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CFD and Performance Simulations of Wind Turbines

16 December 2023

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CFD and Performance Simulations of Wind Turbines

Wind Turbine Airfoil CFD Analyses

Ezgi Orbay Akcengiz, Nilay Sezer Uzol
Dept. of Aerospace Engineering, METU
METU RÜZGEM

16 December 2023

Wind Turbine Airfoil CFD Analyses

Content:

- Introduction
  - CFD simulations for airfoils
  - Computational grids
- Mesh Generation using GMSH
- CFD analysis in SU2
- Wind turbine airfoil CFD simulations

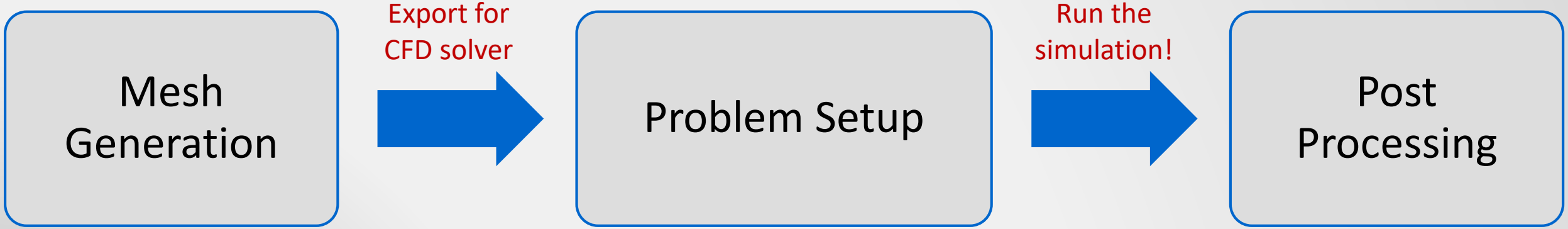
Wind Turbine Airfoil CFD Analyses

Introduction

- Aerodynamic design of a wind turbine rotor:
  - is mostly based on fast Blade Element Momentum (BEM) Theory analysis
  - requires accurate lift and drag polars for a wide range of Reynolds numbers
- For a typical modern non-linearly twisted and tapered blade:
  - There is a distribution of a family of airfoils along the radius
- Airfoil aerodynamic characteristics are generally obtained through a combination of numerical simulations and wind tunnel tests during both airfoil design and blade design processes.
- Because of the limited availability of wind tunnel data in limited Reynolds number ranges, obtaining accurate numerical results is of vital importance.

Wind Turbine Airfoil CFD Analyses

CFD simulations for airfoils



2D/3D
Mesh topology
Grid cell type

Problem definition - Solver
Turbulence & Transition model
Freestream conditions
BC definitions
Numerical method & Time integration
Linear solver
Flow & Turbulence numerical method
Convergence criteria

Quantitative comparisons
Graph: Cl vs. Aoa,
Cd vs. Aoa, ...
Contour plots
Streamlines

Wind Turbine Airfoil CFD Analyses

CFD simulations for airfoils

- Numerical Solution Approaches:
  - 2-D / 3-D
  - Steady-State / Unsteady
  - RANS / LES

- Turbulence Models:
  - RANS: SA, k–ω SST, Realizable k– ε
  - Hybrid RANS/LES: DES, DDES, IDDES
  - LES
  - DNS (usually low Reynolds numbers)

- Grid Characteristics:
  - Structured / Unstructured / Hybrid / Block-structured / Multi-block
  - 2-D Simulations: O type, C type, C-H type structured grids
  - 3-D Simulations: Spanwise extension of 2-D grids

Wind Turbine Airfoil CFD Analyses

Mesh Generation

- One of the critical steps of CFD analysis is generating the proper computational grid for the problem.

- Depending of the geometry of the model and solution approach, type of grids can be changed.
  - Structured / Unstructured / Hybrid / Block-structured / Multi-block
  - 2-D Simulations: O type, C type, C-H type structured grids
  - 3-D Simulations: Spanwise extension of 2-D grids

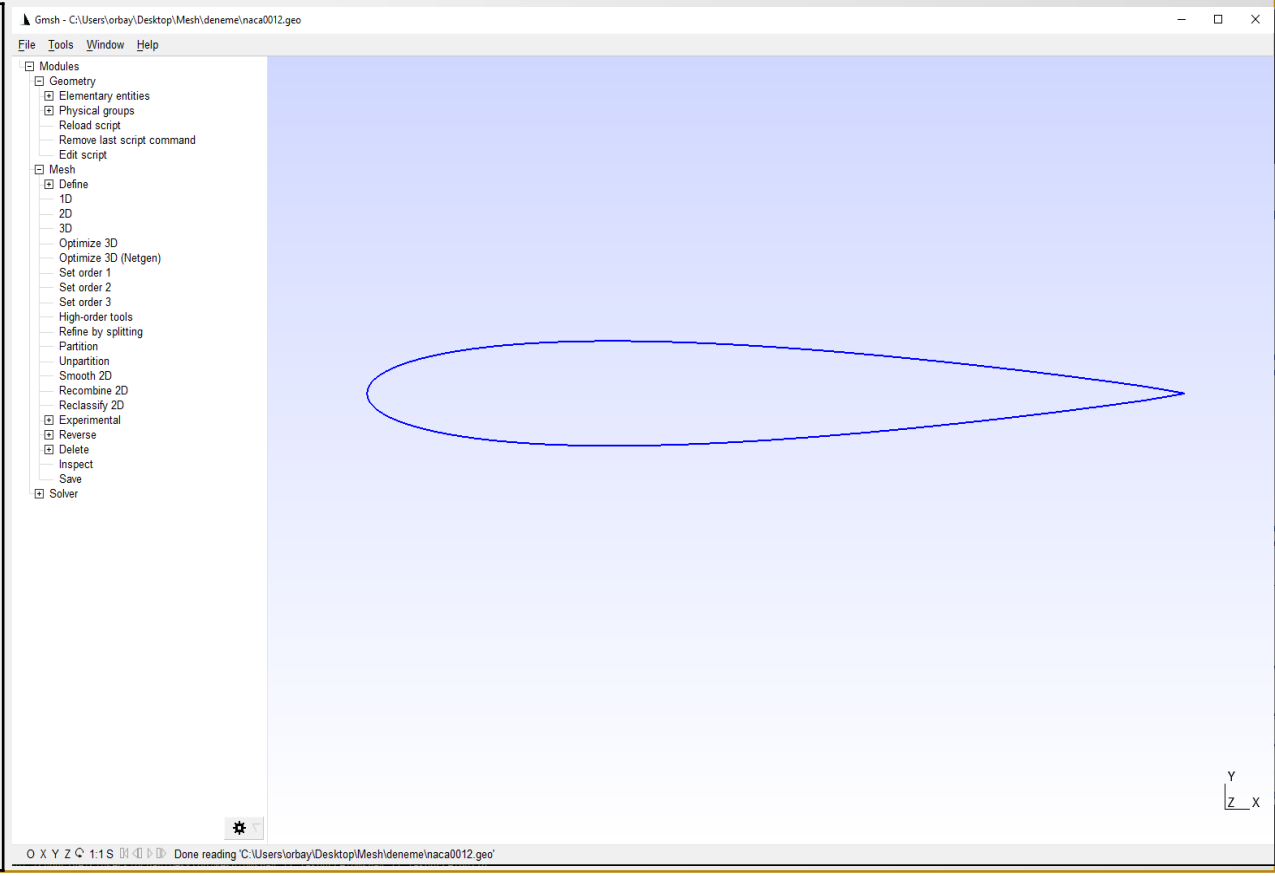
- Mesh generation tools:
  - Pointwise, GMSH

Wind Turbine Airfoil CFD Analyses

Mesh Generation - GMSH

- Gmsh is an open-source tool known for generating unstructured, structured, and hybrid meshes.

airfoil.dat	*this file has the airfoil coordinates.*
toGmsh	*this is an executable of "toGmsh utility code" to generate an airfoil.geo file from the airfoil coordinates.*
makegmsh_geo	*use this script to generate an airfoil.geo file from the airfoil coordinates.*
airfoil.geo	*this is an input file for Gmsh.*
makegmsh_grid	*use this script to generate a mesh file by Gmsh.*
mesh.su2	*this is an output mesh file in SU2 format generated by Gmsh.*



Wind Turbine Airfoil CFD Analyses

Mesh Generation - GMSH

- *Run the scripts to generate the mesh:*

makegmsh_geo: generates airfoil.geo from airfoil.dat

```
#!/bin/sh
./toGmsh airfoil
```

```
$ ./makegmsh_geo
```

makegmsh_grid: generates grid in su2 format using airfoil.geo

```
#!/bin/sh
gmsh -2 airfoil.geo -o mesh.su2 -format su2
```

```
$ ./makegmsh_grid
```

airfoil.dat	*this file has the airfoil coordinates.*
toGmsh	*this is an executable of "toGmsh utility code" to generate an airfoil.geo file from the airfoil coordinates.*
makegmsh_geo	*use this script to generate an airfoil.geo file from the airfoil coordinates.*
airfoil.geo	*this is an input file for Gmsh.*
makegmsh_grid	*use this script to generate a mesh file by Gmsh.*
mesh.su2	*this is an output mesh file in SU2 format generated by Gmsh.*

