LABORATORY

Development of a CFD Method for Aerodynamic Analysis of Large Diameter Horizontal Axis wind turbines

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CFD Solver - Overview

Summary of Features - 1

- PDE solver
- Multi-block capability
- Parallerised using the SPMD paradigm
- Flow Physics: Inviscid, RANS, URANS, DES, LES
- Aeroelastic analysis based on modal representation of structures
- Moving and deforming grids
- Modular code with a uniform data structure based on the linked-list concept

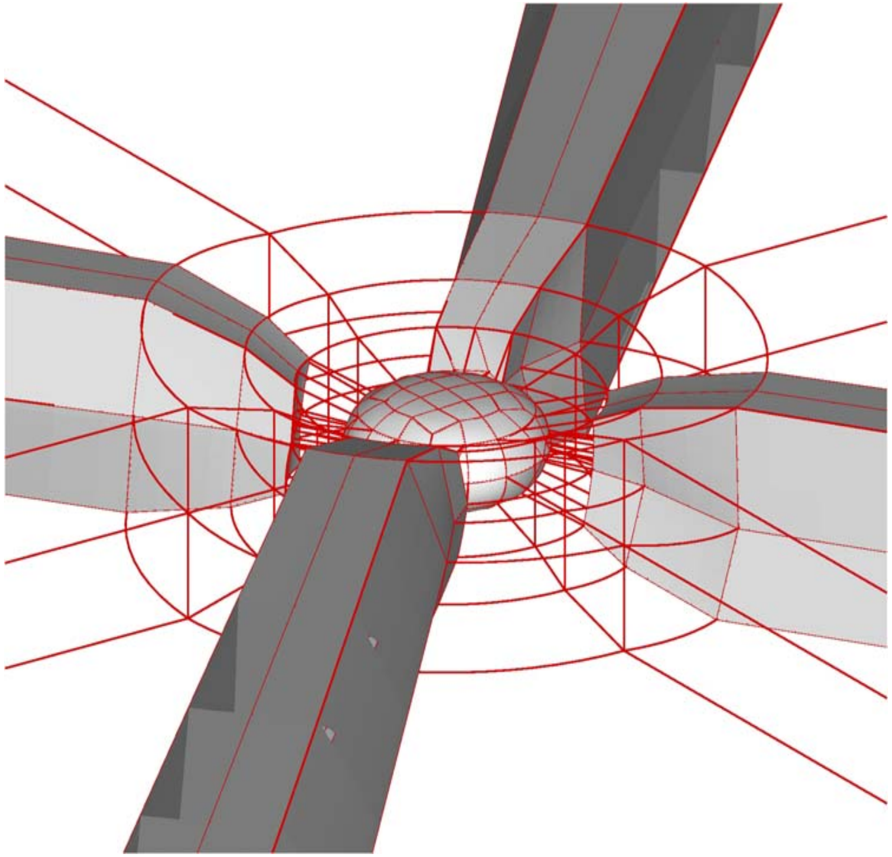
Summary of Features - 2

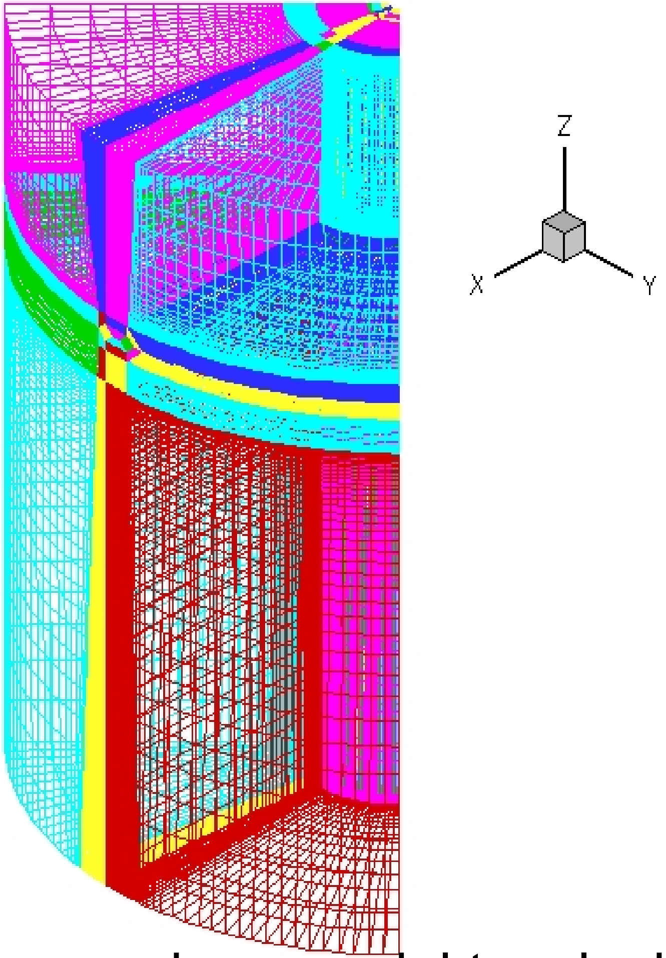
- Control volume method
- Parallel - Shared and Distributed memory
- Multi-block (complex geometry) structured grids
- Unsteady RANS - Variety of turbulence models inc. LES/DES
- Implicit time marching
- Osher's and Roe's schemes for convective fluxes
- MUSCL scheme for formally 3^{rd} order accuracy
- Central differences for viscous fluxes
- Krylov subspace linear solver with pre-conditioning
- Moving grids, sliding planes
- Aeroelastic analysis based on modal representation of structures
- Hover formulation, rotor trimming, blade actuation
- Modular code with a uniform data structure based on the linked-list concept
- Documentation
- Validation database
- Range of utilities for processing data, structural models etc.
- Used by academics and engineers

Requirements

- Minimal requirements
- ANSI C compiler
- MPI libraries for parallel computing
- Grid generation (ICEM CFD at present)
- Post-processing (Tecplot, Fieldview, Vigie, Paraview)
- Any Unix flavour will do
- Optimum (low cost) performance on Beowulf clusters
- Ported to national computing centres, CSAR, HPCx, IAG

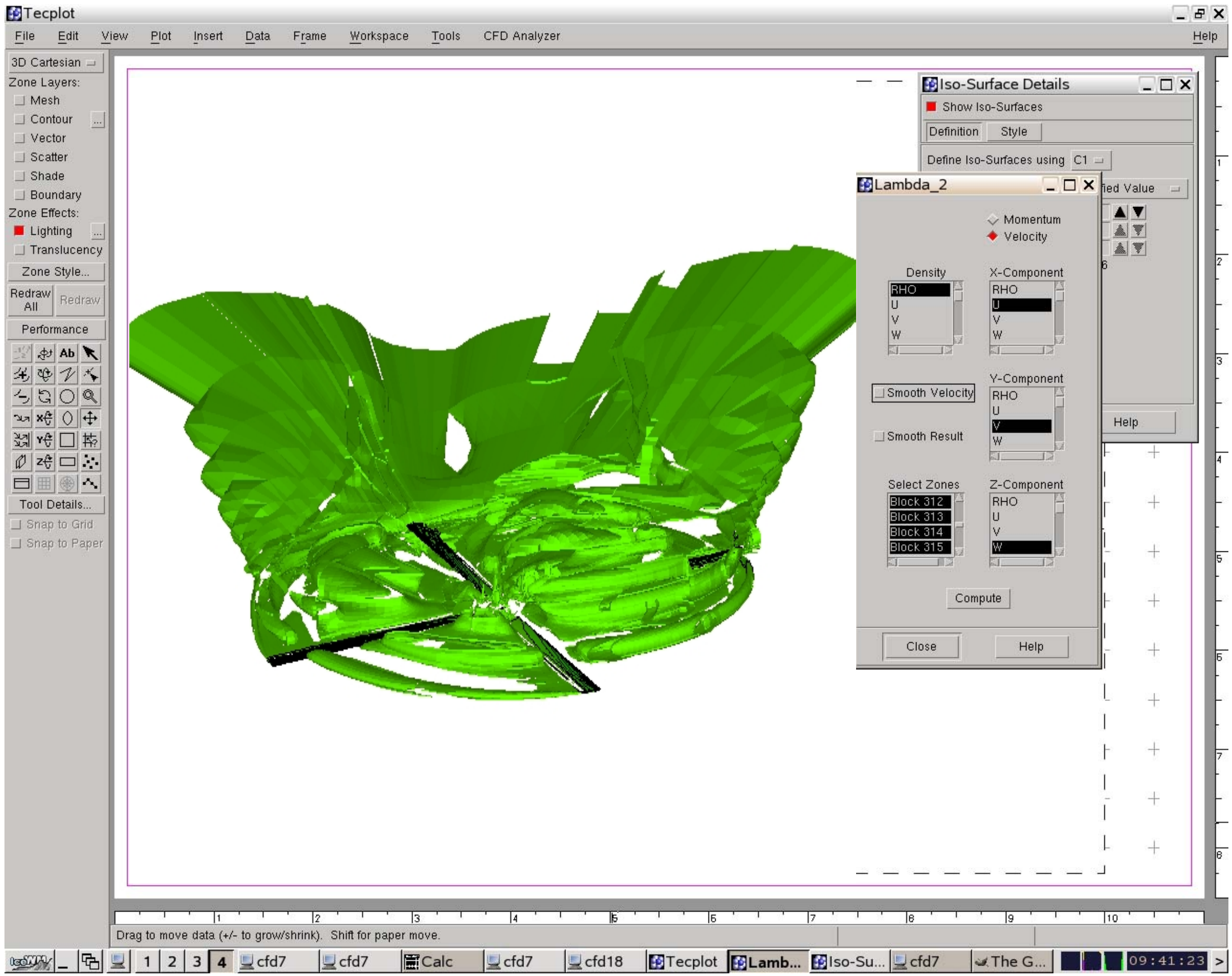
Multi-block topologies for rotor cases - ICEMCFD



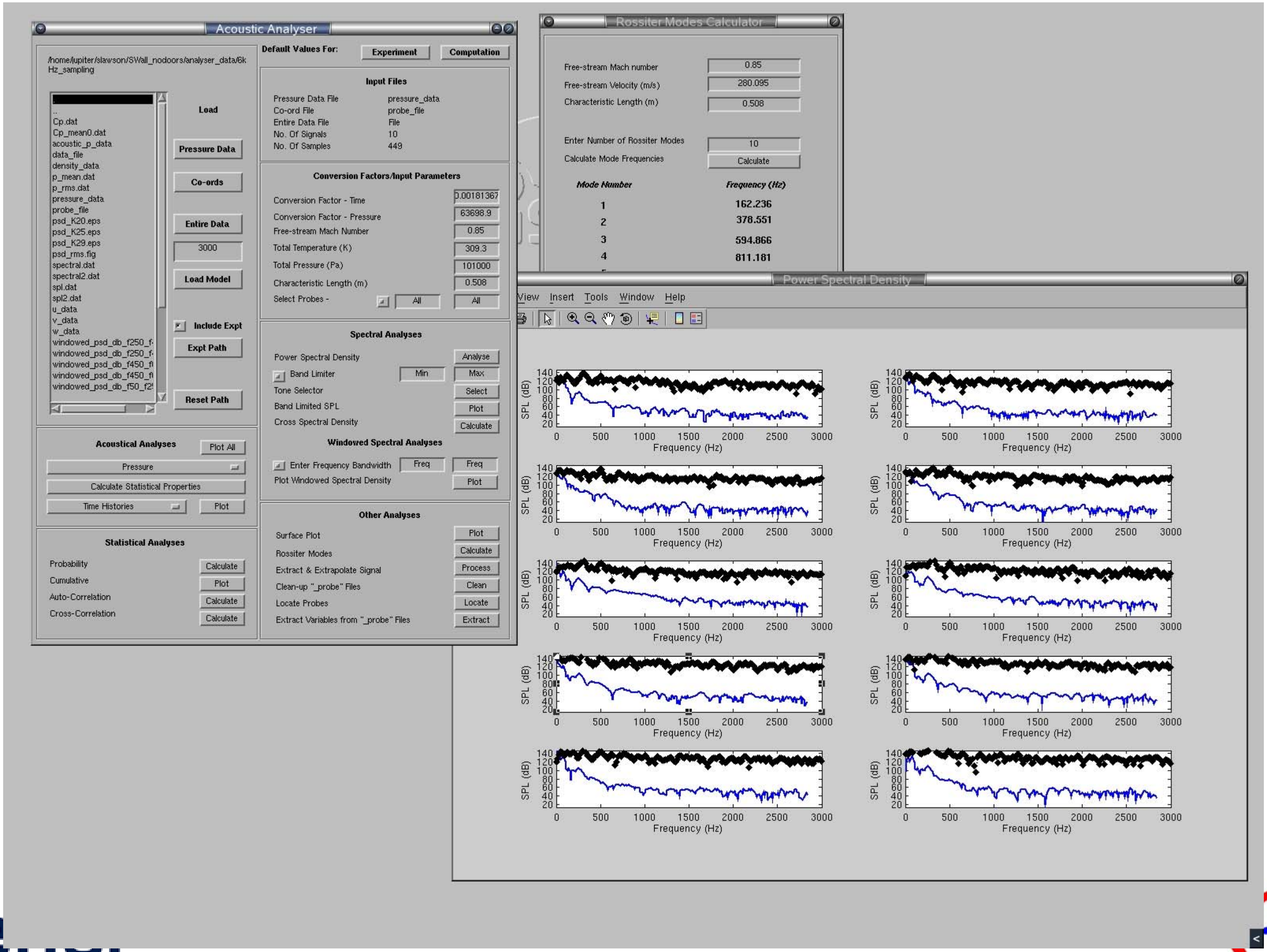


2-4.5M grid points per blade, blade actuation requires special topologies

Add-ons for TECPLOT



Probe Analyser - MATLAB



Validation Database

- Distributed with the solver
- Contains public and restricted cases (sponsor-specific)
- Public cases are accessible via www
- Each case is selected to demonstrate and check a particular feature
- Experimental data are available for all cases
- Sample results are included

Partial List of Validation Cases

RAE2822 Case 9	Attached Flow
ONERA A Aerofoil	Separation under apg
Williams aerofoil	Multi-element sections
NACA0012 & AGARD CT2	Pitching aerofoils, inviscid flow
Bachalo-Johnson Bump	SBL interaction
Delery's Bump C	SBL interaction internal flow
2D cavity flow	Unsteady turbulent flow
Convected vortex	Vorticity confinement
AGARD 445.6 wing	Inviscid aeroelastic
ONERA M6 wing	Viscous turbulent flow over a wing
NACA wing - UNSI	3D dynamic stall
AGARD S-duct	Turbulent separated internal flow
65 and 70-degree delta wing	Vortical turbulent flow
ONERA Rotor 7A/7AD	Helicopter rotor flow
Glasgow BERP tip	Tip flow
NACA0015 oscillating wing	DS - tip flow
LABM low-Re DS cases	Transitional flow - dynamic stall

RAE 2822 Aerofoil

ICEMCFD grid files	Yes
PMB mesh file	Yes
Parameters files	Yes
Previous computational solutions	Yes
Tecplot layout and macros	Yes
Raw computational and experimental data	Yes
Bundled test case (all files)	Yes

Table 20: File downloads for the ONERA-A aerofoil 2D Wing test case

RAE 2822 airfoil as reported in reference [4] and corresponds to test case 6. The section can be seen if figure 14. The freestream flow conditions for this case can be seen in table 21

Initial Conditions	
Freestream Mach number	0.729
Reynolds Number	6.5e+6
Incidence	2.31°
Run information	
Grid Size	4,323 (quasi-2D mesh) actual mesh size is 8,646 and one cell deep
Modelling	Euler, Standard $SA(2000)$, Standard $k-\omega(3000)$, and standard $SST(3007)$

Table 21: Summary of RAE Aerofoil 2822 test case conditions

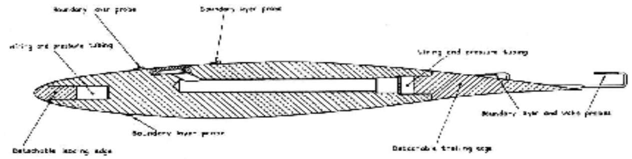


Figure 14: RAE 2822 experimental wing section

Results

Figure 15 shows a comparison of Cp measurements from the RAE aerofoil. It cam be seem that all the results compare well with the experimental data. Closer examination shows that Euler results capture the shock on the upper surface well although there is a peak in the Cp value

at the trailing edge (similar to the ONERA M6 results in figure 7 - remember that negative Cp values are plotted here!). On the whole the $k-\omega$ solution compares most favourably with experiment. The SA model does not capture the shock on the upper surface as well. NOTE: The 2D boundary condition is not very reliable. The flow variables across the 'z' direction differ greatly in some circumstances. It is therefore important to know where to extract 2D data from in terms of a slicing plane along the z plane. This was highlighted previously for the ONERA-A aerofoil and should be investigated for 2D cases.

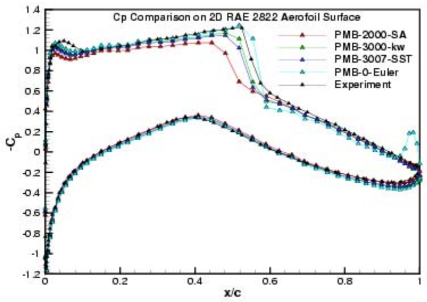


Figure 15: Cp comparison for the RAE 2822 2D wing

Downloads

Table 22 lists the files available for download for the RAE 2D aerofoil test case. Individual files are available for speedy downloads or a bundled option is included containing all the files.

4.3 Williams Aerofoil

Background

The Williams multi-element aerofoil has been looked at for Euler flow. The freestream flow conditions for this case can be seen in table 23.

Documentation

- Organised as a set of Technical Notes
- Important part of the CFD solver
- At present there are 14 technical notes covering various features of the code
- Information is included in the source code in the form of comments
- Under continuous development!

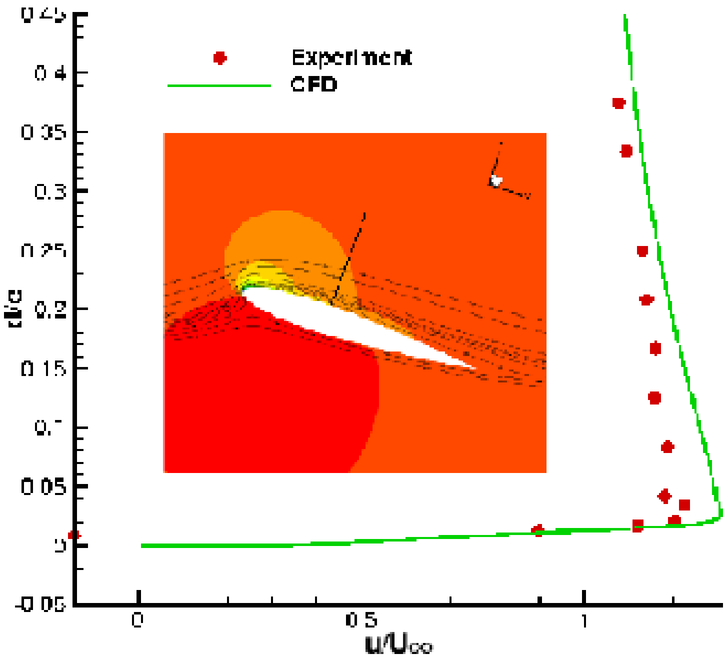
3D DS validation - LABM (i)

