Helicopter Study Weekend

Another Rotary Wing: The Wind Turbine Blade

Sugoi Gómez-Iradi

3rd Year PhD student,
Engineering Department of Liverpool University
Thesis Supervisor: G. Barakos & K. Badcock

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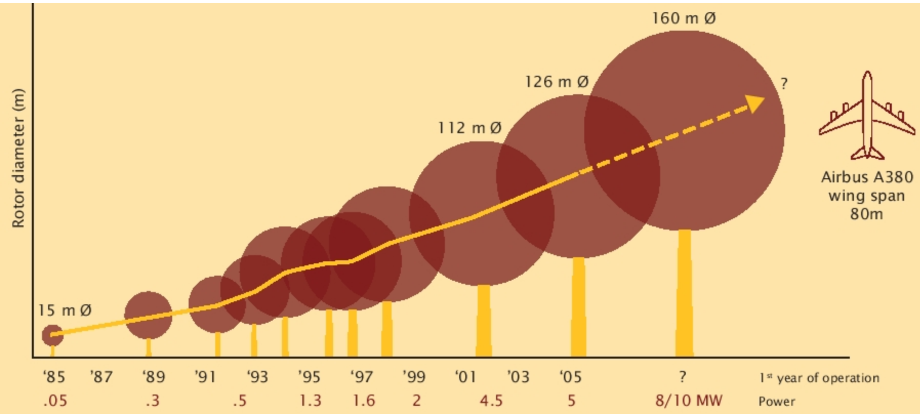
(sugoi@liv.ac.uk)

Background

- The design of large-diameter wind turbines is outside the knowledge envelope of wind turbine manufacturers (Larger diameters wind turbines)
  - Flow compressibility
  - Stalled flow
  - Blade deflection
- CFD base WT design
- The objectives are to take into account compressibility effects, aeroelastic influence and to analyze the computation of HAWT



From EWEA: http://ec.europa.eu/research/energy/nn/nn_pu/renews/005/article_4133_en.htm

Outline

- Description of the CFD solver
- Validation for Wind Turbine flows
  - 2D: S809 aerofoil
  - 3D: Wind tunnel
- Parked and ramping calculations overview
- Steady state calculations and comparisons with unsteady
- Study of geometry and its effect
- Conclusions and future steps

CFD Solver: Summary of Features

- PDE solver (WMB)
- Implicit time marching
- Osher's scheme for convective fluxes
- MUSCL scheme for formally 3rd order accuracy
- Central differences for viscous fluxes
- Multi-block capability
- Paralleled using the SPMD paradigm (just requires MPI)
- Flow Physics: Euler, RANS, URANS, DES
- Aeroelastic analysis based on modal representation of structures
- Moving and deforming grids
- Documentation (Validation database)
- Used by academics and engineers

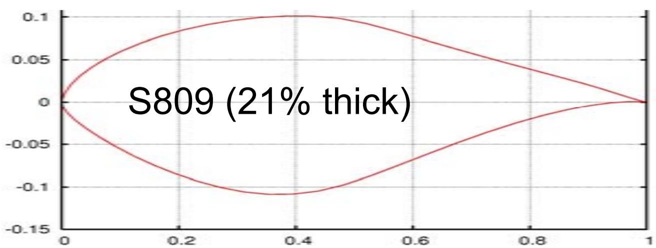
Validation: S809 aerofoil

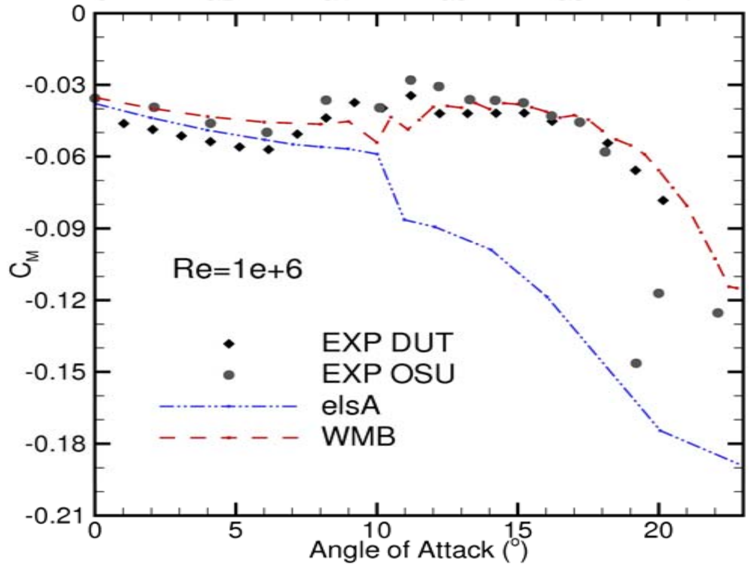
Grid size:

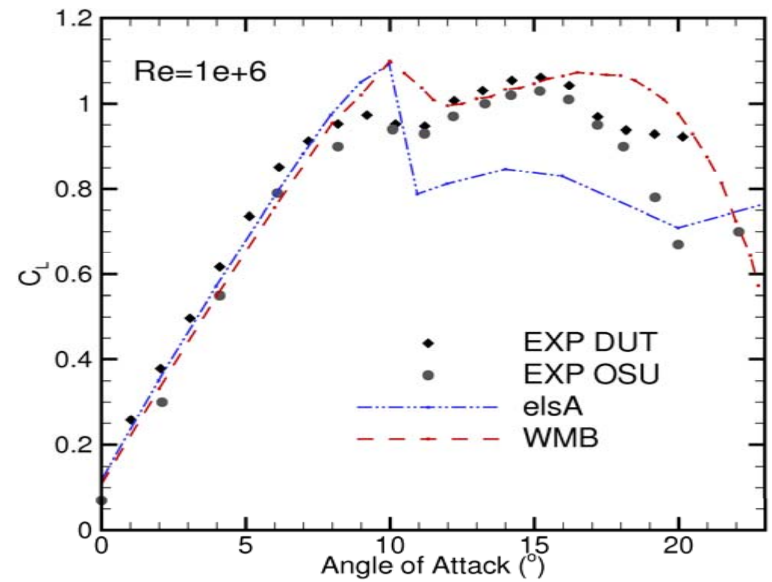
- 19,154 WMB
- 19,215 elsA

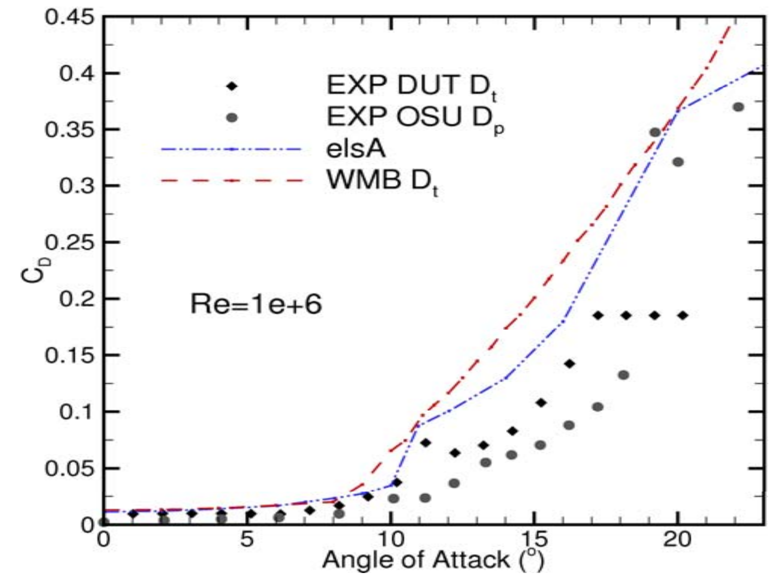
Unsteady calculations above 10° angle of attack

Turbulence model k-ω SST





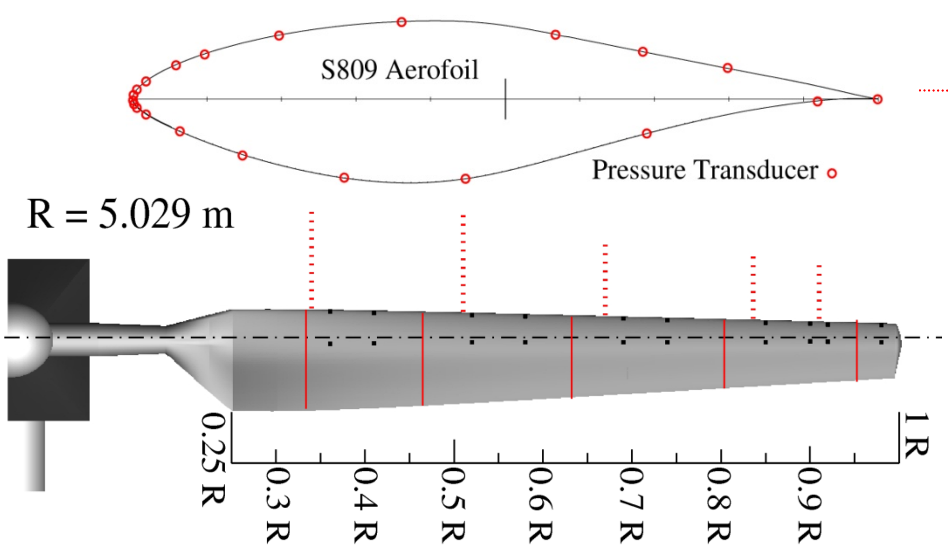




A. Le Pape and J. Lecanu, 3D Navier-Stokes Computations of a Stall-Regulated Wind Turbine, Wind Energy, 7(4):309–324, 2004. DOI:10.1002/we.129.

Data for CFD Validation

- 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
  - 22 Pressure transducers each at 5 span-wise sections
  - Wind tunnel dynamic, static and total pressures, density, temperature, velocity,...