Wind Turbine Airfoil CFD Analyses

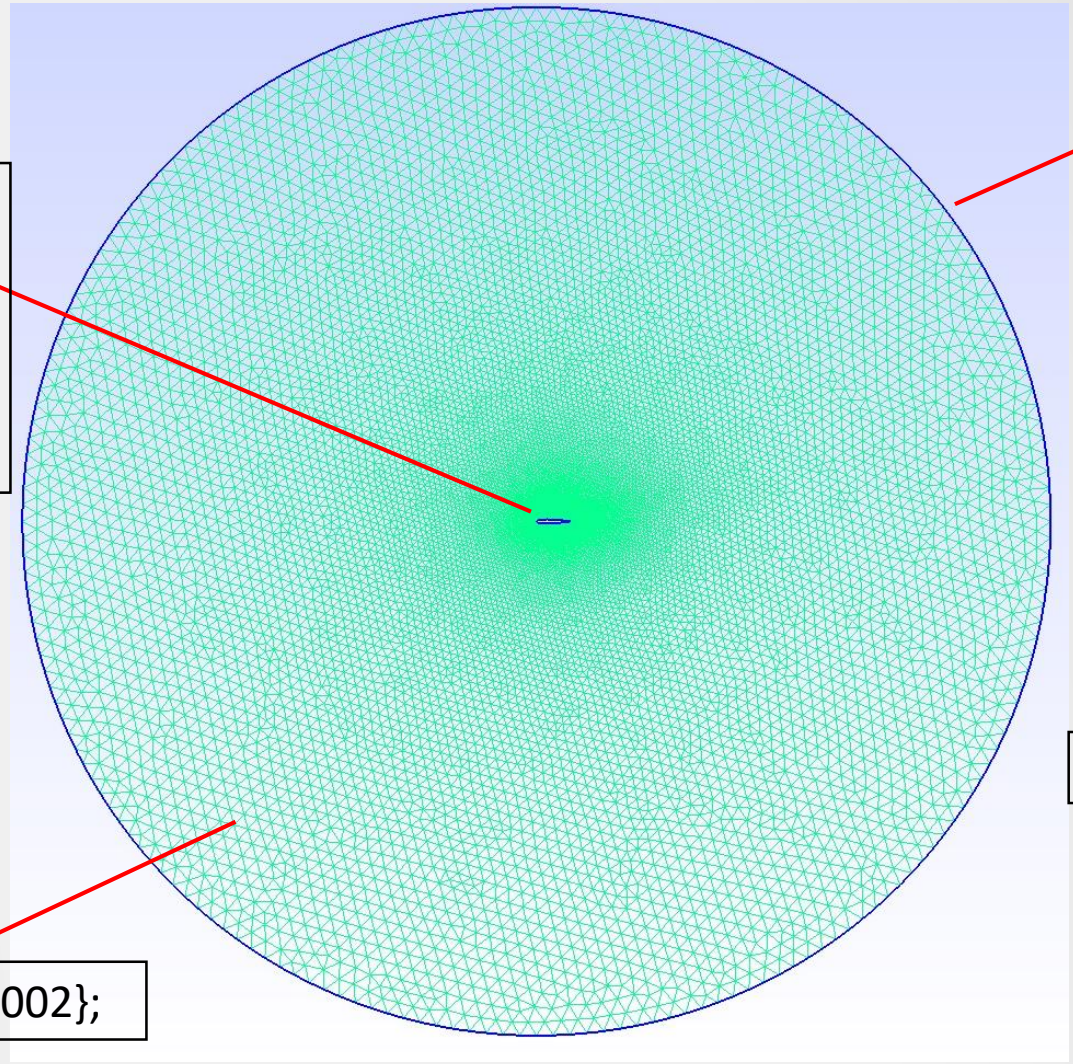
Mesh Generation – GMSH – airfoil.geo

Lines defined by airfoil coordinates

```
// NACA0012
Point(101)={+1.00e+0,+0.00e+0,+0.00e+000,ms2};
Point(102)={+9.919e-1,-1.320e-3,+0.00e+0,ms2};
Point(103)={+9.834e-1,-2.724e-3,+0.00e+0,ms2};
Point(104)={+9.742e-1,-4.206e-3,+0.00e+0,ms2};
...
```

```
Spline(1001)={101 : 101+84};
Spline(1002)={185 : 185+24};
Spline(1003)={209 : 209+83, 101};
```

```
Line Loop(2002)={1001,1002,1003};
```



Circle defined by 4 surronding points and a center point

```
Point(1) = {0,0,0,ms1};
Point(2) = {15,0,0,ms1};
Point(3) = {0,15,0,ms1};
Point(4) = {-15,0,0,ms1};
Point(5) = {0,-15,0,ms1};
```

```
Circle(1) = {2,1.,3};
Circle(2) = {3,1.,4};
Circle(3) = {4,1.,5};
Circle(4) = {5,1.,2};
```

```
Line Loop(2001) = {2, 3, 4, 1};
```

```
Plane Surface(3001)={2001,2002};
```

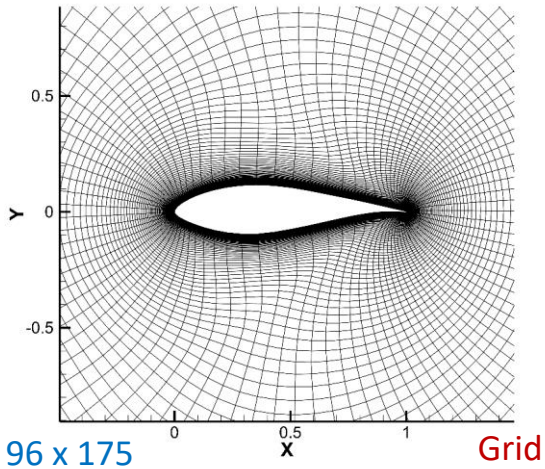
Wind Turbine Airfoil CFD Analyses

Grid Independence Study

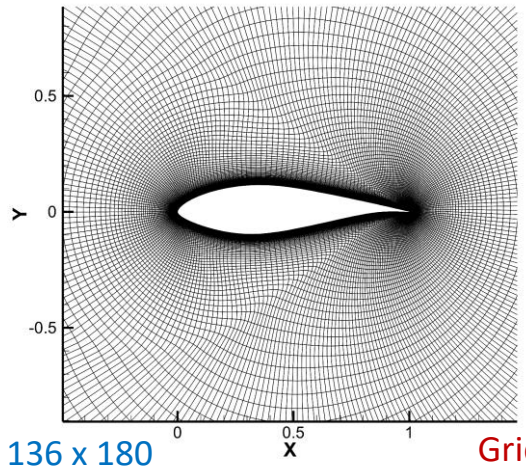
- The solution should be independent on computational grid as possible.
- Therefore, grid independence study is performed.
- Grid cell size is increased and decreased by a constant factor in every direction systematically.
- For a structured computational mesh:
  - Generally, grid cell size are changed with a factor of √2, so the area of a cell is doubled or halved.
  - The change in the cell edge size is performed for every direction by keeping growth ratio as constant.

