34TH SYMPOSIUM ON NAVAL HYDRODYNAMICS

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Assessment of Numerical and Modeling Errors of RANS-based Transition Models for Low-Reynolds Number 2-D Flows

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Objectives

- Applied Vehicle Tecnology (AVT) 313:
  Incompressible Laminar-to-Turbulent Flow Transition Study

  In this effort, an assessment will be made of existing capabilities of CFD codes to predict transitional flows of interest as well as an assessment of relevant data for validation of transition prediction.
- Topics:
  Reynolds Averaged Navier-Stokes (RANS) prediction of laminar to turbulence transitional flows;
- Two and three-dimensional test cases selected for the assessment of the simulation of transitional flows based on RANS. Present paper focus on the two-dimensional test cases.

Objectives

- Applied Vehicle Tecnology (AVT) 313:
  Incompressible Laminar-to-Turbulent Flow Transition Study

  Goals of two-dimensional test cases:

  - Check the consistency of the solutions obtained with different RANS solvers in sets of geometrically similar grids using the same (nominal) mathematical model and boundary conditions;

  - Assess the impact of transition models on the numerical convergence properties of RANS solvers;

  - Compare the solutions obtained with the Reynolds Averaged Navier-Stokes (RANS) equations using turbulence and transition models to experimental data and Large-Eddy Simulation results

Mathematical Model

- Time-averaged continuity and momentum equations using the Shear-Stress Transport (SST) $k-\omega$, two-equation eddy-viscosity model.
- Two Local Correlation Transition Models (LCTM) tested:

1. $\gamma - \mathrm{Re}_\theta$ model of R.B. Langtry and F.R.Menter (https://arc.aiaa.org/doi/10.2514/1.42362)

2. γ model of F.R.Menter, P.E.Smirnov, T.Liu and R. Avancha (https://link.springer.com/article/10.1007/s10494-015-9622-4)

Flow Solvers

- RANS flow solvers used in this study:

Flow Solver	Participant	Label	Discretization Technique	Mach
Ansys CFX-v18.2	DRDC	DRDC	Finite Volume	0
FUN3D v13.6	NASA LARC	LARC-F	Finite Volume	0.1
ISIS-CFD	ECN	ECN	Finite Volume	0
OVERFLOW v2.3b	NASA LARC	LARC-O	Finite Differences plus overset	0.1
STAR-CCM+ v2021.3	SIREHNA	SIRH	Finite Volume	Steady
ReFRESCO 2.4	IST-MARIN	IM, IM2	Finite Volume	Steady

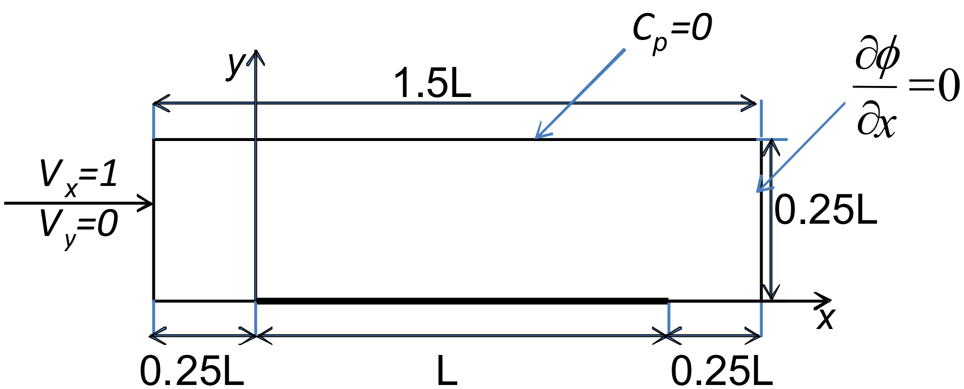
Flow Solvers

- Large Eddy Simulation results available for four test cases using LASSIE
  "Large Eddy Simulations and RANS models for airfoils at low Reynolds number"
  Pietro Catalano and Donato de Rosa
  (https://doi.org/10.2514/6.2020-2990)

- Large Eddy Simulations performed for one test case by INM-CNR using the flow solver χnavis that uses finite volume and overset grids techniques.

Test Cases
Flow over a flat plate (Natural and bypass transition)

- Standard test cases available in the ERCOFTAC Classic Database with experimental data available for skin friction coefficient and mean velocity profiles.

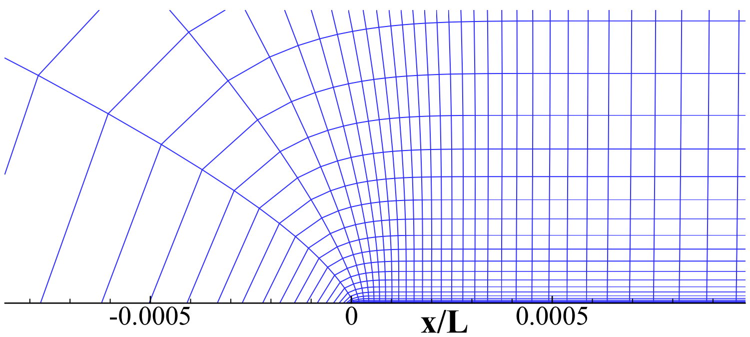


	Natural	Bypass
Variable	T3AM	T3A
V_x	V_∞	V_∞
V_y	0	0
P	$\partial P/\partial x = 0$	$\partial P/\partial x = 0$
k	$1.504 \times 10^{-4} V_\infty^2$	$4.319 \times 10^{-3} V_\infty^2$
ω	$60.1621 V_\infty / L$	$154.25 V_\infty / L$
γ	1	1
I	0.0100135	0.0536609
ν_t	25ν	280ν

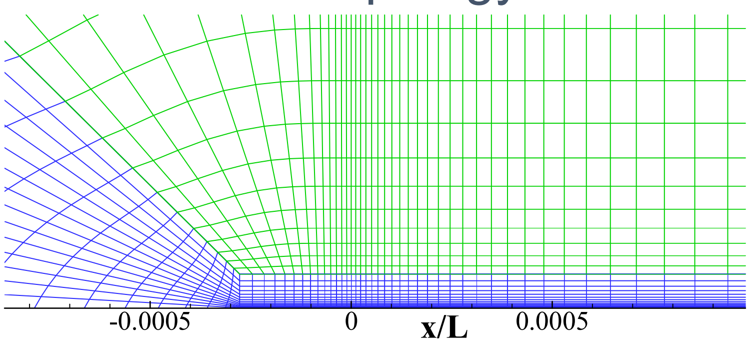
Test Cases
Flow over a flat plate (Natural and bypass transition)

- Three sets of geometrically similar grids available

O topology



HO topology

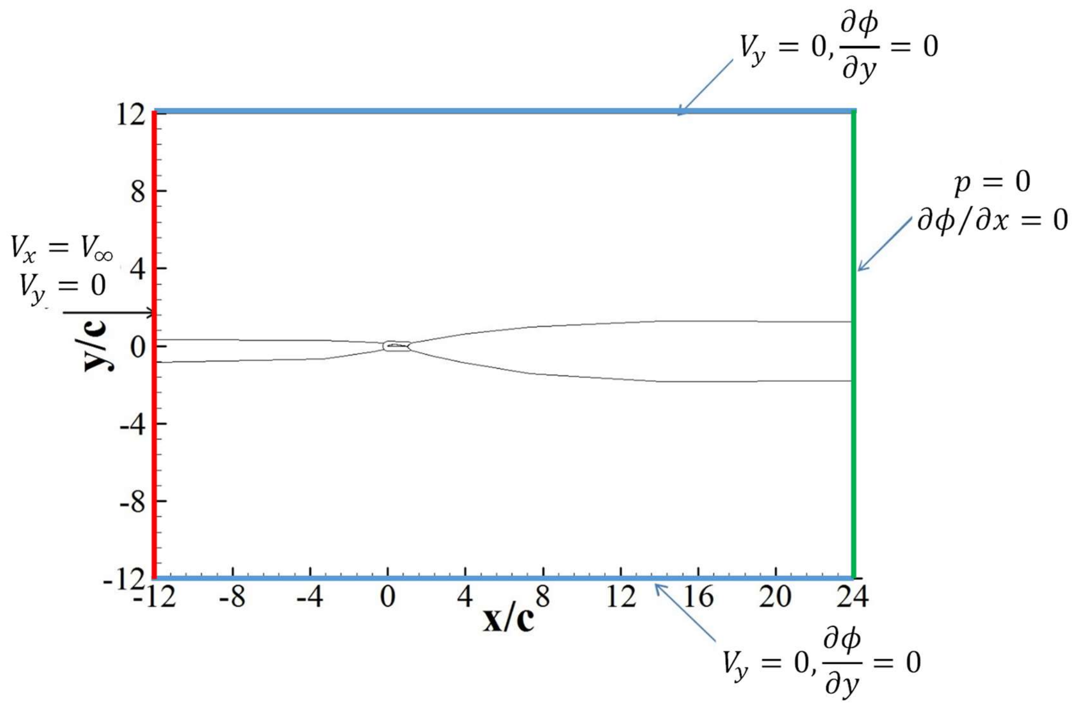


Grid	H topology		O topology		HO topology	
	N_{plate}	r_i	N_{plate}	r_i	N_{plate}	r_i
1	1024	2.5	1024	2.5	2560	1.
2	896	2.86	896	2.86	2048	1.25
3	768	3.33	768	3.33	1792	1.43
4	640	4.	640	4.	1600	1.6
5	512	5.	512	5.	1280	2.
6					1024	2.5
7					896	2.85
8					768	3.2
9					640	4.

Test Cases

Flow around the Eppler 387 airfoil at angles of attack of $\alpha = 1°$ and $\alpha = 7°$ with $Re = 3 \times 10^5$ (Separation induced transition)

- Experimental data available for the pressure coefficient on the surface of the airfoil

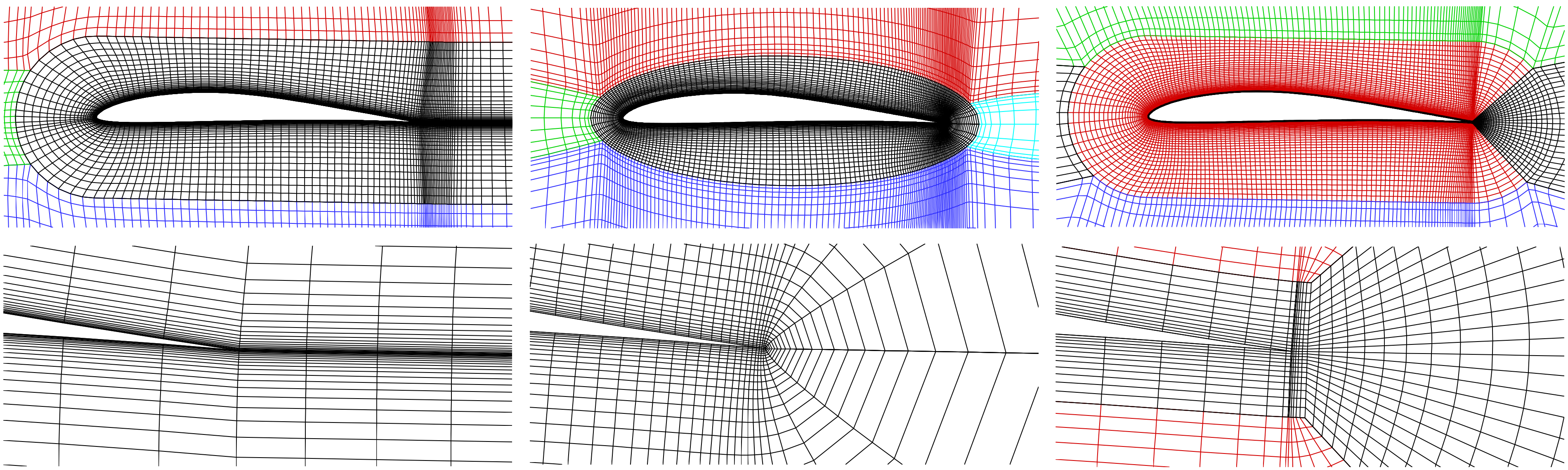


Test Cases

Flow around the Eppler 387 airfoil at an angle of attack of $\alpha = 1°$ with $Re = 3 \times 10^5$ (Separation induced transition)

- Three sets of grids available

C topology | O topology | CO topology



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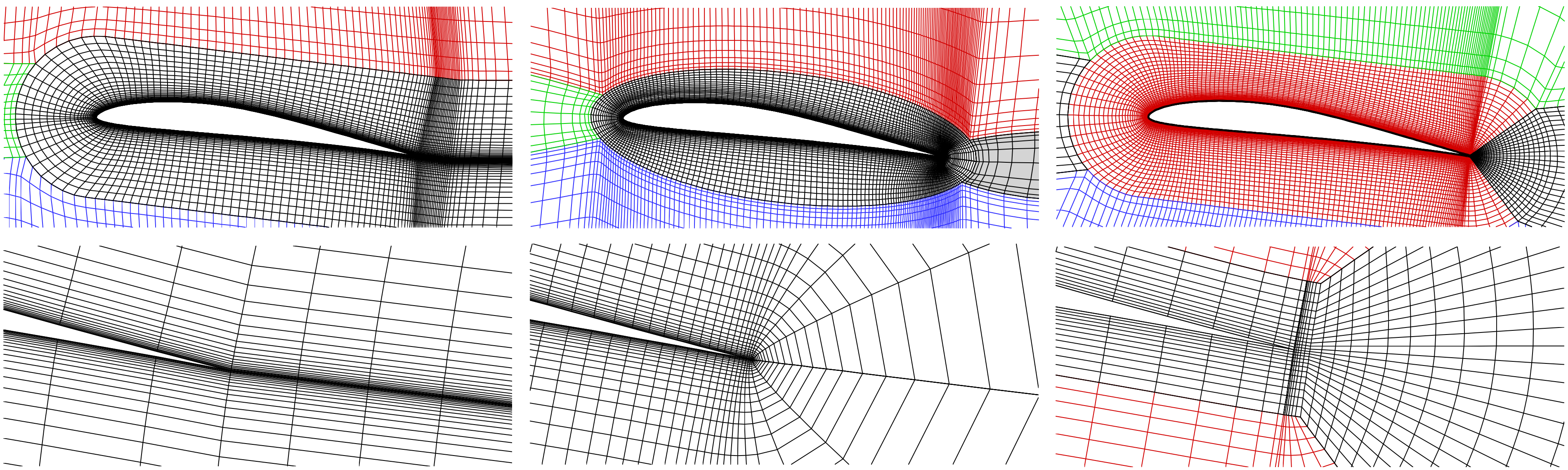
Test Cases

Flow around the Eppler 387 airfoil at an angle of attack of $\alpha = 1°$ with $Re = 3 \times 10^5$ (Separation induced transition)

