Validation of AVATAR airfoils using SU2 code

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Overview

Objectives

- Verify the SU2 software as a reliable CFD solver for the AVATAR project.
- Validate the results of the AVATAR partners using the SU2 software and investigate the different results obtained through different methods.
- Investigate the influence of the various mesh types and parameters on the solution accuracy and time.
- Observe and verify the speedup obtained by running the SU2 software on a cluster and investigate its effect on the solution time.

Why Stanford SU2 code ?

- Open-source, Unstructured CFD solver.
- PDE - constrained optimization and aerodynamic shape optimization capabilities.
- Modular Object Oriented (C++) code which increases flexibility and ease of implementation of new equations.
- Tested for various aerodynamic problems.

Methodology and tools

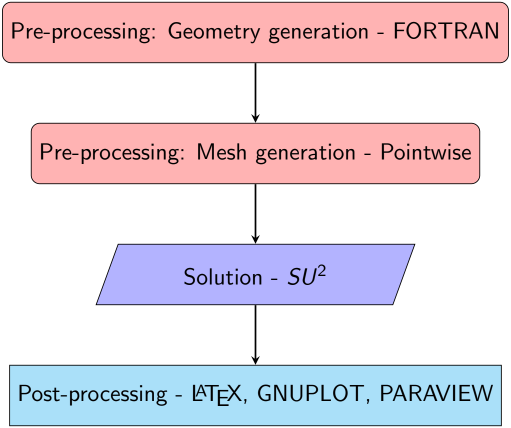


Table: System configuration of each of the nodes in the HPC cluster, Reynolds

Configuration	Value
Model Name:	Intel(R) Xeon(R) CPU E5-2670 @2.30GHz
Threads per core	2
Cores per socket	12 (or 18)
Sockets	2
NUMA nodes	2
L1d Cache	32K
L1i Cache	32K
L2 Cache	256K
L3 Cache	30720K

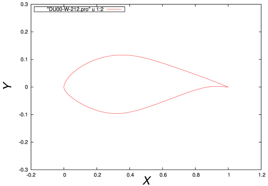
Total number of cores available were: $13 \times (12 \times 2) + 2 \times (18 \times 2) = 384$

Airfoil Geometries

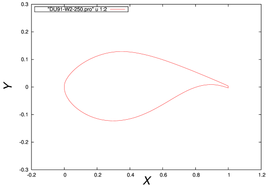
Geometry parameters

- DU00-W-212 : Maximum thickness is 21.2 % of the chord length.
- DU91-W2-250 : Maximum thickness is 25.0 % of the chord length.
- DU97-W-300 : Maximum thickness is 30.0 % of the chord length.
- DU00-W2-350 : Maximum thickness is 35.0 % of the chord length.
- DU00-W2-401 : Maximum thickness is 40.1 % of the chord length.

