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Workshop on Wind Energy Computational Analyses

Wind Turbine Rotor CFD Analyses by using SU2

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21 September 2022

Content:

1. Wind Turbine Rotor Aerodynamics and CFD Implementations
2. SU2 Capabilities and Tutorial
3. Applications

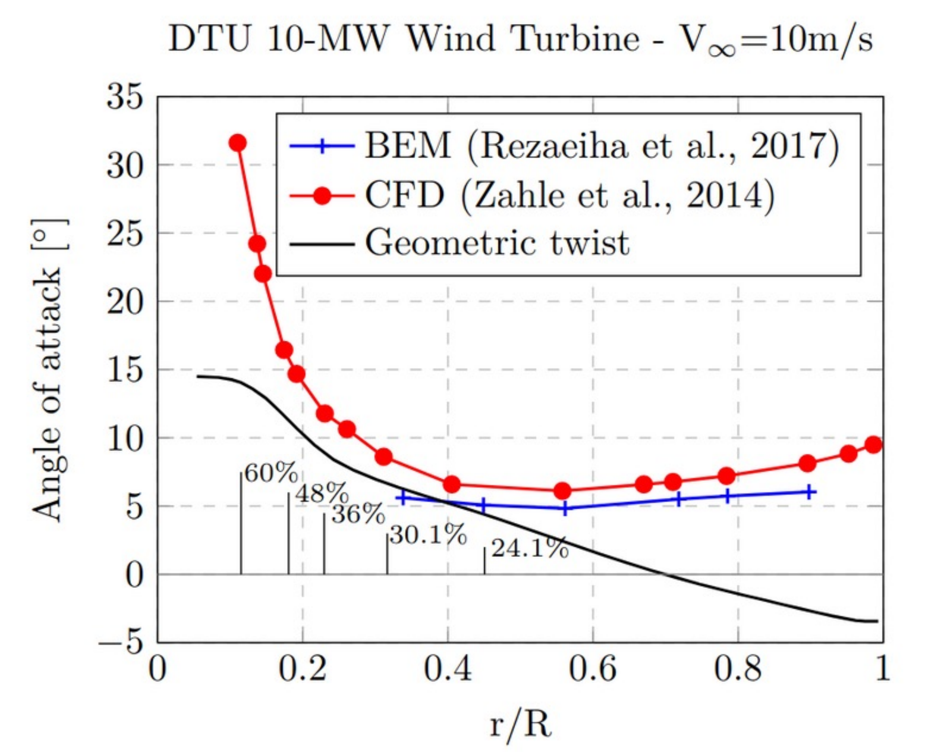
Content

Wind Turbine Rotor Aerodynamics and CFD Implementations

Flow Over the Blade

For a commercial wind turbine,

- $M_{tip} \approx 0.2$: Incomressibility persists but compressibility is knocking on the door.
- Angle of attack: Exceeding the stall angle near the root, in the linear-regime at the mid and tip sections
- Reynolds number
- Separation
- Transition



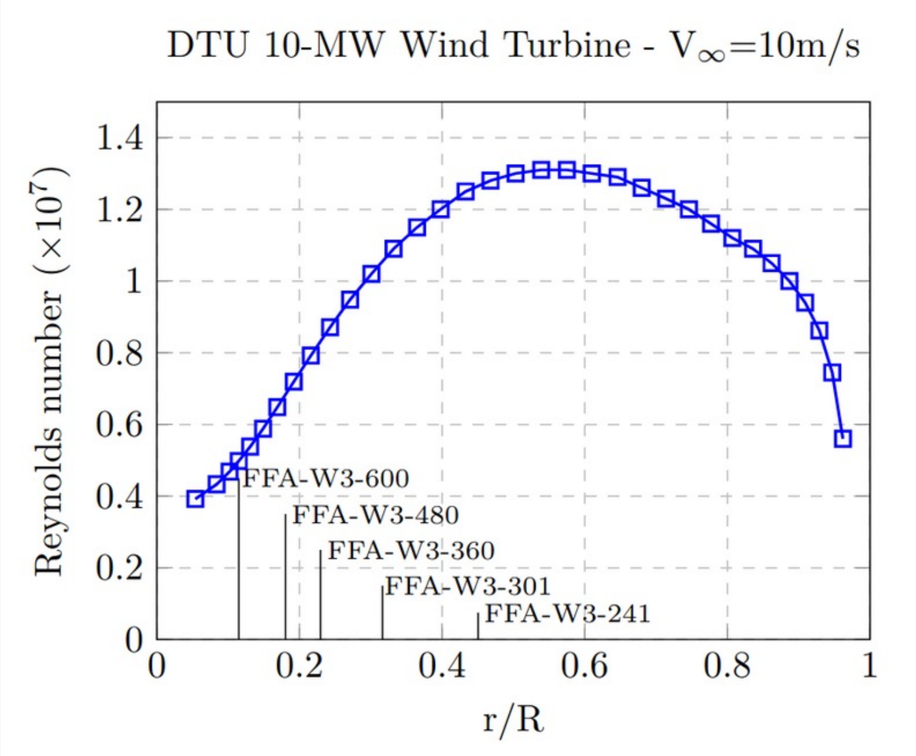
Variation of angle of attack on the DTU 10MW wind turbine blade operating at a wind speed of 10 m/s

Wind Turbine Rotor Aerodynamics and CFD Implementations

Flow Over the Blade

For a commercial wind turbine,

- Compressibility
- Angle of attack
- Reynolds number: In the order of 10 million => high (turbulence) resolution requirement
- Separation
- Transition

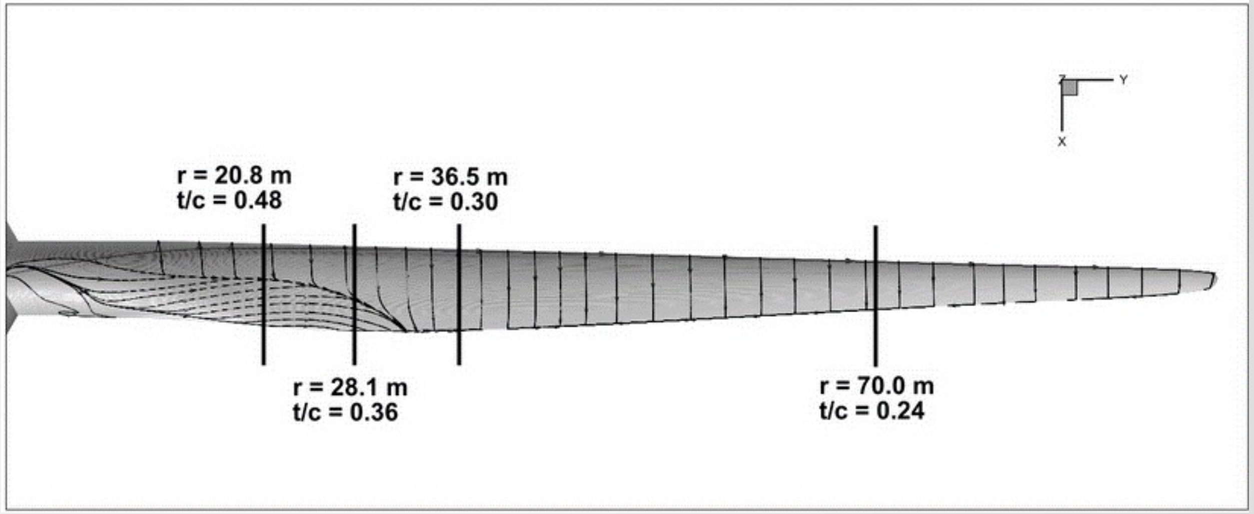


Variation of Reynolds number on the DTU 10MW wind turbine blade operating at a wind speed of 10 m/s