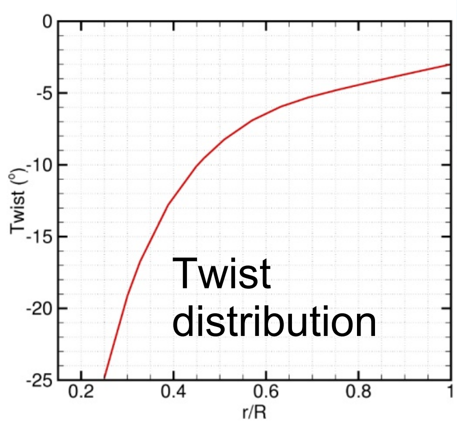
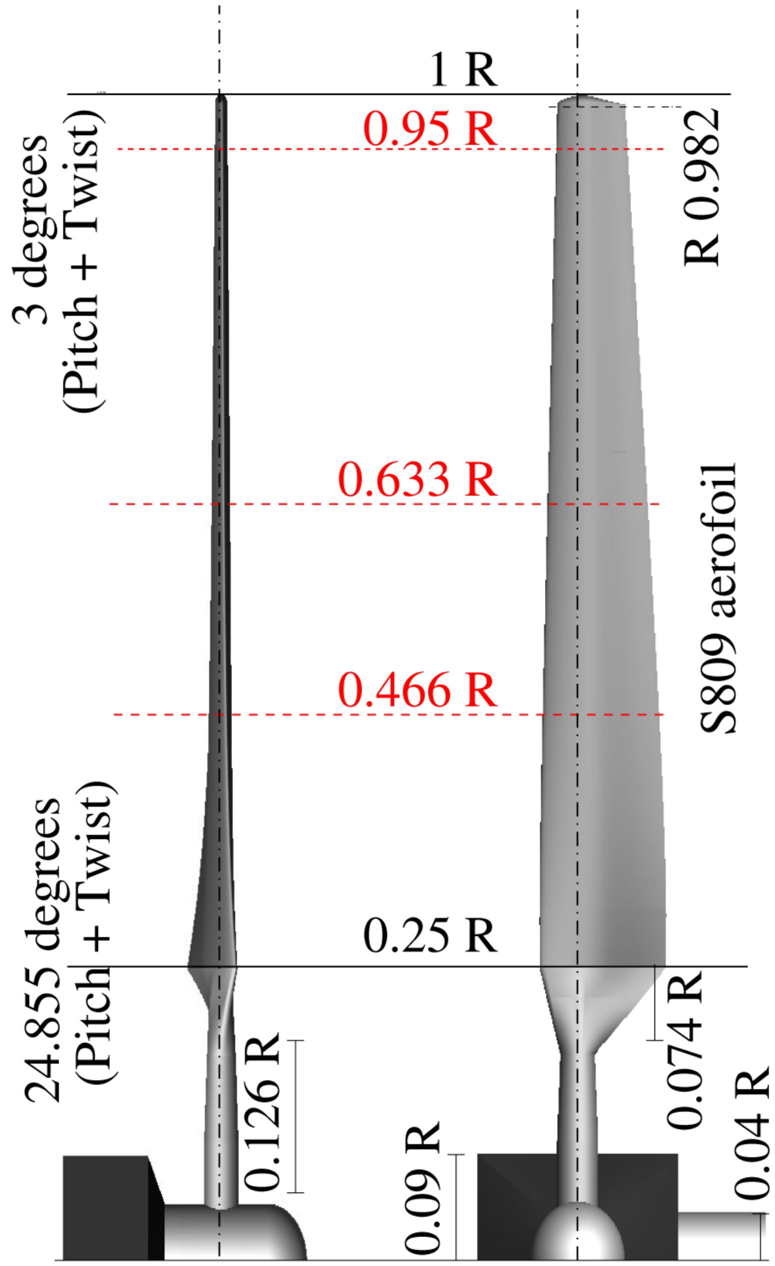
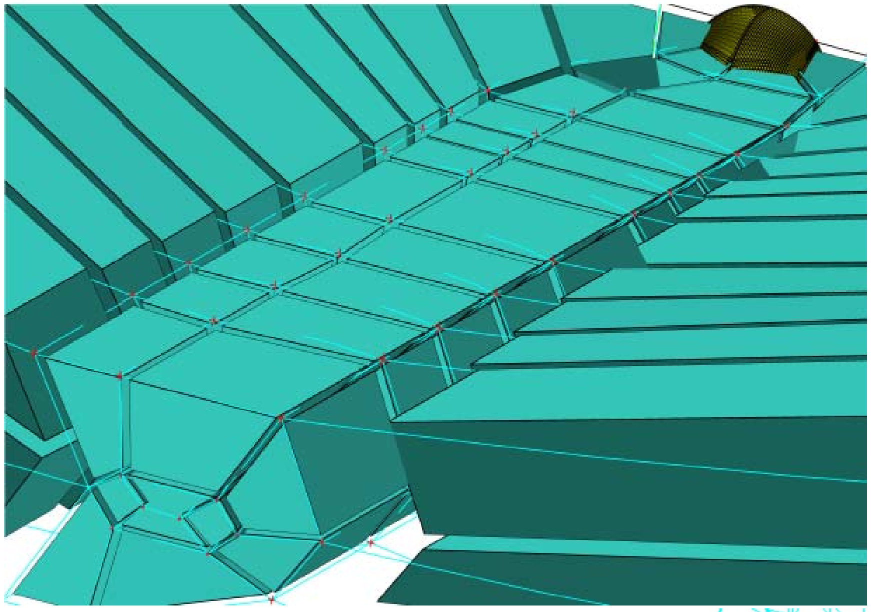
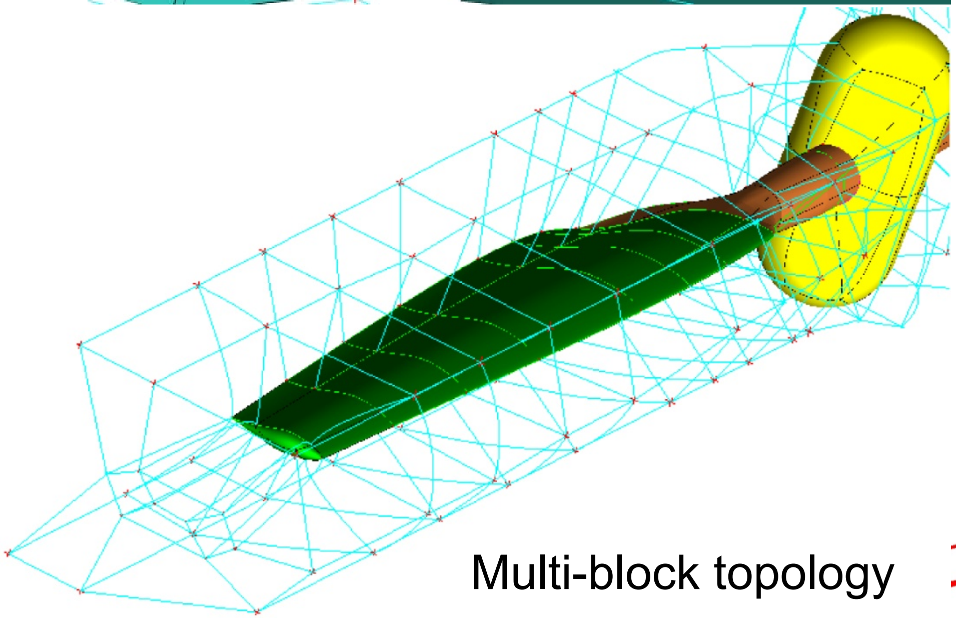


Image taken from M.M. Hand et al. Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns, T.R. NREL/TP-500-29955, NREL, December 2001.







Multi-block topology

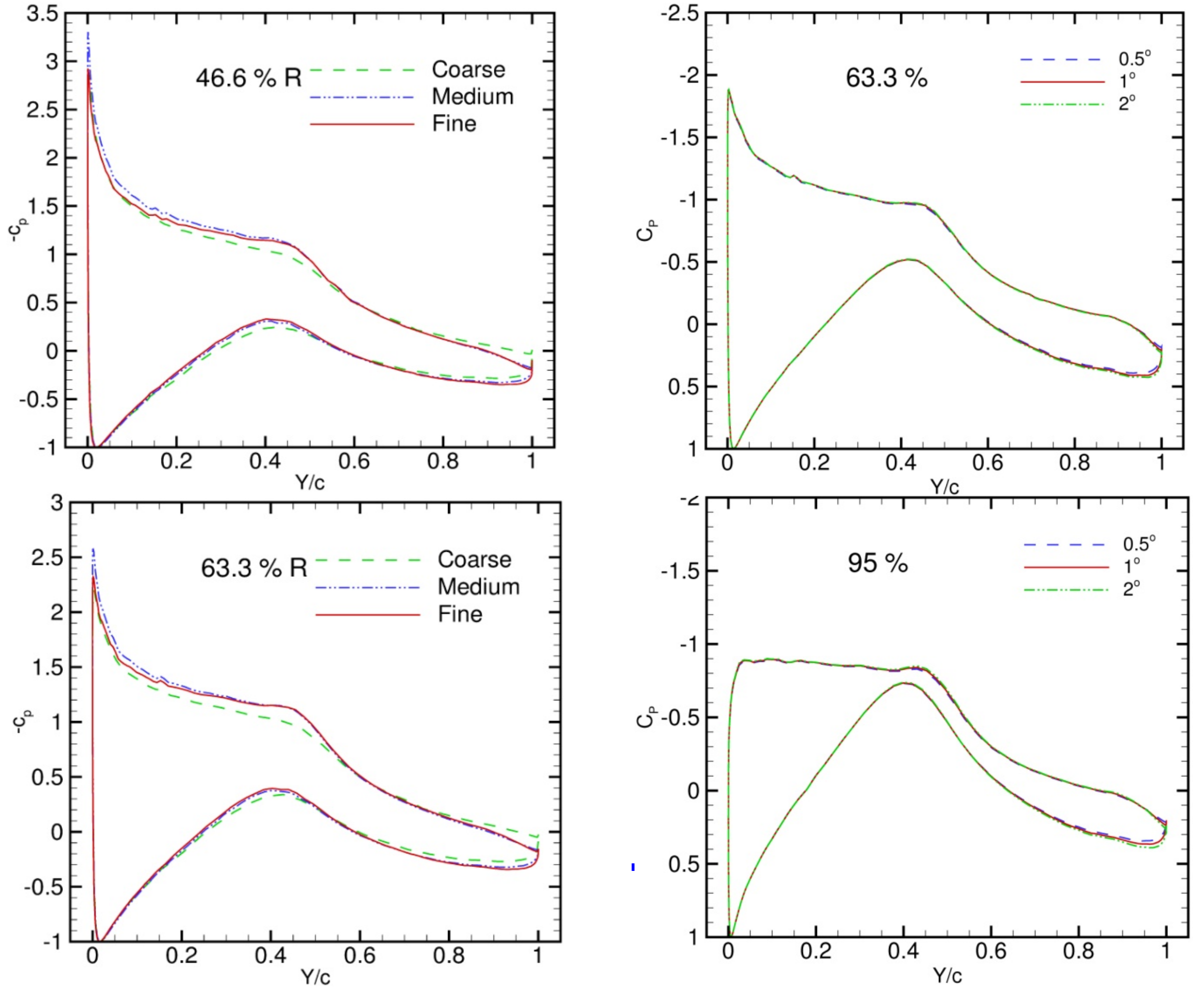
CFD Results - GRID SIZE

- Different grid sizes were analyzed (from 1.3 mill. to 4.6 mill.)
  - The majority of the results were obtained for 3.4 million grid
- Different time steps were analyzed (from 0.5º to 2º in azimuth)