- Three sets of grids available

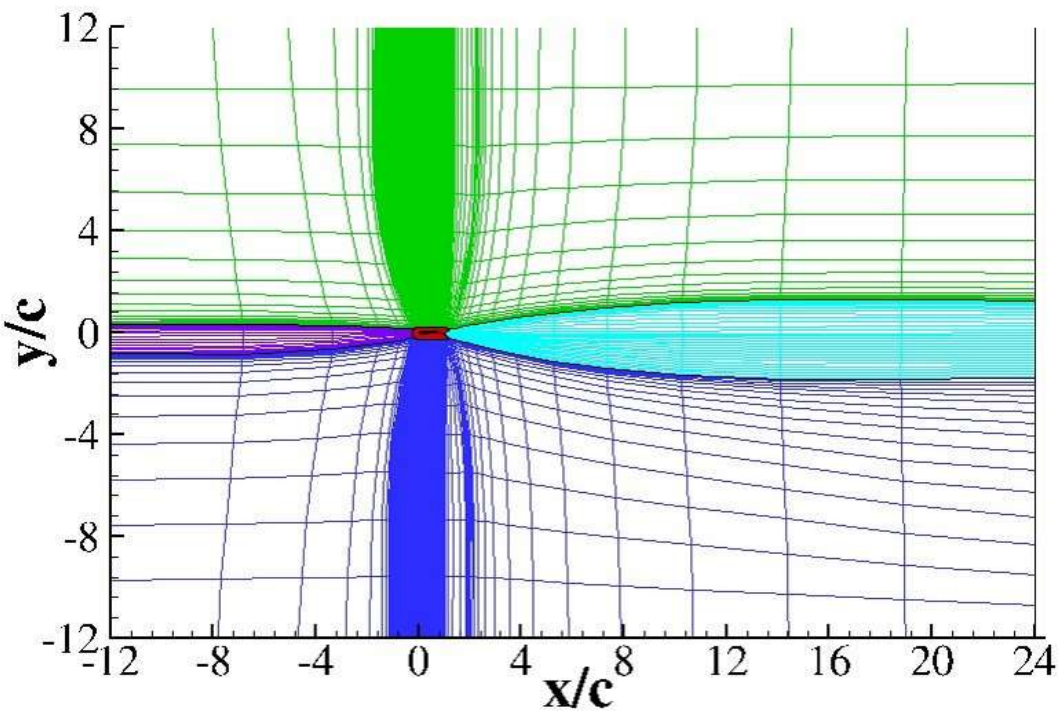
C topology | O topology | CO topology



Test Cases

Flow around the Eppler 387 airfoil at an angle of attack of $\alpha = 7°$ with $Re = 3 \times 10^5$ (Separation induced transition)

- Three sets of grids available

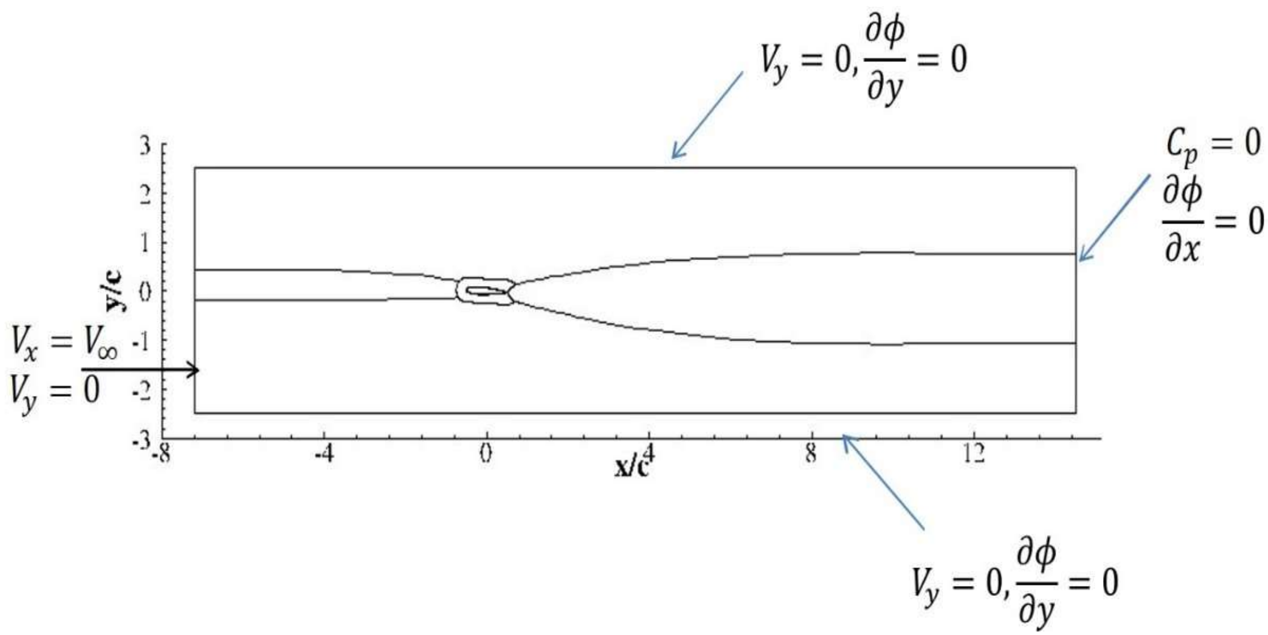


Grid	C topology		O topology		CO topology	
	N_{foil}	r_i	N_{foil}	r_i	N_{foil}	r_i
1	960	3.2	960	3.2	3072	1.
2	840	3.66	840	3.66	2560	1.2
3	720	4.27	720	4.27	2048	1.5
4	600	5.12	600	5.12	1792	1.71
5	480	6.4	480	6.4	1536	2.
6					1280	2.4
7					1024	3.
8					896	3.42
9					768	4.

Test Cases

Flow around the NACA 0015 airfoil at angles of attack of $\alpha = 5°$ and $\alpha = 10°$ with $Re = 1.8 \times 10^5$ (Separation induced transition)

- Experimental data available for the skin friction coefficient on the upper surface of the airfoil

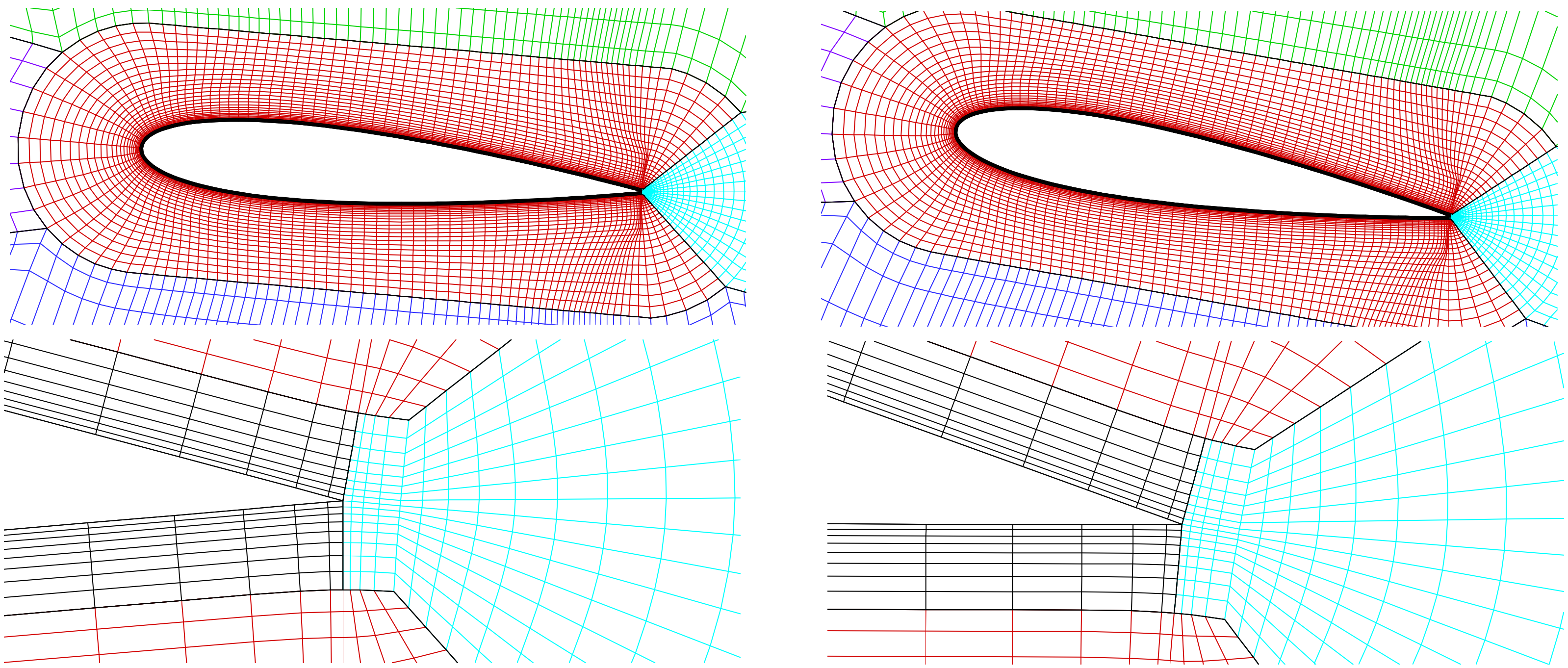


Test Cases

Flow around the NACA 0015 airfoil at angles of attack of $\alpha = 5°$ and $\alpha = 10°$ with $Re = 1.8 \times 10^5$ (Separation induced transition)

- One set of geometrically similar grids available

$\alpha = 5°$ $\alpha = 10°$



Results

Consistency of solutions obtained with different flow solvers

- Numerical uncertainty estimated for all quantities of interest using power series expansions and data from the 5 finest grids available;
- Error bars from all solutions should overlap. We have determined the number of cases that do not exhibit overlapping error bars $N_{\text{no overlap}}$

$$P_{\text{no overlap}} = \frac{N_{\text{no overlap}}}{N_{\text{total}}} \times 100$$

- N_{total} is the number of cases for a given quantity of interest.
- For the cases that do not overlap, we have determined the maximum and average values of $\Delta\phi = \max(\Delta\phi_1, \Delta\phi_2) > 0$ with

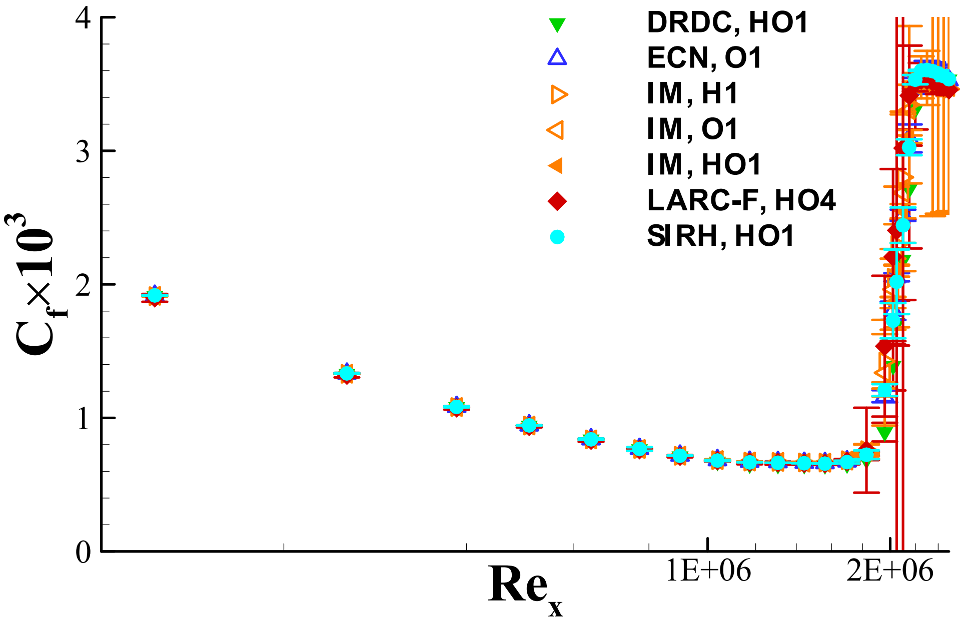
$$\Delta\phi_1 = \left(\phi - U_\phi\right)_i - \left(\phi + U_\phi\right)_j, \Delta\phi_2 = \left(\phi - U_\phi\right)_j - \left(\phi + U_\phi\right)_i$$

Results

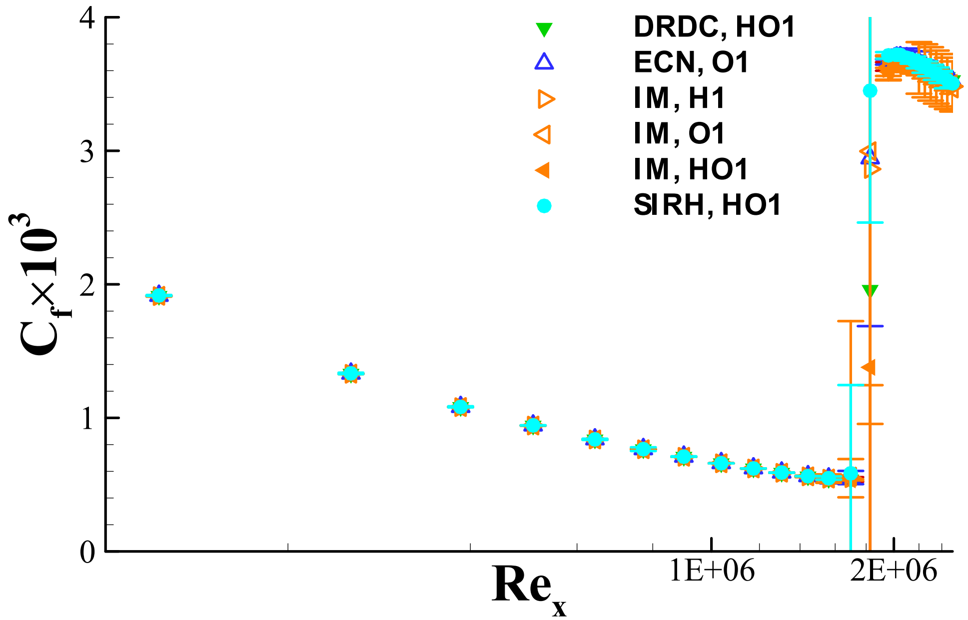
Flow over a flat plate T3AM (Natural transition)

- Skin friction coefficient distribution on the plate.

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$

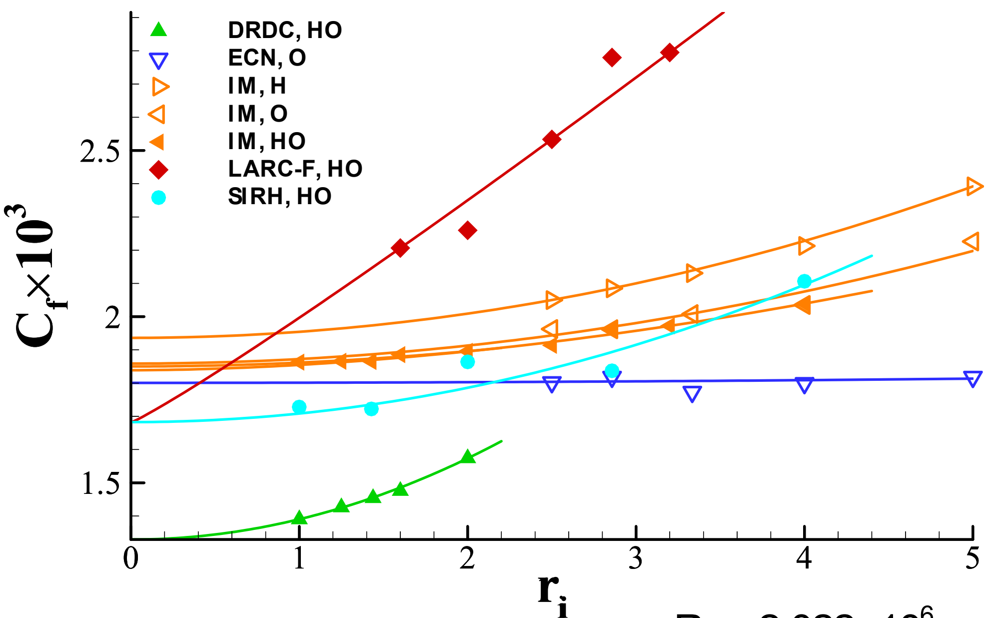


Results

Flow over a flat plate T3AM (Natural transition)

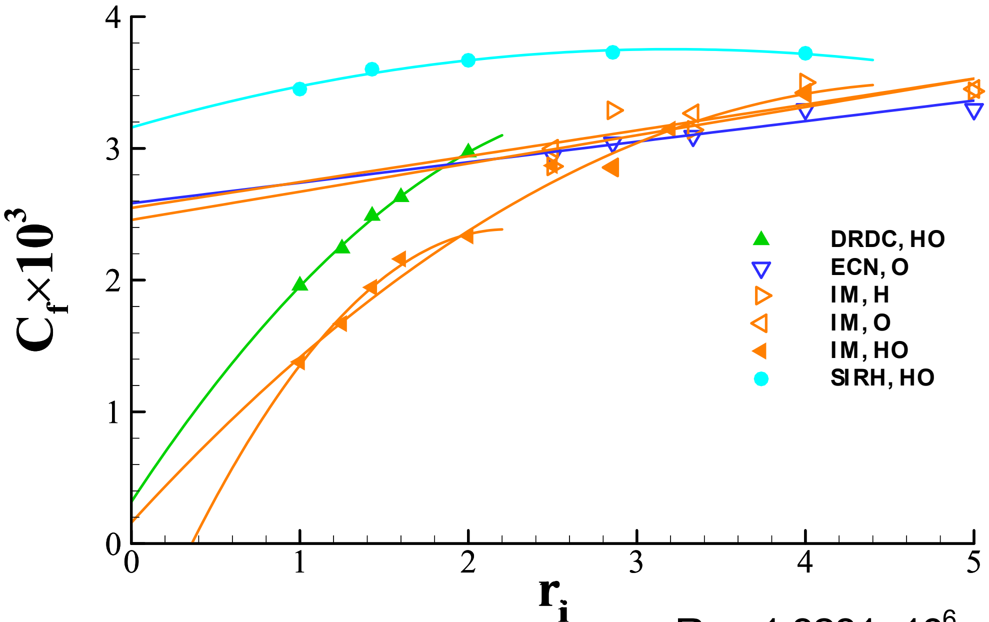
- Skin friction coefficient convergence with grid refinement.