Flow Over the Blade

For a commercial wind turbine,

- Compressibility
- Angle of attack
- Reynolds number
- Separation: Due to high angle of attack and very thick airfoils, separation may be present near the root.
- Laminar-turbulent transition:
  - For small wind turbines, laminar flow may be present
  - For large commercial wind turbines, (usually) fully-turbulent flow



Streamlines on the suction surface of DTU 10MW wind turbine blade operating at a wind speed of 10 m/s[1]

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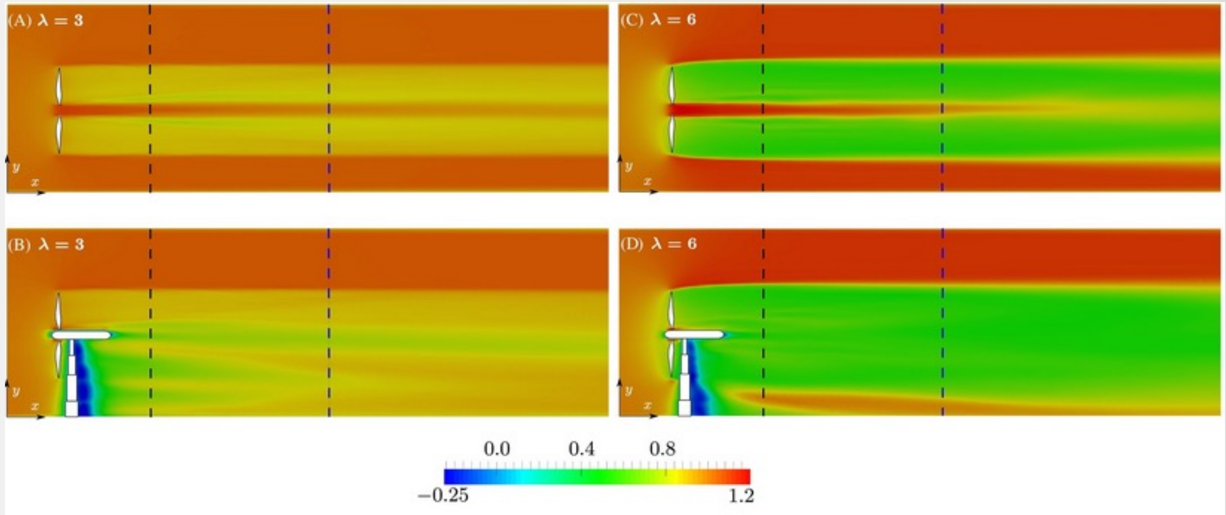
[1] Frederik Zahle et al. “Comprehensive Aerodynamic Analysis of a 10 MW Wind Turbine Rotor Using 3D CFD”. *In: 32nd ASME Wind Energy Symposium*. Reston, Virginia: American Institute of Aeronautics and Astronautics, Jan. 2014. doi: 10.2514/6.2014-0359.

Wind Turbine Rotor Aerodynamics and CFD Implementations

Interactions with Turbine Components

- Spinner, nacelle, tower
- Differences in CFD applications:
  - Wake profile: Symmetrical/Asymmetrical
  - Jet in the center
  - Similar velocity profile over the blade[2]
    - Similar power and thrust for an **individual** turbine



Contours of streamwise velocity in a vertical section with different tip speed ratios and with (B,D) and without (A,C) tower and nacelle[2]

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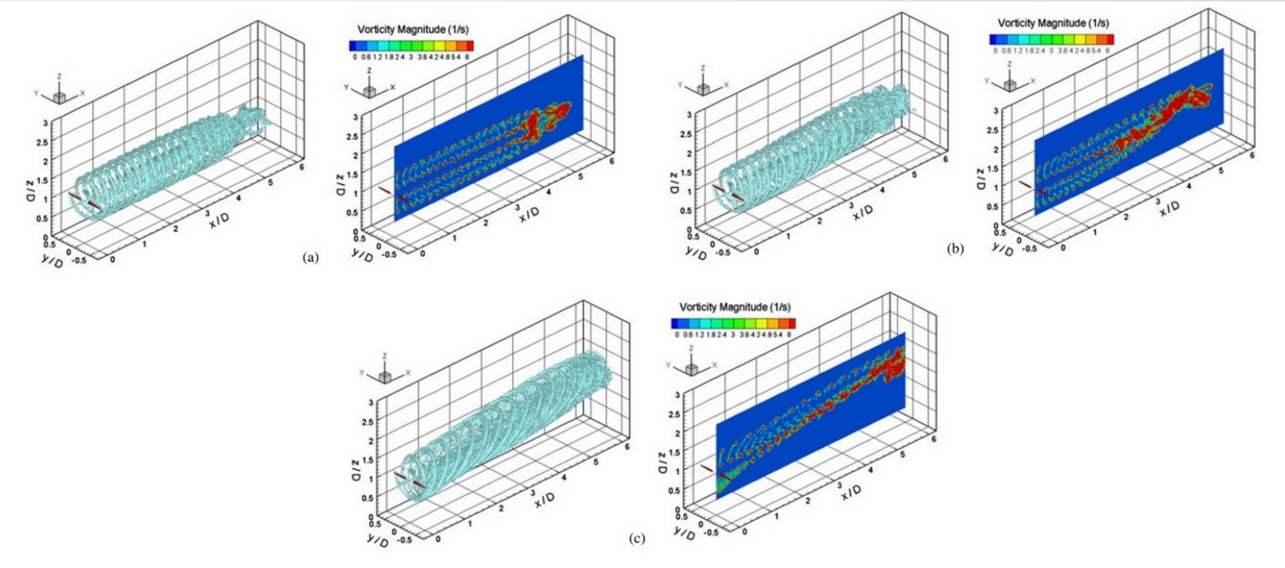
[2] Christian Santoni et al. “Effect of tower and nacelle on the flow past a wind turbine”. In: *Wind Energy* 20.12 (Dec. 2017), pp. 1927–1939. doi: 10.1002/we.2130

Wind Turbine Rotor Aerodynamics and CFD Implementations

Interactions with Non-turbine Elements

- Ground: complex terrain
  - Wind farm placement
- Sea: coupling with a hydrodynamic solver
- Atmospheric boundary layer (ABL):
  - Non-uniform inlet velocity profile
  - Affects the incoming flow velocity and turbulence
  - Impacts the wake and turbine performance
  - May not affect the turbine performance if the rotor is outside of ABL (some commercial WTs)



Isovorticity surfaces and vorticity magnitude distributions within the wake after 10 revolutions on the y=0 plane for different wind shear (ABL) cases: (a) uniform inflow, (b) normal wind profile, and (c) extreme wind shear[3]