Coarse: 1.3 mill.
59,400 surface points

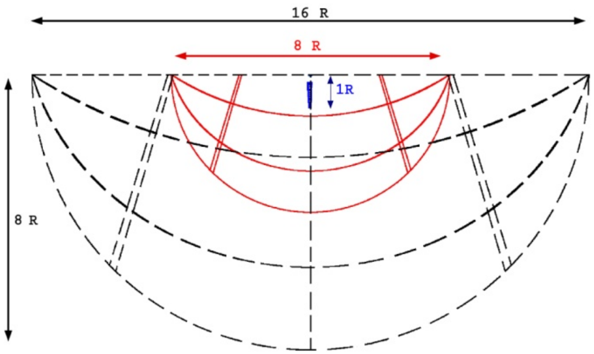
Medium: 3.4 mill.
68,600 surface points

Fine: 4.6 mill.
83,440 surface points

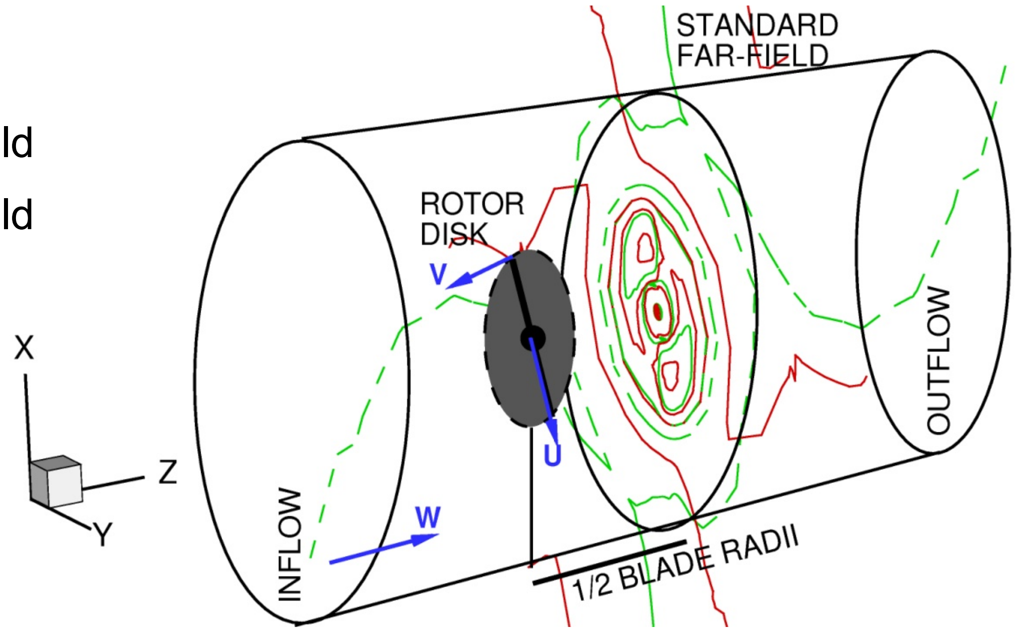


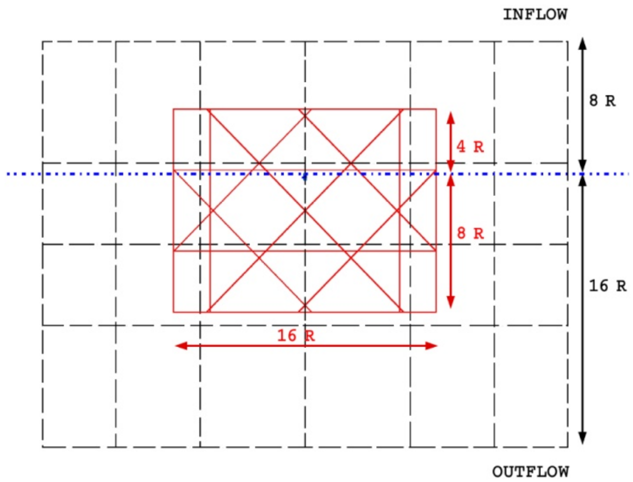
CFD Results - Far-Field Location

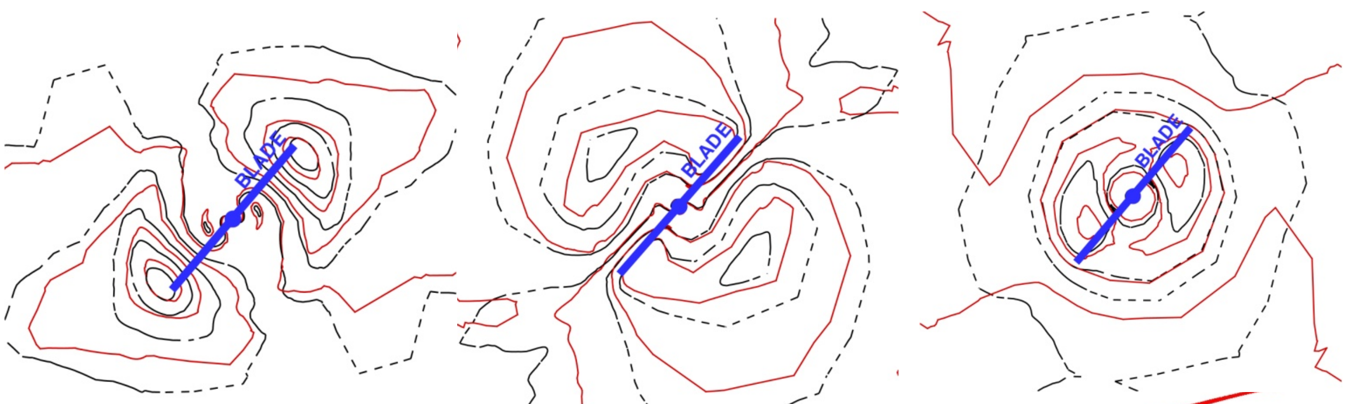
- Effect of far-field location was analyzed
  - From 2 blade radii inflow, 4 R outflow and 4 R far-field
  - From 4 blade radii inflow, 8 R outflow and 8 R far-field



Contours are taken half radii downwind wind turbine







U velocity

V velocity

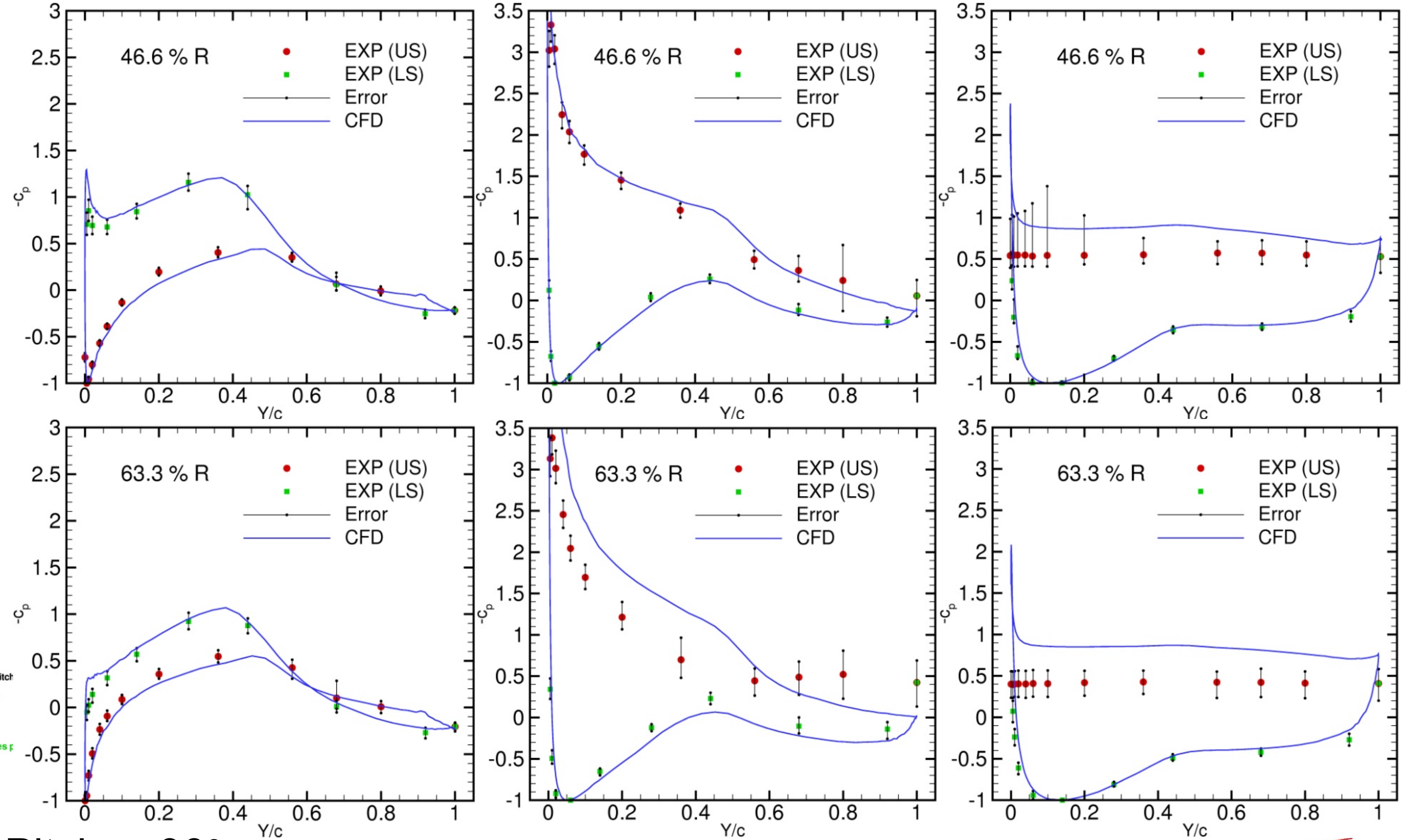
W velocity

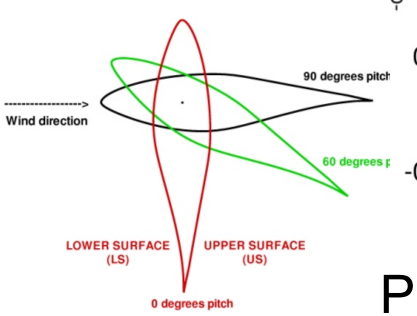
Parked and Ramping

20 m/s

Grid size: 2,416,584

Turbulence model: k-ω



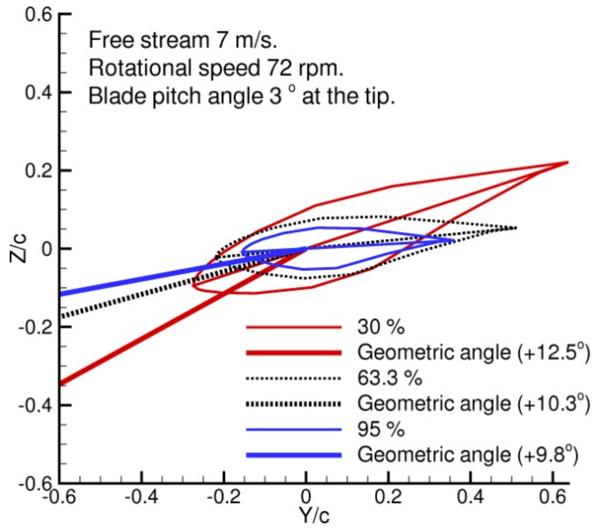


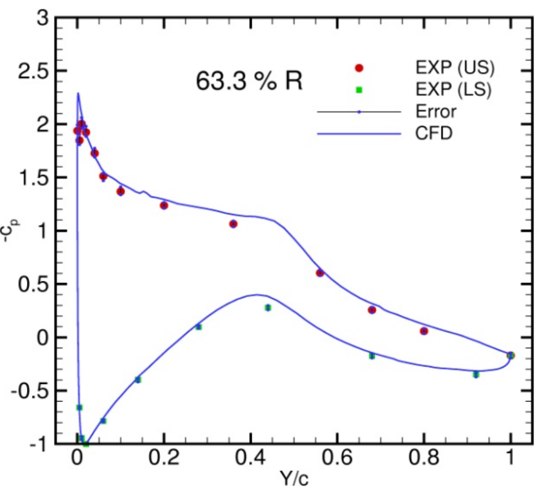
Pitch: 90° 70° 40°

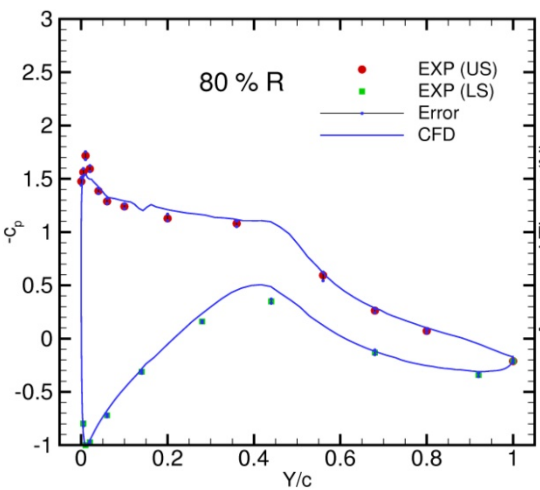
Positive pitch when the LE changes towards the inflow