SST $k-\omega+\gamma-Re_\theta$



$Re = 2.022\times10^6$

SST $k-\omega+\gamma$



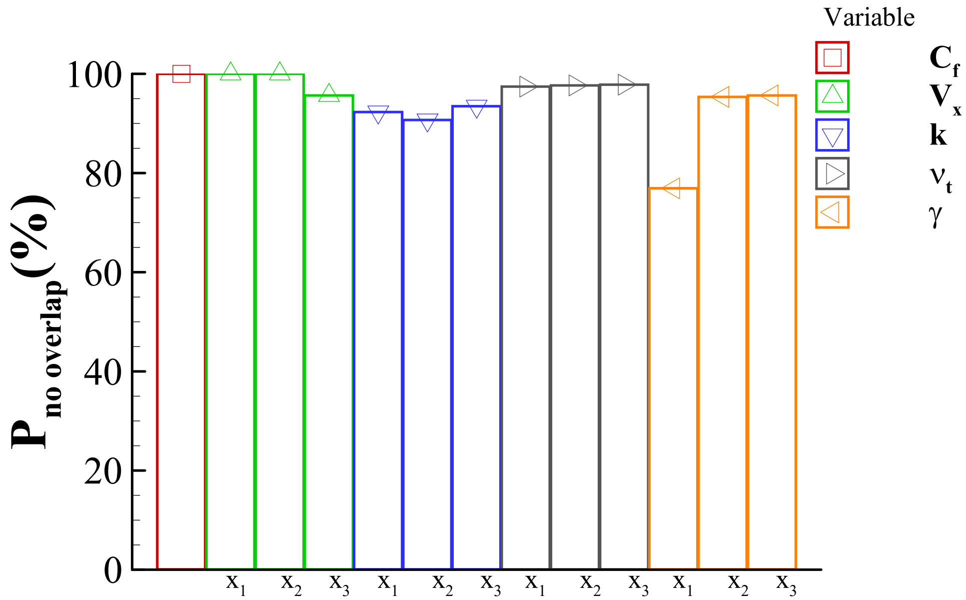
$Re = 1.8281\times10^6$

Results

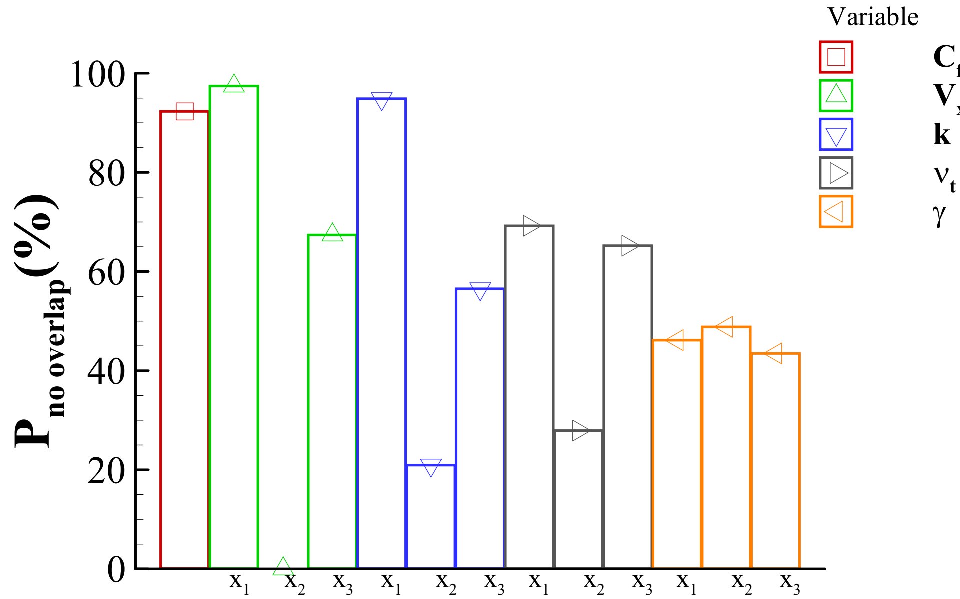
Flow over a flat plate T3AM (Natural transition)

- Check of overlapping error bars

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$

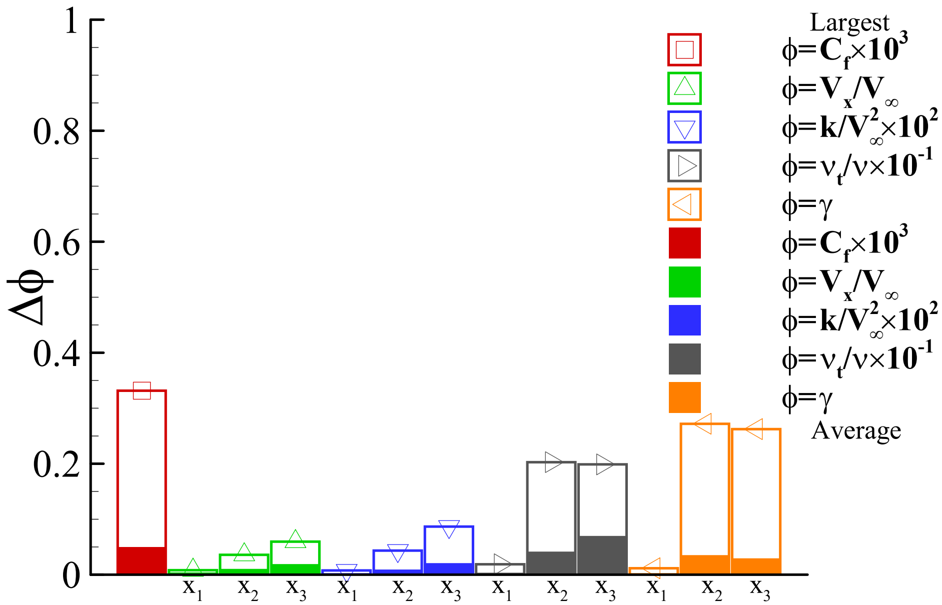


Results

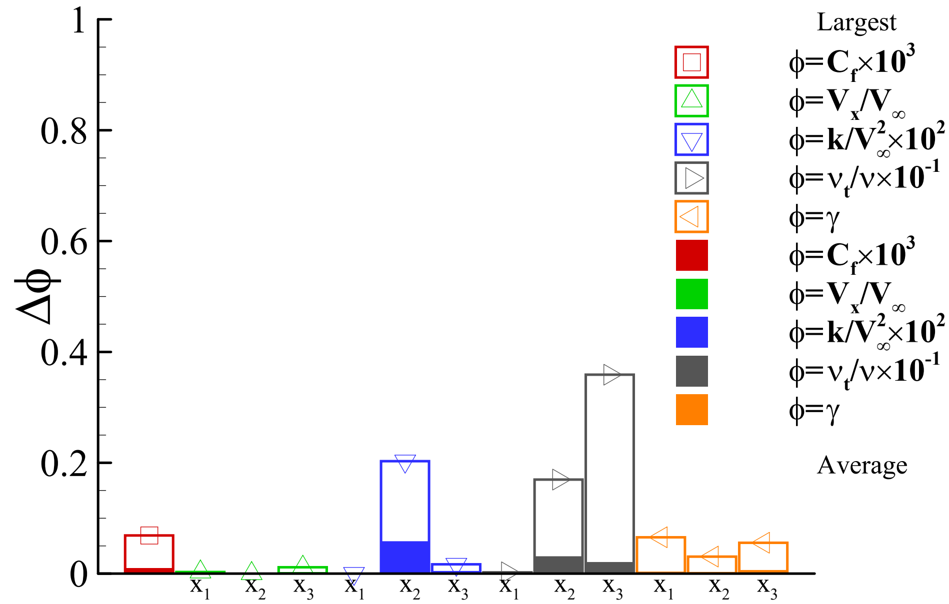
Flow over a flat plate T3AM (Natural transition)

- Maximum and average values of the discrepancies between solutions

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$

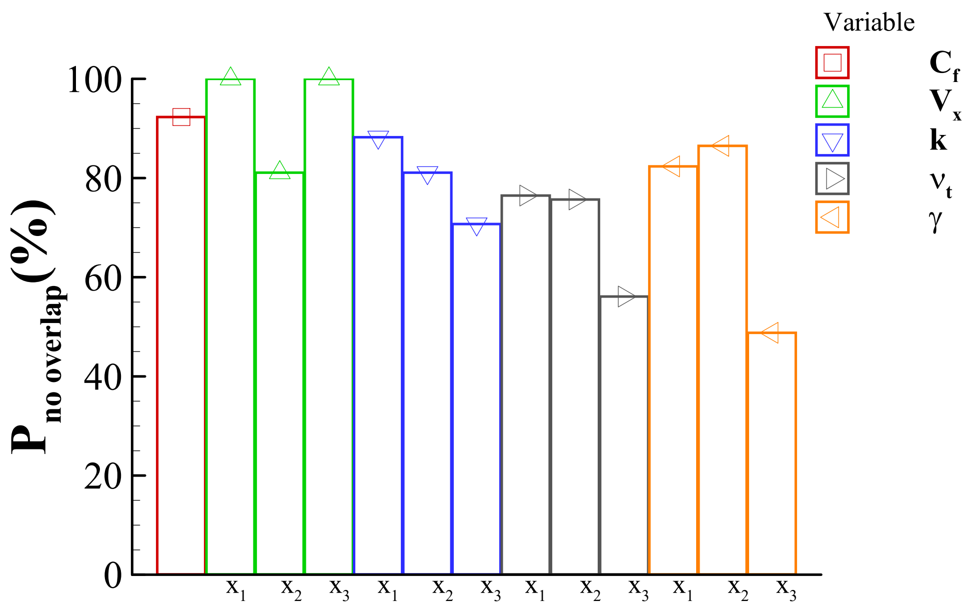


Results

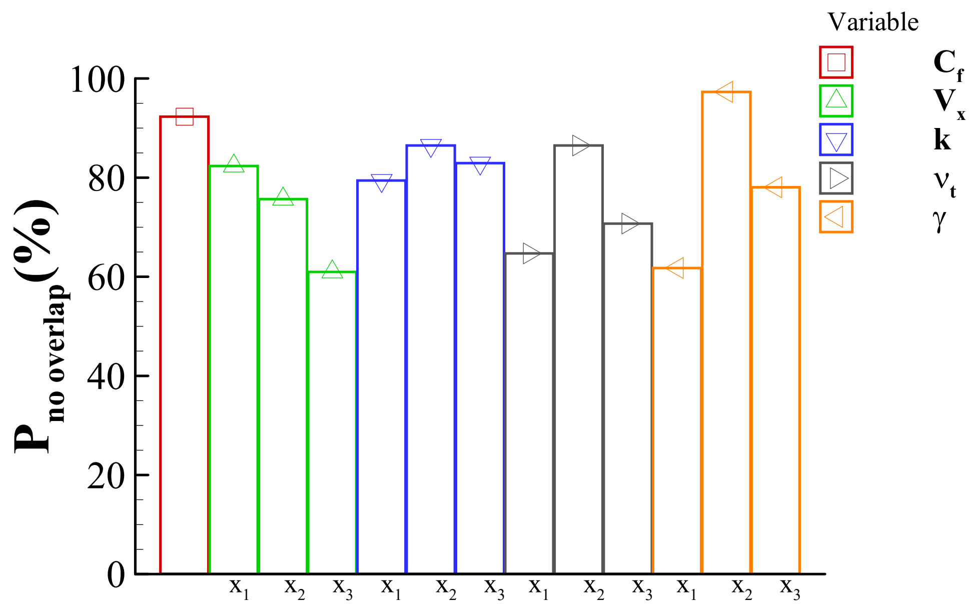
Flow over a flat plate T3A (Bypass transition)

- Check of overlapping error bars

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$

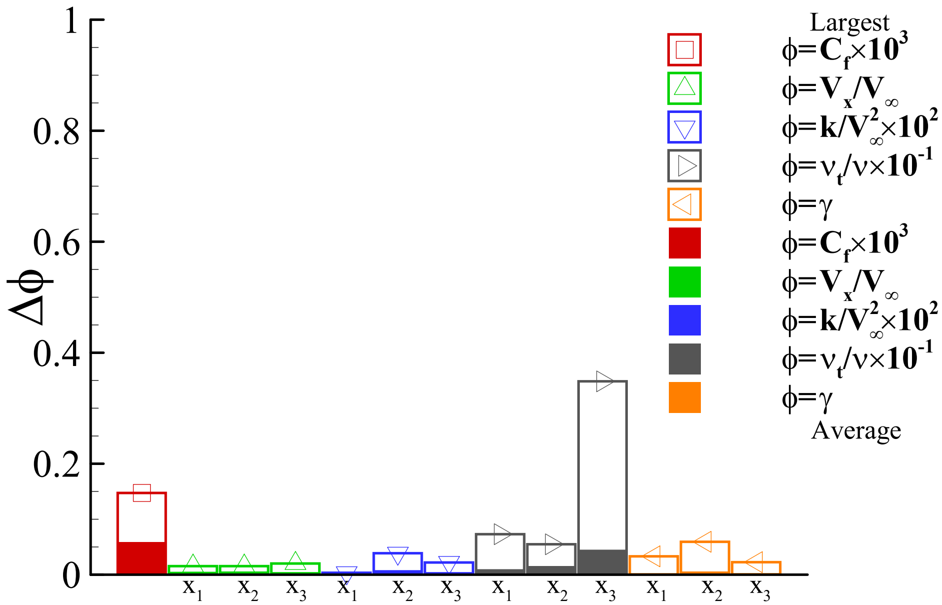


Results

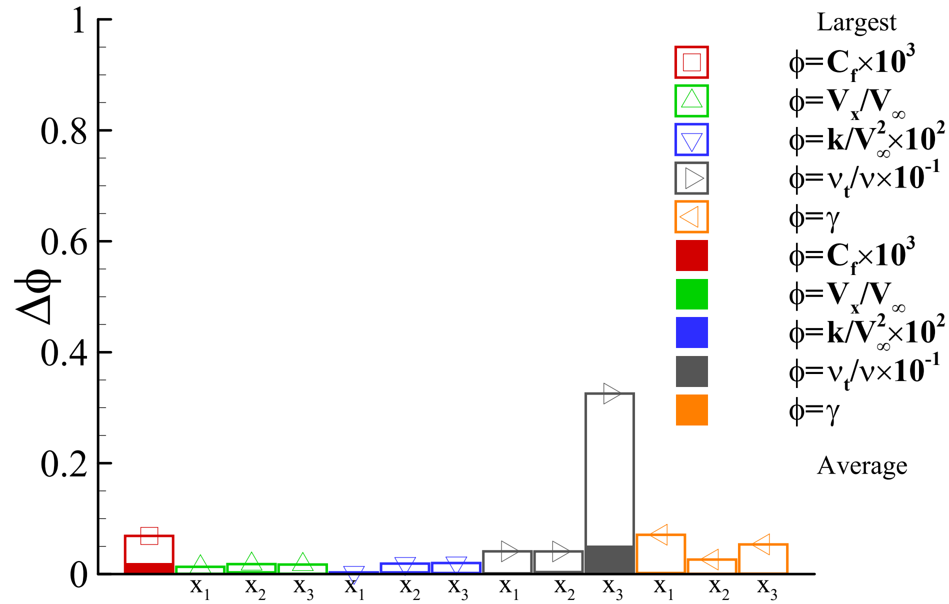
Flow over a flat plate T3A (Bypass transition)

