Validation of intermittency model for transition prediction in a RANS flow solver

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Outline

- Introduction and motivations
- Numerical framework
  - ✓ Flow solver
  - ✓ Transition model
- Validation
  - ✓ Flat plate (ERCOFTAC T3A and T3B)
- Applications
  - ✓ S809 Airfoil
  - ✓ Prolate Spheroid
- Concluding Remarks

Introduction

- Address the issue of transition phenomenon in RANS simulations
  - ✓ Location and region
- Improve simulation capabilities of in-house RANS flow solver
  - ✓ Transition prediction
  - ✓ Simulation of free-transition flows
- Assessment of transition model

RANS Flow solver

UZEN Code

- Flow Solver for steady and unsteady Euler, and RANS equations
- Spatial Discretization
  - ✓ Structured Multi-Block, Finite Volume
  - ✓ Cell Centered with blended 2nd and 4th order artificial dissipation
- Dual-Time Stepping for unsteady flows
- Time Advancement for steady flows
  - ✓ Runge-Kutta with multigrid, local time-stepping, residual averaging
- Turbulence Models
  - ✓ Baldwin-Lomax
  - ✓ Spalart-Allmaras
  - ✓ Myong-Kasagi, NLEV (Shih formulation) κ-ε
  - ✓ κ-ω : Wilcox, Kok TNT, Menter BSL and SST, SST-LR
  - ✓ DES for SA and κ-ω SST
  - ✓ XLES for κ-ω TNT

Transition Model

Transport equation for intermittency

$$\frac{\partial \rho\gamma}{\partial t} + \frac{\partial \rho U_j \gamma}{\partial x_j} = P_\gamma - D_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial \gamma}{\partial x_j}\right]$$

$$P_\gamma = F_{length}\rho S\gamma(1-\gamma)F_{onset}$$

$$D_\gamma = c_{a2}\rho\Omega\gamma F_{turb}(c_{e2}\gamma - 1)$$

SST turbulence model interaction

$$\frac{\partial \rho\kappa}{\partial t} + \frac{\partial \rho U_j \kappa}{\partial x_j} = \gamma P_\kappa + P_\kappa^{lim} - \max(\gamma, 0.1)D_\kappa + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\kappa \mu_t)\frac{\partial \kappa}{\partial x_j}\right]$$

P_κ^{lim} is an additional production term

Transition Model

Triggering functions

$$\mathrm{F}_{\mathrm{onset1}} = \frac{Re_V}{C_{onset} Re_{\theta c}}$$

$$\mathrm{Re}_{\theta c}(Tu_L, \lambda_{\theta L}) = C_{Tu1} + C_{Tu2} exp[-C_{Tu3} Tu_L F_{PG}(\lambda_{\theta L})]$$

Original model

$$\mathrm{C}_{\mathrm{onset}} = 2.2$$

$$\mathrm{C}_{\mathrm{Tu1}} = 100.00$$

$$\mathrm{C}_{\mathrm{Tu2}} = 1000.00$$

Modified model

$$\mathrm{C}_{\mathrm{onset}} = \min\left\{4.84, \max[2.2, 1.388 \ln(Re \times 10^{-6}) + 0.705]\right\}$$

$$1 \times 10^6 \leq Re \leq 15 \times 10^6$$

$$\mathrm{C}_{\mathrm{Tu1}} = 163.00$$

$$\mathrm{C}_{\mathrm{Tu2}} = 1002.25$$

1. Colonia, S., Leble, V., Steijl, R., and Barakos, G., “Calibration of the 7—Equation Transition Model for High Reynolds Flows at Low Mach,” Journal of Physics: Conference Series, Vol. 753, Sep 2016
2. Colonia, S., Leble, V., Steijl, R., and Barakos, G., “Assessment and Calibration of the γ-Equation Transition Model at Low Mach,” AIAA Journal, Jan 2017

Test cases

- Validation
  - ✓ ZPG Flat plate
    - (**T3A & T3B** ERCOFTAC T3 Series[1])
- 2D Flow
  - ✓ S809 airfoil[2]
    - Incompressible flow at $Re=2.0x10^6$ and $\alpha=1°, 6°, 9°$
- 3D flow:
  - ✓ 6:1 prolate spheroid[3]
    - Incompressible flow at $Re=2.0x10^6$ and $\alpha=5°, 10°, 15°$

1. Coupland, J., “ERCOFTAC special interest group on laminar to turbulent transition and retransition: T3A and T3B test cases,” A309514, 1990
2. Somers, D. M., “Design and experimental results for the S809 airfoil,” Tech. rep., Jan.1997
3. Kreplin, H. P., Meier, H., and Maier, A., “Wind tunnel model and measuring techniques for the investigation of three-dimensional turbulent boundary layers,” 1978

ZPG Flat plate

T3A

- $M=0.0152$
- $Re=5.67 \times 10^5$ (on a length L = 1.6 m)
- $Tu=3.3\%$
- $\mu_t/\mu=12.0$

T3B

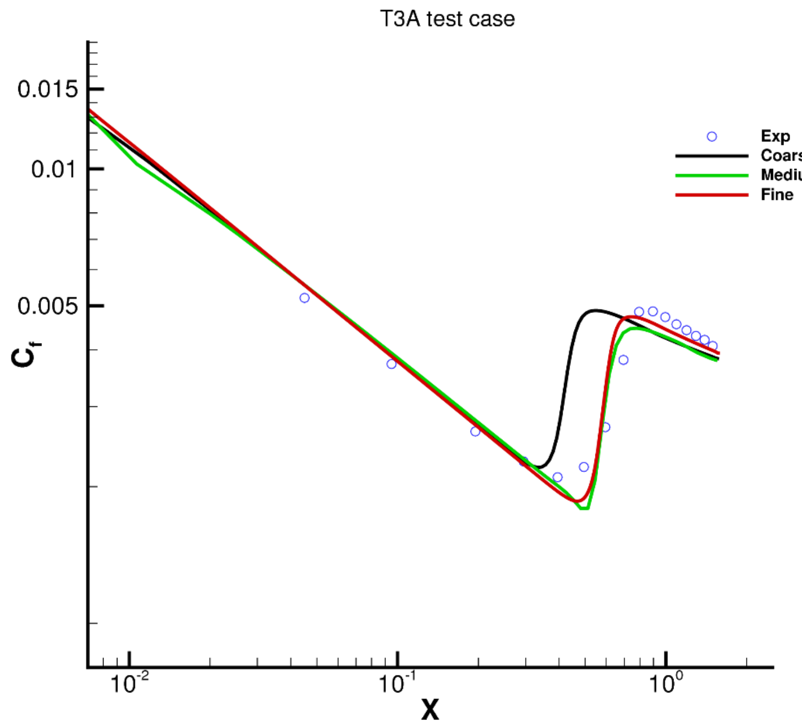
- $M=0.0276$
- $Re=1.03 \times 10^6$ (on a length L = 1.6 m)
- $Tu=6.0\%$
- $\mu_t/\mu=90.0$

