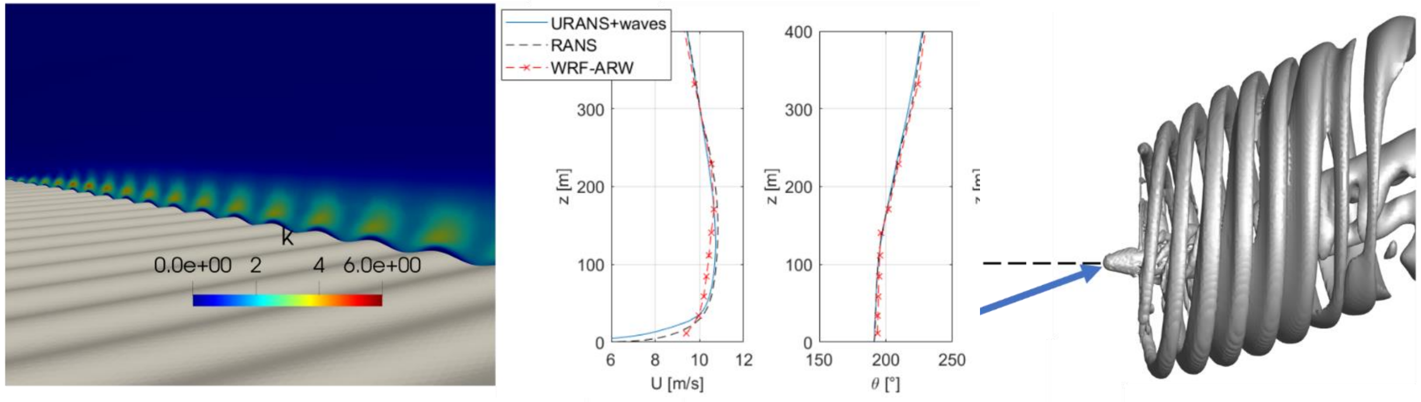
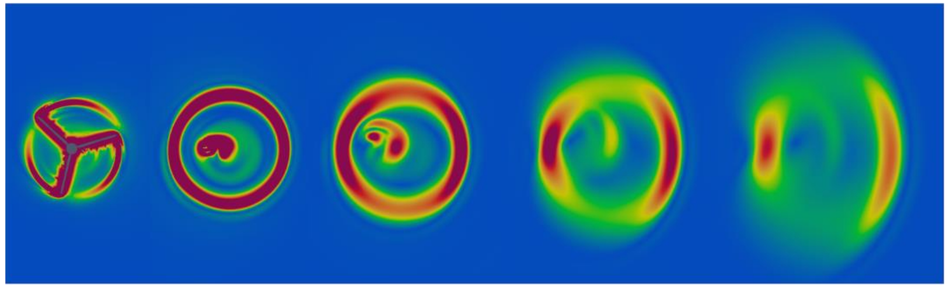
High-resolution prediction of wind profile and wind turbine aerodynamics using CFD and HPC

Alessio Castorrini (1)



HPC-Europa 3 – Project: HPC1796WT3

In collaboration with
M. S. Campobasso(2)
S. Gentile(3)



(1) School of Engineering, University of Basilicata, Potenza, Italy
(2) Department of Engineering, Lancaster University, Lancaster, United Kingdom
(3) National Research Council of Italy (CNR) - Institute of Methodologies for Environmental Analysis (IMAA), Tito Scalo (PZ), Italy

Webinar

@ EPCC, University of Edinburgh, UK, 20/04/2022

Biography

Alessio Castorrini
Researcher

Institution and department
Università degli Studi della Basilicata · School of Engineering (SI-UniBas)

Affiliations

Lancaster University
Visiting Researcher
2019-2022

Waseda University
Visiting Researcher
2015

Education

Sapienza Università di Roma
Doctor of Philosophy (PhD), Industrial Engineering
2013 - 2017

Sapienza Università di Roma
Master's degree, Aerospace, Aeronautical and Astronautical Engineering
2010 - 2013

Sapienza Università di Roma
Laurea in Ingegneria Aerospaziale, Laurea I Livello
2006 - 2009

Teaching

Sapienza Università di Roma
Fluid Structure interaction
2019-2021

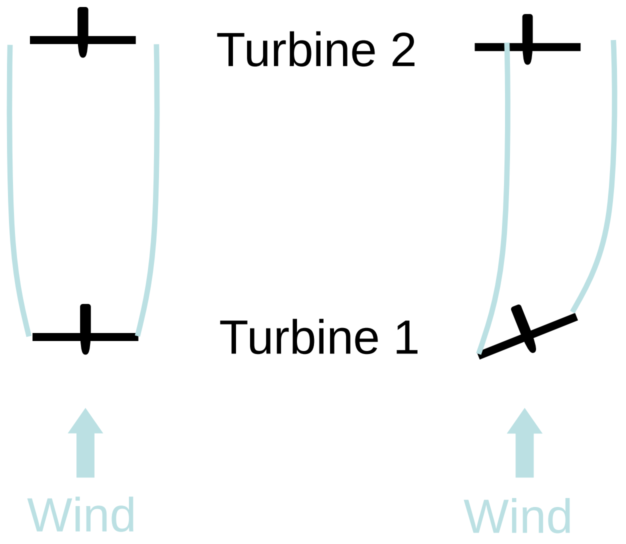
Università degli Studi della Basilicata
Metodi agli elementi finiti per l'interazione fluido struttura
2019-2022

Project background and overview

Problem 1

Average power loss due to wind turbine wakes can reach the 20% in large offshore wind farms

Numerical simulation supports the design and optimization of wind farms layout and control strategies for energy loss reduction



Wake effect behind turbines at Vattenfall's Horns Rev wind farm off Denmark. Photo by: Vattenfall

Project aim

Use of HPC to simulate with high level of accuracy the aerodynamics of a wind turbine rotor using rotor resolved geometry, to verify the reliability of results obtained with a lower order model commonly adopted to simulate wind farms

Project background and overview

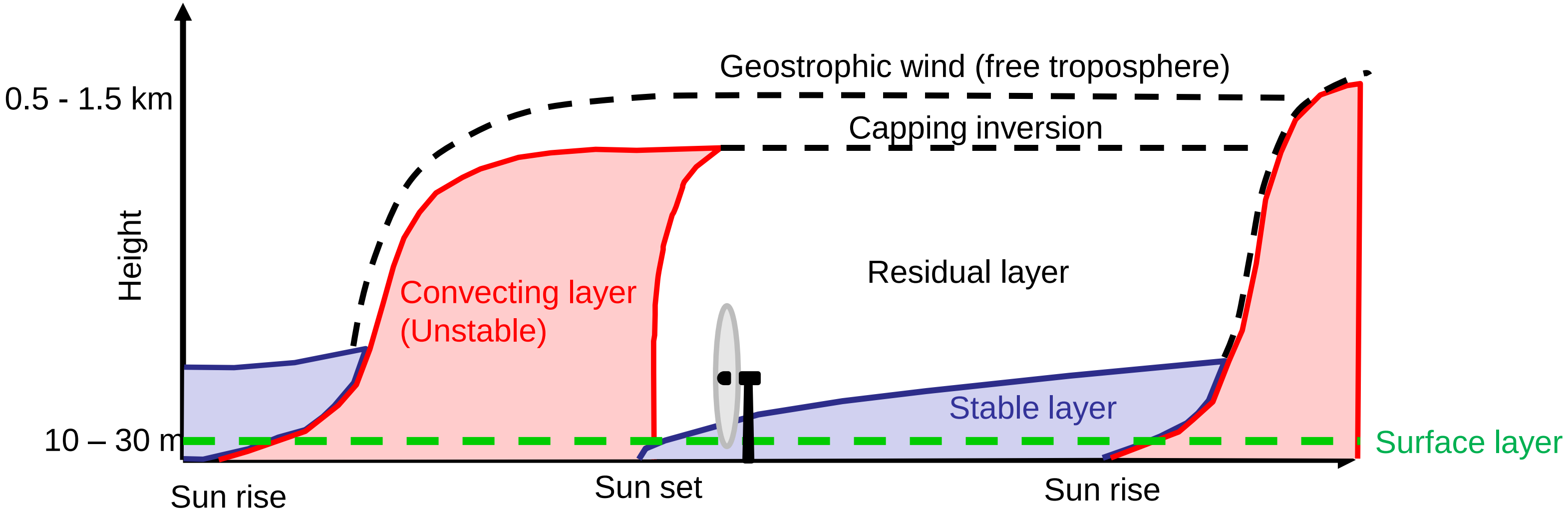
Problem 2

New wind turbines design reach nominal powers up to 15MW and rotor diameters of more than 200 m

→ Blades can span heights from 30 m to 330 m above the ground

→ High-resolution CFD allow to provide reliable wind vertical profiles for surface layer and neutrally stratified ABL (Inflow BC based on similitude theory and theoretical profiles)

→ Mesoscale models (Numerical weather prediction) allows to simulate the whole atmosphere dynamics including microphysics and thermal effects but it does not have sufficient resolution to catch local surface effects.



Project aim

Use of HPC to generate with the CFD a realistic wind prediction over an offshore location forcing unstable wind from NWP as boundary condition and including wave motion with a moving grid approach

Challenges in wind farm and wind turbine aerodynamics

For **reliable numerical simulation** of wind farms we need:

- Accurate modelling of the wind turbine aerodynamics (and loads)
  - Actuator line model
  - Rotor resolved geometry simulation
- Adequate wake resolution to assess the energy resource available to wind turbines downstream
  - Reynolds Averaged Navier Stokes (RANS) Simulation
  - Hybrid LES-RANS (DDES)
  - Large Eddy Simulation (LES)
- Realistic wind inflow at the rotors
  - Neutral Atmospheric Boundary Layer (ABL) Log-Law
  - Steady ABL-RANS
  - Unsteady ABL-RANS
  - LES