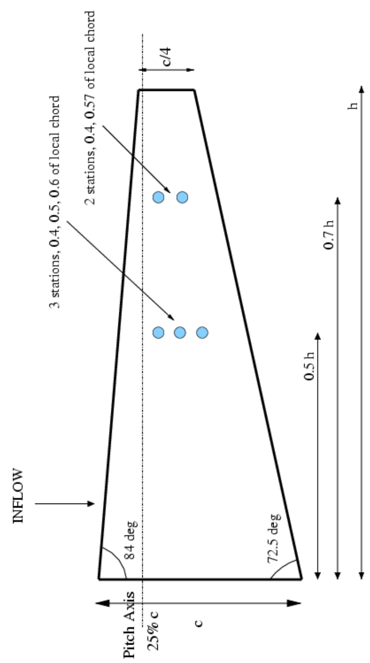
Pitching motion, k = 0.048

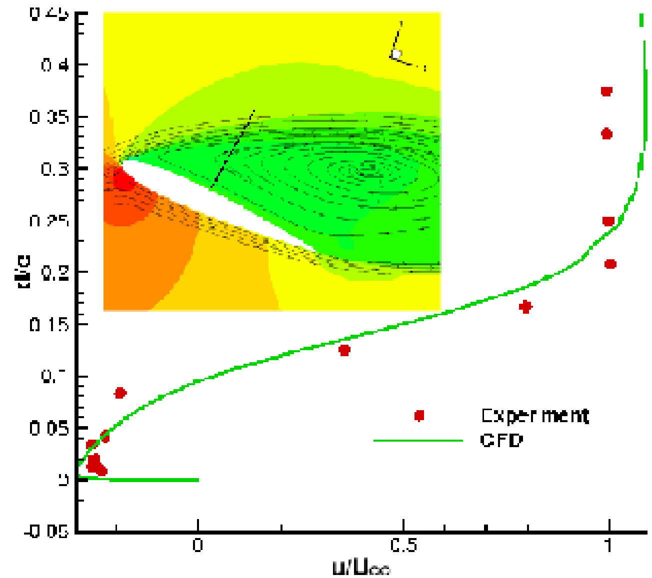
AoA=18 + 6 sin(wt)

x/c = 0.4

z/c =0.5





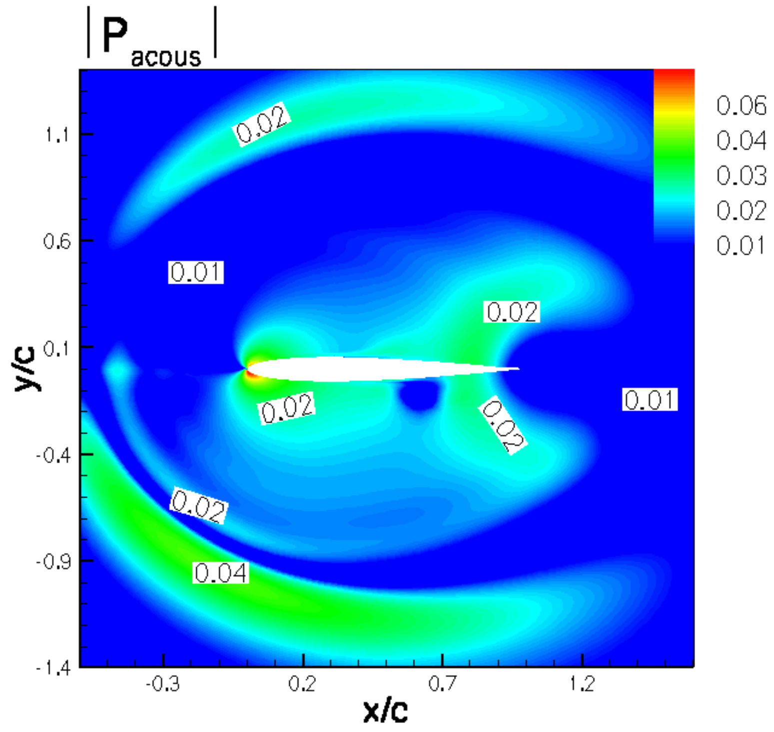


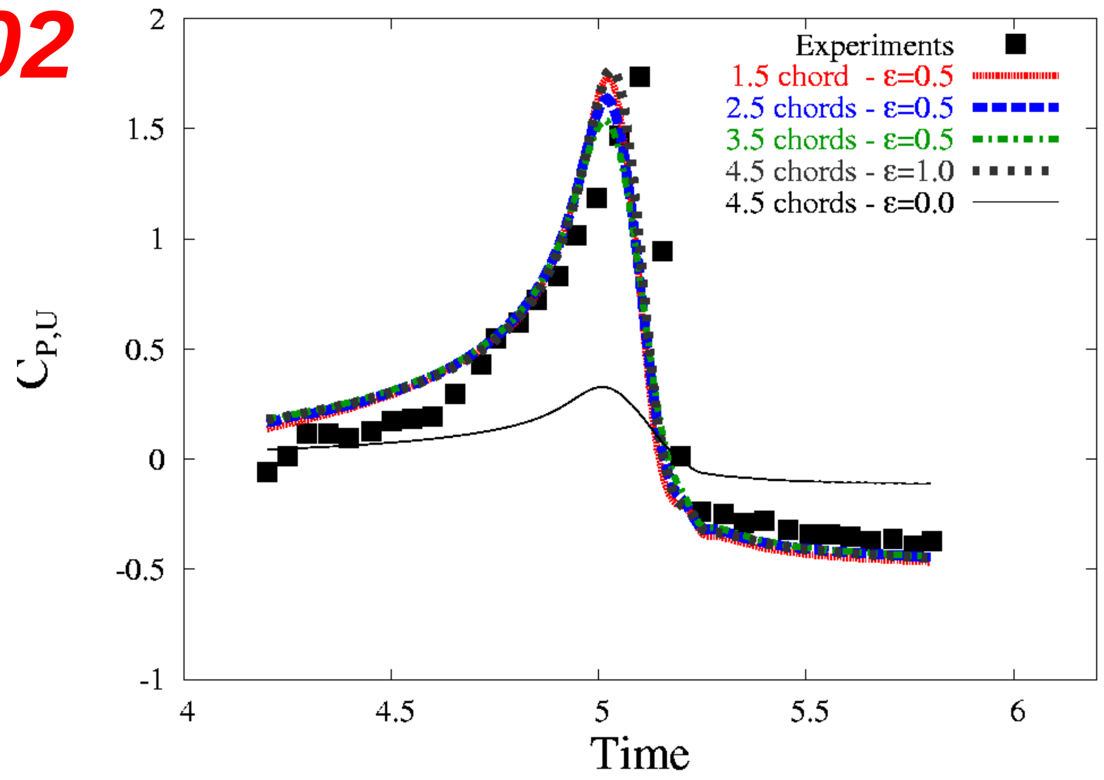
AoA = 18 deg upstroke

AoA = 24 deg

Blade-Vortex Interaction

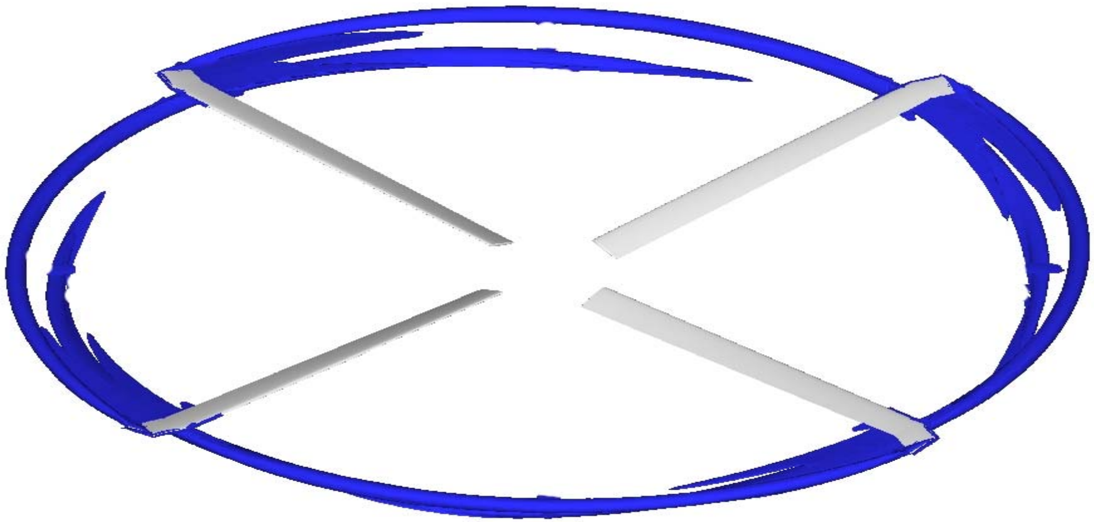
x/c=0.02

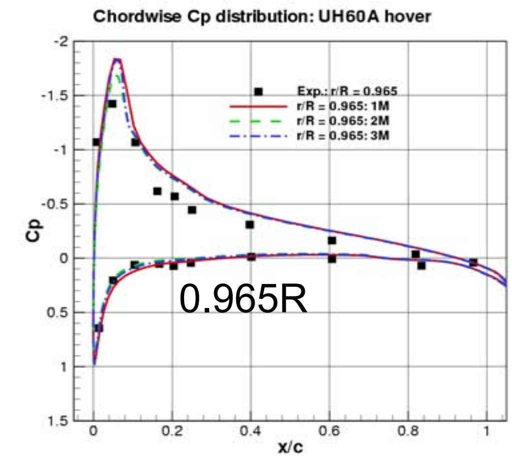


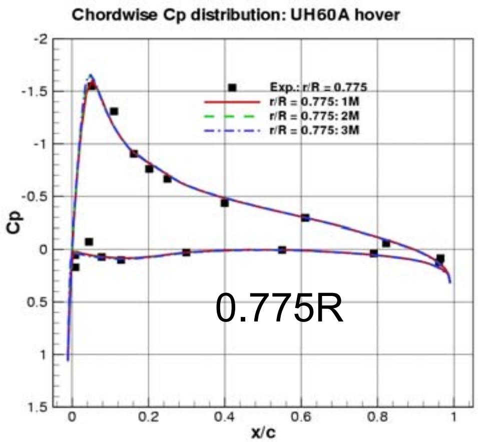


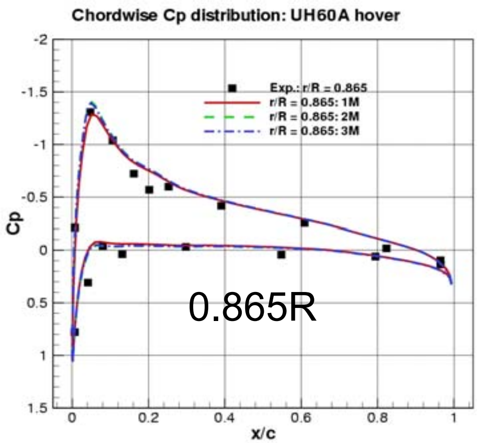
CFD – Validation - UH-60A Model Main Rotor Tests - Lorber

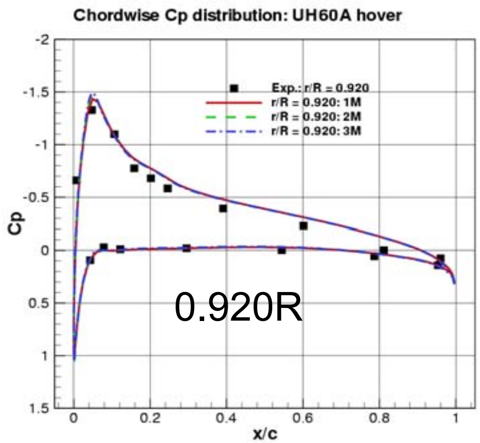
UH60A - Hover M_T = 0.626, 10.5° collective, 2.31° coning

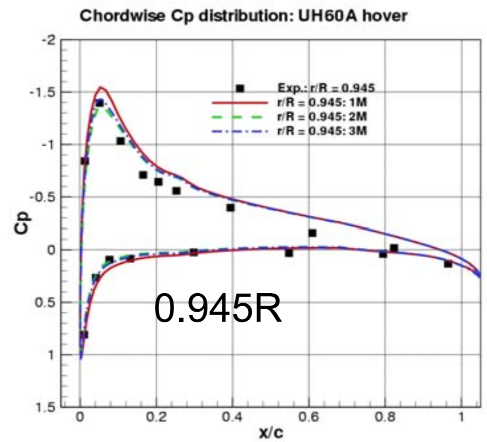










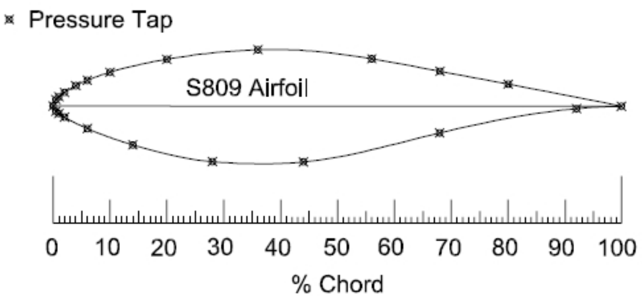


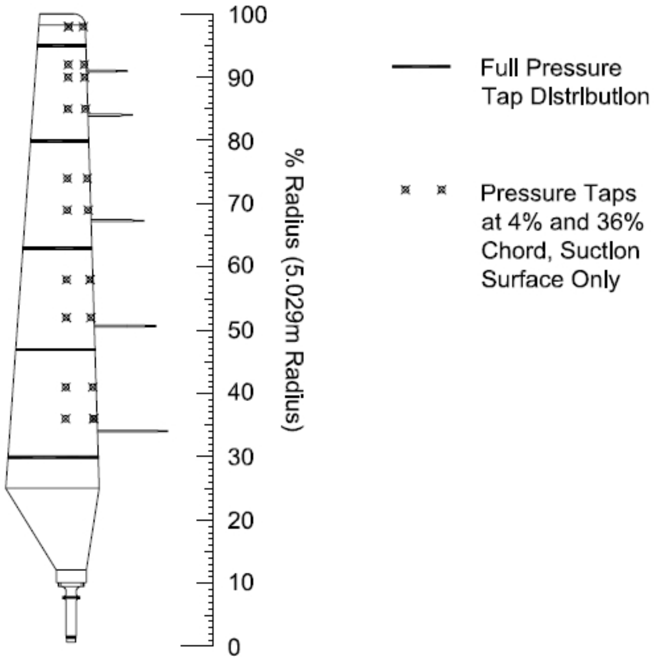
Sponsors of our work

HAWT - Multi-Block Topologies

Annex XX Data

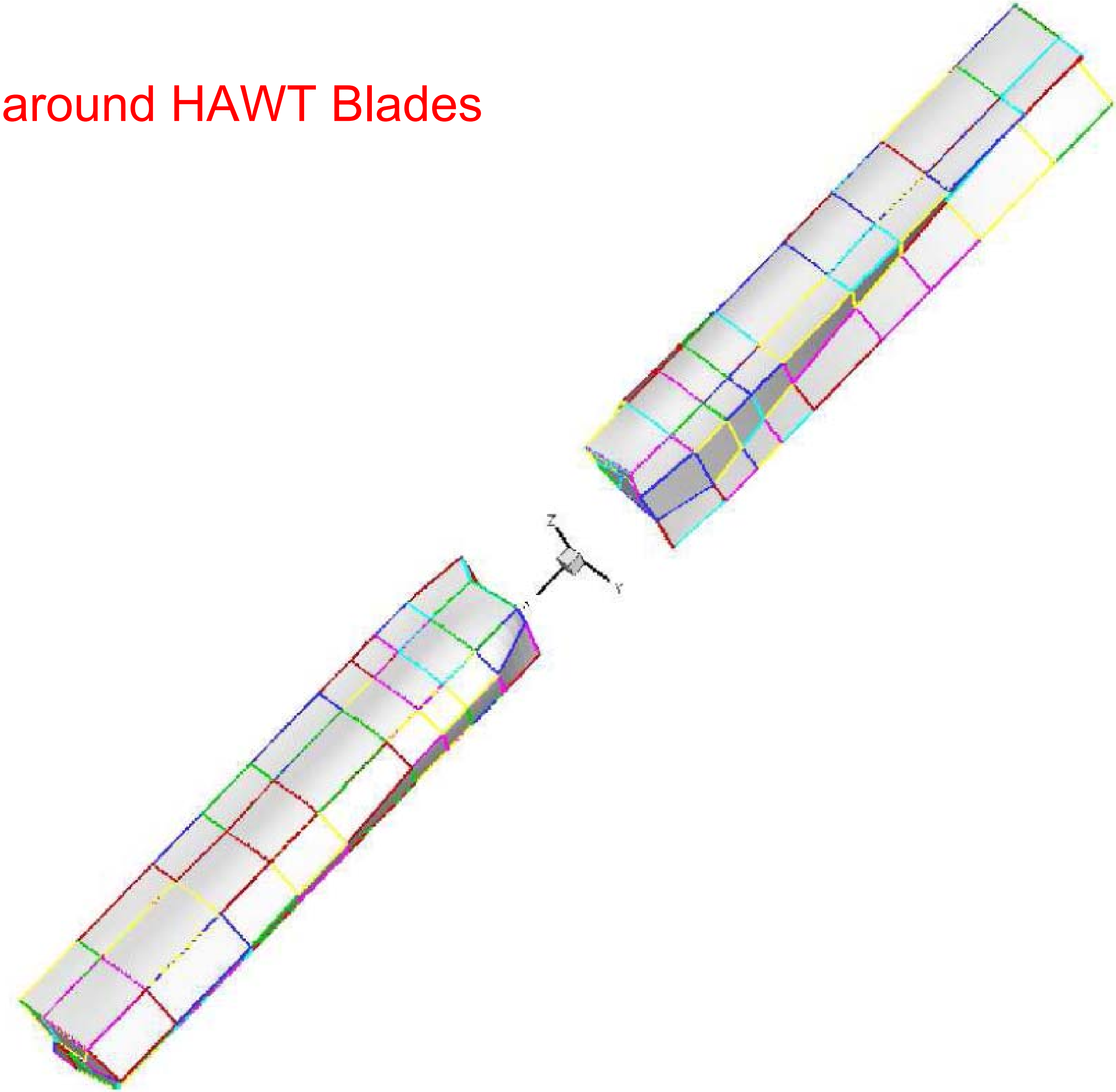
- **NASA Ames wind tunnel 24.4 m x 36.6 m test section**
- **Two bladed upwind wind turbine, with S809 aerofoil after the 25% of the span**
- **Test instrumentation (Input)**
  - **22 Pressure taps each at 5 spanwise possitions**
  - **Accelerometers in both blades (edge & flap) and in the nacelle (yaw, fore-aft & pitch)**
  - **Strain gauges in both blades (root. edge & flap)**
  - **Wind tunnel's dynamic, static and total pressures density, temperature, velocity,...**





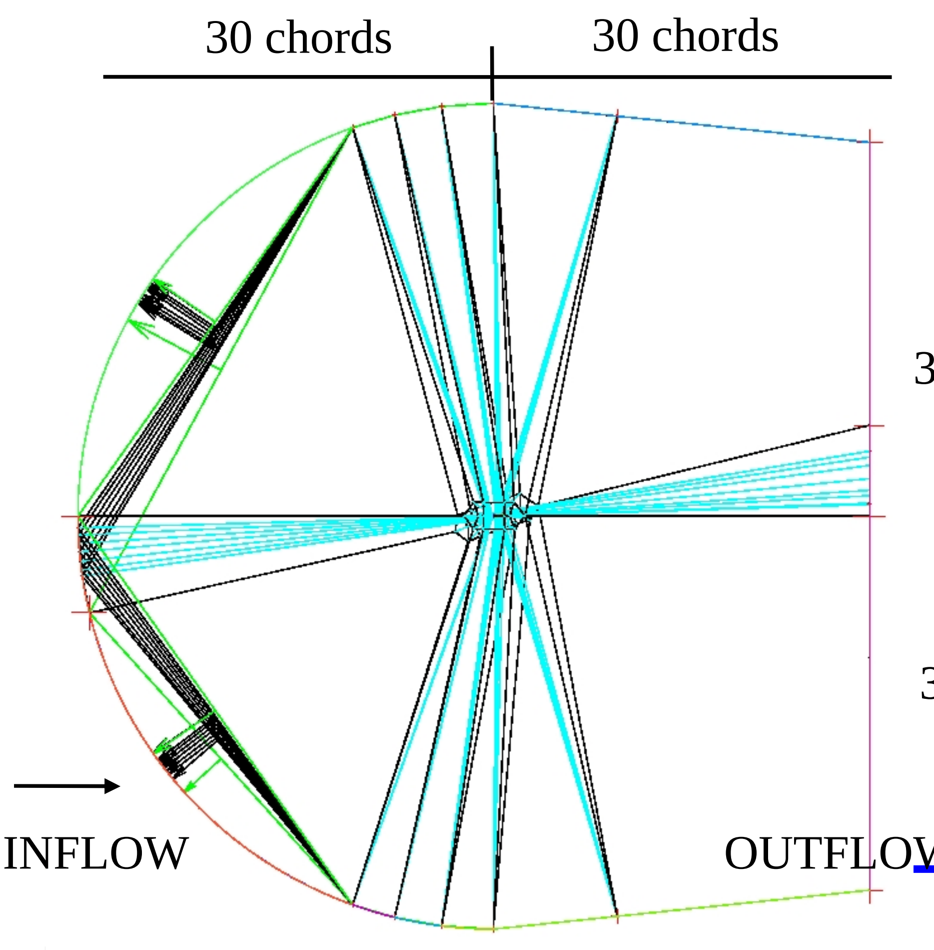
- **Data files (Output)**
  - **Raw data & Averaged data (Azimuth & Cycle)**
  - **Azimuthal and raw average data were used**

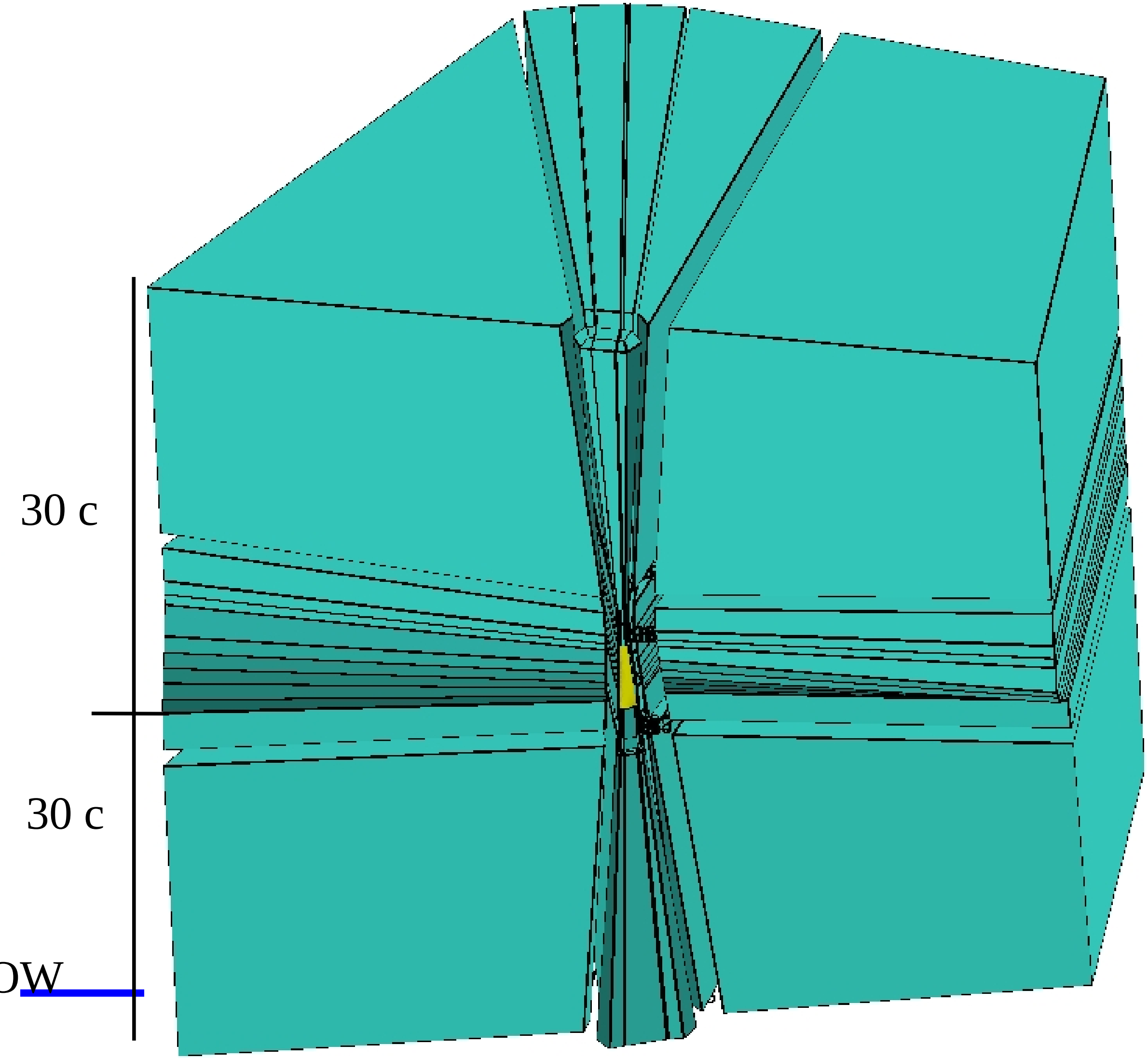
Rigid Blocks around HAWT Blades



Case L (Parked and Pitching cases)