Grid:

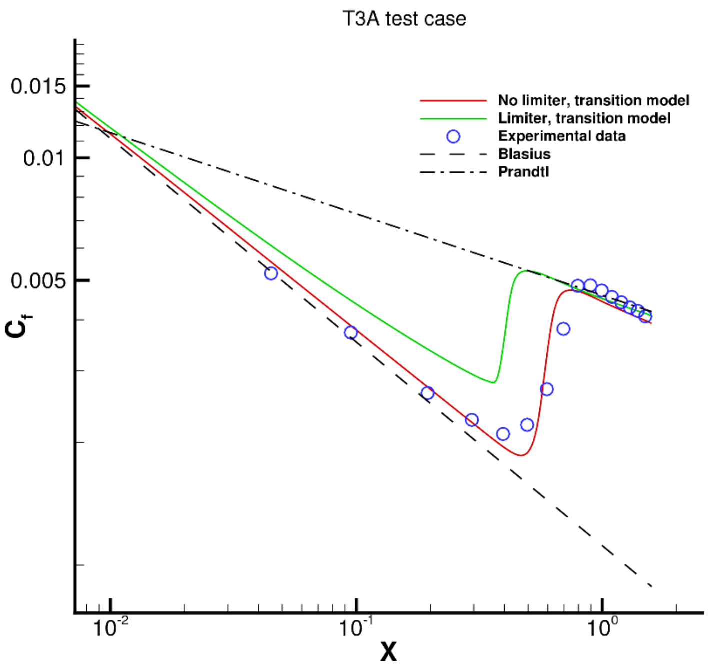
2 blocks structured type

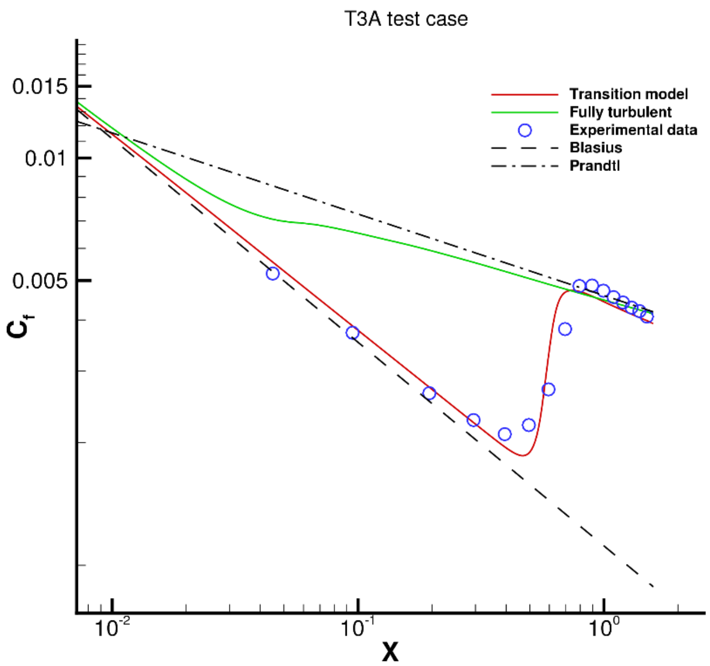
Rectangular domain $\Omega = [-0.2, 1.6] \times [0, 0.3]$ (flat plate starts at $x = 0$)

Three grid levels (40256 cells on fine mesh)



T3A flat plate





Limiter on turbulence variables

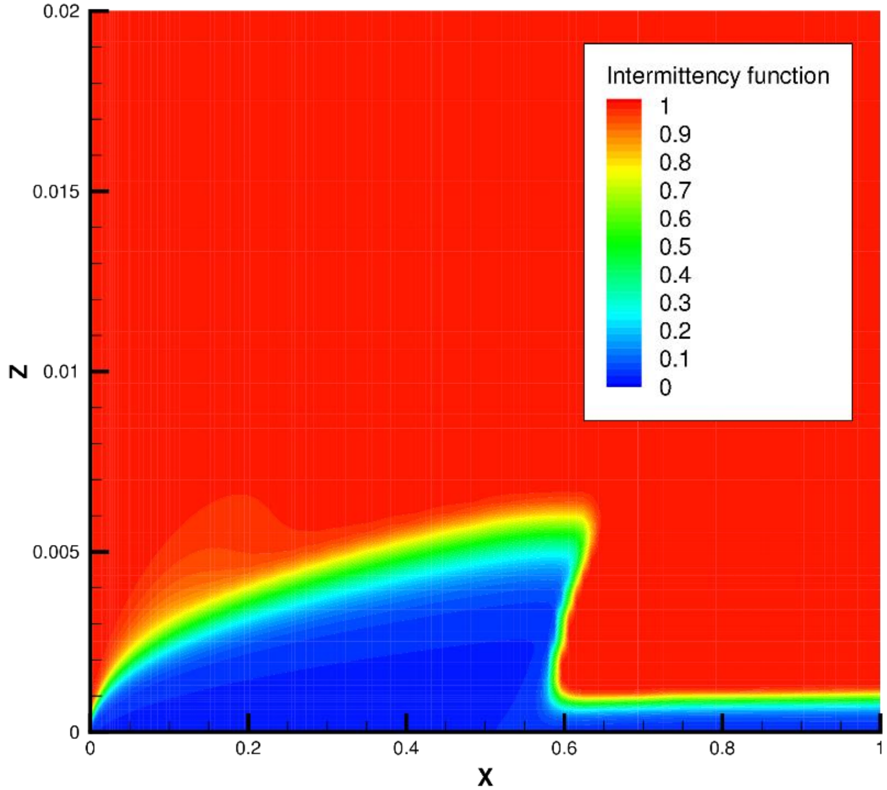
$$\kappa \geq \kappa_{fs}\,, \omega \geq 10\,\frac{U_\infty}{L_{ref}}$$

Both laminar and transition region are missed

Clear improvement in flow computation between “fully turbulent” and “transitional” simulations