  Can be coupled with Numerical Weather Prediction

Challenges in wind farm and wind turbine aerodynamics

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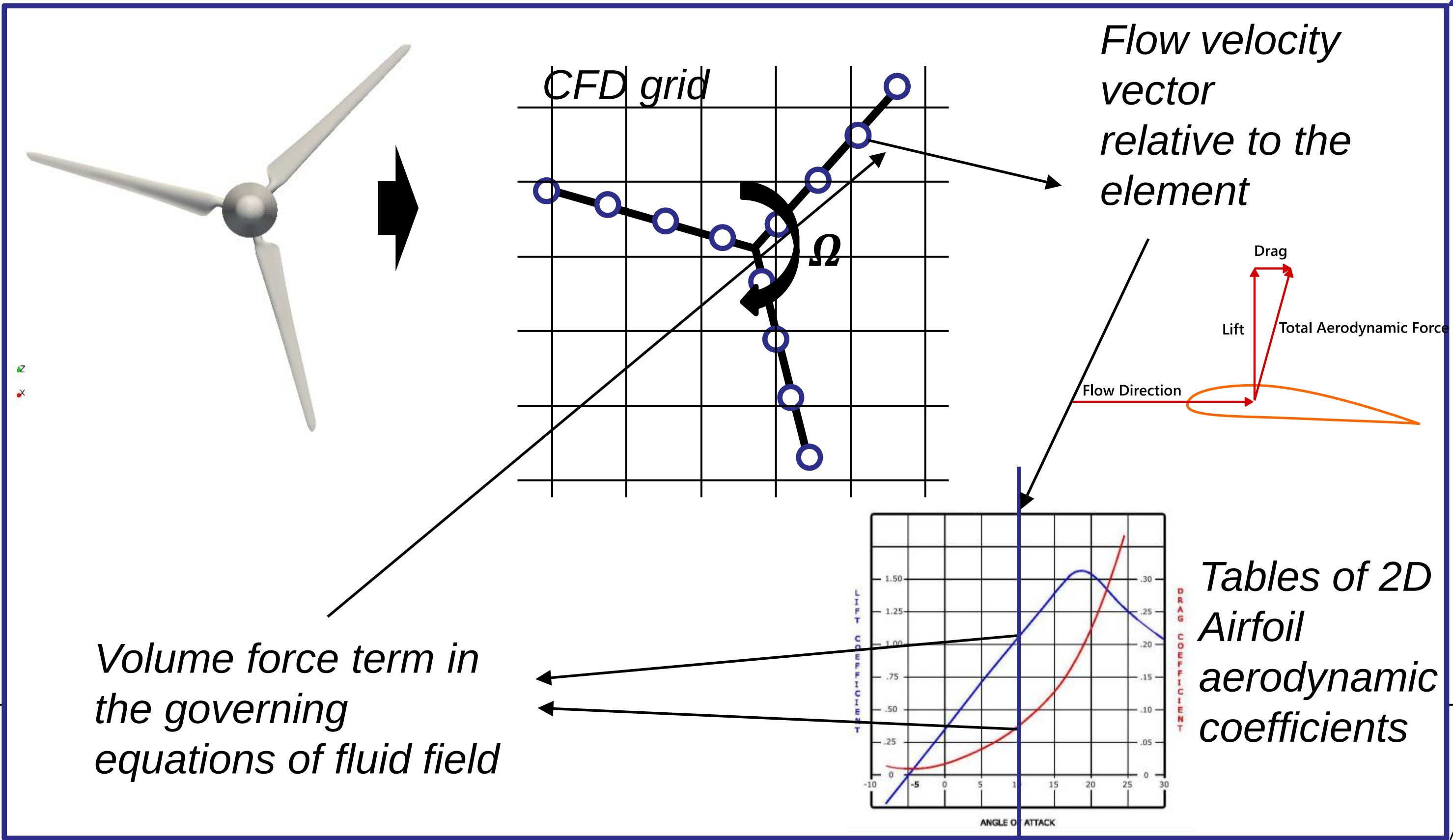


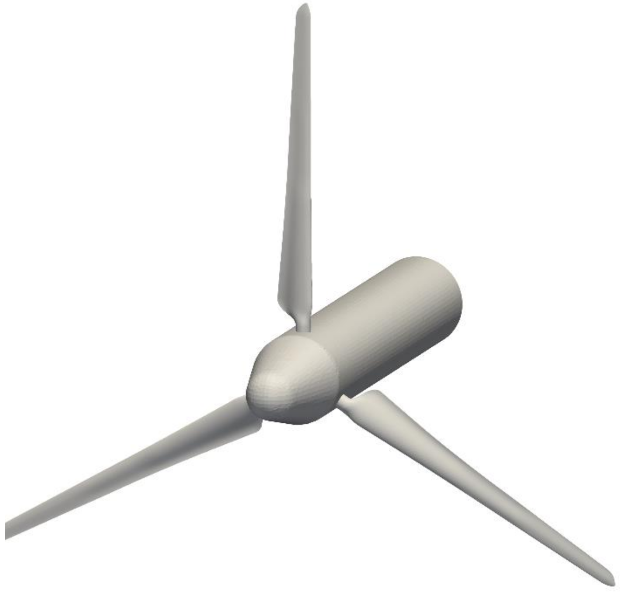
- Neutral Atmospheric Boundary Layer (ABL) Log-Law
- Steady ABL-RANS
- Unsteady ABL-RANS
- LES

Can be coupled with Numerical Weather Prediction

- Wind turbine aerodynamics using rotor resolved geometry and actuator line model
  - Baseline model and numerical experiment
  - CFD modelling and boundary conditions
  - Computational domain, scalability and grid sensitivity analyses
  - Validation for axial and yawed wind
  - Wake analysis and comparison with reduced order models
- Study of the effect of marine waves on the wind profile
  - Case study
  - CFD modelling and boundary conditions
  - Computational domain and grid sensitivity analyses
  - Results

Baseline model and test conditions

Experimental wind turbine rotor from MEXICO project (Model Experiments in Controlled Conditions)



Radius	5.5 m
Blade length	2.04 m
Chord range	0.24 m – 0.05 m
Velocity	44.52 rad/s
Max Reynolds num.	5.5 x 10^5

[1] Snel, H., J. G. Schepers, and B. Montgomerie. "The MEXICO project (Model Experiments in Controlled Conditions): The database and first results of data processing and interpretation." *Journal of Physics: Conference Series*. Vol. 75. No. 1. IOP Publishing, 2007.
[2] Schepers JG, Boorsma K, Cho T, et al. Final report of IEA Task 29, Mexnext (Phase 1): Analysis of Mexico wind tunnel measurements. Energy Research Centre of the Netherlands 2012; ECN-E-12-004. .

Baseline model and test conditions

Experimental wind turbine rotor from MEXICO project (Model Experiments in Controlled Conditions)

Validation ← *Experimental data available [1,2]* (tests 1–6)

Test ID	Wind velocity (m/s)	Yaw angle (°)	TSR (-)
1	10	0	10,0
2	15	0	6,7
3	24	0	4,2
4	10	30	10,0
5	15	30	6,7
6	24	30	4,2
7	15	20	6,7

Typical configuration for wake control → *Application* (test 7)

[1] Snel, H., J. G. Schepers, and B. Montgomerie. "The MEXICO project (Model Experiments in Controlled Conditions): The database and first results of data processing and interpretation." *Journal of Physics: Conference Series*. Vol. 75. No. 1. IOP Publishing, 2007.

[2] Schepers JG, Boorsma K, Cho T, et al. Final report of IEA Task 29, Mexnext (Phase 1): Analysis of Mexico wind tunnel measurements. Energy Research Centre of the Netherlands 2012; ECN-E-12-004. .

CFD modelling and numerical solver

Governing equations

- 3D, Steady and Unsteady Incompressible Navier-Stokes equations

Turbulence modelling

- Reynolds Averaged Navier Stokes (RANS) + k-ω SST turbulence closure (eddy viscosity model)
- Delayed Detached Eddy Simulation (Hybrid LES - RANS k- ω SST)

Wind turbine modelling

- Full rotor simulation
- Actuator line model

Numerical solver

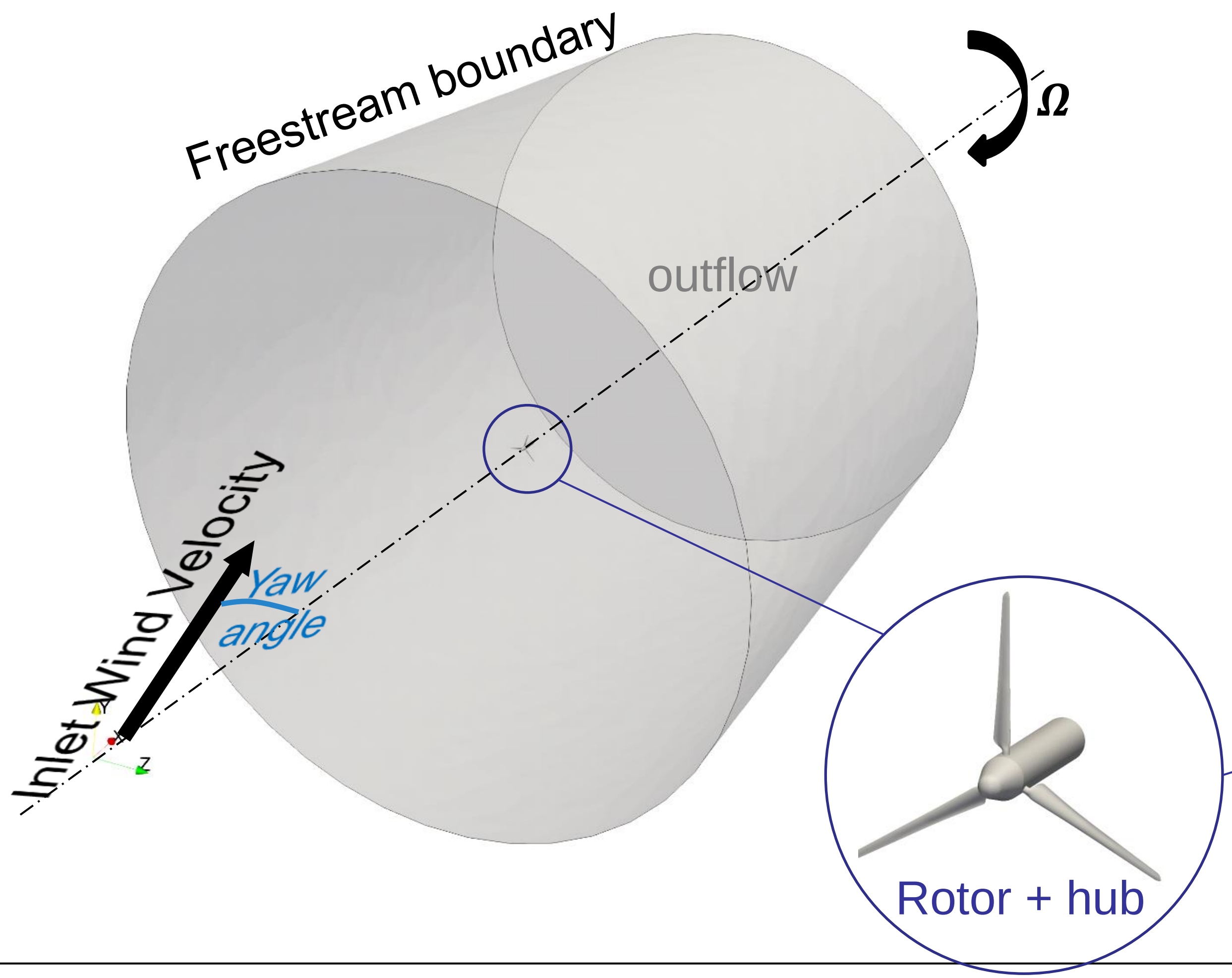
- *openFoam.v2106**
  - Finite volume technique
  - SIMPLE (Semi-Implicit Method for Pressure Linked Equations) – algorithm for steady solutions
  - PIMPLE (Pressure-Implicit with Splitting of Operators + SIMPLE) - algorithm for unsteady solutions
- MPI based domain decomposition - Mesh decomposition with METIS algorithm
- Dynamic Mesh