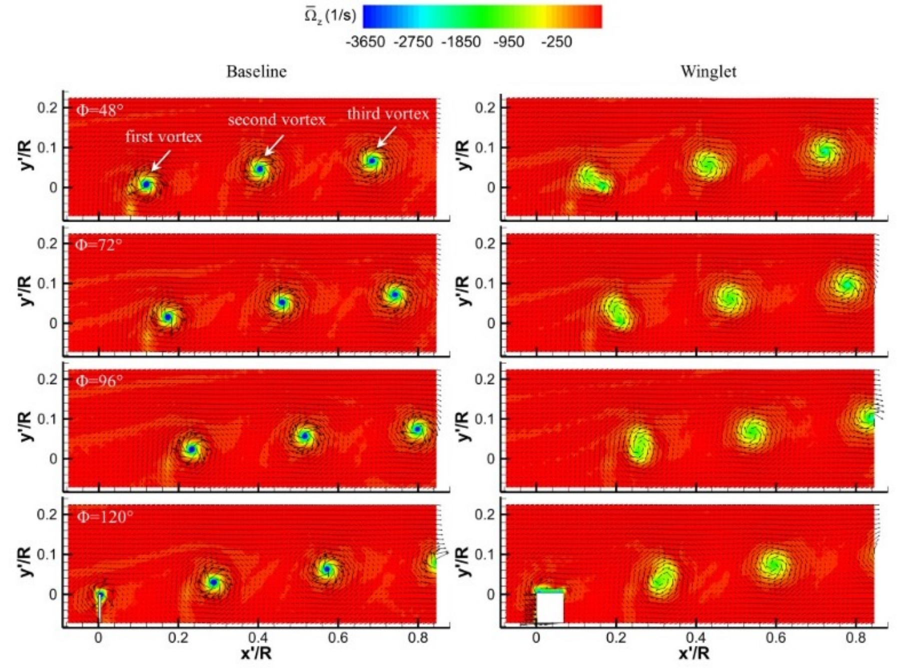
---

[3] Nilay Sezer-Uzol and Oguz Uzol. “Effect of steady and transient wind shear on the wake structure and performance of a horizontal axis wind turbine rotor”. In: *Wind Energy* 16.1 (Jan. 2013), pp. 1–17. doi: 10.1002/we.514

Wind Turbine Rotor Aerodynamics and CFD Implementations

Wakes

- Reduced velocity and increased turbulence
    - Affects the wind turbine performance
- Tip vortices
- Affected by the wind turbine control
- Unsymmetrical wakes
- Partial alignment



Phase-averaged out-of-plane vorticity distributions for different rotor phases for baseline (left) and winglet (right) cases[4]

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[4] Yaşar Ostovan, M. Tuğrul Akpolat, and Oğuz Uzol. "Experimental investigation of the effects of winglets on the tip vortex behavior of a model horizontal axis wind turbine using particle image velocimetry". In: *Journal of Solar Energy Engineering, Transactions of the ASME* 141.1 (2019), pp. 1–13. issn: 15288986. doi: 10.1115/1.4041154.

Wind Turbine Rotor Aerodynamics and CFD Implementations

Wakes

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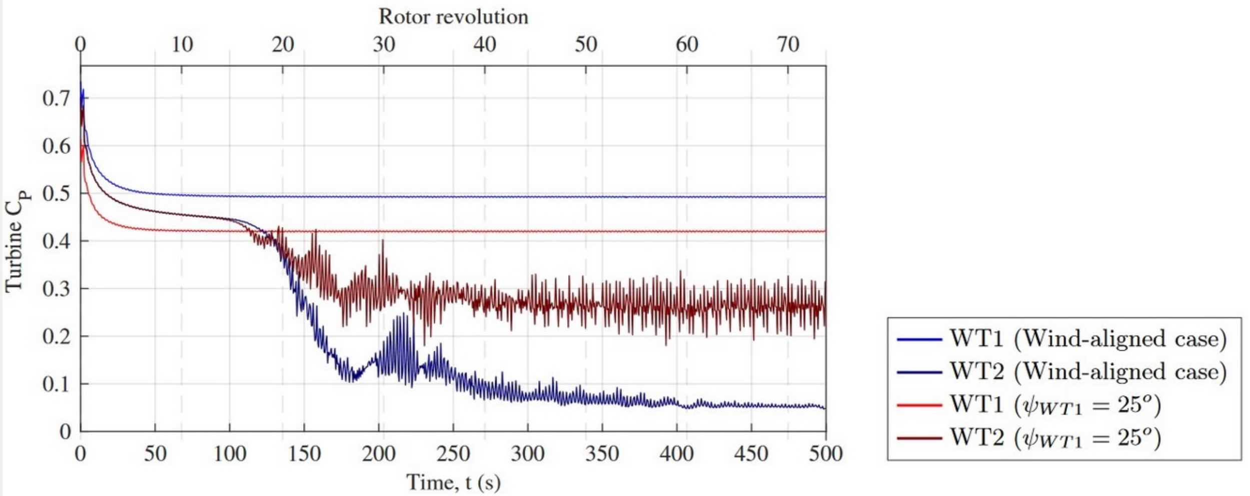

Power coefficient histogram of upstream and downstream wind turbines with and without wind turbine control[5]

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[5] Huseyin C. Onel and Ismail H. Tuncer. “A comparative study of wake interactions between wind-aligned and yawed wind turbines using LES and actuator line models”. In: *Journal of Physics: Conference Series* 1618.6 (Sept. 2020), p. 062009. doi: 10.1088/1742-6596/1618/6/062009

Wind Turbine Rotor Aerodynamics and CFD Implementations

Wakes

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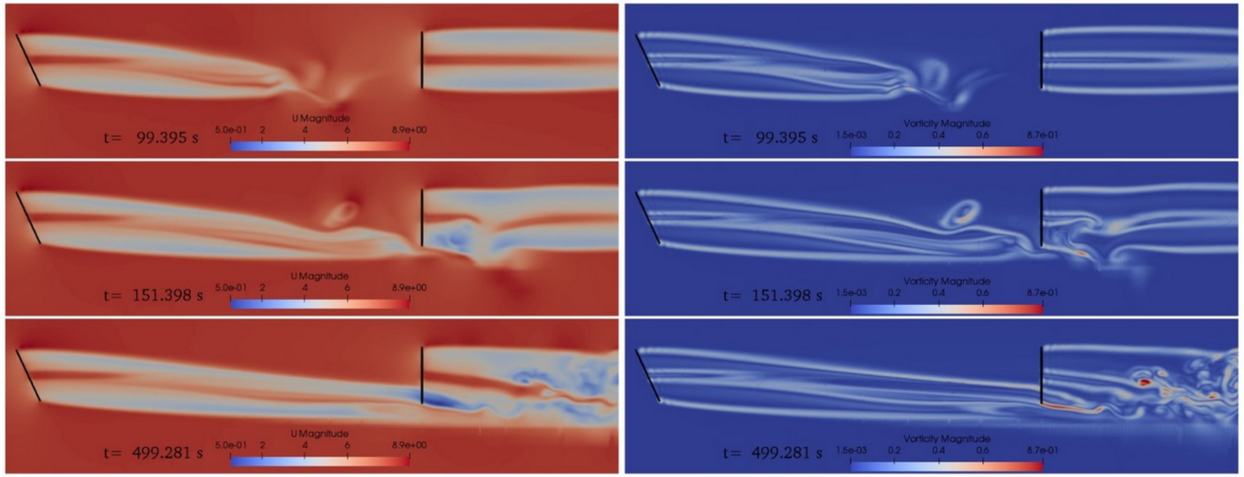

