Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

Numerical Fluid Mechanics

Master in Aerospace Engineering

Airfoil flow at high Reynolds number

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Nov 10th, 2023

1. Introduction

This report outlines the computational methodology and results of a series of simulations conducted with the mesh and fluent data provided to analyse the flow around a 3m-chord NACA0012 airfoil. The simulations are configured to emulate turbulent flow at a high Reynolds number (Re) of 6.0×106, representative of many real-world aeronautical applications. In this series of simulations, the aerodynamic coefficients of lift and drag are critical performance indicators.

Ultimately, a conclusion drawn regarding the ability of the RANS physical model in predicting the aerodynamic performance of an airfoil under fully turbulent flow conditions.

2. Mesh convergence study

Three sets of structured mesh and unstructured mesh are generated. The structured mesh is generated with the values calculated for *h1*, *g*, n_c.

- *h1*, the size first wall cell.
- *g*, the growth rate (or expansion ratio), for the cells in the boundary layer.
- *n_c*, the number of cells along the airfoil chord.

Table 1 : Structured mesh parameters

Mesh	h1	g	n_c	Number of cells [k]
M1	6mm	1.25	34	4.3
M2	0.6mm	1.2	68	13.2
M3	0.14mm	1.1	123	45.9

Table 2 : Structured mesh influence

	AoA=0°			**AoA=10°**		
	Cl	***Cd***	***Cl/Cd***	***Cl***	***Cd***	***Cl/Cd***
Exp.	0.00	0.0082	-	1.07	0.0120	89
XFOIL Tu=0.07% TN	0.00	0.0051	-	1.12	0.0097	124
XFOIL Tu=1.0% TN	0.00	0.0067	-	1.11	0.0101	110
XFOIL Tu=0.07% TF 1%	0.00	0.0082	-	Not conv.	Not conv.	Not conv.
M1	0.00	0.0097	-	0.8944	0.0356	25.1243
M2	0.00	0.0079	-	1.0521	0.0155	67.8862
M3	0.00	0.0083	-	1.0539	0.0146	71.9582

TN: natural transition, TF: forced transition

Table 3 : Unstructured mesh parameters

Mesh	Cell size on airfoil	Cell size around airfoil	Cell size far-field	Number of cells [k]
M1_unst	30mm	60mm	3m	19.9
M2_unst	15mm	30mm	3m	38.1
M3_unst	7.5mm	15mm	3m	90.2

Table 4 : Unstructured mesh influence

	AoA=0°			AoA=10°		
	Cl	***Cd***	***Cl/Cd***	***Cl***	***Cd***	***Cl/Cd***
Exp.	0.00	0.0082	-	1.07	0.0120	89
XFOIL Tu=0.07% TN	0.00	0.0051	-	1.12	0.0097	124
XFOIL Tu=1.0% TN	0.00	0.0067	-	1.11	0.0101	110
XFOIL Tu=0.07% TF 1%	0.00	0.0082	-	Not conv.	Not conv.	Not conv.
M1_unst	-0.0012	0.0111	-0.1119	0.5592	0.0835	6.6970
M2_unst	-0.0016	0.0104	-0.1554	0.6208	0.0651	9.5361
M3_unst	-0.0006	0.0097	-0.0605	0.9652	0.0293	32.9420

Figure 1 : structured and unstructured mesh

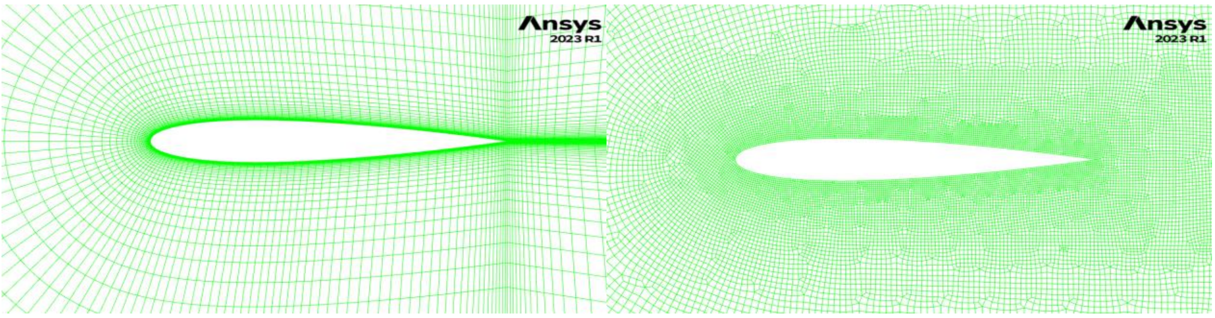
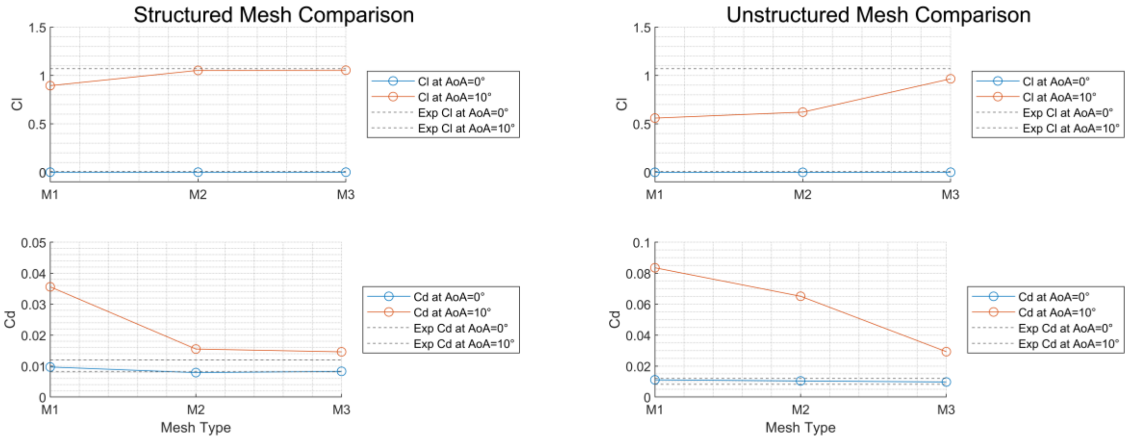