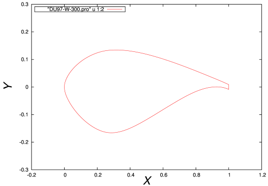
Airfoil Geometries



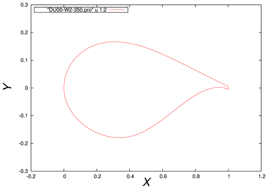
(a) DU00-W-212



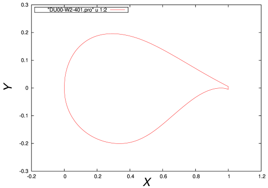
(b) DU91-W2-250



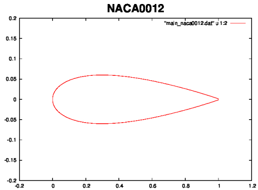
(c) DU97-W-300



(d) DU00-W2-350



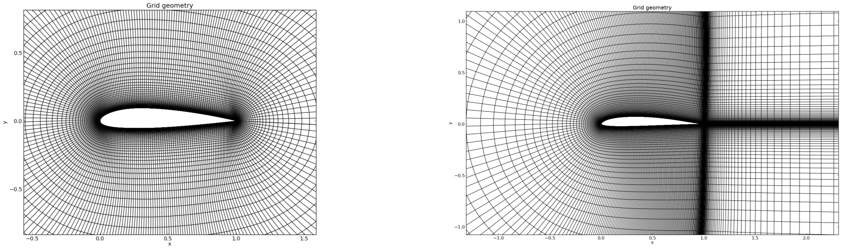
(e) DU00-W2-401



(f) NACA 0012

Figure: Airfoil Geometries

Airfoil Mesh



(a) Orthogonal, O grid

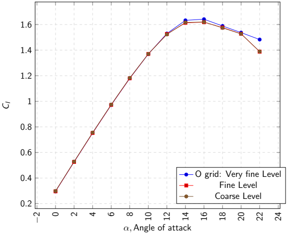
(b) Orthogonal, C grid

Figure: Airfoil Mesh types

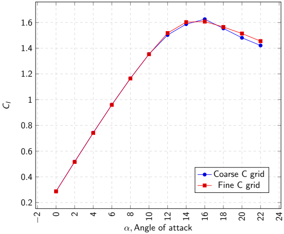
Mesh Independence study

Table: Mesh independence study characteristics

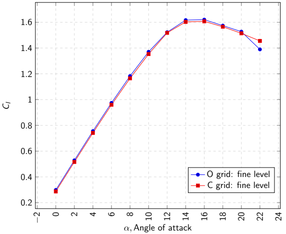
Sl.No.	No of cells	Coarse or Fine	Type of mesh	Δs
1	374750	Very fine	Structured-O Grid	1.1×10^{-6}
2	245754	Fine	Structured-O Grid	2.2×10^{-6}
3	117764	Coarse	Structured-O Grid	4.4×10^{-6}
4	292032	Fine	Structured-C Grid	2.2×10^{-6}
5	163064	Coarse	Structured-C Grid	4.4×10^{-6}



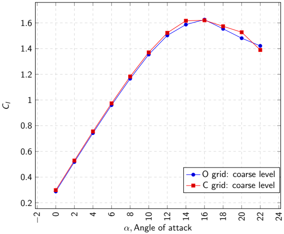
(a) O grid comparison



(b) C grid comparison

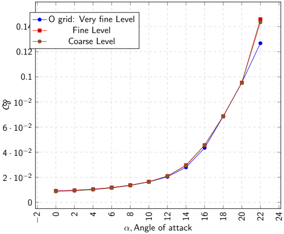


(c) C & O grids at fine level

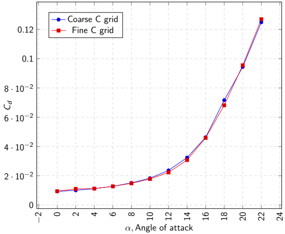


(d) C & O grids at coarse level

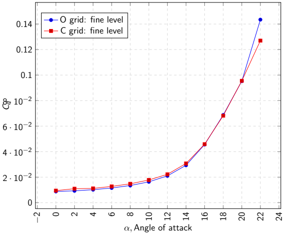
Figure: C_l: Mesh independence study of DU-00-W-212 at Re $= 13 \times 10^6$



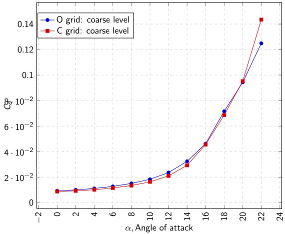
(a) O grid comparison



(b) C grid comparison



(c) C & O grids at fine level



(d) C & O grids at coarse level

Figure: C_d: Mesh independence study of DU-00-W-212 at Re $= 13 \times 10^6$

Mesh Independence study

Table: Mesh independence simulation timings in min

Mesh Type	Till $\alpha = 20$	Till $\alpha = 22$	Till $\alpha = 24$
Very fine O grid	2184	2513	3848
Fine O grid	795	924	1829
Coarse O grid	286	706	1129
Fine C grid	1903	2954	4005
Coarse C grid	2044	2644	3244

Which level of mesh to choose ?

1. Error percentages should be observed for Angles of attack lesser than 12 degrees, below which there is no separation visible and a criteria which takes into account the time for simulation and the accuracy is to be chosen.