(a) Velocity contours (b) Vorticity contours

Wake development behind a yawed upstream turbine[5]

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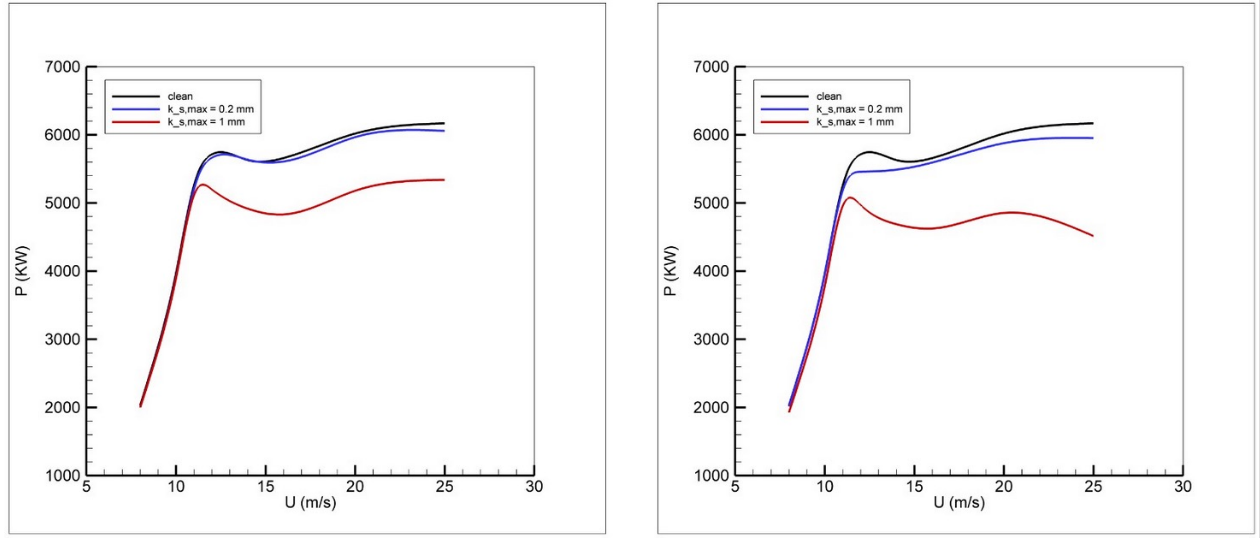
[5] Huseyin C. Onel and Ismail H. Tuncer. “A comparative study of wake interactions between wind-aligned and yawed wind turbines using LES and actuator line models”. In: *Journal of Physics: Conference Series* 1618.6 (Sept. 2020), p. 062009. doi: 10.1088/1742-6596/1618/6/062009

Wind Turbine Rotor Aerodynamics and CFD Implementations

Additional Considerations

- Surface roughness:
  - Leading edge contamination and erosion
  - Deterioration of turbine performance
  - CFD applications:
    - Direct modelling through the mesh
    - Roughness models
- Aeroelasticity (Fluid-structure interaction)
- Wind farm control
- Gusts
- Aeroacoustics



(a) 40 microns

(b) 150 microns

Power output with contaminated turbine blades with different contaminant particle sizes[6]

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[6] Serkan Özgen, Eda Bahar Sarıbel, and Ali Rıza Yaman. “Effect of blade contamination on power production of wind turbines”. In: *Journal of Physics: Conference Series* 2265.3 (May 2022), p. 032012. doi: 10.1088/1742-6596/2265/3/032012

Wind Turbine Rotor Aerodynamics and CFD Implementations

Additional Considerations

- Surface roughness
- Aeroelasticity
- Wind farm control:
  - Novel methods require high-fidelity CFD simulations
- Gusts
- Aeroacoustics

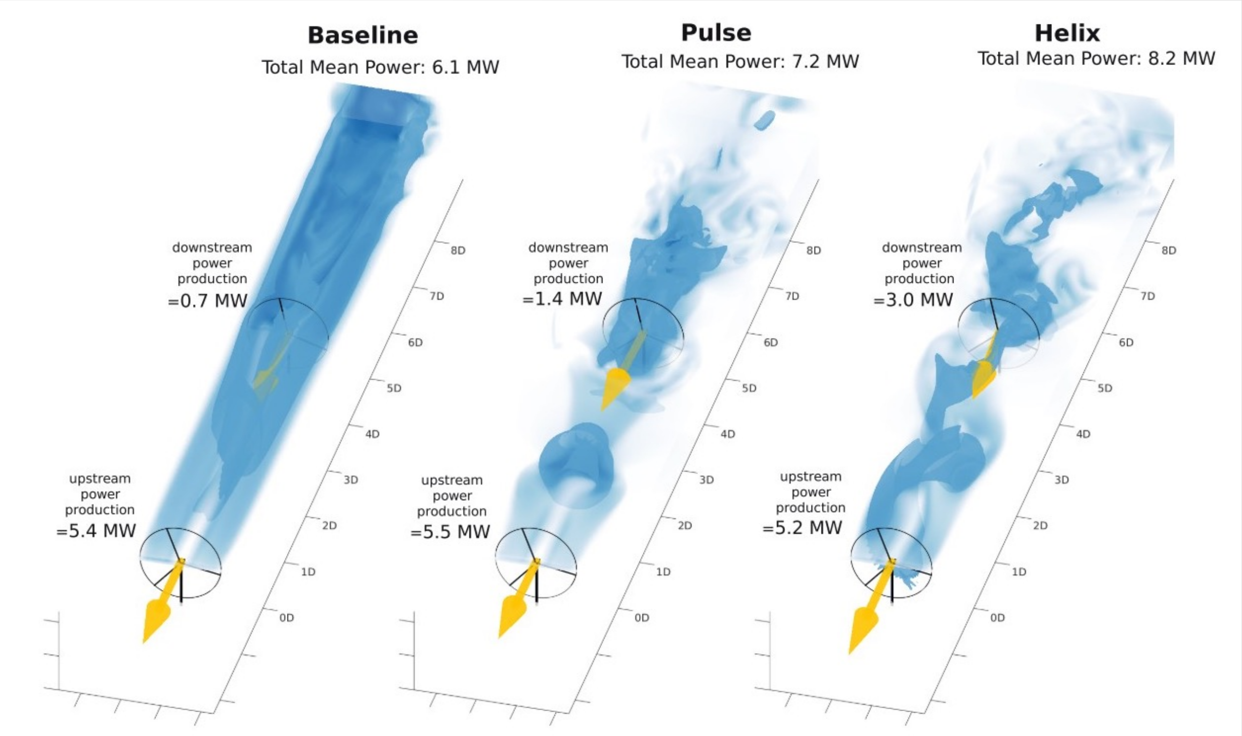

Illustration from a LES study of a stable normal operation wake (left), wake resulting from (periodic) dynamic induction control (middle), wake resulting from the helix approach (right) along downstream distances[7]