- Maximum and average values of the discrepancies between solutions

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$

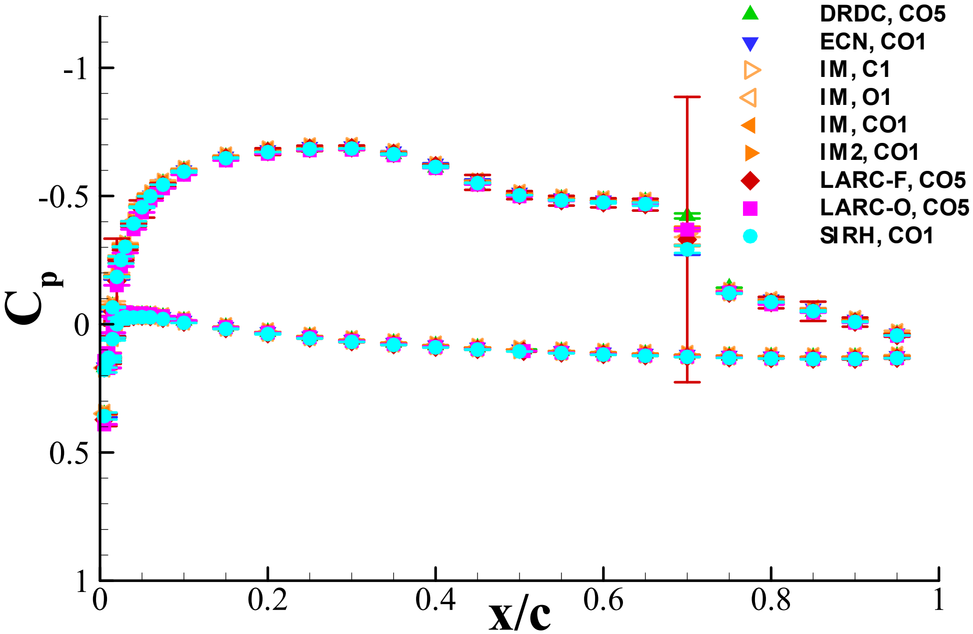


Results

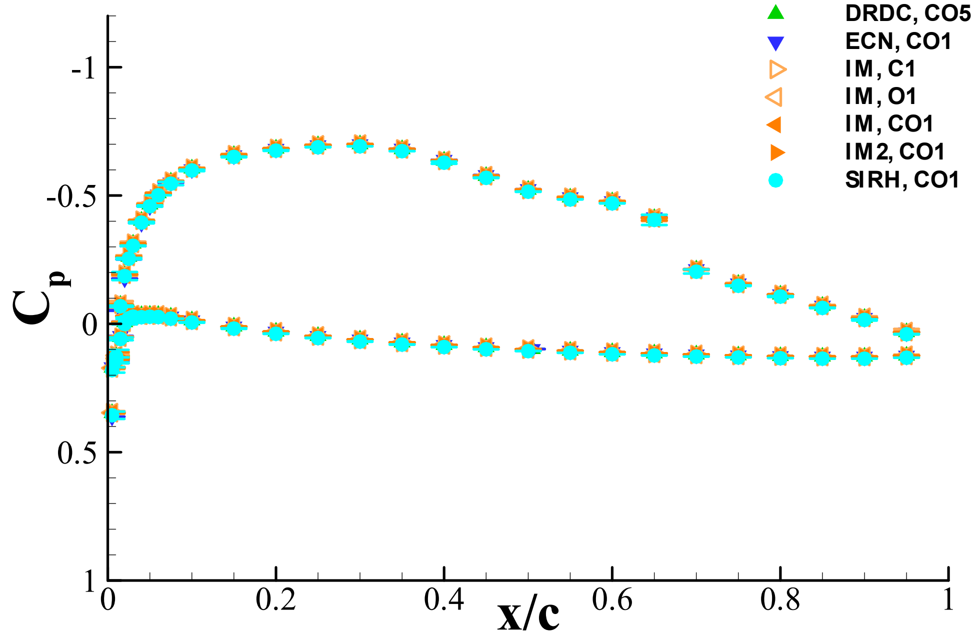
Flow around the Eppler 387 airfoil at $\alpha = 1°$ and $Re = 3 \times 10^5$ (Separation induced transition)

- Pressure coefficient distribution on the surface of the airfoil.

SST $k - \omega$+$\gamma - Re_\theta$



SST $k - \omega$+γ

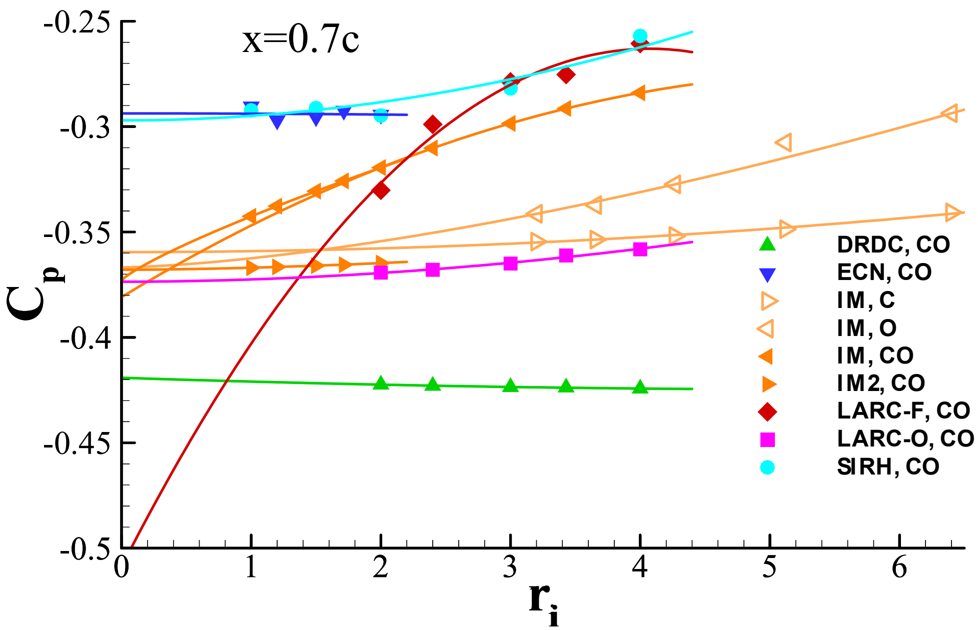


Results

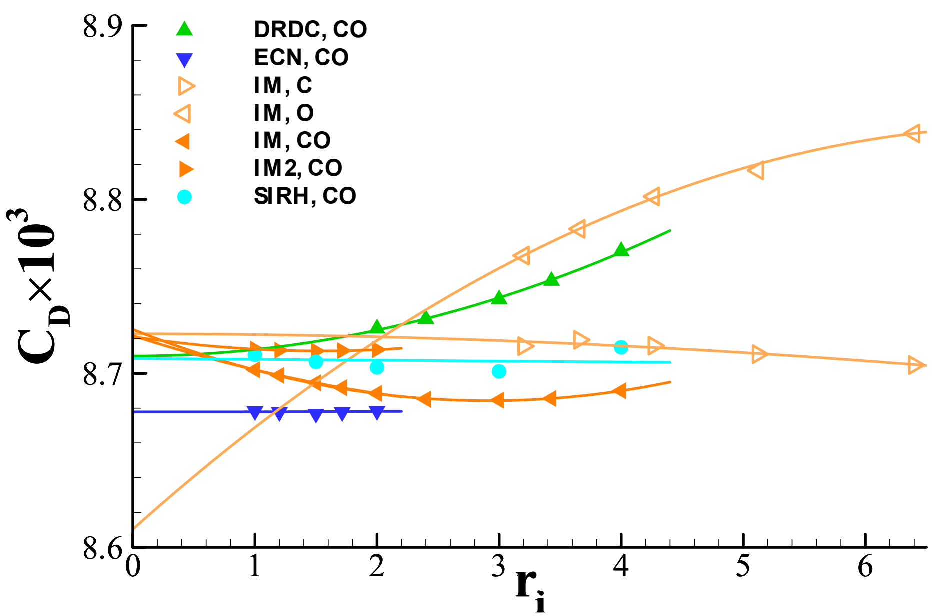
Flow around the Eppler 387 airfoil at $\alpha = 1°$ and $Re = 3 \times 10^5$ (Separation induced transition)

- Pressure coefficient convergence with grid refinement.

SST $k-\omega$+$\gamma - Re_\theta$



SST $k-\omega$+γ

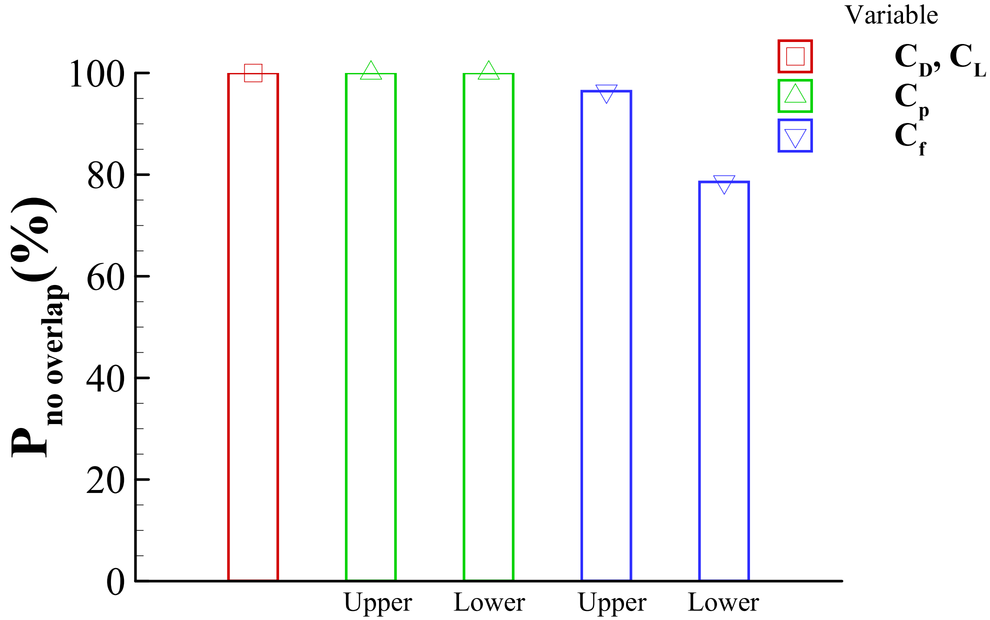


Results

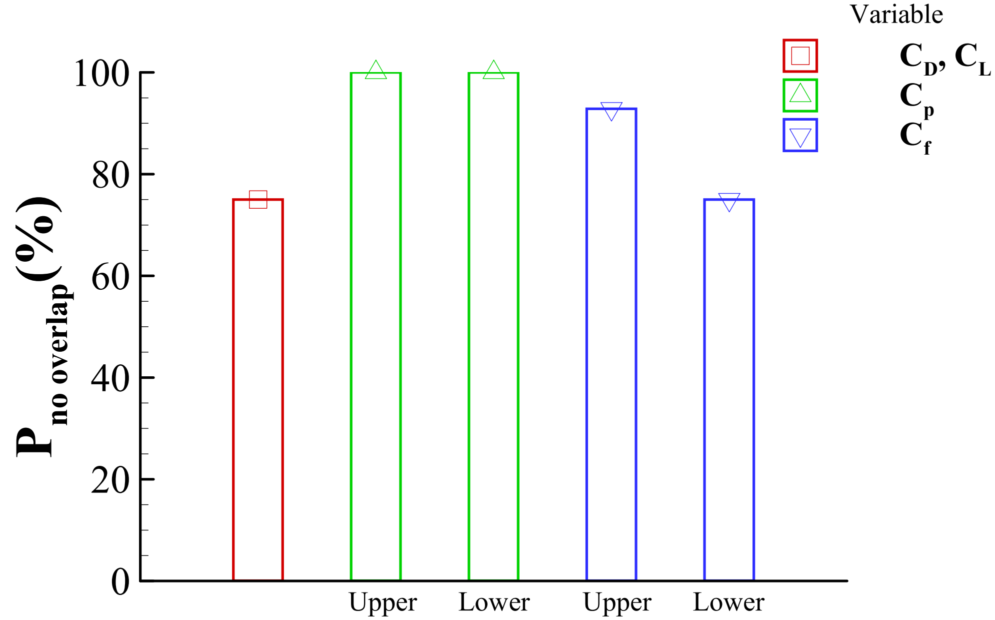
Flow around the Eppler 387 airfoil at $\alpha = 1°$ and $Re = 3 \times 10^5$ (Separation induced transition)