Table: Mesh independence study, error in percentage for C grid

Angle of attack	C_l: Coarse to fine	C_d: Coarse to fine
0	0.37	-1.46
2	0.37	-8.70
4	0.22	-0.19
6	0.11	-0.07
8	0.10	2.17
10	0.08	2.88
12	-1.00	6.20
14	-0.97	5.48
16	1.16	0.88
18	-0.71	5.09
20	-2.18	-1.16
22	-2.33	-1.66

Table: Mesh independence study, error in percentage for O grid

α	C_l:C to F	C_d:C to F	C_l:F to VF	C_d:F to VF
0	0.79	-3.71	-0.18	0.52
2	0.42	-3.61	-0.11	0.30
4	0.39	-3.38	-0.08	-0.09
6	0.25	-2.76	-0.09	-0.45
8	0.23	-2.29	-0.08	-0.94
10	0.03	-1.15	-0.06	-1.42
12	-0.20	-0.02	0.27	-2.99
14	0.21	-1.20	1.20	-6.14
16	0.12	-0.15	1.44	-5.01
18	-0.18	0.08	0.77	-0.25
20	-0.03	-0.04	0.62	0.17
22	0.09	-1.66	6.39	-15.11

Table: Configurations for the SU^2 solver.

Parameter	Choice
Solver	Incompressible; Steady
Governing Equation	Navier Stokes
Turbulence model	Menter SST
Density	1.00
Freestream Velocity	$(\cos(\alpha)\ \sin(\alpha)\ 0)$
Freestream Viscosity	$\frac{1}{Re}$
Linear Solver	FGMRES
Precondiitoner for linear solver	LU symmetric Gauss Seidel
Multigrid	NO
Convective Numerical Method	Flux difference splitting by Roe.
Slope Limiter	Venkatakrishnan
Convergence criterion(P and K.E)	8 orders of magnitude reduction

Boundary Conditions and other settings

- No-slip condition on the airfoil wall.
- Far-field condition at the outer walls.
- 70 chord lengths to the top and bottom walls, 100 chord lengths to the right wall and 70 chord lengths to the left.
- Inlet Velocity: Magnitude: 1 m/s, Direction: $\{cos(\alpha), \sin(\alpha), 0\}$, α : angle of attack
- Initial solution for each angle of attack was the solution computed from the previous angle of attack.

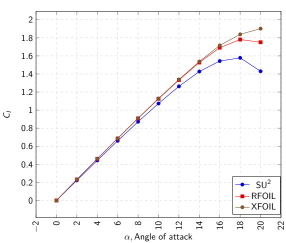
Reynolds numbers for different airfoils

Table: Reynolds numbers for different airfoils

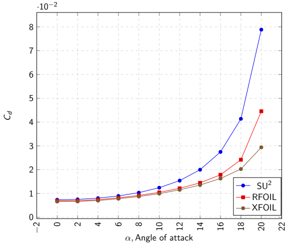
Airfoil	Re
DU00-W-212	1.30E+007
	1.60E+007
	2.00E+007
DU00-W2-250	1.30E+007
	1.60E+007
	2.00E+007
DU00-W2-350	1.40E+007
DU91-W2-401	1.10E+007
DU97-W-300	1.70E+007

Solution methods used by AVATAR partners.

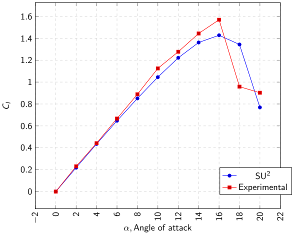
1. ECN - XFOIL (Integral boundary layer solvers using Viscid-Inviscid interaction) and RFOIL (improvement of XFOIL for rotating airfols).
2. TU Delft - OpenFOAM (Open source CFD solver.)
3. DTU - EllipSys (Wind energy flow solver)
4. CENER - Wind Multi-block (compressible URANS solver, structured.)
5. NTUA - MaPFlow (MPI enabled compressible solver with preconditioning in low Mach number regions)
6. UoS - FLOWer (compressible, RANS solver)



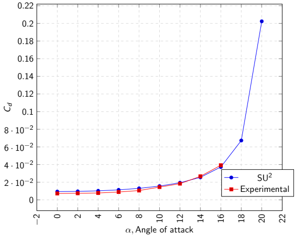
(a) C_l: Re $= 13 \times 10^6$



(b) C_d: Re $= 13 \times 10^6$



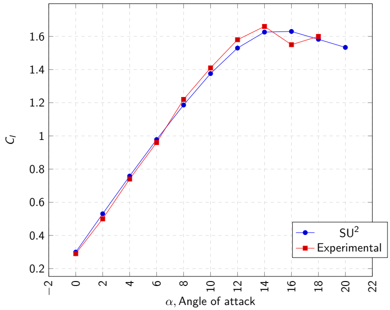
(c) C_l: Re $= 3 \times 10^6$



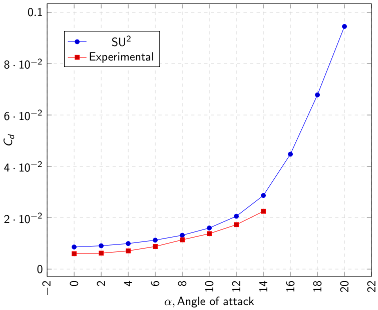
(d) C_d: Re $= 3 \times 10^6$

Figure: NACA0012: Experimental, RFOIL and XFOIL comparisons.