176 blocks
2.4 million cells
Blade boundary 10^{-5}

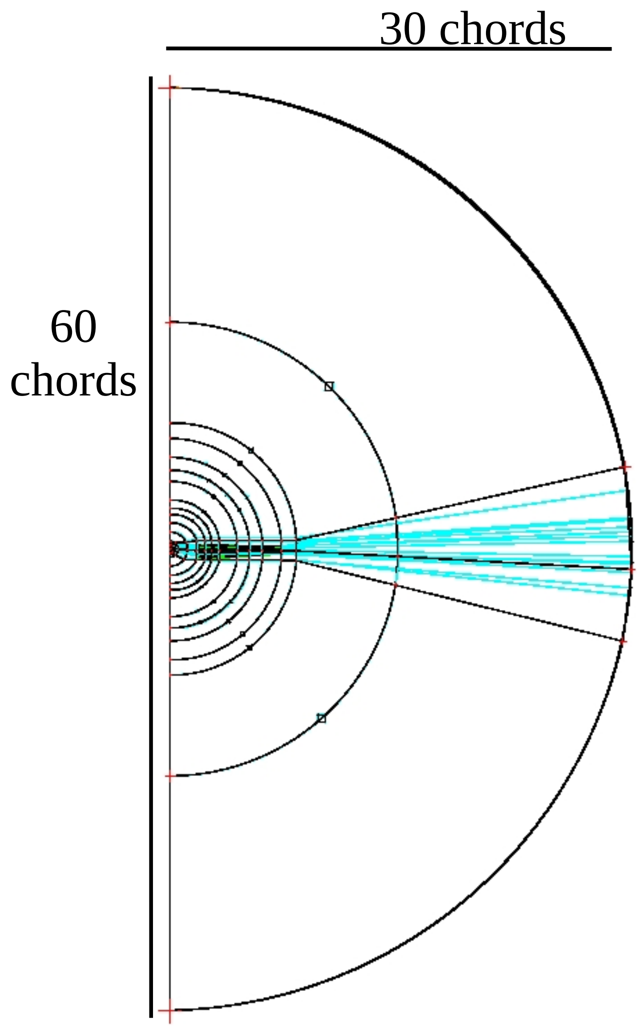


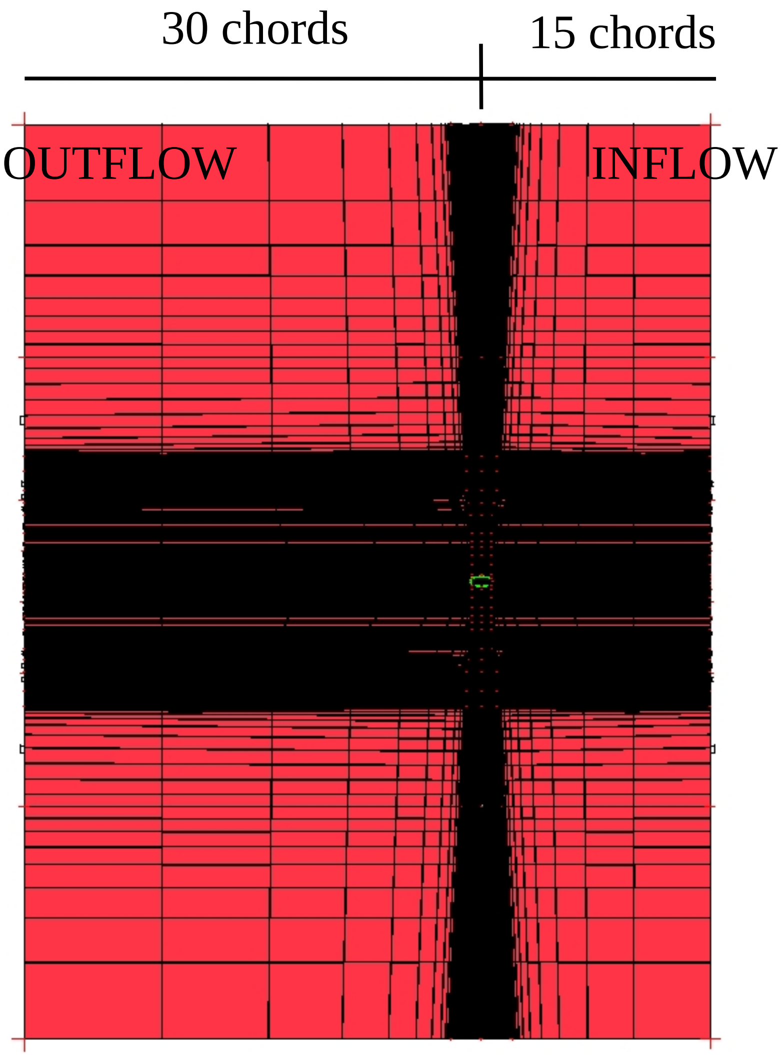


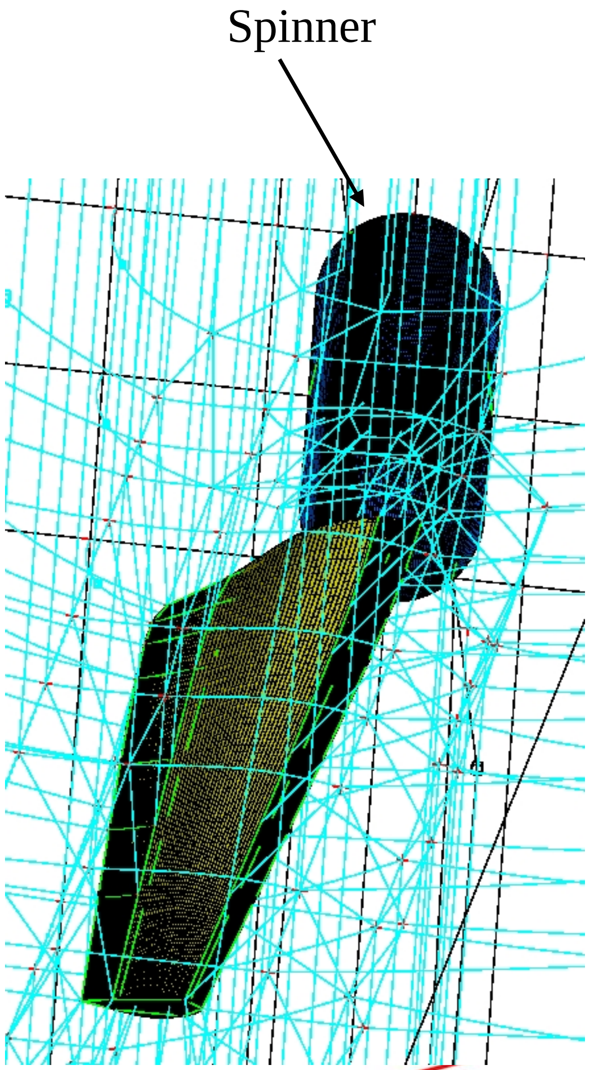
1 Radius = 6.8 chords

524 blocks
4.55 million cells
Blade boundary 10^{-5}

Clean Configuration

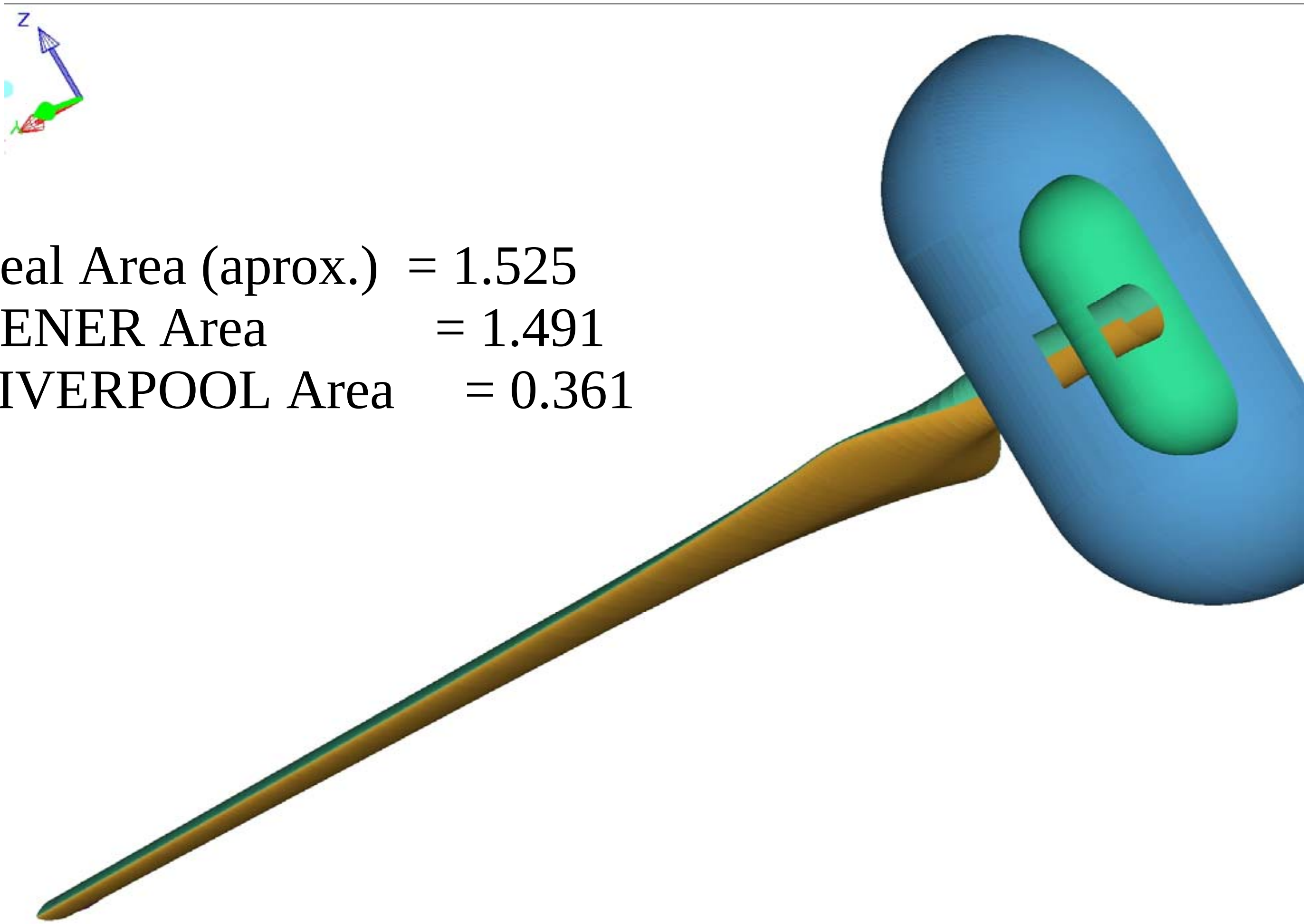






1 Radius = 6.8 chords

Investigation of the Blade Shape



Real Area (aprox.) = 1.525
CENER Area = 1.491
LIVERPOOL Area = 0.361

`

First Results

Steady and Unsteady States

Unsteady Navier-Stokes Equations:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \left(\rho u_i\right)}{\partial x_i} = 0$$

Momentum Conservation

$$\frac{\partial \left(\rho u_i\right)}{\partial t} + \frac{\partial \left(\rho u_i u_j\right)}{\partial x_j} = \rho f_i - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Energy equation

$$\frac{\partial \rho E}{\partial t} + \frac{\partial}{\partial x_j}\left[u_i\left(\rho E + p\right)\right] - \frac{\partial}{\partial x_j}\left(u_i \tau_{ij} - q_j\right) = 0$$

$$E = \rho\left[e + \frac{1}{2}u_i u_i\right] \quad \tau_{ij} = \mu\left[\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right]$$

Steady and Unsteady States

Steady Navier-Stokes Equations:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0$$

Non-Inertial frame of reference

Momentum Conservation

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \rho f_i - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} - \rho \vec{\omega} \times \vec{u}_i$$

Energy equation

$$\frac{\partial \rho E}{\partial t} + \frac{\partial}{\partial x_j} [u_i (\rho E + p)] - \frac{\partial}{\partial x_j} (u_i \tau_{ij} - q_j) = 0$$

No temporal variation, so their derivate respect the time is equal to zero

Turbulence Modelling

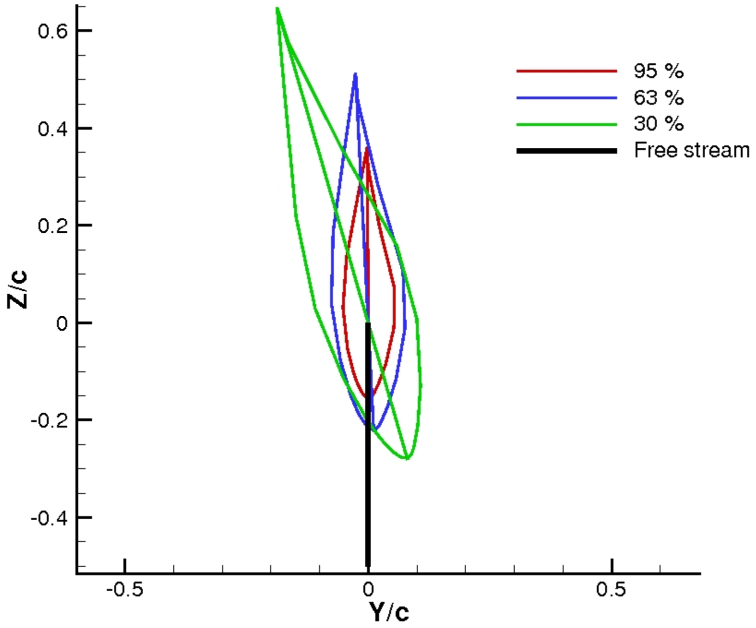
κ-ω of Wilcox

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho U_j k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \rho\left(P - \beta^* \omega k\right)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_j}(\rho U_j \omega) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + \rho\left(\frac{\alpha}{\nu_t}P - \frac{\beta}{\beta^* \omega^2}\right) + \rho S_l$$

D.C Wilcox, Simulation of Transition with a Two-Equation Turbulence Model, AIAA Journal, Vol. 32, No. 2, February 1994

L20000 Case



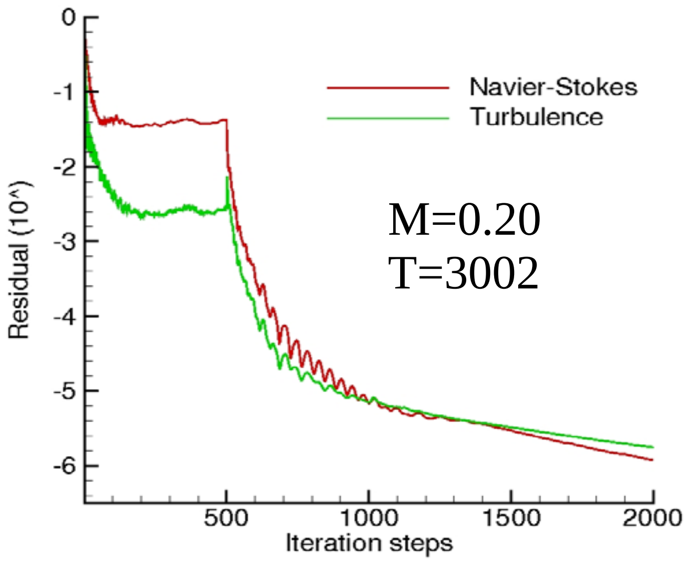
Parameter	Value	Units	Source
Tunnel velocity	20.161	m/s	V275
Averaged Rotational speed	0	rpm	V217
Tunnel air density	1.2309	Kg/m^3	V277
Wind tunnel temperature	12.343	°C	V187
Tunnel static pressure	101,269.73	Pa	V279
Tunnel dynamic pressure	250.17	Pa	V276
Dynamic fluid viscosity	1.7655^{-5}	Pa s	calculated
Reynolds number	1,035,940	-	calculated
Mach number	0.0593	-	calculated

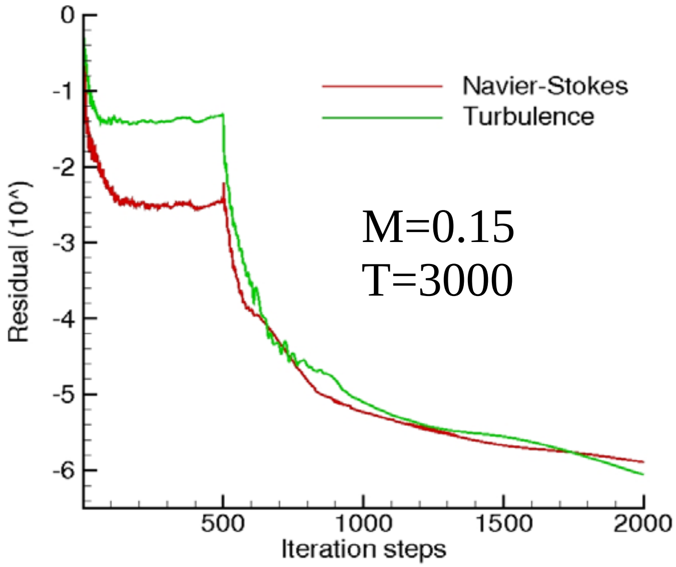
Parameter	Value	Units
Tunnel velocity	20.161	m/s
V_{tip}	0	m/s
λ	0	-
Reynolds number	1,035,940	-
chord	0.737	m
k	1.1577×10^{-4}	-
M_{FS} (imposed)	0.15/0.20	-

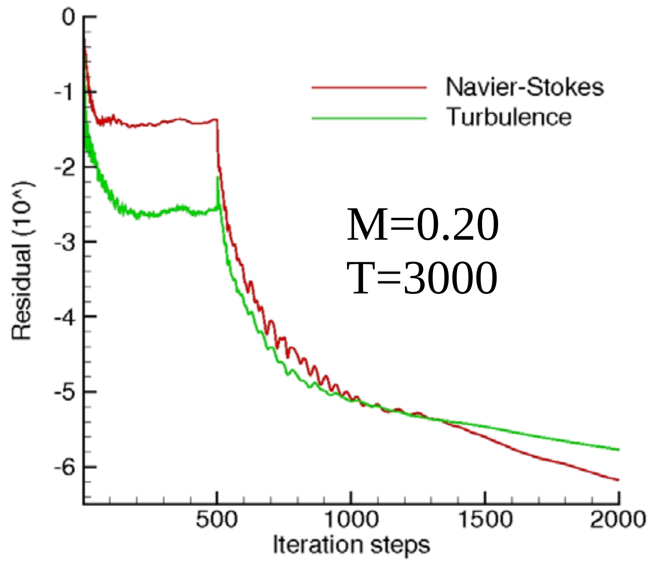
L20000 Case

Computation

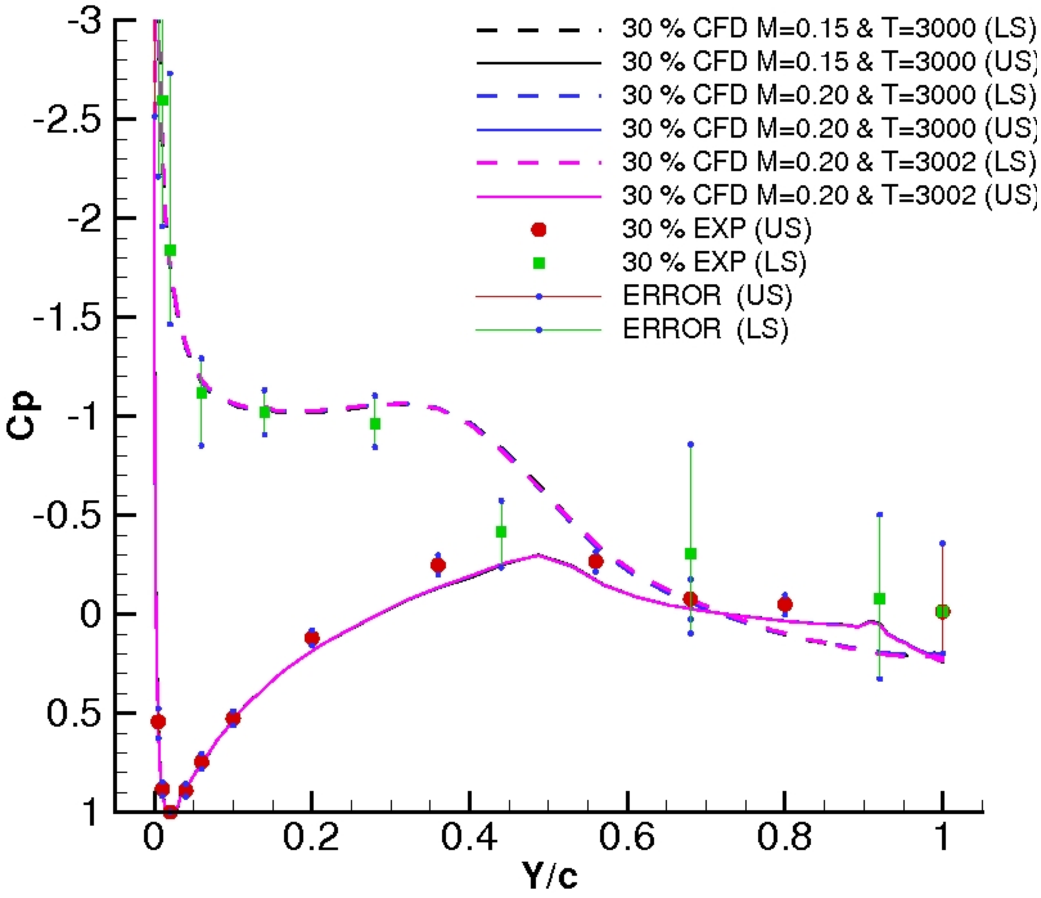
- Grid Size: 2,416,584
- Load Balance: 8 computers – 0.2%
- Convegency: All in 2000 steps to 10^{-6}
- Mach number: 0.15 (1) & 0.20 (2)
- Turbulence model: 3000 (2) & 3002 (1)