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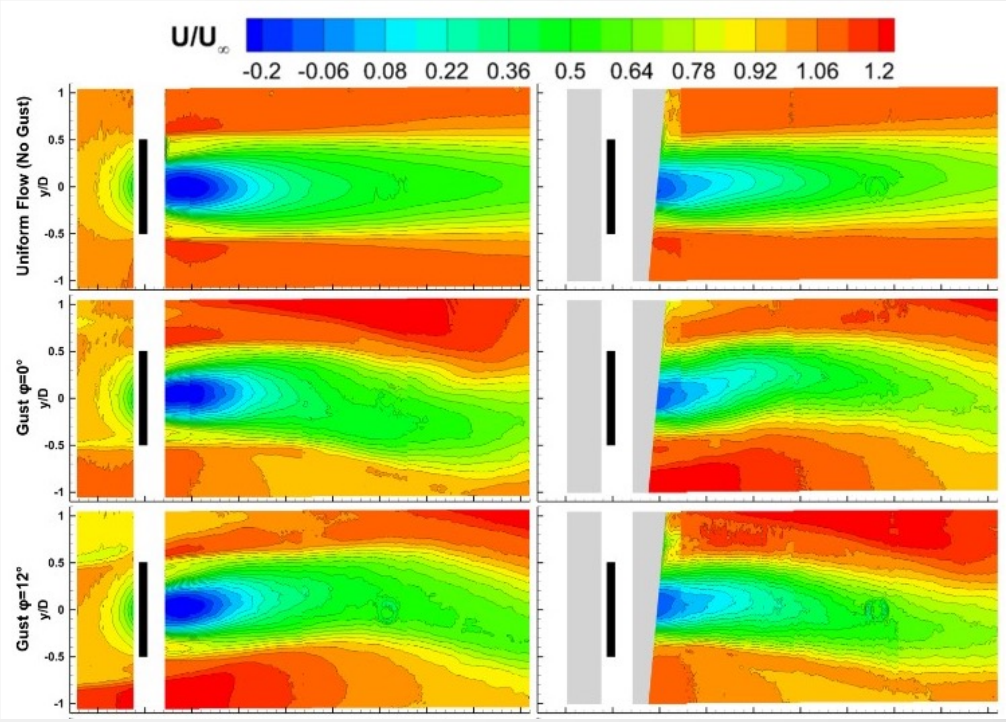
[7] Johan Meyers et al. “Wind farm flow control: prospects and challenges”. In: *Wind Energ. Sci. Discuss. [preprint]* (2022). doi: 10.5194/wes-2022-24.

Wind Turbine Rotor Aerodynamics and CFD Implementations

Additional Considerations

- Surface roughness
- Aeroelasticity
- Wind farm control
- Gusts:
    - brief increase in the speed of the wind
    - may reduce the effectiveness of wind turbines
- Aeroacoustics



PIV measurement results of a porous disc (left) and model wind turbine (right) under uniform flow, porous disc under gusty inflow, when the gust vanes are at 0, 12 degrees, respectively[8]

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[8] İmge Yığılı et al. “Design of a gust generator and comparison of model wind turbine and porous disc wake flows in a transverse gust”. In: *Journal of Physics: Conference Series* 2265.2 (May 2022), p. 022108. doi: 10.1088/1742-6596/2265/2/022108

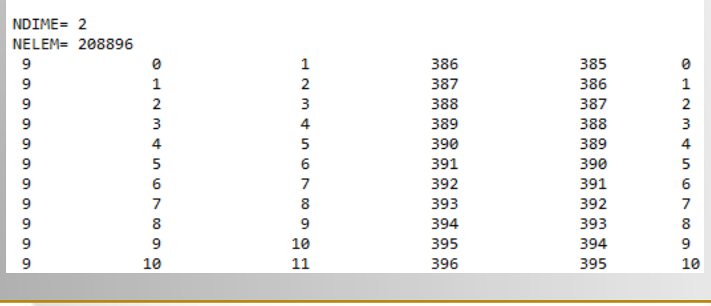
Wind Turbine Rotor CFD Analyses by using SU2

Content

SU2 Capabilities and Tutorial

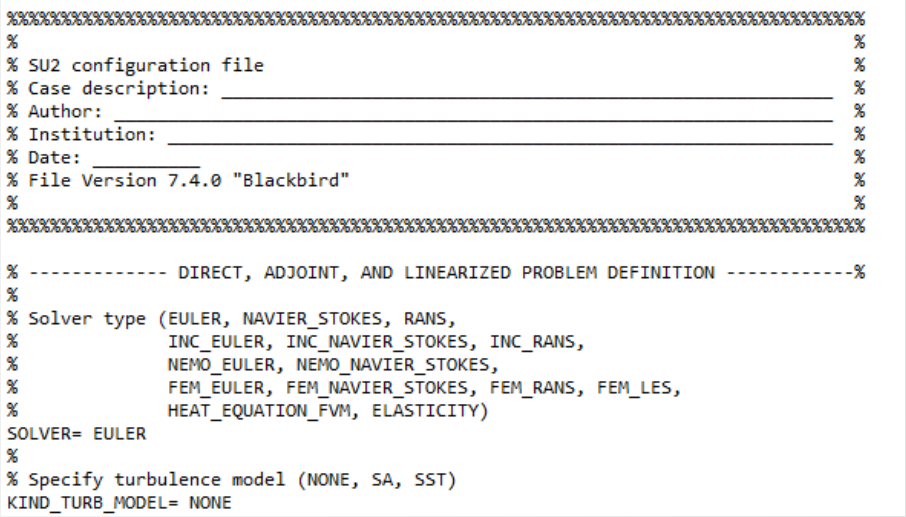
Fundamentals

- Inputs:
  - Configuration file (through the `SU2_CFD` command)
    - `SU2_CFD config_template.cfg`
    - `mpirun -n 16 SU2_CFD config_template.cfg`
    - Python scripts : `python parallel_computation.py -f config_template.cfg -n 16`
  - Mesh file (through the configuration file)
    - `MESH_FILENAME`
    - `MESH_FORMAT = SU2` or `CGNS`



```
NDIME= 2
NELEM= 208896
 9          0          1          386          385          0
 9          1          2          387          386          1
 9          2          3          388          387          2
 9          3          4          389          388          3
 9          4          5          390          389          4
 9          5          6          391          390          5
 9          6          7          392          391          6
 9          7          8          393          392          7
 9          8          9          394          393          8
 9          9         10          395          394          9
 9         10         11          396          395         10
```

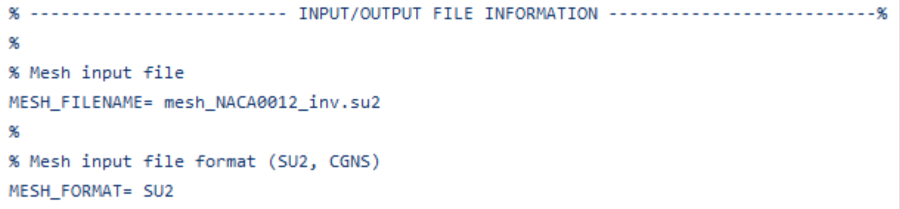
SU2 format mesh file



```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                              %
% SU2 configuration file                                                       %
% Case description: _________________________________________________________  %
% Author: ___________________________________________________________________  %
% Institution: ______________________________________________________________  %
% Date: __________                                                             %
% File Version 7.4.0 "Blackbird"                                               %
%                                                                              %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% ------------- DIRECT, ADJOINT, AND LINEARIZED PROBLEM DEFINITION ------------%
%
% Solver type (EULER, NAVIER_STOKES, RANS,
%               INC_EULER, INC_NAVIER_STOKES, INC_RANS,
%               NEMO_EULER, NEMO_NAVIER_STOKES,
%               FEM_EULER, FEM_NAVIER_STOKES, FEM_RANS, FEM_LES,
%               HEAT_EQUATION_FVM, ELASTICITY)
SOLVER= EULER
%
% Specify turbulence model (NONE, SA, SST)
KIND_TURB_MODEL= NONE
```