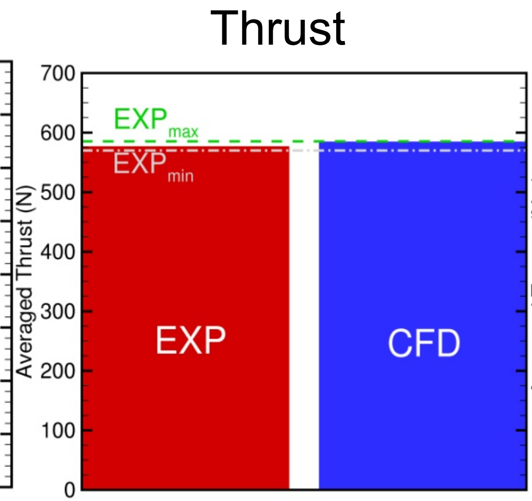
7 m/s Wind: Working Conditions

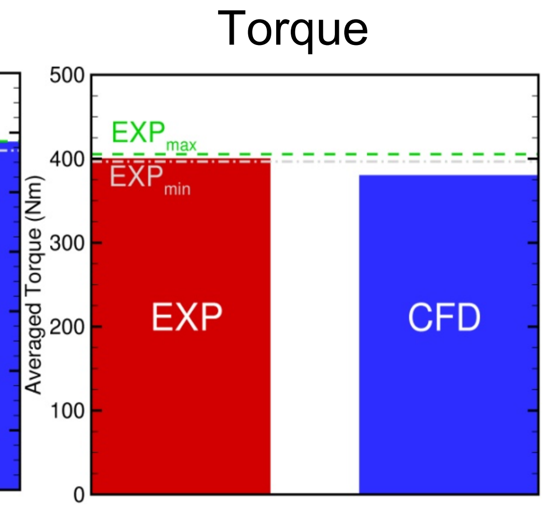
- Assumptions:
  - No tower
  - Steady and attached flow
  - 3 full rotations
- Grid and CFD computation:
  - 3.4 mill. cells
  - k-ω turbulence model









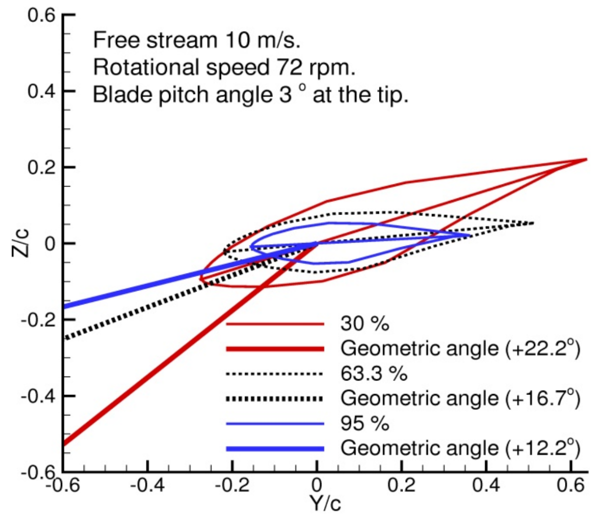


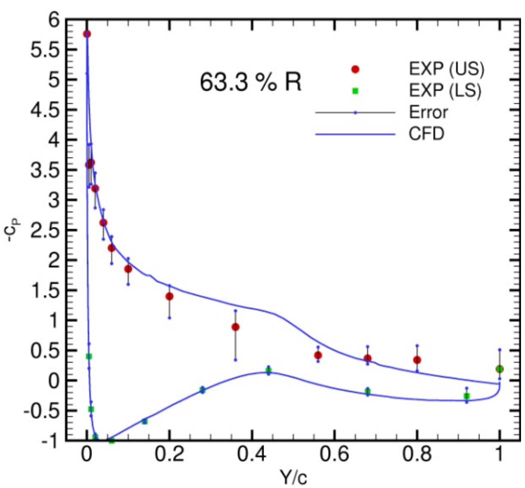
Run number: S0700000

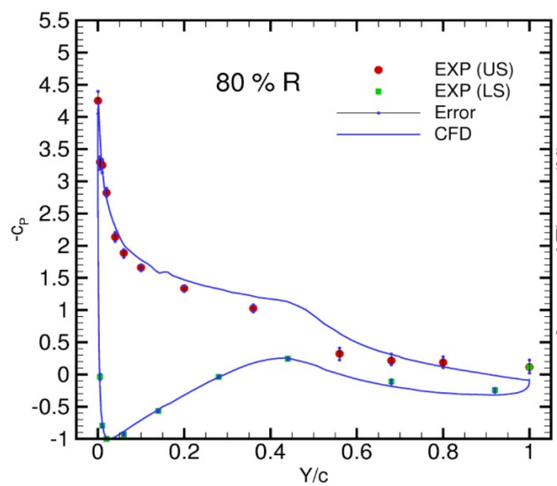
10 m/s Wind: Stalled Flow

- Assumptions:
  - No tower
  - Attached and separated flow
  - 3 full rotations

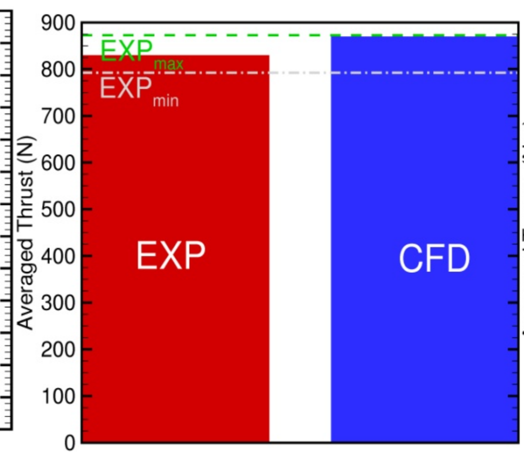
- Grid and CFD computation:
  - 3.4 mill. cells
  - k-ω turbulence model



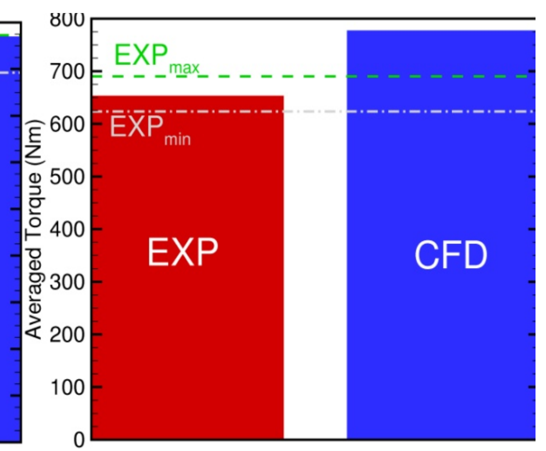




Thrust



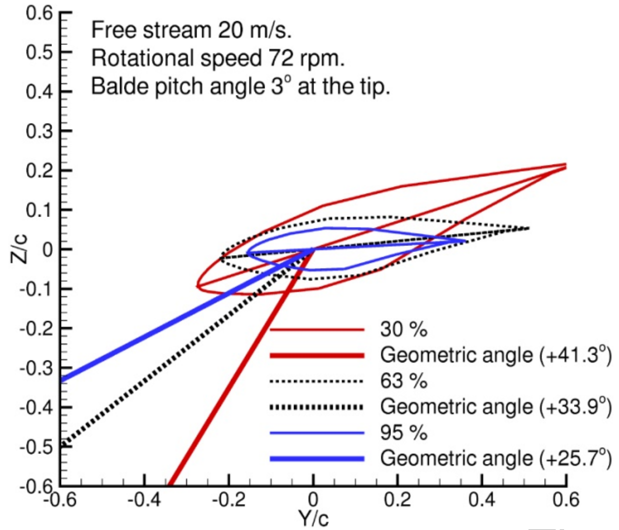
Torque

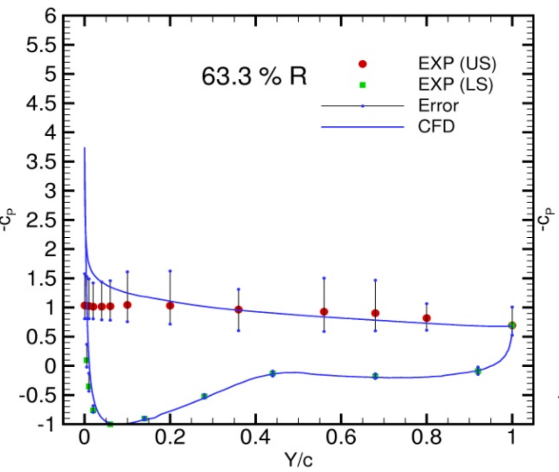


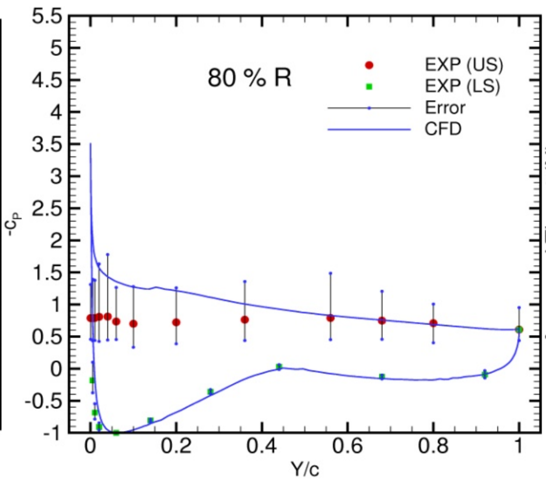
Run number: S1000000

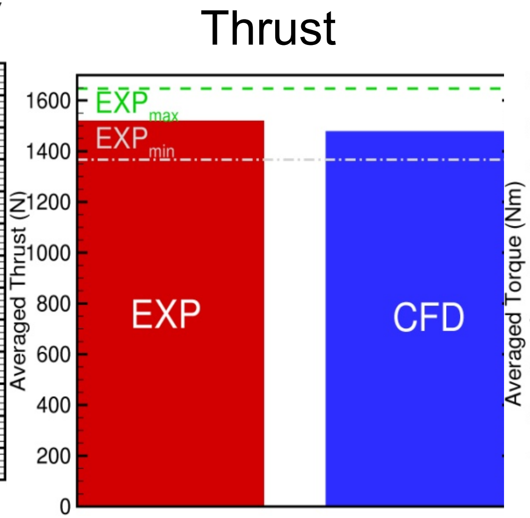
20 m/s Wind: Deep Stalled Flow

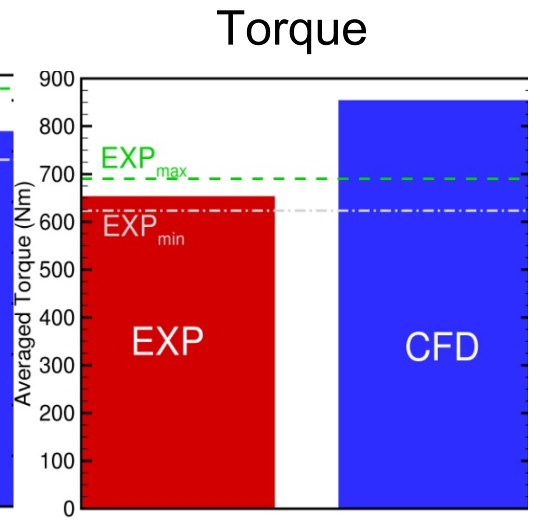
- Assumptions:
  - No tower
  - Stalled flow
  - 3 full rotations
- Grid and CFD computation:
  - 6.4 mill. cells
  - k-ω turbulence model