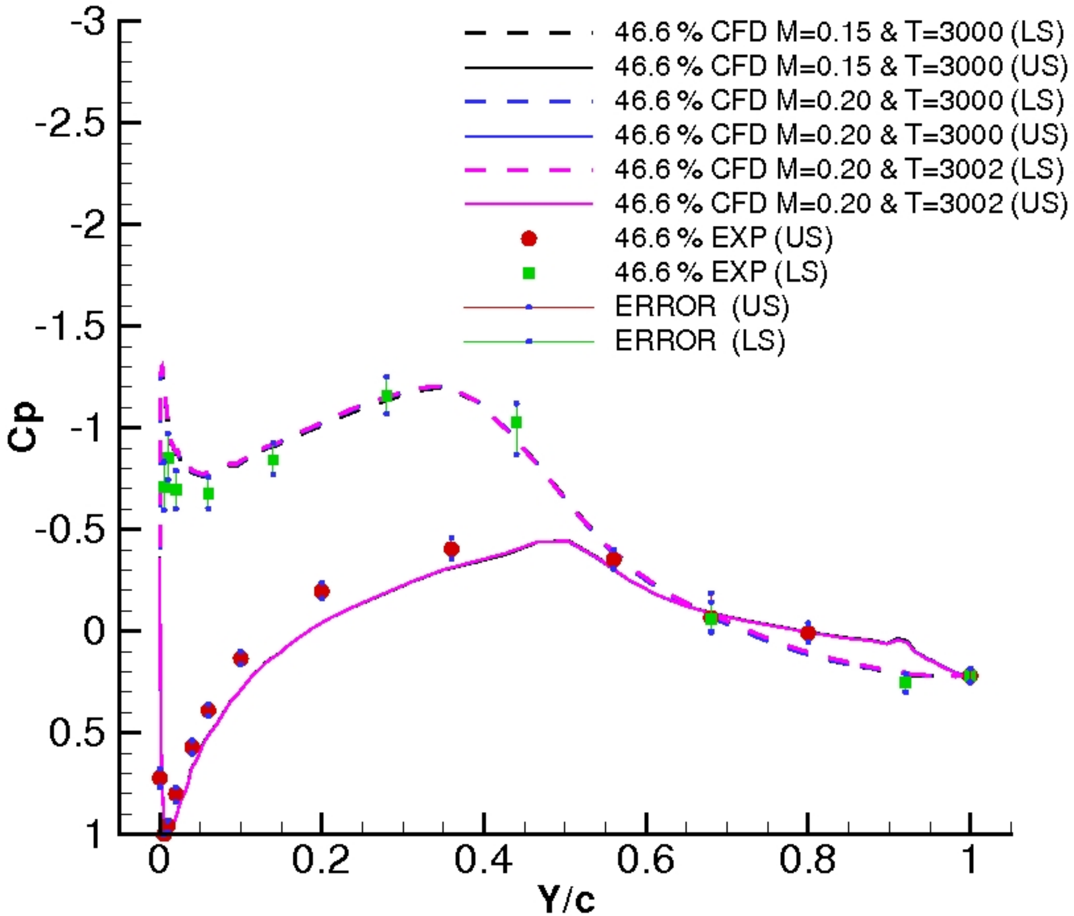




L20000 Case

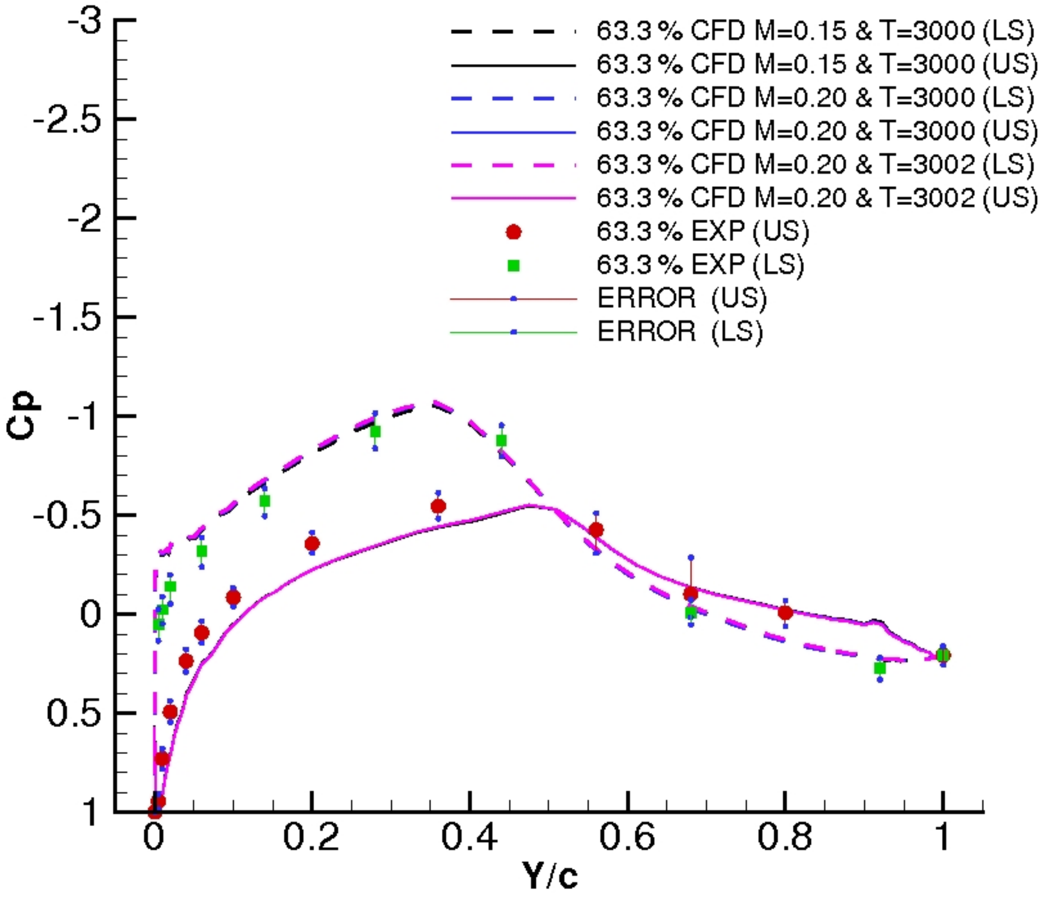


30 % CFD M=0.15 & T=3000 (LS)
30 % CFD M=0.15 & T=3000 (US)
30 % CFD M=0.20 & T=3000 (LS)
30 % CFD M=0.20 & T=3000 (US)
30 % CFD M=0.20 & T=3002 (LS)
30 % CFD M=0.20 & T=3002 (US)
30 % EXP (US)
30 % EXP (LS)
ERROR (US)
ERROR (LS)
Cp
Y/c

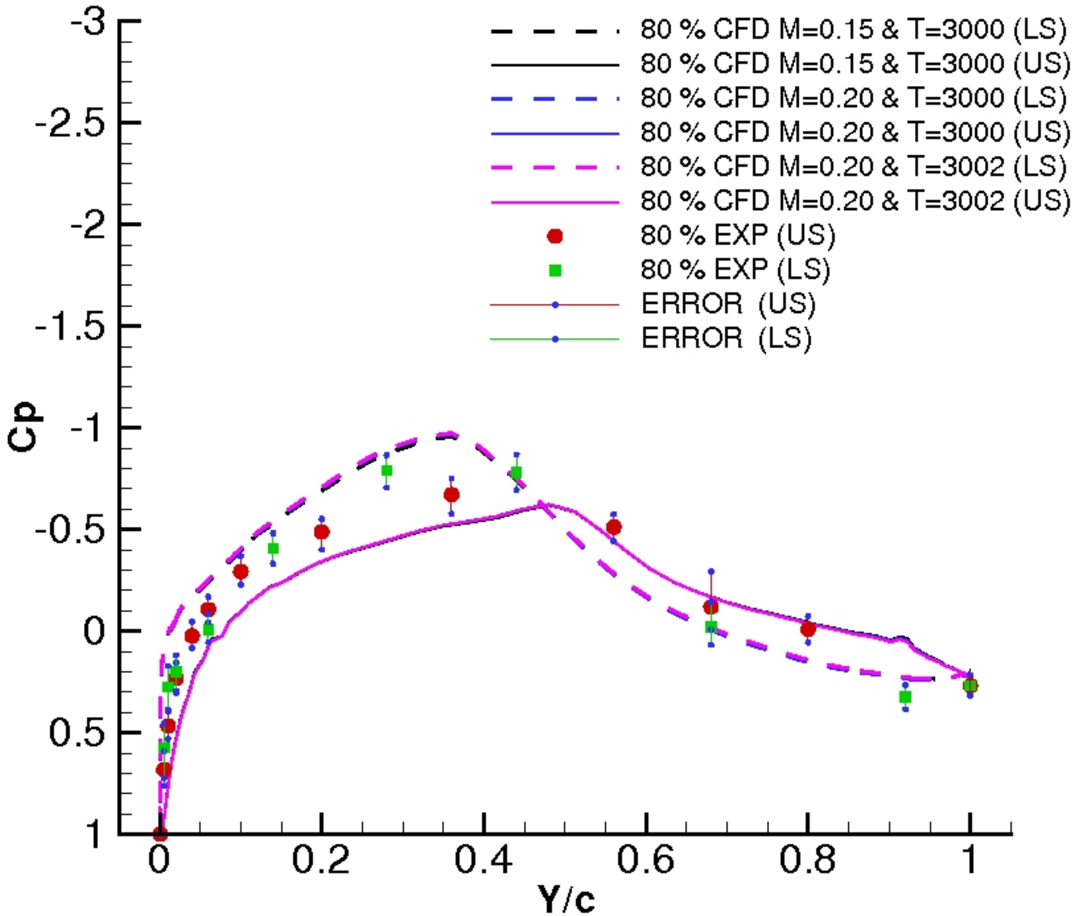


46.6 % CFD M=0.15 & T=3000 (LS)
46.6 % CFD M=0.15 & T=3000 (US)
46.6 % CFD M=0.20 & T=3000 (LS)
46.6 % CFD M=0.20 & T=3000 (US)
46.6 % CFD M=0.20 & T=3002 (LS)
46.6 % CFD M=0.20 & T=3002 (US)
46.6 % EXP (US)
46.6 % EXP (LS)
ERROR (US)
ERROR (LS)
Cp
Y/c

L20000 Case

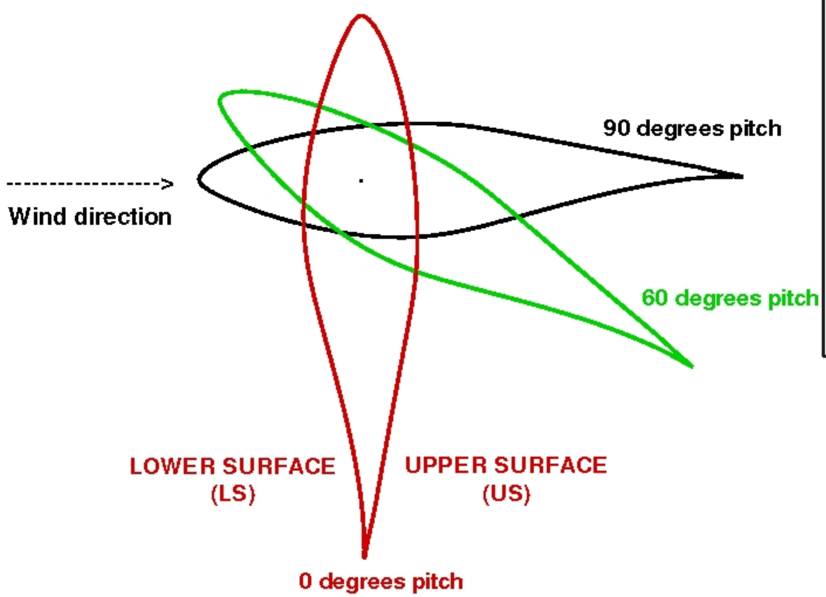


-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Cp
0
0.2
0.4
0.6
0.8
1
Y/c
63.3 % CFD M=0.15 & T=3000 (LS)
63.3 % CFD M=0.15 & T=3000 (US)
63.3 % CFD M=0.20 & T=3000 (LS)
63.3 % CFD M=0.20 & T=3000 (US)
63.3 % CFD M=0.20 & T=3002 (LS)
63.3 % CFD M=0.20 & T=3002 (US)
63.3 % EXP (US)
63.3 % EXP (LS)
ERROR (US)
ERROR (LS)



-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Cp
0
0.2
0.4
0.6
0.8
1
Y/c
80 % CFD M=0.15 & T=3000 (LS)
80 % CFD M=0.15 & T=3000 (US)
80 % CFD M=0.20 & T=3000 (LS)
80 % CFD M=0.20 & T=3000 (US)
80 % CFD M=0.20 & T=3002 (LS)
80 % CFD M=0.20 & T=3002 (US)
80 % EXP (US)
80 % EXP (LS)
ERROR (US)
ERROR (LS)

L2000ST0SD Case



Positive pitch when the LE changes towards the inflow

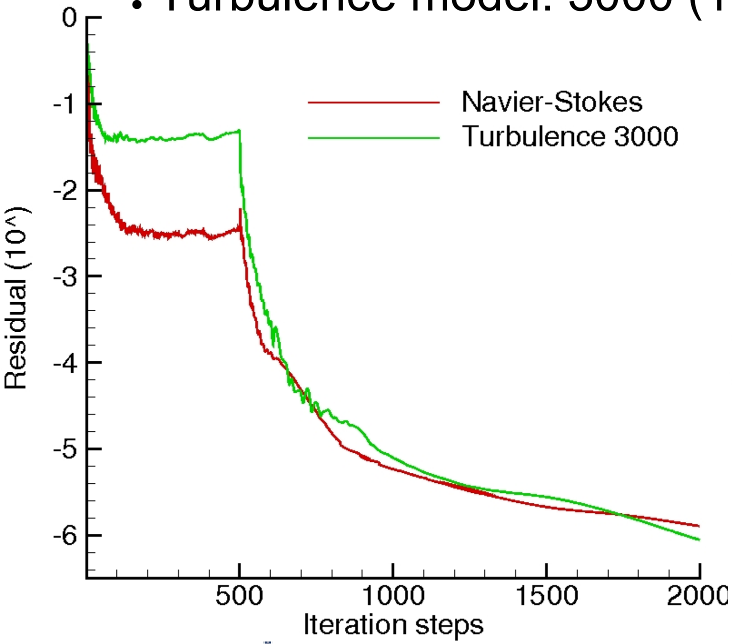
Parameter	Value	Units	Source
Tunnel velocity	20.121	m/s	V275
Averaged Rotational speed	0	rpm	V217
Tunnel air density	1.2313	Kg/m^3	V277
Wind tunnel temperature	12.256	°C	V187
Tunnel static pressure	101,271.89	Pa	V279
Tunnel dynamic pressure	249.25	Pa	V276
Pitch ratio	0.68499	°/s	V161
Dynamic fluid viscosity	1.7652^{-5}	Pa s	calculated
Reynolds number	1,034,396	-	calculated
Mach number	0.0592	-	calculated

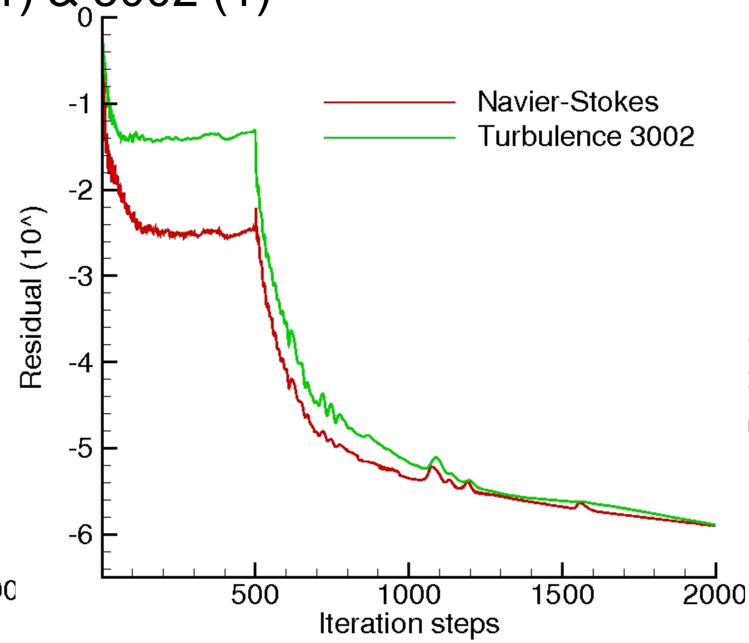
Parameter	Value	Units
Tunnel velocity	20.205	m/s
V_{tip}	0	m/s
λ	0	-
Reynolds number	1,035,000	-
chord	0.737	m
k	$1.1577x10^{-4}$	-
M_{FS} (imposed)	0.15	-

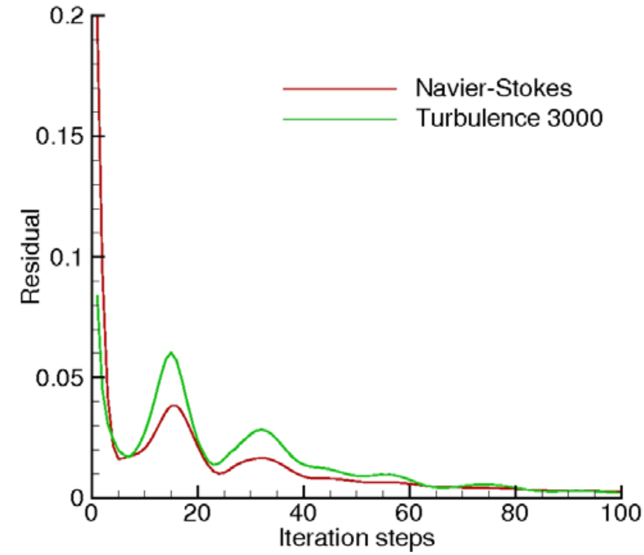
L2000ST0SD Case

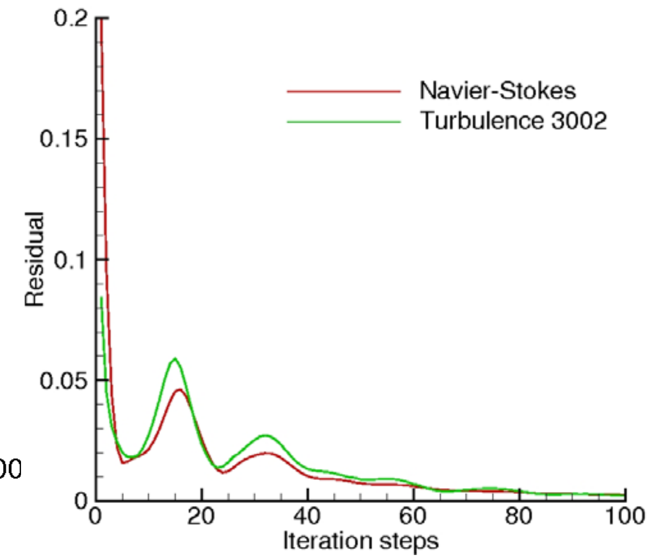
Computation

- Grid Size: 2,416,584
- Load Balance: 24 computers – 3.7%
- Convegency:
  - Initially in 2000 steps to 10^{-6} (Euclidean Convergence)
  - 2^{-3} for the azimuthal variation (Unsteady Convergence)
- Mach number: 0.15
- Turbulence model: 3000 (1) & 3002 (1)



