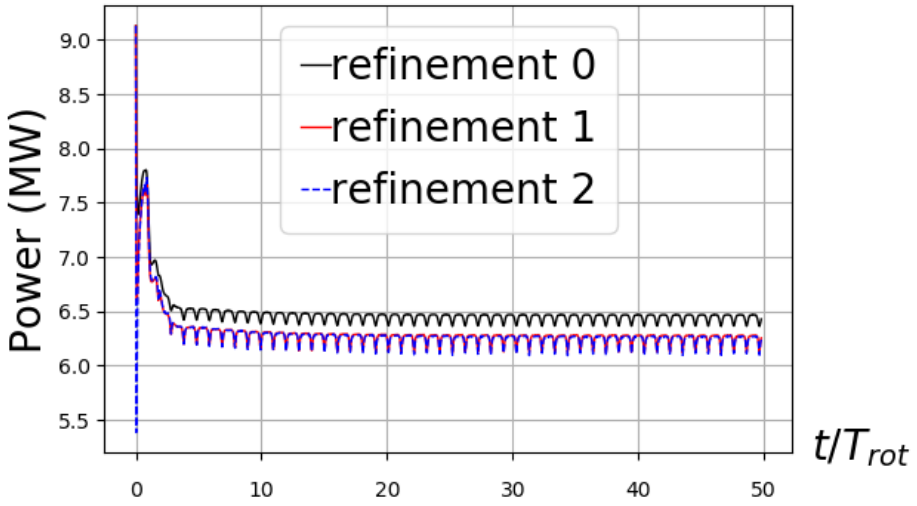
- Size of domain: $(3D \times 3D \times (0{,}5D + 1{,}7D))$
- $TSR = 7{,}55$ (“optimal”) e $\mathrm{U}_\infty = 11{,}4\ m/s$ (“rated”)
- Discretization $\Delta x = \Delta y = \Delta z = h = h_0 2^{-i}$, where $h_0 \approx 6$, $i = 0{,}1{,}2$