High Reynolds number validation for DU-00-W-212



(a) C_l



(b) C_d

Figure: High Reynolds number validation of DU-00-W-212 at Re $= 15 \times 10^6$

Comparison of SU^2 results with RFOIL and XFOIL.

DU21 and DU25 airfoils

1. Under-prediction of lift and over-prediction of drag in linear regions. Attributable to fully turbulent flow simulated.
2. Stall prediction is close by to RFOIL though not accurate enough.

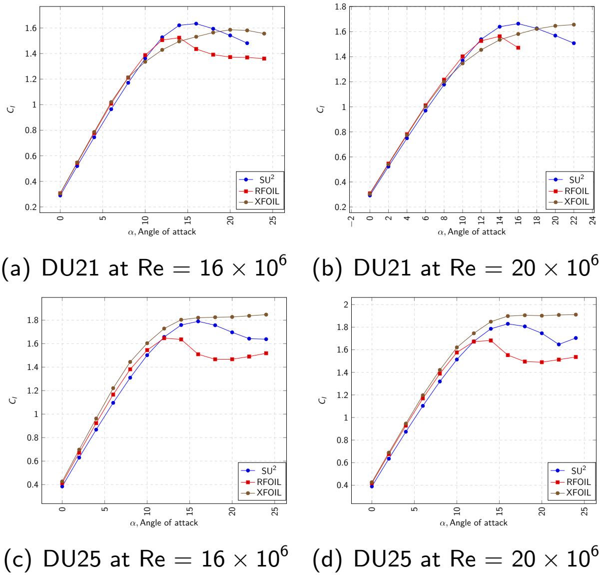
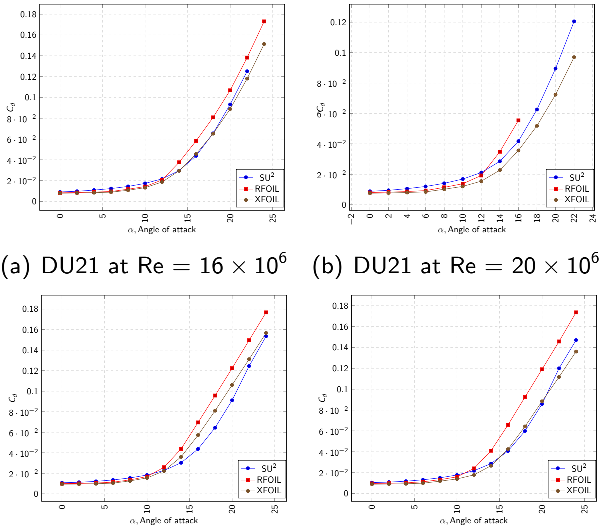


Figure: C_l characteristics of airfoils: Part 1



(a) DU21 at Re = 16×10^6 (b) DU21 at Re = 20×10^6

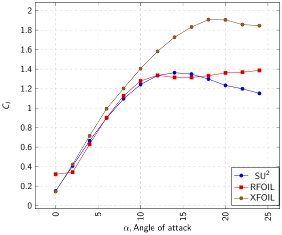
(c) DU25 at Re = 16×10^6 (d) DU25 at Re = 20×10^6

Figure: C_d characteristics of airfoils: Part 1

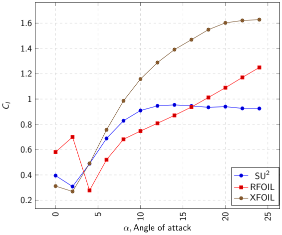
Comparison of SU^2 results with RFOIL and XFOIL.

DU350, DU401 and DU300 airfoils

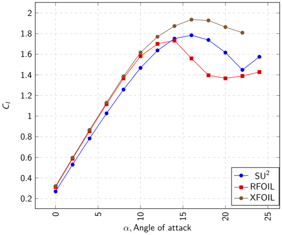
1. DU350 and DU 401: Prediction of stall for low angles of attack is not observed as done for RFOIL.
2. DU350 and DU300 : Stall prediction is very comparable to RFOIL.
3. DU300 and DU350 : Lift curve shows very similar behaviour to RFOIl.
4. DU401: Thickest airfoil, SU^2 prediction more accurate than RFOIL and XFOIL. RFOIL and XFOIL do not converge.