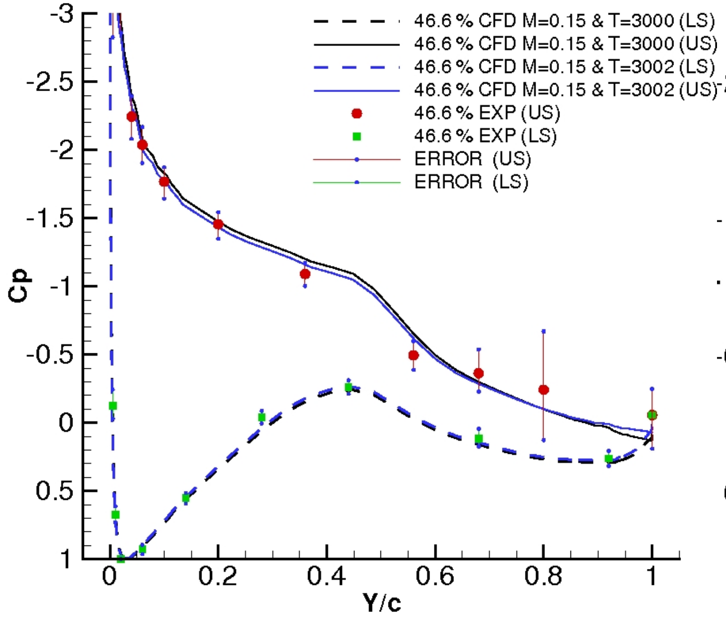


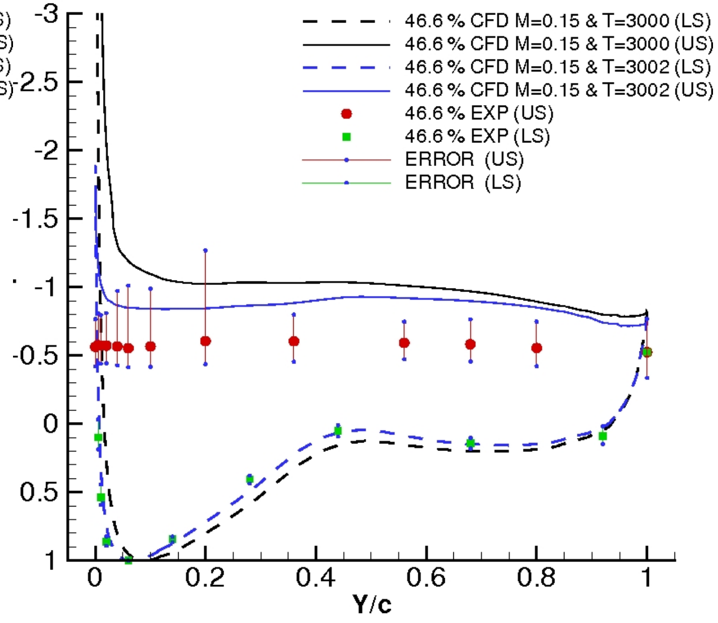




L2000ST0SD Case

46.6 %





70º pitch

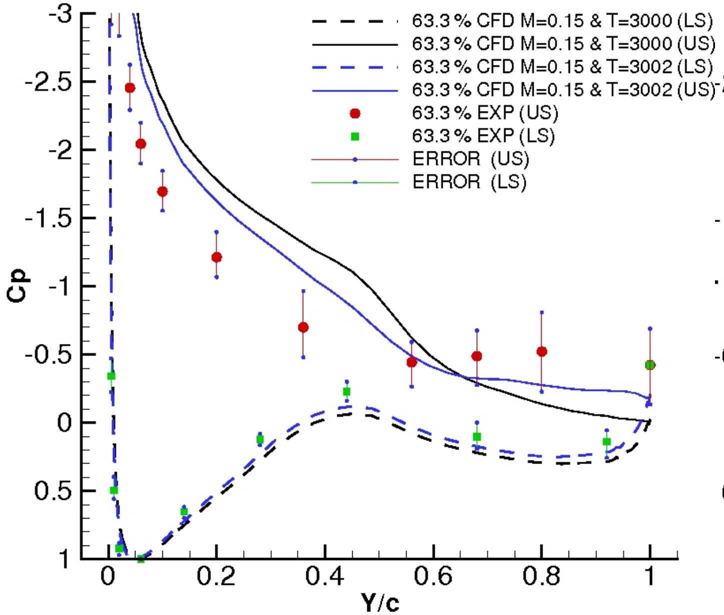
(76.530º local pitch)

50º pitch

(56.530º local pitch)

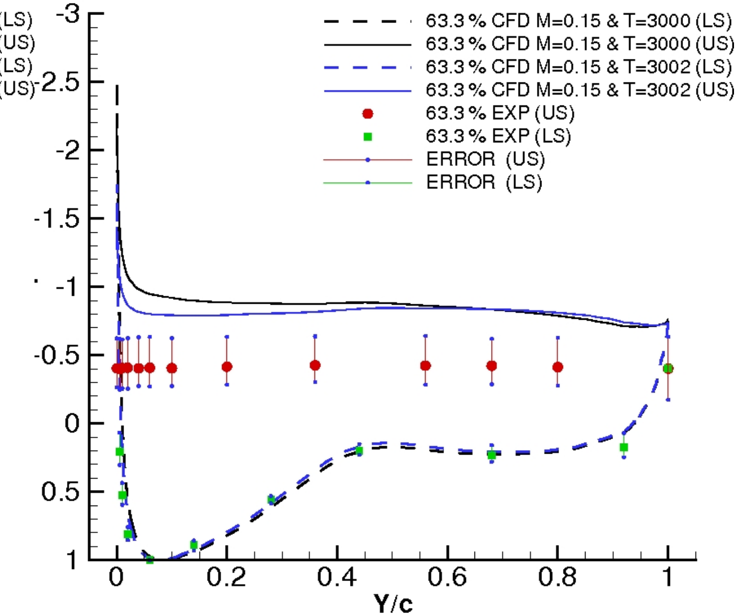
L2000ST0SD Case

63.3 %



70º pitch

(72.930º local pitch)

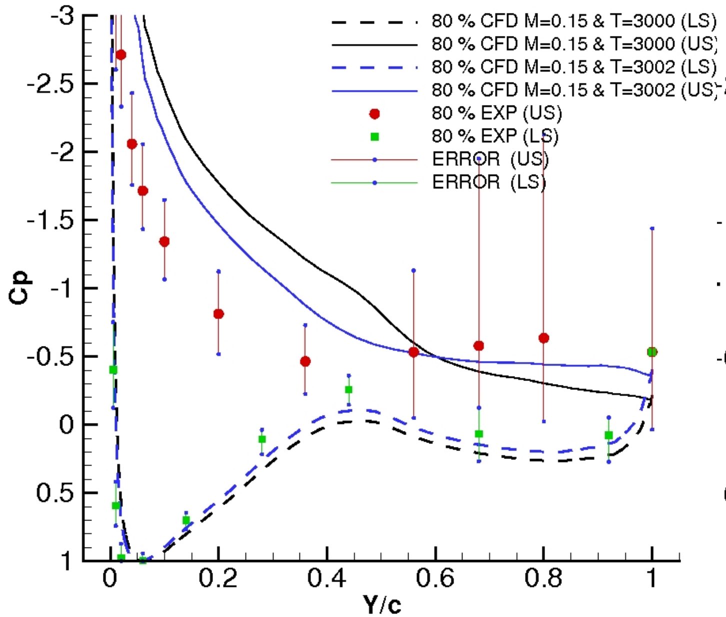


50º pitch

(52.930º local pitch)

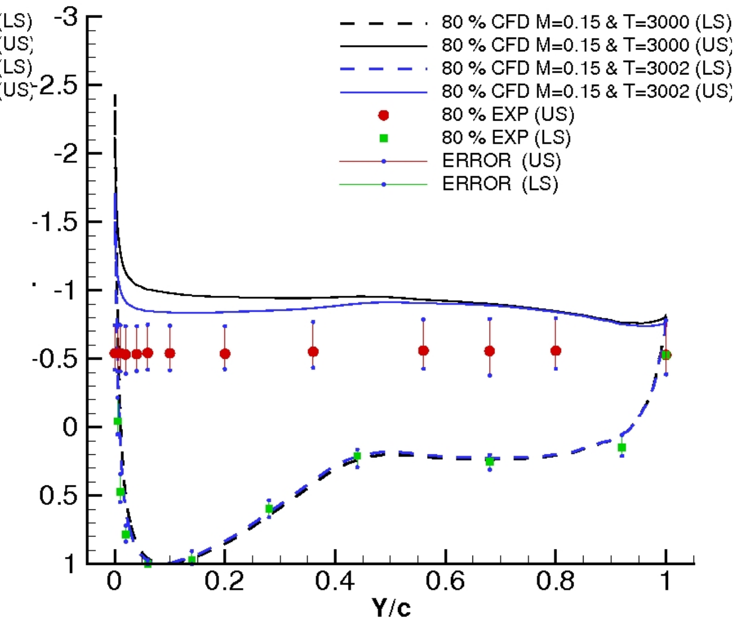
L2000ST0SD Case

80 %



70º pitch

(71.434º local pitch)

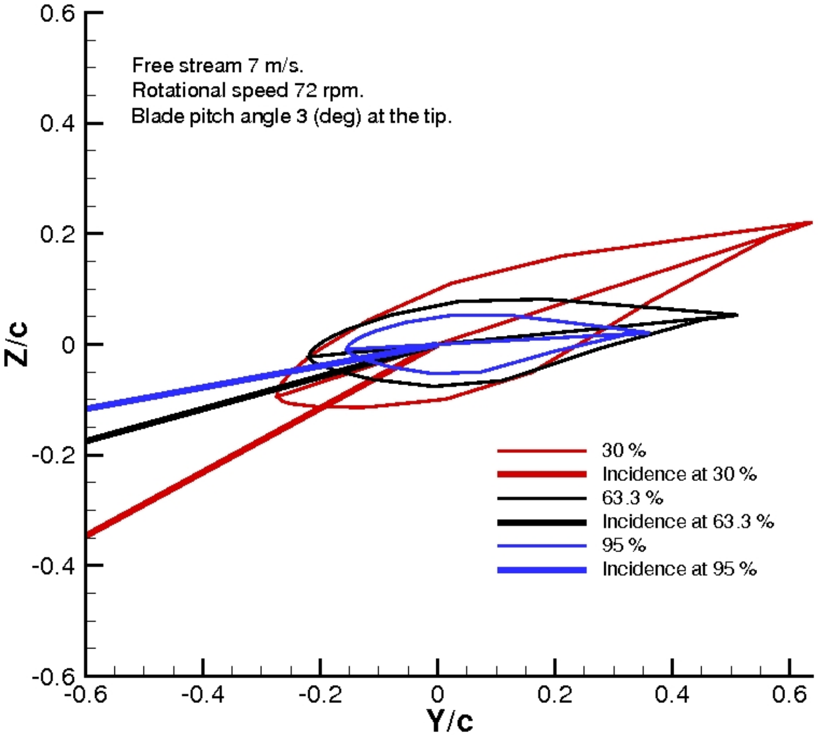


50º pitch

(51.434º local pitch)

S0700000 Case – Steady Computation

Parameters	Value	Units	Source
Tunnel velocity	7.017	m/s	V275
Averaged Rotational speed	71.866	rpm	V217
Tunnel air density	1.2458	Kg/m^3	V277
Wind tunnel temperature	11.13	°C	V187
Tunnel static pressure	101,955	Pa	V279
Tunnel dynamic pressure	30.678	Pa	V276
Yaw angle	0.011	°	V204
Pitch angle	2.986	°	V173
Dynamic fluid viscosity	1.7601^{-5}	Pa s	calculated
Reynolds number	365,989	-	calculated
Mach number	0.0206	-	calculated



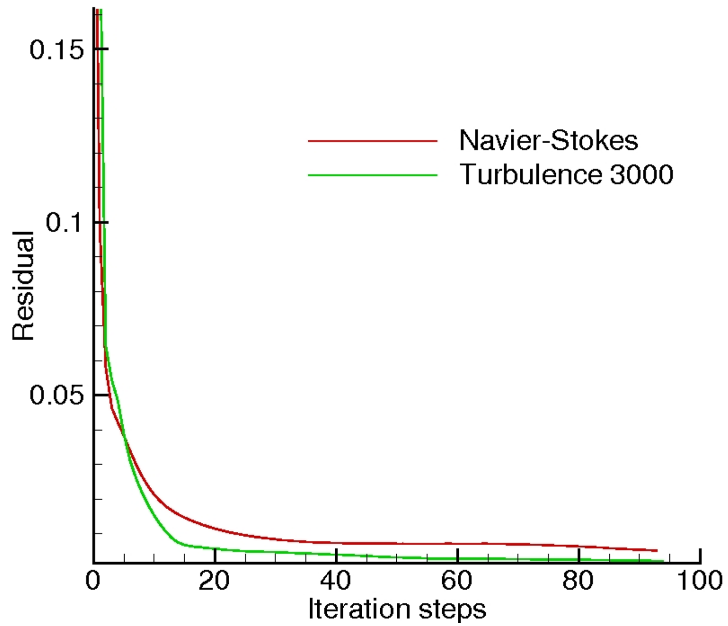
S0700000 Case

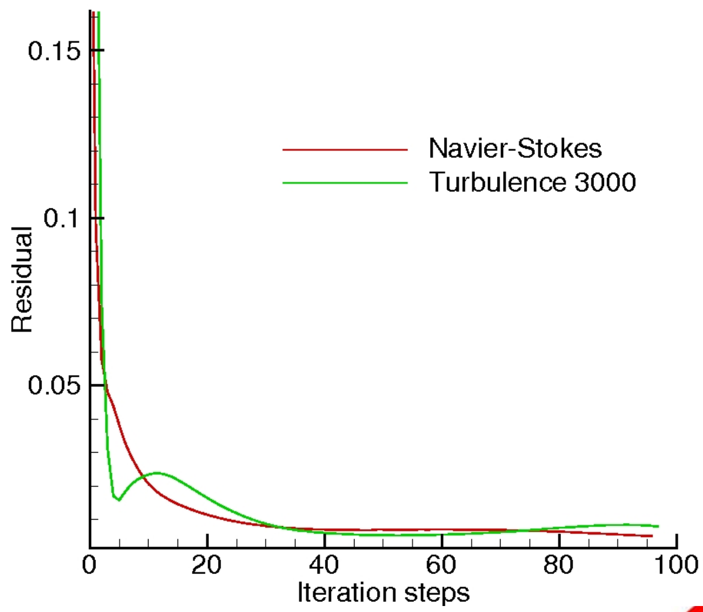
Computation

- Grid Size: 4,552,304
- Load Balance: 33 computers – 0.7 %

 Mach number: 0.1 (1)

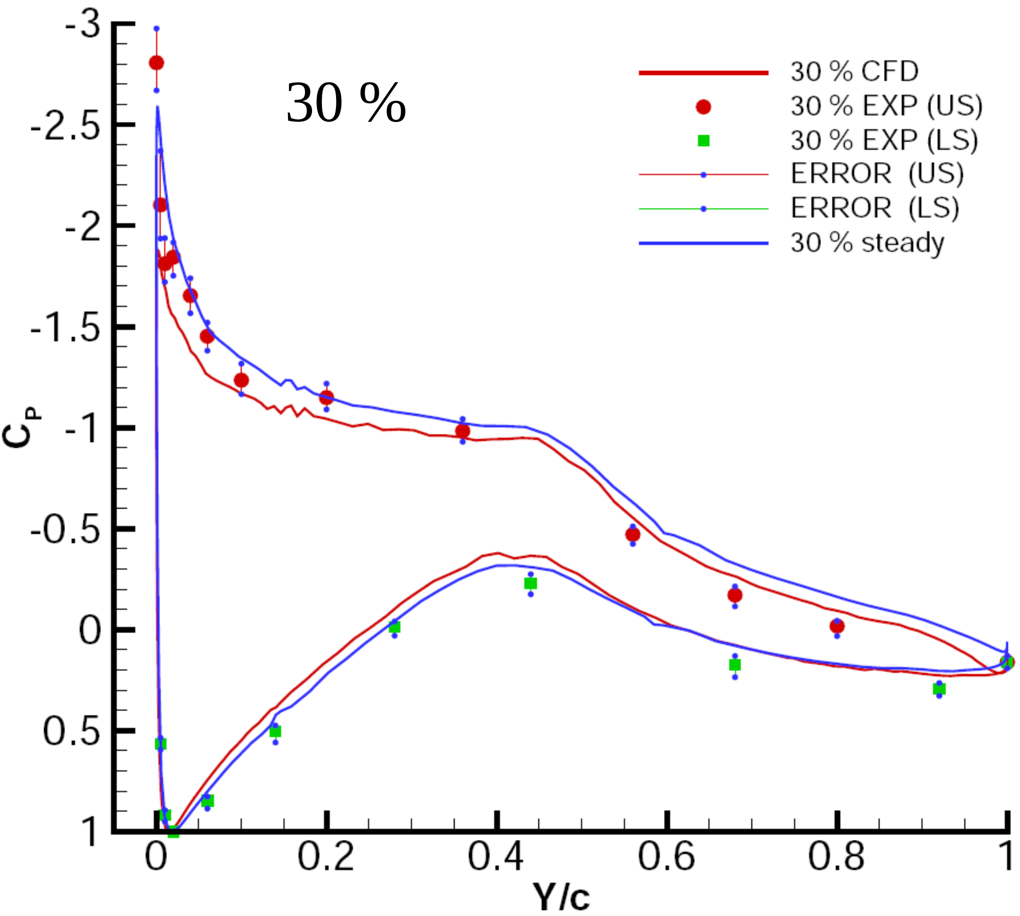
- Turbulence model: 3000 (1)