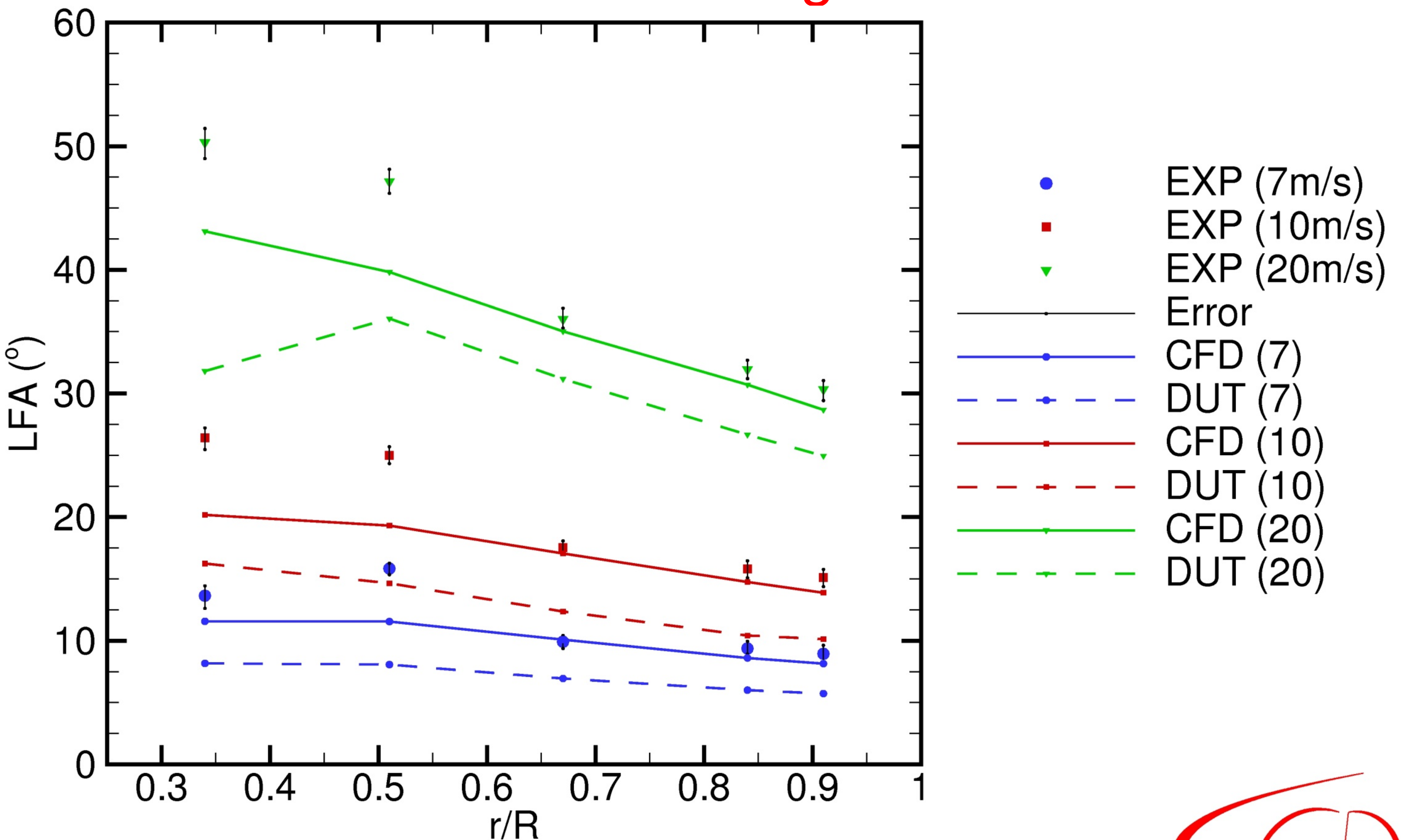






Run number: S2000000

Local Flow Angles

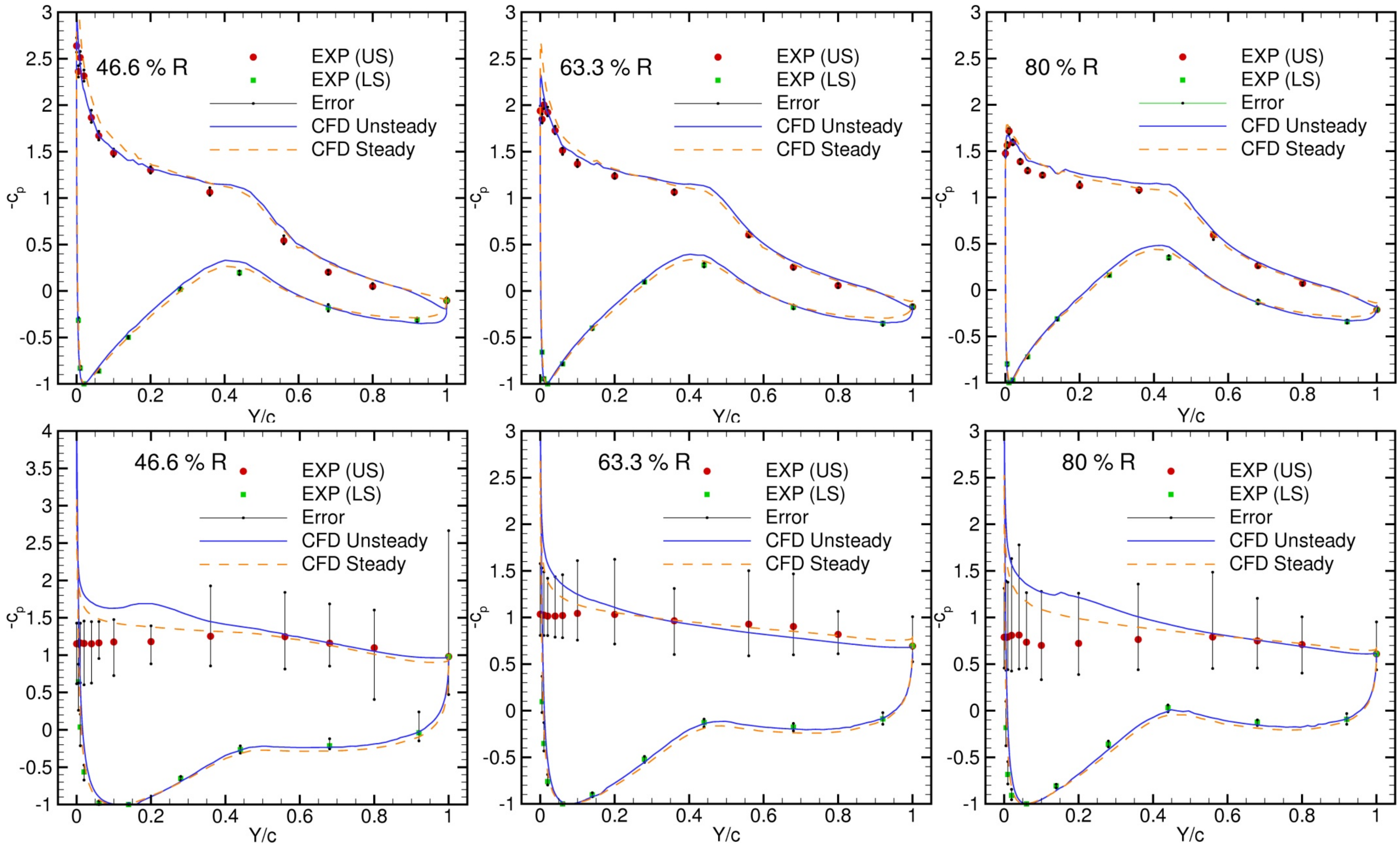


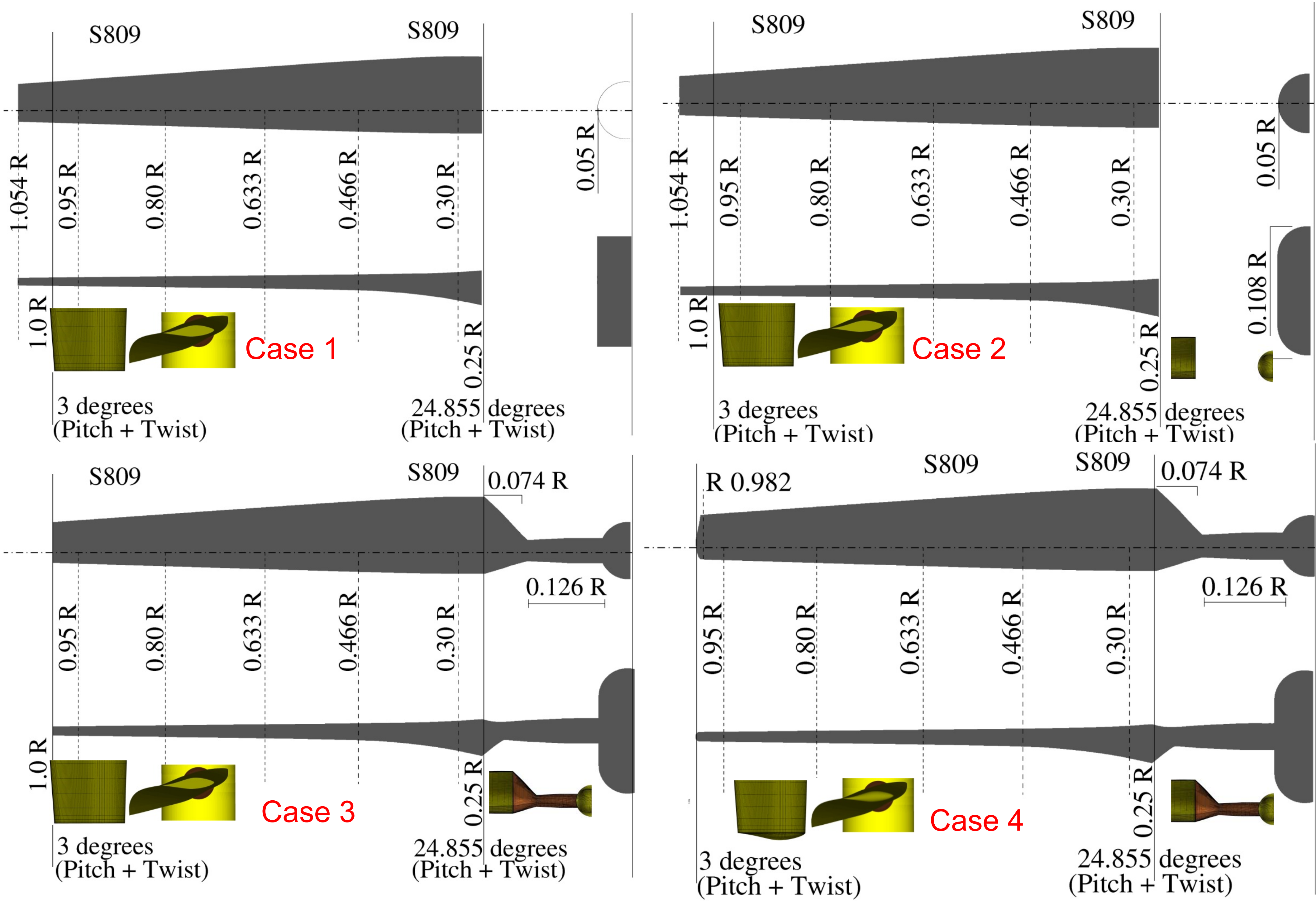
T. Sant, G. van Kuik and G.J.W. van Bussel, Estimating the Angle of Attack from Blade Pressure Measurements on the NREL Phase VI Rotor Using a Free Axial Conditions, Journal of Wind Energy, 9:549–577, 2006. DOI:10.1017/we.201