(a) DU350 at Re $= 14 \times 10^6$

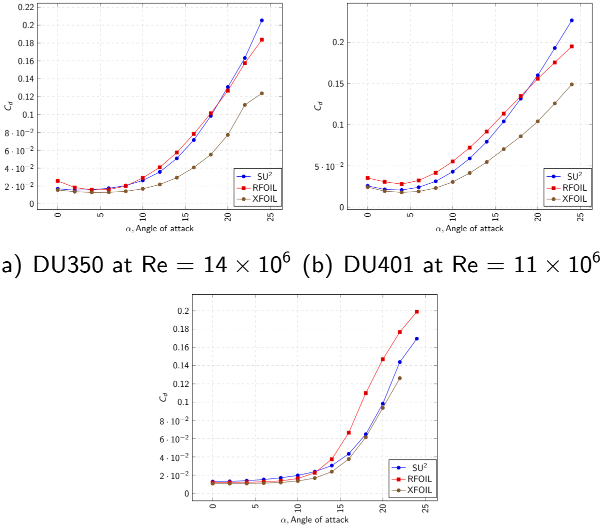


(b) DU401 at Re $= 11 \times 10^6$



(c) DU300 at Re $= 17 \times 10^6$

Figure: C_l characteristics of airfoils: Part 2



(a) DU350 at Re $= 14 \times 10^6$ (b) DU401 at Re $= 11 \times 10^6$

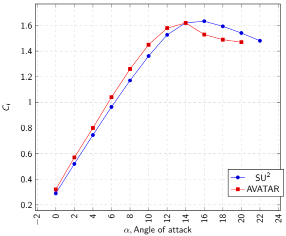
(c) DU300 at Re $= 17 \times 10^6$

Figure: C_d characteristics of airfoils: Part 2

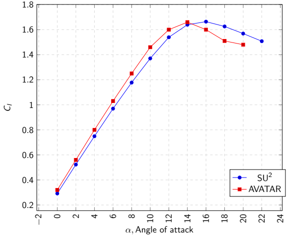
Comparison of SU^2 results with AVATAR results.

DU21 and DU250 airfoils

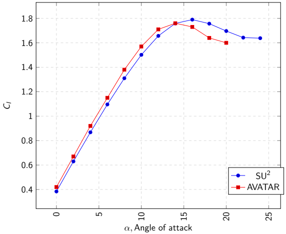
1. Under-prediction of lift and over-prediction of lift.
2. Predicts stall earlier.
3. As the Re increases, the behaviour becomes similar.



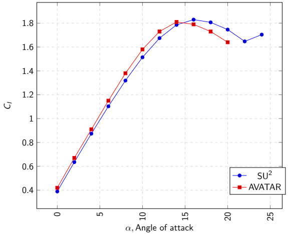
(a) DU212 at Re $= 16 \times 10^6$



(b) DU212 at Re $= 20 \times 10^6$

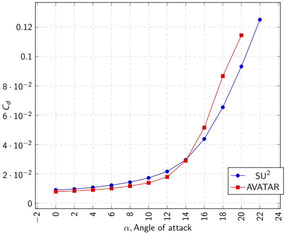


(c) DU250 at Re $= 16 \times 10^6$

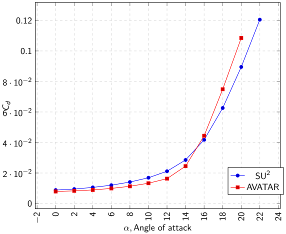


(d) DU250 at Re $= 20 \times 10^6$

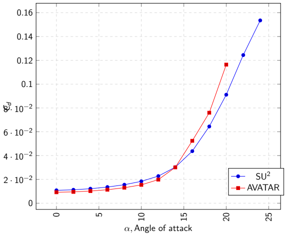
Figure: Comparison of C_l characteristics of airfoils with AVATAR: Part 1