Mesh generation tool

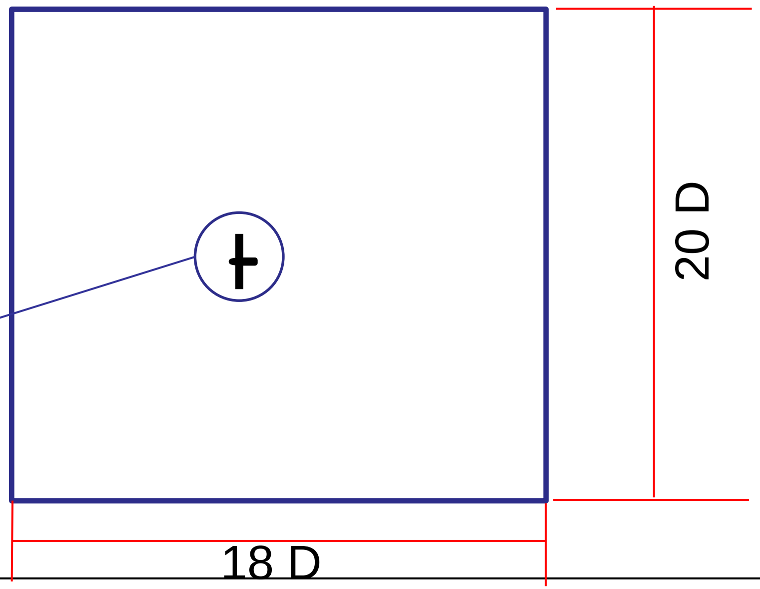
- *cfMesh***

(*) https://www.openfoam.com/
(**) https://cfmesh.com/

CFD domain and boundary conditions

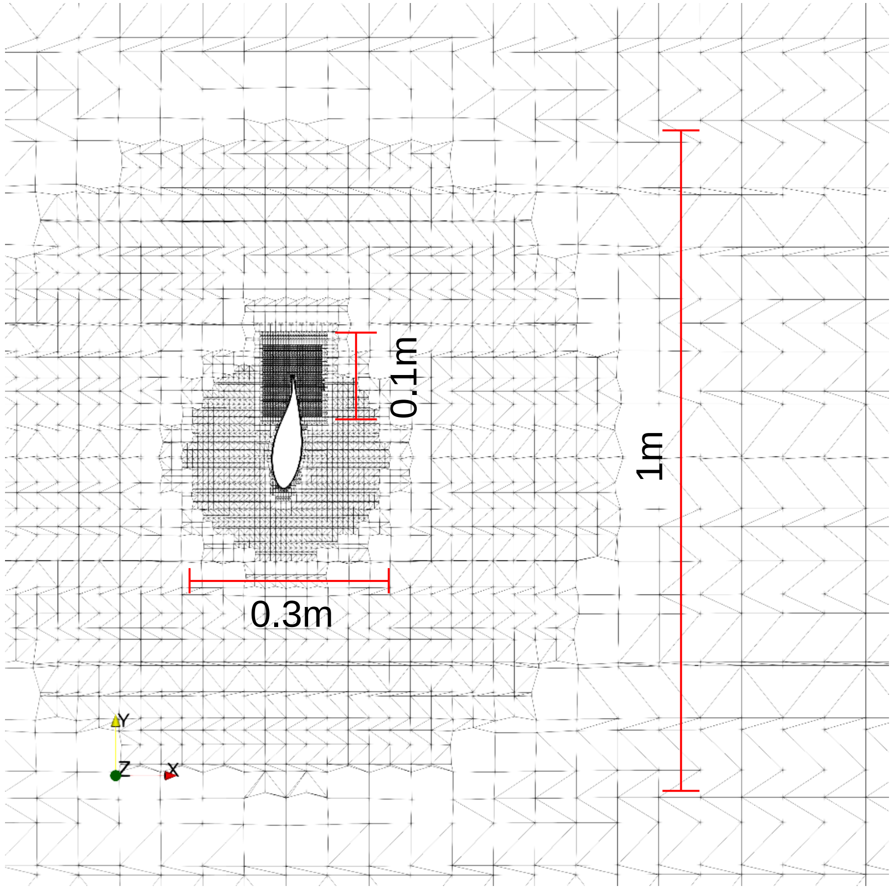


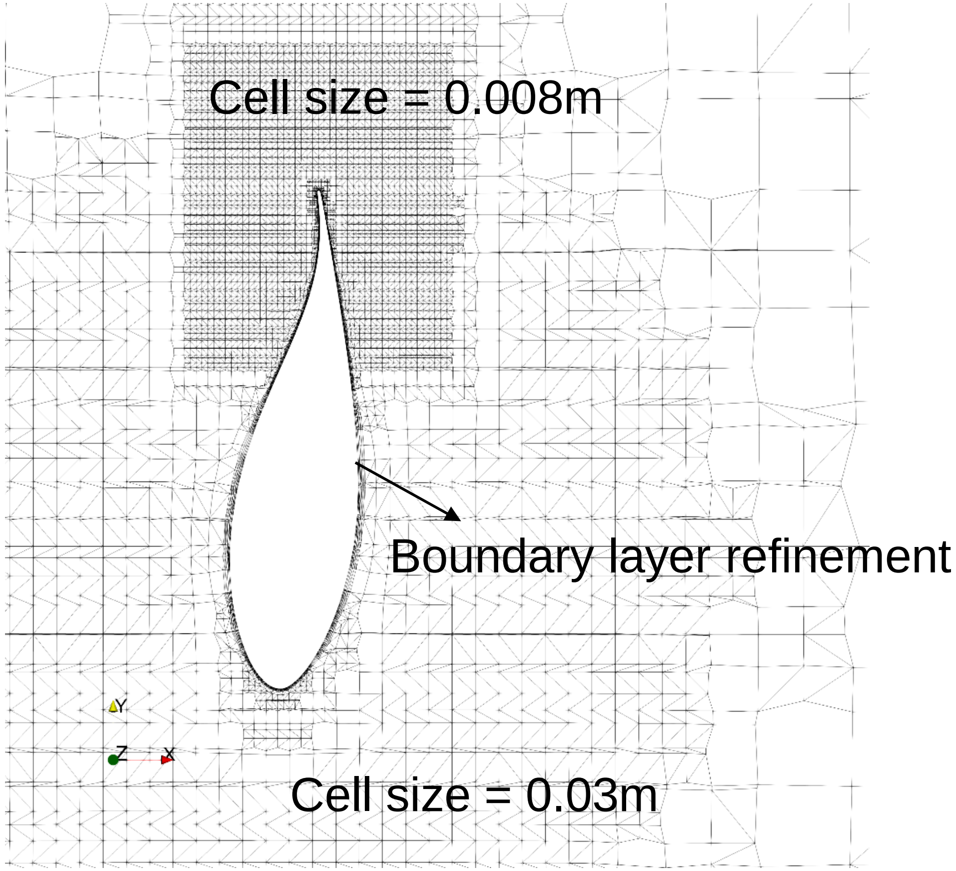
- Isolated rotor (no tower, no ground)
- Domain rotates with the rotor
- Freestream boundary conditions are applied to inflow and lateral boundaries
- Neumann – zero gradient conditions are applied at the outflow

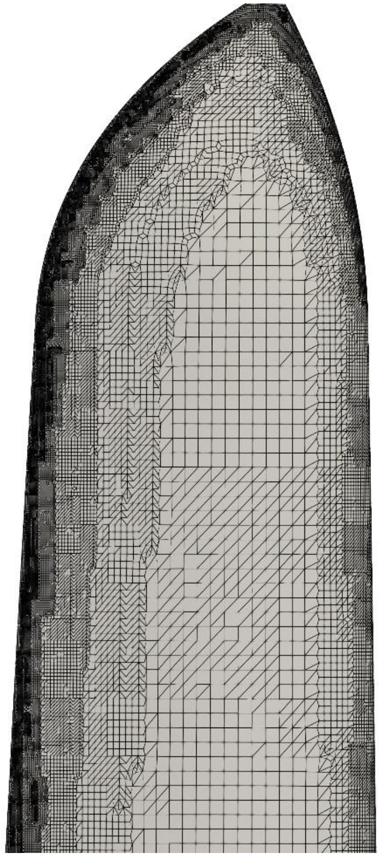


Mesh at the blade

Zoom, Full rotor case - blade cut (plane Z = 1 m → r = 0.5R)