Configuration text file



```
% ------------------------ INPUT/OUTPUT FILE INFORMATION --------------------------%
%
% Mesh input file
MESH_FILENAME= mesh_NACA0012_inv.su2
%
% Mesh input file format (SU2, CGNS)
MESH_FORMAT= SU2
```

Mesh file information within the SU2 configuration file

SU2 Capabilities and Tutorial

Fundamentals

- SU2 uses an outer time loop to march through the physical time, and an inner loop which is usually a pseudo-time iteration or a (quasi-)Newton scheme.
- Time dependency is set by:
  - `TIME_DOMAIN = NO` : Steady simulation (Only an inner time loop)
  - `TIME_DOMAIN = YES` : Unsteady simulation
- The number of iterations are controlled by
  - Steady simulation: `ITER = 1000`
  - Unsteady simulation:
    - `TIME_STEP = 1.0`
    - `MAX_TIME = 50.0`
    - `INNER_ITER = 100`
    - `TIME_ITER = 200`

Simulation time = MIN(`TIME_ITER*TIME_STEP,MAX_TIME`)

- Time marching methods for solving the differential equations:
  - First-order dual-time stepping: `TIME_MARCHING = DUAL_TIME_STEPPING-1ST_ORDER`
  - Second-order dual-time stepping: `TIME_MARCHING = DUAL_TIME_STEPPING-2ND_ORDER`
  - Conventional time stepping: `TIME_MARCHING =  TIME_STEPPING`

SU2 Capabilities and Tutorial

Fundamentals

Boundary conditions (BC):

- Constant heatflux wall, in other words no-slip condition:
  - `MARKER_HEATFLUX = (Wall1, 1e05,` **`Wall2, 0.0`**`)`

    Name of the BC Heatflux in [W/m^2] Adiabatic wall
  - Other no-slip conditions: `MARKER_HEATTRANSFER, MARKER_ISOTHERMAL`
- Farfield boundary condition (freestream values):
  - `MARKER_FAR = (farfield)`
- Outlet boundary condition:
  - `MARKER_OUTLET = (outlet, 0.0)`
    - `Compressible: ( outlet marker, back pressure (static thermodynamic), ... )`
    - `Inc. Pressure: ( outlet marker, back pressure (static gauge in Pa), ... )`
    - `Inc. Mass Flow: ( outlet marker, mass flow target (kg/s), ... )`

SU2 Capabilities and Tutorial

Fundamentals

Boundary conditions (BC):

- Inlet boundary condition:
  - `INLET_TYPE = TOTAL_CONDITIONS` or `MASS_FLOW`
  - `MARKER_INLET =`
    - Total Conditions: `(inlet marker, total temp, total pressure, flow_direction_x, flow_direction_y, flow_direction_z, ...)`
    - Mass Flow: `(inlet marker, density, velocity magnitude, flow_direction_x, flow_direction_y, flow_direction_z, ... )`
    - Inc. Velocity, Inc. Pressure
  - One can give a non-uniform inlet profile through:
    - `SPECIFIED_INLET_PROFILE= YES`
    - `INLET_FILENAME= inlet.dat`
      - If SU2 cannot finds a file with the `INLET_FILENAME` then it creates a template file for the mesh specified in the configuration file

SU2 Capabilities and Tutorial

Fundamentals

Boundary conditions (BC):

- Periodic boundary condition (e.g. 120° single-blade simulations):
  - `MARKER_PERIODIC= ( periodic marker, donor marker, rotation_center_x, rotation_center_y, rotation_center_z, rotation_angle_x-axis, rotation_angle_y-axis, rotation_angle_z-axis, translation_x, translation_y, translation_z, ...)`

Output:

- To list the all possible output fields for the given configuration file, run the command:
  - `SU2_CFD -d config_template.cfg` (performs a dry run)
- Rotor application:
  - `ROTATING_FRAME` (figure of merit, thrust, torque) group within the screen/history output fields
  - `VORTEX_IDENTIFICATION` group within the volume output fields

SU2 Capabilities and Tutorial

Dynamic Mesh

- To define the type of dynamic mesh:
  - `GRID_MOVEMENT= RIGID_MOTION, ROTATING_FRAME,` or `STEADY_TRANSLATION`
  - `RIGID_MOTION:` Physically rotating the mesh
  - `ROTATING_FRAME:` Implementing the flow equations in the rotating coordinate frame with additional source terms
- Definitions:
  - `MACH_MOTION = 0.2` (Used for initializing and computing force coeffs. with dynamic meshes)
  - `MOTION_ORIGIN = 0.0 0.0 0.0`
  - `ROTATION_RATE = 0.0 0.0 5.0` (Angular velocity vector [rad/s])

SU2 Capabilities and Tutorial

Flow Over the Blade

- Transition models (valid for Version 7.4.0)
  - SA-BCM
    - `KIND_TURB_MODEL= SA`
    - `SA_OPTIONS= BCM`
    - `KIND_TRANS_MODEL= BC` (earlier than Version 7.3.1)
  - SST LM (Langtry-Menter Trans. SST)
    - `KIND_TURB_MODEL= SST`
    - `KIND_TRANS_MODEL= LM`
  - Turbulence intensity
    - `FREESTREAM_TURBULENCEINTENSITY= 0.05` (=5%)
- Wall functions:
  - Markers: `MARKER_WALL_FUNCTIONS=(wall1,STANDARD_WALL_FUNCTION, wall2, EQUILIBRIUM_WALL_MODEL)`
  - The von Karman constant: `WALLMODEL_KAPPA`
  - The wall function model constant B: `WALLMODEL_B`
  - The y+ value below which the wall function is switched off: `WALLMODEL_MINYPLUS`

SU2 Capabilities and Tutorial

Interactions with Rotor Components

- To include both rotating and non-rotating components, the user must specify different configuration files for those components.
- Main configuration file:
  - `MULTIZONE=YES`
  - `CONFIG_LIST = ( input_inner.cfg, input_outer.cfg )`
  - `MARKER_ZONE_INTERFACE= ( interface_inner, interface_outer )`
  - `MARKER_FLUID_INTERFACE= ( interface_inner, interface_outer )`
    - Each zone is discretized independently
  - `KIND_INTERPOLATION= NEAREST_NEIGHBOR,ISOPARAMETRIC,` or `SLIDING_MESH`
    - Specifies how values are communicated over the interfaces