"Steady State" Calculations

7 m/s

20 m/s

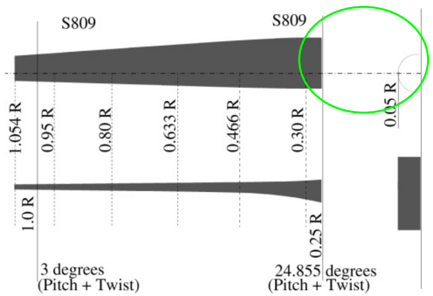




S809
S809
1.054 R
0.95 R
0.80 R
0.633 R
0.466 R
0.30 R
0.05 R
1.0 R
0.25 R
Case 1
3 degrees
(Pitch + Twist)
24.855 degrees
(Pitch + Twist)
S809
S809
1.054 R
0.95 R
0.80 R
0.633 R
0.466 R
0.30 R
0.05 R
0.108 R
1.0 R
0.25 R
Case 2
3 degrees
(Pitch + Twist)
24.855 degrees
(Pitch + Twist)
S809
S809
0.074 R
0.126 R
0.95 R
0.80 R
0.633 R
0.466 R
0.30 R
1.0 R
0.25 R
Case 3
3 degrees
(Pitch + Twist)
24.855 degrees
(Pitch + Twist)
R 0.982
S809
S809
0.074 R
0.126 R
0.95 R
0.80 R
0.633 R
0.466 R
0.30 R
0.25 R
Case 4
3 degrees
(Pitch + Twist)
24.855 degrees
(Pitch + Twist)

CFD Results

1



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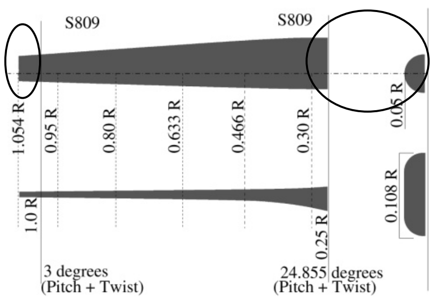

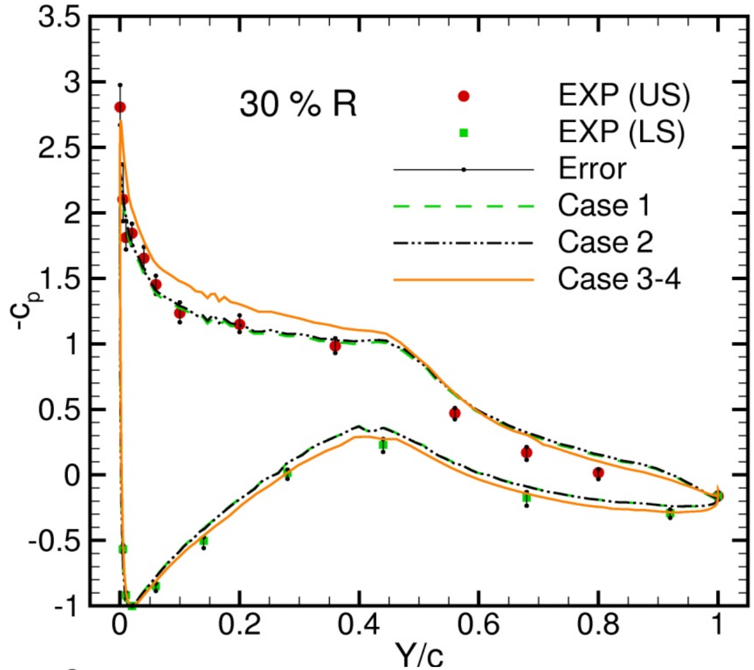

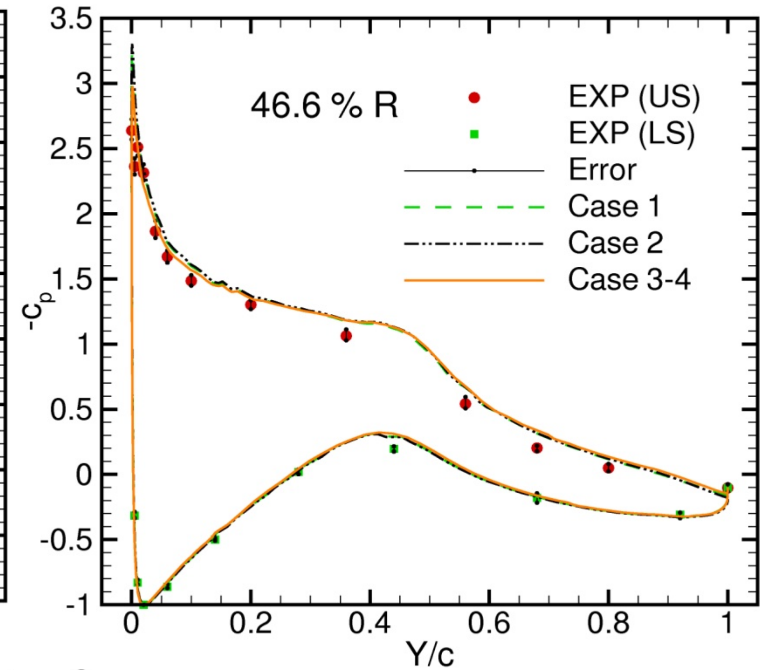

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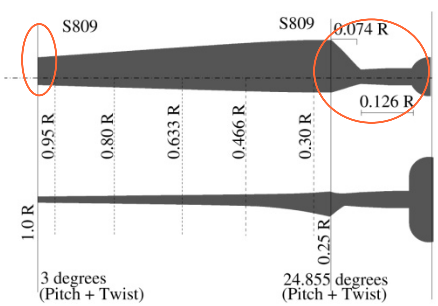

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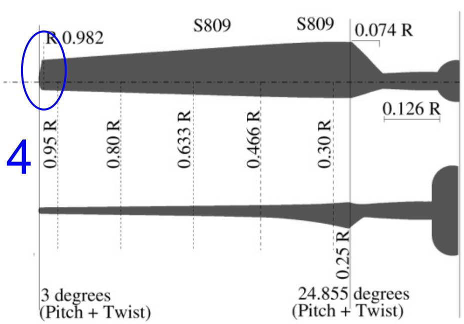
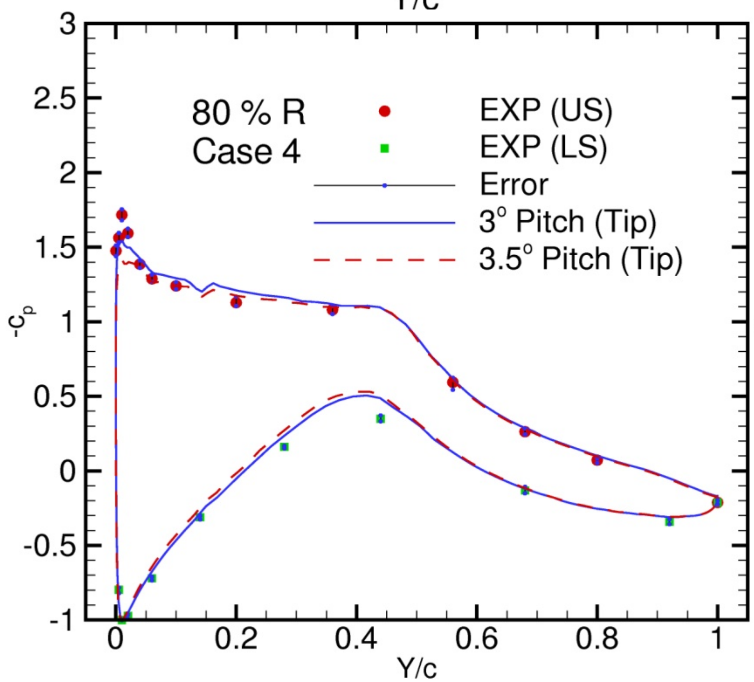
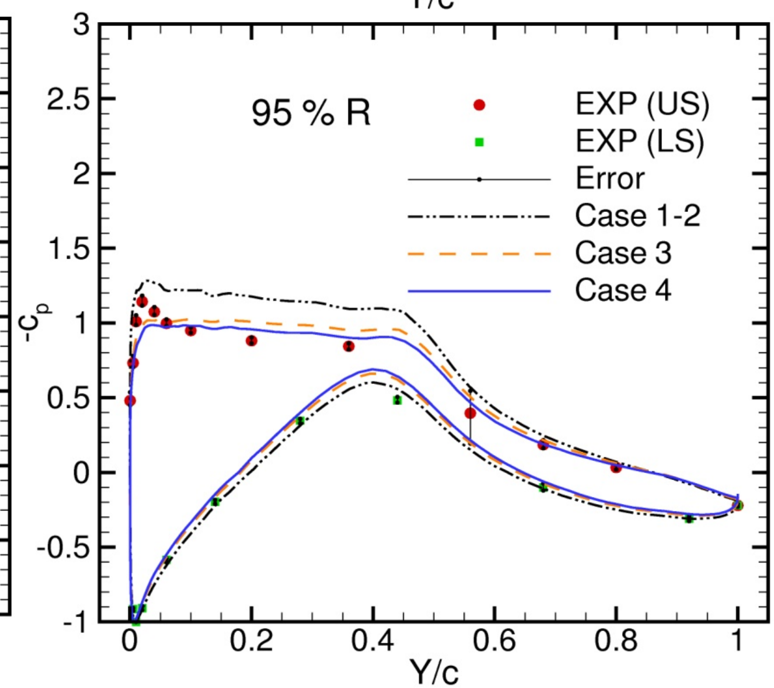
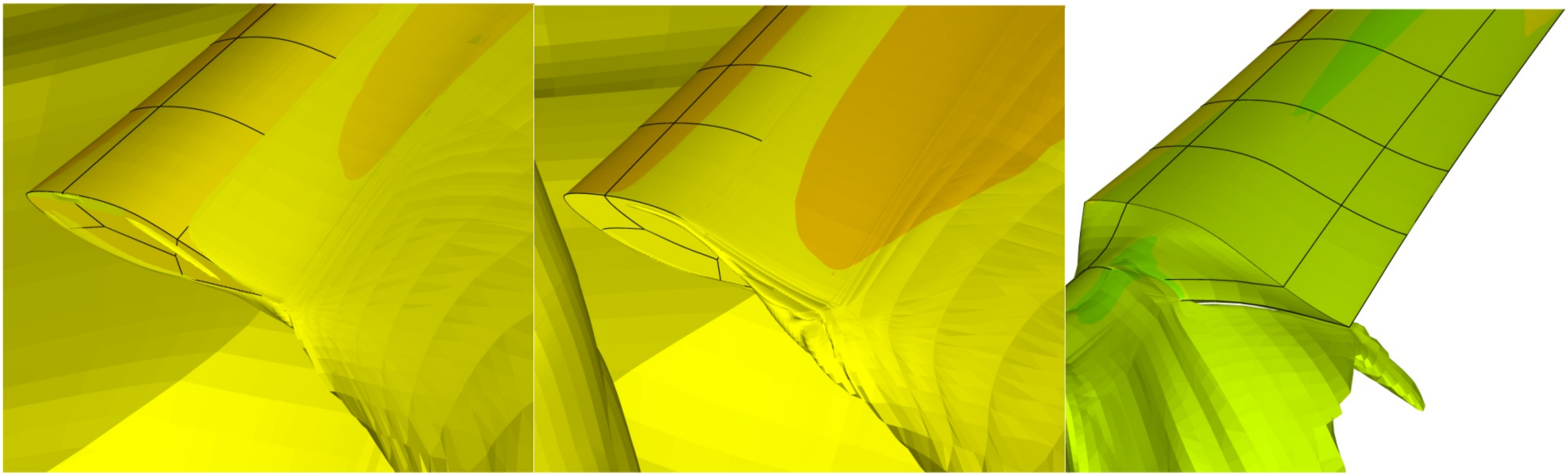