T3A flat plate

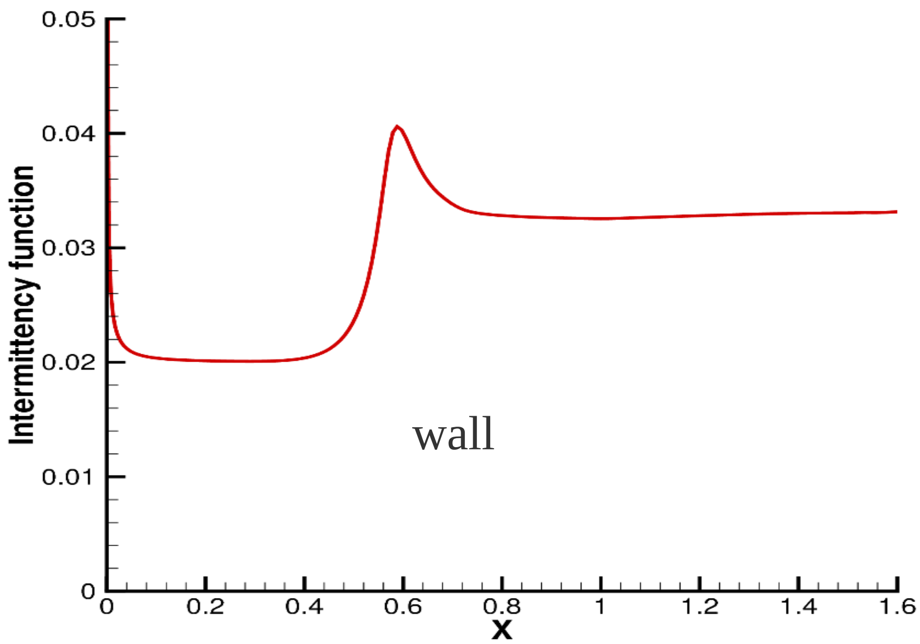
Intermittency function field



Transition detected at about x=0.6 (x/L=0.37)

T3A flat plate

Intermittency function field

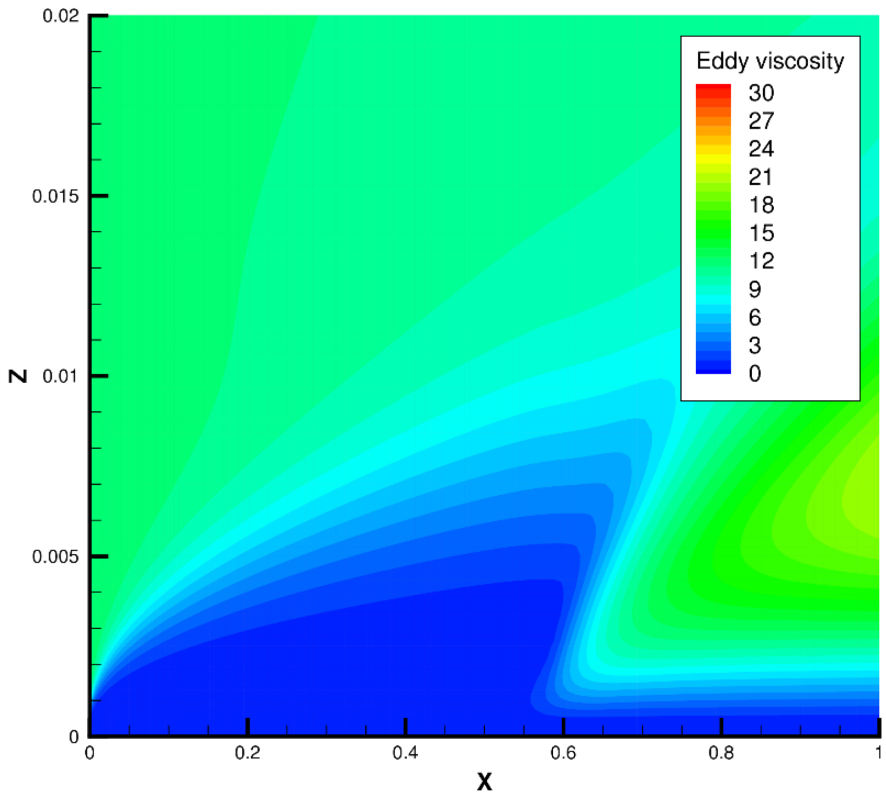


Transition detected at about x=0.6 (x/L=0.37)

γ distribution at wall

T3A flat plate

Intermittency function field



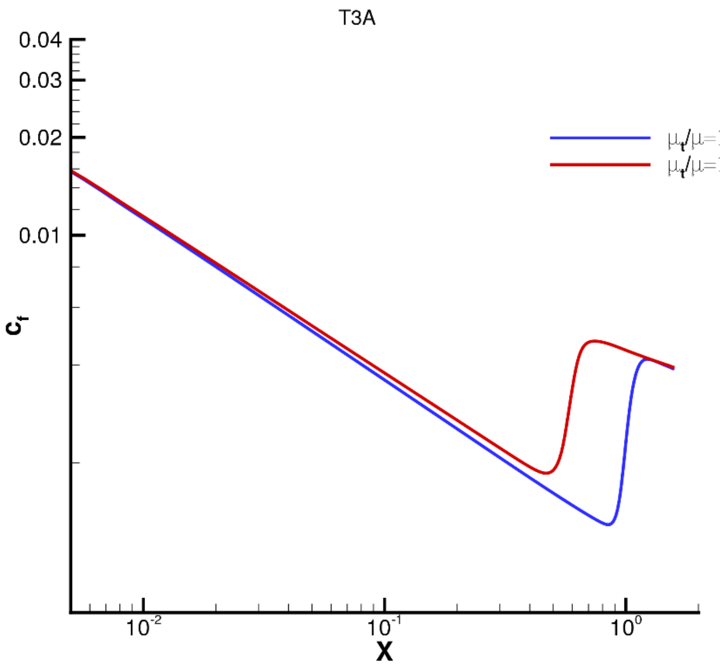
Transition detected at about x=0.6 (x/L=0.37)