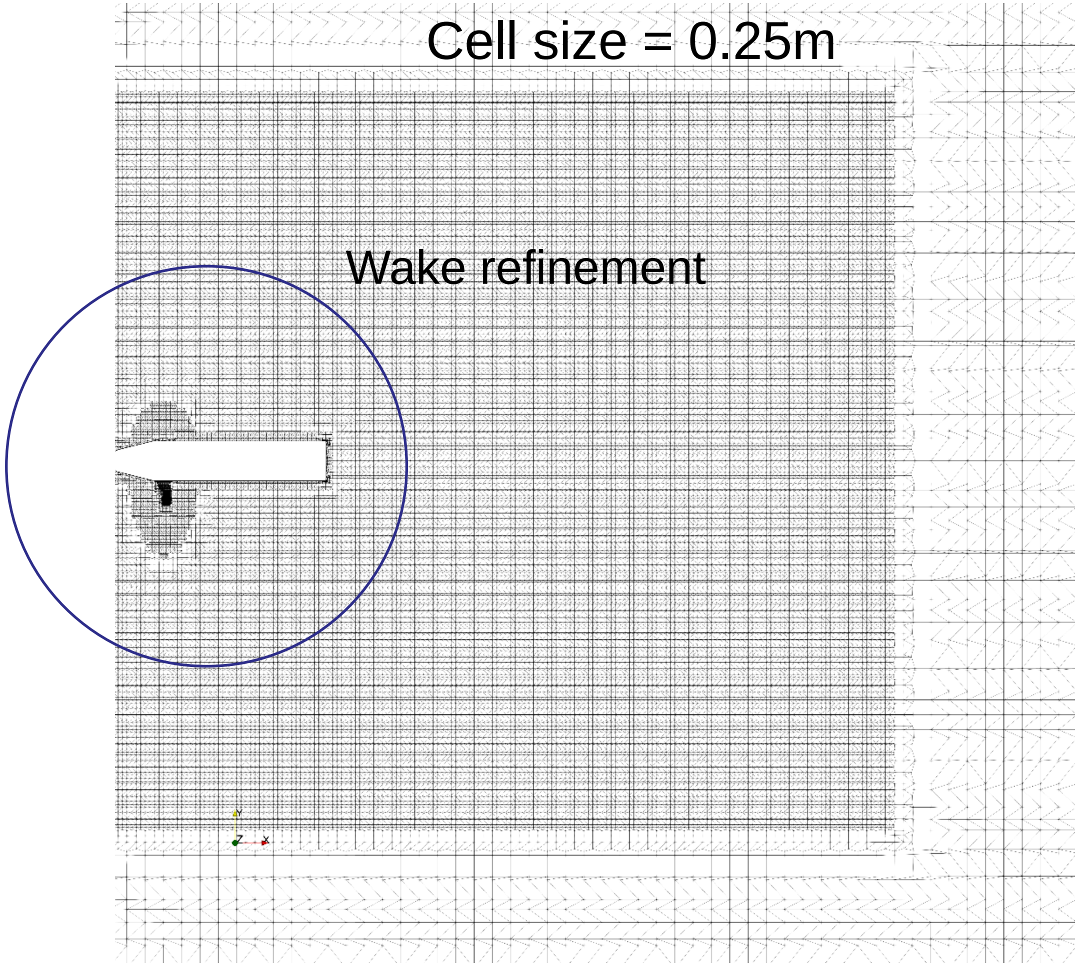




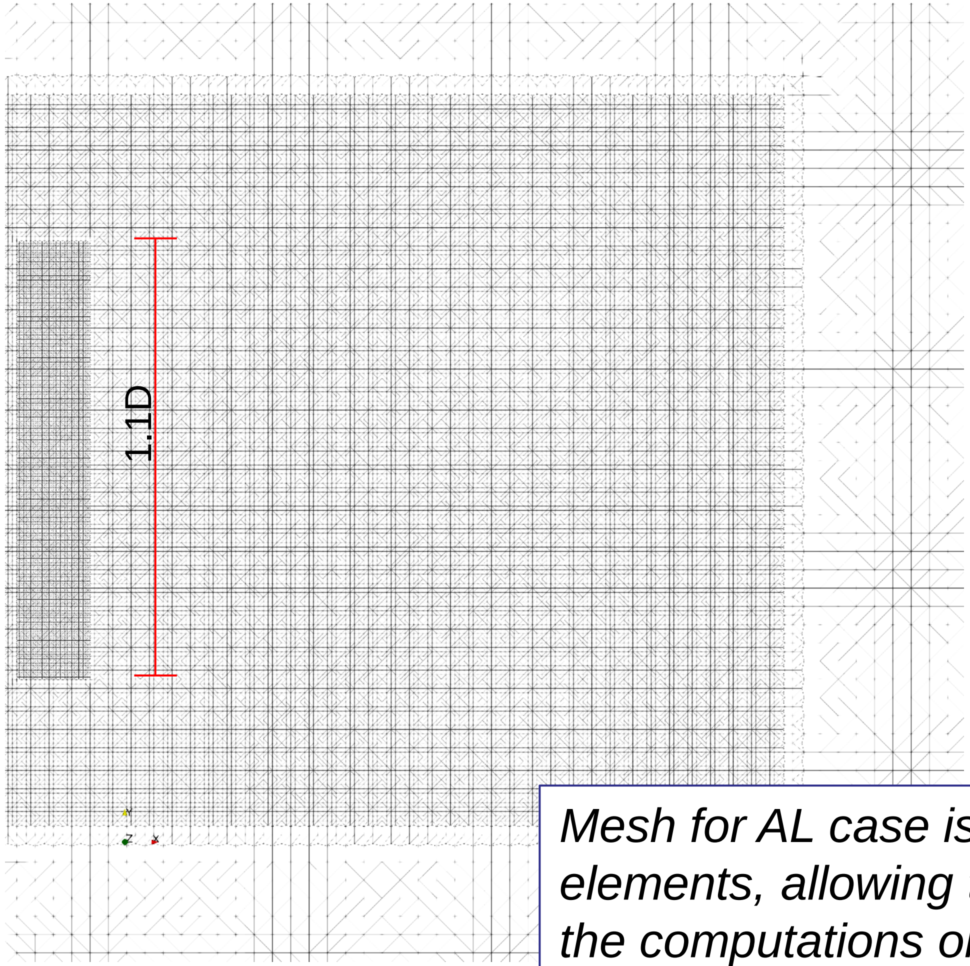
Mesh near the rotor for validation cases (1-6)

Zoom on near wake region, cut (plane Z = 0)

Full rotor



Actuator line



Mesh for AL case is 6M elements, allowing to run the computations on a local machine

Scalability and grid sensitivity analyses

- Speed up test has been done over 7 time steps of the full rotor URANS simulation with 10 PIMPLE iterations

Archer2 Nodes	MPI processes	Wall clock time (s)	Ideal time	Speed up	Ideal speed up
1	128	370,4	16	1,00	1
4	512	92,6	4	4,00	4
8	1024	46,2	2	8,02	8

- Three refinement levels have been used for case 1, verifying the grid independence for the medium refinement grid

Grid	Nodes	Thrust (N)	Err. (%)	Torque (Nm)	Err. (%)
Coarse	11.779.063	1013,5	2,79	71,0	2,94
Medium	23.512.896	987,8	0,18	72,1	1,40
Fine	40.547.879	986,1	0	73,1	0

Thrust	**Torque**
974 N	68 Nm

Exp.

Simulation info

- Three steady simulations:
  - 15000 pseudo-time steps

- Three time dependent simulations:
  - 6 seconds physical time
  - 1° of revolution per time step
  - 7 PIMPLE iterations per time step

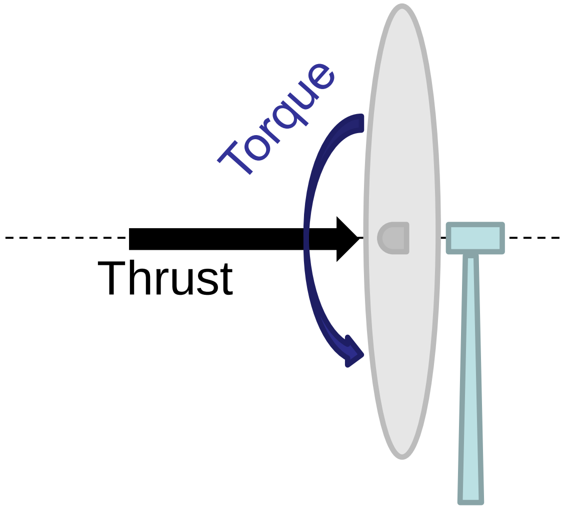
- Resources for 1 steady simulation
  - 4 ARCHER2 nodes (512 MPI processes / cores)
  - (around) 3 hours w.c.t.
  - (around) 1,5K core hours

- Resources for 1 unsteady simulation
  - 8 ARCHER2 nodes (1024 MPI processes / cores)
  - (around) 29,1 hours w.c.t.
  - (around) 30K core hours

Verification with measured data

Blade integral load, averaged in one revolution of the rotor, shows minimal differences with respect to the measurements. CFD tends to slightly underestimate the axial force (Thrust)

Actuator line model provides good results in terms of loads for both axial and yawed wind tests

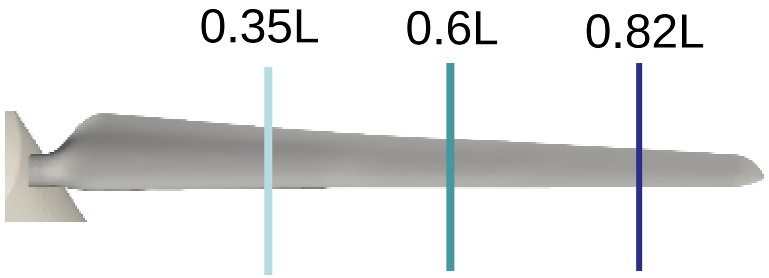


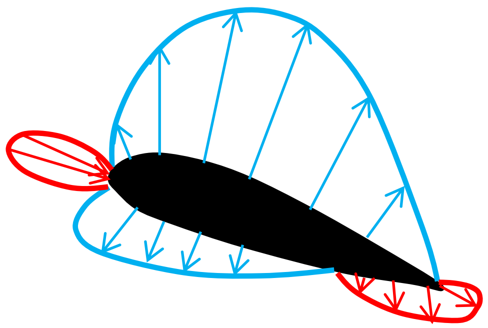
Y = 0°	Case 1 (TSR = 10.0)		Case 2 (TSR = 6.7)		Case 3 (TSR = 4.2)	
	Thrust (N)	Torque (Nm)	Thrust (N)	Torque (Nm)	Thrust (N)	Torque (Nm)
Exp.	974	68	1663	317	2173	715
CFD (FR)	987	72	1703	325	2124	515
CFD (AL)	1027	77	1658	322	w.i.p.	w.i.p.

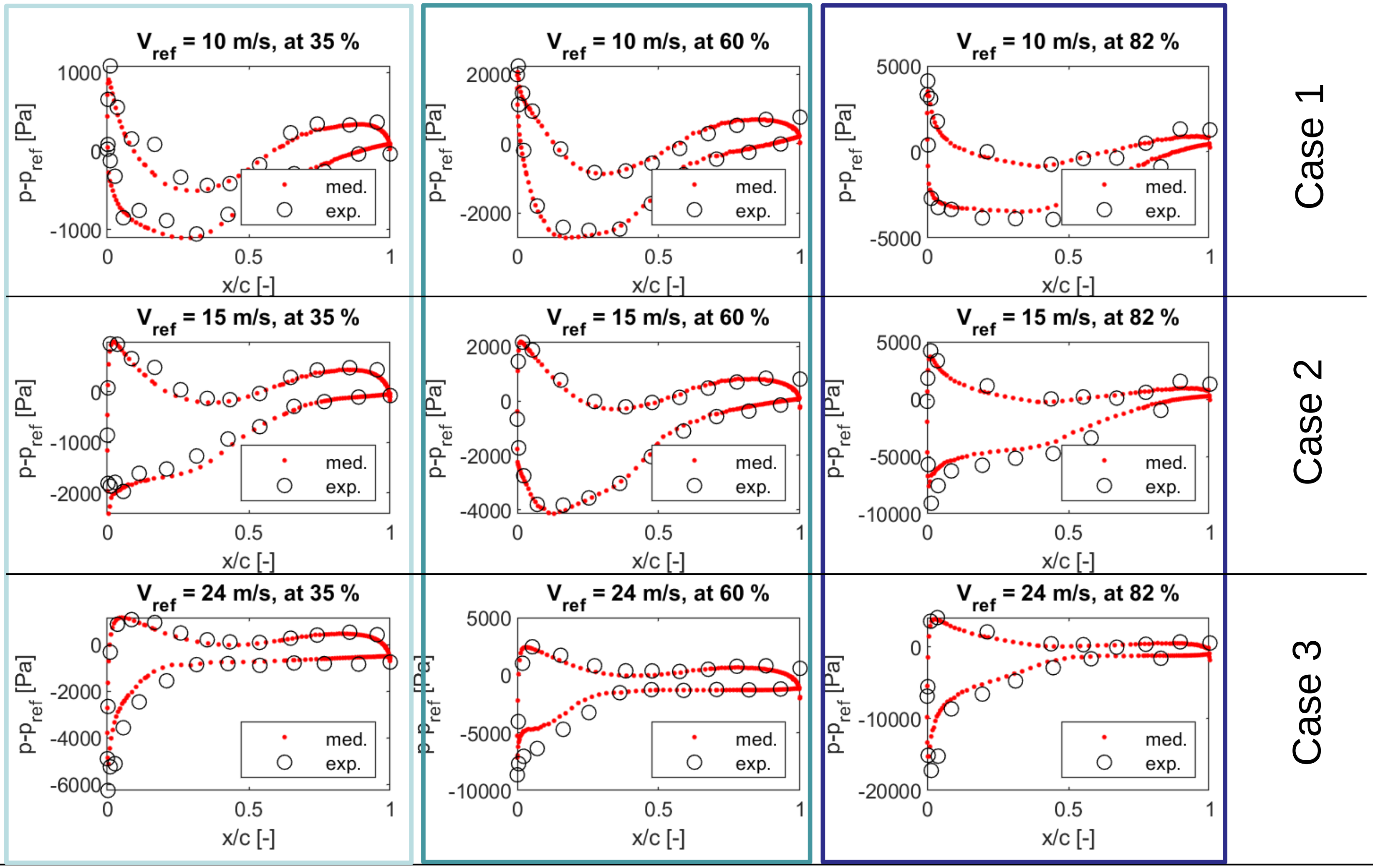
Y = 30°	Case 4 (TSR = 10.0)		Case 5 (TSR = 6.7)		Case 6 (TSR = 4.2)	
	Thrust (N)	Torque (Nm)	Thrust (N)	Torque (Nm)	Thrust (N)	Torque (Nm)
Exp.	884	51	1480	242	2012	562
CFD (FR)	809	51	1353	227	1937	525
CFD (AL)	w.i.p.	w.i.p.	1325	262	1559	465