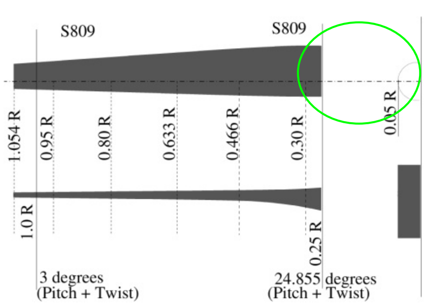




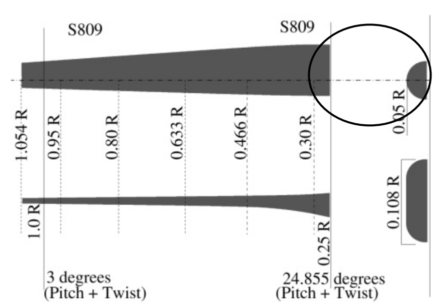
CFD Results: Flow Visualization - ROOT



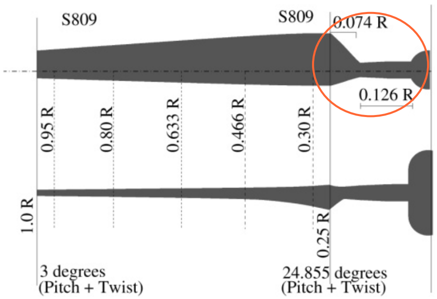
Case 1



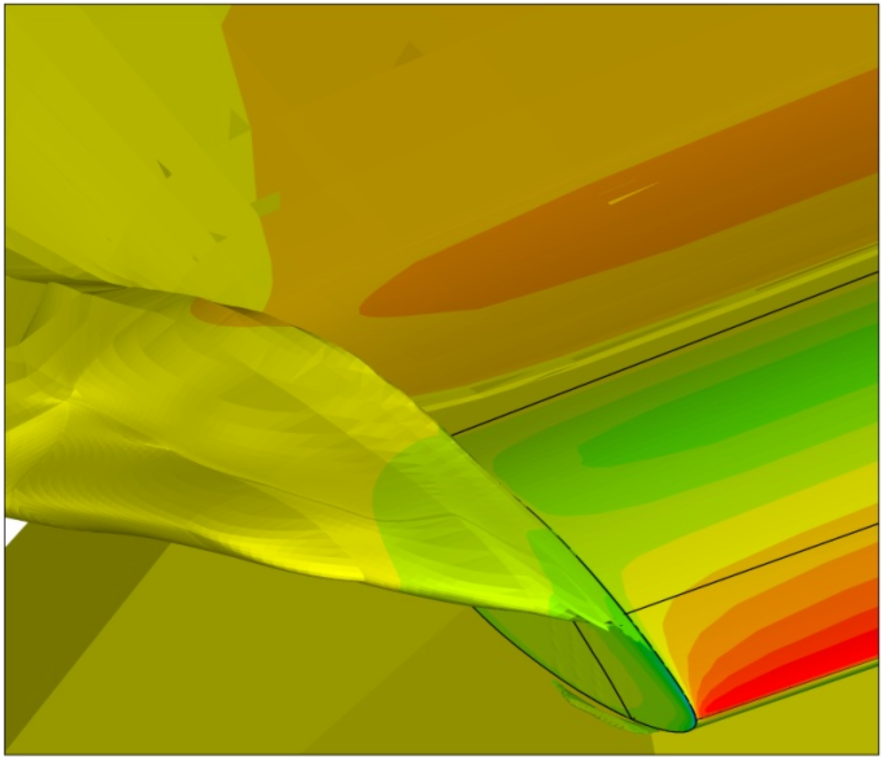
Case 2

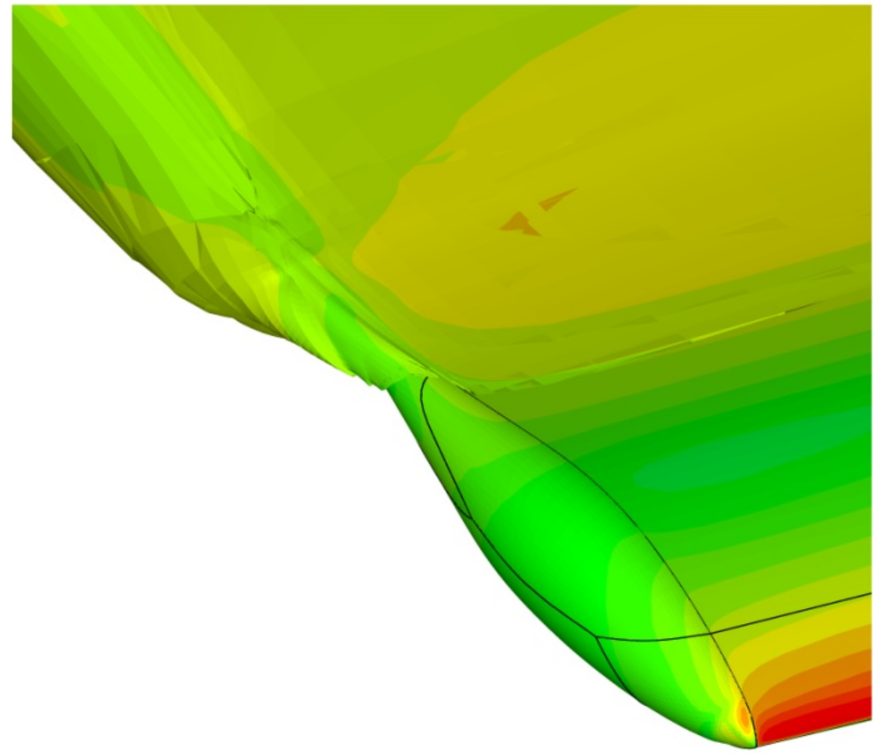


Case 3-4

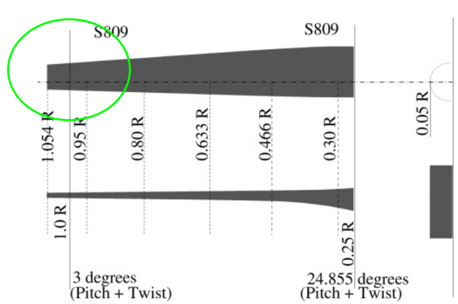


CFD Results: Flow Visualization - TIP

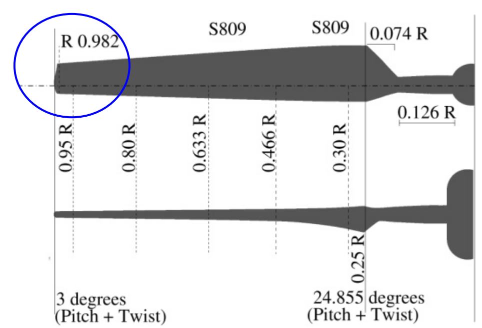




Case 1-2

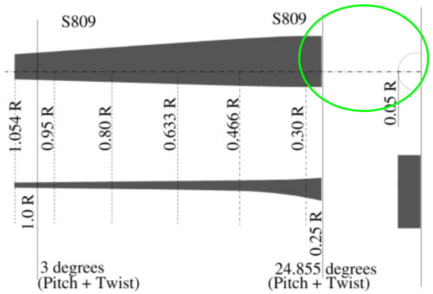


Case 4



CFD Results

Thrust & Torque

1


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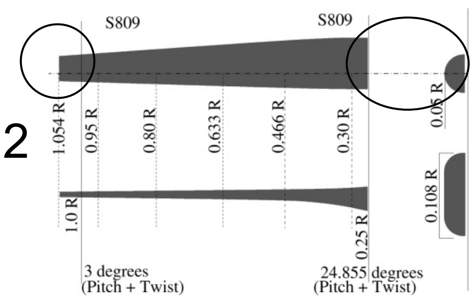

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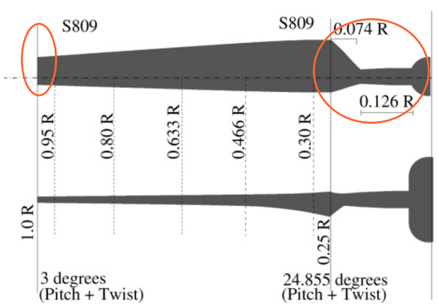