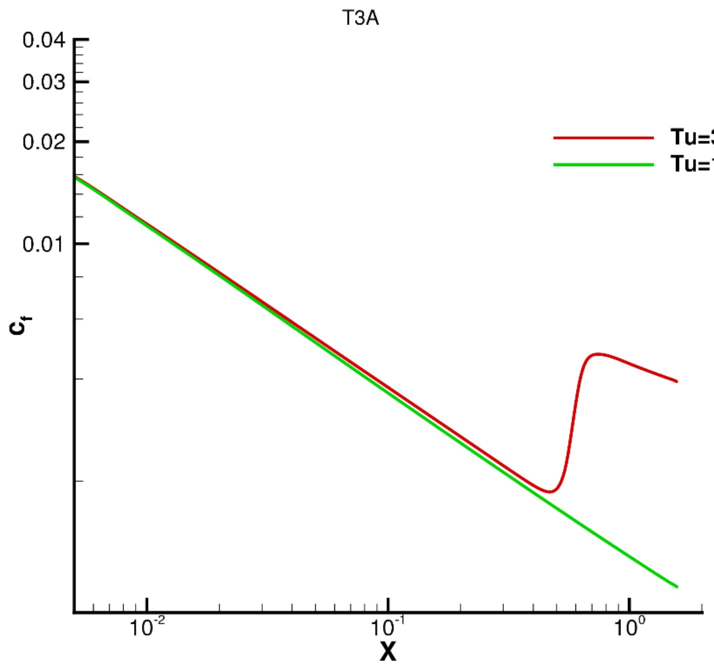
γ distribution at wall

Effect on eddy viscosity field

T3A flat plate

Effect of free-stream turbulence



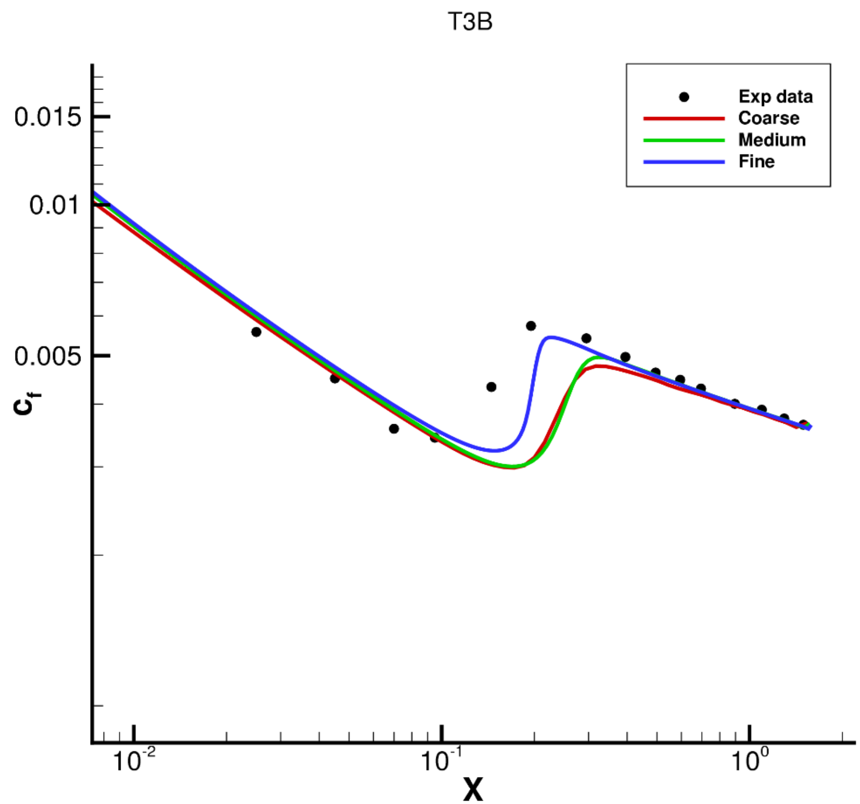


Lowering freestream eddy viscosity ratio: delayed transition onset

Lowering freestream turbulence intensity: no transition (fully laminar)

T3B flat plate

- M=0.0276
- Re=1.03 x 10^6 (on a length L = 1.6 m)
- Tu=6.0%
- μ_t/μ=90.0



Transition onset detected downstream

Transition region predicted satisfactorily

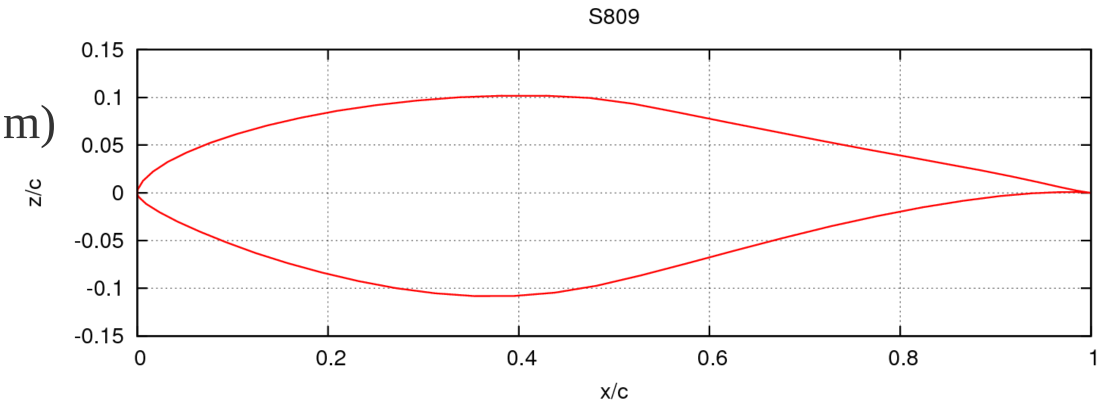
Turbulent region well predicted

2D Flow

S809 Airfoil

The S809 is a 21%-thick, laminar-flow airfoil designed for horizontal-axis wind-turbine applications. Short laminar bubbles at high Reynolds number

- M=0.10
- Re=2.00 x 10^6 (on a length L = 1.0 m)
- α=1°, 6°, 9°
- Tu=0.07%
- μ_t/μ=0.1



Grid:

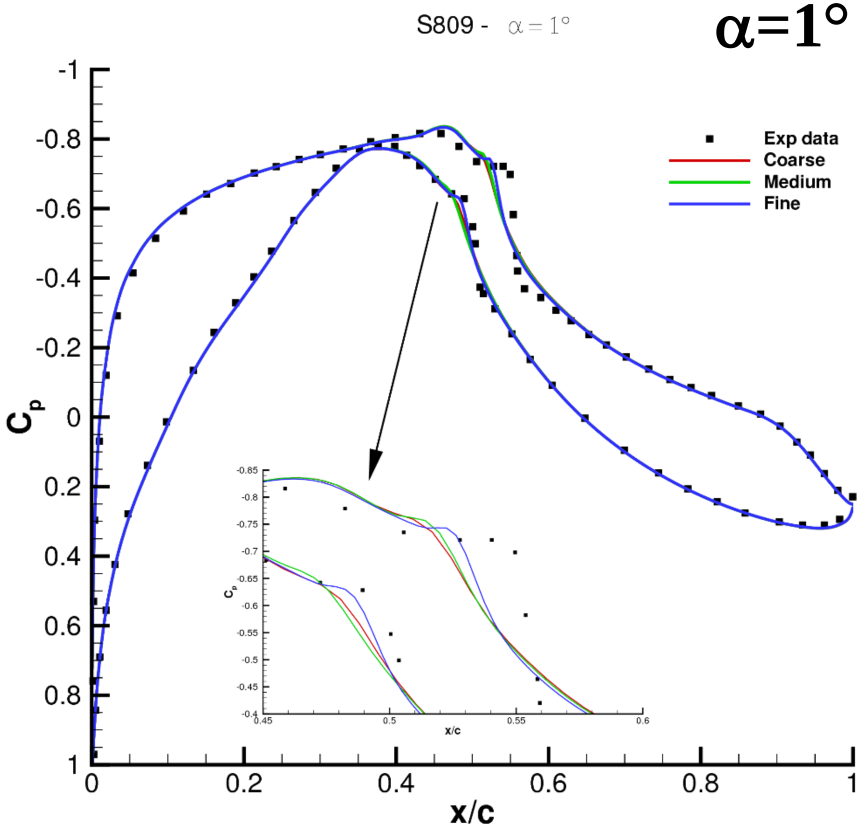
C topology, single block structured type