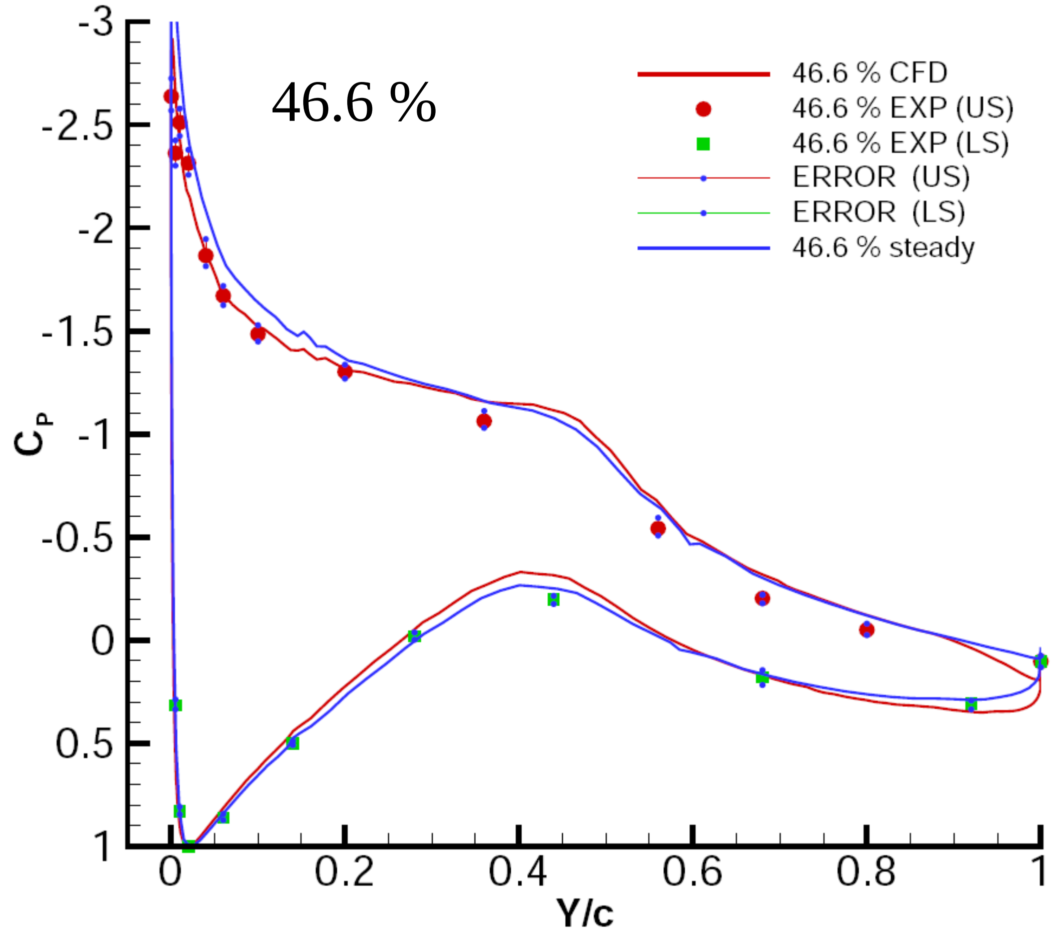




S0700000 Case – Steady Computation

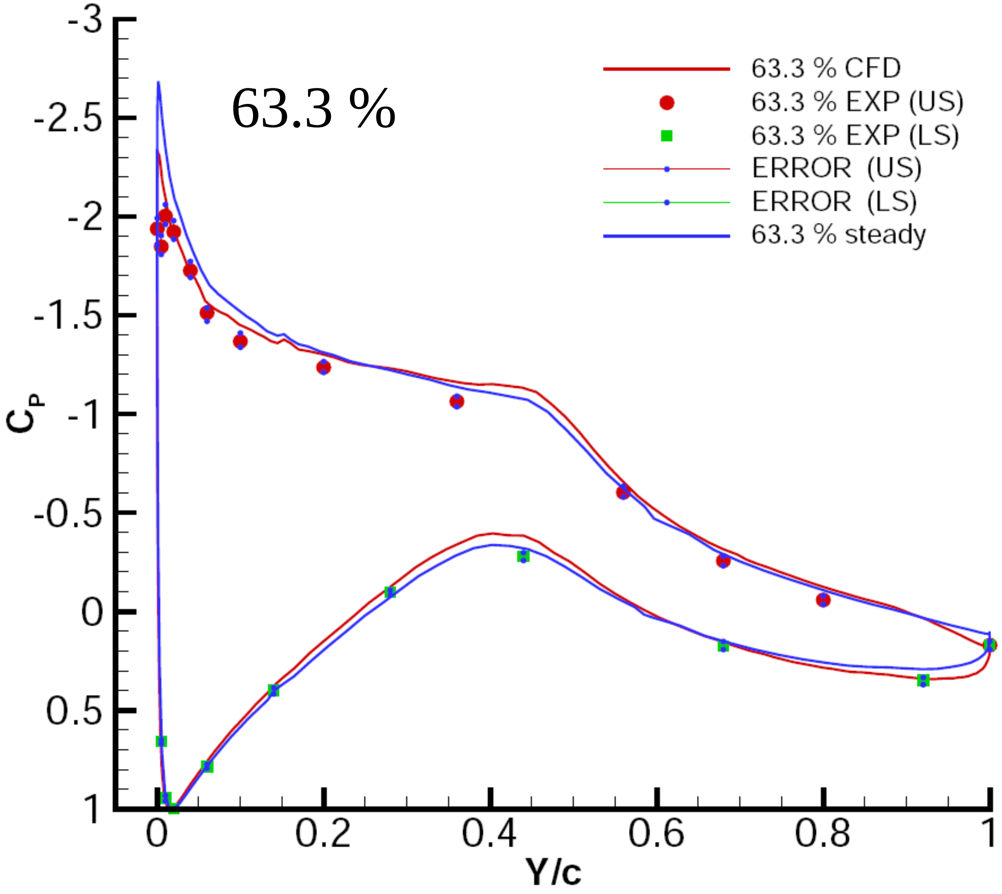
C_P distribution

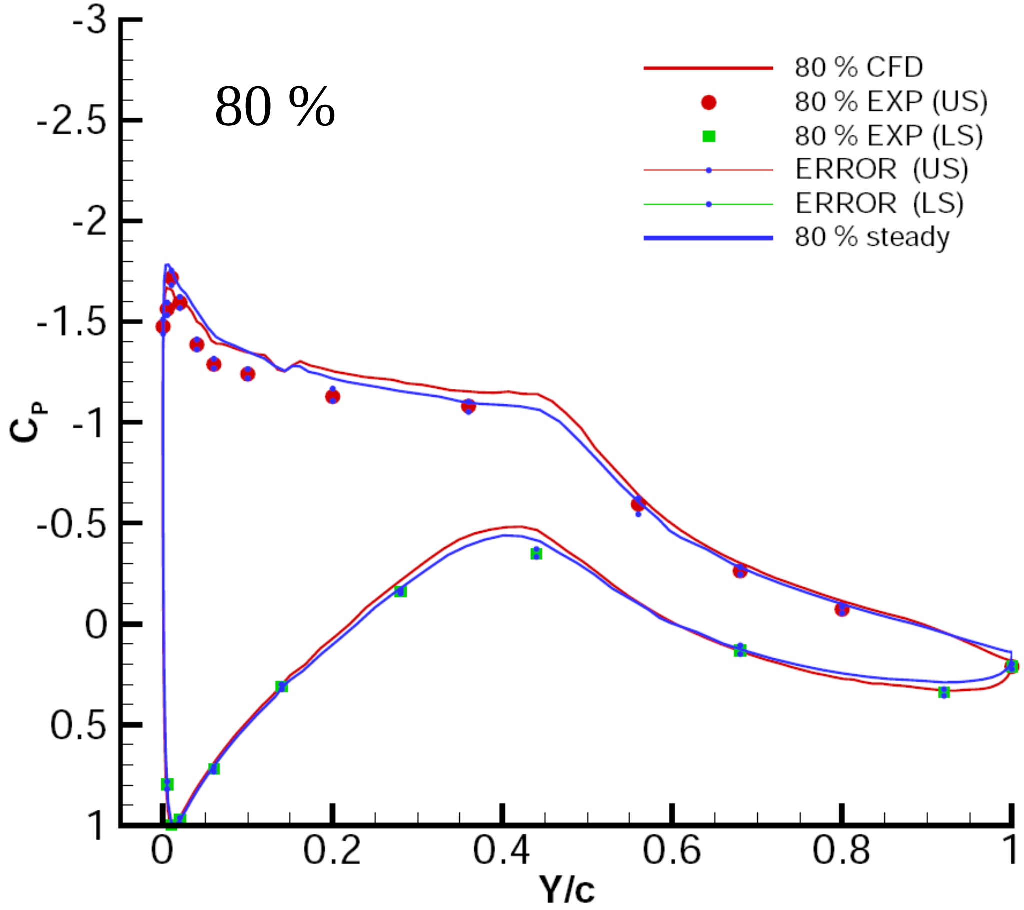




S0700000 Case – Steady Computation

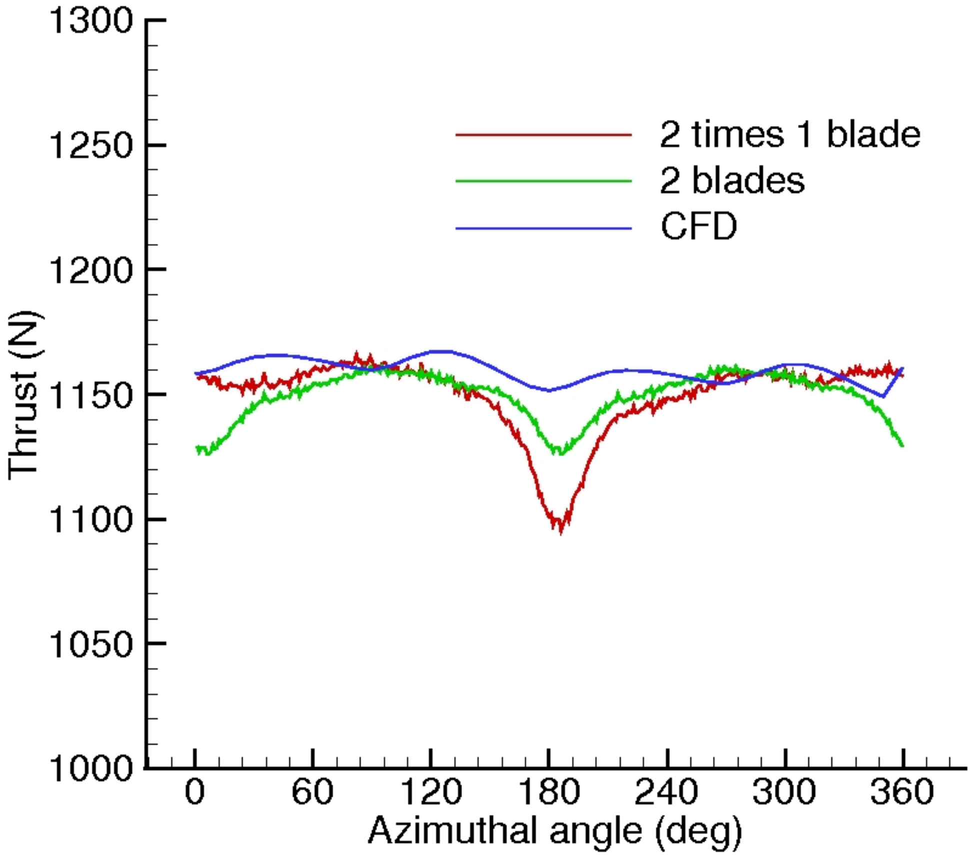
C_P distribution

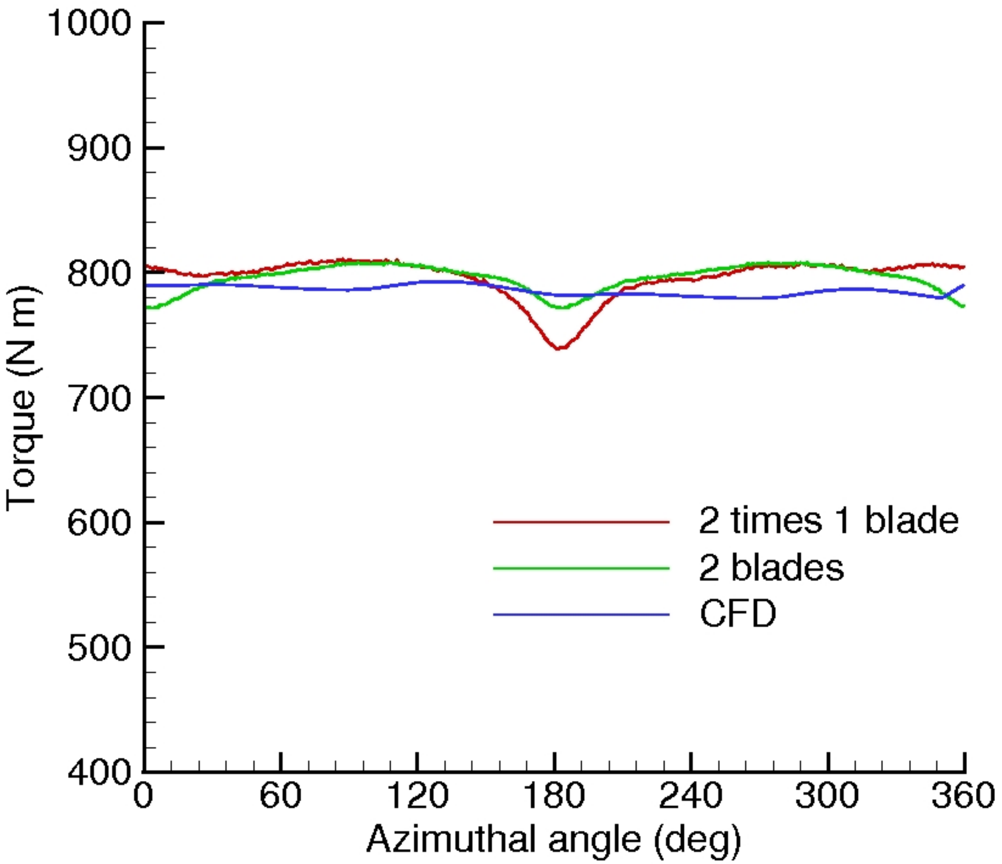




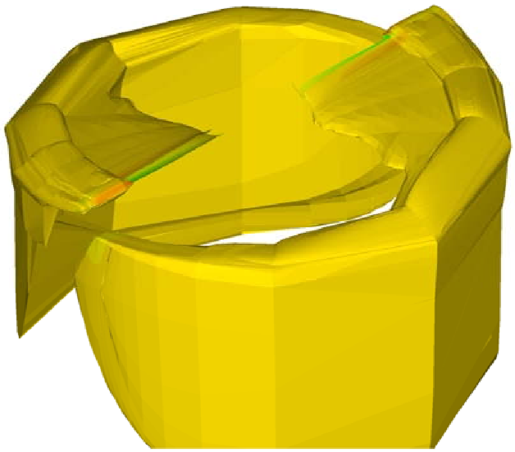
S0700000 Case

Integrated Loads

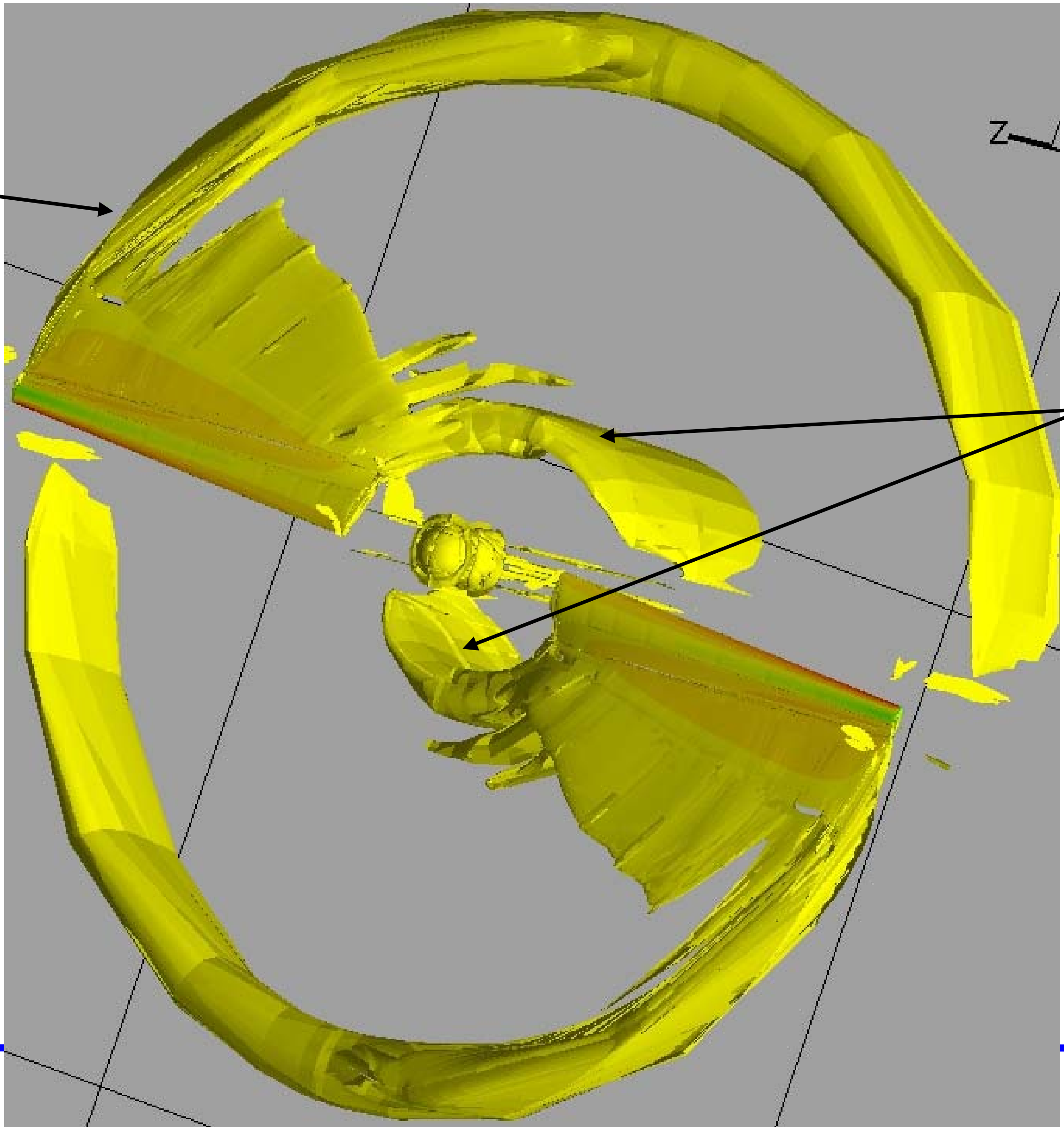




S0700000 Case



Re_T

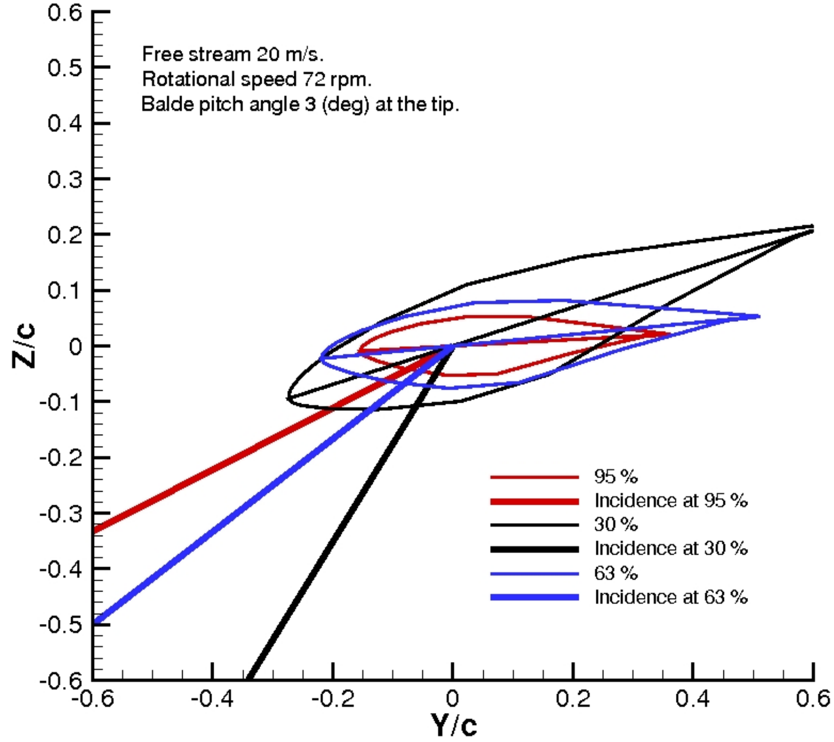


λ_2

S2000000 Case - Unsteady Computations

High wind speed and stalled behaviour

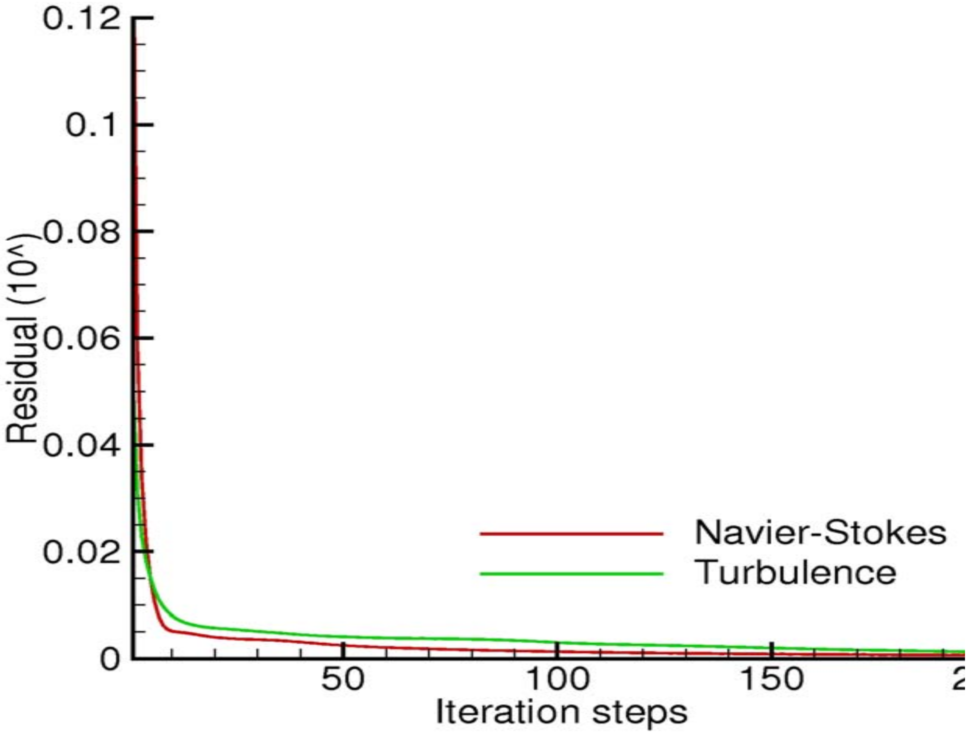
Parameters	Value	Units	Source
Tunnel velocity	20.131	m/s	V275
Averaged Rotational speed	72.014	rpm	V217
Tunnel air density	1.2213	Kg/m^3	V277
Wind tunnel temperature	14.48	°C	V187
Tunnel static pressure	101,205	Pa	V279
Tunnel dynamic pressure	247.455	Pa	V276
Yaw angle	0.141	°	V204
Pitch angle	2.995	°	V173
Dynamic fluid viscosity	1.7601^{-5}	Pa s	calculated
Reynolds number	1,029,480	-	calculated
Mach number	0.0592	-	calculated

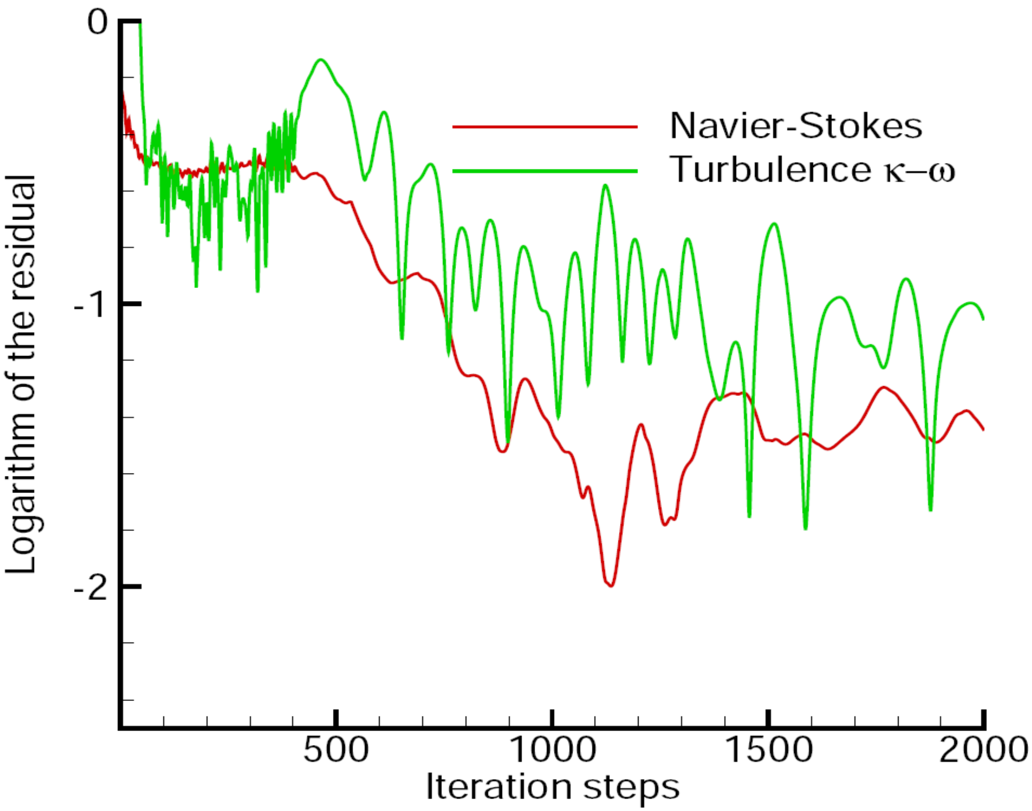


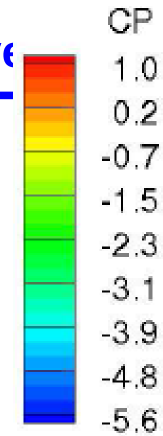
Reynolds number based in the maximum chord of the blade and the free stream velocity.