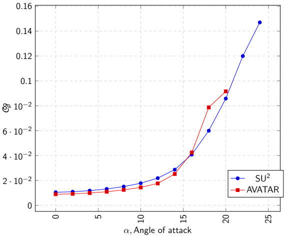
(a) DU212 at Re $= 16 \times 10^6$



(b) DU212 at Re $= 20 \times 10^6$



(c) DU250 at Re $= 16 \times 10^6$



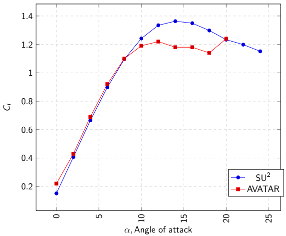
(d) DU250 at Re $= 20 \times 10^6$

Figure: Comparison of C_d characteristics of airfoils with AVATAR: Part 1

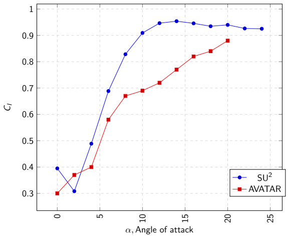
Comparison of SU^2 results with AVATAR results.

DU300, DU350 and DU401 airfoils

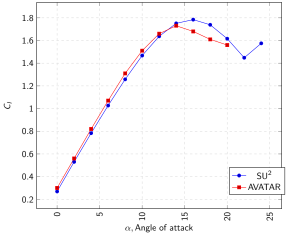
1. DU350: Very good agreement in linear regions. Stall predicted earlier. Under-prediction after stall.
2. DU401: Unfortunately, AVATAR results are unreliable here.
3. DU300: Very good agreement in linear regions, though a slight under-prediction of lift and a slight over-prediction of drag is observed.



(a) DU350 at Re $= 14 \times 10^6$

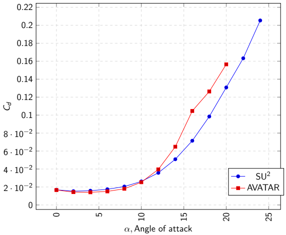


(b) DU401 at Re $= 11 \times 10^6$

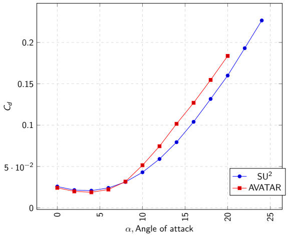


(c) DU300 at Re $= 17 \times 10^6$

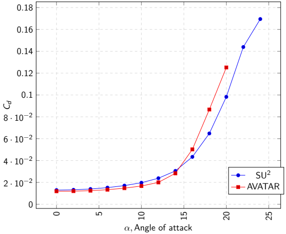
Figure: Comparison of C_l characteristics of airfoils with AVATAR: Part 2



(a) DU350 at Re $= 14 \times 10^6$



(b) DU401 at Re $= 11 \times 10^6$



(c) DU300 at Re $= 17 \times 10^6$

Figure: Comparison of C_d characteristics of airfoils with AVATAR: Part 2

Conclusions

Summary and conclusions

1. It was verified that SU^2 can be successfully used as a reliable CFD solver. The results were validated for various cases:
   1. NACA 0012 airfoil: Validated with RFOIL and XFOIL at high Reynolds number of 13 million, Validated with experimental results at a Reynolds number of 3 million.
   2. DU-00-W-212 airfoil: Validated with experimental results for a high Reynolds number of 15 million.
2. Comparison with SU^2, RFOIL, XFOIL and other AVATAR tools show similar behaviour in the linear regions. Differences were observed in stall prediction and behaviour after stall.

Recommendations

Pitfalls

1. Care must be taken during meshing for sharp and blunt trailing edge airfoils. A mesh independence study is an important aspect to make the solution computationally efficient for larger cases.
2. For simple geometries it is always preferrable to use a structured mesh. The solution is faster and may also be more accurate.
3. Initial and boundary conditions are important for the solution accuracy and time. Using an angle of attack that is close to the present angle of attack will considerably improve both accuracy and time.
4. Turbulence models must be chosen carefully. Though the SA model is was made keeping airfoil applications in mind, in this case, it proves to be less accurate than the Menter SST model.
5. Curvature of the airfoil surface should be taken into account while meshing.

Future work

1. Conversion of the SU^2 code from a compressible solver using artificial incompressibility to a complete incompressible solver.
2. Unsteady simulations may be performed to get a more accurate result of the flow around the airfoil at higher angles of attack, particularly beyond stall when there is full separation of flow.
3. Inclusion of a transition model into the SU^2 code so that the results are comparable to that of experimental results as fully turbulent flows are generally not observed in airfoils.

Thank You

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