Wind Turbine Airfoil CFD Analyses

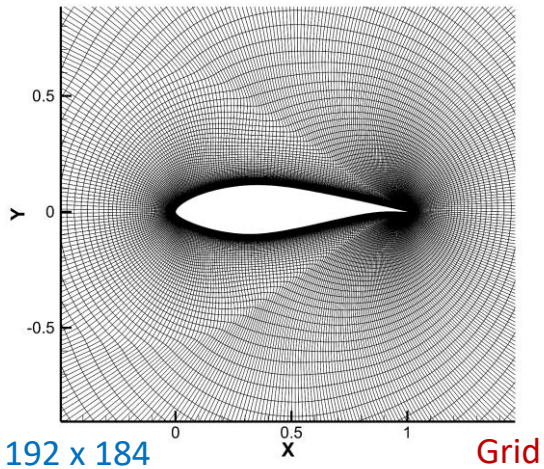
Grid Independence Study



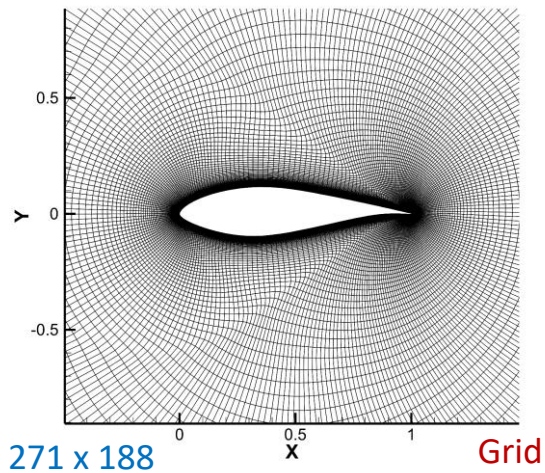
96 x 175 Grid 9



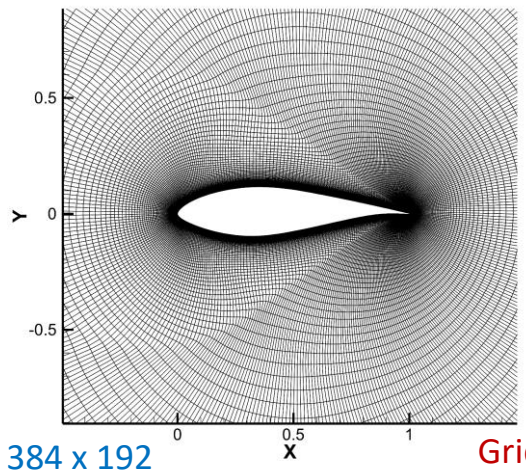
136 x 180 Grid 8



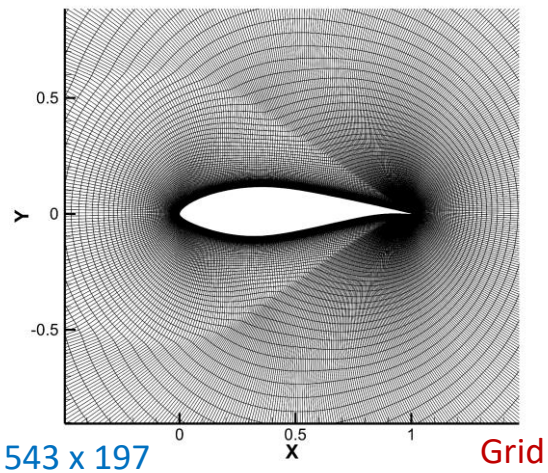
192 x 184 Grid 7



271 x 188 Grid 6



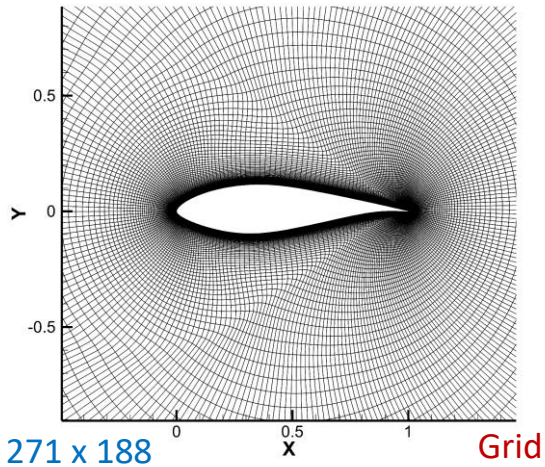
384 x 192 Grid 5



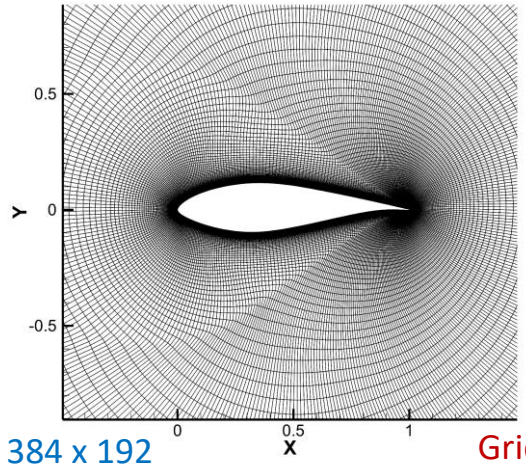
543 x 197 Grid 4

Wind Turbine Airfoil CFD Analyses

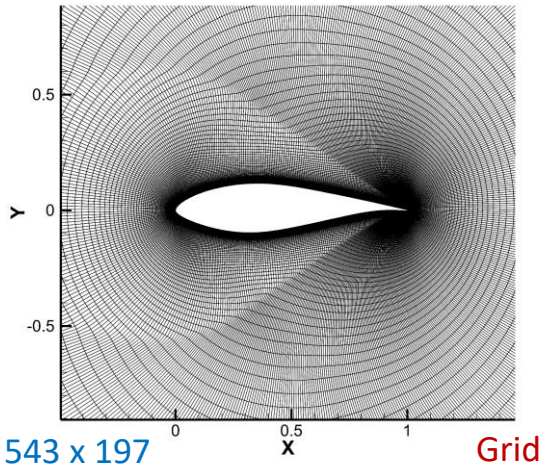
Grid Independence Study



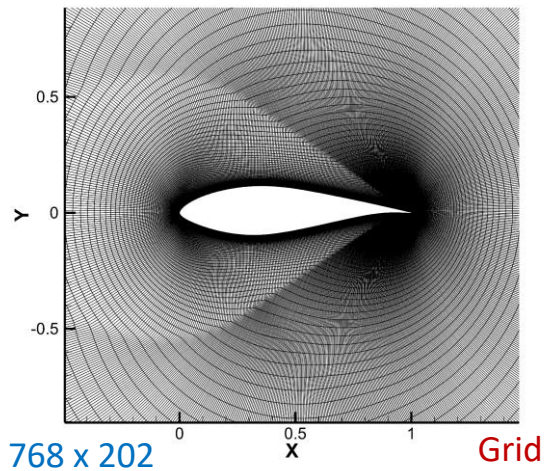
271 x 188 Grid 6



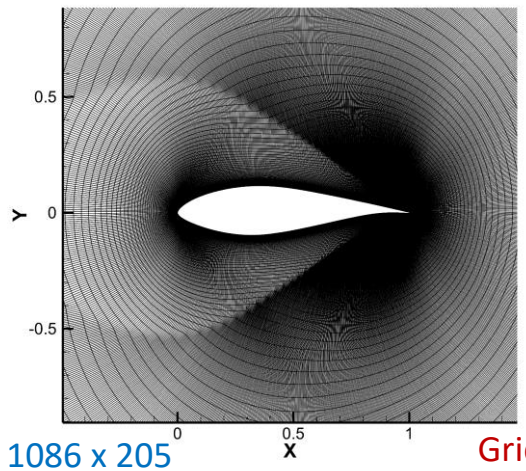
384 x 192 Grid 5



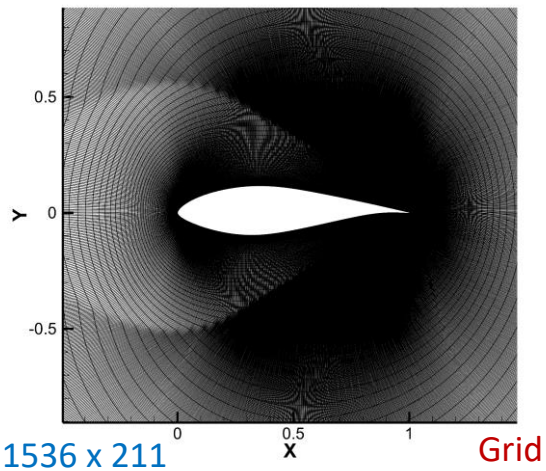
543 x 197 Grid 4



768 x 202 Grid 3



1086 x 205 Grid 2

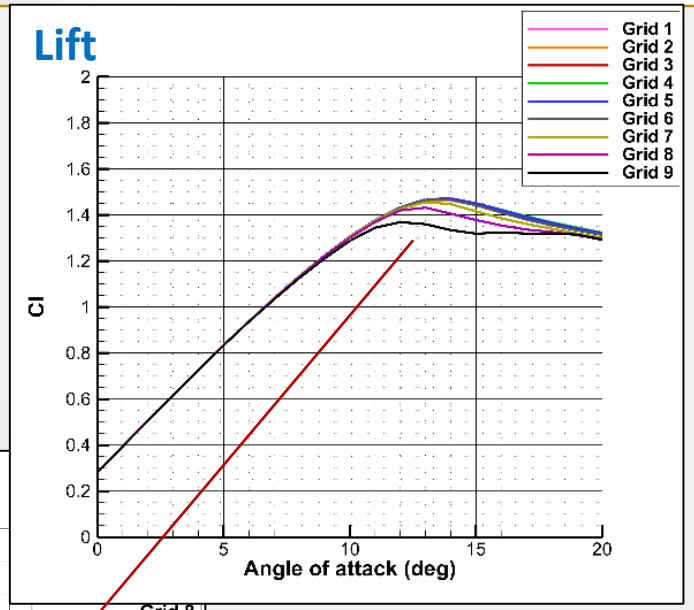


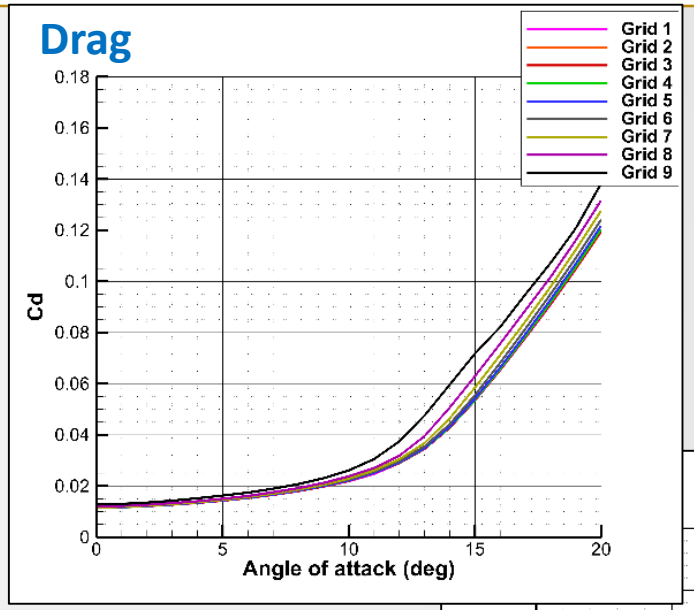
1536 x 211 Grid 1

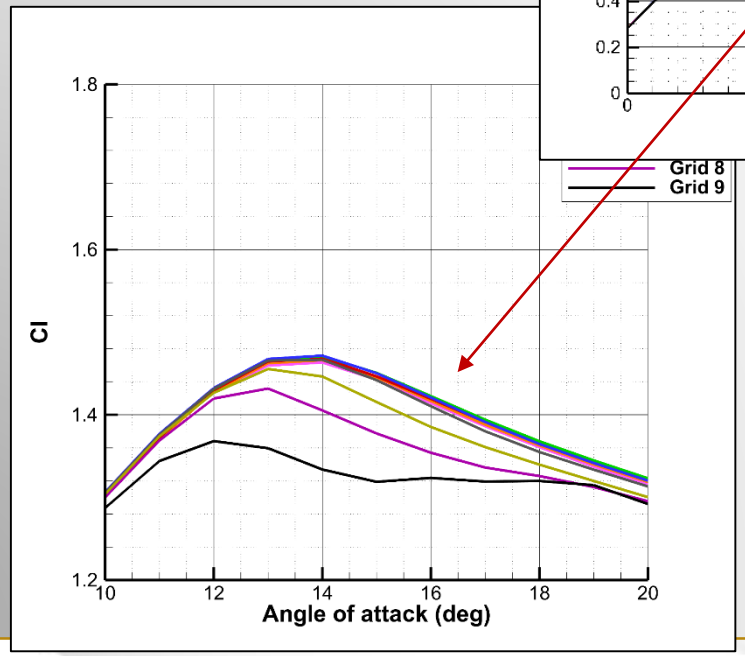
Wind Turbine Airfoil CFD Analyses

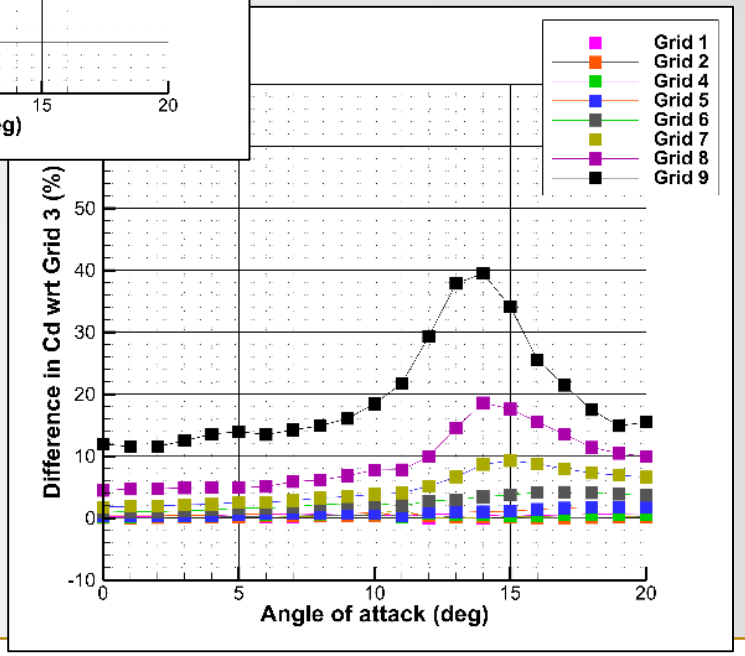
An Example for Grid Independence Study

DU00-W-212
Re = 3e6
M = 0.074







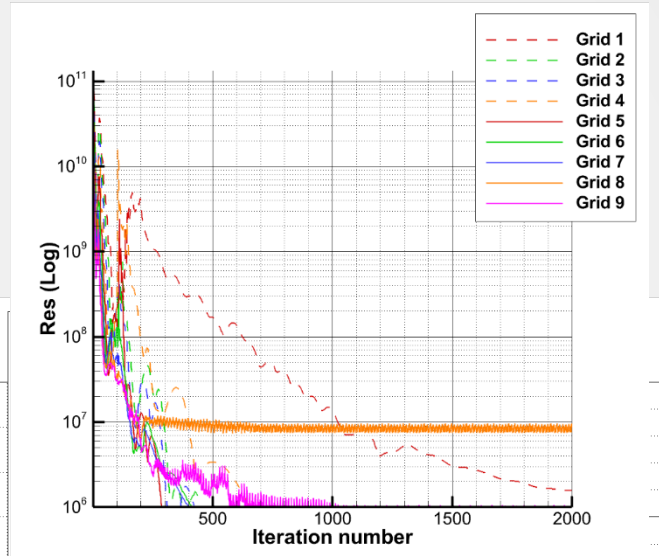


Wind Turbine Airfoil CFD Analyses

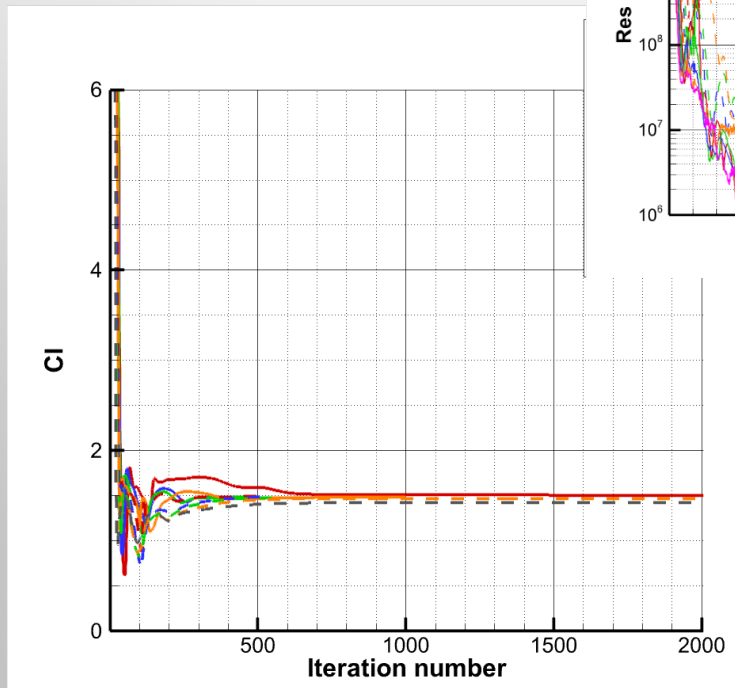
An Example for Grid Independence Study

DU00-W-212
Re = 3e6
M = 0.074

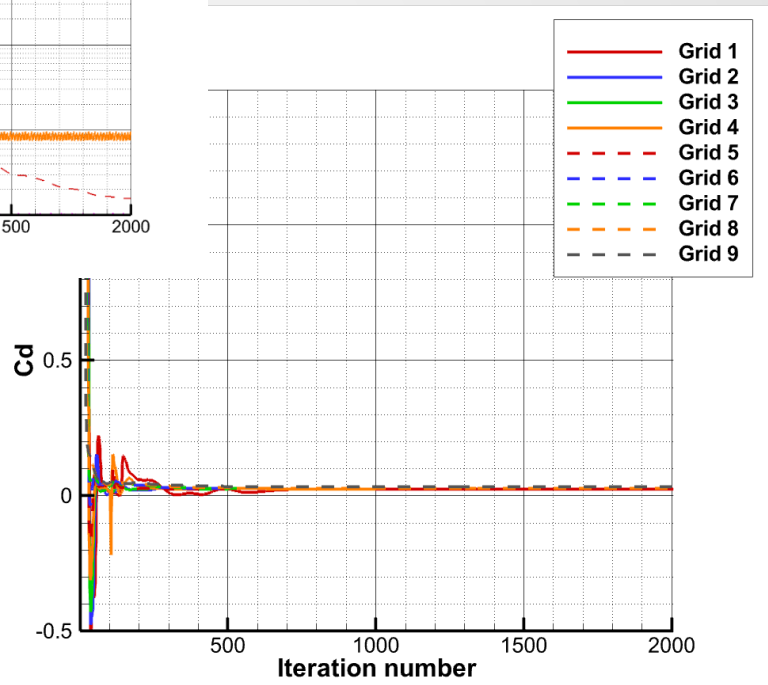
Residual



Lift



Drag



Wind Turbine Airfoil CFD Analyses

CFD simulations in SU2