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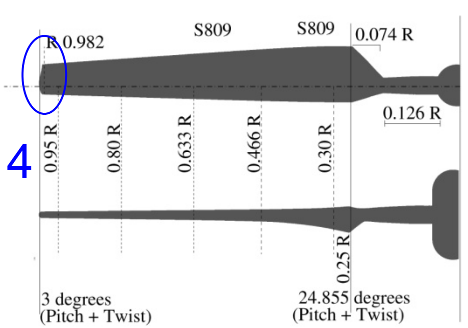
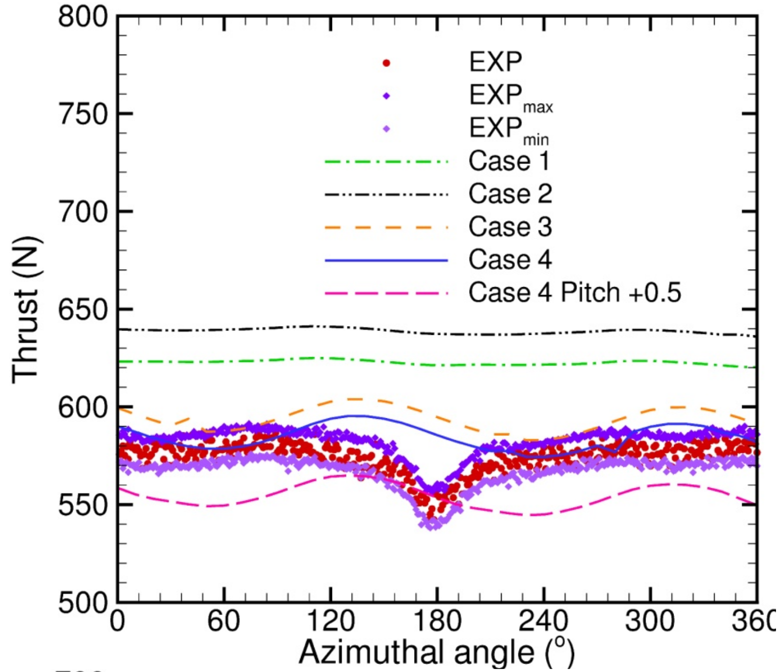
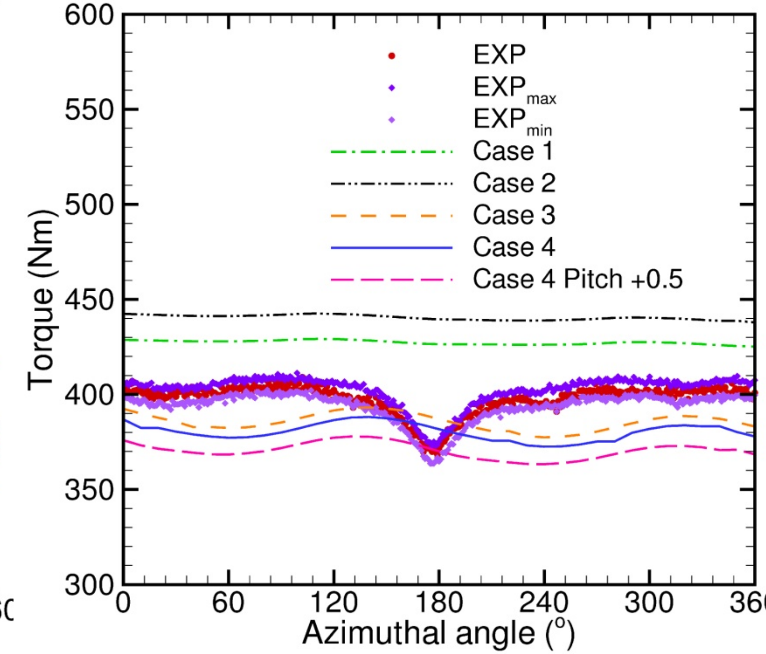
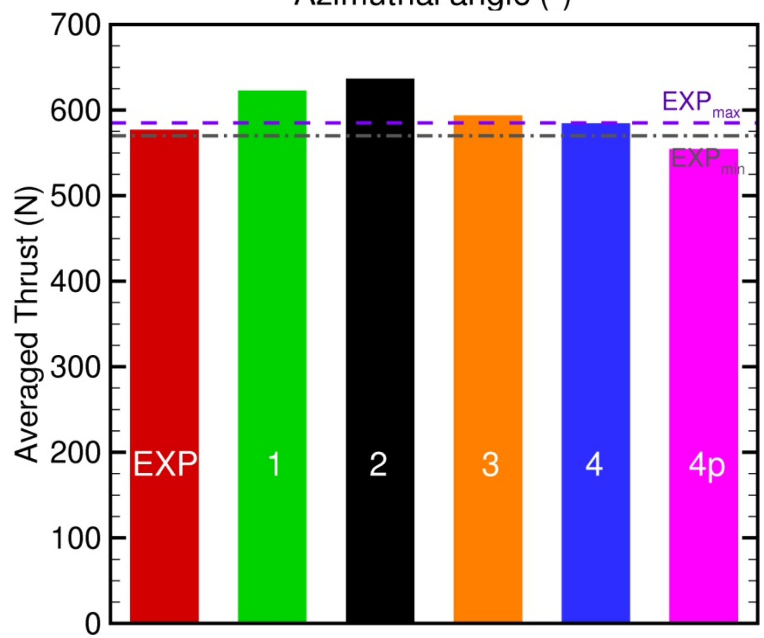
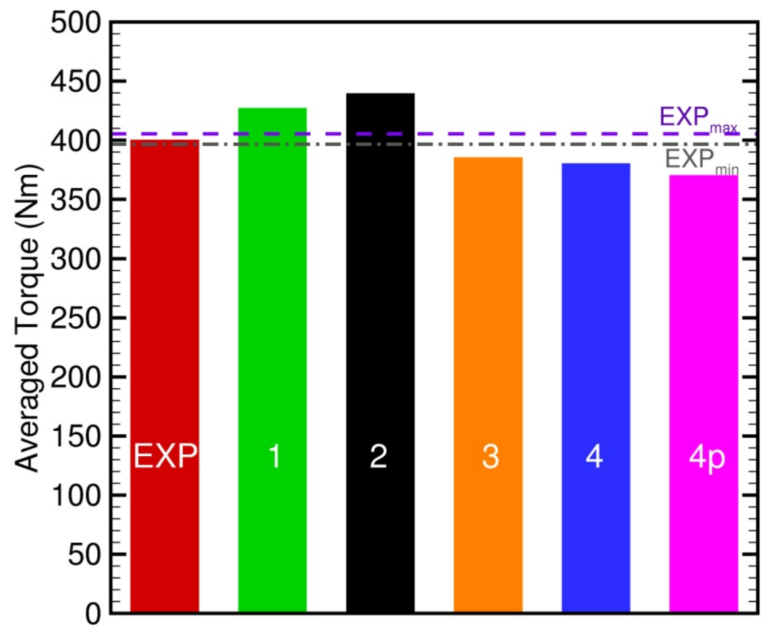


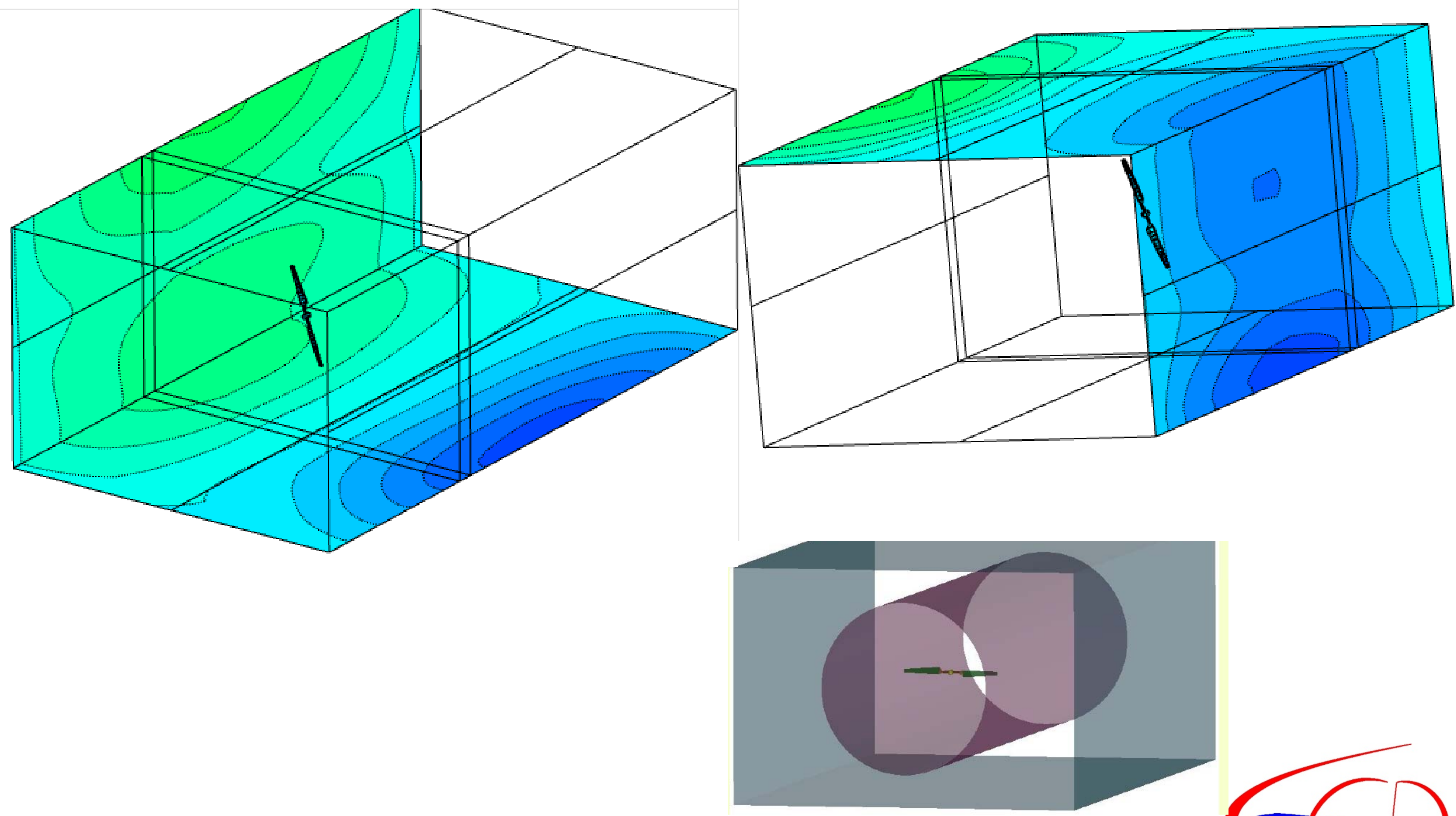








Sliding Grids



Summary and Next Steps

CFD solver was validated for working conditions.

- Stalled flow needs further investigation

Blade geometry variations were studied and their sensitivity analyzed.

- Aspect ratio and adequate pitch are essential outputs as expected.
    - 5.4 % longer blade increases the thrust and torque in 10%.
    - 0.5^{o} pitch angle differences affects more than 5 % in the total thrust.
- Tip and root sections have smaller role and can be neglected for first calculations.
    - Thrust and torque difference between rounded and flat tips less than 1%.

Next step will be using the sliding grid technique to analyze the effects of the tower, nacelle and the ground in the wind turbine aerodynamics.

LABORATORY