- Check of overlapping error bars

SST $k-\omega$+$\gamma-Re_\theta$



SST $k-\omega$+γ

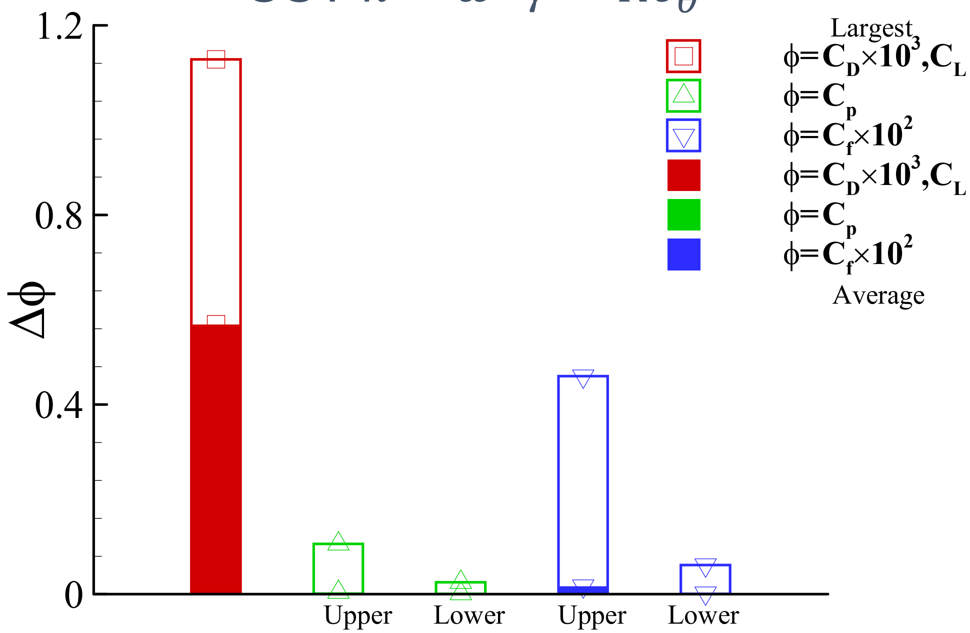


Results

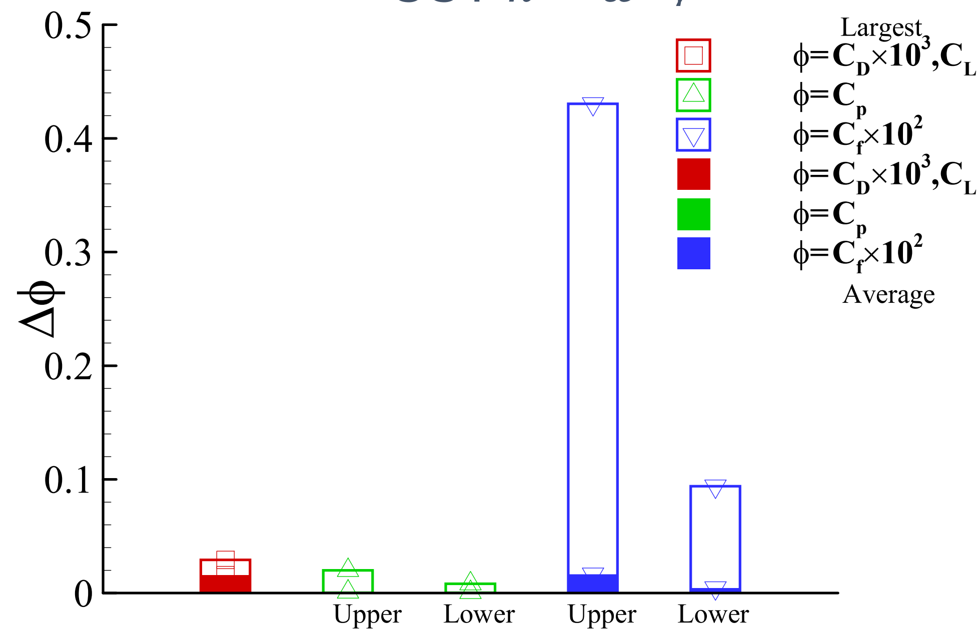
Flow around the Eppler 387 airfoil at $\alpha = 1°$ and $Re = 3 \times 10^5$ (Separation induced transition)

- Maximum and average values of the discrepancies between solutions

SST $k - \omega$+$\gamma - Re_\theta$



SST $k - \omega$+γ

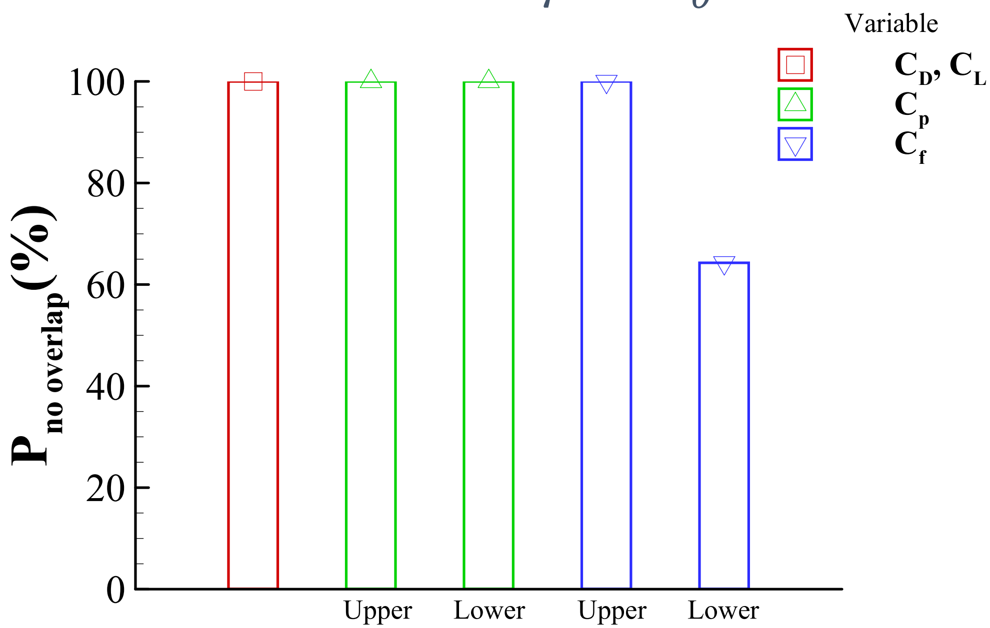


Results

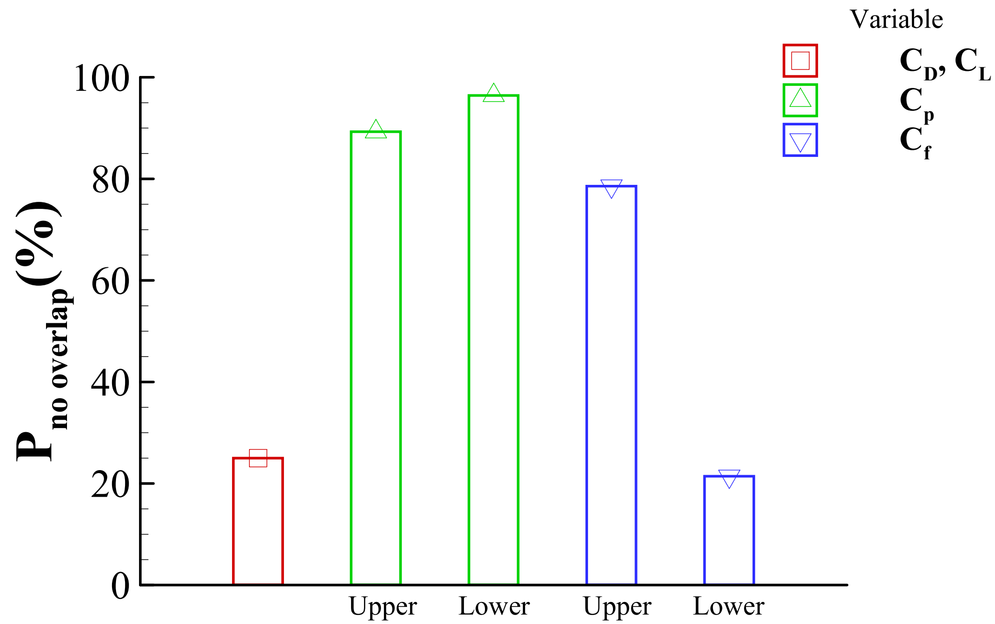
Flow around the Eppler 387 airfoil at $\alpha = 7°$ and $Re = 3 \times 10^5$ (Separation induced transition)

- Check of overlapping error bars

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$



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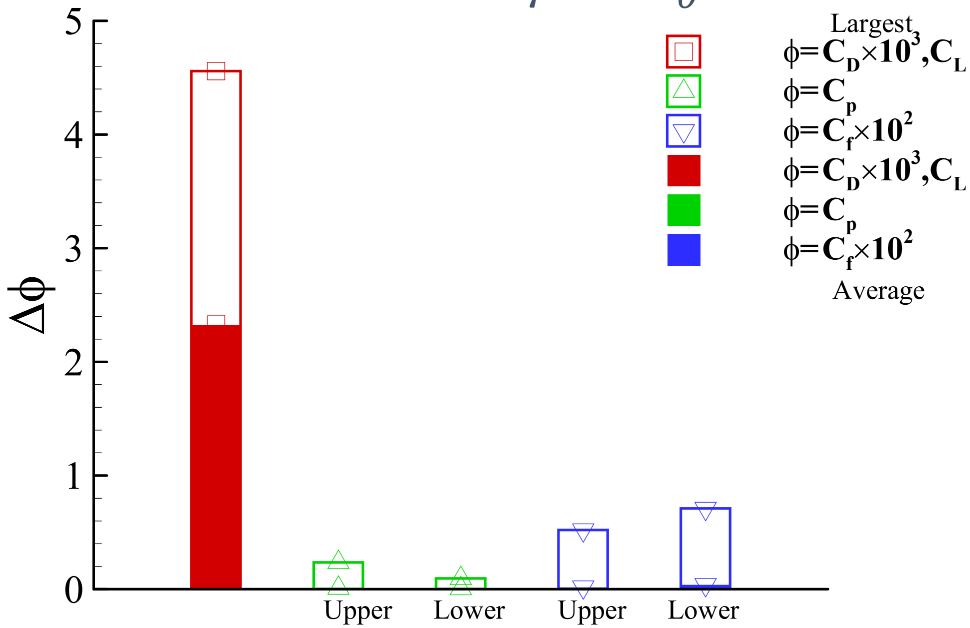
Results

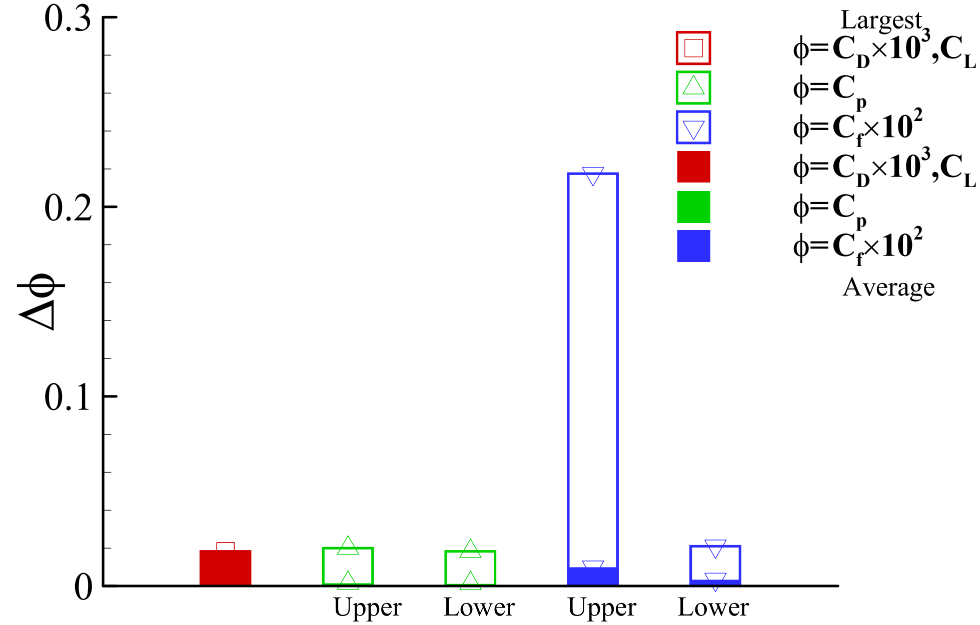
Flow around the Eppler 387 airfoil at $\alpha = 7°$ and $Re = 3 \times 10^5$ (Separation induced transition)

- Maximum and average values of the discrepancies between solutions

SST $k-\omega$+$\gamma - Re_\theta$



SST $k-\omega$+γ

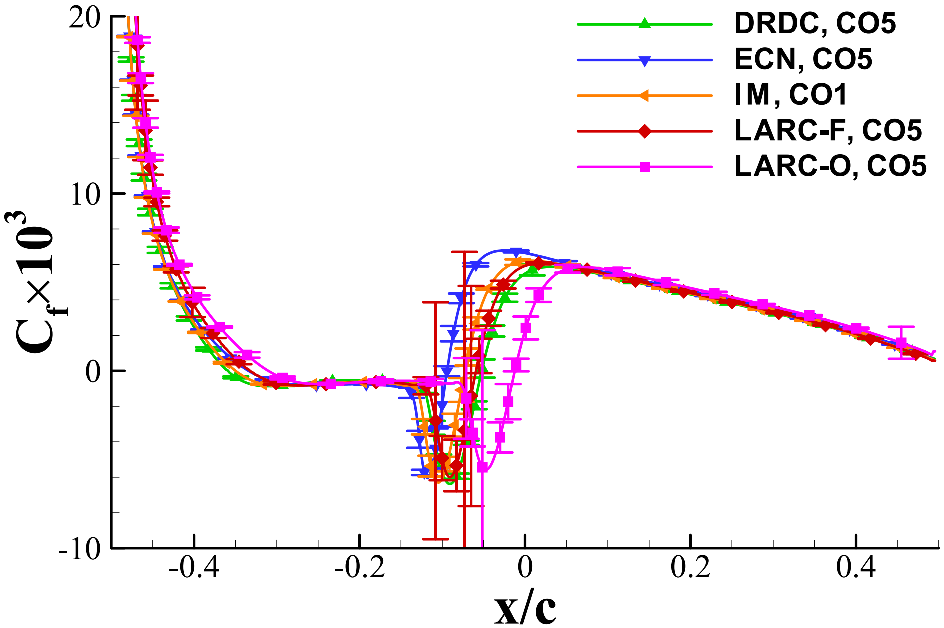


Results

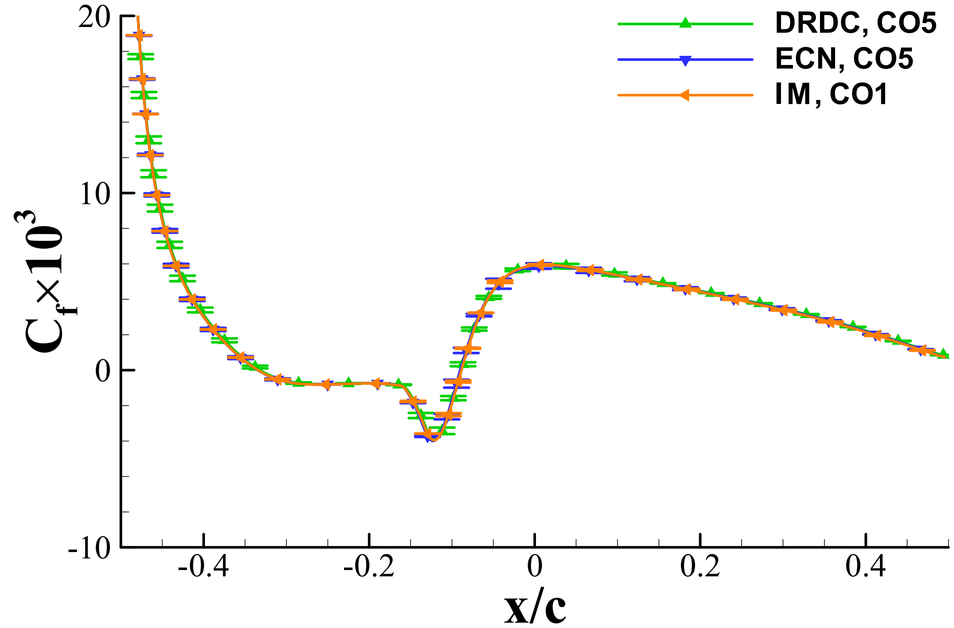
Flow around the NACA 0015 airfoil at $\alpha = 5°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)

- Skin friction coefficient distribution on the upper surface of the airfoil.