Figure 2 : Cl, Cd results of Structured and Unstructured mesh



From the above (figure 2) for structured mesh, the M2 mesh has reached a level of convergence, although the values of Cd obtained through its simulations at AoA = 10° are still slightly different from the experimental values. For all three sets of unstructured mesh, the results obtained for AoA = 10° are very poor. This can also be inferred from the mesh (figure 1) that, the structured mesh have a fine near-wall mesh that captures the boundary layer better, but the unstructured mesh do not have a sufficiently thin near-wall mesh, which makes their simulations of the boundary layer have a low fidelity. Therefore, M2 structured mesh is chosen considering the cost and accuracy.

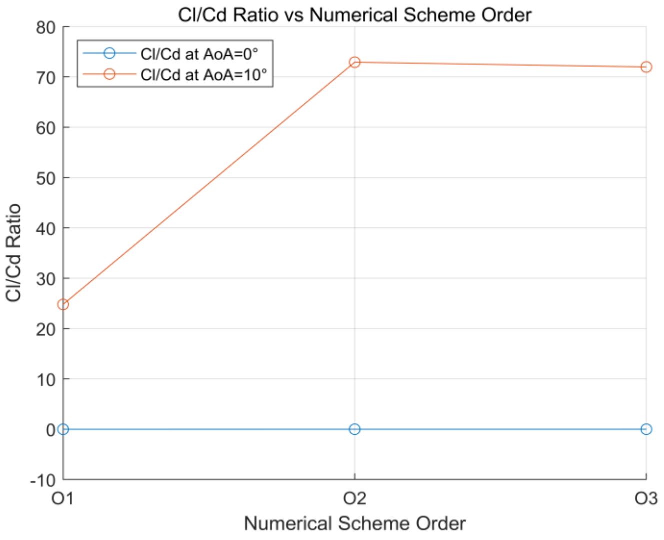
3. Numerical Scheme Influence

The influence of the main spatial numerical schemes (O1, O2, O3) are analysed.

Table 5 : Comparison of Cl, Cd, Cl/Cd

Scheme order	AoA=0°			AoA=10°		
	Cl	***Cd***	***Cl/Cd***	***Cl***	***Cd***	***Cl/Cd***
O1	-0.0001	0.0124	-0.0098	0.9398	0.0379	24.7900
O2	0.0000	0.0079	-0.0045	1.0556	0.0145	72.9006
O3	0.0000	0.0083	-0.0024	1.0539	0.0146	71.9582

Figure 4 – Cl/Cd=f(Order)



Notably, there is a large increase from O1 to O2, suggesting that the second-order scheme may more accurately capture aerodynamic effects. The slight decrease from O2 to O3 is negligible, suggesting that the gain in Cl/Cd improvement diminishes as the order scheme is increased.

This situation suggests that switching from a first-order scheme to a second-order scheme significantly improves the accuracy of the simulations in predicting aerodynamic performance. However, the increased complexity of the third-order scheme does not appear to correspondingly improve the prediction accuracy of this metric. This trade-off is critical to the computational efficiency and accuracy of aerodynamic simulations.

Also, the time taken to perform simulation in each case of numerical scheme order change is observed and the difference is very small. Because it is a smaller simulation, sometimes there can be other factors affecting than he simulation complexity itself.