Verification with measured data

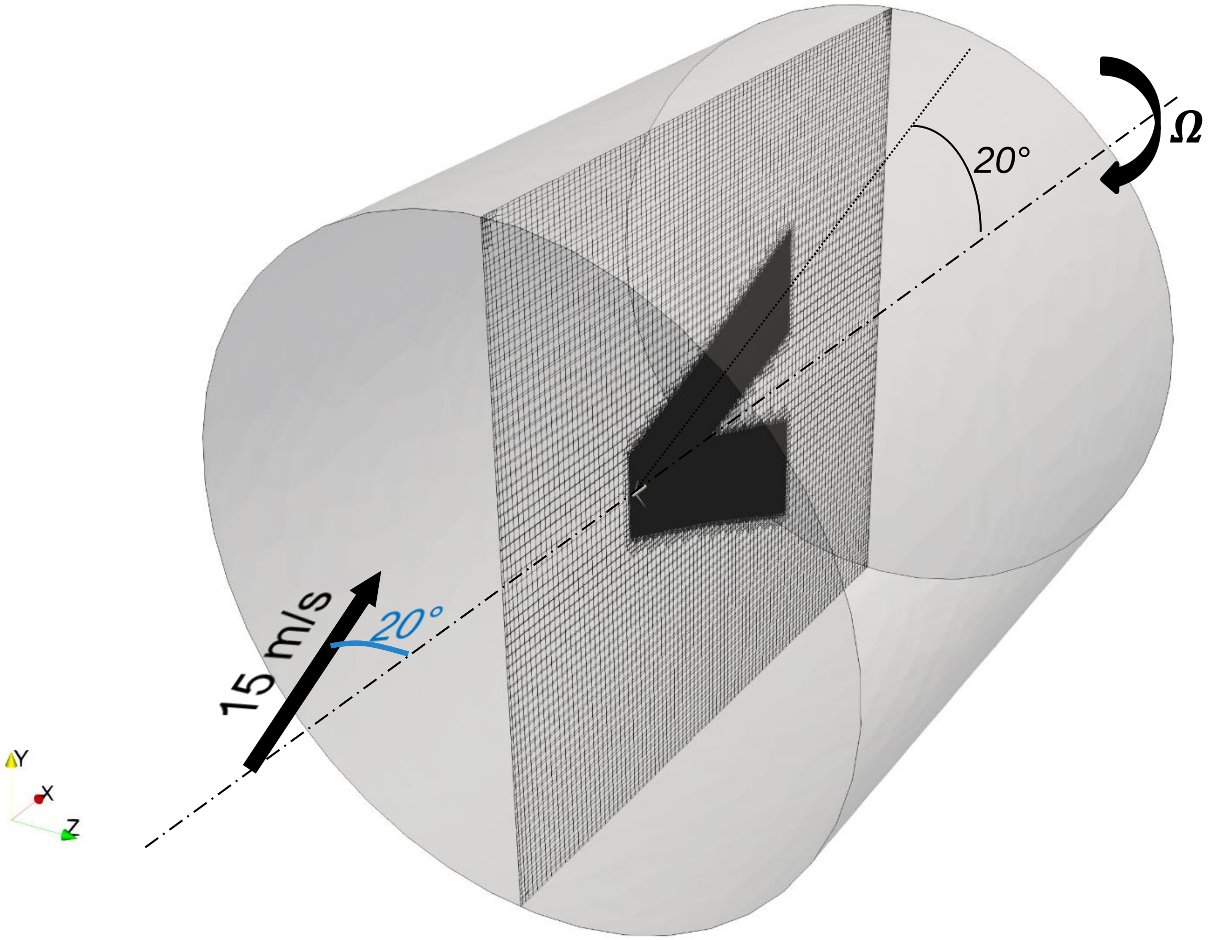
Pressure distribution over three sample sections along the span shows minimal differences in tests with axial wind (1,2,3)







Application to a possible setup for wake control strategy (Case 7)



- Extended wake refinement region
- DDES turbulence modelling
- 20° Yaw angle
- 15 m/s wind velocity

→ 113.830.868 nodes

Simulation info

- Two time dependent simulations:

1. (Start up) URANS simulation
   - ➢ 6 seconds physical time
   - ➢ 2° of revolution per time step
   - ➢ 7 PIMPLE iterations per time step

- Resources
  - ➢ 8 ARCHER2 nodes (1024 MPI processes / cores)
  - ➢ (around) 75 hours w.c.t.
  - ➢ (around) 76K core hours

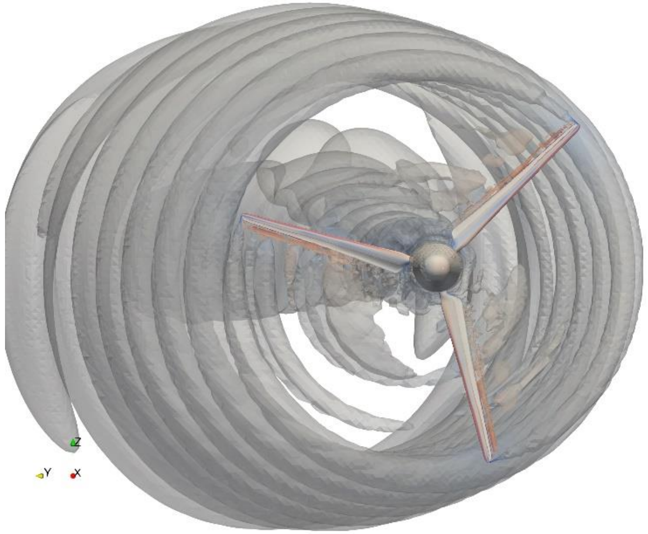
2. DDES simulation
   - ➢ 1,5 seconds of physical time
   - ➢ 0,5° of revolution per time step
   - ➢ 7 PIMPLE iterations per time step

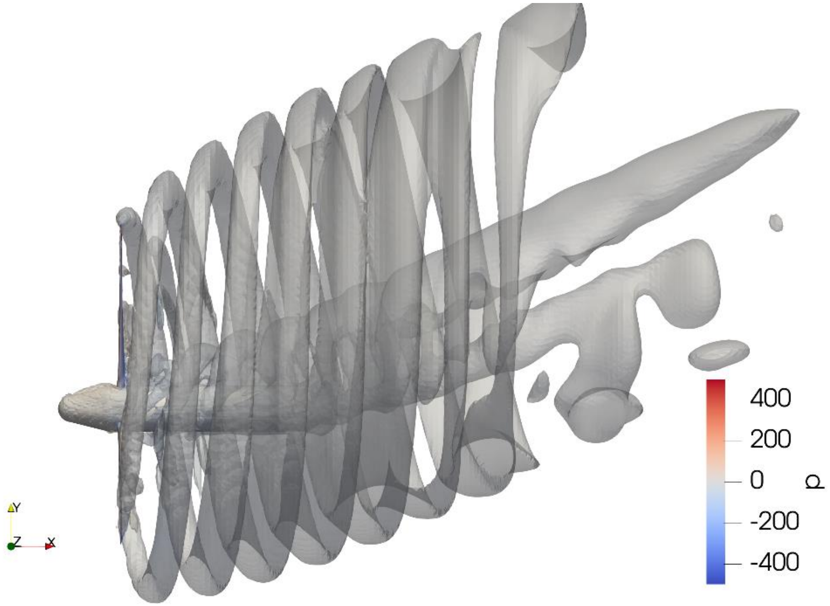
- Resources
  - ➢ 8 ARCHER2 nodes (1024 MPI processes / cores)
  - ➢ (around) 72 hours w.c.t.
  - ➢ (around) 73K core hours

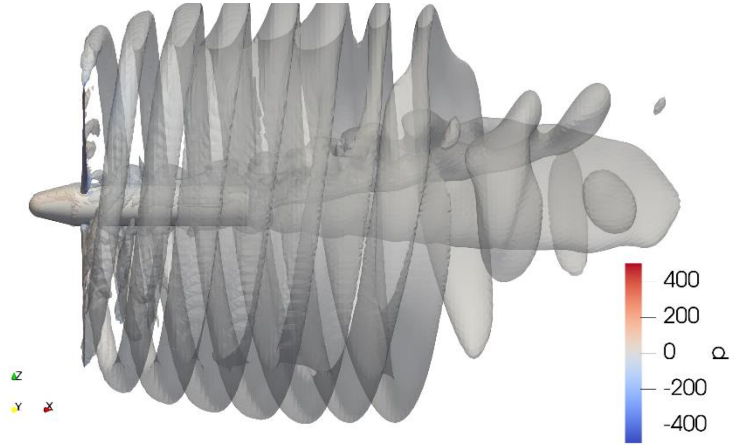
Wake analysis

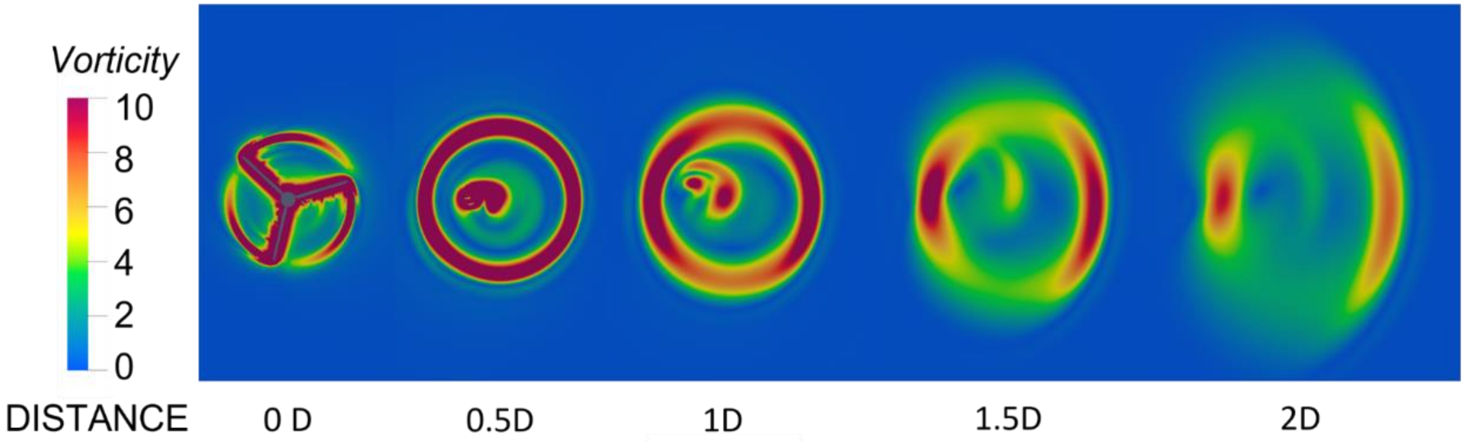
Iso-vorticity surfaces help to visualize the wake structure in terms of large vortices

Downstream diffusion of the wake is driven by the large turbulent kinetic energy produced close to the rotor surfaces









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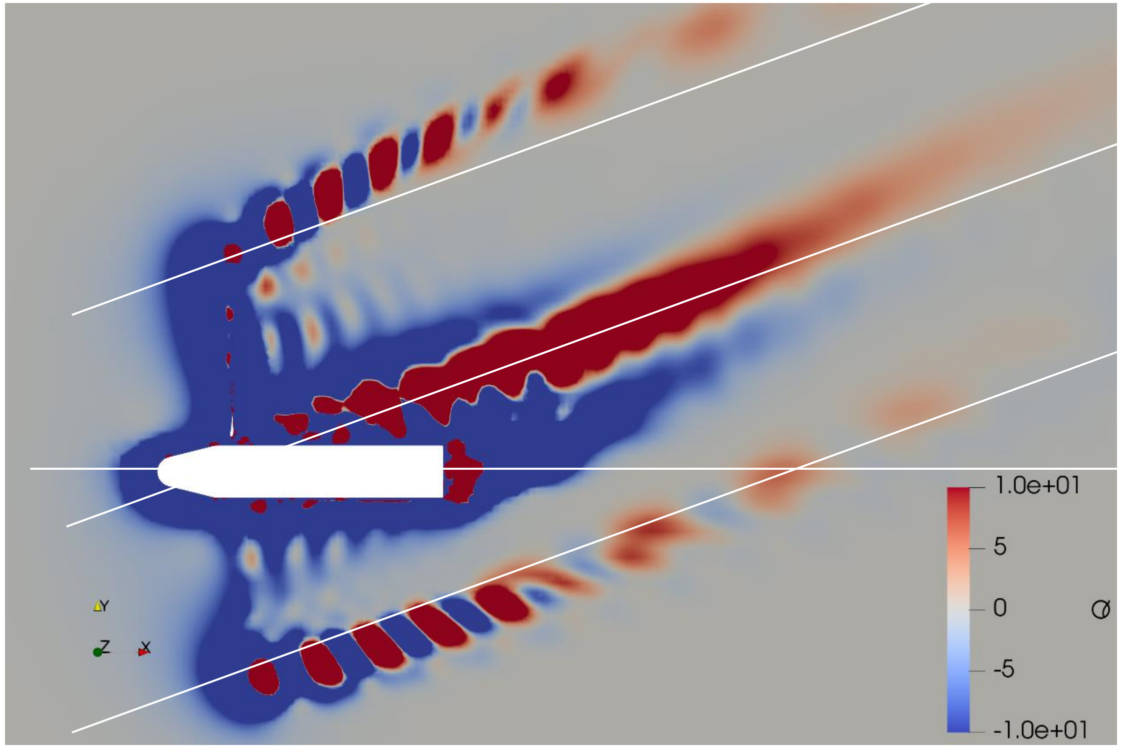
A first comparison with AL model