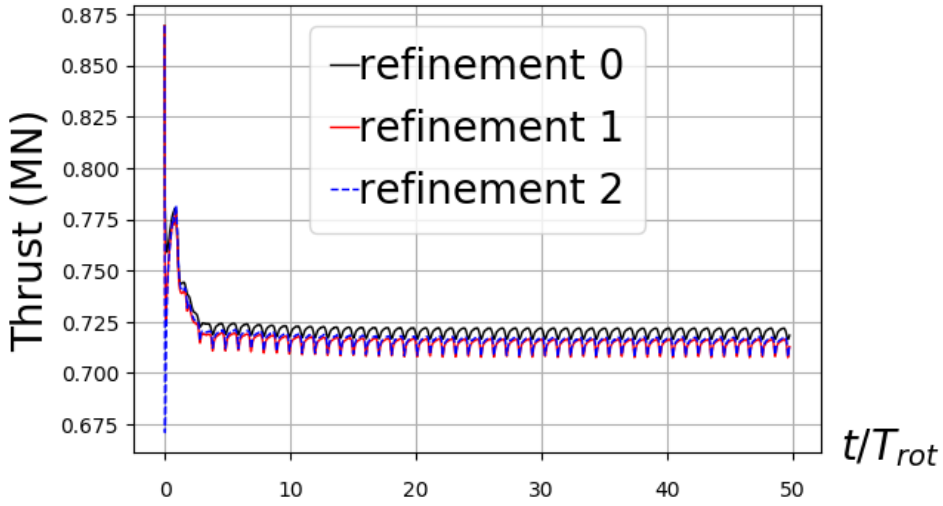




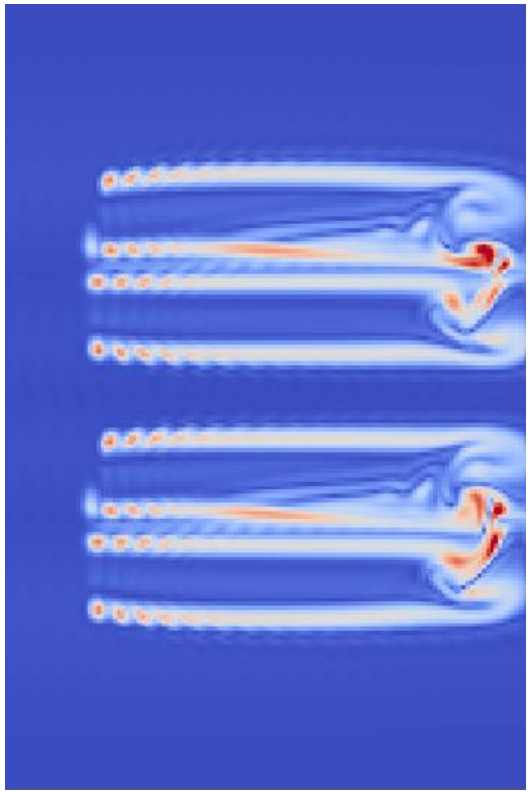


Mesh refinement studies

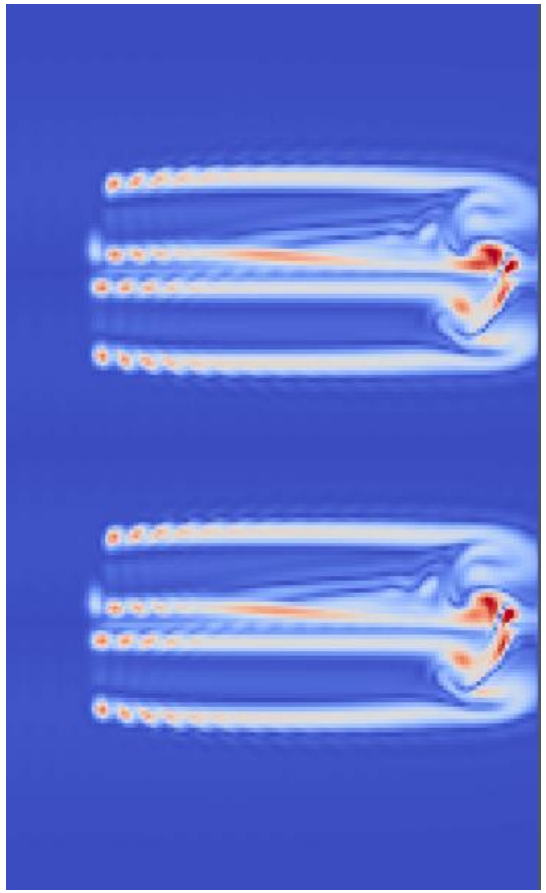




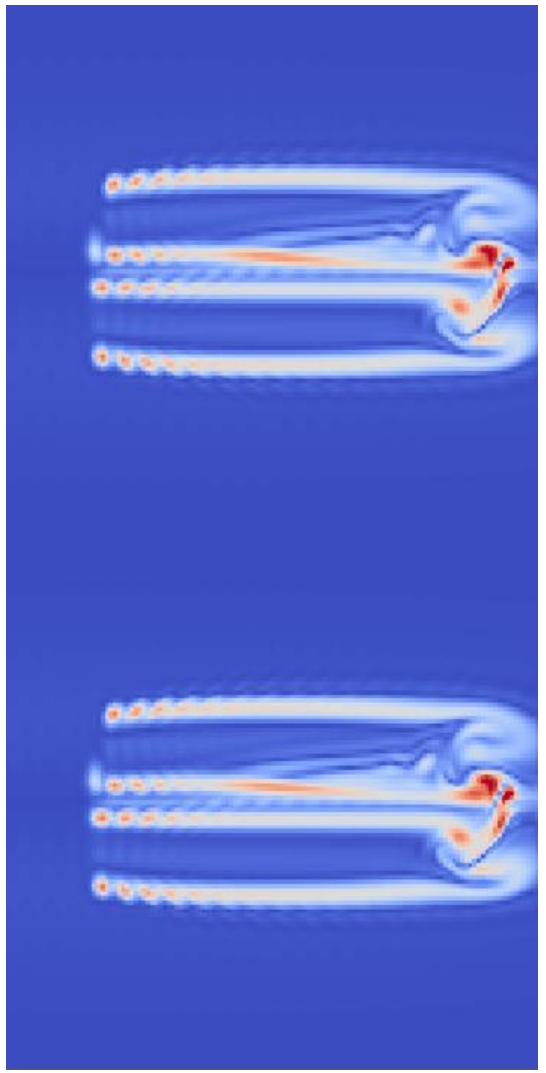