- SU2 is a computational analysis and design package that has been developed to solve multiphysics analysis and optimization tasks using unstructured mesh topologies.
  - Compressible/Incompressible Euler and Navier-Stokes
  - RANS, Hybrid RANS/LES solution methods
- The turbulence models for RANS available in SU2:
  - Spalart Allmaras
  - Spalart Allmaras with transition model
  - k−ω SST
  - k−ω SST with transition model

Wind Turbine Airfoil CFD Analyses

CFD simulations in SU2

Input files:	**Output files:**
• Mesh file • Configuration file • Job script file	• Flow • Surface flow • History • Restart file

Wind Turbine Airfoil CFD Analyses

SU2 – Mesh File

Mesh input file: Mesh1.su2

- Problem dimension:

  NDIME= 2

- Inner element connectivity:

  NELEM= 688471

  9 0 2355 6525 3230 0

  9 2355 2356 6526 6525 1

  9 2356 2357 6527 6526 2

  ...

- Node coordinates:

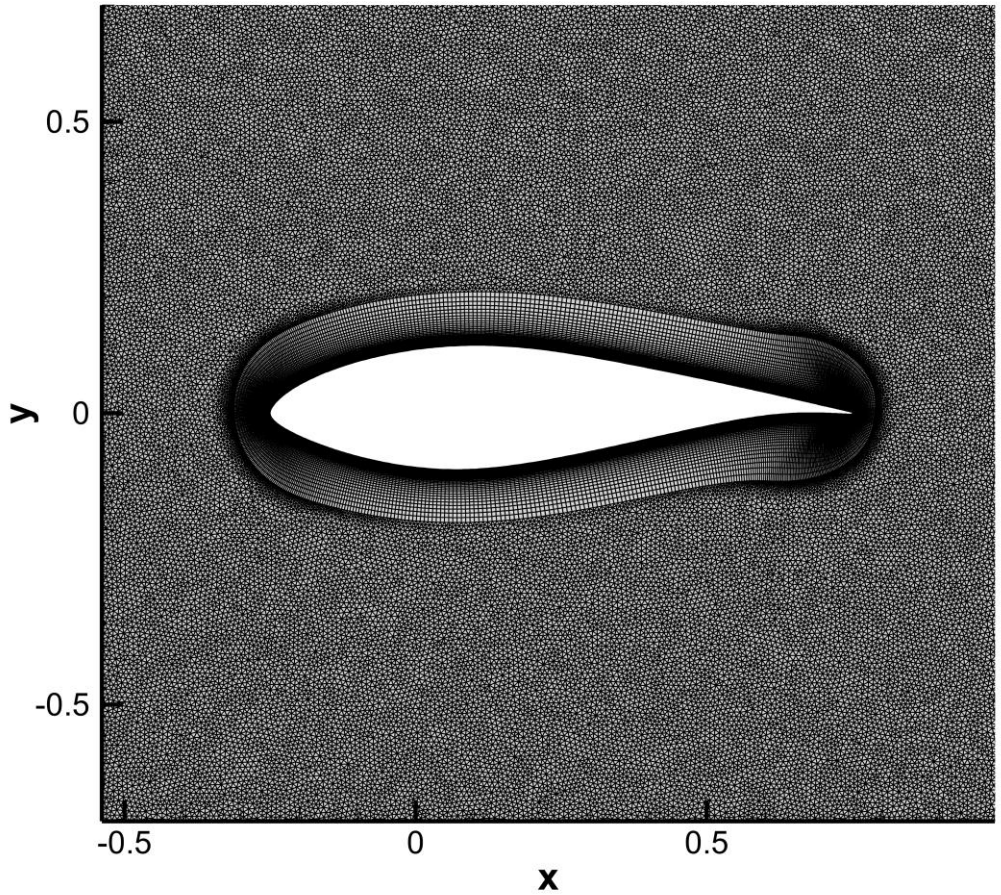
  NPOIN= 389388

  0.74692769 -0.067835931 0

  11.900000 1.2500000 1

  11.900000 -1.2500000 2

  ...



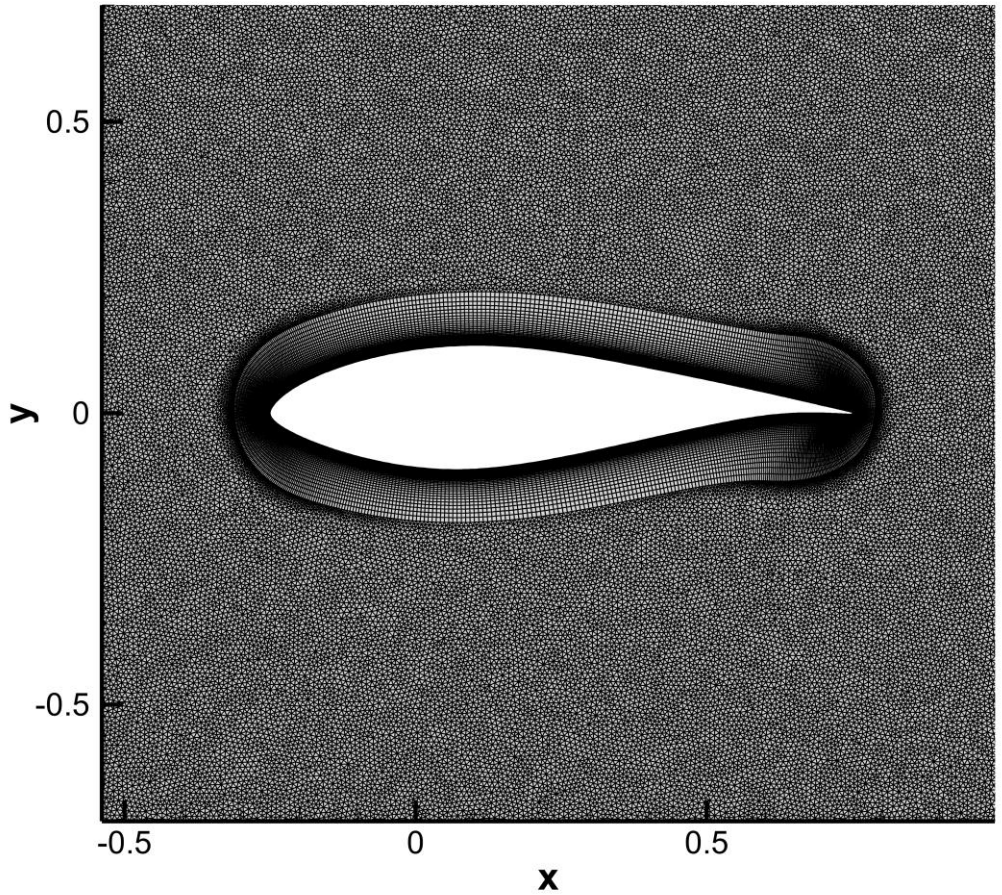
Wind Turbine Airfoil CFD Analyses

SU2 – Mesh File

Mesh input file: Mesh1.su2

- Boundary elements

```
NMARK= 4
MARKER_TAG= WT_walls
MARKER_ELEMS= 2344
 3    3   13
 3   13   14
 3   14   15
...
MARKER_TAG= airfoil
MARKER_ELEMS= 433
 3    0 2355
 3  2355 2356
 3  2356 2357
...
```