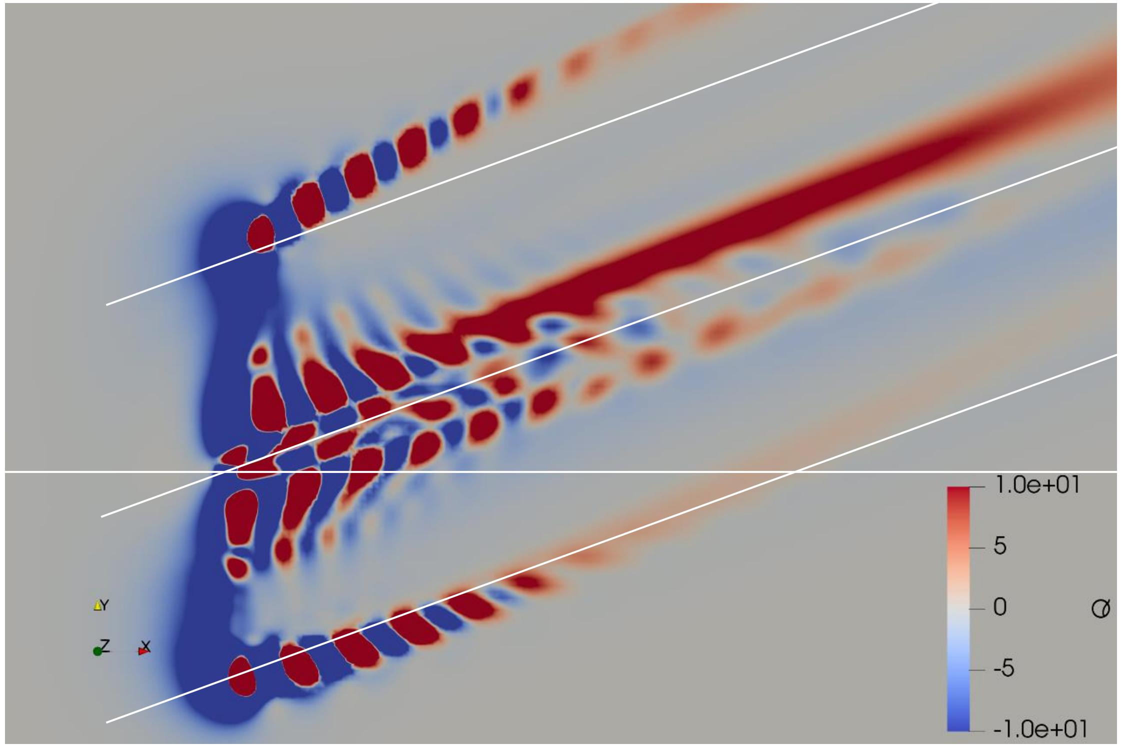
Simulation U = 15m/s, TSR = 6,7 , Y = 20°

Q-criterion, cut (plane Z = 0)

Full rotor



Actuator line



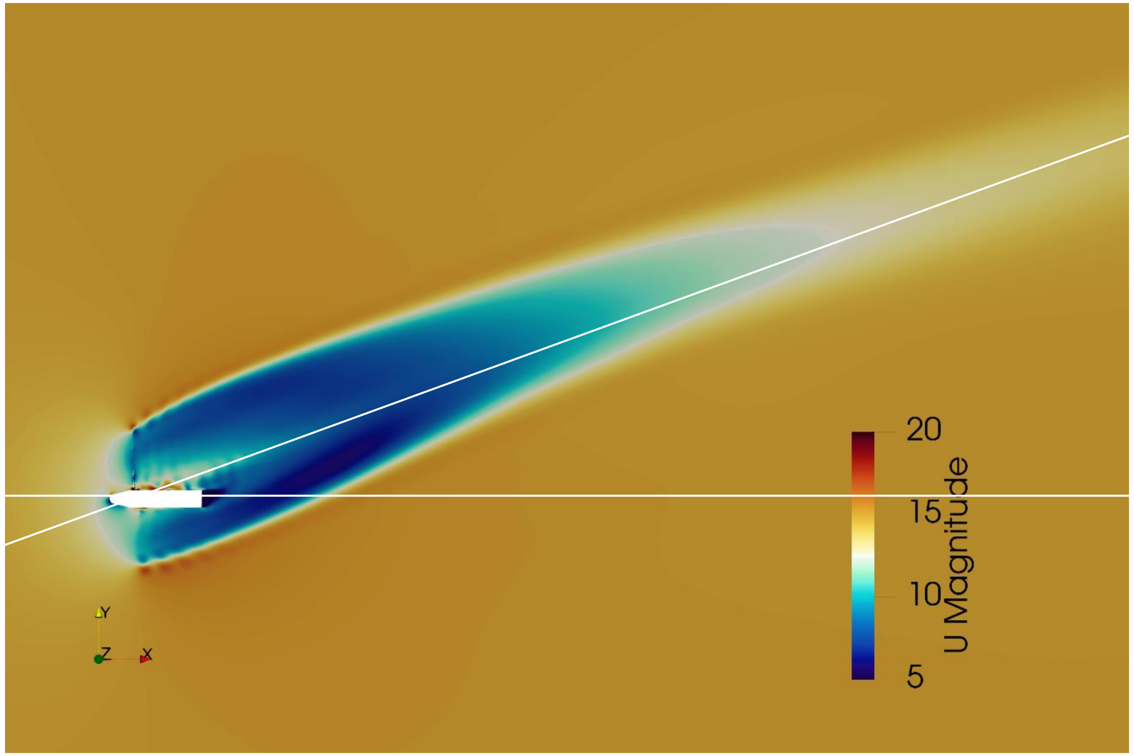
Results given by the two models shows very small differences in the near field wake

A first comparison with AL model

Simulation U = 15m/s, TSR = 6,7 , Y = 20°

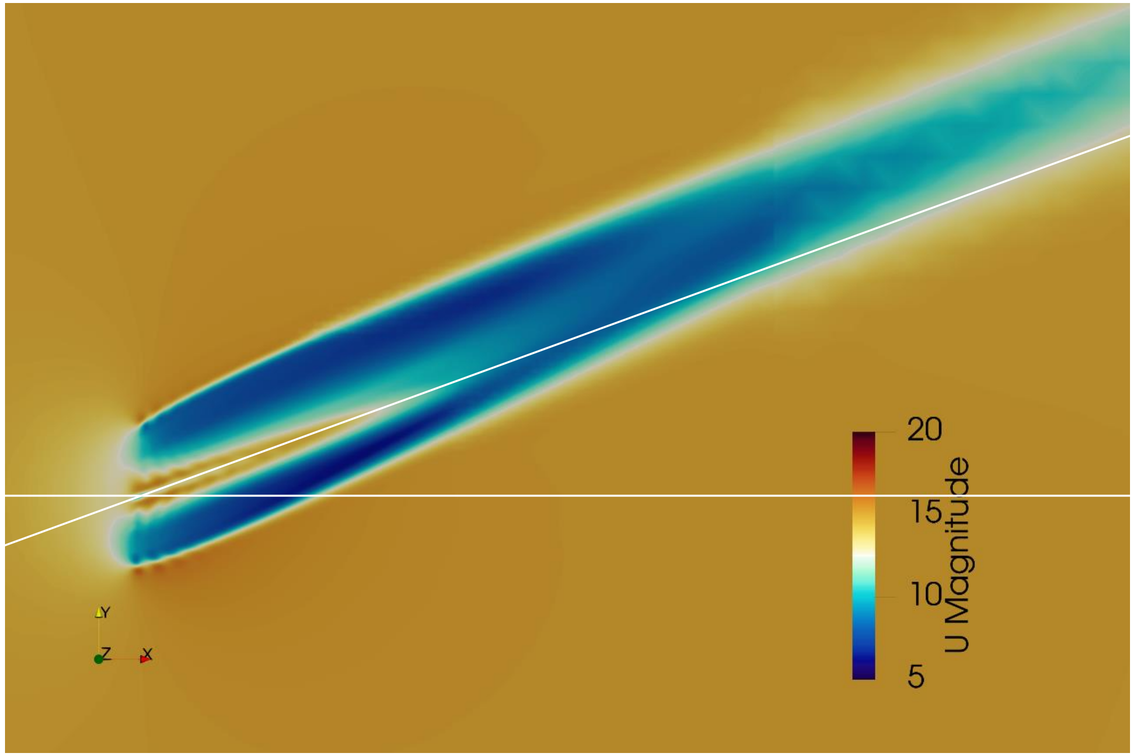
Velocity magnitude, cut (plane Z = 0)

Full rotor



Thrust = 1419.4 N
Torque = 255.7 Nm

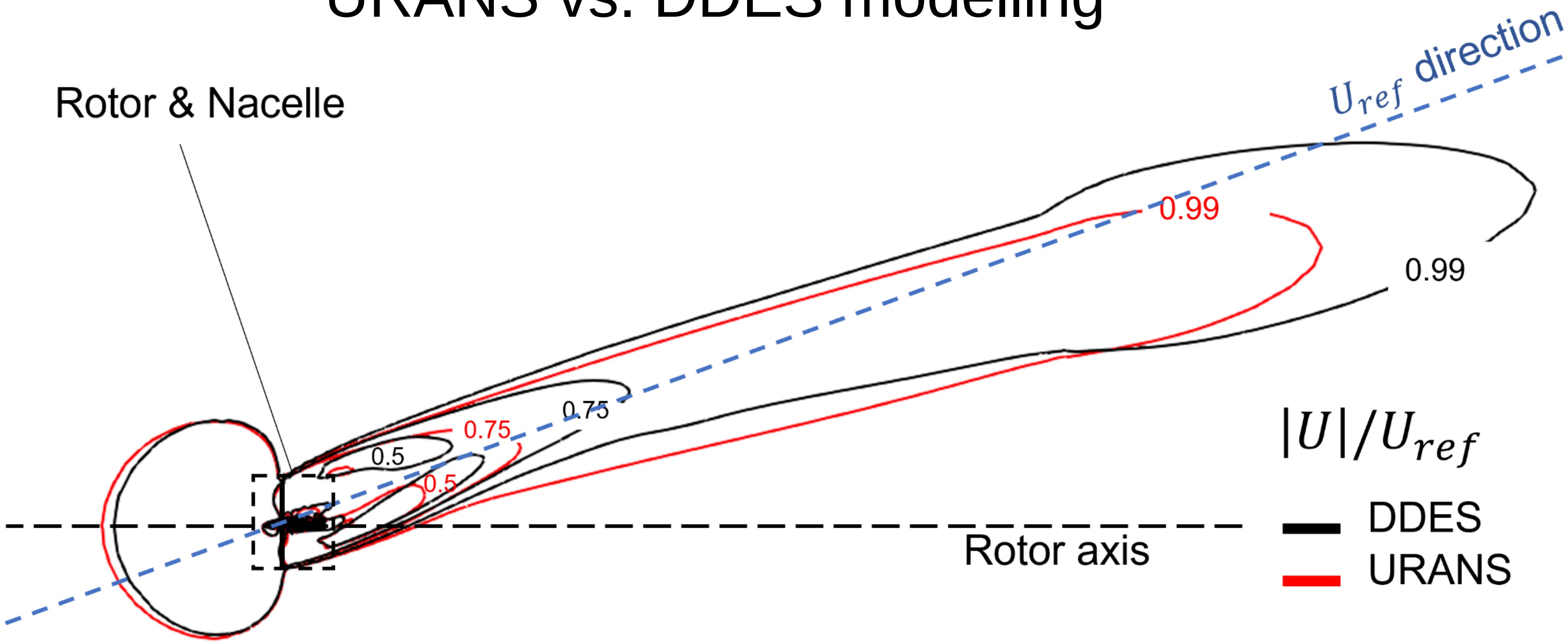
Actuator line



Thrust = 1499.9 N
Torque = 291.9 Nm

Wake deflection due to rotor-flow reaction force is similarly predicted by both the models