SU2 Capabilities and Tutorial

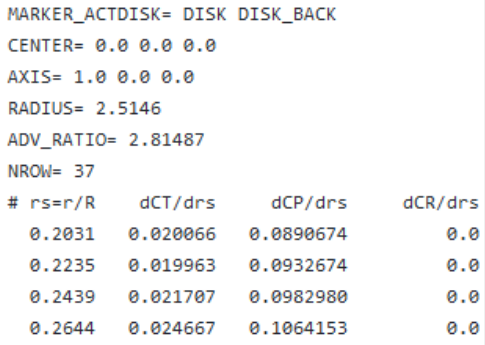
Interactions with Rotor Components

- `input_inner.cfg:`
  - `GRID_MOVEMENT= RIGID_MOTION`
  - `MESH_FILENAME= rotor.su2`
- `input_outer.cfg:`
  - `GRID_MOVEMENT= NONE`
  - `MESH_FILENAME= outer_cylinder.su2`

SU2 Capabilities and Tutorial

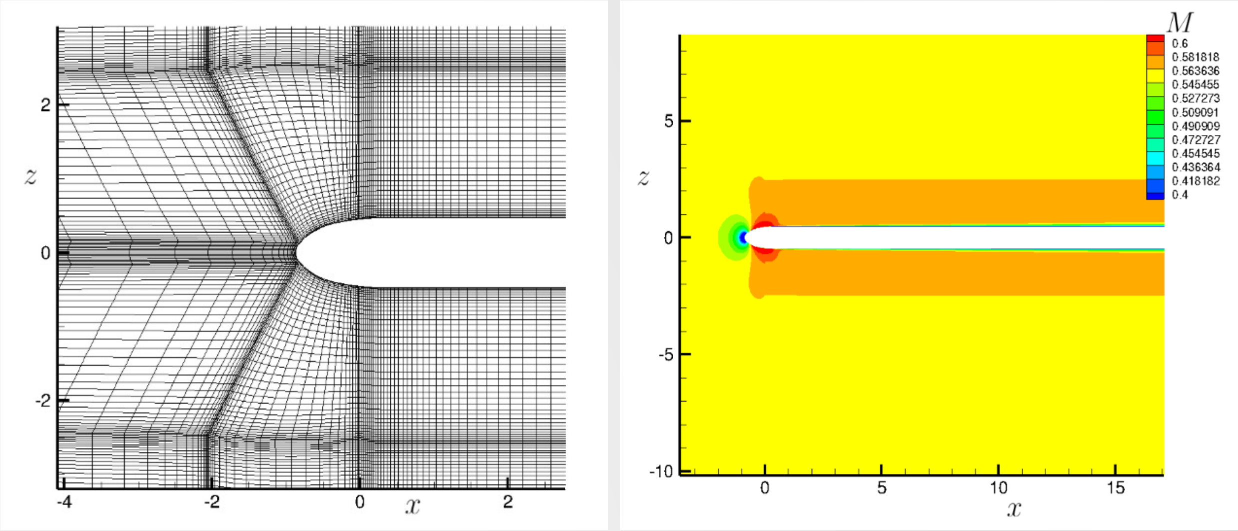
Actuator Disk

- The actuator disk model in SU2 is not much suitable with wind turbines, but still usable
- Commands:
  - `MARKER_ACTDISK= (inlet face marker, outlet face marker, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0)`
  - `ACTDISK_TYPE= VARIABLE_LOAD`
  - `ACTDISK_FILENAME= actuatordisk.dat`



```
MARKER_ACTDISK= DISK DISK_BACK
CENTER= 0.0 0.0 0.0
AXIS= 1.0 0.0 0.0
RADIUS= 2.5146
ADV_RATIO= 2.81487
NROW= 37
# rs=r/R     dCT/drs     dCP/drs       dCR/drs
   0.2031    0.020066    0.0890674         0.0
   0.2235    0.019963    0.0932674         0.0
   0.2439    0.021707    0.0982980         0.0
   0.2644    0.024667    0.1064153         0.0
```

Sample actuator disk file



Mesh details for the actuator disk with a semi-infinite spinner test case (left) and SU2 Mach number contour[9]

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[9] E. Saetta, L. Russo, and R. Tognaccini. “Implementation and validation of a new actuator disk model in SU2”. In: *SU2 Conference 2020* (June 2020).

SU2 Capabilities and Tutorial

Surface Roughness and Gusts

- SU2 contains a model to simulate surface roughness.
- `WALL_ROUGHNESS = (wall1, ks1)`
  - `ks1` is the equivalent sand grain roughness height on each of the wall in meters.

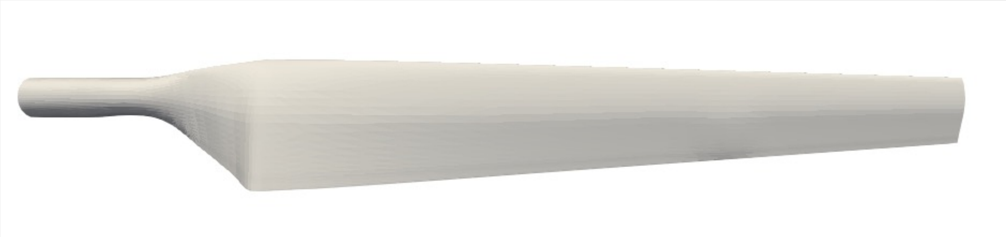
- SU2 contains a gust model for top-hat, sine, 1-cos, vortex, and extreme operating gust (EOG) gust types.
  - **Only in 2D!** However, the developers are working on for a 3D model.
  - Commands:
    - `WIND_GUST = YES`
    - `GUST_TYPE = TOP_HAT, SINE, ONE_M_COSINE, VORTEX,` or `EOG`
    - `GUST_DIR = X_DIR` or `Y_DIR`
    - `GUST_WAVELENGTH= 10.0` (in meters)
    - `GUST_PERIODS= 1.0` (Number of gust periods)
    - `GUST_AMPL= 10.0` (in m/s)
    - `GUST_BEGIN_TIME= 0.0`
    - `GUST_BEGIN_LOC= 0.0`

Content

Applications

Test Case Configuration

- NREL Phase VI wind turbine
  - 2 blades
  - Rotor radius: 5.029 m
  - Rotational speed: 72 RPM = 7.54 rad/s
  - S809 airfoil starting at r/R=25%
- u_∞= 9 m/s (uniform inlet)
- λ = 4.2 (tip speed ratio)