Wind Turbine Airfoil CFD Analyses

SU2 – Configuration file

Configuration Input File: rans.cfg

```
% ------------- DIRECT, ADJOINT, AND LINEARIZED PROBLEM DEFINITION --------%
%Physical governing equations (EULER, NAVIER_STOKES, WAVE_EQUATION,
HEAT_EQUATION, FEM_ELASTICITY, POISSON_EQUATION)
   SOLVER= RANS
% Specify turbulent model (NONE, SA, SA_NEG, SST)
   KIND_TURB_MODEL= SA
% Restart solution (NO, YES)
   RESTART_SOL= NO
```

Wind Turbine Airfoil CFD Analyses

SU2 – Configuration file

```
% ------------------- COMPRESSIBLE FREE-STREAM DEFINITION -----------------%
% Mach number (non-dimensional, based on the free-stream values)
   MACH_NUMBER= 0.074
% Angle of attack (degrees, only for compressible flows)
   AOA= 0.0
% Free-stream temperature (288.15 K by default)
   FREESTREAM_TEMPERATURE= 301.1
% Reynolds number (non-dimensional, based on the free-stream values)
   REYNOLDS_NUMBER= 3E6
% Reynolds length (1 m by default)
   REYNOLDS_LENGTH= 1.0
```

Wind Turbine Airfoil CFD Analyses

SU2 – Configuration file

```
% ------------------- BOUNDARY CONDITION DEFINITION ----------------------%
% Navier-Stokes wall boundary marker(s) (NONE = no marker)
   MARKER_HEATFLUX= ( airfoil, 0.0, WT_walls, 0.0 )
% Farfield boundary marker(s) (NONE = no marker)
   MARKER_FAR= ( inlet, outlet )
% Marker(s) of the surface to be plotted or designed
   MARKER_PLOTTING= ( airfoil )
% Marker(s) of the surface where the functional (Cd, Cl, etc.) will be
evaluated
   MARKER_MONITORING= ( airfoil )
```

Wind Turbine Airfoil CFD Analyses

SU2 – Configuration file

```
% ------------- COMMON PARAMETERS DEFINING THE NUMERICAL METHOD -----------%
% Courant-Friedrichs-Lewy condition of the finest grid
   CFL_NUMBER= 10.0
% Number of total iterations
   ITER= 5000

% ---------------------- LINEAR SOLVER DEFINITION ----------------------%
% Linear solver or smoother for implicit formulations (BCGSTAB, FGMRES,
SMOOTHER)
   LINEAR_SOLVER= FGMRES
% Preconditioner of the Krylov linear solver (ILU, LU_SGS, LINELET, JACOBI)
   LINEAR_SOLVER_PREC= LU_SGS
% Min value of the residual (log10 of the residual)
   CONV_RESIDUAL_MINVAL= -12
```

Wind Turbine Airfoil CFD Analyses

SU2 – Configuration file

```
% ------------------------ INPUT/OUTPUT INFORMATION ----------------------%
% Output file format (PARAVIEW, TECPLOT, STL)
   TABULAR_FORMAT= TECPLOT
% Writing solution file frequency
   OUTPUT_WRT_FREQ= 1000
% Screen output fields
   SCREEN_OUTPUT= (LINSOL_ITER, LINSOL_RESIDUAL, INNER_ITER, RMS_DENSITY,
   LIFT, DRAG)
   HISTORY_OUTPUT= (ITER, WALL_TIME, RMS_RES, AERO_COEFF)
   OUTPUT_FILES= (RESTART_ASCII, TECPLOT, SURFACE_TECPLOT_ASCII)
```

Wind Turbine Airfoil CFD Analyses

Test Case - DU 00-W-212

2-D CFD Simulations

Computational Method:

- The 2-D compressible, steady-state Reynolds-Averaged Navier-Stokes (RANS) equations are solved with two turbulence models and two different transition models.
  - Euler implicit method
  - Low Mach Roe scheme with second-order spatial integration
  - Scalar upwind solver with a first-order spatial integration scheme for turbulence
  - Max 40000 iterations until convergence (with Residual value of 1e-12)
  - FGMRES method with LU-SGS preconditioning for the linear solver
- The simulations are done for Reynolds numbers of 3M, 9M, and 15M.
- Turbulence Models:
  - Spalart Allmaras (S-A)
  - $k-\omega$ SST (SST)
- Transition Models:
  - Langtry-Menter (LM) – two-equation transition model (Menter, F. R., Langtry, R., and Volker, S., 2006)
  - Baş-Çakmakçıoğlu Model (BÇM) – one-equation transition model (Cakmakcioglu, S. C., Bas, O., and Kaynak, U., 2018)

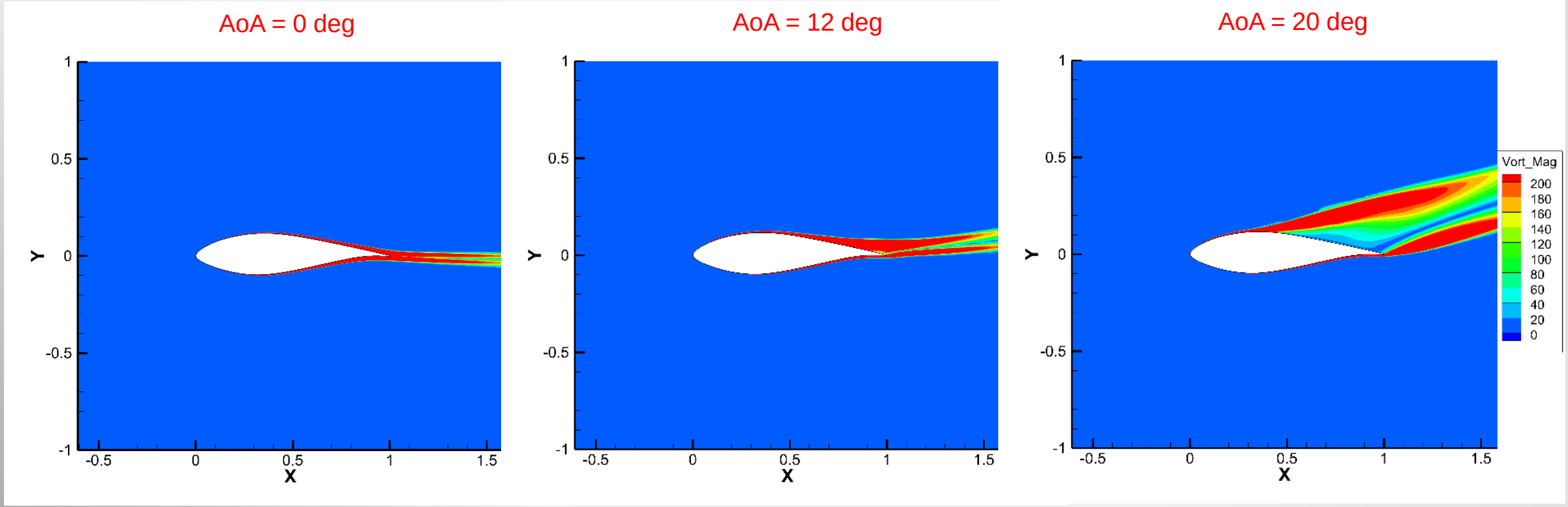
*Menter, F.R. et al. Transition Modelling for General Purpose CFD Codes. Flow Turbulence Combust **77**, 277–303.*
*Cakmakcioglu, S. C et al. (2018) "**A correlation-based algebraic transition model.**" Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*