URANS vs. DDES modelling



DDES model helped to slightly extend the wake resolution downstream

This can be further improved by using grids at the far field and boundary conditions which are more suitable for an LES-type simulation

Prediction of wind inflow using NWP and CFD

- Selection of a site, day and time for the test

→ Location of the FINO2 research platform (Baltic Sea)

→ Day: 15/12/2012, Time 10:30 a.m.

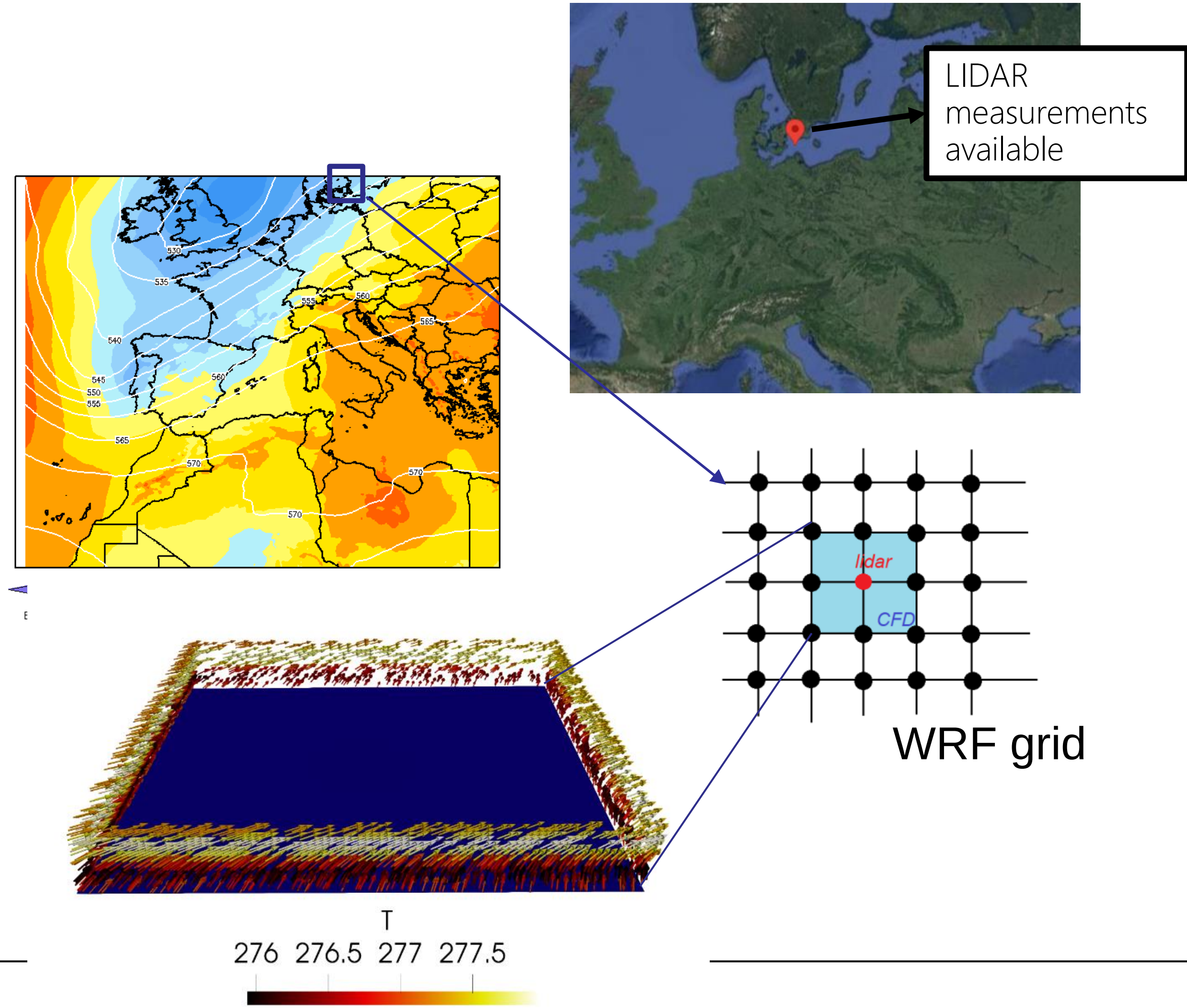
- Mesoscale simulation of the wind field with NWP

→ Mesoscale data provided by CNR-IMAA performing a 48 hours of simulation with Weather Research and Forecast* (WRF)

- Local-scale CFD domain definition and generation of appropriate BC from mesoscale data (wind velocity, temperature, turbulence intensity)

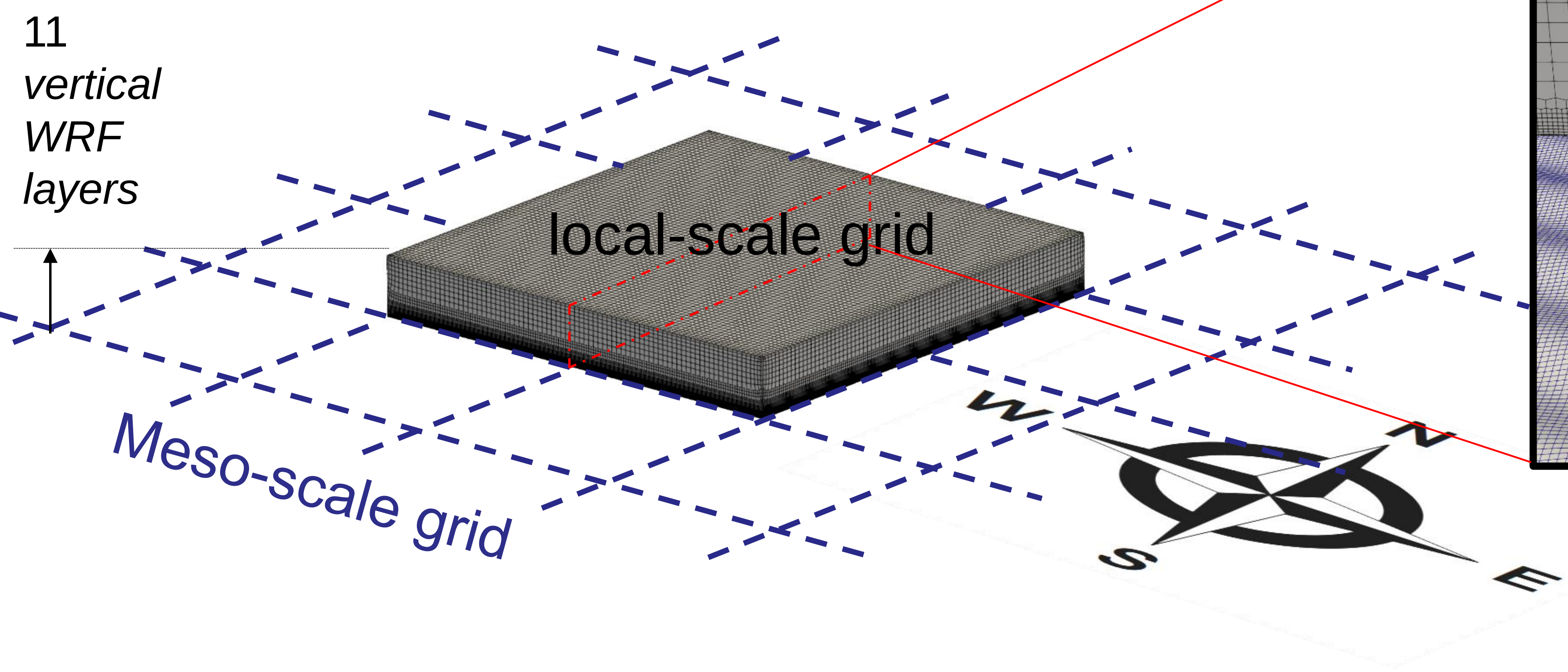
- RANS simulation + k-ε turbulence closure (eddy viscosity model) + buoyancy and temperature transport equations + volume forces for ABL + sea waves motion

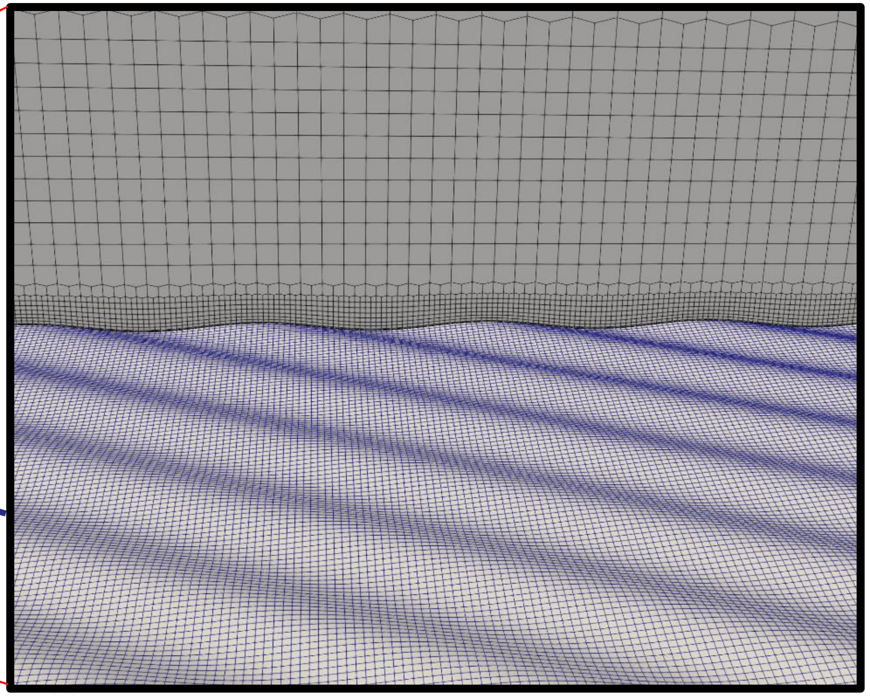
(*) https://www2.mmm.ucar.edu/wrf/users/