Farfield set at 1000 chords

Three grid levels (152064 cells on fine mesh)

S809 Airfoil

α=1°



Good agreement with the experimental data for all grid levels

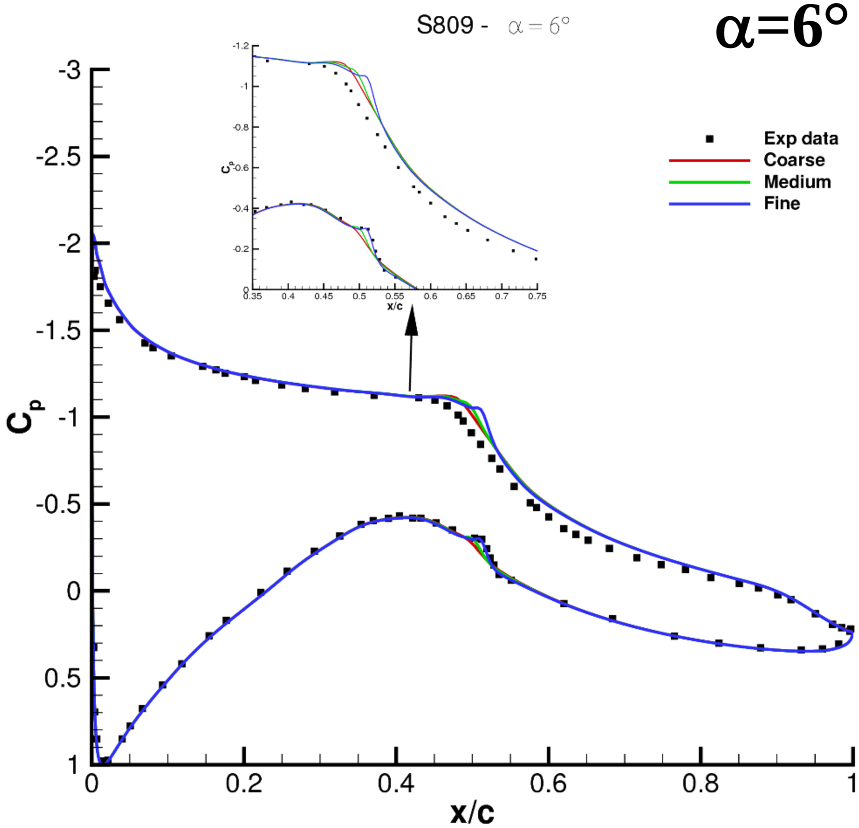
Laminar bubbles detected on both upper and lower surfaces

Refining the mesh improves the accuracy in modeling the bubble

	C_l	$C_{d\ tot}$	C_m	x_{tr}, upper side	x_{tr}, lower side
EXP	0.2673	0.7149E-02	-0.0491	0.55	0.50
Coarse	0.2823	0.6350E-02	-0.04898	0.53	0.49
Medium	0.2832	0.6320E-02	-0.04896	0.53	0.48
Fine	0.2816	0.6304E-02	-0.04881	0.54	0.49

S809 Airfoil

α=6°



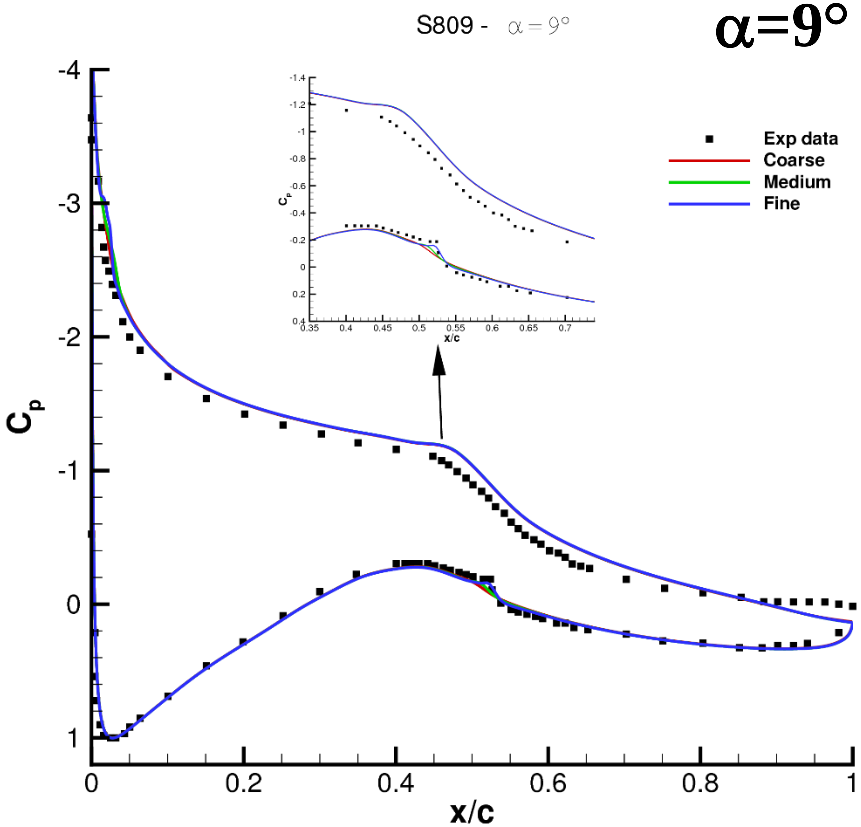
Good agreement with the experimental data for all grid levels

Transition on the upper side is predicted downstream with respect to experiments

Delayed transition induces a bubble that is not observed in the experimental data

	C_l	$C_{d\ tot}$	C_m	x_{tr}, upper side	x_{tr}, lower side
EXP	0.823	0.9637E-02	-0.0529	0.268-0.291	0.52
Coarse	0.877	0.7012E-02	-0.0621	0.49	0.50
Medium	0.879	0.6836E-02	-0.0624	0.50	0.51
Fine	0.879	0.6816E-02	-0.0622	0.52	0.52