4. Boundary condition influence

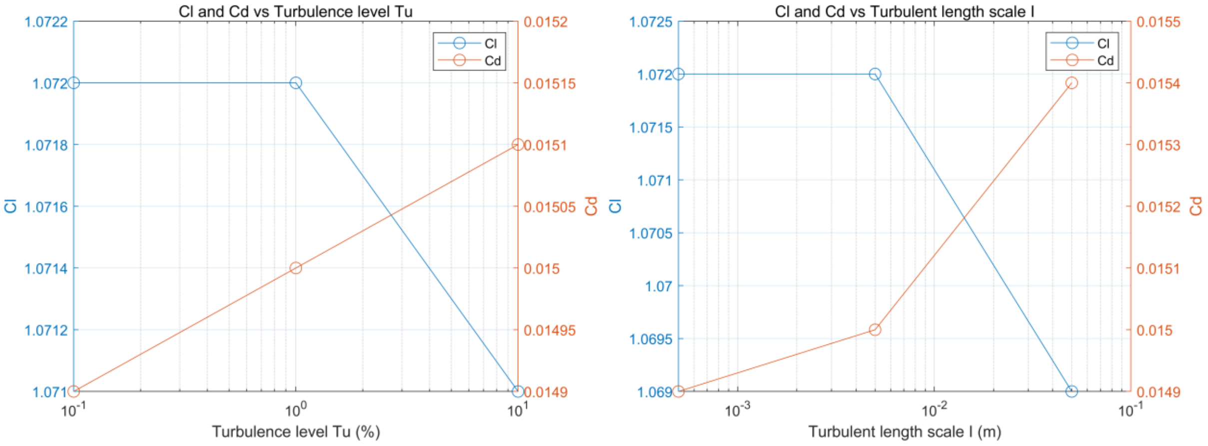
Turbulent characteristics of the inflow (inlet): Turbulence level Tu and turbulent length scale are changed to understand the influence of artificially induced turbulence in the simulation and the data below clearly shows decrease in Cl/Cd as, either the turbulence scale or intensity increases, which is expected.

- Tu1: Tu=1%, l=0.005m (ref)
- Tu2: Tu=0.1%, l=0.005m
- Tu3: Tu=10%, l=0.005m
- TuL1: Tu=1%, l=0.05m
- TuL2: Tu=1%, l=0.005m
- TuL3: Tu=1%, l=0.0005m

Table 6 : Influence of induced inlet turbulence

AoA=10°	***Cl***	***Cd***	***Cl/Cd***
Tu1	1.072	0.0150	71.4667
Tu2	1.072	0.0149	71.9463
Tu3	1.071	0.0151	70.9272
TuL1	1.069	0.0154	69.4156
TuL2	1.072	0.0150	71.4667
TuL3	1.072	0.0149	71.9463

Figure 5 – the influence of turbulence level and turbulent length scale



5. Turbulence model influence

The influence of various turbulence models is studied. SA, k-ω, k-ω-SST, k-ε realizable models are tested for steady case and K-ω stnd, K-ω SST, K-ε rng, K-ε realizable, SA, DES-kω-SST models are tested for unsteady case.

Table 7 : Comparion of turbulence models-steady

Steady	AoA=0°			AoA=10°		
	Cl	Cd	Cl/Cd	Cl	Cd	Cl/Cd
SA	0.0000	0.0083	-0.0032	1.0664	0.0146	72.9212
k-ω	0.0000	0.0088	-0.0010	1.0728	0.0150	71.4628
k-ω-SST	-0.0001	0.0098	-0.0094	1.0539	0.0146	71.9582
k-ε realizable	-0.0001	0.0098	-0.0099	1.0599	0.0166	63.8263
k-ε rng	-	-	-	1.061	0.01759	60.3184
DES-kω-SST				1.058	0.01403	75.4098

6. Conclusion

Table 8 : Validation of models with Exp data.

	Nasa CFL3D	**RANS-k-w sst**	**RANS-SA**	**Difference**
AoA	0°			
CL	0	2.34e-5	3.9e-5	
CD	0.00819	0.00828	0.00837	9e-5 ; 18e-5
CL/CD	-			
AoA	10°			
CL	1.0909	1.053	1.059	
CD	0.01231	0.01467	0.01556	0.00236 ; 0.00325
CL/CD	88.6	71.77	68.059	16.83 ; 20.541
AoA	15°			
CL	1.5461	1.4389	1.4841	
CD	0.02124	0.02913	0.02803	0.00789 ; 0.00679
CL/CD	72.8	49.395	52.946	23.405 ; 19.854

The Influence of different parameters on the simulations is studied. Though the simulations are not very accurately done, it is clear that, these parameters must be tuned according to the specific flow conditions, the goals of the simulation, and the available computational resources. With an appropriate mesh, selection of the turbulence model is very important. For example, in some cases, the simplicity and efficiency of the SA model might be sufficient. While in other cases, the k-omega SST model could provide more accurate results. It is clear that validation studies and sensitivity analyses are necessary to determine the most suitable model, etc., for a given simulation.