Wind Turbine Airfoil CFD Analyses

Sample Test Case – DU 00-W-212

2-D CFD Results: Grid 3 - Re= 3M

Vorticity Magnitude



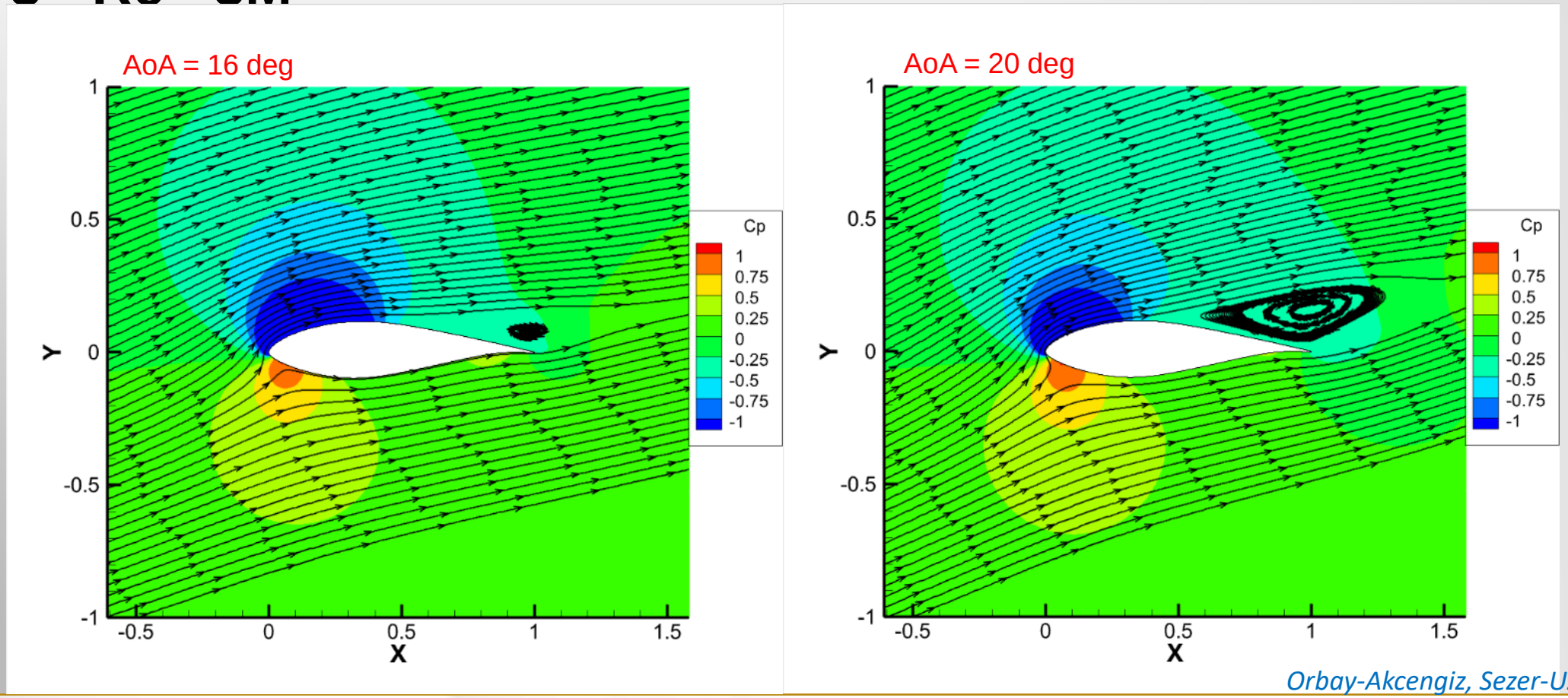
Orbay-Akcengiz, Sezer-Uzol, WESC 2021

Wind Turbine Airfoil CFD Analyses

Sample Test Case – DU 00-W-212

2-D CFD Results: Grid 3 - Re= 3M

Pressure Coefficient & Streamlines



Orbay-Akcengiz, Sezer-Uzol, WESC 2021

Wind Turbine Airfoil CFD Analyses

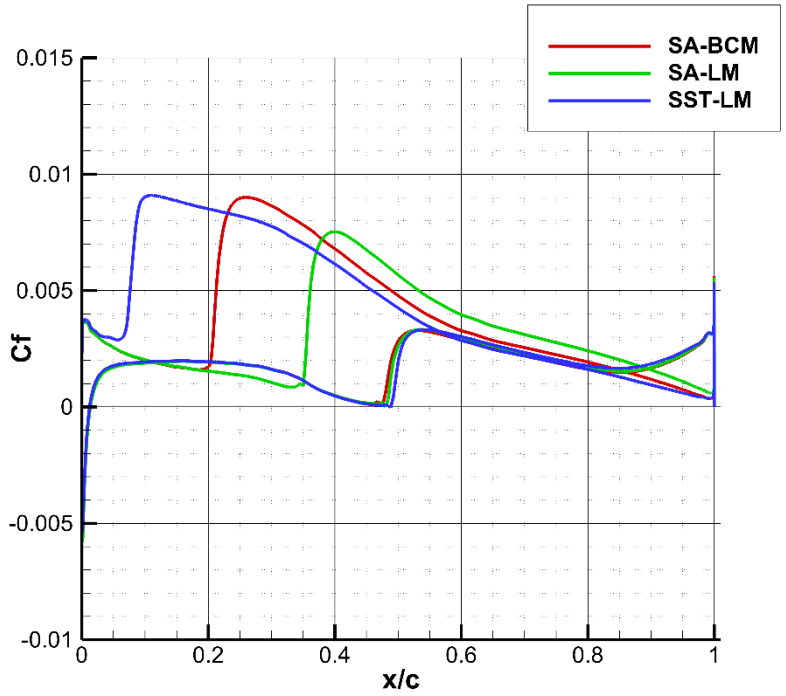
Sample Test Case – DU 00-W-212

2-D CFD Results:

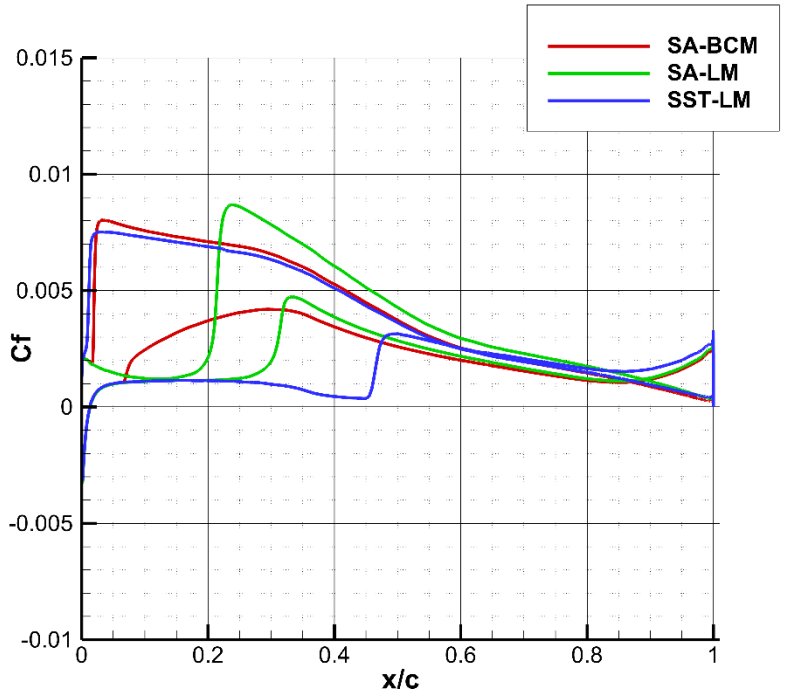
AOA = 6 deg

Skin Friction Coefficient

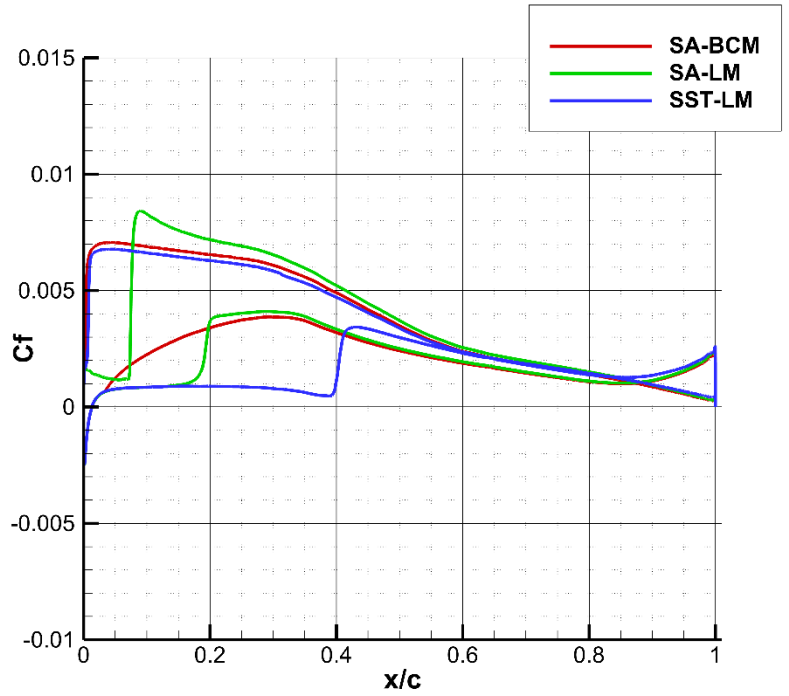
Re = 3 M



Re = 9 M



Re = 15 M



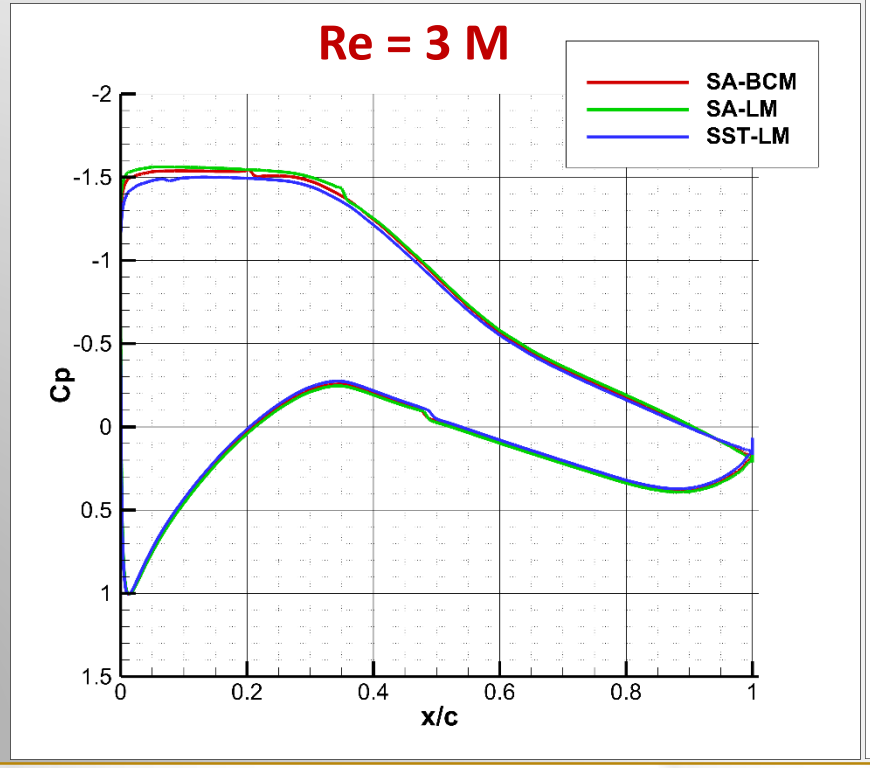
Orbay-Akcengiz, Adam, Sezer-Uzol, WESC 2023