S809 Airfoil



α=9°

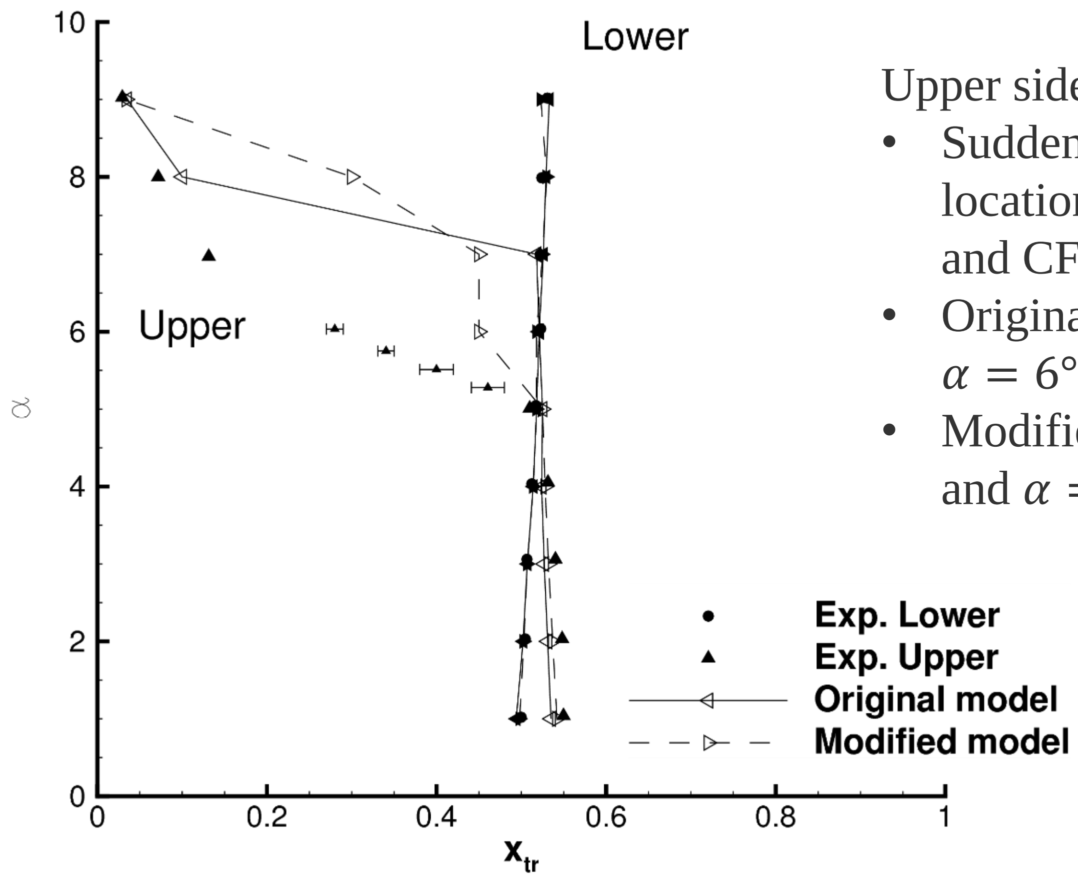
Slight over-prediction on upper side

A bubble, not clearly visible in the experimental data, is returned by numerical simulation on the leading edge region

	C_l	$C_{d\ tot}$	C_m	x_{tr}, upper side	x_{tr}, lower side
EXP	1.012	N/A	-0.0429	0.03	0.53
Coarse	1.127	0.1427E-01	-0.0598	0.02	0.51
Medium	1.132	0.1448E-01	-0.0568	0.03	0.52
Fine	1.132	0.1474E-01	-0.0569	0.03	0.53

S809 Airfoil

Transition location



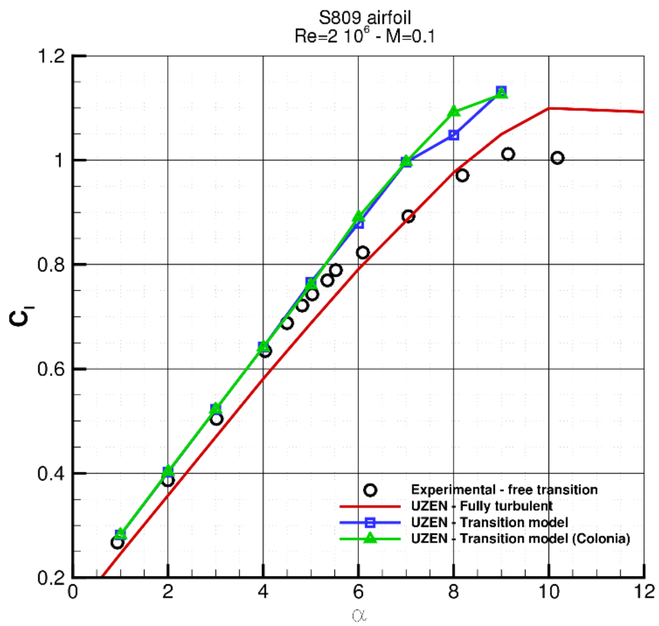
Lower side:

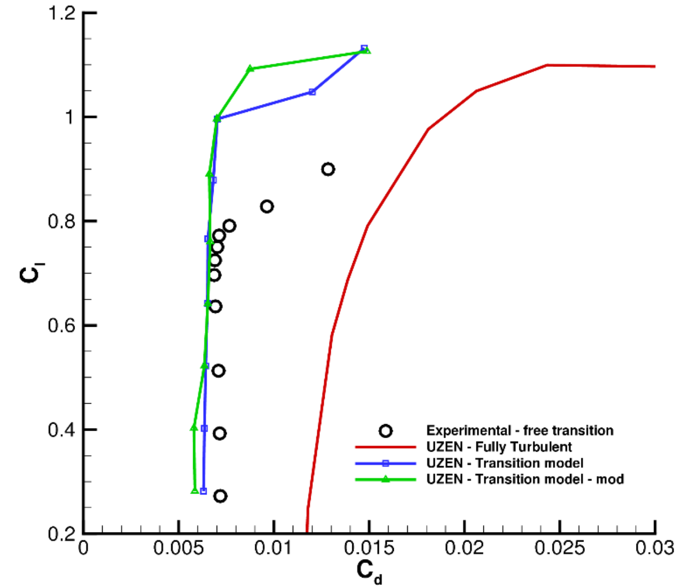
- Numerical results match experimental data

Upper side:

- Sudden upstream movement of transition location with α present in both experiments and CFD
- Original model: good agreement except for $\alpha = 6°$ and $\alpha = 7°$
- Modified model: betters solutions at $\alpha = 6°$ and $\alpha = 7°$ but worsens at $\alpha = 8°$

S809 Airfoil





C_d and C_l show a shift wrt experimental data

Fully turbulent results (red line) provide a higher drag coefficient than the experimental one

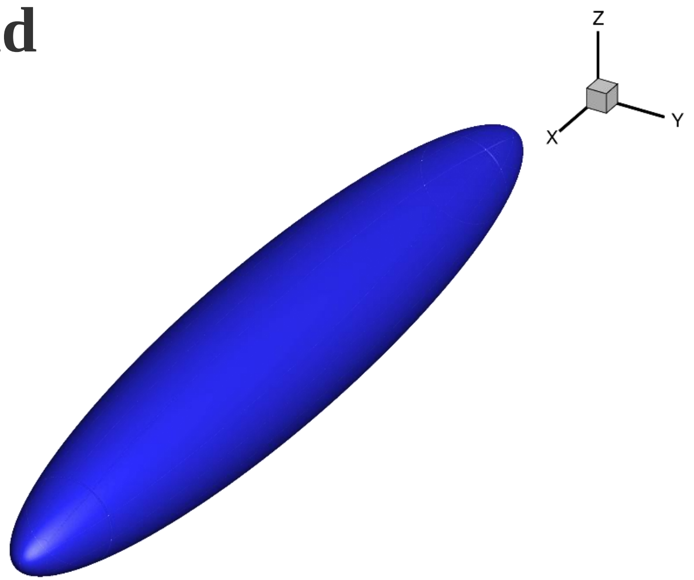
Original transition model (blue line) good comparison up to Cl=0.8

Transition model with modification proposed by Colonia et al.[1,2] (green line) are comparable with the original model.