Side-by-side, co-rotation



1.5*D*

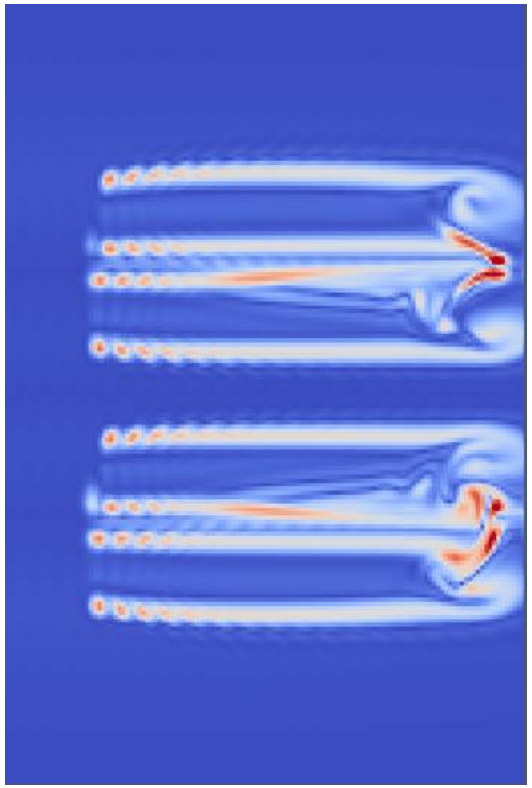


2*D*

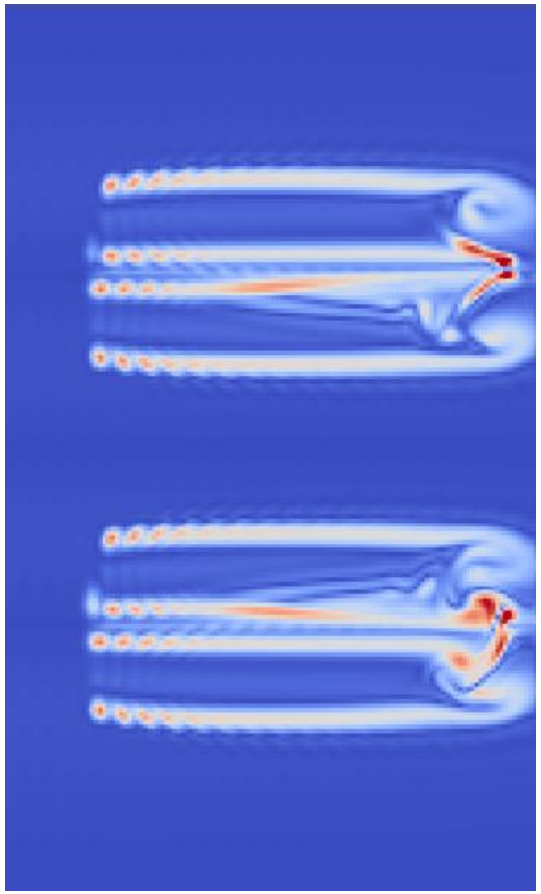


3*D*

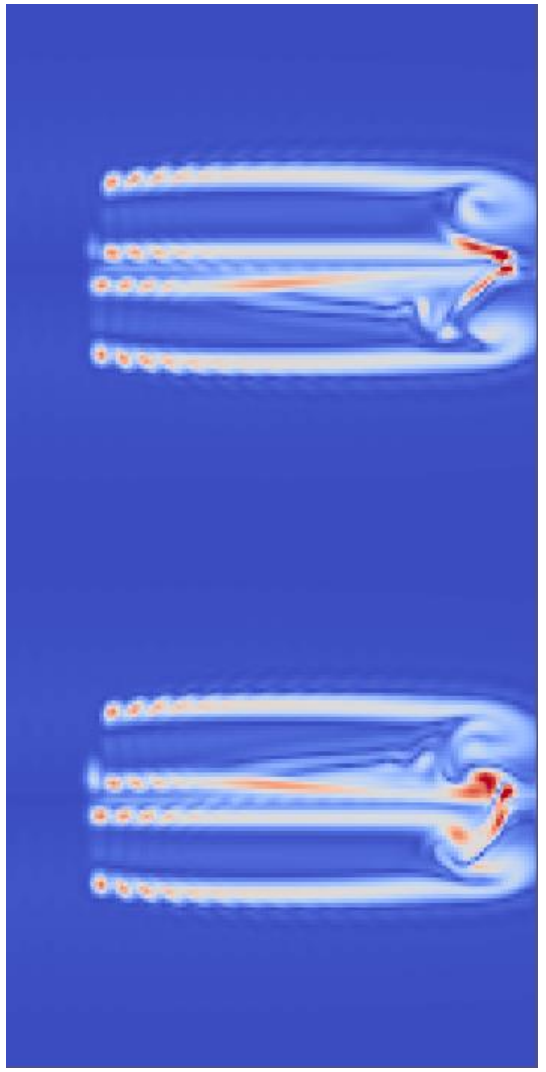
Side-by-side, counter-rotation