S2000000 Case (Unsteady State)

- Grid Size = 6,550,400 (524 blocks)
- Load Balance = 55 processors (97.7%)
- Turbulence model: κ-ω of Wilcox







S2000000 Case - Steady Computation

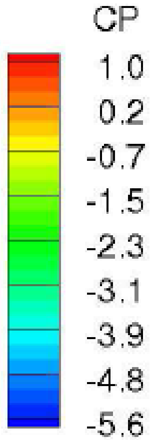
Lower Surface (Pressure side)
0º azimuth angle

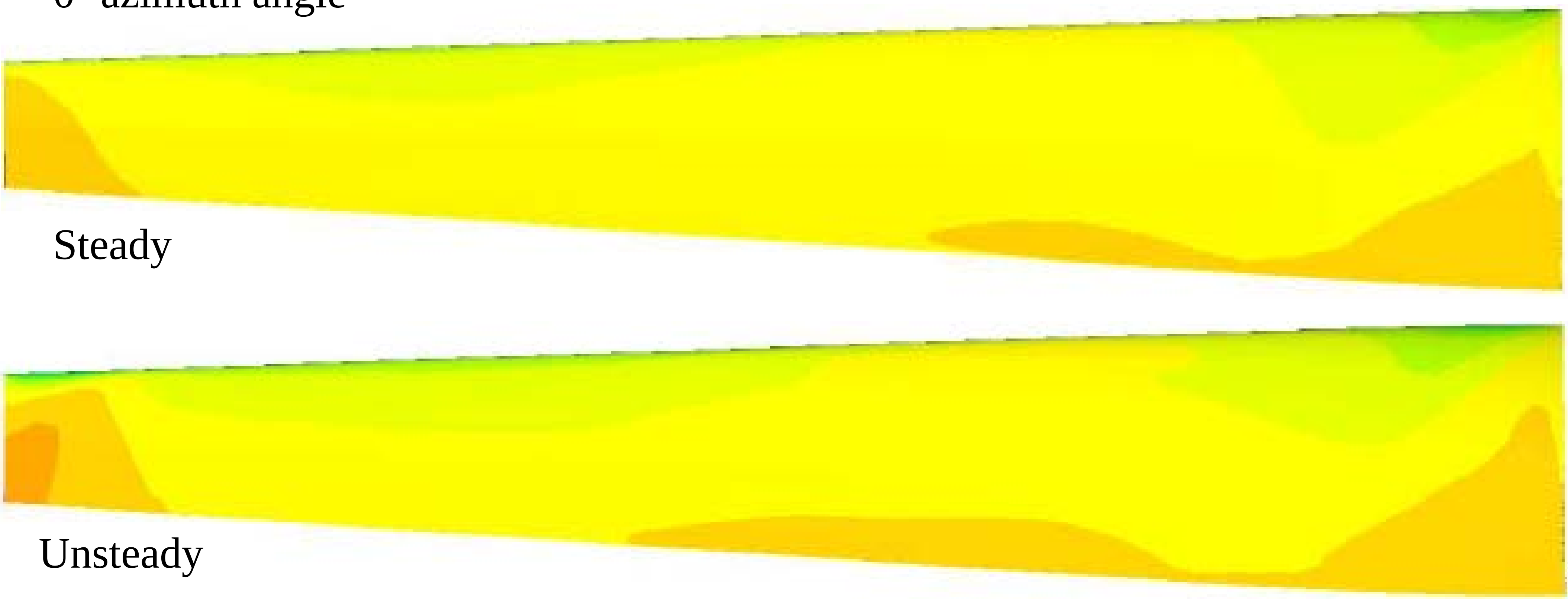
Steady

Unsteady

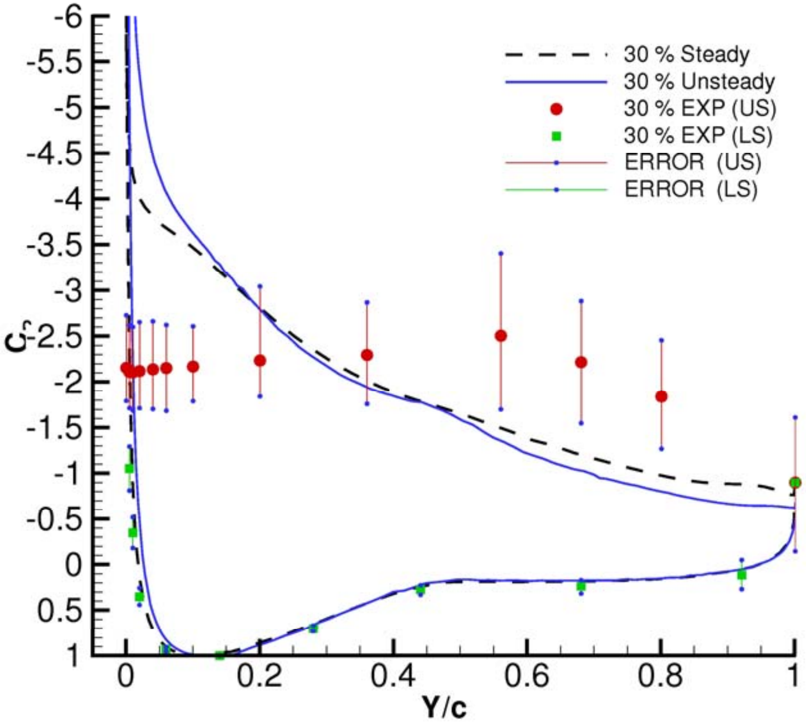
S2000000 Case - Steady Computation

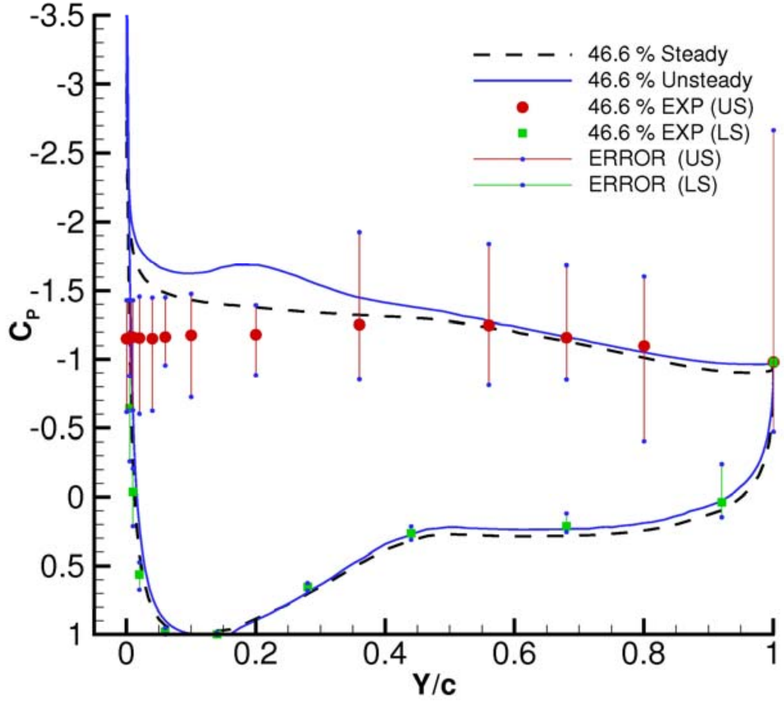
Upper Surface (Suction side)
0º azimuth angle



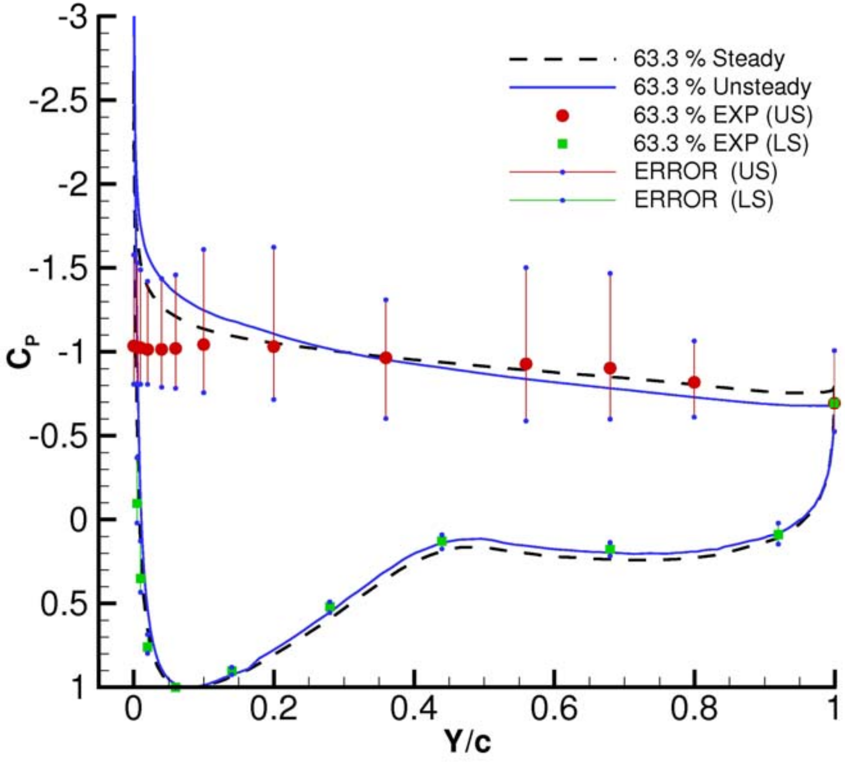


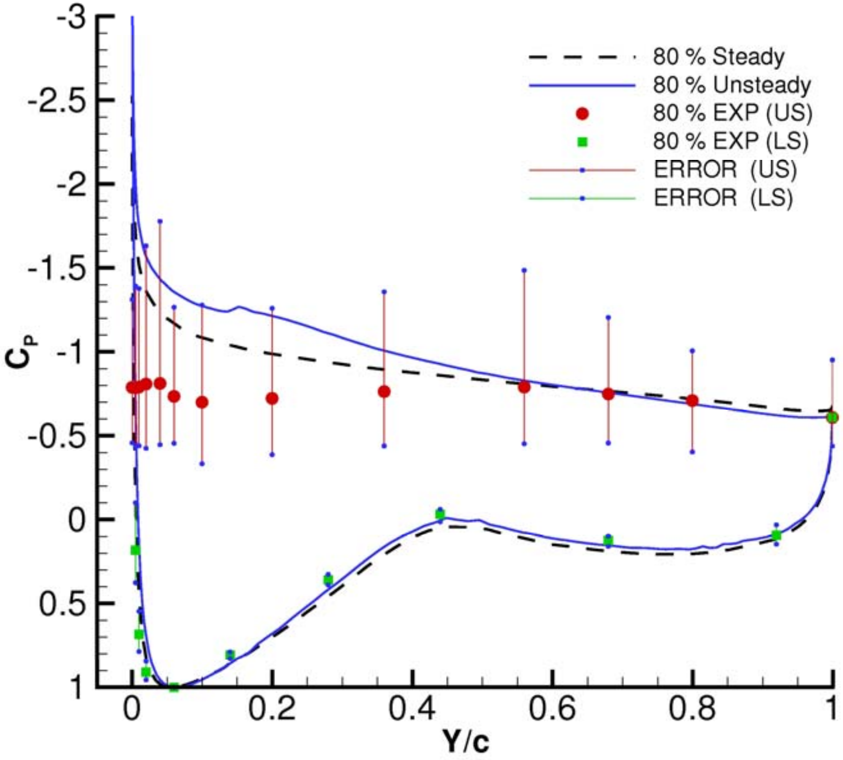
20m/s


30 % Steady
30 % Unsteady
30 % EXP (US)
30 % EXP (LS)
ERROR (US)
ERROR (LS)
Cp
Y/c

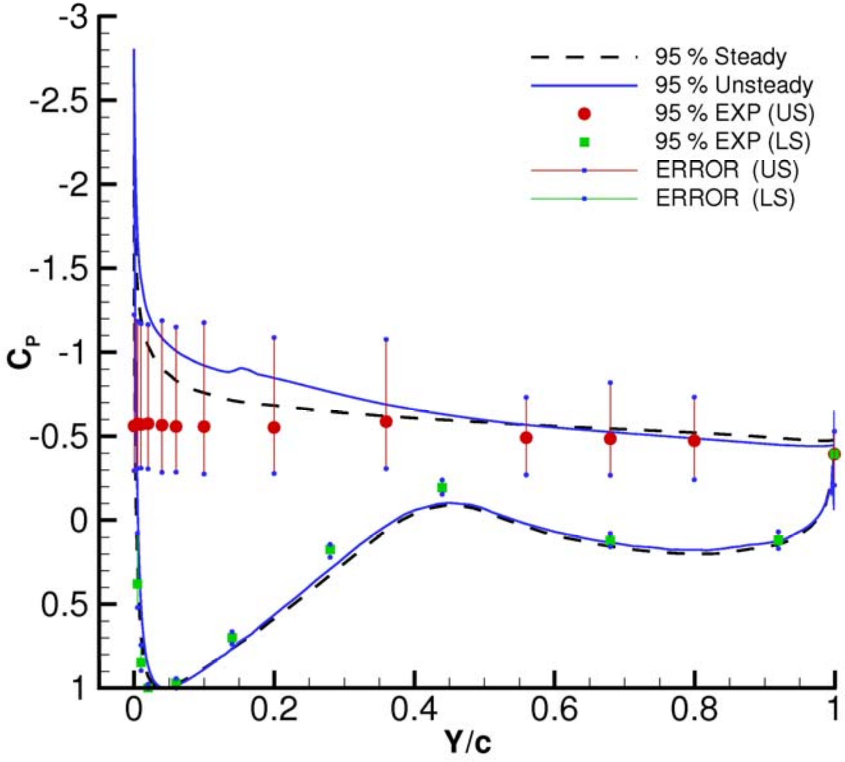

46.6 % Steady
46.6 % Unsteady
46.6 % EXP (US)
46.6 % EXP (LS)
ERROR (US)
ERROR (LS)
Cp
Y/c

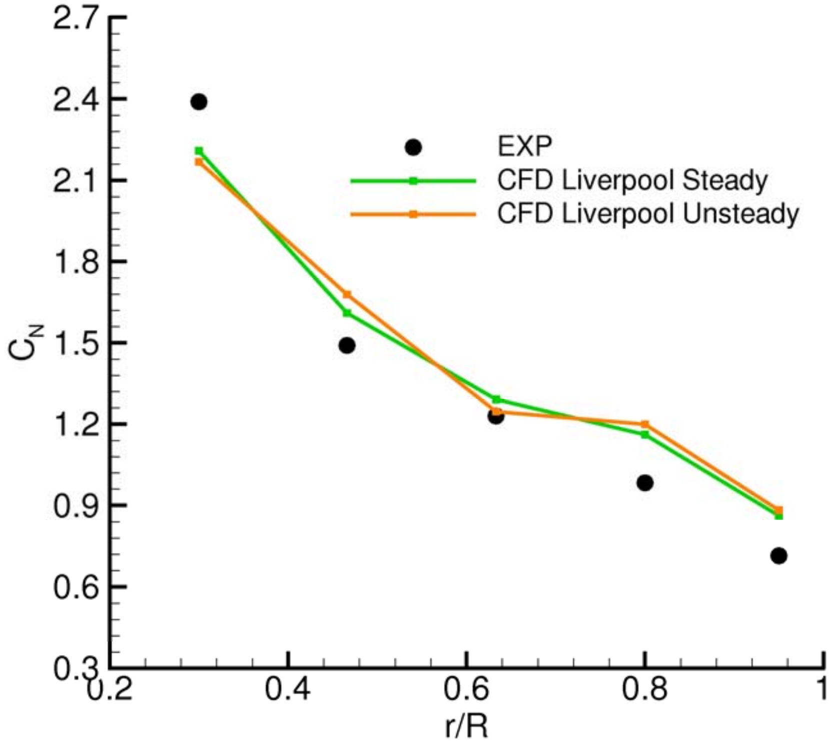
20m/s


63.3 % Steady
63.3 % Unsteady
63.3 % EXP (US)
63.3 % EXP (LS)
ERROR (US)
ERROR (LS)
C_p
Y/c


80 % Steady
80 % Unsteady
80 % EXP (US)
80 % EXP (LS)
ERROR (US)
ERROR (LS)
C_p
Y/c

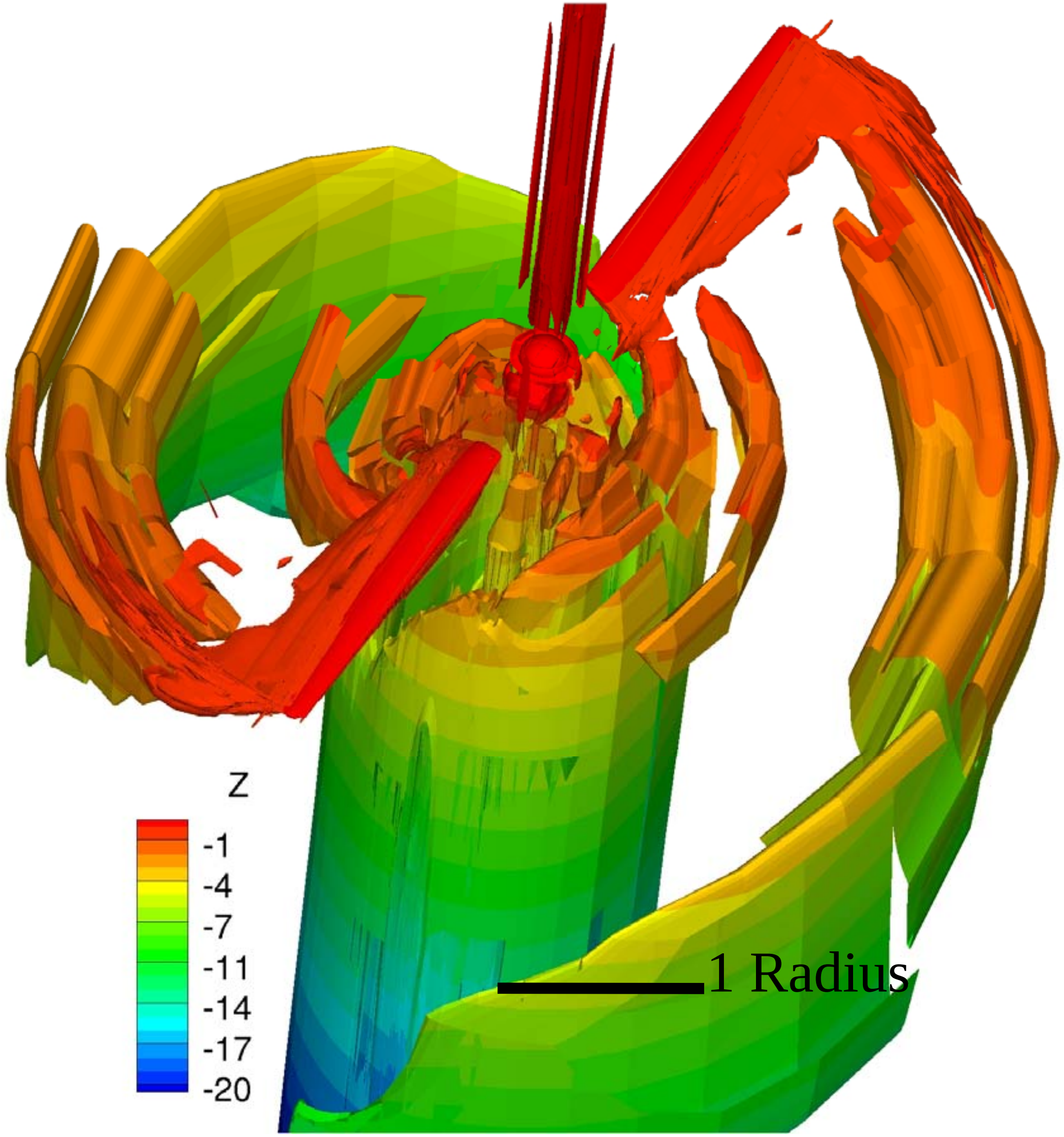
20m/s


95 % Steady
95 % Unsteady
95 % EXP (US)
95 % EXP (LS)
ERROR (US)
ERROR (LS)
C_p
Y/c
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
0
0.2
0.4
0.6
0.8
1


EXP
CFD Liverpool Steady
CFD Liverpool Unsteady
C_N
r/R
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.2
0.4
0.6
0.8
1

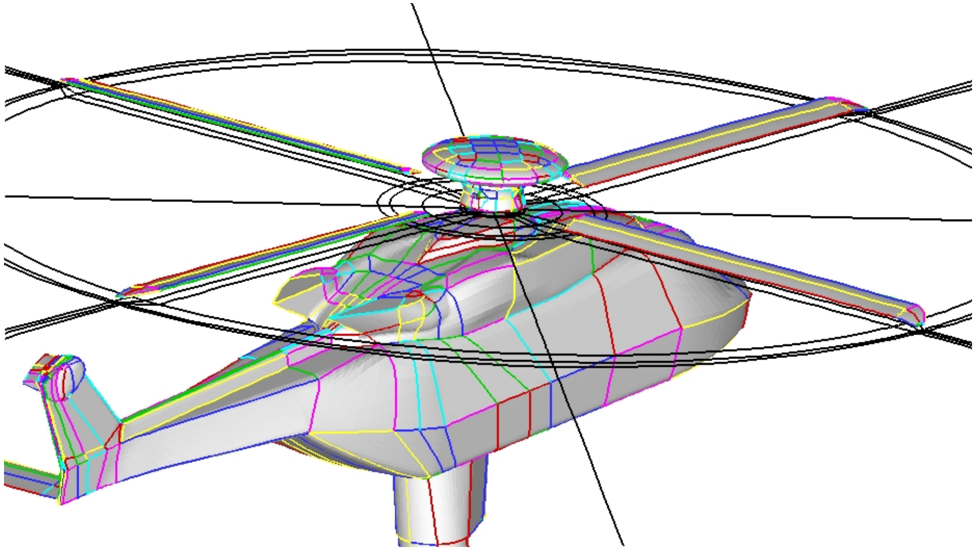
S2000000 Case (Unsteady Flow Solution)