1. Colonia, S., Leble, V., Steijl, R., and Barakos, G., "Calibration of the 7—Equation Transition Model for High Reynolds Flows at Low Mach," Journal of Physics: Conference Series, Vol. 753, Sep 2016
2. Colonia, S., Leble, V., Steijl, R., and Barakos, G., "Assessment and Calibration of the γ-Equation Transition Model at Low Mach," AIAA Journal, Jan 2017

3D Flow

6:1 Prolate spheroid



- M=0.13
- Re=6.50 x 10^6 (on a length L = 1.0 m)
- α=5°, 10°, 15°
- Tu=0.15%
- μ_t/μ=0.1

Grid:

C topology, 16 blocks structured type

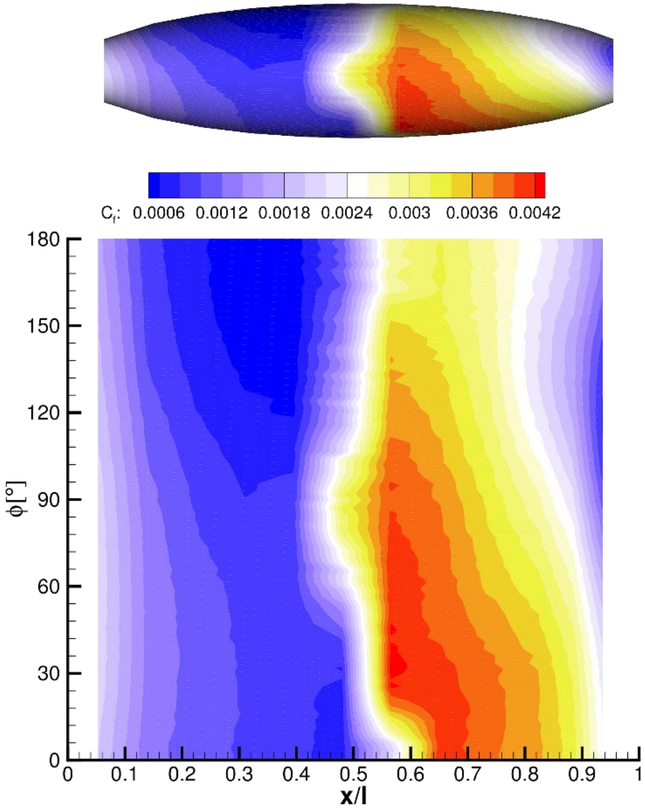
Farfield set at 1000 chords

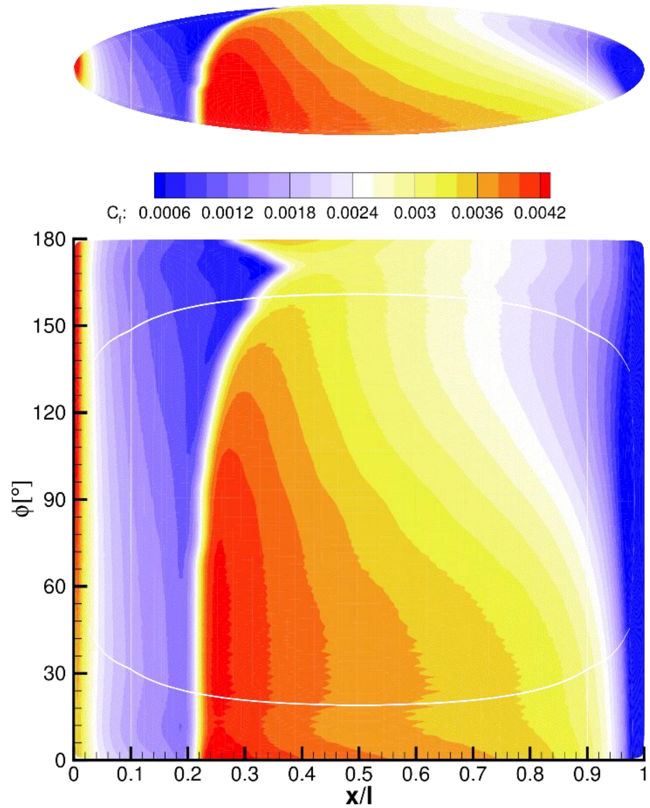
Approx. 8 x 10^6 cells

6:1 Prolate spheroid

Skin friction distribution

α=5°





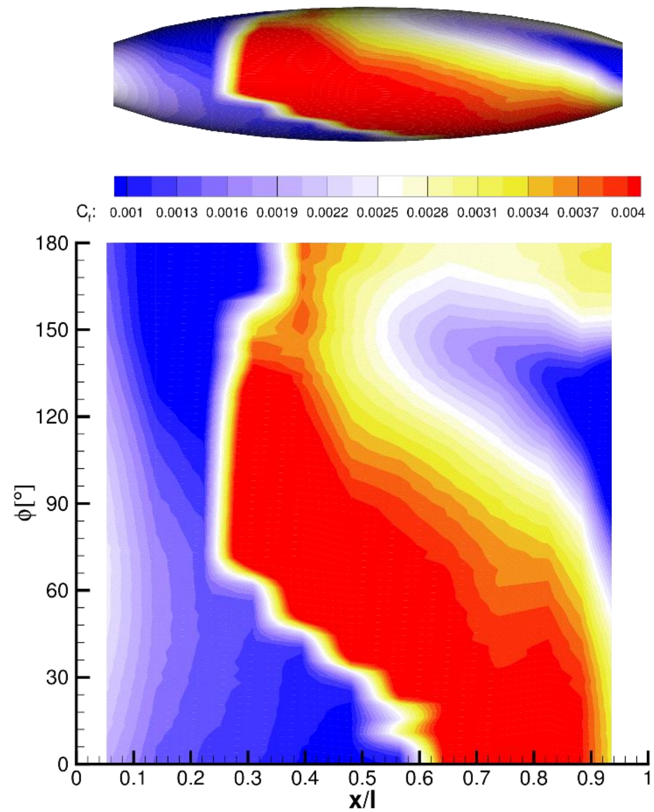
Transition onset at α = 5° is predicted too far upstream