1.5*D*

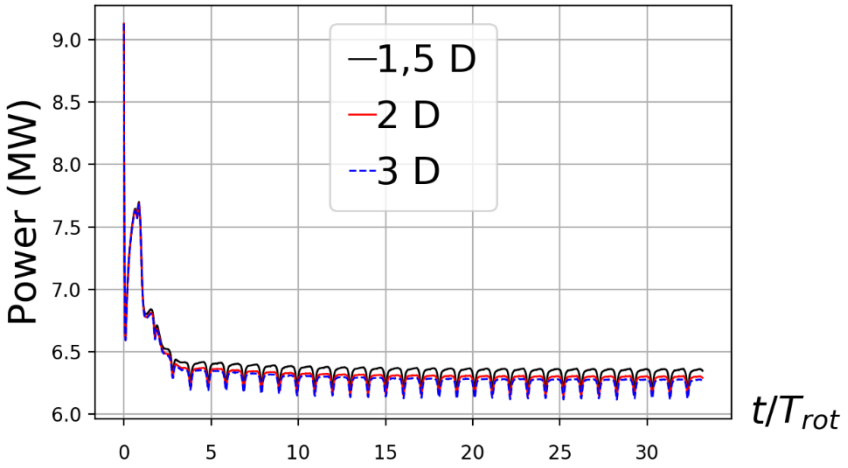


2*D*

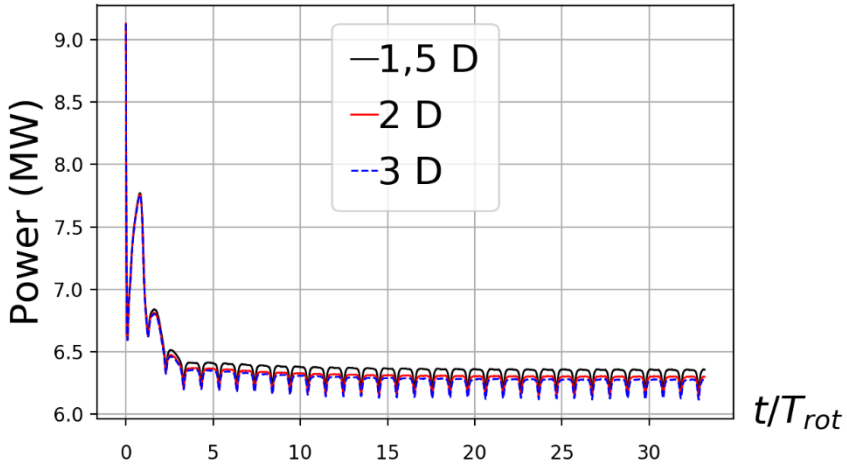


3*D*

Two turbines in parallel

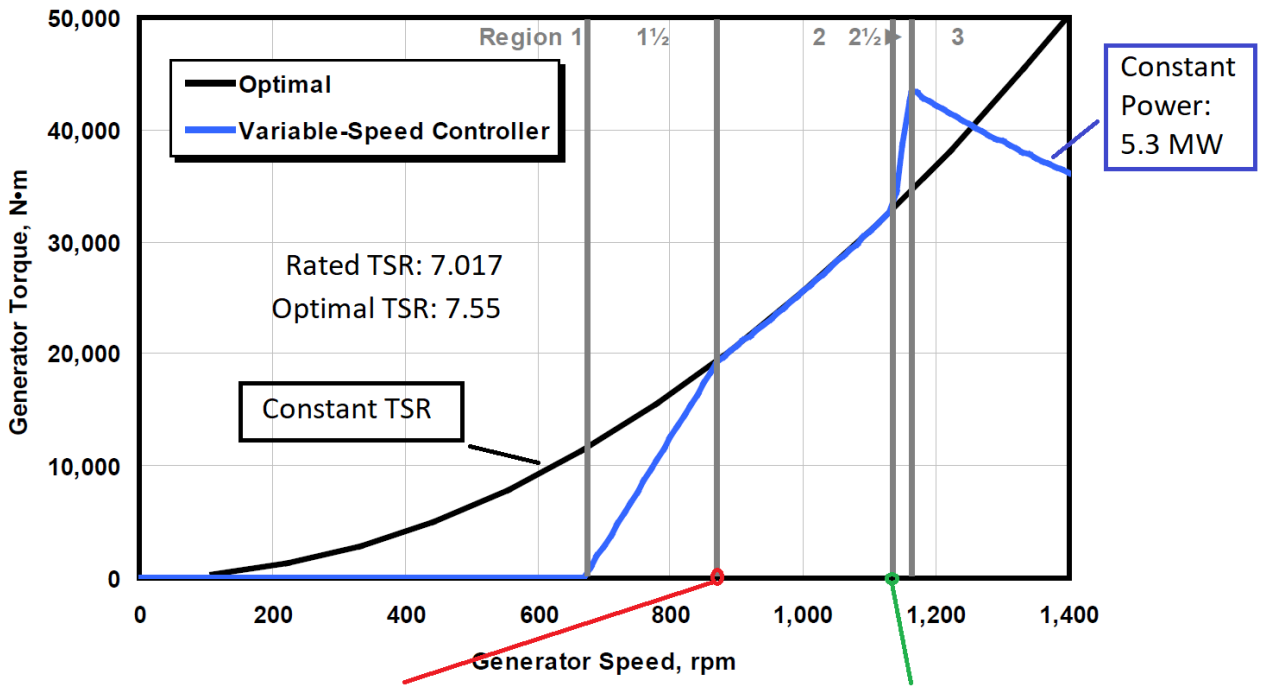