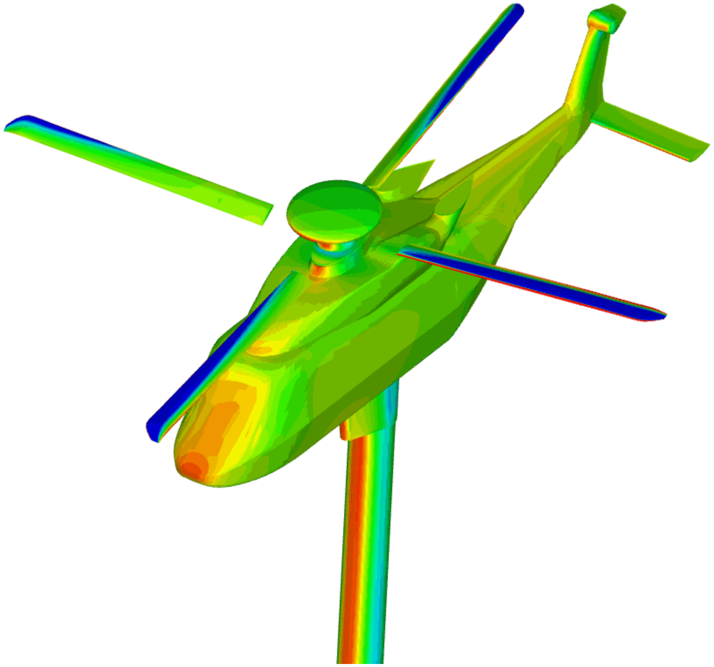
λ_2

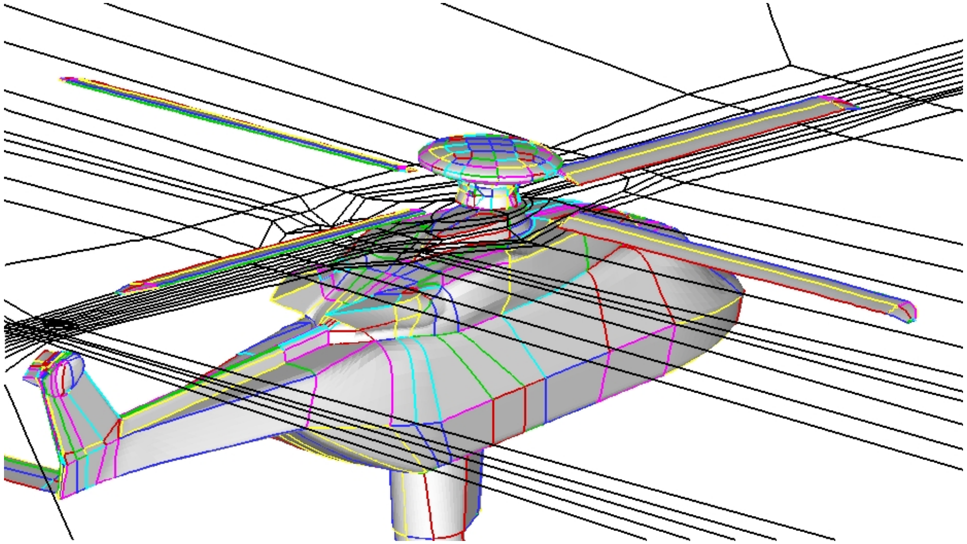


Future Steps

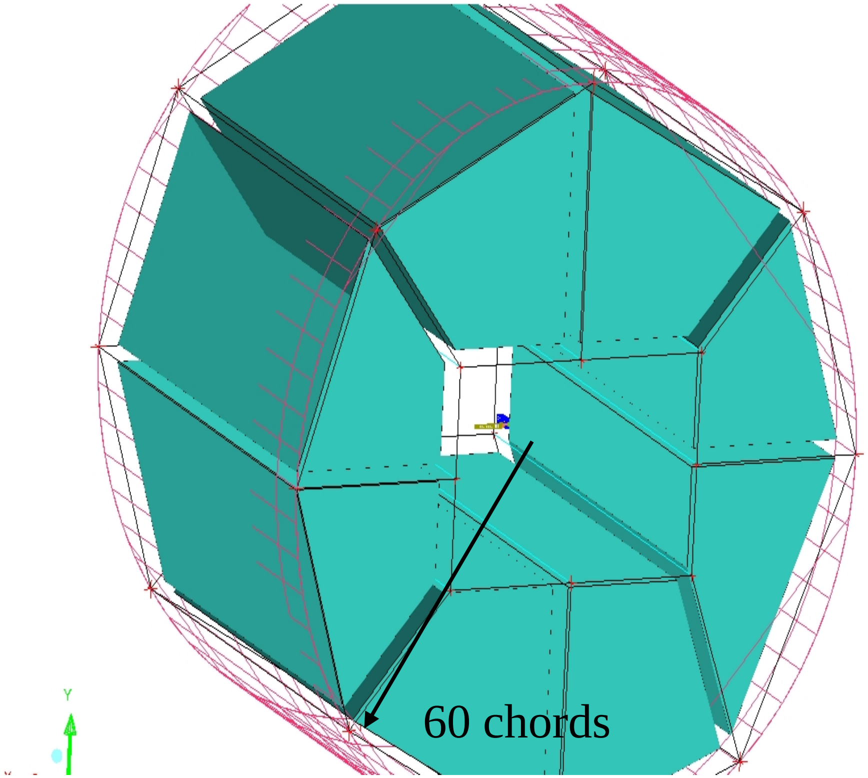
Sliding Meshes



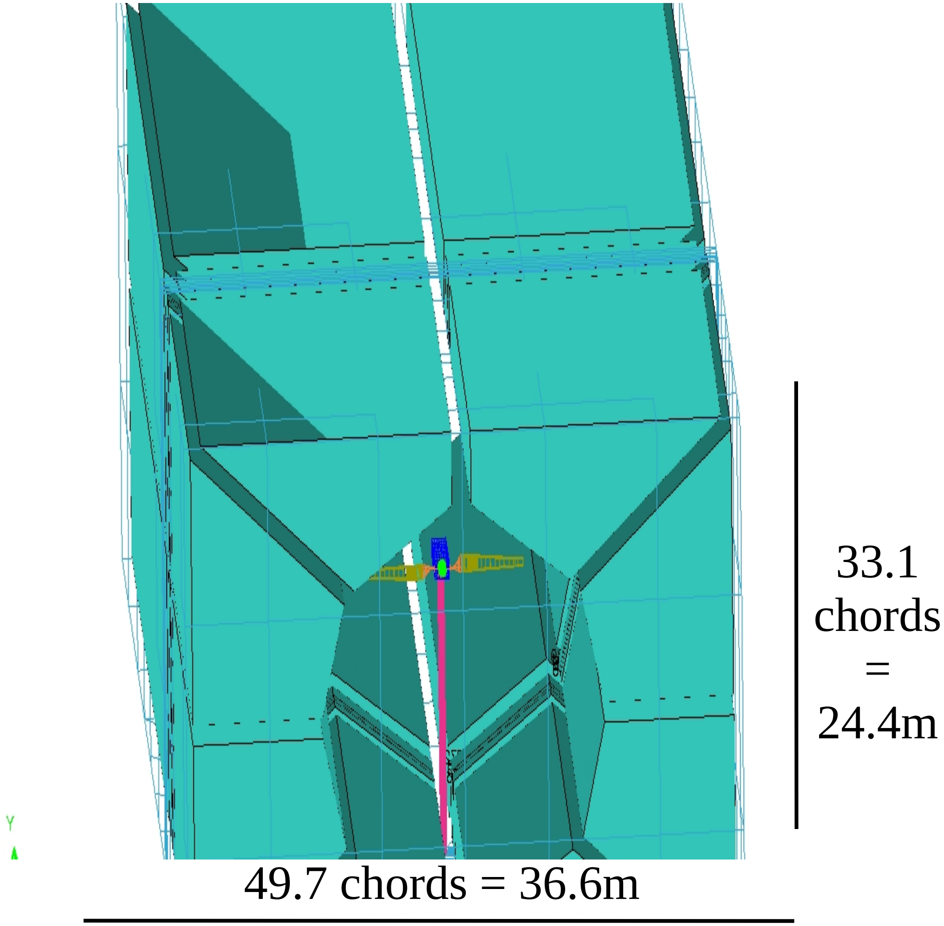




Free Stream and Wind Tunnel Configurations



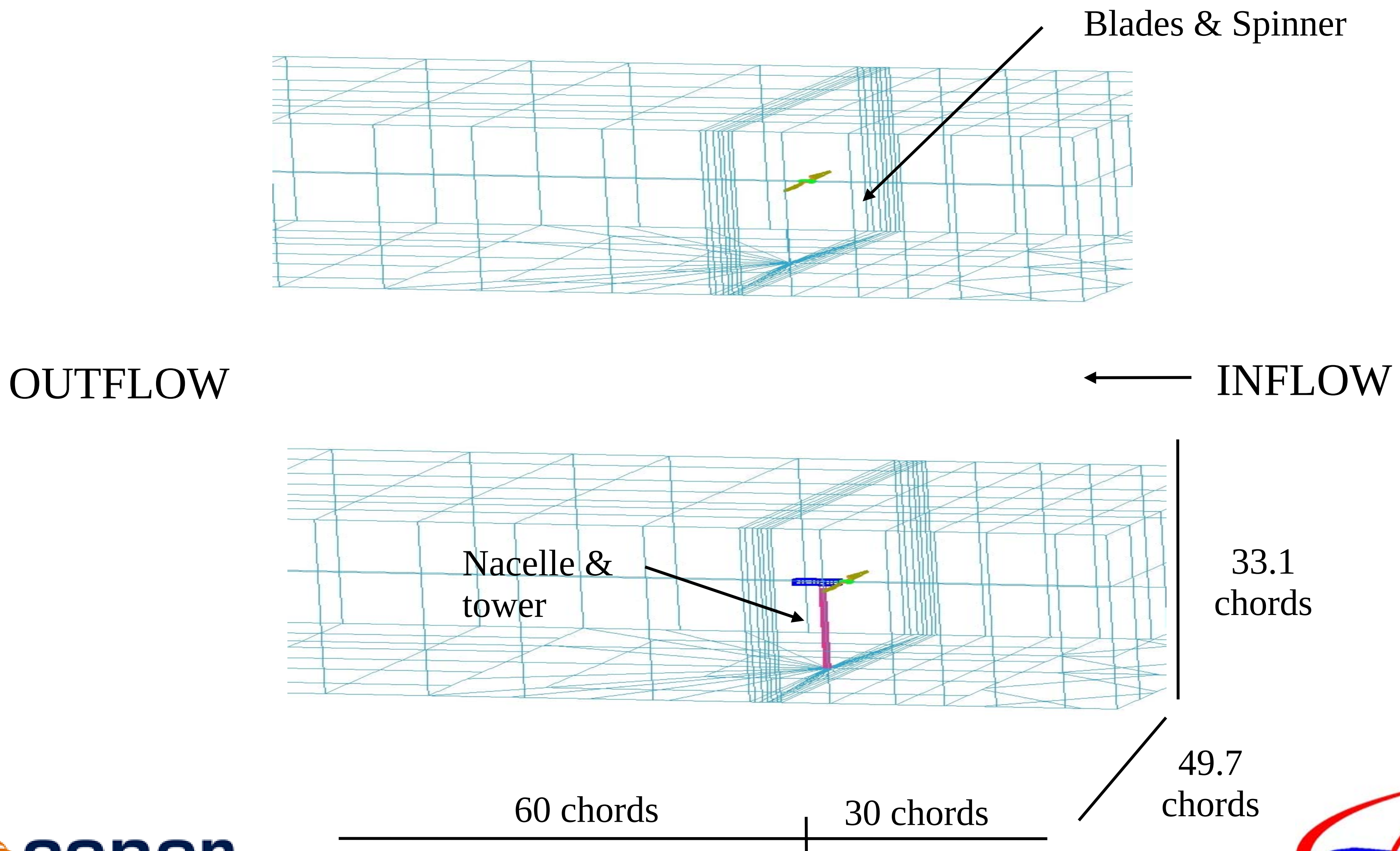
Free stream configuration
60 chords away from the wind turbine hub



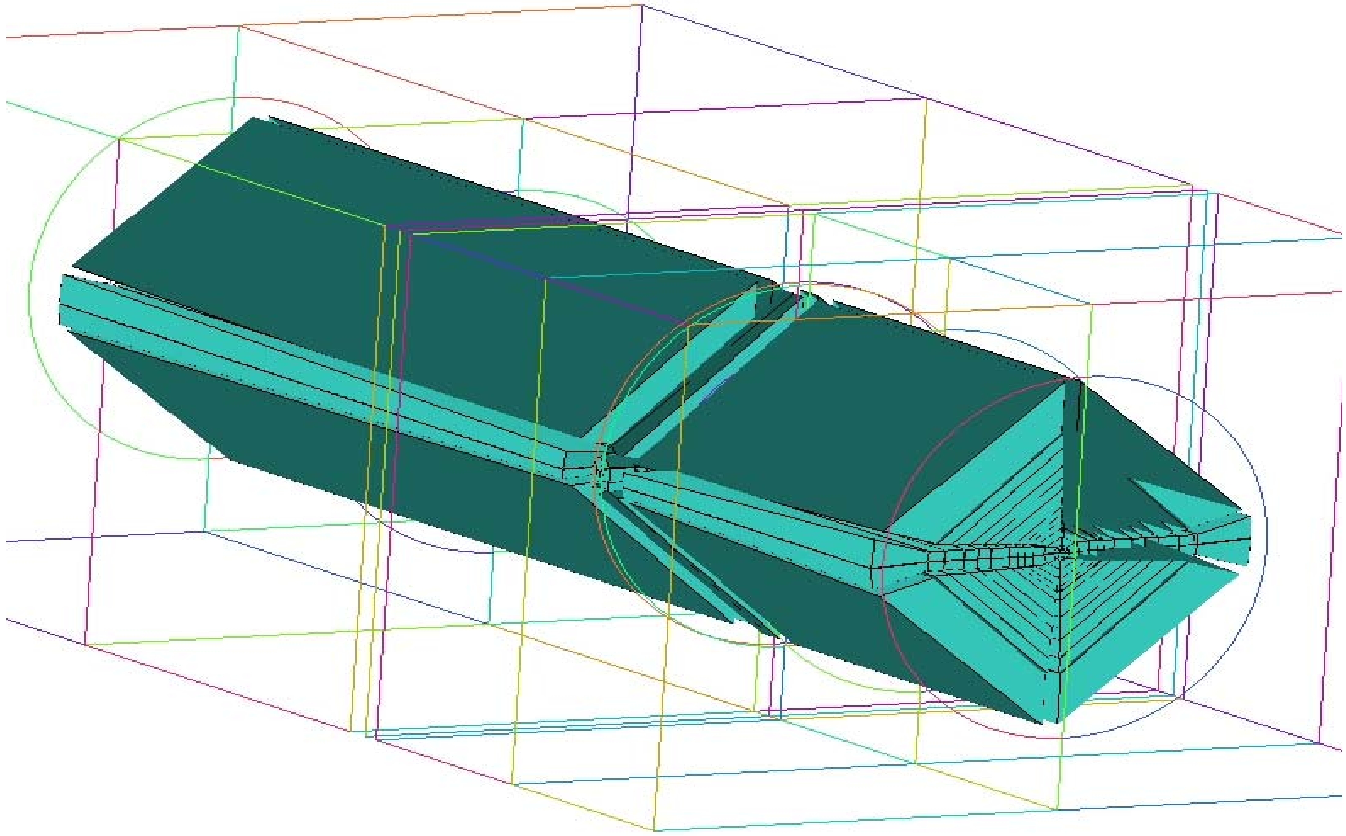
Wind tunnel configuration
Dimensions normalised with the maximum chord in the blade

1 Radius = 6.8 chords

Rotor, Nacelle and Tower Configurations



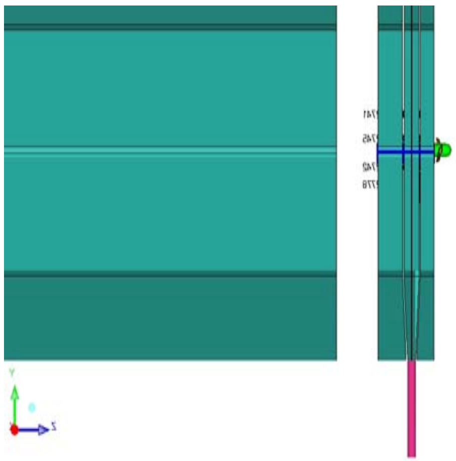
Sliding Grids

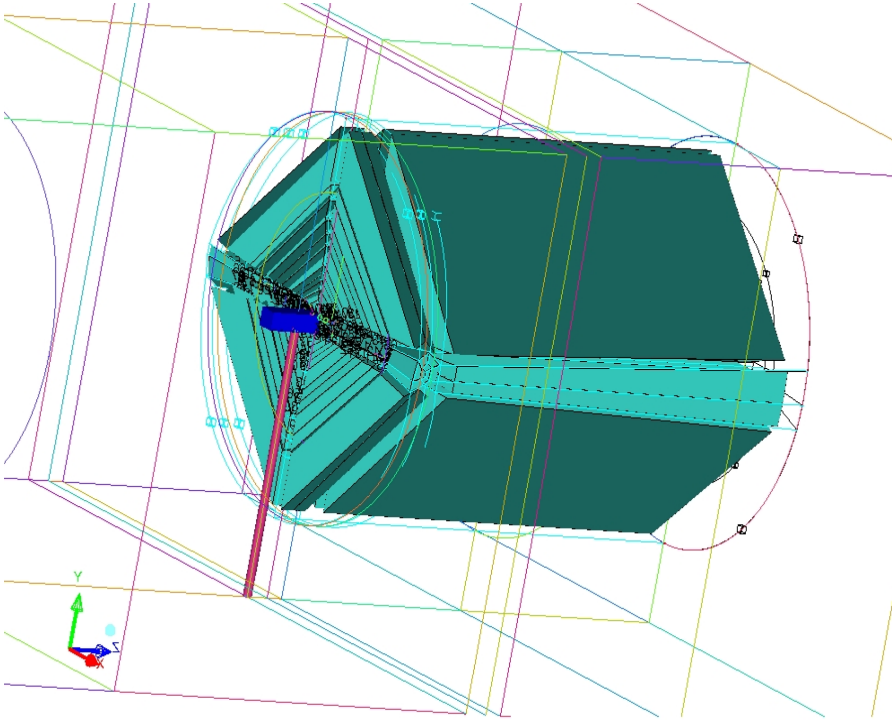


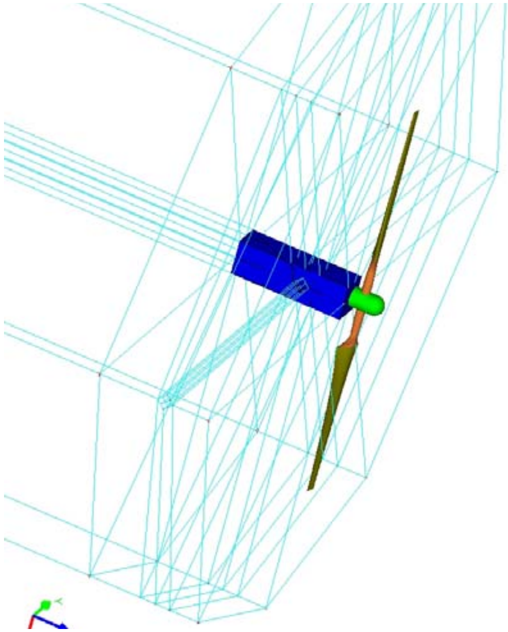
F	F	F
R	R	R
F	F	F

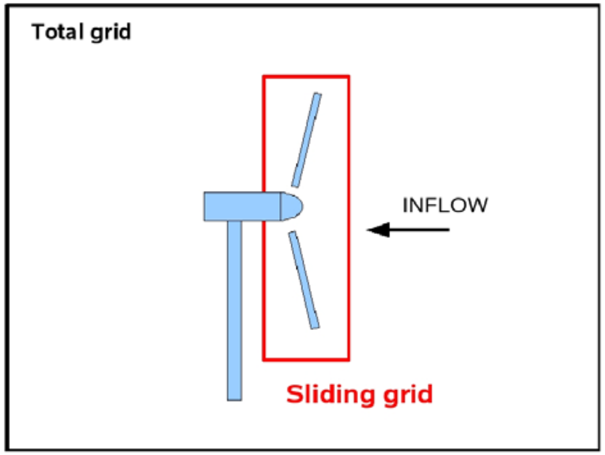
F = Fix
R = Rotating

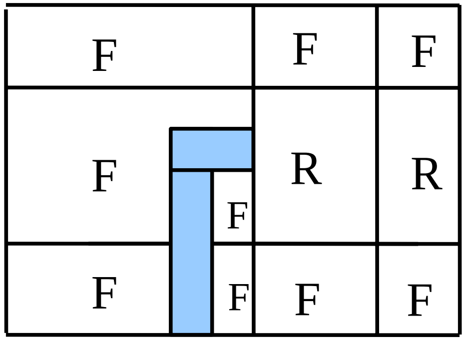
Sliding Grids







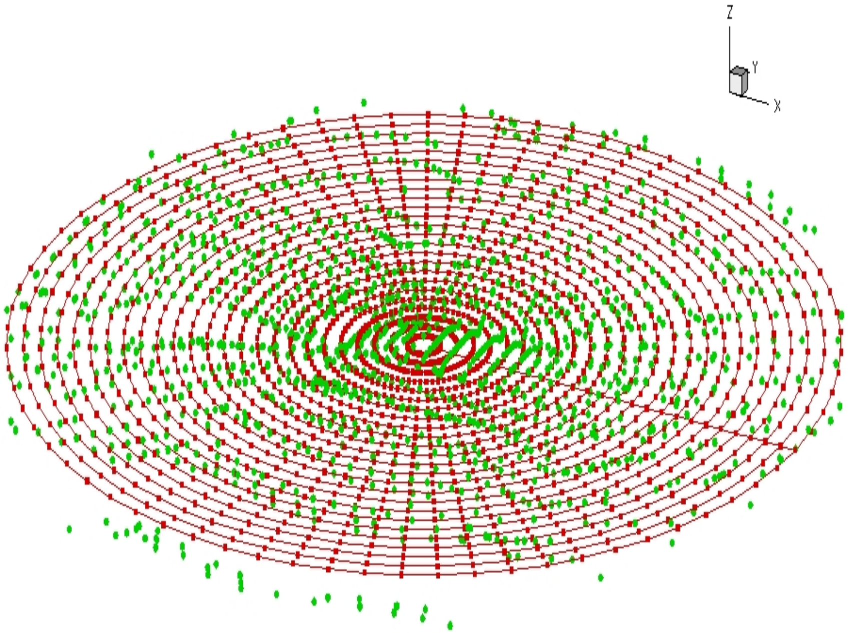




F = Fix
R = Rotating

Sliding Plane Method

- Formation of regular intermediate planes to avoid general cloud-to-cloud interpolations
- Interpolate from fixed mesh to corresponding intermediate planes
- Interpolate from rotating mesh to corresponding intermediate planes
- Set halo-cells on both side of sliding plane using data on intermediate planes
- Intermediate plane data stored on each CPU
- Identification on small patches of regular planes




Questions?