SST $k-\omega$+$\gamma - Re_\theta$



SST $k-\omega$+γ

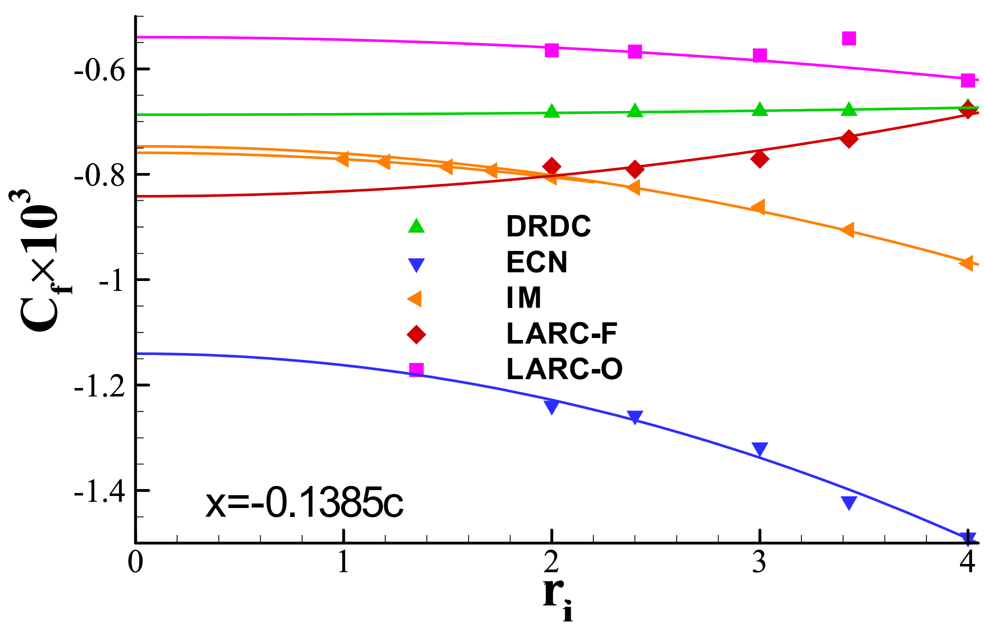


Results

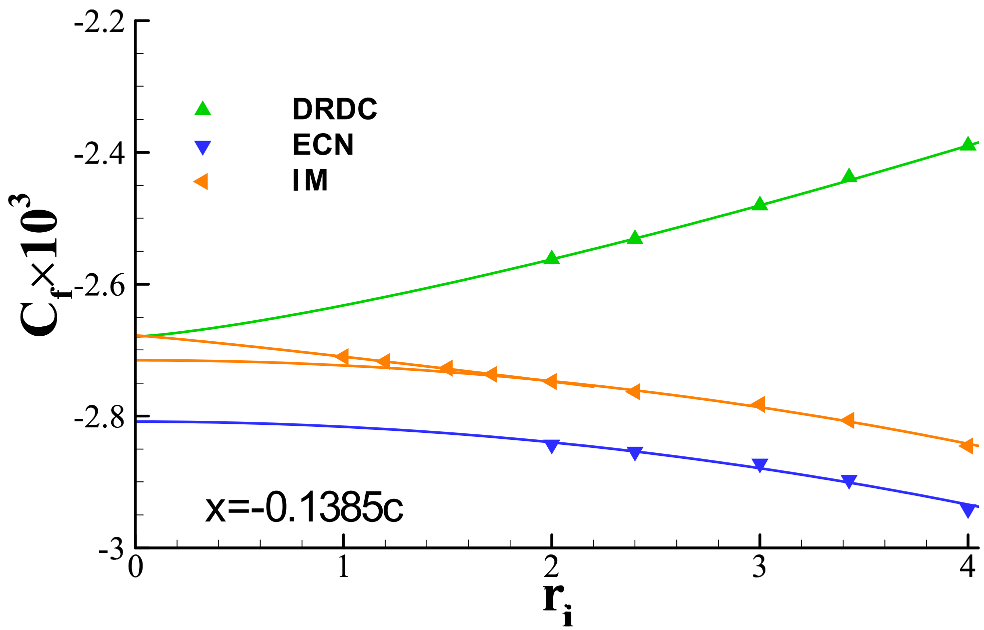
Flow around the NACA 0015 airfoil at $\alpha = 5°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)

- Skin friction coefficient convergence with grid refinement.

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$

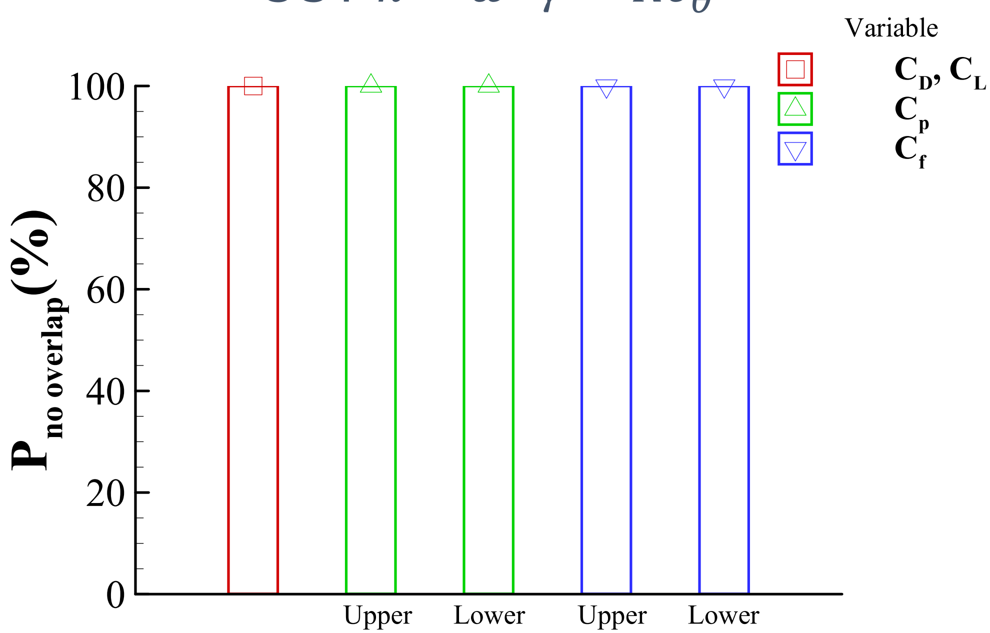


Results

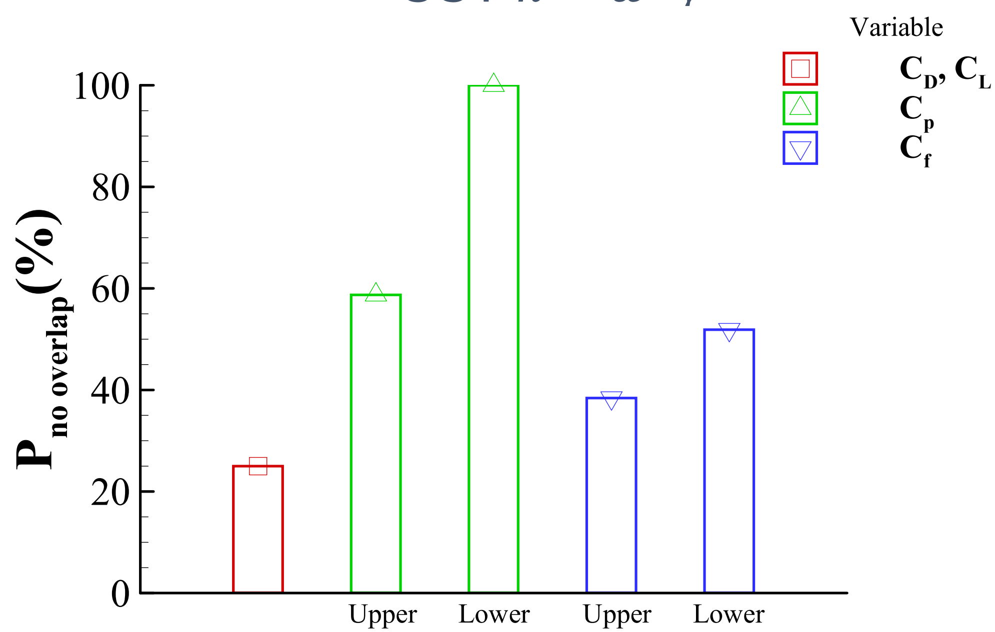
Flow around the NACA 0015 airfoil at $\alpha = 5°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)

- Check of overlapping error bars

SST $k-\omega+\gamma-Re_\theta$



SST $k-\omega+\gamma$

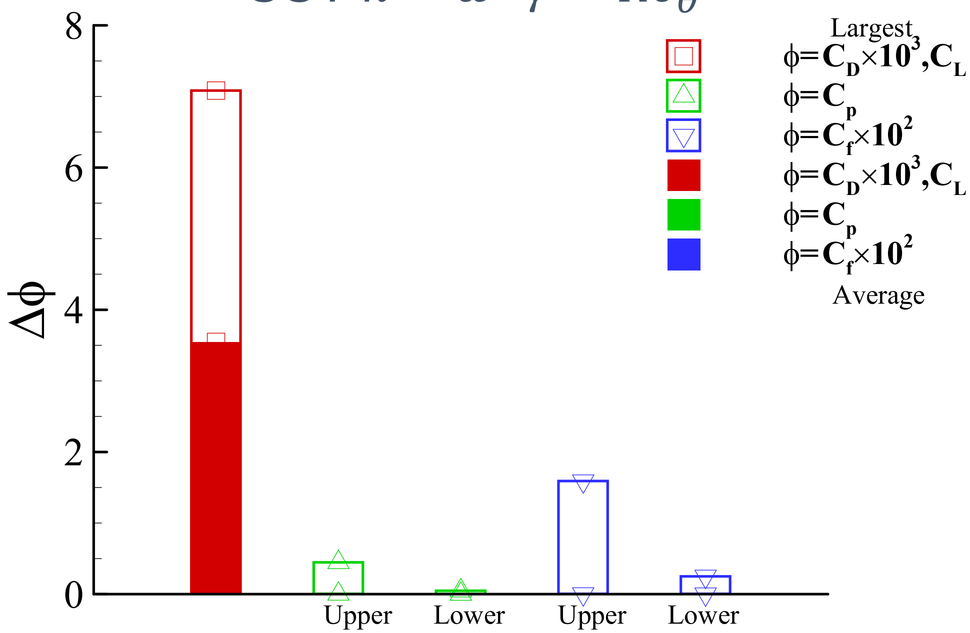


Results

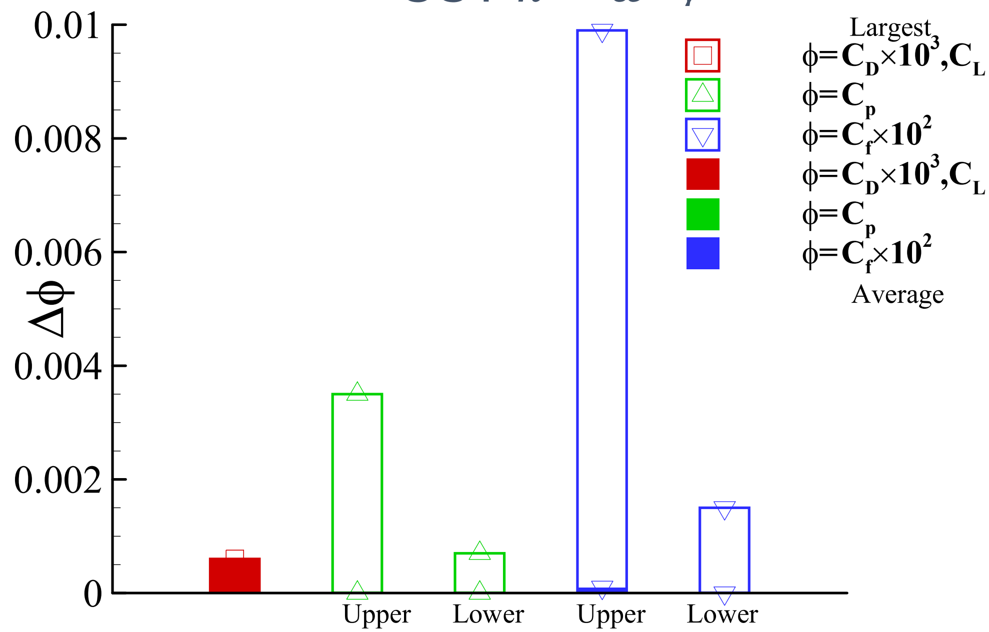
Flow around the NACA 0015 airfoil at $\alpha = 5°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)

- Maximum and average values of the discrepancies between solutions

SST $k-\omega$+$\gamma-Re_\theta$



SST $k-\omega$+γ



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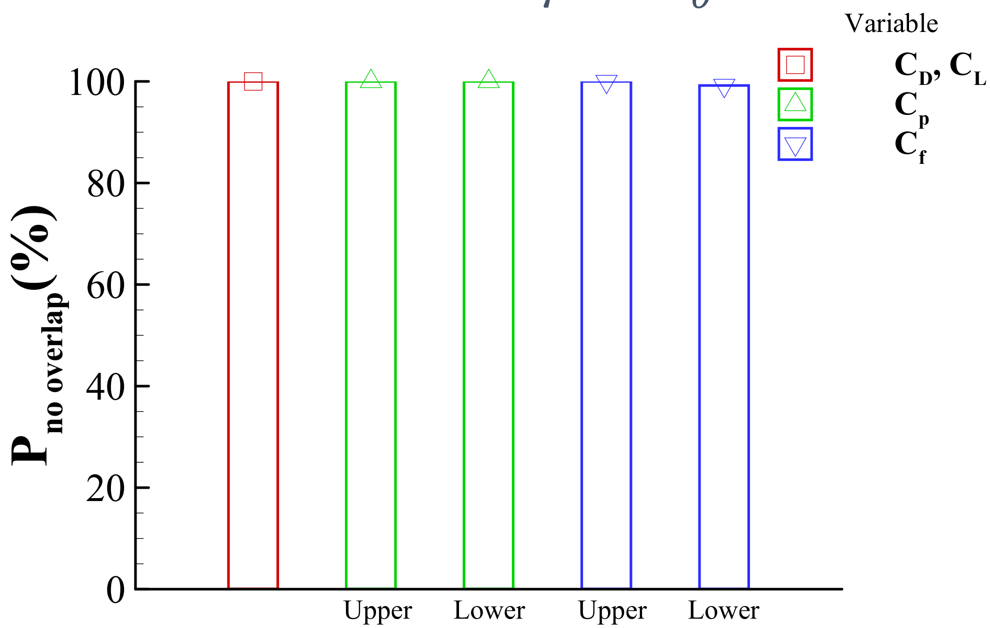
Results

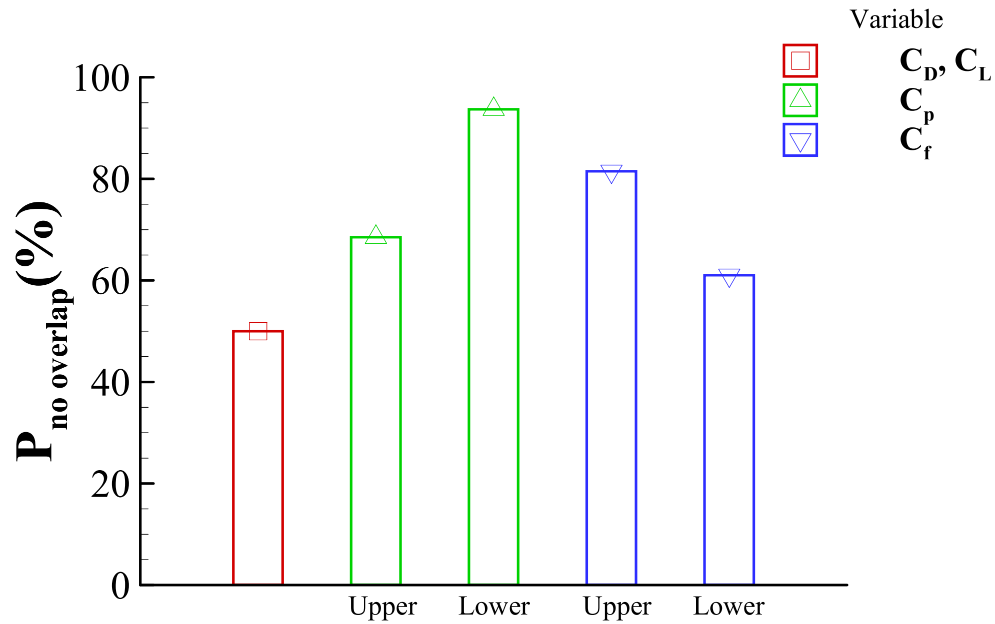
Flow around the NACA 0015 airfoil at $\alpha = 10°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)