Co-Rotation

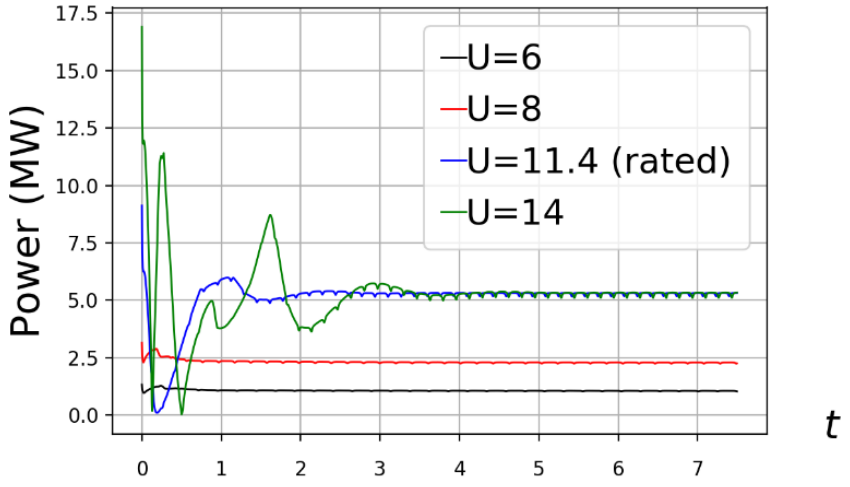


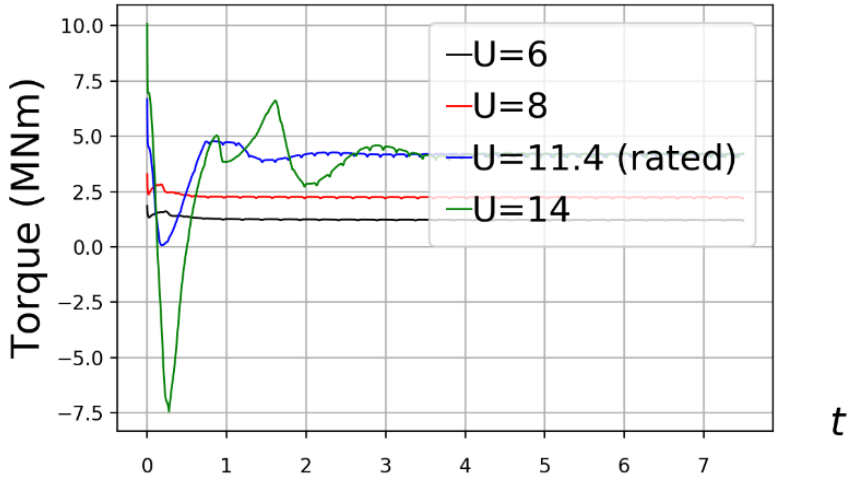
Counter-Rotation

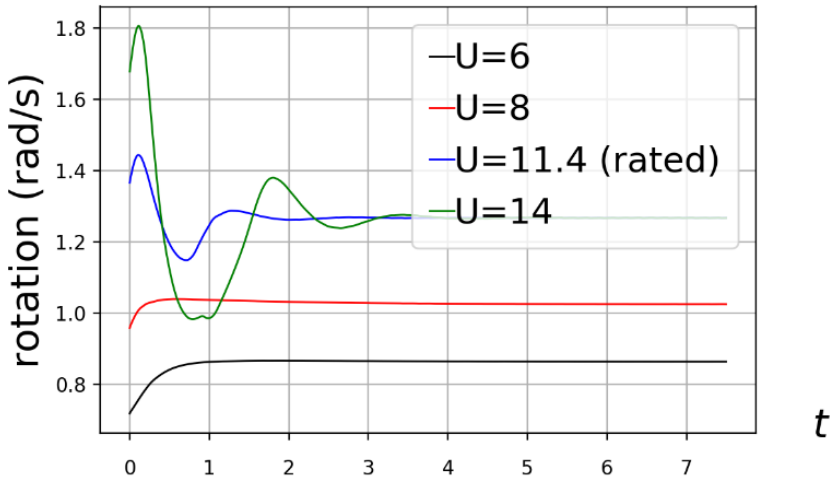
Simulation with control on isolated turbine