Wind Turbine Airfoil CFD Analyses

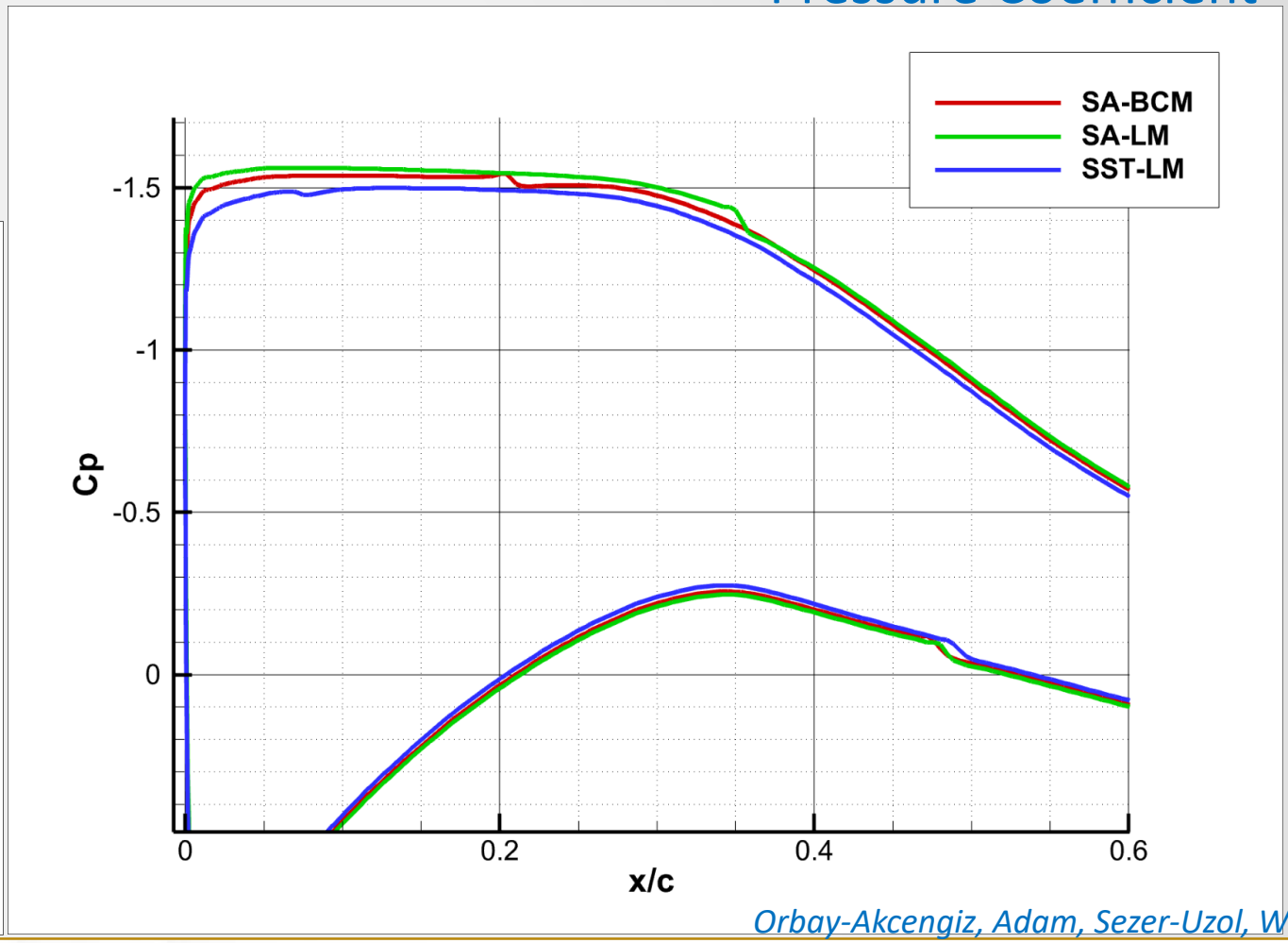
Sample Test Case – DU 00-W-212

2-D CFD Results:

AOA = 6 deg



Pressure Coefficient



Orbay-Akcengiz, Adam, Sezer-Uzol, WESC 2023

Wind Turbine Airfoil CFD Analyses

Sample Test Case – DU 00-W-212

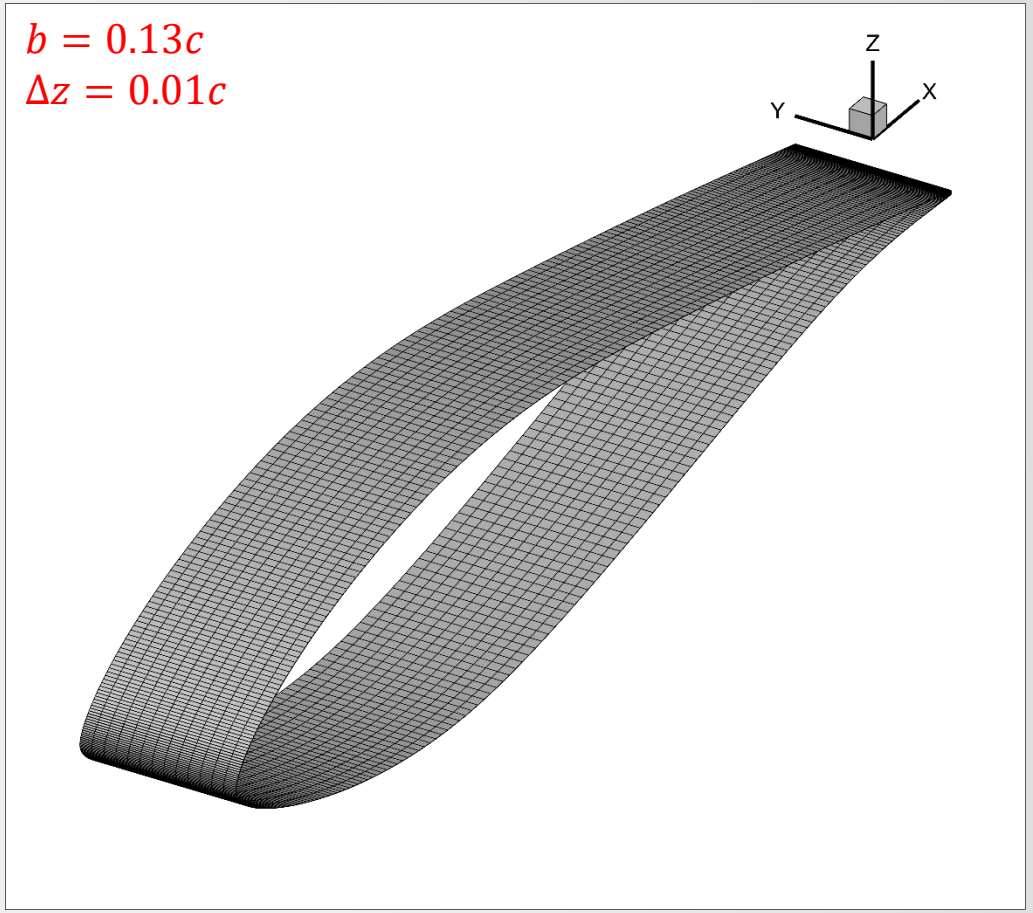
3-D CFD simulations

Computational Grid:

- 2-D computational grid (coarse 2 – grid_c2) is extended in spanwise direction.
- Selection of span length: $b = 1c, 0.5c, 0.25c, 0.13c$
- Grid cell size in spanwise direction: $\Delta z = 0.01c$

Computational Method:

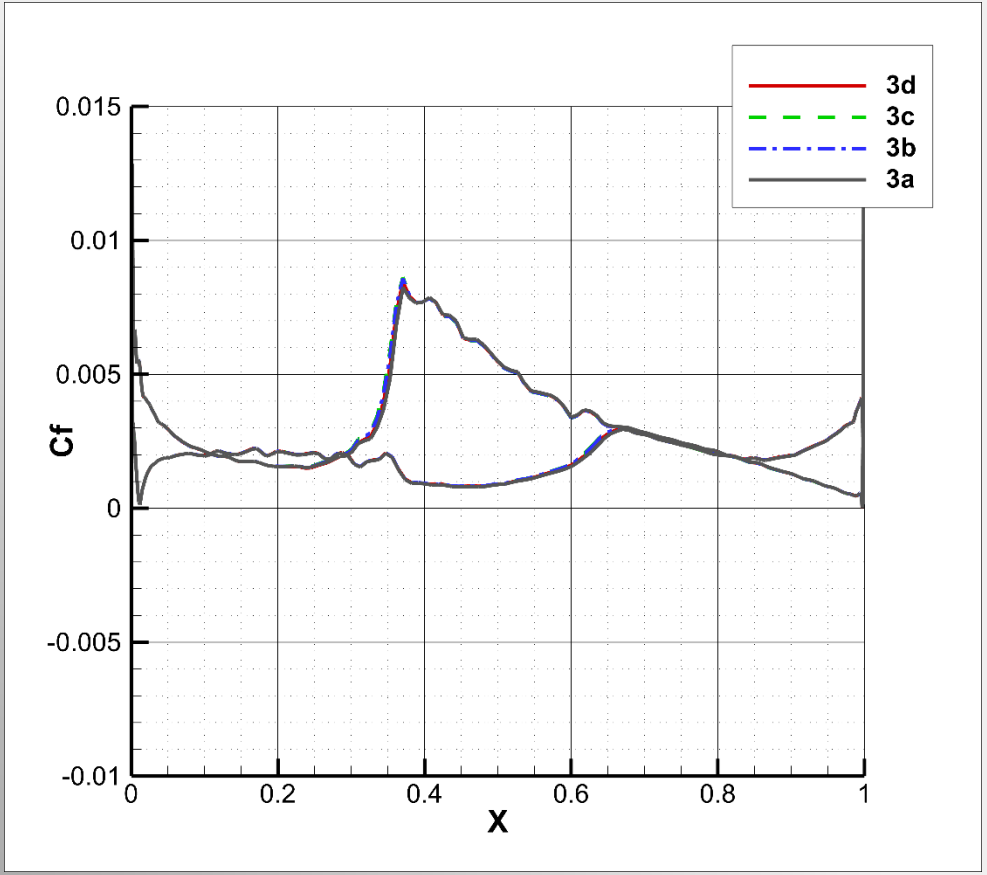
- Steady-state RANS equations are solved with S-A turbulence model and LM transition model for the span length study.
- The selected grid is then utilized to solve the flowfield around airfoil by using hybrid RANS/LES turbulence model, SA-EDDES (Shur, 2015)
  - Dual-time stepping method with 5 sub-iterations
- Flow conditions: Re=3e6 and M=0.141