- Check of overlapping error bars

SST $k-\omega$+$\gamma-Re_\theta$



SST $k-\omega$+γ

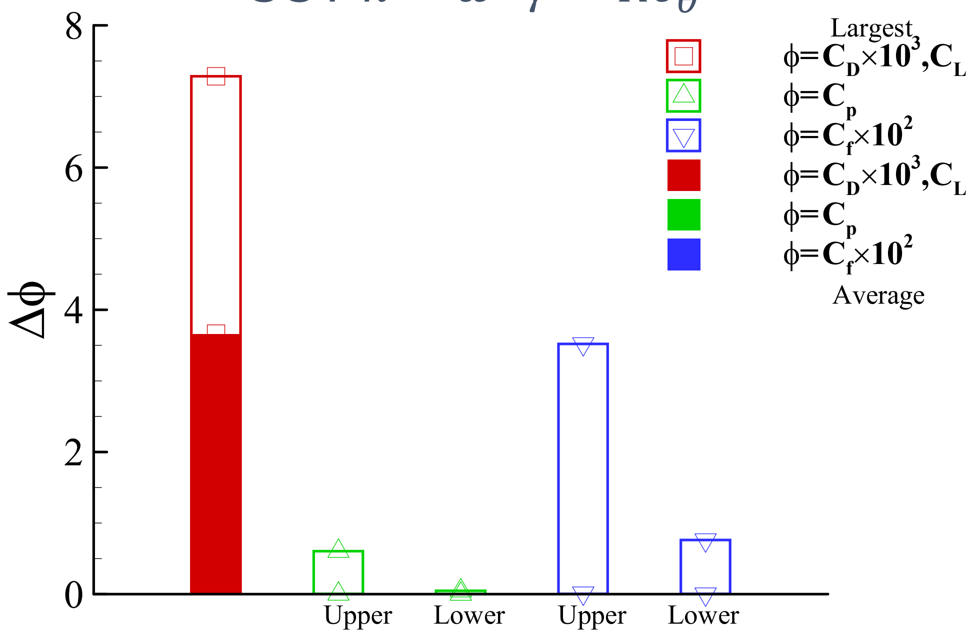


Results

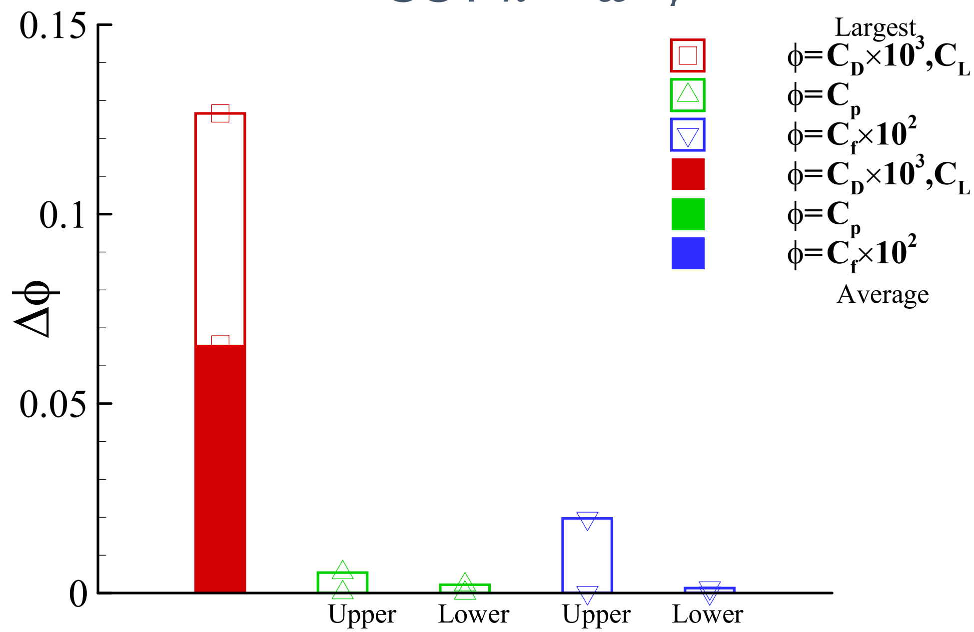
Flow around the NACA 0015 airfoil at $\alpha = 10°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)

- Maximum and average values of the discrepancies between solutions

SST $k-\omega$+$\gamma-Re_\theta$

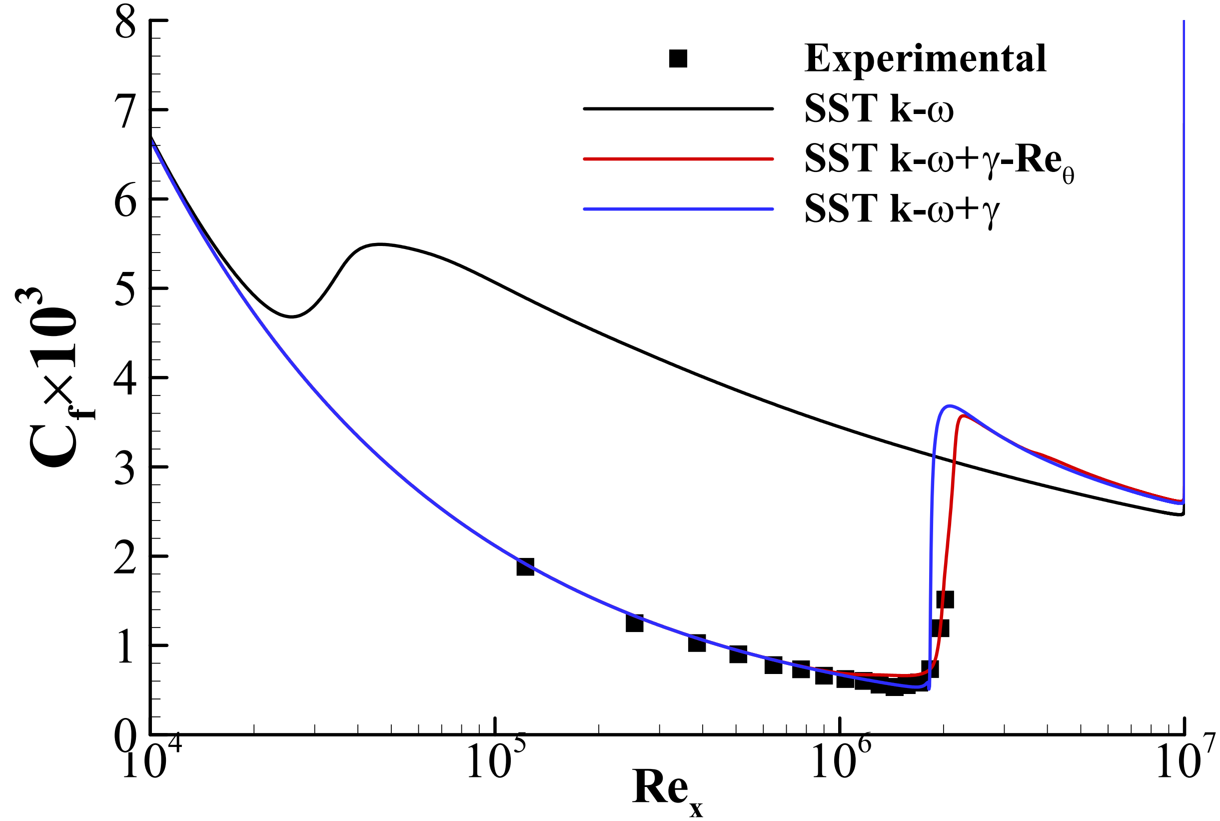


SST $k-\omega$+γ



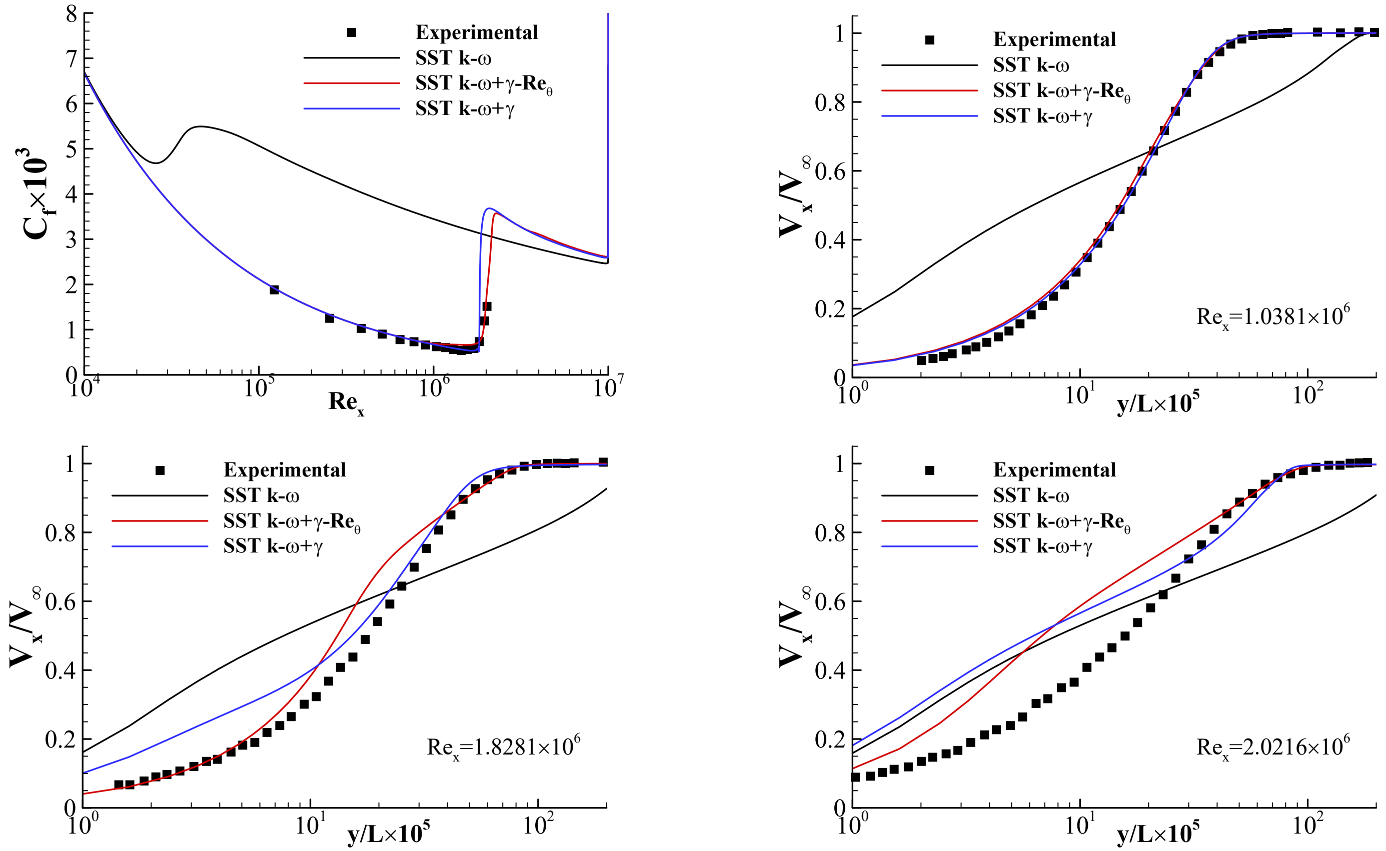
Results

Flow over a flat plate T3AM (Natural transition)



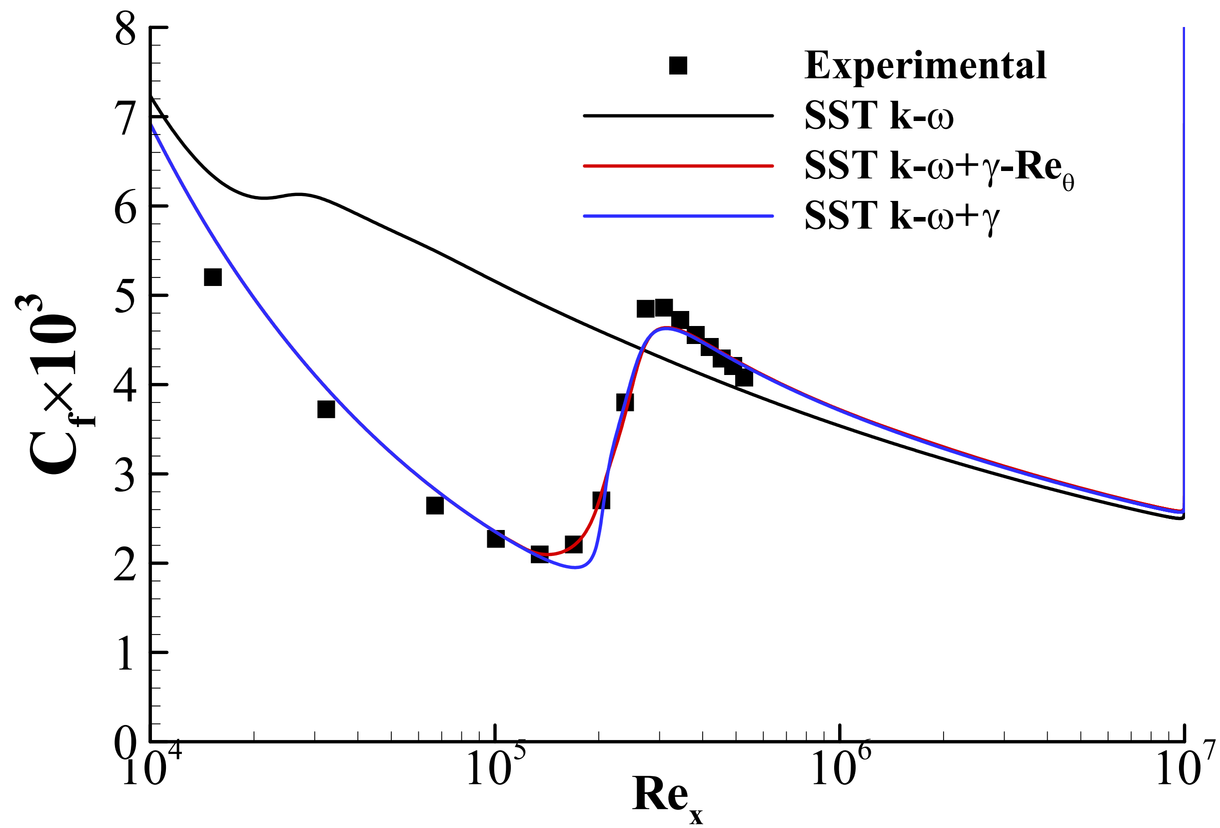
Results

Flow over a flat plate T3AM (Natural transition)