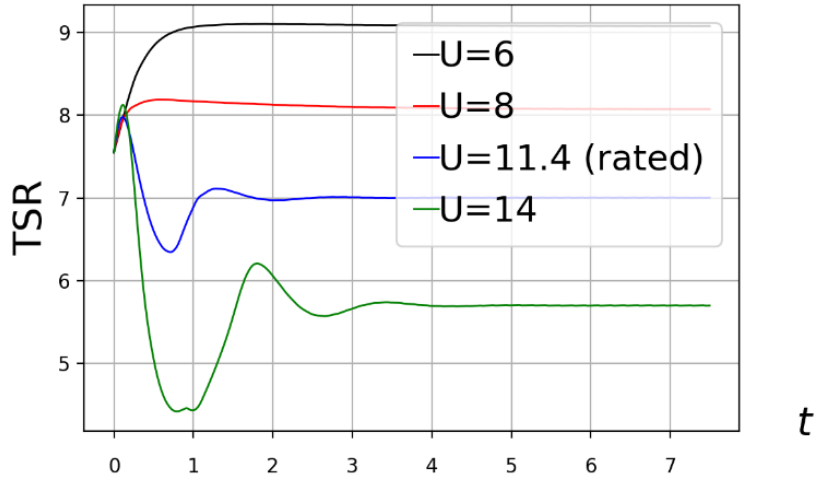


Simulation with WInc3D





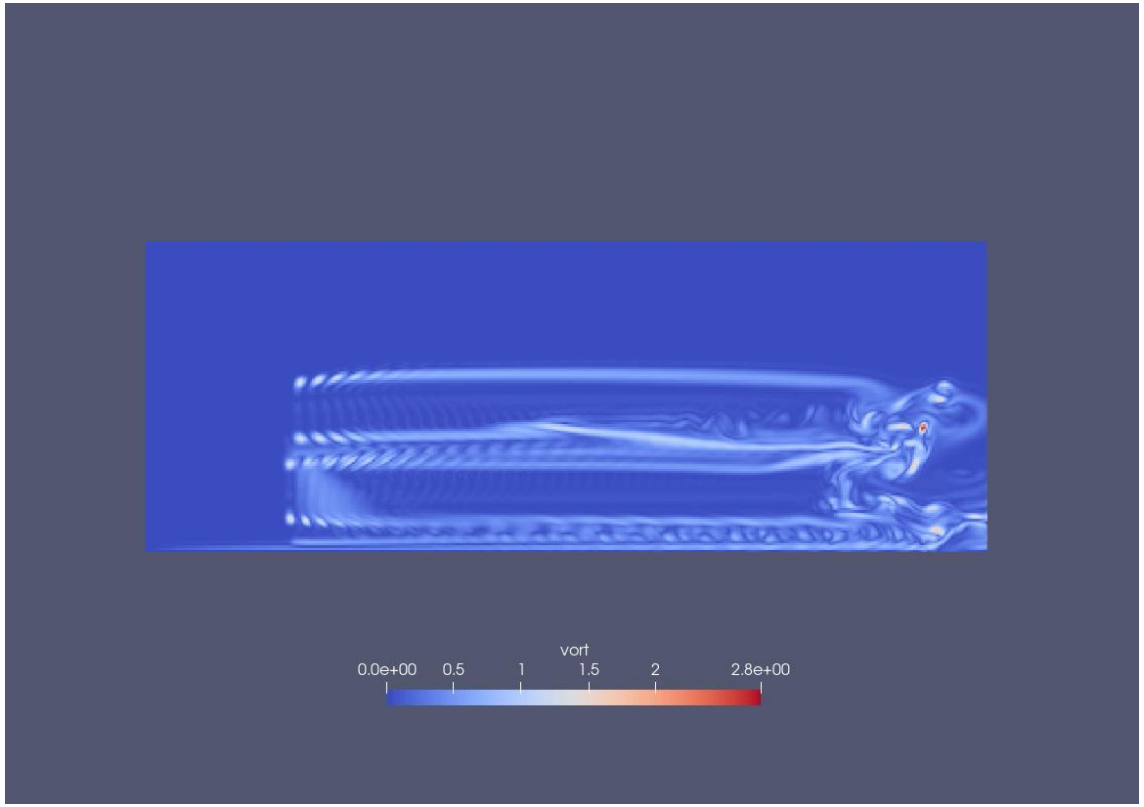




Wind turbine wake on moving platform

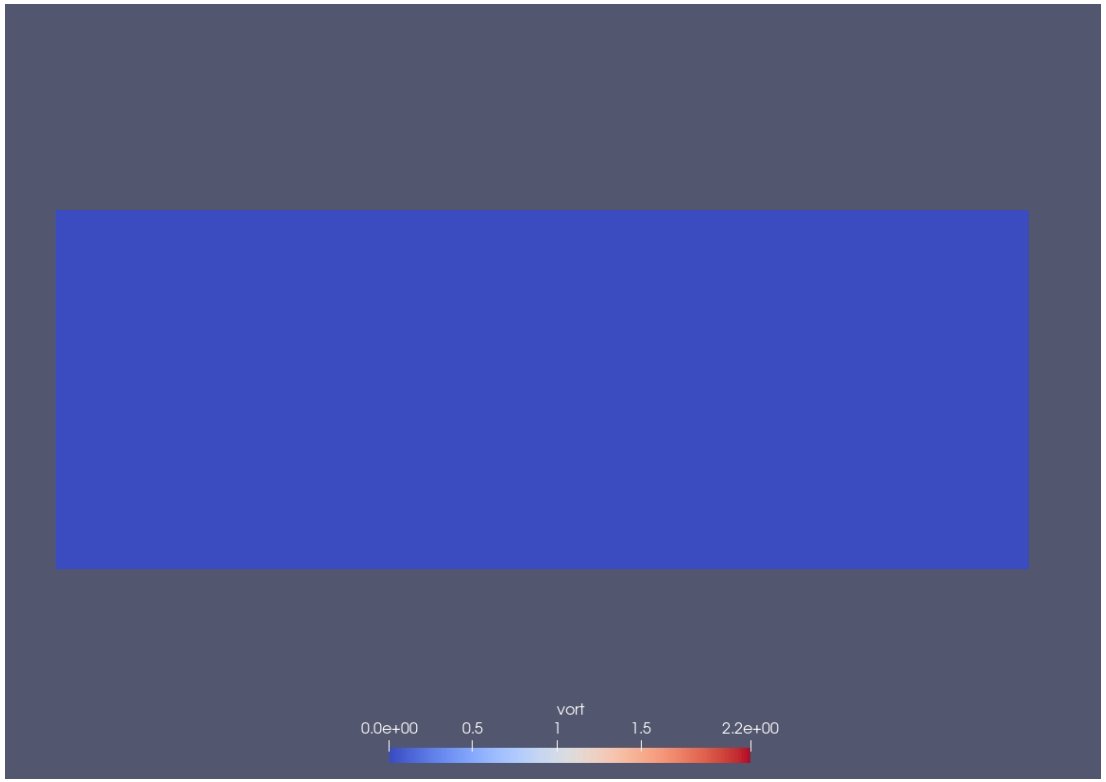
- Movement of the platform may modify the structure on the wake
- This could favour turbulent structures, shortening the wake
- Simulations performed with code WInc3D, high-order finite diferences