Wind Turbine Airfoil CFD Analyses

Sample Test Case – DU 00-W-212

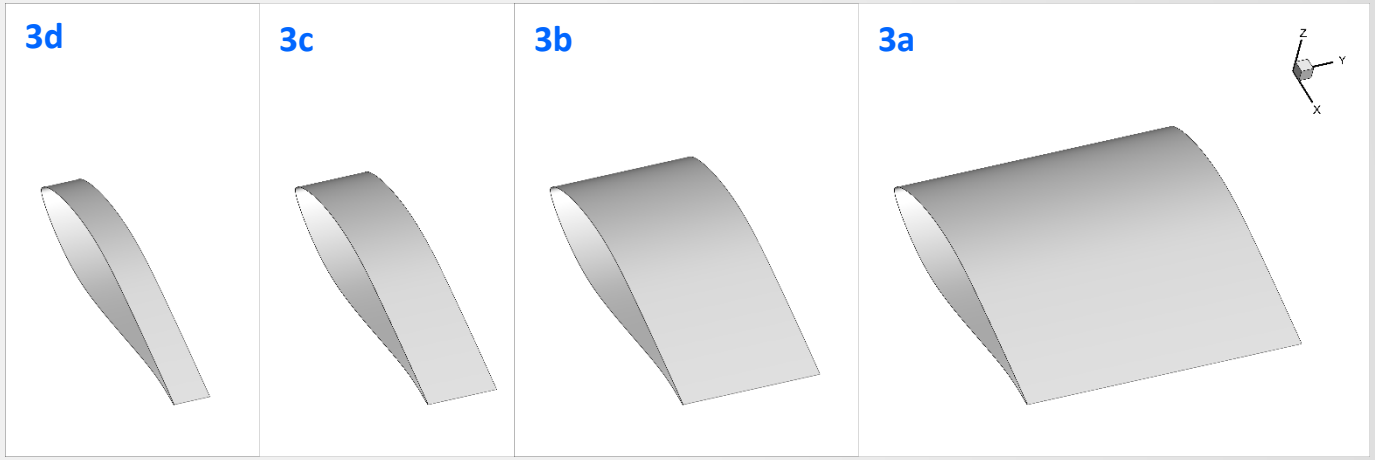
3-D CFD simulations



Re=3e6 and Aoa = 6 deg
RANS, SA-LM
Number of iterations = 20000
Order of residual drop = 3

Grid	3d	3c	3b	3a
Span length (c)	0.13	0.25	0.50	1.00
Wall-Clock time (h)	4.54	9.16	14.18	25.78

	3d	3c	3b	3a	WT (METU)
Cd	0.00895	0.00890	0.00892	0.00885	0.0095
Cl	1.0044	1.0040	1.0044	1.0049	1.0505



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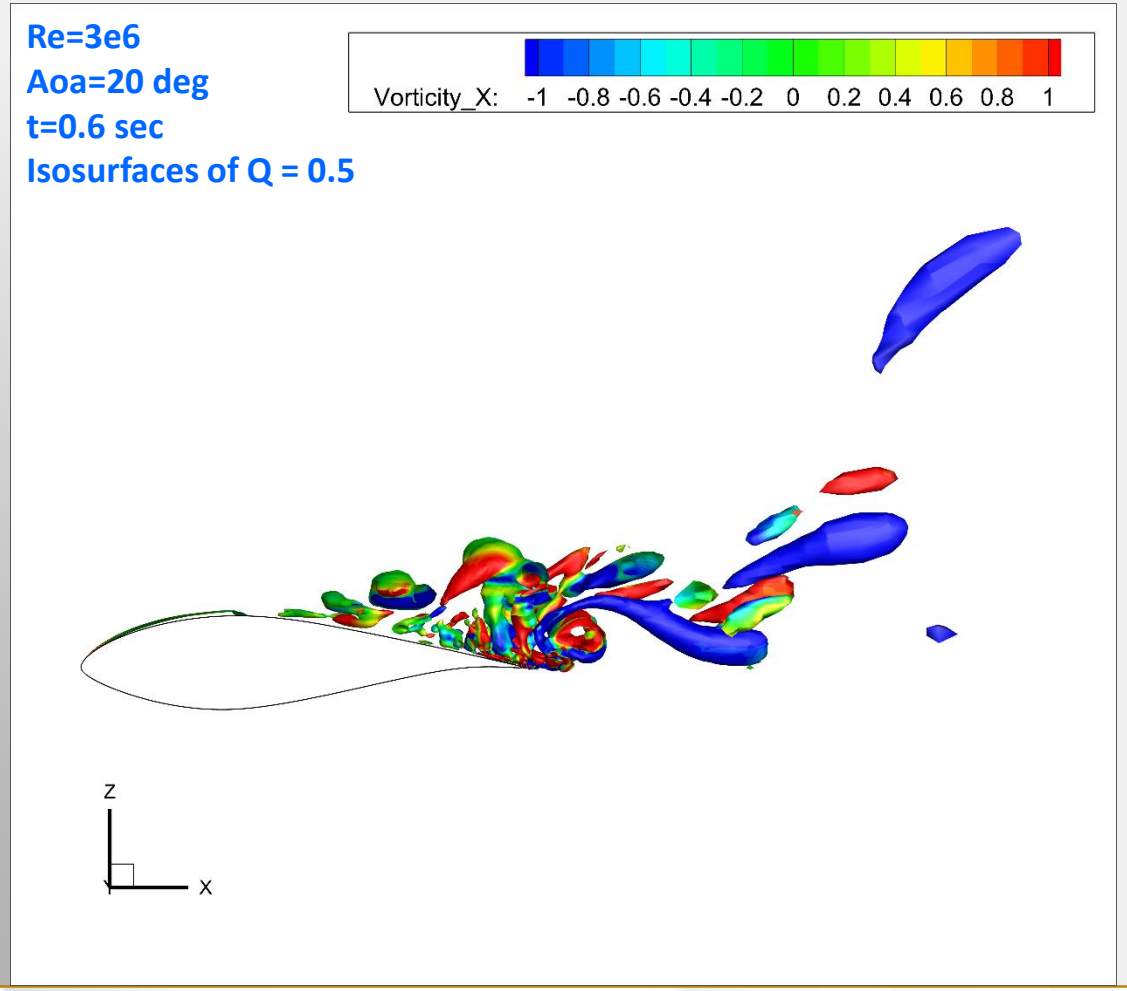
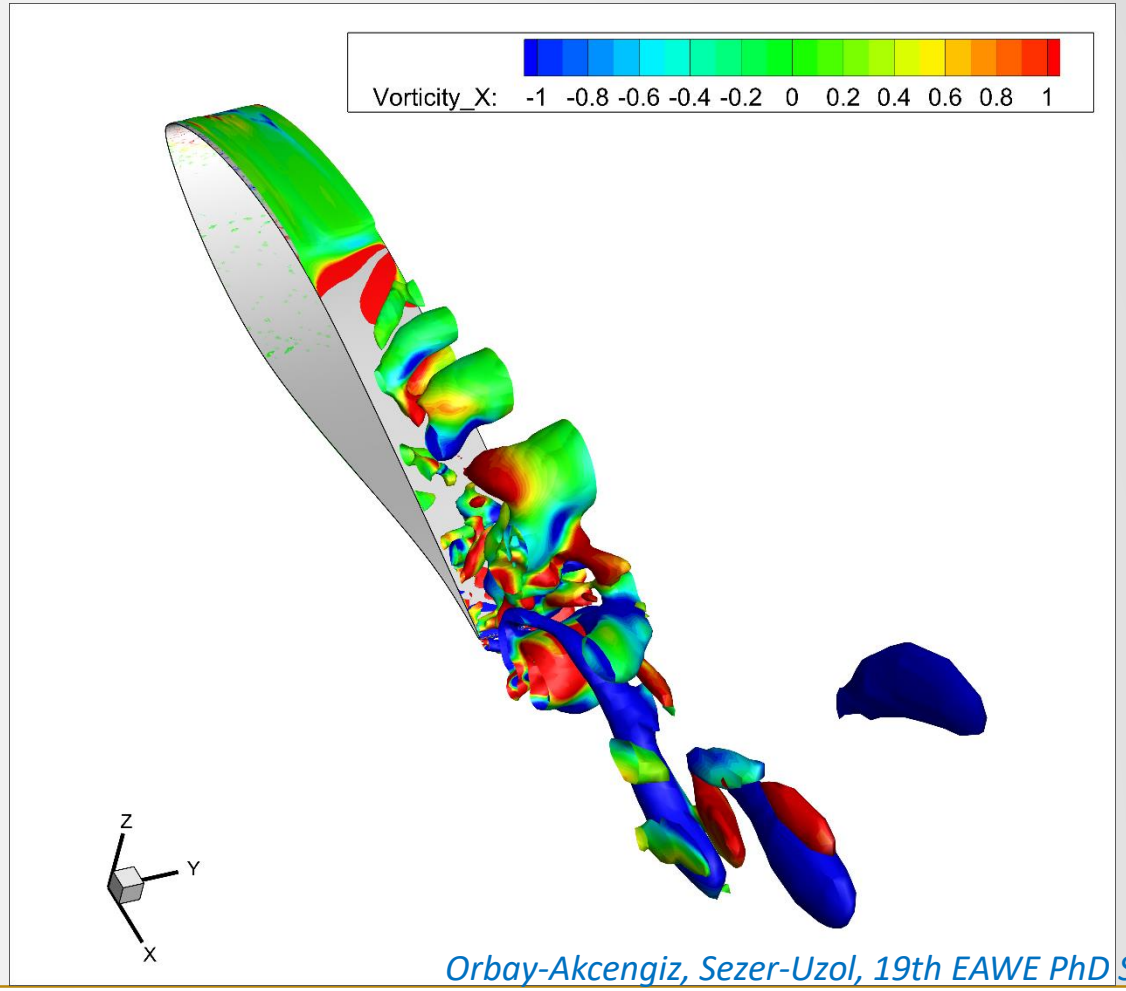
Wind Turbine Airfoil CFD Analyses

Sample Test Case – DU 00-W-212

3-D CFD Results: SA-EDDES with LM transition model

Re=3e6
Aoa=20 deg
t=0.6 sec
Isosurfaces of Q = 0.5





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Wind Turbine Airfoil CFD Analyses

Conclusion

- In this presentation, wind turbine airfoil CFD analyses are explained briefly.
- The grid generation and the solution methodology are discussed.
- Grid independence study procedure is shown.
- The steps of howto generate a simple O-grid around NACA0012 airfoil by using gmsh is mentioned.
- The steps of how to run a simple simulation using SU2 are presented.
- Also, the results for a sample test case for a wind turbine airfoil are presented.

METU RÜZGEM	https://ruzgem.metu.edu.tr
HPC@ODTÜ	https://www.hpc.info.tr
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