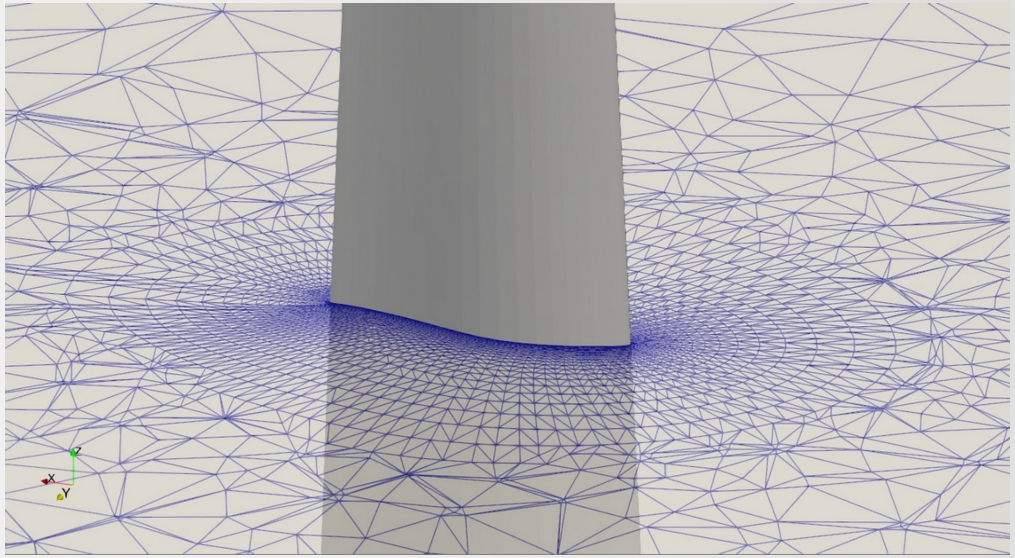


NREL Phase VI wind turbine blade

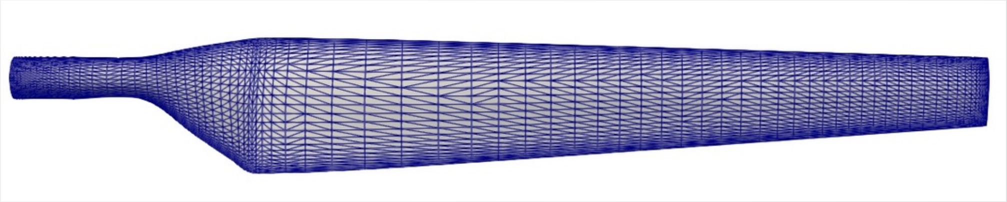
Applications

Test Case Configuration

- Single blade with periodic boundaries
- 800k cells and 10k surface cells
- Boundary layer with a first cell height of $\Delta y = 1\times10^{-4}$ m and $y^{+}_{max} \approx 25$
- Boundaries:
    - Inlet (-x): 5D
    - Side (circular): 5D
    - Outlet (+x): 50D



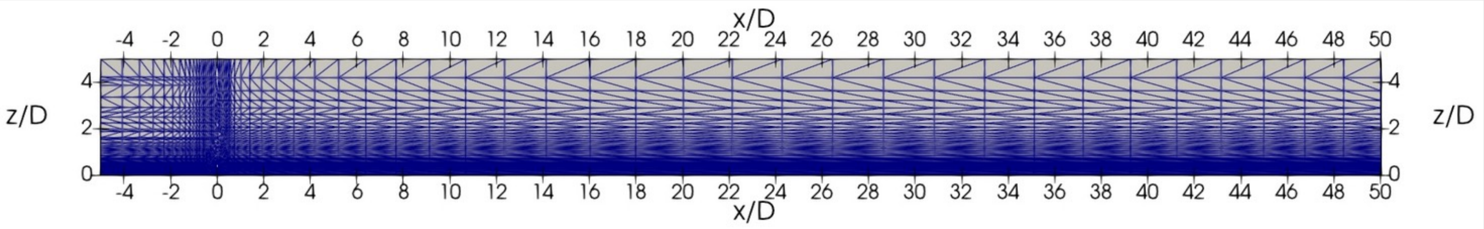
Mesh on the z=3 m cross-section (check the mesh near the surface)



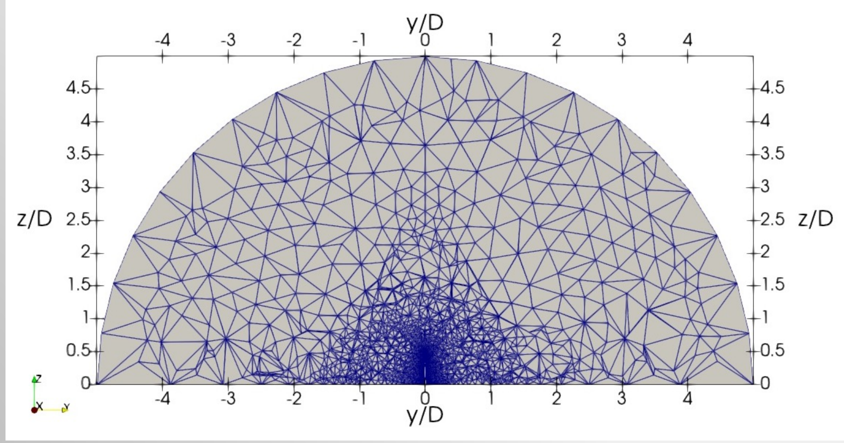
Surface mesh

Applications

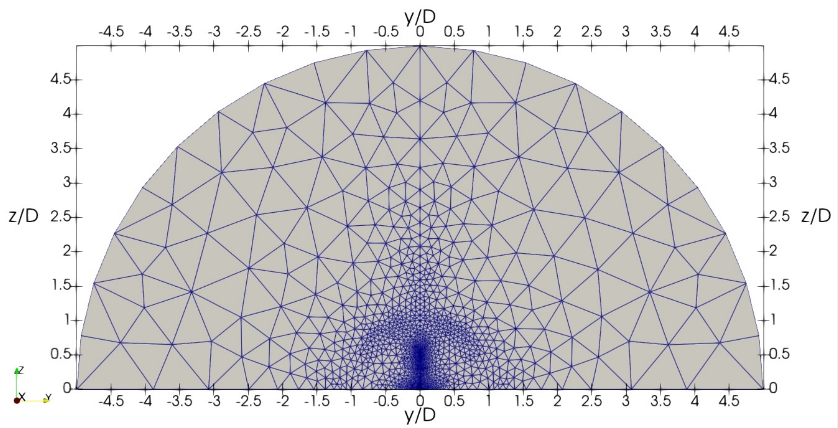
Test Case Configuration



Mesh on the y=0 cross-section



Mesh on the x=0 cross-section



Mesh on the x=0 cross-section

Applications

SU2 Configuration

- 3 simulations:
  - Half (Single blade) configuration, rigid mesh motion, unsteady simulation
    - 10h on 16 cores for a 4 seconds (approx. 5 revolutions) simulations
  - Full (Two-blade) configuration, rigid mesh motion, unsteady simulation
    - 20h on 16 cores for a 4 seconds (approx. 5 revolutions) simulations
  - Half (Single blade) configuration, rotating frame, steady simulation
    - 2h on 16 cores for 12,000 iteration (log(RMS density) = -3 for this case)

- Shall we check the configuration files?

Applications

Results

- Shall we check the output files?
  - history.csv
    - Variation of residuals, force coefficients, moment coefficients with time (iterations)
  - flow.vtu
    - Volume flow results
  - surface_flow.vtu
    - Surface flow results
  - forces_brakedown.dat
    - Force and moment breakedown by surface

Applications

Results

Streamwise velocity variations along the blade from the rigid motion single blade (left), rigid motion two-blade (center), and reference frame (right) simulations

Applications

Possible Improvements

- Shorter first cell height, so lower y^+
    - If not, implementing the wall functions
- Transition model to capture the laminar flow and laminar-turbulent transition
- Remaining rotor components and non-rotor components for interactions
- Atmospheric boundary layer (non-uniform inlet velocity profile) since this is a small turbine (rotor within the ABL)
- Wind tunnel walls if there will be a validation against experimental data
- Finer mesh around the blade to preserve the turbulent structures

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