Computational domain and grid sensitivity analyses

- Cartesian mesh type generated with *cfMesh* application
- Hierarchical domain decomposition





Waves properties

Period: 8 sec
Length: 35 m
Height: 2 m

Simulation info

- Smaller domain but long run
  - ➢ 600 seconds physical time
  - ➢ 0.05 seconds time step
  - ➢ 7 PIMPLE iterations per time step

- Resources for one simulation
  - ➢ 4 ARCHER2 nodes (512 MPI processes / cores)
  - ➢ (around) 16 hours w.c.t.
  - ➢ (around) 8K core hours

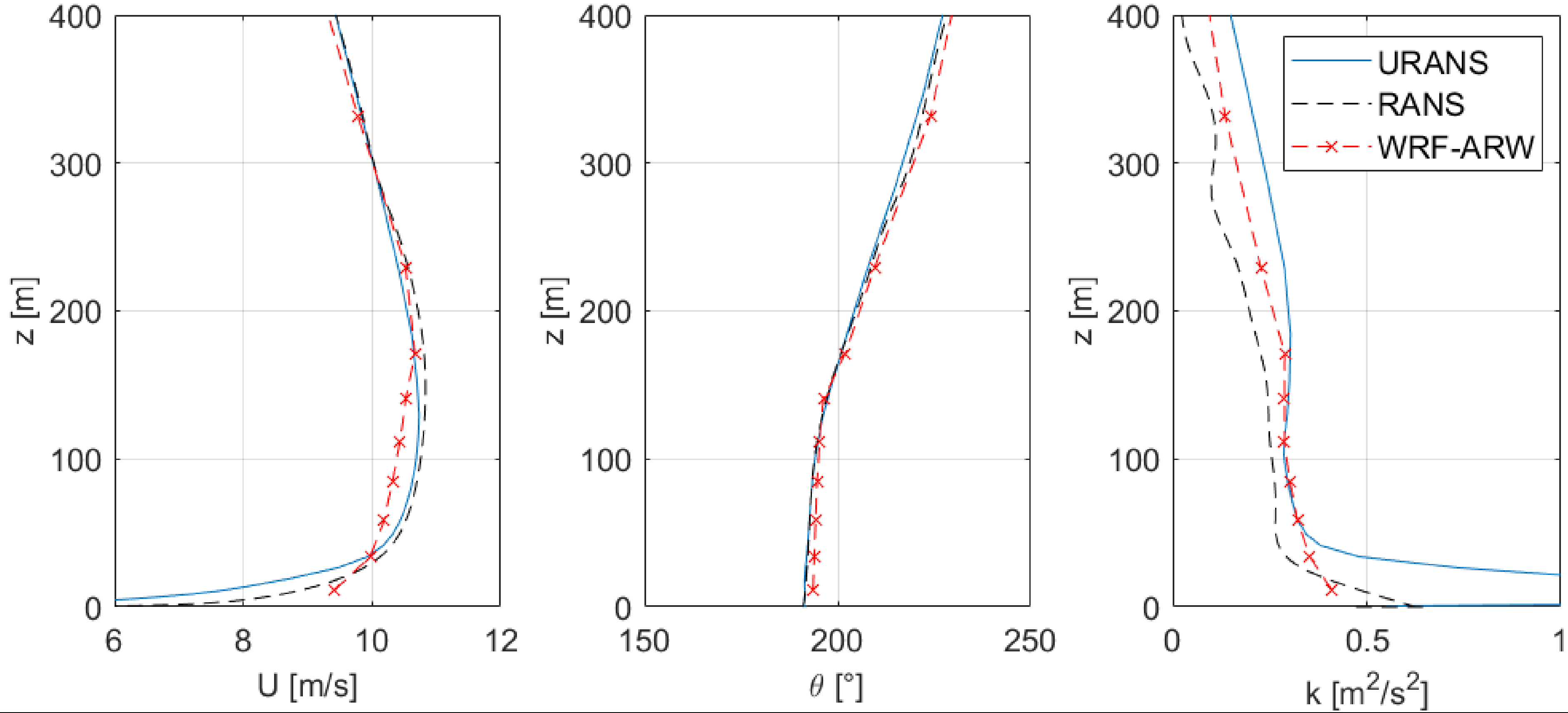
Grid sensitivity analyses

- Three refinement levels have been tested with the steady RANS solver verifying the grid independence for the medium grid

Number of cells	Average y+	RMSE U (m/s)	RMSE Dir (◦)	RMSE k (m2/s2)
3.350.479	313.8 (min 65.4)	0.2962	0.4072	0.30874
12.577.954	285.8 (min 68.1)	0.0194	0.1095	0.00867
18.889.390	285.1 (min 76.3)	-	-	-

Results

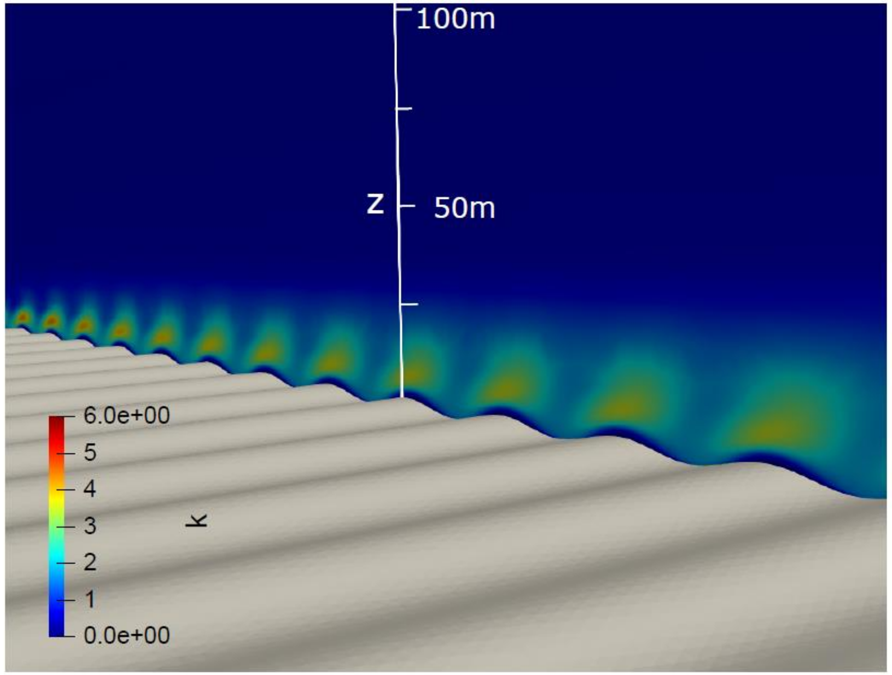
- Wind vertical profiles (Velocity, direction, turbulent kinetic energy)

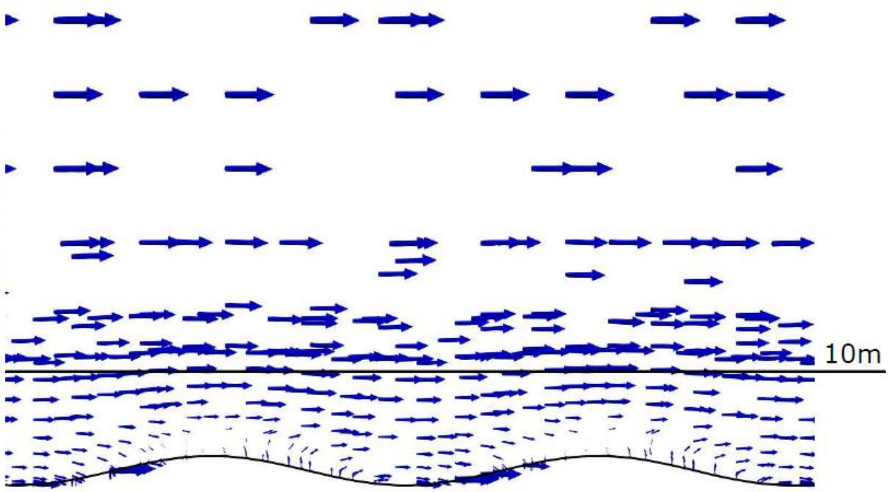


Results

Effect of waves motion

- Turbulence production in the first part of the surface layer
- Upwash effect





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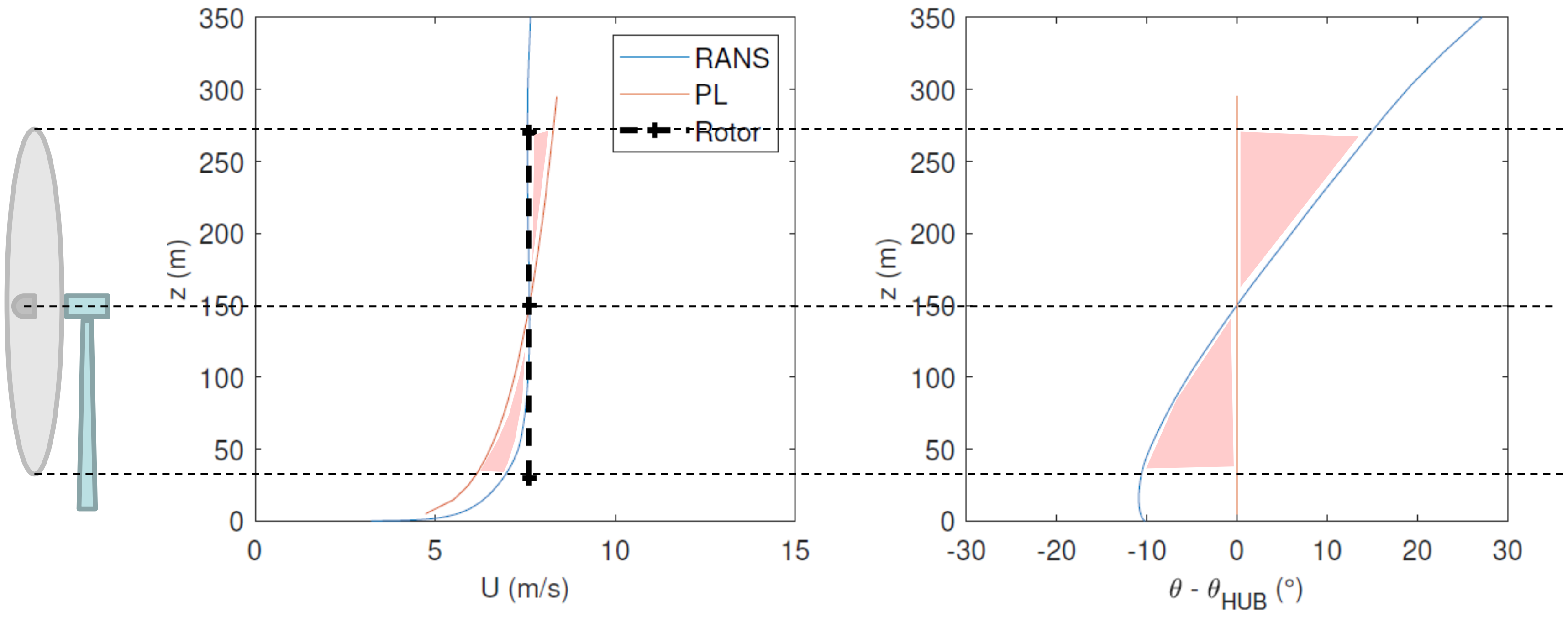
Results

- Comparison of the wind profile with a theoretical wind vertical profile based on power-law (PL)



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Thank you!

alessio.castorrini@unibas.it