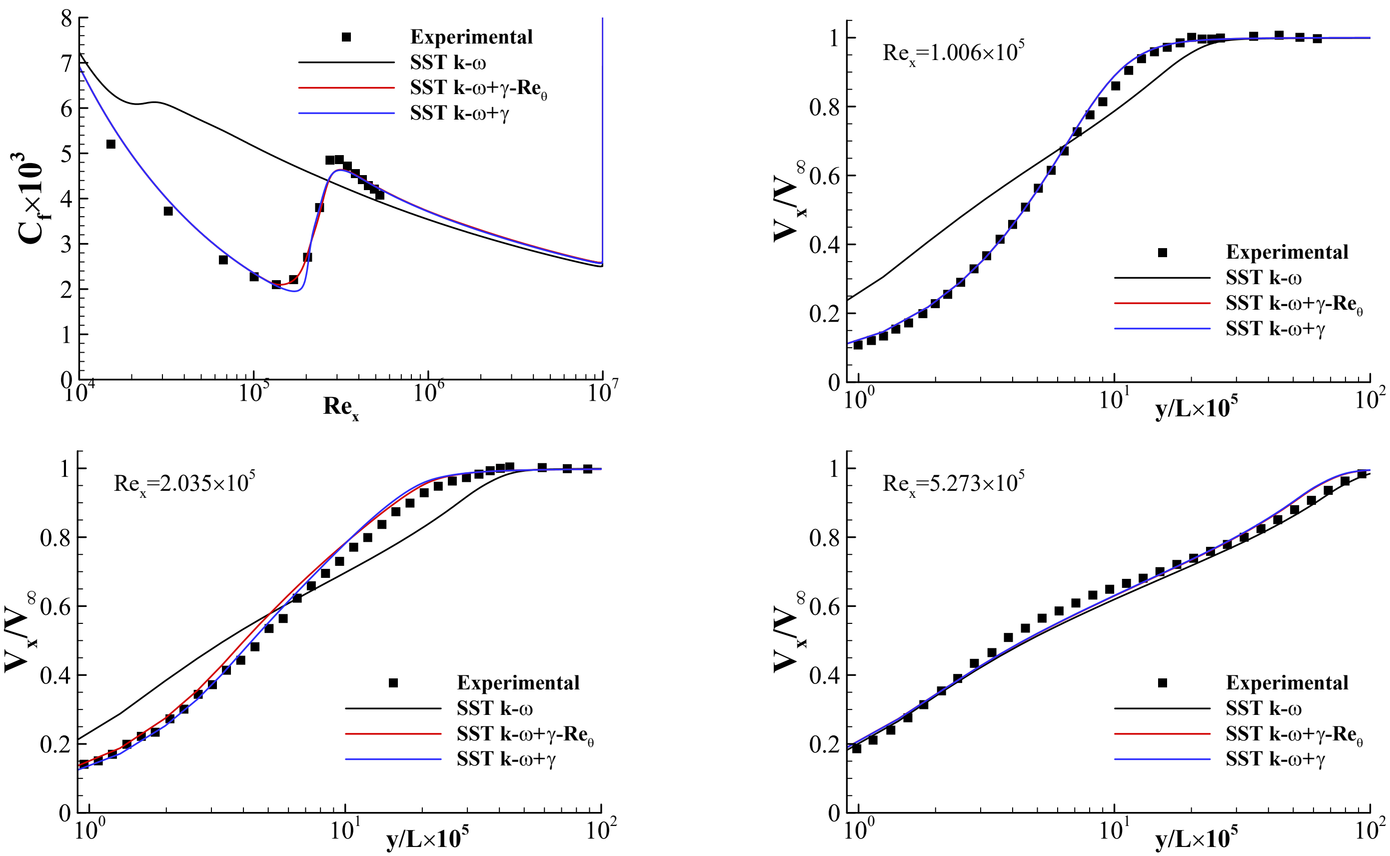
Results

Flow over a flat plate T3A (Bypass transition)



Results

Flow over a flat plate T3A (Bypass transition)



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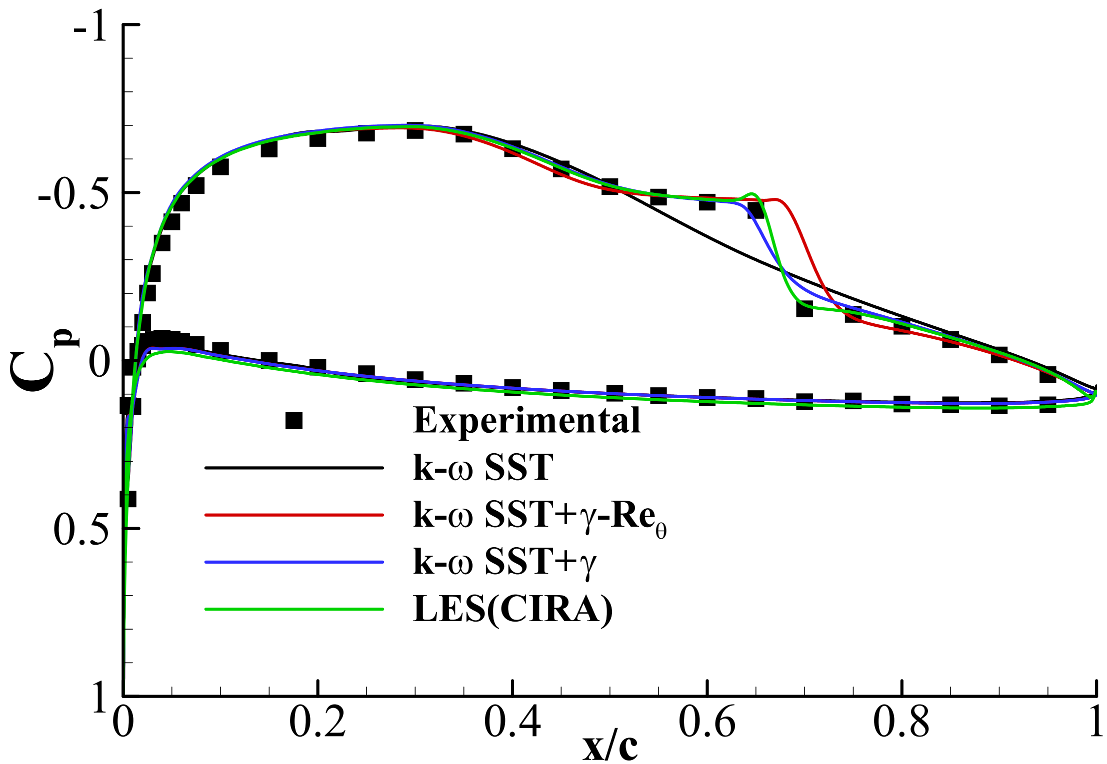
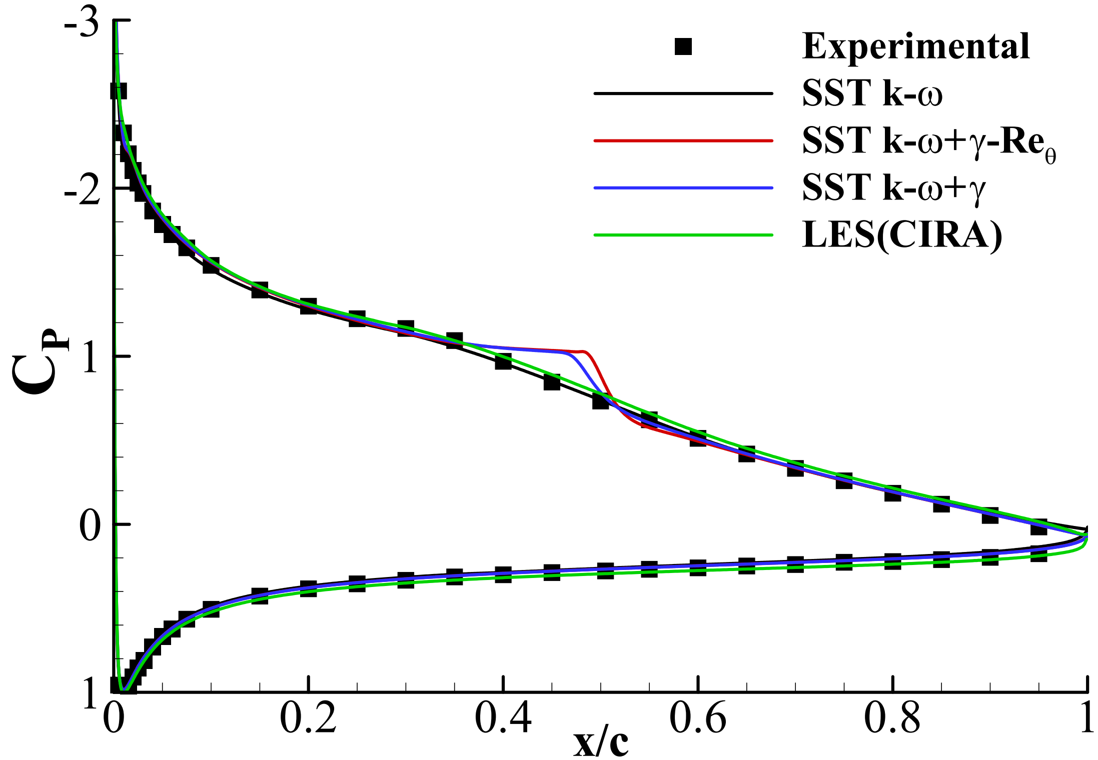
Results

Flow around the Eppler 387 airfoil at $\alpha = 1°$ and $Re = 3 \times 10^5$ (Separation induced transition)



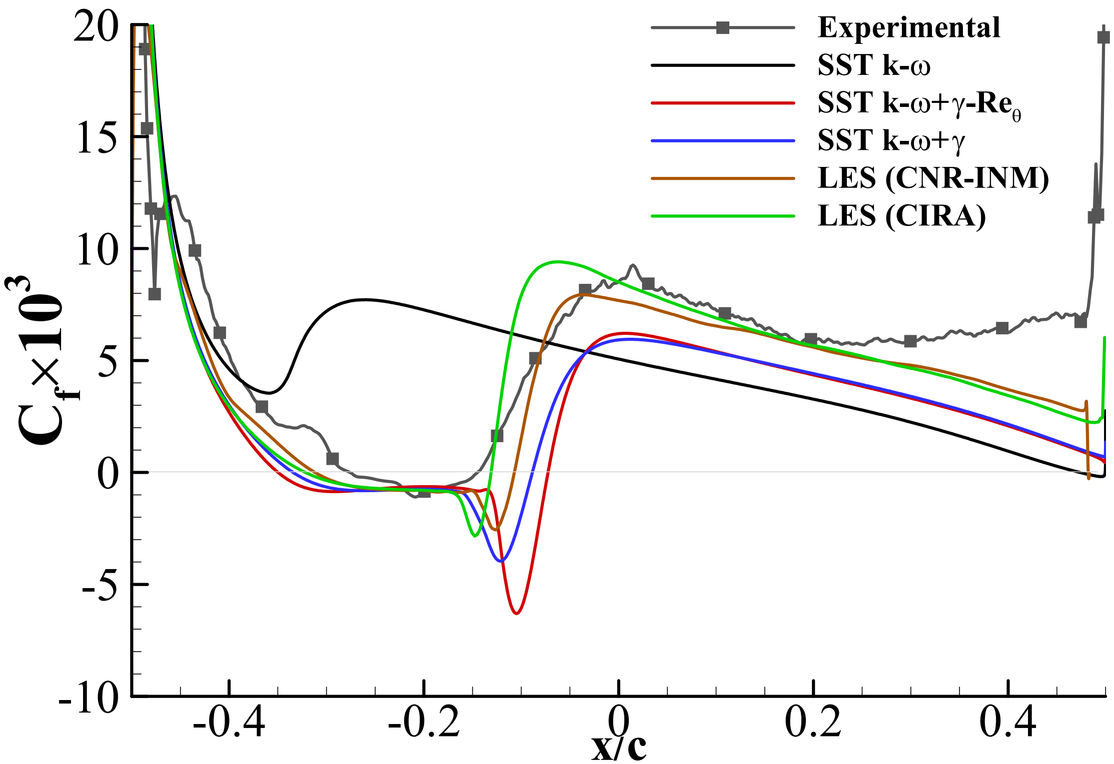
Results

Flow around the Eppler 387 airfoil at $\alpha = 7°$ and $Re = 3 \times 10^5$ (Separation induced transition)



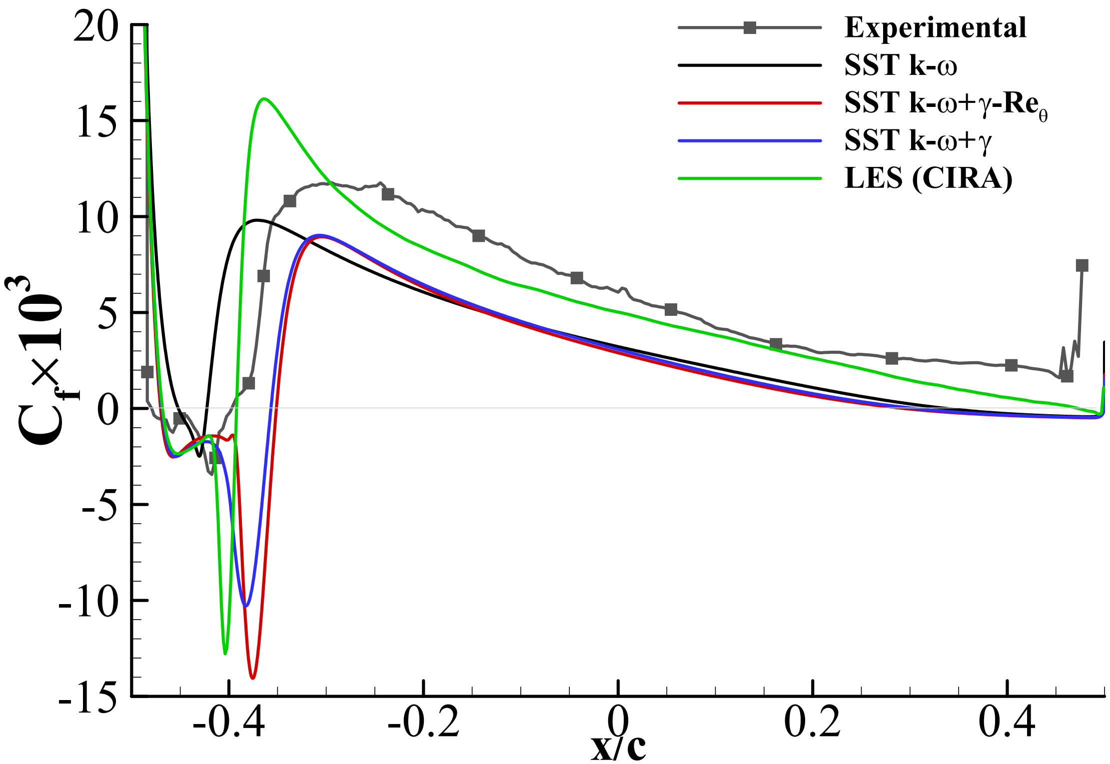
Results

Flow around the NACA 0015 airfoil at $\alpha = 5°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)



Results

Flow around the NACA 0015 airfoil at $\alpha = 10°$ and $Re = 1.8 \times 10^5$ (Separation induced transition)



Conclusions

- Most of the consistency checks performed for all of the test cases showed non-overlapping error bars for the solutions obtained with nominally the same mathematical model but different RANS solvers.

- Reasons for the discrepancies are:
  - the estimated error bars are not conservative;
  - the details of the nominal identical turbulence and transition models are not identical in all flow solvers;
  - the implementations of the turbulence and transition models have “bugs”;

- There are differences in the details of the implementations of the turbulence and transition models and in the flow settings (*M=0* versus *M=0.1*) that are contributing to the differences between flow solvers

Conclusions

- It is clear that transition models are required for RANS based computations of low Reynolds number flows due to the unphysical location of transition predicted by standard turbulence models.
- The lack of a test case with all the information required to simulate a low Reynolds number flow in identical conditions to the experiment hampers the ability to quantify accurately the modelling error of the simulations.
- Detailed results of this exercise are available at
  http://web.tecnico.ulisboa.pt/ist12278/Workshop_AVT_313_2D_cases/Workshop_AVT_313_2D_cases.htm
  Just “google” AVT-313 Transition Workshop ☺!