- Large Eddy Simulation w/ actuator line method
- Heave, surge and pitch movements are simulated at rated TSR
- Frequency of motion at half of the rotation frequency
- Linear amplitudes (heave/surge) of 4 m and pitch of 4°

Wind turbine wake on moving platform



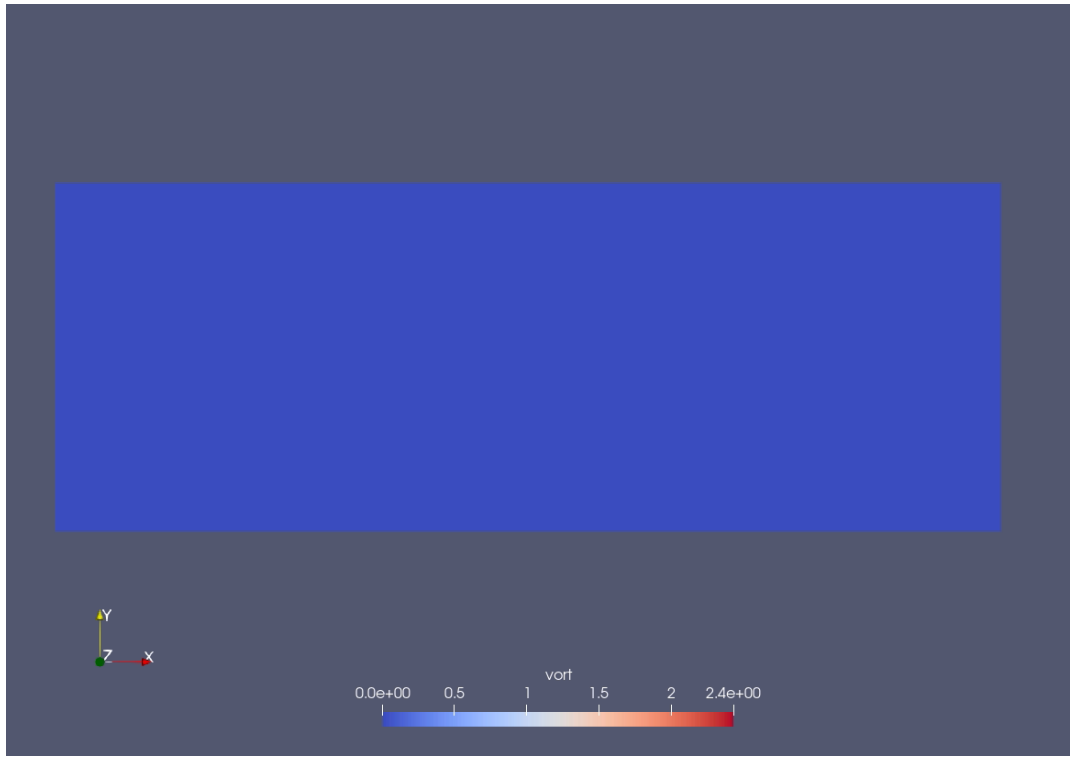
Unperturbed solution (no movement, no incoming turbulence)