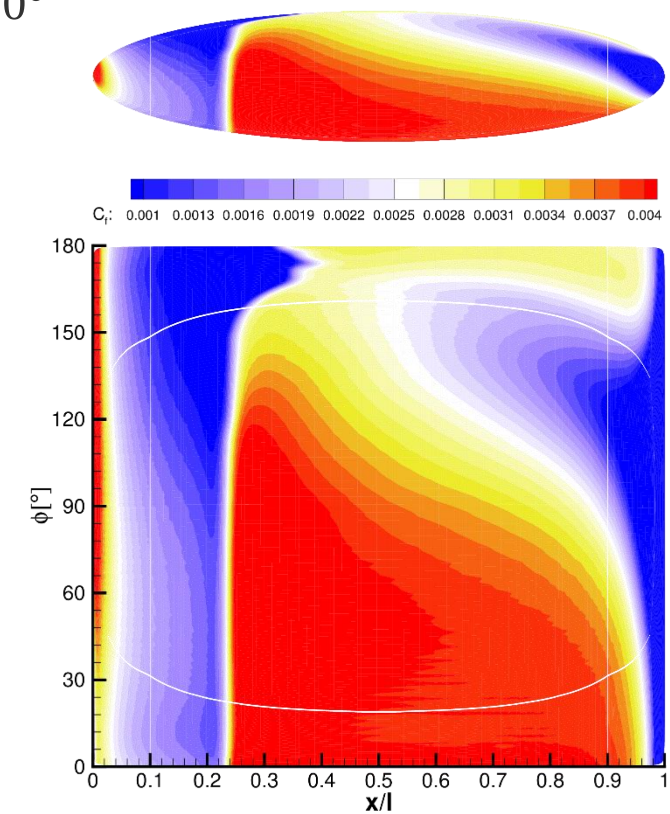
Good agreement on leeward side

6:1 Prolate spheroid

Skin friction distribution

α=10°





Good agreement with experiments, except leeward region $0° \leq \phi \leq 60°$

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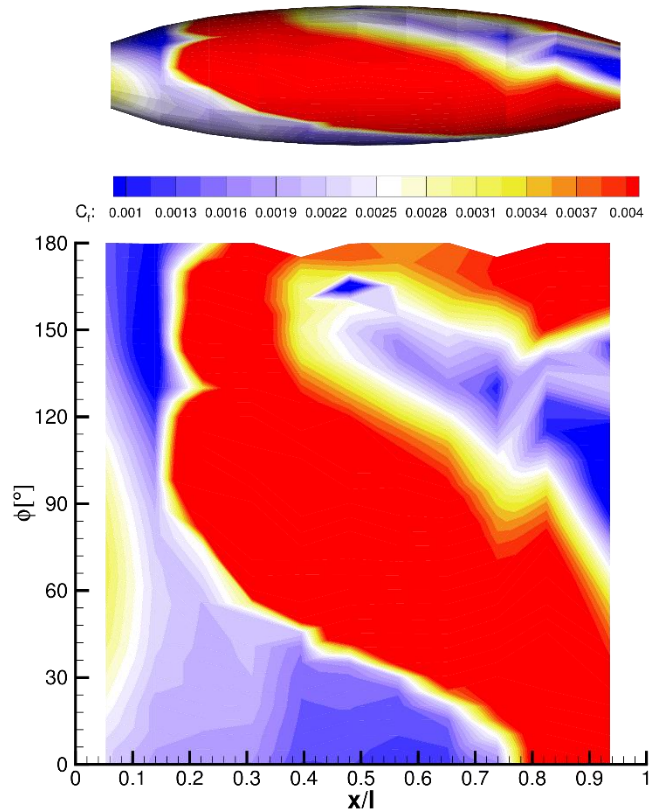
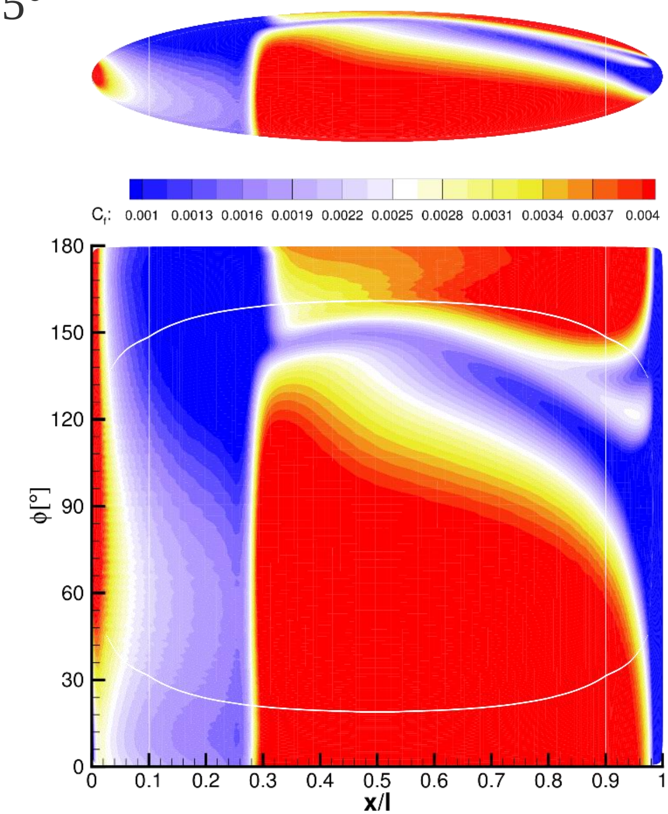
6:1 Prolate spheroid

Skin friction distribution

$\alpha=15°$





Transition is predicted slightly downstream

Good agreement with experiments, except region $0° \leq \phi \leq 60°$

Conclusions

- Transition model based on intermittency function γ implemented in the UZEN in-house developed flow solver

- Assessment for 2D and 3D test cases:
  - ✓ satisfactory results
  - ✓ ERCOFTAC T3A and T3B test cases
    - Dependence on freestream turbulent variables
  - ✓ S809 airfoil
    - Original and a modified version of the model applied
    - Separation bubbles and transition abscissa well predicted
  - ✓ 6:1 prolate spheroid
    - Good agreement on leeward side at all incidences
    - Some discrepancies while on windward side

Future Activities

Focus will be:

- simulation of long separation bubbles, e.g. SD7003 airfoil,
- implement correlation functions for the crossflow instabilities[1,2]

1. Grabe, C. and Krumbein, A., "Extension of the $\gamma - Re\theta t$ Model for Prediction of Crossflow Transition," 52nd Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics (AIAA), Jan 2014.
2. Grabe, C., Shengyang, N., and Krumbein, A., "Transition Transport Modeling for the Prediction of Crossflow Transition," 2016.