Wind turbine wake on moving platform



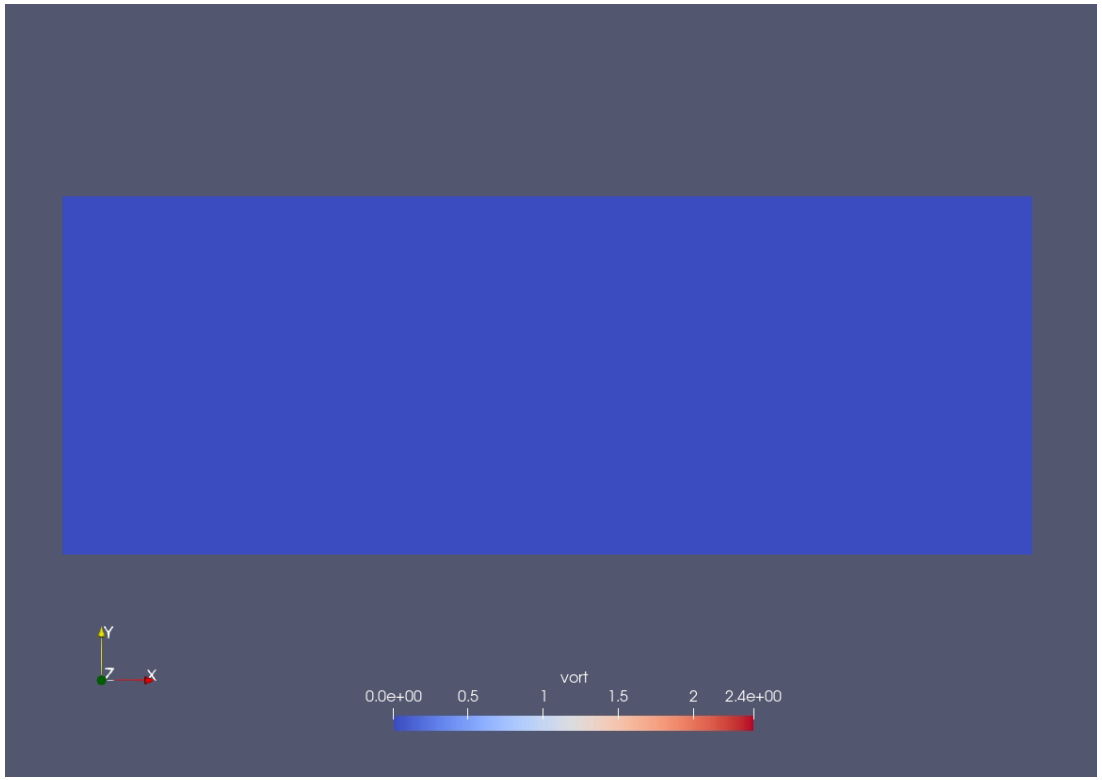
Surge

Wind turbine wake on moving platform



Pitch

Wind turbine wake on moving platform



Heave

Wind turbine wake on moving platform

- Movement of turbine does trigger turbilence earlier
- Main instability mechanism is vortex ‘‘pairing‘‘
- Further work: investigate the effect of motion using smaller amplitudes

Acknowledgements

- FAPESP (Grant 2019/01507-8)
- Imperial College team
- KTH team